GEOLOGY AND
EXPLORATION OF THE

NATIONAL PETROLEUM RESERVE IN ALASKA,

1974 to 1982

USGS tent camp at Drenchwater Creek, East Ramparts, De Long Mountains, Alaska, August 1951. Copyrighted painting, used by permission of Marvin D. Mangus, Anchorage, Alaska.

Geology and Exploration of the National Petroleum Reserve in Alaska, 1974 to 1982

GEORGE GRYC, Editor

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Studies of the stratigraphy, petrology, structure, geochemistry, and hydrocarbon resources contribute to a portrait of the geology and petroleum potential of the National Petroleum Reserve in Alaska

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FOREWORD

Few regions have had as long, interesting, and complicated a history of exploration for mineral resources, particularly petroleum, as the Arctic Slope of Alaska. Oil seepages along the Arctic coast were reported in the early 1900's, and the U.S. Geological Survey (USGS) began mapping the region in 1901. Prospecting permits were filed by commercial interests as early as 1921, and in 1923 President Harding, anticipating a need for oil for the U.S. Navy, set aside the western half of the Arctic Slope as Naval Petroleum Reserve No. 4 (NPR-4), more recently redesignated as the National Petroleum Reserve in Alaska (NPRA). Exploration by both the federal government and industry continued, culminating in 1968 in the discovery of North America's largest oil field at Prudhoe Bay.

Throughout this long history, the U.S. Geological Survey, in keeping with its chartered responsibilities, has been the principal source for geological and geophysical information concerning the Arctic Slope and has participated in many aspects of the exploration and development of its petroleum resources. The accumulated information can be found in a long list of USGS publications. The gradual building of this knowledge base, culminating in a major discovery, is a fascinating case history and demonstrates again the long lead time required to find and develop mineral resources.

The USGS published the first geologic map and description of the Reserve in 1930, following a reconnaissance survey of NPR-4 made at the request of the U.S. Navy. Anticipating a wartime need for more domestic reserves of oil, the Navy undertook a major exploration program from 1944 to 1953, using the latest techniques of geophysical surveys and drilling. Again, the USGS provided the geologic support and documented all of the exploration activities in a series of USGS professional papers. This "Pet-4" program pioneered many techniques for petroleum exploration in the Arctic. Oil and gas accumulations were discovered, but all were too small for commercial development in such a remote and difficult region.

The drilling at Prudhoe Bay provided new geologic data and a new geologic model for exploration in NPR-4. Stimulated by the Prudhoe Bay discovery and spurred on by the OPEC oil embargo of 1973 the U.S. Navy began a second exploration of NPR-4 in 1974.

After the Pet-4 program was terminated in 1953, the USGS continued its geologic mapping in areas adjacent to the Reserve, especially in the Brooks Range. Integrating this information with data from Prudhoe Bay, the USGS published new interpretations of the framework geology and the potential mineral resources of northern Alaska. These publications not only provided possible new approaches to petroleum exploration but led in addition to the discovery of a major zinc deposit in the Brooks Range just south of NPR-4. Extensive reserves of coal were also described in the western part of the Reserve and adjacent areas.

Following on the passage of the National Environmental Policy Act of 1970 and the Alaska Native Claims Act of 1971, the U.S. Congress passed the Naval Petroleum Reserves Production Act of 1976. This Act transferred the responsibility for the newly redesignated NPRA to the Department of the Interior (DOI), directed the continuation of the exploration programs, and mandated a series of studies on all the resources and future management of the Reserve. The contract for the ongoing U.S. Navy exploration program was also transferred, and DOI directed the USGS to manage those activities. Geophysical surveys were completed for the entire Reserve, more than 22,500 line kilometers (14,000 miles). Test wells were drilled systematically in all areas of the Reserve on the basis of prospective geologic models or ''plays.'' Additional gas deposits were discovered in the Barrow area, and oil shows appeared in many of the tests. However, no major petroleum deposits were discovered. The Barrow gas deposits were developed to supply the local community and federal establishments, and a major cleanup program was completed in areas disturbed by previous drilling and other federal activities. The federal exploration program was terminated and a leasing program was authorized by Congress in 1981.

All of the geological and geophysical information that was collected during the exploration program supervised by the USGS from 1976 to 1982 was released to the public as it was accumulated and organized. Much of the subsurface data is in digital format as well as in hard (printed) copy. The major contractors prepared final technical reports, and these too were released to the public. Thus all basic information on the NPR-4/NPRA has been and continues to be available. The publication of the present volume summarizes much of this information and documents several ongoing USGS research projects that were begun during the exploration program or that have special significance to the geology of the NPRA. The U.S. Geological Survey has thus continued its long-term commitment to publish geological and geophysical information on this interesting and important region in the U.S. Arctic.

Dallas L. Peck
Director, U.S. Geological Survey

CONTENTS

Foreword Dallas L. Peck III

EXPLORATION HISTORY

Chapter 1. Introduction and role of the U.S. Geological Survey
George Gryc 1

2. History of exploration in the National Petroleum Reserve in Alaska, with emphasis on the period from 1975 to 1982
John F. Schindler 13

RESOURCE ASSESSMENT

Chapter 3. Comparison of six assessments of the hydrocarbon resources of the the National Petroleum Reserve in Alaska
Kenneth J. Bird and Richard B. Powers 77

4. The geologic basis for appraising undiscovered hydrocarbon resources in the National Petroleum Reserve in Alaska by the play-appraisal method
Kenneth J. Bird 81

5. Methods for assessing the petroleum resources in the National Petroleum Reserve in Alaska
Betty M. Miller 117

6. Policy analyses of the National Petroleum Reserve in Alaska—methods and applications
Paul Bugg, Stanley Miller, and Loring P. White 129

GEOLOGIC FRAMEWORK

Chapter 7. Stratigraphy, structure, and palinspastic synthesis of the western Brooks Range, northwestern Alaska
Charles F. Mayfield, Irvin L. Tailleur, and Inyo Ellersieck 143

8. Bedrock geologic map of the National Petroleum Reserve in Alaska
Charles F. Mayfield, Irvin L. Tailleur, and Charles E. Kirschner 187

9. Petroleum potential of representative stratigraphic and structural elements in the National Petroleum Reserve in Alaska
Charles E. Kirschner and Barbara A. Rycerski 191

10. Regional geology and petroleum potential of the United States Chukchi shelf north of Point Hope
Arthur Grantz and Steven D. May 209

11. Geologic framework, petroleum potential, and environmental geology of the United States Beaufort and northeasternmost Chukchi Seas
Arthur Grantz, Steven D. May, and David A. Dinter 231

Chapter 12. Depositional facies, petrography, and reservoir potential of the Fortress Mountain Formation (Lower Cretaceous), central North Slope, Alaska
Cornelius M. Molenaar, Robert M. Egbert, and Lee F. Krystinik 257

13. Sedimentology of the Nanushuk Group, North Slope
A. Curtis Huffman, Jr., Thomas S. Ahlbrandt, and Susan Bartsch-Winkler 281

14. Geology of the Upper Devonian and Lower Mississippian(?) Kanayut Conglomerate in the central and eastern Brooks Range
William P. Brosgé, Tor H. Nilsen, Thomas E. Moore, and J. Thomas Dutro, Jr. 299

15. Alaskan North Slope stratigraphic nomenclature and data summary for government-drilled wells
Kenneth J. Bird 317

16. Structure-contour and isopach maps of the National Petroleum Reserve in Alaska
Kenneth J. Bird 355

GEOCHEMISTRY

Chapter 17. Evaluation of petroleum source rocks in the National Petroleum Reserve in Alaska, using organic-carbon content, hydrocarbon content, visual kerogen, and vitrinite reflectance
Leslie B. Magoon and Kenneth J. Bird 381

18. Oil and gas source rocks in the National Petroleum Reserve in Alaska
George E. Claypool and Leslie B. Magoon 451

19. Organic geochemistry, hydrocarbon occurrence, and stratigraphy of government-drilled wells, North Slope, Alaska
Leslie B. Magoon, Kenneth J. Bird, George E. Claypool, Dennis E. Weitzman, and Richard H. Thompson 483

20. Organic facies and thermal maturity of sedimentary rocks in the National Petroleum Reserve in Alaska
Geoffrey S. Bayliss and Leslie B. Magoon 489

21. Geochemistry of oil occurrences, National Petroleum Reserve in Alaska
Leslie B. Magoon and George E. Claypool 519

22. Geochemistry of oil-field water from the North Slope
Yousif K. Kharaka and William W. Carothers 551

23. Inorganic chemical analyses of black shale from wells in the National Petroleum Reserve in Alaska
William P. Brosgé and Irvin L. Tailleur 563

24. Helium surveying, a geochemical exploration technique for petroleum on the North Slope
Alan A. Roberts and Kimberley I. Cunningham 583

GEOPHYSICS

Chapter 25. Depositional history and seismic stratigraphy of Lower Cretaceous rocks in the National Petroleum Reserve in Alaska and adjacent areas
Cornelius M. Molenaar 593

Chapter 26. Low-level aeromagnetic surveying for petroleum in Arctic Alaska
Terrence J. Donovan, John D. Hendricks, Alan A. Roberts, and Patricia Termain Eliason 623

27. Cretaceous remagnetization of Paleozoic sedimentary rocks in the Brooks Range, Alaska
John W. Hillhouse and Sherman Grommé 633

28. Temperature and depth of permafrost on the Arctic slope of Alaska
Arthur H. Lachenbruch, John H. Sass, Lawrence A. Lawver, Max C. Brewer, B. Vaughn Marshall, Robert J. Munroe, John P. Kennelly, Jr., S. Peter Galanis, Jr., and Thomas H. Moses, Jr. 645

PALEONTOLOGY

Chapter 29. Distribution of large-scale depositionally related biostratigraphic units, National Petroleum Reserve in Alaska
Michael B. Mickey and Hideyo Haga 657

30. Megafossil biostratigraphy of some deep test wells, National Petroleum Reserve in Alaska
J. Thomas Dutro, Jr., and Norman J. Silberling 667

31. Early Mississippian (Tournaisian) ostracodes from the Lisburne test well, northern Alaska
Israel Gregory Sohn 687

32. Distribution patterns of facies, radiolarians, and conodonts in the Mississippian to Jurassic siliceous rocks of the northern Brooks Range, Alaska
Benita L. Murchey, David L. Jones, Brian K. Holdsworth, and Bruce R. Wardlaw 697

33. Radiolarian biostratigraphy of the Otuk Formation in and near the National Petroleum Reserve in Alaska
Charles D. Blome, Katharine M. Reed, and Irvin L. Tailleur 725

34. Paleozoic radiolarian biostratigraphy of the northern Brooks Range, Alaska
Brian K. Holdsworth and Benita L. Murchey 777

RESERVOIR ROCKS

Chapter 35. Sandstone petrography of the Nanushuk Group and Torok Formation
Susan Bartsch-Winkler and A. Curtis Huffman, Jr. 801

36. Stratigraphy and diagenetic alteration of Ellesmerian sequence siliciclastic rocks, North Slope, Alaska
Peter C. van de Kamp 833

SPECIAL STUDIES

Chapter 37. The U.S. Geological Survey-Bureau of Land Management cultural resources program in the National Petroleum Reserve in Alaska, 1977-1981
Edwin S. Hall, Jr., and Robert Gal 859

38. Engineering geology studies in the National Petroleum Reserve in Alaska
Reuben Kachadoorian and Frederick E. Crory 899

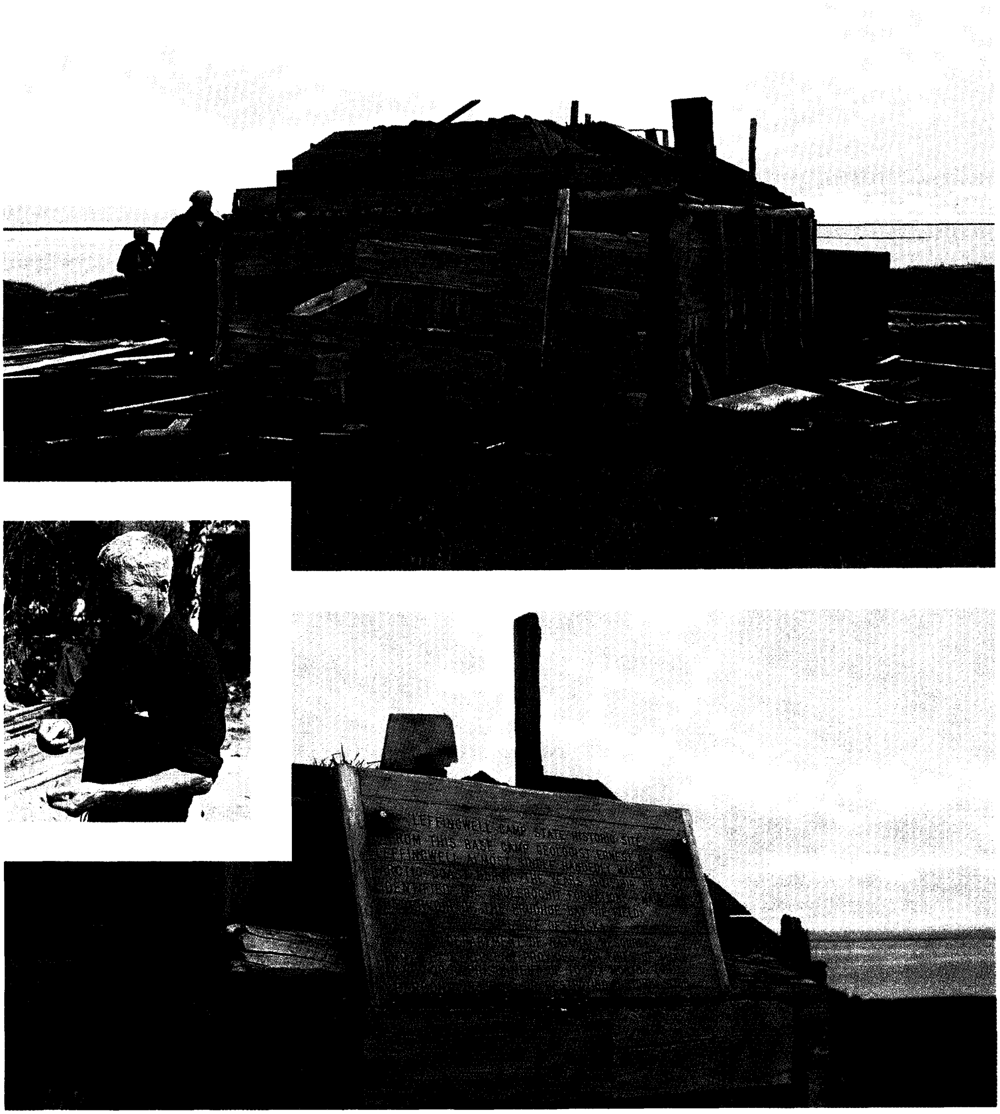
39. The National Petroleum Reserve in Alaska computer data and graphics system—an aid to geologic interpretation
Larry A. Wilcox, Theresa A. Coit, and Leslie B. Magoon 923

PLATES

[In separate box]

PLATE 2.1. The National Petroleum Reserve in Alaska showing geographic regions and well locations.
7.1. Allochthon map of the western Brooks Range, Alaska.
7.2. Cross sections of the western Brooks Range, Alaska.
7.3. Palinspastic map of the western Brooks Range, Alaska, just before the Brooks Range orogeny.
7.4. Hypothetical plate-tectonic scheme for the Brooks Range orogeny.
8.1. Bedrock geologic map of the National Petroleum Reserve in Alaska.
8.2. Cross sections to accompany the bedrock geologic map of the National Petroleum Reserve in Alaska.
9.1. Structural provinces and structural and stratigraphic elements in the National Petroleum Reserve in Alaska.
9.2. Selected structural and stratigraphic features interpreted from regional reflection seismic lines in the National Petroleum Reserve in Alaska.
9.3. Correlation sections A-A′ and B-B′ across the northern part of the Arctic platform in the National Petroleum Reserve in Alaska.
9.4. Correlation sections C-C′ and D-D′ across the northern part of the Arctic platform in the National Petroleum Reserve in Alaska.
9.5. Correlation sections E-E′ and F-F′ across the northern part of the Arctic platform in the National Petroleum Reserve in Alaska.
9.6. Correlation sections G-G′ and H-H′ across the northern part of the Arctic platform in the National Petroleum Reserve in Alaska.
9.7. Correlation section I-I′ across the northern part of the Arctic platform in the National Petroleum Reserve in Alaska.
14.1. Generalized geologic map showing distribution of the members of the Kanayut Conglomerate and the Noatak Sandstone in the central and eastern Brooks Range, Alaska.
19.1. Geology, geochemistry, and hydrocarbon occurrence in Iko Bay No. 1 and East Teshekpuk No. 1 wells, North Slope, Alaska.
19.2. Geology, geochemistry, and hydrocarbon occurrence in Tunalik No. 1 well, North Slope, Alaska.
19.3. Geology, geochemistry, and hydrocarbon occurrence in Kugrua No. 1 well, North Slope, Alaska.
19.4. Geology, geochemistry, and hydrocarbon occurrence in Peard No. 1 and Kuyanak No. 1 wells, North Slope, Alaska.
19.5. Geology, geochemistry, and hydrocarbon occurrence in South Barrow No. 3, Walakpa No. 1, and Walakpa No. 2 wells, North Slope, Alaska.
19.6A. Geology, geochemistry, and hydrocarbon occurrence in South Barrow No. 1, South Barrow No. 9, and South Barrow No. 16 wells, North Slope, Alaska.
19.6B. Geology, geochemistry, and hydrocarbon occurrence in South Barrow No. 2, South Barrow No. 4, and South Barrow No. 13 wells, North Slope, Alaska.
19.6C. Geology, geochemistry, and hydrocarbon occurrence in Avak No. 1, South Barrow No. 15, South Barrow No. 12, and South Barrow No. 19 wells, North Slope, Alaska.
19.6D. Geology, geochemistry, and hydrocarbon occurrence in South Barrow No. 14, South Barrow No. 17, South Barrow No. 18, and South Barrow No. 20 wells, North Slope, Alaska.
19.7. Geology, geochemistry, and hydrocarbon occurrence in North Simpson No. 1, West Dease No. 1, and Tulageak No. 1 wells, North Slope, Alaska.
19.8. Geology, geochemistry, and hydrocarbon occurrence in Simpson No. 1 and South Simpson No. 1 wells, North Slope, Alaska.
19.9. Geology, geochemistry, and hydrocarbon occurrence in East Simpson No. 1 and East Simpson No. 2 wells, North Slope, Alaska.
19.10. Geology, geochemistry, and hydrocarbon occurrence in Drew Point No. 1 and J.W. Dalton No. 1 wells, North Slope, Alaska.

PLATE 19.11. Geology, geochemistry, and hydrocarbon occurrence in W.T. Foran No. 1 and Cape Halkett No. 1 wells, North Slope, Alaska.
19.12. Geology, geochemistry, and hydrocarbon occurrence in North Kalikpik No. 1 and Atigaru Point No. 1 wells, North Slope, Alaska.
19.13. Geology, geochemistry, and hydrocarbon occurrence in Meade No. 1 and South Meade No. 1 wells, North Slope, Alaska.
19.14. Geology, geochemistry, and hydrocarbon occurrence in Topagoruk No. 1 and East Topagoruk No. 1 wells, North Slope, Alaska.
19.15. Geology, geochemistry, and hydrocarbon occurrence in Ikpikpuk No. 1 well, North Slope, Alaska.
19.16. Geology, geochemistry, and hydrocarbon occurrence in South Harrison Bay No. 1 well, North Slope, Alaska.
19.17. Geology, geochemistry, and hydrocarbon occurrence in Awuna No. 1 and Kaolak No. 1 wells, North Slope, Alaska.
19.18. Geology, geochemistry, and hydrocarbon occurrence in Oumalik No. 1 and East Oumalik No. 1 wells, North Slope, Alaska.
19.19. Geology, geochemistry, and hydrocarbon occurrence in North Inigok No. 1 and Koluktak No. 1 wells, North Slope, Alaska.
19.20. Geology, geochemistry, and hydrocarbon occurrence in Fish Creek No. 1 and West Fish Creek No. 1 wells, North Slope, Alaska.
19.21. Geology, geochemistry, and hydrocarbon occurrence in Inigok No. 1 well, North Slope, Alaska.
19.22. Geology, geochemistry, and hydrocarbon occurrence in Square Lake No. 1, Wolf Creek No. 1, Wolf Creek No. 3, and Titaluk No. 1 wells, North Slope, Alaska.
19.23. Geology, geochemistry, and hydrocarbon occurrence in Lisburne No. 1 well, North Slope, Alaska.
19.24. Geology, geochemistry, and hydrocarbon occurrence in Knifeblade No. 1, Knifeblade No. 2A, and Umiat No. 1 wells, North Slope, Alaska.
19.25. Geology, geochemistry, and hydrocarbon occurrence in Seabee No. 1 well, North Slope, Alaska.
19.26. Geology, geochemistry, and hydrocarbon occurrence in Umiat No. 2 and Umiat No. 11 wells, North Slope, Alaska.
19.27. Geology, geochemistry, and hydrocarbon occurrence in Gubik No. 1, Gubik No. 2, and Grandstand No. 1 wells, North Slope, Alaska.
19.28. Vitrinite reflectance and hydrocarbon data for Tunalik No. 1 well, North Slope, Alaska.
19.29. Vitrinite reflectance and hydrocarbon data for Peard No. 1 and Kuyanak No. 1 wells, North Slope, Alaska.
19.30. Vitrinite reflectance and hydrocarbon data for Walakpa No. 1 and Walakpa No. 2 wells, North Slope, Alaska.
19.31. Vitrinite reflectance and hydrocarbon data for West Dease No. 1 and Tulageak No. 1 wells, North Slope, Alaska.
19.32. Vitrinite reflectance and hydrocarbon data for East Simpson No. 1 and East Simpson No. 2 wells, North Slope, Alaska.
19.33. Vitrinite reflectance and hydrocarbon data for J.W. Dalton No. 1 and South Meade No. 1 wells, North Slope, Alaska.
19.34. Vitrinite reflectance and hydrocarbon data for Ikpikpuk No. 1 well, North Slope, Alaska.
19.35. Vitrinite reflectance and hydrocarbon data for Awuna No. 1 well, North Slope, Alaska.
19.36. Vitrinite reflectance and hydrocarbon data for North Inigok No. 1 and Koluktak No. 1 wells, North Slope, Alaska.
19.37. Vitrinite reflectance and hydrocarbon data for Inigok No. 1 well, North Slope, Alaska.
19.38. Vitrinite reflectance and hydrocarbon data for Lisburne No. 1 well, North Slope, Alaska.
19.39. Vitrinite reflectance and hydrocarbon data for Seabee No. 1 well, North Slope, Alaska.
36.1. Isopach maps for three stratigraphic intervals in coastal plain wells, North Slope, Alaska.



This base camp was used by Ernest de K. Leffingwell (inset), 1907 to 1914, as he mapped the Canning River region and the Arctic coast from Point Barrow to the U.S.-Canada border. Photographs by George Gryc.

EXPLORATION HISTORY

The National Petroleum Reserve in Alaska (NPRA), an area as large as the State of Indiana, lies north of the Arctic Circle on the northern slope of the Brooks Range. The NPRA is cut off from the rest of Alaska by the jagged peaks, up to 2,750 m (9,000 ft) in elevation, of the east-west-trending Brooks Range.

Exploration in this remote and isolated region has been and continues to be driven by the hunt for oil—first whale oil and now rock oil, or petroleum. Oil seepages at Point Simpson on the Arctic Coast were reported by whalers in the early 1900's, and the hunt for commercial oil deposits began as early as 1921. In 1923 the NPRA was set aside by Presidential Order as a future reserve for the U.S. Navy.

The two chapters that follow describe part of the long history of exploration by the federal government in the NPRA.

1. INTRODUCTION AND ROLE OF THE U.S. GEOLOGICAL SURVEY

By GEORGE GRYC

BACKGROUND

The chapters that follow present the results of research and management studies that were undertaken by the U.S. Geological Survey (USGS) to support the 1974-1981 exploration program in the National Petroleum Reserve in Alaska (NPRA), formerly the Naval Petroleum Reserve No. 4 (NPR-4). The NPRA-related activities, especially the study and interpretation of geological, geophysical, and geochemical data, supplemented ongoing USGS studies and thus fulfilled, in part, the general mission of the USGS, which is to map the geology and assess the natural resources of the Nation.

This most recent exploration program was begun in NPR-4 by the U.S. Navy in 1974. In 1975 the U.S. Navy awarded a management contract to Husky Oil NPR Operations, Inc., which joined with Tetra Tech, Inc., and Geophysical Services, Inc., to conduct, compile, and interpret the geophysical surveys. The drilling of test wells and other operational and logistical activities were subcontracted by Husky to several different companies.

The Naval Petroleum Reserves Production Act of 1976 transferred responsibility for the newly redesignated NPRA and all in-force contracts to the Department of the Interior, which in turn assigned the exploration program and other related activities to the USGS beginning on June 1, 1977. The program was terminated by Congress in 1981, and leasing of the lands in the NPRA was authorized.

When the USGS assumed overall supervision of the program, a policy was initiated to make all acquired technical data public as promptly as possible. Consequently, weekly drilling reports were issued, and the results of the geophysical surveys were made available as soon as the data had been put into usable form. This information was incorporated into several oil-industry service files and is available in both hard copy and computer format. When the program was terminated, final reports were required of Husky Oil NPR Operations, Inc., and Tetra Tech, Inc. Most of these reports were immediately released to the public through the National Geophysical Data Center, National Oceanic and Atmospheric Administration, in Boulder, Colorado 80303. Thus nearly all the technical data were available in 1981, when the exploration program was terminated and the leasing program was authorized by Congress.

When the USGS was assigned the overall direction of the exploration program in 1977, in-house studies were begun to provide the knowledge on which to base informed and objective guidance. The studies ranged from detailed stratigraphy and geochemistry to synthesis and interpretation of the geological framework of the NPRA and adjacent areas. In addition, the large volume and rapid accumulation of this new information stimulated research in data storage and processing.

As a result of these studies, 39 separate papers have been prepared by USGS authors and coworkers. Although these papers cover a wide range of subjects, they are here published in one volume for the convenience of the user and to document as completely as possible the results of the program supervised by the USGS. These reports also build upon and add to the geologic knowledge of Arctic Alaska.

These 39 chapters are organized into sections entitled:

- Exploration history
- Resource assessment
- Geologic framework
- Geochemistry
- Geophysics
- Paleontology
- Reservoir rocks
- Special studies

ACKNOWLEDGMENTS

This volume of 39 papers by 62 authors, prepared over a period of several years, presented many difficult production problems. The authors are credited and acknowledged in the individual chapters. Their contributions and patience are much appreciated. However, the momentum and continuity that brought this volume to completion is largely the result of the dedicated work of Mary M. Brosgé, Catherine C. Campbell, and Peter H. Stauffer. For their skill, "know-how," patience, and perseverance, I express my special admiration and deep appreciation.

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EXPLORATION HISTORY

The discovery and development of northern Alaska's petroleum resources began in the early years of the 20th century with expeditionary traverses by USGS topographers and geologists and other intrepid explorers. The information that was gathered was recorded in USGS publications, including those by Schrader (1904), Brooks (1909), and Leffingwell (1919). These early reports, and the perceived potential shortage of oil for the Nation's navy, led President Warren G. Harding to set aside the Naval Petroleum Reserve No. 4 in 1923.

Traversing hundreds of miles by foot, horse, dog team, and river boat, topographers and geologists of the USGS surveyed the Reserve for the first time from 1923 through 1926. The first maps of the Reserve, accompanied by a description of the geology and an assessment of the mineral resources, were prepared by Smith and Mertie and published in 1930 as USGS Bulletin 815. Their report includes an excellent summary of earlier explorations in the region.

The first modern program of petroleum exploration in NPR-4, involving drilling and geophysical and geological surveys, was started as a wartime measure by the U.S. Navy in 1944. From 1945 through 1952, 45 shallow core tests and 36 relatively shallow test wells were drilled for a total of 51,590 m (169,250 ft) of borehole. One large and two small oil accumulations, two small gas accumulations, and three possible gas accumulations were discovered. The Barrow gas deposit was developed for local use. About 5,370 line kilometers (3,357 mi) of seismic-reflection surveys and 625 line kilometers (391 mi) of seismic-refraction surveys were completed within and adjacent to the Reserve. Virtually all of northern Alaska was mapped geologically and topographically at reconnaissance scales. Field traverses were first made by foot and river boat, then by tracked vehicle, and in the final year by helicopter. The USGS provided the geologic support for the program and prepared final reports when the program was recessed in 1953. These reports—U.S. Geological Survey Professional Papers 301 through 305—provide a history of the program, all of the technical data resulting from drilling, maps, reports of the geologic field studies, and a summary of the geophysical surveys. Professional Paper 301 by John C. Reed (1958) is an excellent summary of the program as well as a year-by-year project history. In addition to these publications, all of the geophysical reports and profiles are available as open-file reports, and the subsurface cores and cuttings are available for public inspection and study in Anchorage, Alaska.

The next exploration program was stimulated by the oil discovery at Prudhoe Bay in 1968 and the Organization of Petroleum Exporting Countries (OPEC) oil embargo that began in 1973. In 1974 the U.S. Navy allotted funds in their Naval Petroleum Reserve budget to begin a small exploratory program in NPR-4, and in 1975 Congress approved and allotted funds for a much larger program. Also in 1975, the U.S. Navy awarded a 5-yr contract to Husky Oil NPR Operations, Inc., to manage and conduct a full-scale petroleum exploration program in NPR-4.

The Naval Petroleum Reserves Production Act of 1976, Public Law 94-258, renamed the Reserve the National Petroleum Reserve in Alaska and assigned several tasks to the Department of the Interior (DOI). As of June 1, 1977, three of these tasks were reassigned to the U.S. Geological Survey. They were: (1) to continue the program of exploration begun by the U.S. Navy, including the prime management contract with Husky Oil NPR Operations, Inc.; (2) to continue the operation and management of the Barrow gas fields that supply fuel to the Barrow community and nearby Government facilities; and (3) to complete the cleanup program begun by the U.S. Navy in the Reserve and adjacent areas. The Act also named the U.S. Geological Survey to a task force "to conduct a study to determine the values of, and best uses for, the lands contained in the reserve ***" (Section 105c, paragraphs 1 and 2).

Although the U.S. Geological Survey had had a major role in the exploration of northern Alaska and the NPR-4 since the turn of the century, these new assignments in the NPRA contained some unusual aspects that did not fit into its regular organization and program. Because of the increased awareness of environmental problems (National Environmental Policy Act of 1969) and the changes in land status and ownership (Alaska Statehood Act of 1958 and The Alaska Native Claims Settlement Act of 1971), the program in the NPRA took on new significance and had high public visibility. It was anticipated that there would be changes in the management of the NPRA within a year or two depending on the results of the studies mandated by Congress in Public Law 94-258, Sections 105b and 105c.

The Arctic setting required special advance planning and accommodation to the seasons. Costs of such operations in the Arctic are 7 to 10 times greater than in the States to the south. The contract with Husky Oil NPR Operations, Inc., was also transferred to the USGS, and when the USGS took over the program in 1977, costs already totaled nearly $100 million. To accommodate all of these unusual aspects, the USGS decided to plan and supervise the program through a special, single-purpose task force, the Office of National Petroleum Reserve in Alaska (ONPRA), reporting to the Director's Office.

The ONPRA was organized with program and budget operations located in the USGS national headquarters, Reston, Virginia; a research and exploration unit in the Western Regional Center in Menlo Park, California; and an operations center in Anchorage, Alaska. The prime contractor, Husky, was headquartered in Cody, Wyoming, and maintained a project and operations office in Anchorage and an exploration office in Houston, Texas—a major center for petroleum exploration services. Oil-field supplies and materials were shipped by land to Seattle, Washington, and then by sealift to the Husky staging base at Lonely on the Arctic coast. This complex network of bases and communications centers is typical of petroleum exploration and development in the Arctic.

Knowing that the field program would be terminated soon and a new management structure established, the ONPRA staff was kept to a minimum, and there was virtually no research staff. For any research program it was necessary to reach out to other USGS offices and set up cooperative projects, many of which are here recorded. A small fraction of the exploration funding—actually less than 1 percent—was used for these studies.

Operations in the field, such as drilling and geophysical surveys, were performed by subcontractors through Husky, the prime contractor. The compilation and interpretation of the subsurface and seismic data were also done by contract, primarily by Geophysical Services, Inc., and Tetra Tech, Inc.—both located in Houston. In addition, there was a need for research in aspects of the program not directly tied to the operational schedules and having possible long-range application. Many of these research programs coincided with the Survey's chartered responsibilities to map the geology of the United States, to assess the mineral and water resources, and to study and interpret geologic processes.

Despite the complexities and difficulties, the exploration of the NPRA and the other mandates of the Naval Petroleum Reserves Production Act were completed at the pace and on the schedule set by Congress. A total of 28 test wells were drilled between 1974 and 1982, of which 7 were under U.S. Navy management. Indications of oil and (or) gas were found in nearly all the test wells, but no deposits of sufficient size to warrant development were discovered. In the Walakpa No. 1 well, a gas deposit was discovered that is certainly of sufficient size for local development and use. In addition to the 28 test wells, 6 exploratory and development wells were drilled in the Barrow area to supplement the local gas supply. Systematic sampling and logging of more than 75,000 m (250,000 ft) of borehole have defined the subsurface geology of an area of about 96,000 km^2 (37,000 mi^2), and nearly 24,000 line kilometers (15,000 mi) of seismic surveys was completed and interpreted. All of this information is now available to the public; the reports presented in this volume add useful compilations and further interpretations.

A more complete history of what John F. Schindler has designated the second exploration (1975 to 1982) of the Reserve is included in this volume (chapter 2). As the former chief environmental officer for Husky Oil NPR Operations, Inc., Schindler played an important role and had an intimate knowledge of the program. His report was prepared originally for the Husky final report; it is included here to provide a chronological sequence for the acquisition of the technical data presented in other chapters of this volume.

RESOURCE ASSESSMENT

The Naval Petroleum Reserves Production Act of 1976 directed the Secretary of the Interior to "*** commence further petroleum exploration of the reserve as of the date of transfer ***" (Section 104d) and also to "*** establish a task force to conduct a study to determine the values of, and best uses for, the lands contained in the reserve ***" (Section 105c(2)) and mandated another study (Section 105b) "*** to determine the best overall procedures to be used in the development, production, transportation, and distribution of petroleum resources in the reserve." Thus Sections 105b and 105c added two new mandates, namely, not only assessment of the petroleum resources, but also evaluation of alternative management procedures and of the economic and environmental consequences of such procedures. Therefore, a numerical economic model and a resource assessment suitable for such modeling were essential. The exploration program also had to be designed to meet these objectives.

The U.S. Navy's exploration program plan in NPR-4 was outlined in an unpublished paper titled, "Engineering Plan for Assessment and Evaluation of Naval Petroleum Reserve No. 4, Alaska" dated March 1973 and updated in January 1975. The plan called for an assessment and evaluation of this large area by means of interdependent geophysical and geological studies and test-well drilling during two 5-yr "periods of activity—the first 5-year period primarily directed toward assessment of the projected extension of the pre-Cretaceous medium depth Prudhoe Bay production trend westward into the coastal region of NPR-4. Additionally, two deep-depth tests up to 23,000 ft (7,000 m) in the southern part of the Reserve are scheduled to establish a basis for a second 5-year period of deep-test evaluations in the more remote areas of the Reserve.'' The January 1975 update of this plan shortened the total timespan to 7 years but stressed assessment and evaluation of the entire area, stating that ''any discovery definition, reservoir evaluation, or production drilling is not within the scope of this plan.''

The traditional USGS methods of estimating petroleum resources used volumetric analyses, analogs based on subjective judgments, statistical analyses of drilling histories, or combinations of these. Such methods had long been used in assessing the Nation's resources, but they were difficult to reproduce and did not provide the details required by an economic model.

To meet the need for an assessment method suitable for economic modeling and an exploration strategy suitable for longer range planning, the USGS decided to use the ''play'' approach—a well-established industry technique. A ''play'' defines an area in which possible oil or gas deposits have similar characteristics, such as the same stratigraphic sequence, the same reservoir rock, and (or) the same trapping mechanisms.

Although the Navy's general program was already underway when the USGS assumed management, specifications for additional geophysical surveys and sites for test-well drilling had to be planned on a yearly basis. Furthermore, planning for supplies and materials a year in advance was required. Thus the play approach not only met the economic modeling required, but also provided the basis for advance planning.

Initially 11 plays were defined for program planning by the ONPRA staff. These were based largely on stratigraphy, but one—the southern disturbed belt—was based on structural criteria. When these were adapted for resource appraisal, 17 plays were defined. The geologic basis for these plays and their use in appraising the undiscovered hydrocarbon resources in the NPRA are described by Bird in this section (chapter 4).

In another paper, Bird and Powers (chapter 3) summarize and compare six assessments of the undiscovered hydrocarbon resources in the NPRA that were published during the period 1968-80. The assessments range from 0.2 to 10.7 billion bbl of recoverable crude oil and 0.8 to 78.7 trillion ft^3 of gas, and they show a downward trend from 1968 to 1980.

Miller (chapter 5) further describes the methods and procedures used for assessing the petroleum resources of the NPRA and discusses the geologic and exploration submodels developed from the resource appraisal. These submodels were then integrated with development and economic submodels using a Monte Carlo simulation.

The results of these simulations transformed the resource assessments into a format that was then used to simulate and test various management plans and policy decisions as required by Section 105b of the Act. Bugg, Miller, and White (chapter 6) describe this procedure and its use in the final paper of this section.

GEOLOGIC FRAMEWORK STUDIES

Planning a systematic petroleum exploration program or assessing the petroleum potential of a given region generally involves applying a reference model to the geologic knowledge available. This framework model is assembled from many detailed studies that are compiled and then synthesized and interpreted. As more details are added to the framework, both the validity of the details and that of the framework are tested. It is in this sense that several studies completed under the NPRA program are here included under the general heading ''Geologic Framework.''

The geologic framework for northern Alaska and the NPRA has been developed largely through the exploration for and assessment of petroleum resources. Although systematic geologic studies in the region started in the early 1900's, the first general framework studies, coupled with petroleum assessment, began in the NPR-4 in 1923 and were described by Smith and Mertie (1930). Mertie followed up on his studies in northern and central Alaska with a framework paper (Mertie, 1930) entitled ''Mountain Building in Alaska.''

The next giant step in the development of a geologic framework of the NPR-4 and northern Alaska began in 1944 with the U.S. Navy's oil exploration program. A large volume of geological and geophysical data was collected between 1944 and 1953 (Reed, 1958). As the work progressed, short papers and abstracts were published, and other papers were presented orally at scientific meetings. Payne (1948, 1955; see also Gryc and others, 1951) was particularly active in the building of a geologic framework for Alaska. Payne described for the first time the major tectonic elements of northern Alaska—the Brooks Range geanticline, Colville geosyncline, Barrow arch, and Barrow platform (later called the Arctic platform). He believed that this platform was the northern source for part of the rock sequence of Mississippian to early Mesozoic age in northern Alaska. The northern-source concept was of particular significance to subsequent petroleum exploration in the region.

Payne and others (1952) completed a structural and stratigraphic framework for northern Alaska, and their studies kindled a renewed interest in the geology and petroleum potential of the Arctic. In 1948, Eardley published a synthesis of Arctic geology and suggested the presence of a former landmass, which he called "Ancient Arctica," in the area that is now part of the Arctic Ocean basin. He postulated that the "Arctic Sea" was an "intra-shield mediterranean" that began to sink in Carboniferous time and that the surrounding land areas as well as the floor of the "Arctic Sea" were "continental crust material chiefly of shield character." He viewed the Brooks Range as an extension of the North American Cordillera. He questioned the northern source for "any of the sediments of the Northern Alaska trough" and suggested that they came from the early Brooks Range. Eardley was optimistic on the petroleum potential of the entire Arctic region.

The framework concepts of Payne and Eardley prevailed for many years, but after the NPR-4 exploration program was suspended in 1952, attention turned to the then largely unmapped Brooks Range. Geologic mapping by Jones and Grantz, Tailleur, Brosgé, Dutro, Reiser, and others began to document a complex thrusting history. Grantz and Jones (1964) described different facies in the foothills of the central Brooks Range that had been juxtaposed by thrust faulting and suggested that this was probably true elsewhere in northern Alaska. Tailleur and others (1966) described the presence in the western Brooks Range of several coeval rock sequences of unlike facies that had been juxtaposed by large-scale thrust faulting. Palinspastic reconstruction suggested displacements of tens and even hundreds of kilometers. Snelson and Tailleur (1968) reached similar conclusions after Snelson's independent mapping for an oil company. Although thrust faulting had been recognized in the Brooks Range by earlier mappers, such large-scale displacements as those proposed by Tailleur and Snelson had not been suggested. Stimulated by the writings of Carey (1958) and others, Tailleur (1969a, b, 1973; Tailleur and others, 1967; Tailleur and Snelson, 1968) began to apply the concepts of plate tectonics to the large-scale dislocations in the Brooks Range and to the origin of the Arctic Ocean Basin. He postulated that the Canada Basin of the Arctic Ocean was formed by post-Triassic rifting and that the Alaska-Chukchi continental edge rotated counterclockwise to its present position. These concepts provided a new framework not only for northern Alaska but also for all of Arctic North America.

The development of this new framework is here described in the paper by Mayfield, Tailleur, and Ellersieck (chapter 7). Also in this section is a new geologic map of the NPRA compiled by Mayfield, Tailleur, and Kirschner (chapter 8). On this map Kirschner and Rycerski (chapter 9) have identified representative structural and stratigraphic elements and have evaluated their petroleum potential.

In separate papers, Grantz and May (chapter 10) and Grantz, May, and Dinter (chapter 11) suggest a geologic framework for the shelf areas of the Beaufort and Chukchi Seas and evaluate their petroleum potential. Grantz and coauthors demonstrate the close relationship between the geology of the NPRA and the continental shelves; they stress the value of extrapolating the onshore geology offshore and vice versa.

The 1974-82 program in the NPRA emphasized exploration by means of geophysical surveys and drilling, whereas the earlier exploration programs of 1923-26 and 1944-53 included substantial geologic field and laboratory studies. Many of the stratigraphic and structural elements defined in those earlier programs (Payne and others, 1952) have stood the test of time. However, new concepts and techniques in sedimentology and especially in seismic stratigraphy have been applied, and old ideas have been modified or supplemented. The papers in this volume on the Fortress Mountain Formation by Molenaar (chapter 25) and Molenaar, Egbert, and Krystinik (chapter 12) and on the Nanushuk Group by Huffman, Ahlbrandt, and Bartsch-Winkler (chapter 13) have added to our knowledge of the genesis and depositional style of these rock units and thus have aided in subsurface projections and analyses of reservoir potential.

In the NPR-4 program of 1944-53, prospects deeper than 3,000 m (10,000 ft) were considered difficult to explore and probably uneconomical. Thus emphasis was placed on the study of shallower rock units, particularly those of Mesozoic age. As the exploration progressed and only small deposits were discovered, attention was turned to older rocks at fairly shallow depths along the Barrow arch and in the foothills. Prospects in these rocks had been identified and plans for test drilling were underway when the program was suspended. The discoveries in the Prudhoe Bay region opened the possibilities of large hydrocarbon deposits in older reservoirs. To provide additional information on these older formations, geologists returned to the areas where these rocks were exposed. The paper in this volume on the Kanayut conglomerate by Brosgé, Nilsen, Moore, and Dutro (chapter 14) documents some of the results of these studies.

The last two papers in the geologic framework section are by Bird and were prepared to provide a reference for stratigraphic nomenclature (chapter 15) and a synthesis of structural data (chapter 16), so that geologic information from previous and current studies in nearby areas can be readily integrated. They also provide a geologic framework for the preceding papers in this volume as well as for the geochemical data and source-rock studies that follow. These chapters will be helpful in efforts to integrate the geologic information in this and earlier USGS reports with the final reports by Husky Oil NPR Operations, Inc., and Tetra Tech, Inc., previously noted. They will be particularly important in studying the seismic-based contour maps of the Tetra Tech reports. The Tetra Tech maps are based on seismic reflections (parastratigraphic units), and Bird has adjusted these to stratigraphic boundaries established in the wells. In the preparation of these two reports he used the computerized data base that is described by Wilcox and others (chapter 39).

GEOCHEMISTRY

The three principal requirements for the accumulation of petroleum resources are a source, a trap, and a reservoir. Many geologists add and emphasize the need for a seal to prevent escape of hydrocarbons as a fourth requirement. The overall geologic history, particularly the history of the diagenesis and maturation of the sedimentary rocks, is likewise important.

These requirements were recognized early in the history of the NPRA by Smith and Mertie (1930). Mapping of geologic structures and delineation of potential traps were the major goals of the NPR-4 program from 1945 to 1952. Structure was mapped at the surface by geologic field parties, by photogeologists working with the first complete aerial photographic coverage of the Reserve (Fischer, 1952), and by geophysicists working with seismic reflection and refraction data (Dana, 1952; Woolson and others, 1962). Many potential traps, particularly anticlines, were defined and mapped, and several were drilled. One of these was the Umiat anticline, where a large oil field was found. The Barrow high was defined by seismic surveys, and test drilling led to the discovery of Alaska's longest producing hydrocarbon deposit—the South Barrow gas field. Potential reservoirs were sampled in the field and in the subsurface, and the samples were studied extensively in the laboratory (Krynine, 1952; Yuster, 1952). These studies demonstrated the paucity of good reservoir rocks and the problem caused by clayey matrices in the Cretaceous sequences.

Potential source rocks are described in the earliest reports on the region. For example, Schrader (1904) and Smith and Mertie (1930) published analyses of petroleum from crude-oil seepages and coal from surface exposures and shallow mines. Stadnichenko (1929) studied samples of supposed "mother rocks" of petroleum collected by P.S. Smith in northern Alaska and concluded that "The boghead from Alaska is a rich mother rock in which the main source of oil resides in the algal colonies, the spore rock is also a rich oil shale ***." This early report is interesting in the light of recent studies of hydrocarbon maturation. Stadnichenko had developed some good leads in hydrocarbon maturation but apparently did not follow them further.

During the NPR-4 program of 1945 to 1952, more qualitative information was gathered about the widespread presence of organic rocks, oil shales, and other black shales, as well as some quantitative data on phosphate deposits (Patton and Matzko, 1959) in areas adjacent to the Reserve. Tourtelot and Tailleur (1966) followed up on some of the newly discovered oil-shale occurrences and collected further quantitative information.

However, the application of geochemical studies of source rocks to hydrocarbon exploration is a fairly recent development. Although it cannot be directly applied to spotting drilling locations, the knowledge gained is useful in evaluating basins and even prospects. A paper by Bird (chapter 4) in this volume describes the use of source-rock information in the appraisal of undiscovered hydrocarbon resources.

The 1974-81 program seemed ideally suited to a systematic collection of samples for geochemical analysis and study. The program was designed to sample, over a fairly short period, a large part of one extensive sedimentary basin. Thus sampling and analytical procedures could be standardized, and the results would be compatible. The volume of samples to be analyzed and the turnaround time desired were beyond the capacity of USGS laboratories, and so the work was contracted to Geochem Research, Inc., of Houston, Texas, and Global Geochemistry Corp. of Canoga Park, California. The volume of analytical data that resulted was so great that it seemed advantageous to store, retrieve, and process the data by computers. For this purpose a contract was let to Petroleum Information Corp. of Denver, Colorado. These data were then integrated with a complete NPRA computer data and graphics system, as described by Wilcox, Coit, and Magoon in chapter 39.

A paper in this section by Magoon and Bird (chapter 17) summarizes the data on source-rock richness, type, and thermal maturity from 63 test wells drilled by the Federal Government within or adjacent to the Reserve. The paper includes contour maps of these geochemical characteristics for 12 stratigraphic units. The thermal maturity, as measured by vitrinite reflectance, increases from north to south and is higher in the west than in the east. Within the NPRA, Upper Cretaceous and Tertiary rocks are in the diagenetic stage of petroleum generation, whereas considerable volumes of Lower Cretaceous and Jurassic rocks have reached the liquid-window or catagenic stage, and most pre-Jurassic rocks are in the metagenic stage.

In a companion paper, Claypool and Magoon (chapter 18) indicate that the western and southern parts of the NPRA are unfavorable for the occurrence of large crude oil accumulations but are favorable for gas. The northeastern part of the Reserve appears to be the most favorable for large accumulations of crude oil.

Bayliss and Magoon (chapter 20) select four wells, spread from the western to the eastern border of the Reserve (Tunalik, Oumalik, Walakpa, and Inigok), for a detailed geochemical summary and evaluation using organic-carbon content, visual-kerogen analysis, thermal-alteration-index observations, vitrinite reflectance, and C_1-C_4 hydrocarbon composition. They conclude that the average organic content for each of 11 different rock units above the basement complex meets the minimum requirements, regardless of lithology, for that unit to be a potential source for hydrocarbons.

Magoon and Claypool (chapter 21) present the results of geochemical analyses of 44 crude oil samples, 25 of free oil and 19 of extracted oil. They classify them into three major NPRA oil types: type A, post-pebble shale unconformity, which comprises the pebble shale, Simpson, and Umiat oil subtypes; type B, pre-pebble shale unconformity, which includes the Barrow oil subtype; and type C, the condensates. The important distinguishing differences are the carbon and sulphur isotope values, sulfur content, and, to a lesser extent, American Petroleum Institute (API) gravity.

In a series of 39 plates, Magoon, Bird, Claypool, Weitzman, and Thompson (chapter 19) use the computer-based data system to relate the geochemistry of individual wells to the geology, including well logs, lithology, rock units, paleontologic zones, and age. The data were largely compiled by machine in a few weeks, in contrast to a similar set of charts for the NPR-4 test wells published in USGS Professional Paper 305, which were laboriously compiled by hand over a period of several years.

A study by Kharaka and Carothers (chapter 22) of the chemical and isotope properties of water from oil fields on the North Slope indicates that the water is meteoric in origin but heavier than present-day meteoric water, requiring that the mean annual temperatures at the time of recharge were 15-20 °C higher than at present. They conclude that warmer climatic conditions prevailed during Miocene and earlier times and discuss some of the tectonic implications of this observation.

Many of the rock units cored in wells can be correlated with rock units exposed at the surface for which geochemical anomalies or mineral deposits have been reported. Brosgé and Tailleur (chapter 23) selected 163 shale samples from subsurface rock units for inorganic chemical analyses. They tabulated the concentrations of 10 major elements and 22 trace elements and conclude that the black shales from the NPRA do not differ markedly from the average shale worldwide. However, the data suggest some interesting regional relations that support other conclusions about the geologic framework. Rocks of the Brookian sequence, which were derived from the ancestral Brooks Range to the south, are richer than others in base metals, whereas the Ellesmerian rocks derived from a northern source are richer in the elements commonly associated with deposits of phosphate and thorium.

Most oil and gas deposits in the United States contain higher-than-normal background concentrations of helium, and so do the deposits on the North Slope. For many deposits, near-surface indications can be detected that result from microseepages of hydrocarbons. On the basis of such observations, Roberts and Cunningham (chapter 24) studied the possible application of direct-detection techniques to prospecting for hydrocarbons. These techniques are well suited to remote wilderness areas because they are nondestructive and relatively inexpensive. The results of the study suggest that the technique is applicable to northern Alaska, even though some of the results are ambiguous.

In summary, the geochemical studies support the general conclusion that the NRPA is underlain by source rocks of sufficient richness to produce large quantities of oil and gas. However, the rock types and their maturation history suggest that the Reserve is gas prone, with the possible exception of the northeast quadrant. The exploration drilling to date supports this conclusion.

A vast amount of geochemical data has been compiled for this volume. Detailed data for each well are available in both hard copy and computer format from the National Geophysical Data Center. These data can thus be combined with other information from the North Slope, both onshore and offshore, for independent evaluation of the NPRA and adjacent areas.

GEOPHYSICS

Modern geophysical techniques for petroleum exploration in Arctic regions, such as seismic reflection and refraction, gravity, and airborne magnetic surveys, were pioneered in the NPR-4 by Woolson and others (1962). The Arctic setting presented special problems, not only in logistics but also in the methods used and in their interpretation. Permafrost was the main problem, as it is in virtually all activities in the Arctic. The permafrost layer is highly variable in thickness, lithology, and ice content. This variability affects the velocity of the sonic waves, and the results of seismic surveys must be adjusted accordingly or entirely false interpretations can result. For example, synclines or flat-lying beds may be interpreted as anticlines or domes.

In the NPR-4 exploration program (1945-53) and in the more recent program (1974-81), the seismic surveys and interpretations were made by contractors—a common practice in the oil industry. In the earlier program this work was done by United Geophysical, Inc. (Woolson and others, 1962) and in the recent program by Geophysical Services, Inc., and Tetra Tech, Inc. (Bruynzeel and others, 1982).

In the recent program the USGS staff worked with the contractors at several stages during the geophysical surveys. The areas to be surveyed and studied were delineated by the USGS. The eventual geologic interpretations were also reviewed by USGS field geologists in a workshop exchange, thus providing good geologic input. Inasmuch as seismic surveys involve remote sensing, two or more interpretations are possible or even equally probable. For that reason the original data, including field tapes, have been made available for independent processing and interpretation.

USGS geologists have utilized the seismic data in their geologic interpretations, but no complete set of contour maps and cross sections has been made by the USGS. Molenaar (1985) made extensive use of the seismic information to correlate and describe the depositional history of the Nanushuk Group and related rocks. In a paper in this volume (chapter 25) he utilizes the seismic data in conjunction with well and surface data to prepare a set of cross sections and maps to illustrate his interpretation of the depositional history and seismic stratigraphy of the Lower Cretaceous rocks in the NPRA. A similar interpretation based on the then-limited seismic and well data was made in the NPR-4 program by Payne and others (1952). Kirschner and others (1983) illustrated and described some of the regional seismic lines in the NPRA in a volume edited by A.W. Bally.

Aeromagnetic surveys were pioneered in the NPR-4 in 1945 and 1946 under the direction of J.R. Balsley. A generalized map of the results was published by Payne and others (1952). Recently, additional magnetic surveys of the NPRA have been flown by private service companies, and the results of some of these surveys are included in the Tetra Tech final reports.

The aeromagnetic surveys reported by Donovan, Hendricks, Roberts, and Eliason (chapter 26) were flown for quite a different purpose. Magnetic anomalies of high wave number measured at low altitude are believed to be caused by magnetic minerals formed by the reduction of hydrated iron oxides or hematite as a direct result of seeping hydrocarbons or associated compounds. These anomalies provide the basis for possible detection of hydrocarbon deposits. Aeromagnetic surveys for this purpose would be particularly applicable to remote areas such as northern Alaska. Experiments in the NPRA and adjacent areas have demonstrated that these kinds of magnetic anomalies are associated with known occurrences of hydrocarbons.

Hillhouse and Grommé (chapter 27) sampled the Late Devonian and Mississippian rocks in the Brooks Range and analyzed their paleomagnetic poles in an attempt to determine plate-tectonic movements. They conclude that these rocks were remagnetized after major thrusting and folding, and thus hypothetical earlier counterclockwise rotation of Arctic Alaska cannot be detected by this method in the area sampled.

The last paper in the geophysics section (chapter 28) is by Lachenbruch and others. It records and analyzes measured equilibrium temperatures from 24 exploration wells. Selected test wells in the NPRA were sealed off in such a way as to permit reentry with simple logging equipment and thus to provide an opportunity to conduct research for as long as the boreholes were accessible. The measurements provided information on permafrost depth and temperature over much of the North Slope and in three distinct physiographic provinces—the Arctic Coastal Plain, foothills, and northern Brooks Range. Analysis of the data collected to date shows a conspicuous climatic warming since the middle of the 19th century.

The geophysical studies by the USGS in the NPRA supplement those completed by the contractors and demonstrate the different interpretations possible while using the same basic data. The vast amount of seismic data acquired and recorded in public files provides excellent source material for further study of the geology and petroleum potential of the Reserve.

PALEONTOLOGY

The application of paleontology, particularly micropaleontology, to the exploration for hydrocarbons is especially useful in a large, remote region such as the NPRA. It has proved its value in the correlation of rock layers penetrated by the drill as well as of those exposed at the surface. It not only provides a major dating tool but also provides another criterion for interpreting the depositional and diagenetic history of the rocks. In the subsurface, microfossils are more useful than large fossils because the samples obtained from the borehole are small.

Systematic study of microfossils in Arctic North America was pioneered by the USGS in the 1944-51 NPR-4 program. Samples were shipped by air to a USGS laboratory in Fairbanks, Alaska, where they were analyzed. The results were sent back to the Reserve within a few days, or even hours if the situation was critical. The information collected was published (Bergquist, 1966), and the type materials are available for further study.

In the more recent program (1974 to 1981) several wells were drilled simultaneously and with improved drilling techniques, and thus samples accumulated more rapidly. Since drilling was limited in most locations to the winter months, great efforts were made to complete the test well before the spring breakup. As a result, the volume of samples to be studied and the short turnaround time required exceeded the capacity of the USGS laboratories and staff, and the work had to be contracted out. Although different contractors were used during the 8-yr program, two micropaleontologists were involved most of the time. M.B. Mickey and Hideyo Haga provided many of the identifications and age ''calls'' of palynomorphs and foraminifers used in this volume, and they have produced a special compilation and synthesis that is included here (chapter 29). Detailed information for each test well is available through the National Geophysical Data Center, and type materials are available for study through the USGS.

Utilizing data from 18 wells, Mickey and Haga describe 6 biostratigraphic units, ranging in age from early Mississippian to Tertiary, which they believe correlate with major recognizable seismic intervals. Isochore maps of these units within the NPRA are included. Mickey and Haga emphasize that the interpretation of the seismic stratigraphy is the next step in explaining the stratigraphy and structure in the NPRA.

Megafossils, including large foraminifers, have been found in cores from several test wells in the NPRA. Dutro and Silberling have compiled data from 14 wells and have documented (chapter 30) 14 stratigraphic intervals based on megafossils. The rocks range in age from possible Late Devonian to the Albian in the late Early Cretaceous.

Poorly preserved ostracods of Lower Mississippian age were found in the Lisburne No. 1 well, and Sohn has prepared a short paper (chapter 31) describing and illustrating these forms.

Recently, fossil radiolarians have proved useful in interpreting biostratigraphy and in correlating rock units in complex geologic terranes. They are especially useful where fine-grained siliceous sedimentary rocks containing few if any other fossils are predominant. As an aid to surface mapping and in anticipation of test drilling in the southwestern corner of the NPRA, a program of radiolarian studies was initiated and financed. These studies required special laboratory facilities and instrumentation. Some of the results of these ongoing studies are included in this section.

In a summary paper (chapter 32) Murchey, Jones, Holdsworth, and Wardlaw state, ''Mississippian to Jurassic fine-grained siliceous rocks in the northern Brooks Range of Alaska constitute one of the longest known records of continuous deposition of siliceous pelagic and hemipelagic sediments in the world.'' Fossils from several hundred samples collected mainly from the western Brooks Range were recovered by a special etching process. The fossils include radiolarians, conodonts, sponge spicules, and carbonate fossils generally preserved as some form of quartz or pyrite. Murchey and others describe four siliceous rock facies, their key fossils, and their range from Mississippian to Jurassic. The paleontologists relate these fossils to three structural associations.

Blome, Reed, and Tailleur (chapter 33) describe the radiolarian biostratigraphy of the Otuk Formation in the southwestern part of the Reserve, an area of highly superposed and disordered structure—a severe test in correlation and interpretation. Seven measured sections and radiolarian zonations are described in detail.

In another paper Holdsworth and Murchey (chapter 34) summarize the Paleozoic radiolarian biostratigraphy of the northern Brooks Range. Six radiolarian faunal groups are described and correlated to a reference section at Nigu Bluff in the southwestern quadrant of the NPRA.

These studies complete the record for paleontological work under the NPRA program. Well-by-well details of microfossil occurrences, species distribution, abundance, and related lithology are available through the National Geophysical Data Center in Boulder, Colorado. Also available are palynology reports that describe palynomorph assemblages of dinoflagellates, acritarchs, pollen, and spores; and micropaleontology reports that include descriptions of foraminifers, radiolarians, and other fossils, as well as of mineral and rock fragments.

RESERVOIR ROCKS

The reservoir characteristics of the subsurface layers drilled in the NPRA have been systematically recorded and analyzed by the exploration contractors through the use of well logs and selected laboratory methods. The data and analyses, including all well logs, can be found in the Husky and Tetra Tech final reports and in the open-file materials available from the National Geophysical Data Center.

To supplement the subsurface testing and the reservoir studies and to gain a better understanding of the depositional and diagenetic history of the rocks in the NPRA, field surveys were made part of the exploration program. Some of the results of these studies are included in the geologic framework reports, but two are included here to illustrate the type of reservoir studies initiated under this program.

The Nanushuk Group and related rocks (Cretaceous age, Brookian sequence) were studied and sampled extensively in the field. This work resulted in a series of reports that were published as USGS Bulletin 1614 (Huffman, 1985); an earlier summary was published by Ahlbrandt in 1979 as USGS Circular 794. These publications include maps, diagrams, petrographic and paleontologic descriptions, and analyses that depict the tectonics, depositional cycles, and environments of deposition of the Nanushuk Group. For this volume Bartsch-Winkler and Huffman (chapter 35) have prepared a detailed petrographic analysis of the Nanushuk Group and Torok Formation. Samples from 8 measured sections and 20 test wells were examined for compositional differences. The authors conclude that the Nanushuk Group and Torok Formation are a transitional unit containing deltaic, interdeltaic, and shallow-marine sandstone and shale. They distinguish two depositional lobes (western and central) on the basis of lithologic and paleontologic evidence. Petrographic analyses and actual measurements of porosity and permeability lead them to conclude that the reservoir characteristics of these rocks are poor in the western part of the Reserve but slightly better in the eastern and northern parts.

The Ellesmerian rocks of the NPRA and adjacent areas have been studied in detail in the laboratory by van de Kamp (under contract to the USGS), and his report is included here (chapter 36). Marine to nonmarine sandstone of Permian through Jurassic age from 19 wells in the NPRA and 9 wells in the Prudhoe Bay area was studied to develop a means of predicting reservoir characteristics. Van de Kamp concludes that primary porosity sometimes provides the reservoir; for example, the Barrow sandstone serves as the reservoir rock in the producing Barrow gas fields. In the Prudhoe Bay field the principal producing horizon is the Ivishak Formation of the Sadlerochit Group, which is Permian and Triassic in age. This reservoir rock has extensive secondary porosity formed by the solution of carbonates and silicates that were exposed to meteoric waters during the early Cretaceous. In contrast, however, equivalent rock units in the NPRA and the Jurassic Kingak Shale are commonly tightly cemented by quartz and carbonate minerals.

From the drilling results and the studies recorded here, it can be concluded that the absence of good reservoirs is a major reason why hydrocarbon deposits of economic value have not been discovered in the NPRA.

SPECIAL STUDIES

The Naval Petroleum Reserves Production Act of 1976, which mandated continued exploration of the Reserve, also emphasized the need to protect other values during the exploration process. This requirement covered protection of recreational, fish and wildlife, historical, scenic, and environmental values. To satisfy these requirements, special instructions and stipulations were included in all contracts for work, such as winter seismic operations, winter-trail and road construction, and drilling. Monitoring and inspection procedures to ensure compliance with these stipulations and all applicable laws and regulations were shared with the Bureau of Land Management (BLM), which has the overall responsibility for surface management in the NPRA. The USGS and BLM agreed on procedures in a Memorandum of Understanding with Cooperative Procedures dated January 25, 1977 (Federal Register, v. 42, no. 16, January 25, 1977, p. 4542-4546). The procedures included the preparation and public release of an Annual Plan of Operation and an Environmental Assessment for each area of operation. This important part of the exploration program was described in some detail by Britton (1978).

Protection of cultural resources required an inventory at each site or alternative site targeted for exploration. Cultural remains found in the NPRA included a wide range of artifacts and relics, such as stone tools, prehistoric housepits and cachepits, tent rings, rock carvings, burials, reindeer corrals, trading posts, and shipwrecks. All were identified and inventoried by professional archeologists, and some were recorded in the National Register of Historic Places. Many new sites were added to this register. Disturbance of such sites was avoided in most instances. If it could not be avoided, the sites were excavated and properly documented for the record. Only four sites were excavated and studied, and each added valuable data to the cultural record. A summary of the USGS-BLM cultural resource program by Hall and Gal is included in this volume (chapter 37).

Another special aspect of the exploration program was the design and construction of facilities in this Arctic region that is underlain by virtually continuous frozen ground—permafrost. Permafrost contains large amounts of near-surface ice in the form of wedges, masses, and intergranular ice. Therefore construction must not disturb the thermal regime, or thaw and ground subsidence would result. A complete record of the construction of each site, including airstrips, can be found in the Husky final report. The construction of facilities, such as airstrips and roads required for year-round drilling, presented an ideal opportunity for research in engineering geology. Thus, cooperative studies with other USGS offices and with the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) were undertaken. One of these studies is summarized for this volume by Kachadoorian and Crory (chapter 38).

Still another special problem was the storage and retrieval of the large amount of technical data that had already accumulated and continued to accumulate at an accelerating rate. A machine-based system was the obvious solution, and beginning in 1977 a computer-based data and graphics system was set up. This project was an extension of an existing USGS contract with Petroleum Information Corp. It provided the Well History Control System information and produced geologic data-processing software. Thirteen files were constructed for the NPRA data, including files on wells, digital logs, multiple tops, daily drilling records, paleontology, porosity and permeability, geochemical data, petrography, outcrop data, and API numbers. Three files were organized by latitude and longitude: base map, seismic surveys, and gravity observations. Software programs were available to create reports, graphics, or maps from these files. The report by Wilcox, Coit, and Magoon (chapter 39) describes the building of these files and illustrates their use in studying the framework geology and petroleum potential of the NPRA.

REFERENCES

Ahlbrandt, T.S., ed., 1979, Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, 163 p.

Bergquist, H.R., 1966, Micropaleontology of the Mesozoic rocks of northern Alaska: U.S. Geological Survey Professional Paper 302-D, p. 93-227.

Britton, M.E., 1978, Petroleum exploration and environmental protection in the Alaskan Arctic: U.S. Geological Survey Yearbook, Fiscal Year 1978, p. 27-38.

Brooks, A.H., 1909, The mining industry in 1908: U.S. Geological Survey Bulletin 379-A, p. 21-62.

Bruynzeel, J.W., Guldenzopf, E.C., and Pickard, J.E., 1982, NPRA final report, 1974-1981: 183 p., 3 vols., 71 maps, scale 1:500,000. [Available from National Geophysical Data Center, 325 Broadway, E/GC, Dept. CNP, Boulder, Colorado 80303]

Carey, S.W., 1958, A tectonic approach to continental drift, *in* Carey, S.W., ed., Continental drift; a symposium: Hobart, Australia, Tasmania University Press, p. 177-355.

Dana, S.W., 1952, Geophysical summary, *in* Payne, T.G., and others, Geology of the Arctic slope of Alaska: U.S. Geological Survey Oil and Gas Investigations Map OM-126, scale 1:1,000,000, sheet 2.

Eardley, A.J., 1948, Ancient Arctica: Journal of Geology, v. 56, no. 5, p. 409-436.

Fischer, W.A., 1952, Structure, *in* Payne, T.G., and others, Geology of the Arctic slope of Alaska: U.S. Geological Survey Oil and Gas Investigations Map OM-126, scale 1:1,000,000, sheet 2.

Gryc, George, Patton, W.W., Jr., and Payne, T.G., 1951, Present Cretaceous stratigraphic nomenclature of northern Alaska: Washington Academy of Science Journal, vol. 41, no. 5, p. 159-167.

Huffman, A.C., Jr., ed., 1985, Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, 129 p.

Jones, D.L., and Grantz, Arthur, 1964, Stratigraphic and structural significance of Cretaceous fossils from Tiglukpuk Formation, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 48, no. 9, p. 1462-1474.

Kirschner, C.E., Gryc, George, and Molenaar, C.M., 1983, Regional seismic lines in the National Petroleum Reserve in Alaska, *in* Bally, A.W., ed., Seismic expression of structural styles: American Association of Petroleum Geologists Studies in Geology, no. 15, v. 1, p. 1.2.5-1–1.2.5-14.

Krynine, P.D., 1952, Reservoir petrography of sandstones, *in* Payne, T. G., and others, Geology of the Arctic slope of Alaska: U.S. Geological Survey Oil and Gas Investigations Map OM-126, scale 1:1,000,000, sheet 2.

Leffingwell, E. de K., 1919, The Canning River region, northern Alaska: U.S. Geological Survey Professional Paper 109, 251 p.

Mertie, J.B., Jr., 1930, Mountain building in Alaska: American Journal of Science, ser. 5, v. 20, p. 101-124.

Molenaar, C.M., 1985, Subsurface correlations and depositional history of the Nanushuk Group and related strata, North Slope, Alaska, *in* Huffman, A.C., Jr., ed., Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 37-59.

Patton, W.W., Jr., and Matzko, J.J., 1959, Phosphate deposits in northern Alaska: U.S. Geological Survey Professional Paper 302-A, p. 1-17.

Payne, T.G., 1948, Tectonic and sedimentary setting of Naval Petroleum Reserve No. 4, northern Alaska [abs.]: Abstracts of Papers Presented at the Annual Meeting of the American Association of Petroleum Geologists, March 1948, Denver, p. 36-37.

—— 1955, Mesozoic and Cenozoic tectonic elements of Alaska: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-84, scale 1:5,000,000.

Payne, T.G., and others, 1952, Geology of the Arctic slope of Alaska: U.S. Geological Survey Oil and Gas Investigations Map OM-126, 3 sheets, scale 1:1,000,000.

Reed, J.C., 1958, Exploration of Naval Petroleum Reserve No. 4 and adjacent areas, northern Alaska, 1944-53; part 1, History of the exploration: U.S. Geological Survey Professional Paper 301, 192 p.

Schrader, F.C., 1904, A reconnaissance in northern Alaska across the Rocky Mountains, along Koyukuk, John, Anaktuvuk, and Colville rivers and the Arctic coast to Cape Lisburne, in 1901, *with notes* by W.J. Peters: U.S. Geological Survey Professional Paper 20, 139 p.

Smith, P.S., and Mertie, J.B., Jr., 1930, Geology and mineral resources of northwestern Alaska: U.S. Geological Survey Bulletin 815, 351 p.

Snelson, Sigmund, and Tailleur, I.L., 1968, Large-scale thrusting and migrating Cretaceous foredeeps in western Brooks Range and adjacent regions of northwestern Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 52, no. 3, p. 567.

Stadnichenko, Taisia, 1929, Microthermal studies of some "mother rocks" of petroleum from Alaska: American Association of Petroleum Geologists Bulletin, v. 13, no. 7, p. 823-840.

Tailleur, I.L., 1969a, Speculations on North Slope geology: Oil and Gas Journal, v. 67, no. 38 (September 22), p. 215-220, 225-226.

—— 1969b, Rifting speculation on the geology of Alaska's North Slope: Oil and Gas Journal, v. 67, no. 39 (September 29), p. 128-130.

—— 1973, Probable rift origin of the Canada Basin, Arctic Ocean, *in* Pitcher, M.G., ed., Arctic geology: American Association of Petroleum Geologists Memoir 19, p. 526-535.

Tailleur, I.L., Brosgé, W.P., and Reiser, H.N., 1967, Palinspastic analysis of Devonian rocks in northwestern Alaska, *in* Oswald, D.H., ed., International symposium on the Devonian System: Calgary, Alberta, Canada, Alberta Society of Petroleum Geologists, v. 2, p. 1345-1361.

Tailleur, I.L., Kent, B.H., and Reiser, H.N., 1966, Outcrop/geologic maps of the Nuka-Etivluk region, northern Alaska: U.S. Geological Survey open-file report, 7 sheets, scale 1:63,360.

Tailleur, I.L., and Snelson, Sigmund, 1968, Large-scale flat thrusts in the Brooks Range orogen, northern Alaska [abs.]: Geological Society of America Special Paper 101, p. 217.

Tourtelot, H.A., and Tailleur, I.L., 1966, Oil yield and chemical composition of shale from northern Alaska: U.S. Geological Survey open-file report, 17 p.

Woolson, J.R., and others, 1962, Seismic and gravity surveys of Naval Petroleum Reserve No. 4 and adjoining areas, Alaska: U.S. Geological Survey Professional Paper 304-A, p. 1-25.

Yuster, S.T., 1952, Summary of core analysis results, *in* Payne, T.G., and others, Geology of the Arctic slope of Alaska: U.S. Geological Survey Oil and Gas Investigations Map OM-126, scale 1:1,000,000, sheet 2.

2. HISTORY OF EXPLORATION IN THE NATIONAL PETROLEUM RESERVE IN ALASKA, WITH EMPHASIS ON THE PERIOD FROM 1975 TO 1982

By JOHN F. SCHINDLER[1]

INTRODUCTION

When the Department of the Navy conducted exploration for oil in Naval Petroleum Reserve No. 4 during the years 1944 to 1953, the stated aim was to ascertain whether or not petroleum existed in commercial amounts in the Alaskan Arctic (Reed, 1958). Those original efforts resulted in a partial appraisal and the discovery of two widely separated possible oil fields (the Umiat and Simpson discoveries), a gas field (South Barrow field) and other gas accumulations of undetermined size. The discovery of gas deposits in the Arctic was of little interest to the Navy at that time. During the intervening years, geologic, seismic, and logistic methods and techniques became much more sophisticated. The so-called second exploration, 1975 to 1982, had the advantage of the knowledge previously gained and the improved techniques of investigation and operation.

When Public Law 94-258 transferred the reserve and the responsibility for its exploration from the Secretary of the Navy to the Secretary of the Interior, a subtle change took place in exploration philosophy. The congressional mandate directed the Secretary of the Interior to learn as much as possible about the reserve and its renewable and nonrenewable resources in order to plan its wise management and utilization. The principal aim of this second period of exploration became the acquisition of knowledge—the discovery of oil or gas was a hoped-for, but yet secondary, objective.

This report provides a historical overview of this more recent (1975-1982) exploration. It was prepared originally to serve as a unifying prologue for a series of contract reports by Husky Oil NPR Operations, Inc., concerning various phases of the project (see list at end of chapter).

The program of Government exploration and investigation of the oil resources of the Alaskan North Slope spans a period of 38 years (1944 to 1982) and has witnessed the use of many types of equipment, methods of investigation, and logistical support. All of this reflects the progress in technology and an increased respect for the environment. The severe climate of the Arctic has been an overriding influence affecting plans, budgets, and operations. Few other areas of the world require such attention to climatic constraints.

The second (1975-1982) exploration program was built on the earlier experience of the U.S. Navy and also on lessons learned at Prudhoe Bay. It evolved into a sophisticated operation and its successful execution is a tribute to all of the personnel involved.

THE ALASKAN ARCTIC

The Arctic Slope of Alaska extends northward from the Brooks Range to the Arctic Ocean and from Cape Lisburne on the west to the United States-Canadian border on the east (for general descriptions, see Brooks, 1906; Reed, 1958). It covers more than 960 km (600 mi) from east to west and 320 km (200 mi) from north to south, and its area includes one-seventh of the State of Alaska. Much of the Arctic Slope is within the National Petroleum Reserve in Alaska (NPRA). The reserve boundary (pl. 2.1) extends due south from Icy Cape (approximate long 162°W.) to the drainage divide of the Brooks Range. It then follows that divide eastward to long 156°10′ W., from where it trends due north to the Colville River. It then follows the Colville to the mouth of the river at approximately lat 70°25′ N., long 151°20′ W. The area of the reserve encompasses approximately 95,000 km^2 (37,000 mi^2) of Arctic terrain.

The Arctic Slope is divided into three physiographic provinces—the coastal plain, the foothills, and the northern slope of the Brooks Range. Each of these provinces has its own unique topography, geology, soil, vegetation, and to some extent climate (pl. 2.1).

THE COASTAL PLAIN

The elevation of the coastal plain ranges from sea level to between 150 and 300 m (500-1,000 ft). It is flat, poorly drained, and underlain almost everywhere by permafrost. Frost polygons with both high and low centers are common, especially where there is a vegetative cover

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(fig. 2.1). About one-fifth of the coastal plain is covered with lakes, which are frozen for nine months of the year. Streams thaw in June and meander toward the coast in broad, shallow silty channels, often braided. Much of the soil is unconsolidated silt and sand, and it generally contains dark-reddish-brown organic material near the surface. Deposits of peat are common. Flood-plain deposits along the rivers and lakes have been sorted by wind and water. The climate of the coastal plain (see Black, 1954) is modified by the cool ocean. The average temperature of the three summer months at the point farthest north (Barrow) is only 3 °C (38 °F), and there are only about 60 days above freezing during the entire summer. During the summer months, winds average more than 19 km/h (12 mi/h), and most of the time it is cloudy or foggy.

FIGURE 2.1.—Arctic Alaska coastal plain east of Dease Inlet, 1979. Polygons (5-12 m on a side) outlined by ice wedges are most common feature. Photograph by S. Krogstad.

FIGURE 2.2.—Foothills province near Archimedes Ridge, August 1978, showing variation of topography in the province. View north-northwestward; photograph by D. Braden.

THE FOOTHILLS

The foothills province consists of rolling hills and valleys with poorly drained lowlands. It is a treeless belt that extends along the entire north side of the Brooks Range, varying in width from about 30 km (20 mi) near the United States-Canadian border to about 130 km (80 mi) in the vicinity of the Colville River. The foothills rise from about 215 m (700 ft) along the northern boundary to as much as 1,220 m (4,000 ft) along the southern boundary. The province consists of two subsections—northern and southern. The northern foothills are characterized by long parallel east-west ridges and valleys, the ridges being formed of rather resistant sandstone and conglomerate (fig. 2.2). The southern foothills have a more complex topography: isolated hills of sandstone or limestone are separated by lowlands underlain by softer shale. The province has three widespread types of soil: (1) the residual silty soils of the uplands, (2) the peat deposits of the wetter lowlands and depressions, and (3) the coarse sand and gravel along the river beds and flood plains. The climate of the foothills is somewhat warmer than that of the coastal plain or the mountain provinces, and the vegetation reflects this higher temperature.

THE MOUNTAINS

The Brooks Range is a northwest continuation of the Rocky Mountain system. Elevations range from approximately 600 to 2,750 m (2,000-9,000 ft). The lowest north-south passes through the mountains are at about 600 km (2,000 ft). Many glacial lakes fill the valleys along the mountain front. The mountains are formed of great thicknesses of limestone, sandstone, conglomerate, and shale. Because of glaciation, frost action, and rapid erosion of slopes by running water, little soil has accumulated and vegetation is sparse. Moraines and outwash deposits are found in many of the mountain valleys.

DRAINAGE

In the coastal plain the streams are shallow and sluggish. They flow in contorted complex channels winding through literally thousands of shallow lakes. Lakes are so numerous that many areas contain more water than land. Lake shores are commonly only a meter or two (a few feet) high, and sometimes lake edges just gradually merge into the swampy tundra. Many lakes are elongate and are oriented with their long axes approximately north-northwest, that is, approximately at right angles to the prevailing northeast-southwest wind direction. The area where these oriented lakes occur covers more than half of the coastal plain.

Within the foothills, major streams are incised as much as 30-60 m (100-200 ft); these streams cross main structural trends and in many places expose the bedrock. In contrast, minor streams and tributaries in the area are largely controlled by structure. The most important river of the foothills is the Colville, which forms a boundary for much of the reserve. The Colville is of interest to geographers because it is the only major river in the world with its entire drainage basin north of the Arctic Circle. As such, it is subject to widely fluctuating water levels, ranging from extreme highs during spring breakup to lows in late July. August rains can also swell the volume of the river dramatically. Except for the Utukok River, all significant rivers and streams rising within the mountainous area of the reserve are tributaries of the Colville River.

CLIMATE

Temperatures vary widely within the reserve, but the weather can generally be described as cold and windy.

The climate along the coast is moderated by the ocean and does not reach the extremes that characterize many parts of interior Alaska. Temperatures as low as −60 °C (−76 °F) have been officially reported from Umiat, but the minimum temperature of record at Barrow is −49 °C (−56 °F). Likewise, in the summer months temperatures in the coastal areas seldom reach 16 °C (60 °F), whereas the interior has temperatures as high as 31 °C (88 °F). The climate of the North Slope may thus be characterized as severe, with long cold winters and short cool summers. There is frequent fog and persistent wind the year round. The warmest month everywhere on the North Slope is July, followed by August and then June. Climate data are provided by the National Oceanic and Atmospheric Administration (1979).

PERMAFROST

Just as all operations above the surface of the ground are influenced by the severe weather of the Arctic Slope, all surface and subsurface activities are affected by permafrost (Lachenbruch, 1962). Permafrost is generally defined as any naturally occurring material that has a temperature below the freezing point of freshwater for 2 or more years. By definition, the presence of moisture is irrelevant. Near the coast, permafrost extends from the base of the seasonal thaw (less than 1 m, or about 2 ft) to a depth of about 120 m (400 ft) at the ocean edge; it increases in depth inland. It is approximately 180 m (600 ft) deep 300-450 m (1,000-1,500 ft) from shore and about 360 m (1,200 ft) deep 6-8 km (4-5 mi) inland. It can be more than 600 m (2,000 ft) deep at its deepest in Arctic Alaska.

Three ground phenomena in the reserve are prominent: polygonally patterned ground, pingos, and oriented lakes.

The polygonal ground patterns, which are evident to even the casual observer, are the surface evidence of ice wedges below. Wedge-shaped vertical ice sheets vary in width from about a decimeter (a few inches) to 3 m (10 ft) at the top and extend 1.2-8 m (4-25 ft) in vertical sections. The wedges are apparently caused by the contraction of the tundra in the winter, which forms cracks. In the spring, water from melting snow runs down into the cracks and freezes, and it remains frozen through the summer. The following winter this ice-filled crack is a zone of weakness, and renewed contraction reopens the crack and the process continues. Over centuries this cycle is thought to produce the vertical wedge-shaped ice forms. The network of wedges forms the boundaries of the surface polygons, their form depending upon the surface drainage. In low or wet areas, low-centered polygons are formed. In higher areas where drainage accelerates the melting along the ice-rich wedge, high-centered polygons are formed.

Pingos are another result of ice formation. Pingos are formed when a rather deep lake drains in a short time. A deep lake is defined as one that does not completely freeze to bottom each winter and the area beneath the lakebed remains thawed. When the lake drains, the moisture in this thaw bulb beneath the old lakebed begins to freeze, both from the surface downward and from the underlying permafrost upward. The theory is that water has been trapped under hydrostatic pressure, and when it freezes it expands. A bulge slowly forms and raises the surface of the tundra. Pingos can be as much as 15 m (50 ft) high, generally forming a clear, sometimes massive, lens-shaped body of ice.

Oriented lakes, so strikingly evident in the northern third of the coastal plain, are found in areas of poor surface drainage. Water is confined to the surface by the underlying cementlike permafrost. The long axes of these lakes are oriented slightly west of north. Every theory imaginable, from prehistoric winds to Paul Bunyan folklore, has been proposed to explain the orientation of these lakes. It is now generally believed that the prevailing northeast winds, which are at right angles to the long axes of the lakes, are the cause of the orientation. When the lake ice begins to thaw in the spring, a narrow moat of water is formed in the shallow area around the perimeter of the lake. The spring winds blow the central mass of ice back and forth across the lake and cause the water of the moat to swirl around the ends of the lake. This shifting of the water rapidly erodes the banks. The ice, of course, protects the longer axes of the lake from most of the erosion. This sequence of events, repeated six, eight, or ten times each season, season after season, gradually forms the elongate lakes at right angles to the prevailing wind direction. Studies with dye and water-current tracers, done during thaw, support this theory (Carson and Hussey, 1962).

Permafrost is far more than just a fascinating scientific phenomenon. It is a dominant factor in engineering, building, and operating in the Arctic. In the summer the wet, soggy tundra is difficult to traverse even on foot. The terrain is impassable for ground vehicles with normal tires. Tractors can operate but leave surface scars that persist for 50 to 100 years. Surface water is abundant in the summer, but no subsurface ground water is present in the long winter months. The only water available is beneath the ice in the deeper lakes. Sewage disposal systems are generally built above ground or in well-insulated utiliducts. Foundations for major structures are usually supported on piles that are set and frozen in holes augered into the permafrost. The structure must then be insulated sufficiently to prevent the building heat from melting the supporting frozen ground. Warm drilling muds can cause special problems. Drilling pads and road locations must be carefully selected so as not to disturb surface drainage and cause erosion, which in turn exposes the permafrost to further degradation. Permafrost problems can be solved, but the solutions are often difficult and expensive.

VEGETATION

The most striking feature of the North Slope of Alaska is the flat, seemingly treeless space stretching endlessly to the horizon. However, there are trees (willow, birch, and alder), but they are so small that they are of little use even for firewood (Britton, 1957; Hulten, 1968). In some of the river valleys trees grow to heights of 5 m (15 ft). Flowering plants are abundant, but the season is very short. Flowers bloom quickly in the continual summer daylight and are present briefly in colorful profusion. The flowers include purple and white anemones, poppies, mustard, saxifrage, roses, and asters (figs. 2.3 and 2.4). Most of the area, excluding the major valley bottoms, is typically tundra—a thick, spongy, matlike growth, made up predominately of grasses, sedges, mosses, lichens, and prostrate shrubs or bushes. Some areas, especially the ridge tops, are almost completely bare of vegetation.

ANIMALS

Of the fauna of the North Slope (see Sage, 1970), the commonest animal is a small rodent, the brown lemming. The lemming population fluctuates every three or four years from almost none to hundreds per acre. Other small animals include mice, shrews, voles, weasels, squirrels, mink, and martin. Larger animals at home on the North Slope include the Arctic wolf, the wolverine, caribou, moose, barren-land grizzly, and Arctic fox (figs. 2.5 and 2.6). The Arctic fox is present in both white and blue color phases, and the red fox in cross and silver color phases. Dall sheep live in the mountains. The wolf and wolverine are very efficient hunters, but they, like most wild animals, avoid contact with man and are not considered dangerous unless cornered. The barren-land grizzly has little fear of anything and is dangerous because of his innate curiosity. Generally, however, he is scared off by a loud noise. Nonetheless, a mother bear with cubs should be given a wide berth. Surprisingly, the Arctic fox is the animal most dangerous to man on the North Slope. Rabies is endemic in the population, and every fox can be considered to be a carrier of the disease. Animals that show an unnatural boldness or lack of fear of man usually are infected, and it is their disease that makes them so fearless.

Birds are present on the reserve in large numbers and in great variety during the brief summer season. Gulls, Arctic terns, and jaegers are common, as are ptarmigan, plovers, and longspurs. Shore birds can be seen on sandy stretches of beaches, and ducks, geese, loons, and swans on the many lakes of the reserve. Hawks, including the rough-leg hawk and the peregrine falcon, are common. Many great snowy owls appear when the lemmings are numerous. For a few weeks in the summer (from about mid-June until about early August), mosquitoes are present in unbelievable swarms. They are harmless so far as disease is concerned, but all activities are plagued by them. Repellents and other sorts of protection are required in order to carry on any effective operations.

INHABITANTS

Anthropologists believe that Eskimos have inhabited the Arctic for more than 8,000 years. Two distinct groups of Eskimos are found on the North Slope: the Nunamiut, an inland people whose mode of living revolved around the caribou; and the Tareumiut, a coastal people whose lives depended on hunting sea mammals (Spencer, 1959). Historically, the Eskimo population consisted of nomadic bands who lived on fish and wildlife. Today the Eskimos of the reserve reside principally in four communities: Ukpeagvik (Barrow) has a population of approximately 3,000; Olgoonik (Wainwright) has a population of approximately 400; the resettled village of Atkasook (Meade River) has a population of approximately 150; and the new village of Nuiqsut on the Colville River has a population of approximately 300. The North Slope Borough estimates its total population at 7,500 persons, of whom 1,750 are concerned with the production of oil and gas (that is, they are temporary residents of Prudhoe Bay).

The first representatives of the Western World to see Wainwright and Barrow were Captain F.W. Beechey and his crew of the H.M.S. *Blossom*. When Beechey had passed Wainwright and was stopped by ice, he sent First Mate Thomas Elson and Seaman William Smyth in an open boat to explore northward. Beechey named the northernmost point of the coast in September 1826, for Sir John Barrow, the First Lord of the Admiralty of the

FIGURE 2.3.—Arctic poppy, *Papaver lapponicum* subsp. *occidentale*, growing near Tunalik No. 1 well in summer 1980. The plants are about 30 cm high.

FIGURE 2.4.—Arctic cotton grass, *Eriphorum vaginatum* subsp. *spissum*, growing near Walakpa No. 1 well in summer 1979. The plants are about 30 cm high.

British Naval Administration and a strong believer in exploratory navigation. The city of Barrow, about 15 km (10 mi) southwest of the point, was called Barrow by the non-Eskimo residents, because they found it easier to pronounce than the Eskimo name (Ukpeagvik). The village of Wainwright was named by Beechey for Lt. John Wainwright, the astronomical observer and navigational officer on his ship.

FIGURE 2.5.—Arctic fox near weather shack at Tunalik, March 1979. Including tail, the animal is about 1 m long. Photograph by P.D.J. Smith.

FIGURE 2.6.—Caribou behind Camp Lonely, 1981. Structure in background is stored drill rig on sled. Photograph by C.K. Lee.

Over the years, the Natives have survived sporadic contacts with the white man that have changed their way of life. They are resilient and able always to return to subsistence living when necessary. Originally the Natives succumbed to common diseases of the white man, such as measles and tuberculosis; but over the years, with increased health care and increased contact, their resistance has improved. The Eskimo people contributed greatly to the early exploration program, as well as to the later one, by sharing their experience in coping with the harsh environment.

TRAVELING

In the early days, the Eskimos traveled great distances by dog team to hunt the caribou. Today they travel by snow machine, again covering great distances pulling sleds behind them. They are often on the trail for two to three weeks following the caribou.

Travel is still most feasible during the winter, especially for large equipment. During the first period of petroleum exploration (1944-1953), large caterpillar tractors were by far the most important pieces of equipment. Tractors are still important but are being supplemented by Rolligons and other vehicles with large rubber tires. Aircraft (figs. 2.7 and 2.8) were already used during the early Navy exploration, but they have become the real workhorses of the Government's latest programs. Modern helicopters became the mode of support for almost all summer operations. Travel will be discussed again in later sections on equipment and each year's history of exploration.

ACKNOWLEDGMENTS

The success or failure of any program depends largely on the contributions of the people involved, and the credit for the successful ex-

ploration of the NPRA belongs to all such personnel. Numerous local, State, and Federal Government agencies contributed to the program, as well as many private organizations and industrial contractors and subcontractors.

EARLY EXPLORATION

As far as the record (see Stefansson, 1922) shows, the first European to see any part of the reserve was Captain James Cook, who in 1778 entered the Bering Strait and sailed northeastward along the coast of Alaska as far as Icy Cape, where the western boundary of the reserve reaches the Arctic Ocean. It was 48 years later in 1826 that Captain F.W. Beechey pushed farther northeastward, was blocked by ice north of Franklin Point, and sent Elson and Smyth north as far as Point Barrow. At the same time, Sir John Franklin was working westward from the McKenzie River and reached a point near the eastern edge of the Colville Delta, where he too was stopped by ice. Eleven years later, in 1837, P.W. Dease and Thomas Simpson, after sailing down the McKenzie, pushed westward past the Colville and reached a point a little beyond Cape Simpson, where they landed and proceeded on foot. A short time later they reached Point Barrow, finally closing the exploration gap after the long trek from the east.

Knowledge of the north was gained from the various expeditions sent out between 1848 and 1853 to search for the missing party of Sir John Franklin, who was lost in 1845. On one of these (in 1849), Lt. Pollen sailed in a small boat from Kotzebue Sound all the way around the Arctic coast to the McKenzie River and then up the river to the Hudson Bay Company post.

In 1848 and almost annually thereafter, American whaling vessels made their way into Arctic waters. In 1881, Lt. P.H. Ray led an international polar expedition to the vicinity of Barrow. By that time northern Alaska had been American territory for 14 years.

The first overland exploration of the reserve was made by Ensign W.L. Howard when he left the valley of the Noatak in the spring of 1886 and proceeded northeast to the valley of the Colville. He continued overland to the Chipp River, followed the river to the coast in a skin boat, and arrived at Point Barrow on July 15 (Croft, 1939; Riverain, 1966).

Starting in the early 1900's, the U.S. Geological Survey sponsored many parties for exploration and geologic investigation, including ones led by W.J. Peters and F.C. Schraeder in 1901 and by E. de K. Leffingwell and Anderson in 1906-1914 (see Leffingwell, 1915). Further valuable contributions were made by Vilhjáimur Stefansson between 1908 and 1918 (see Stefansson, 1922). With the establishment

FIGURE 2.7.—Loading passengers at Lonely airport for flight to Anchorage, March 1981. Photograph by E. Grant.

FIGURE 2.8.—Lockheed Hercules C-130, the workhorse of the air logistics program, Camp Lonely, March 1981. Photograph by E. Grant.

of the Naval Petroleum Reserve by President Harding in 1923, another series of investigations by the U.S. Geological Survey was begun at the request of the Navy Department. By the late 1940's, these, together with the information from the field surveys, provided a reasonably adequate, but still generalized, picture of the major geologic features of the reserve and the surrounding areas. Geographic positions were known with reconnaissance accuracy, and topographic maps had been made of large areas.

THE U.S. NAVY SEARCH FOR OIL: 1944 TO 1953

In February of 1944, the Director of the Naval Petroleum Reserves sent a proposal to the Secretary of the Navy to undertake an exploration and test well drilling program of Naval Petroleum Reserve No. 4. By the following month the feasibility of this proposal had been determined, and the executive and legislative branches of the Government were so informed. A reconnaissance study was made in March and April of that year, and in June the President approved the project. By the end of 1944, a camp had been built near Point Barrow by a Navy construction battalion, and air service was established; the project was ready to proceed. By the spring of 1945, the first tractor-drawn sled train was hauling large tonnages over long distances; the first ship-based expedition that summer was successful, and air support was established. Information from the geological and geophysical investigations as well as from the drilling program was accumulated and interpreted.

In 1946 the operations switched from a military CB (Construction Battalion) detachment to a civilian contractor. Air photography and mapping were done, as well as airborne magnetometer surveys. The first test hole, Umiat Test Well No. 1, was drilled to 1,830 m (6,005 ft). In 1947 more than 4,500 m (15,000 ft) of drilling was completed, and over 700,000 ton miles of winter freight was hauled. Through 1947-48, the results of the drilling were supplying an ever-increasing and ever-improving amount of background data. During 1948, Simpson Test Well No. 1 was drilled to the basement rocks in the Cape Simpson area, and a stratigraphic test well had been drilled near Barrow. In 1949 winter freighting reached a total of 1.3 million ton miles, and South Barrow Test Well No. 2 was completed as a gas well and began supplying gas to the Barrow Camp. In 1950 drilling totaled 11,000 m (36,000 ft) at 16 separate sites. Both the Umiat and Simpson wells showed indications of gas and oil. In 1951 the program was slow to start because of doubt as to whether or not it was to continue. Despite the late start, winter freighting totaled 1,860,000 ton miles, and drilling at over 20 separate sites totaled more than 14,452 m (47,710 ft). The presence of oil at Cape Simpson was verified, and the Umiat field was better defined. In 1952 only 4,615 m (15,142 ft) of hole was drilled at four sites. However, winter freighting totaled 2,412,000 ton miles.

It was decided to recess the exploration in 1953, and equipment and supplies were moved to central points for inventory, storage, or return shipment. No drilling was done, but geologic and geophysical work was continued to logical conclusions. Over the ten-year period of exploration a total of 80 holes (36 cores tests and 44 test wells) were drilled for a total of 51,590 linear m (169,250 linear ft). Most of these were shallow wells, Topagoruk and Oumalik being deeper. Three small oil fields were discovered—Umiat, Simpson, and Fish Creek—and six natural gas fields—Barrow, Gubik, Wolf Creek, Oumalik, Meade, and Square Lake. It is interesting to note that when the exploration was recessed in 1953 by Presidential order, the Navy had a drill rig and supplies ready to move out from the Umiat area to drill on the Shaviovik River, just to the east of Prudhoe Bay.

THE INTERIM: 1953 TO 1974

Between the early Government exploration from 1944 to 1953 and the later program, a number of important events occurred.

In 1947, at the height of the Navy's exploration activity, another branch of the Navy, the Office of Naval Research, established a basic research laboratory in a vacant quonset hut in the Barrow Camp. The laboratory slowly grew in number of staff and in stature, and when the oil-exploration activity closed down, the Arctic Research Laboratory (ARL) fell heir to the Barrow Camp, many of the facilities, and much of the equipment that was declared surplus by the exploration group. The laboratory was the sole occupant of the camp until 1955, when the Air Force, under an agreement with the Navy, assumed the custodial responsibilities in order to use the facility as a base for the construction of the western third of the North American DEW (Distant Early Warning) Line. In 1957, when the DEW Line was commissioned, the Air Force retained the Barrow Camp as a support base for activities along the line. The laboratory was renamed the Naval Arctic Research Laboratory (NARL) in 1968.

The law making Alaska a State was passed and signed in January 1959. This law included the provision that the State might select from Federal lands as much as 42 million hectares (104 million acres) for support of the fledgling State Government. Some leases and exploratory permits were issued on the lands selected, and in 1960 petroleum exploration began on the North Slope east of the Naval Petroleum Reserve No. 4 (Pet-4, later NPRA).

In February of 1968, the Atlantic Richfield Company, drilling on an area of this State land leased jointly with Humble Oil and Refining Company, brought in the first oil well in the area, the Prudhoe Bay No. 1, and four months later made the confirmation strike. Reserves were estimated to be as much as 10 billion barrels. The sheer size of the strike stirred great interest in North Slope exploration and was the basis for the $900 million State of Alaska lease sale of October 1969.

Also in 1969, the National Environmental Policy Act (NEPA) was passed, and one of the sections of this new law required that the Federal Government write an environmental impact statement (EIS) assessing any consequences of Federal actions before they were undertaken. The EIS became a tool used more often in the courts than in the public arena.

In 1971, the Alaska Native Claims Settlement Act was passed, establishing private corporations owned by native stockholders as real-estate and financial forces in the State of Alaska. Then in 1973, the Congress passed the Endangered Species Act prohibiting any Federal activity that would endanger the habitat or the life cycle of certain specified species. All these events and political actions arose for different reasons, but they became closely interwoven during the exploration for Arctic petroleum.

The oil discovered at Prudhoe Bay on State lands selected under the Statehood Act could not get to market, because a pipeline could not be approved across Federal lands. Approval was blocked in the courts by environmentalists acting under the NEPA and in concert with the native-claims proponents. The research done at the NARL became the basis for arguments both pro and con about the proposed construction. After a long confrontation, a better engineering and construction plan ultimately resulted. The time delay, however, became excessive and costly, and the pressures increased for Congress to act.

In 1971, partly as a result of the NEPA, the Navy requested and received from Congress funds to clean up the debris left from earlier Federal Government activities on the reserve. Such cleanups were required at Umiat, Cape Simpson, Point McIntyre, and the Barrow area. When the exploratory program was funded by the Congress in response to the shortage of oil in the early 1970's, a cleanup requirement was included as a line item in the exploration budget. Thereafter, cleanup programs were concurrently funded and carried out during the entire program.

All of these activities focused interest on the Arctic petroleum reserve and the possibility of an oil discovery that would help solve the national energy problem. The Navy formulated a plan for a new Pet-4 exploration program that would test formations deeper than the shallow Cretaceous rocks that were targeted from 1944 to 1953. The Prudhoe Bay discovery was made in rocks deeper and older than Cretaceous, and the same formations were widespread throughout the reserve.

RESUMPTION OF EXPLORATION

The Organization of Petroleum Exporting Countries' (OPEC) oil embargo of 1973 again drew attention to the Naval Petroleum Reserves. Financial support had been proposed earlier in Congress to explore Pet-4 (NPR-4) and Teapot Dome, Wyoming (NPR-3), and to develop Elk Hills, California (NPR-1). The threat of continued oil shortages prompted Congress to add $11.5 million to the Navy budget in the Supplemental Appropriations Act of 1974. Of the $11.5 million, $4.0 million was designated to develop Elk Hills, and $7.5 million was to initiate a small exploratory program in Pet-4. Earlier, for ease in processing the old seismic data, NPR-4 had been arbitrarily divided into five zones, A through E (fig. 2.9). The Navy felt that Zone A was the most promising area to encounter an extension of the Prudhoe Bay productive zones, and, because of the limited funds and time, the program was limited to this area. Thus the Navy began the preparation of a draft environmental impact statement (DEIS) for Zone A in order to carry out the Congressional mandate.

Although the Navy realized that restricting the DEIS to the area of Zone A was not wholly desirable, the funding provided by Congress did not provide for a larger scope of work.

At the same time, the Navy planned to continue its earlier program of seismic surveying and exploratory drilling on Pet-4 in order to assess the petroleum potential of the entire reserve. The new plan called for more than 16,000 km (10,000 line mi) of seismic and geophysical surveys and the drilling of 26 exploratory wells.

Congress, after hearings before a subcommittee of the Armed Services Committee, added $62.5 million to the Fiscal Year 1975 Defense Appropriations Act for the exploration and development of the Naval petroleum reserves. As part of the Administration's national energy program, the President also called for the exploration of NPR-4.

With this expanded funding and with the increase in scope to encompass the entire area of NPR-4, the Navy announced a seven-year program of exploration to obtain a preliminary inventory of the petroleum potential of NPR-4. The Navy then proceeded to prepare a draft environmental impact statement for the program covering the entire reserve.

Ancillary to conducting the earlier Pet-4 oil exploration program, the Navy pioneered in Arctic operations both on land and sea, conducting research on permafrost, sea-ice prediction, and Arctic engineering. Grant funding and logistical support through the Naval Arctic Research Laboratory also provided the impetus for many projects in basic research. The results of this research were put to good use during the construction of the DEW Line during 1955-1957. The oil industry also used this Arctic engineering and research data during the petroleum exploration in the Prudhoe Bay area and in the construction of the development facilities and the pipeline to Valdez. In 1975-76 the information was again used in the preparation of the draft and final environmental impact statements for the NPR-4 program.

Between 1953 and 1974, the Navy drilled eight additional shallow wells (South Barrow Wells Nos. 5 through 12) in the Barrow area to develop the small natural gas field there for the use of the local Government agencies and the people of Barrow. A ninth shallow exploratory well was drilled at Iko Bay in the spring of 1975. This work was not considered part of the expanded exploration program.

NAVY EXPLORATION OPERATIONS, 1974-1975

The early exploration program (1944-1953) ran 5,300 km (3,300 line mi) of seismic data. Although the results were crude when compared to those obtained with modern methods, these 5,300 km of information provided a base for the modern program.

When Congress passed the Supplemental Appropriations Act of 1974, some of the $7.5 million designated for the exploration of Pet-4 was intended to be used for seismic investigations. In the winter and spring of 1974, Geophysical Services, Inc. (GSI), working under the Navy's prime geophysics contractor (Tetra Tech, Inc.), ran 1,625 km (1,016 line mi), mostly in the area known as Zone A.

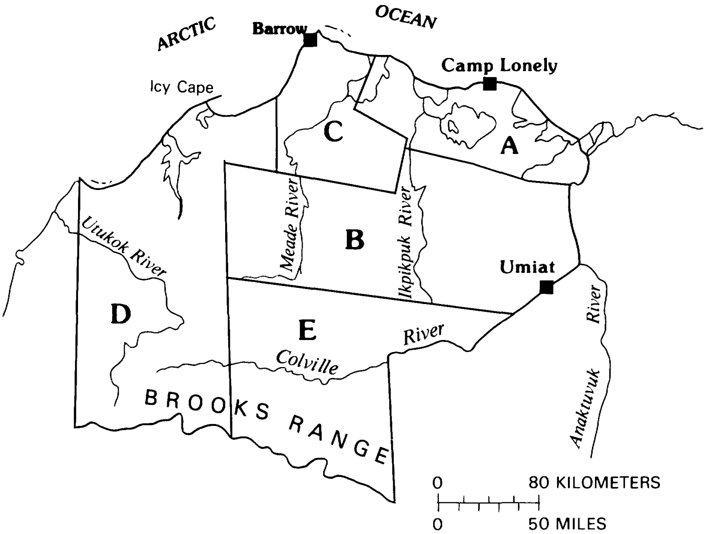

FIGURE 2.9.—Arbitrary division of the NPRA into five zones, A through E, originally created for convenience in processing seismic data.

The Navy recognized both its responsibility to conduct petroleum exploration over the entire reserve and also the respect necessary for the native peoples. Consequently on May 14, 1974, an agreement was reached with the Arctic Slope Regional Corporation and the village corporations. This agreement withdrew any appeals made by the Navy concerning eligibility and withdrawals of lands by the Natives, and, in return, the Navy was allowed to pursue exploration on Native lands that were, or might be, selected. The Navy promised to avoid interference with Native occupancy. The promise was to minimize adverse effects to the environment and damage to the land, and not to impair or otherwise interfere with the wildlife and its habitat or the use of the land to hunt and fish. Under the Settlement Act the subsurface of the entire reserve was retained by the Federal Government.

During the summer of 1974, a 60×90 m (200×300 ft) gravel pad was built at POW 1[2] located at Pitt Point, by Environmental Services, Inc. (ESI), and the materials received from an APUTCO Barge 570 were stored on that pad. These materials included tubular goods, drilling muds, cements, chemicals, piling, wood supplies, and metal stocks. At that time the Navy operated and made purchases directly or through the services of James W. Dalton, an operations manager

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[2] Distant Early Warning (DEW) Radar Station POW I (the "P" is from "Point" and the "OW" from "Barrow").

who was retained under a contract arrangement.

In the fall of 1974, preparations were underway for drilling during the winter season (1974-1975). At that time, the exploration camp at POW 1 consisted of three small orange-colored sleepers (with a total of 18 beds, bunkhouse style), an office unit, and a kitchen-mess hall unit, all set on the gravel near the beach. The contractor (Frontier Sand and Gravel Co.) was hauling material from a sand bar near the mouth of the Smith River to build a pad. A 12×30 m (40×100 ft) prefabricated metal building was erected on piling to serve as a shop facility. Heating and lighting were installed in this building by January 1975. That was the extent of the base camp at the beginning of the year, when the exploration drilling program got underway. The men of the DEW Line had for years referred to the POW 1 Station (Pitt Point) by the unofficial name "Lonely," and the new oil-exploration camp quickly became known as Camp Lonely.

CAPE HALKETT TEST WELL NO. 1

Early in January 1975, work began at Deadhorse (Prudhoe Bay) to ready some of the Frontier Sand and Gravel Company equipment for use in support of the drilling. On January 17, the GSI Caterpillar tractors arrived at Lonely and almost immediately departed for Halkett to start work on the ice runway to be built on nearby lake ice. Cape Halkett No. 1 was located at lat 70°45′ N., long 152°26′ W., approximately 35 km (22 mi) east-southeast of Camp Lonely (see pl. 2.1). Clearing snow to prepare the strip started on the 18th. By January 20, the strip was approved for use by C-130 Hercules aircraft, and the first two Hercules arrived on the 22d. By January 31, 28 C-130 loads had brought in the basic drilling equipment. Thirty men were on the site, and the support contractor (Boatel, Inc.) was operating the camp.

Parts of the camp, generator, and water plant were placed on piling, as was the rig subbase. The rest of the camp units were placed directly on the tundra or ice surface. The area around the rig was low and swampy, so the frozen surface was relatively flat. Berms were built for the fuel pit and sewer pond, and gravel was spread around the area of the rig itself. This gravel was hauled all the way from the Smith River borrow site near Camp Lonely. No reserve pit was dug. The drilling muds were deposited directly on the surface of the tundra, as had been the practice for years in the Barrow gas fields.

Operations slowed up during the first week in February because of high winds, but rig components began to arrive by the 8th. The rig to be used was the Parco Drilling Company No. 128 from Edmonton, Canada. By February 14, 37 of the 46 Hercules loads from Canada had arrived and 10 loads of supplies and fuel. By the 24th the camp, rig piling and caps, and shop were in place, the last nine Hercules loads had arrived, and the rig was moved from the airstrip to the drill sites, a distance of about three-quarters of a mile. Rig-up began on February 27, and the well was spudded on March 24.

Cape Halkett No. 1 bottomed in argillite, the assumed basement, at 3,020 m (9,900 ft) in early May of 1975. Because of the late start, the well was not completed in time to move the rig out without damage to the tundra. Consequently, the rig mast was laid down, and the rig was left for the summer. It was to be moved to the next wellsite in the fall after freeze-up and after a sufficiently thick blanket of snow had accumulated to prevent damage to the tundra.

During the spring of 1975, as a continuation of the 1974 work, GSI gathered 4,030 km (2,519 line mi) of seismic data, mostly in the area known as Zone A. In two years, the program had gathered as much seismic data as the total available to the earlier exploration geologists at the end of the eight-year Pet-4 program (table 2.1).

PROGRAM ADMINISTRATION—1975

Important administrative changes made in 1975 changed the character of the exploration program. In the early spring, the Navy recognized that they now had the task of conducting a large-scale exploration program that was not yet funded. Consequently, they issued a request for proposals for a company, preferably a petroleum company, to serve as operations manager. The successful proposal for this work was submitted by Husky Oil Inc. of Delaware, with headquarters located in Cody, Wyo. Husky formed an ad hoc Alaskan corporation, Husky Oil NPR Operations, Inc., as a wholly owned subsidiary for the operation of the contract. Because of the magnitude of the operation, the contract needed review and approval by the Justice Department as well as by the Defense Department. Authority for the exploration was implicitly included in the legislation (United States Code, chapter 641, sections 7421-7438) of June 30, 1938, which charged the Navy with the "conservation and protection of the reserves," but, because of the history of the so-called Teapot Dome affair, the actual contract required the signature of the President of the United States. Finally, all of the reviews and approvals were completed, and on November 23 President Ford signed the contract, effective December 1, 1975.

In anticipation of the completion of these contracts, the Navy, at the end of the summer of 1975, moved their officer-in-charge, Lt. Comdr. Terrence Woods, from Barrow to

TABLE 2.1.—*Summary of field seismic activity in the National Petroleum Reserve in Alaska, 1944-1981*

[Based on Tetra Tech final reports]

Year	Line distance		Operator	Prime contractor
	km	mi		
			Earlier program	
1944-1953	5,280	3,300	United Geophysical	United Geophysical
			Later program	
1972	99	62	Geophysical Services Inc. (GSI)	U.S. Navy
1973	51	32	GSI	U.S. Navy
1974	1,699	1,062	GSI	Tetra Tech
1975	3,904	2,440	GSI	Tetra Tech
1976	2,304	1,440	GSI	Husky NPR
1977	4,222	2,639	GSI	Husky NPR
1978	3,066	1,916	GSI	Husky NPR
1979	3,042	1,901	GSI	Husky NPR
1980	1,753	1,096	GSI	Husky NPR
1981	946	591	GSI	Tetra Tech
Total	21,086	13,179		

Anchorage. He took temporary office space with M.F. Westfall, the Executive Vice President and Manager of Operations of the fledgling company, Husky Oil NPR Operations, Inc. Consequently, when the contract became effective in December, a nucleus of workers was already in place to begin the program.

EQUIPMENT

In October of 1975, the Navy published the final environmental impact statement (FEIS) for the continuing exploration and evaluation of Zone A. Although the FEIS for Zone A had been necessary to expedite the start of the program, it was recognized that it would be inadequate for the total reserve. Work was immediately begun to expand the FEIS to include all of the exploration work to be conducted within the reserve.

Modern methods of exploration, if exercised with prudent care and caution, could cause minimal disturbance of the tundra. Equipment and supplies that previously had been hauled by D-8 Cat trains, sometimes during the summer with the blade down, now were scheduled to be flown in or moved in winter by rolligons—large vehicles with low-pressure balloonlike tires. Winter seismic trains were made up of a combination of equipment carried on Nodwells or other lightweight tracked vehicles, and camps mounted on Michler Sleighs (a steerable bobsledlike arrangement) pulled by D-7 tractors (figs. 2.10 through 2.13). The Navy produced a set of stipulations governing winter seismic and related geophysical operations, which defined the amount of snow cover and the depth of freeze-down required to avoid damage to the tundra. It also stipulated where camps could be placed, and how rivers were to be crossed. Modern equipment operating within these guidelines proved to be environmentally acceptable (see appendixes 2.1 and 2.2).

NAVY/HUSKY OPERATIONS—SPRING 1976

The old Navy camp at Lonely was obviously not adequate to fill the needs of the expanded operation, so a prefabricated camp of Alberta Trailer Co. (ATCO) units that could be airlifted by C-130 Hercules aircraft was purchased in Canada and flown to Lonely. By the first of March, the camp was partly assembled and placed on pilings. Additional gravel had been added to the pad to provide more storage space. Early operations were hampered by a series of weather problems and having to make do with what was available. The water-hauling and fuel runs were subcontracted to Mukluk Freight to ease the pressure on the camp staff. The catering contract was awarded to ITT Arctic Services, who served as many as 43 people during the month the camp was under construction. During this period the sewage plant was installed, as well as the incinerator, water plant, generators, communication equipment, plumbing, and utilidor.[3] Water sheds, airport sheds, and a shop loft were also built. Though hectic at times, it was a good pioneer operation made possible only through the cooperation of all.

SEISMIC PROGRAM—SPRING 1976

The spring seismic program was highly successful. GSI parties 1182 and 1186 covered 2,300 km (1,440 mi) and produced good to excellent records. Most of the area covered was in the relatively flat coastal plain from the Kuk River to the eastern edge of the reserve, and special attention was given to the Simpson Peninsula.

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[3] Utilidor.—A civil engineering term for an insulated heated conduit (above or below ground) to protect the contained water, steam, sewage, and fire lines from freezing.

EAST TESHEKPUK TEST WELL NO. 1

In January 1976 the crew from the construction contractor, Arctic Slope Alaska General (AS/AG), left Service City, their base camp in the Prudhoe area, to travel overland or, more accurately, over ice, arriving at the East Teshekpuk No. 1 location on January 26. They immediately began to construct the reserve pit and pad. It was planned to excavate a reserve pit at this well rather than release the drilling fluids to the tundra surface as had been done at Halkett. East Teshekpuk was planned for greater depth so there would be a greater volume of mud and cuttings. The site was located on a narrow peninsula of land at the east end of Lake Teshekpuk, approximately 40 km (25 mi) south of Camp Lonely (lat 70°34.2′ N., long 152°56.6′ W.). The construction material for the pad was sand from a deltaic deposit at the mouth of Kealok Creek about 8.5 km (5.3 mi) to the southwest, where the creek emptied into Teshekpuk Lake. A road was cleared over the ice between the drill site and the borrow site. At the same time, a C-130 runway was cleared on the lake ice immediately south of the drilling location. The strip was oriented generally northeast-southwest, the direction of the prevailing winds. Field operations were plagued by frequent storms, blowing snow, and whiteouts, but the site was ready by February 12.

The rig scheduled to drill East Teshekpuk was Parco Rig No. 128. It was stacked at the Cape Halkett location, approximately 27 km (17 mi) to the northeast. However, the rig was moved over ice roads that were laid out in a meandering pattern to take advantage of the frozen lakes, streams, and even sea ice, resulting in a 58-km (36-mi) haul. The move was frequently delayed by high winds and blowing snow; the road had to be cleared and recleared. Mukluk Freight, AS/AG, and Parco personnel all worked together to move the rig. It took from February 4 to February 17 to get the first piece of rig moved. "Digging out" and "Opening road" were the two most frequent entries in the daily reports. Rig-up at East Teshekpuk was actually started on February 22, while the moving of the rig, camp, and supplies continued. Once the drilling camp was in place (February 28), the AS/AG construction camp moved overland to the South Harrison Bay location (lat 70°25.6′ N., long 151°43.8′ W.). Rig-up at East Teshekpuk was completed on March 12, and the well was spudded that same day.

During late April, the drilling fluid in the reserve pit reached such a volume that its depth exceeded

FIGURE 2.10.—All-terrain vehicles used by seismic trains in the NPRA, spring 1975. Note racks on rear bed to hold geophones. Photograph by U.S. Navy.

FIGURE 2.11.—Seismic drill rig mounted on Nodwell vehicle, spring 1975. Photograph by U.S. Navy.

the excavated depth of the pit, and it melted out an ice-rich area of the retaining berm. The failed section of berm was composed principally of material that had been excavated from the reserve pit. As a result of this failure, some mud escaped and flowed to the nearby edge of Teshekpuk Lake. Although the amount was minor and minimal environmental damage was caused, the event inspired a redesign of the reserve pits. All future reserve pits were designed to contain the total estimated volume of drill cuttings and muds below the level of the original tundra surface, and the containment volume provided by the dikes was to serve as a safety factor in case an emergency discharge of mud should occur. Material excavated from the pit was spread as a so-called primary lift in the camp area of the drill pad. Dike material surrounding the reserve pit was to be clean, well-drained, and free of ice masses.

FIGURE 2.12.—Seismic train waiting for supplies along cleared runway near Ikpikpuk River, spring 1975. Photograph by U.S. Navy.

FIGURE 2.13.—Seismic train crossing tundra just north of Umiat, January 1978.

The well was drilled to a total depth of 3,250 m (10,664 ft), reached on May 7, 1976, in order to penetrate and evaluate mainly the Sadlerochit Group and secondarily the pebble shale unit, the Sag River Sandstone, and the carbonate rocks of the Lisburne Group. At the conclusion of the drilling and evaluating operations, the well was abandoned and cement plugs were placed at selected intervals. Diesel oil was left in the wellbore across the permafrost interval to allow for subsequent temperature measurements planned by the U.S. Geological Survey as part of an ongoing North Slope geothermal program. The abandoned wellhead was also designed to accommodate this work.

At the conclusion of the operations, the drilling equipment was rigged down and stacked on the pad for moving; the pad was graded and cleaned up. Seven 14,193-L (3,750-gal) steel fuel tanks were placed in the fuel-containment berm, and approximately 79,000 L (21,000 gal) of JP-5 jet fuel was put in the tanks for summer helicopter use and for the rig move in the early fall. Operations at the site were terminated on May 16, 1976.

SOUTH HARRISON BAY TEST WELL NO. 1

When the AS/AG construction train left the East Teshekpuk site at the end of February for the South Harrison Bay No. 1 drilling site, they almost immediately encountered bad weather. However, the trip was completed in 2½ days, and construction of the South Harrison Bay reserve pit commenced the evening of March 3. Borrow material came from the sand dunes along the edge of Harrison Bay at the mouth of the Kalikpik River, about 11 km (7 mi) west of the drill site. A road was cleared on the ice of the bay for the hauling. It was planned to deliver the rig piling and pile caps that summer by barge. To ensure that an early construction startup would be possible in the fall, a thin sand runway 600 m (2,000 ft) long was constructed to the west of the drill site. A few days were also spent unsuccessfully searching, within a 16-km (10-mi) radius of the site, for a suitable water supply. The South Harrison Bay drill site and runway were completed by March 26, and the construction camp and part of the equipment were demobilized to Service City. The remaining equipment was sent to Camp Lonely for use that summer.

NAVY/HUSKY OPERATIONS: SECOND SEASON— JUNE 1976 TO MAY 1977

SUMMER OPERATIONS

The plans for the 1976 summer cleanup program were made after a reconnaissance of sites was completed in mid-May. Arrangements were made with AS/AG to provide the labor and with Crowley All Terrain Vehicle Company (CATCO) to provide the rolligons. The helicopters and the Twin Otter aircraft that were under contract and based at Lonely were to be used for cleanup and the summer survey.

Two cleanup crews were used—one based at Lonely and one based at Barrow. Between June 15 and September 8, cleanup was completed at Iko Bay and the Barrow area, the Simpson area, POW A, Alaktak, West Topogaruk, the Lonely area, Pitt Point, POW B, and the East Teshekpuk drill site. A total of 23,500 drums were retrieved, and of these 10,650 were crushed and stockpiled. In addition, approximately 340,000 kg (750,000 lb) of debris was collected, 160,000 kg (350,000 lb) of which was burned and the remainder left in stockpiles for later disposal.

The summer survey included staking the five proposed wellsites and the winter trails to each. Water sources were located, borrow sites defined, and soil samples collected. USGS topographic maps (1:63,360-scale series) were used where available. In addition, the all-season road from NARL to the South Barrow Gas Field pressure-reducing station was staked.

At Camp Lonely, physical improvements included the installation of piling for two warehouses, camp extension, and a communications tower (fig. 2.14). Designs were finished for the airport terminal, the

FIGURE 2.14.—Communications tower at Camp Lonely, February 1978.

weather shacks for the wellsites, and the heat-recovery system for Lonely. In addition, the installation of motor-gasoline (Mogas) tanks was completed, making it much more efficient to operate the local transportation.

The 1976 barge delivery included 9,176,350 L (2,424,400 gal) of fuel and 9,282 t (10,233 tons) of supplies. This amount of fuel was far less than the anticipated annual need for the program, but it was the maximum it was possible to store until the storage capacity was increased.

The rest of the summer season was spent cleaning up the pad at Camp Lonely, increasing its size, stabilizing the gravel areas, and sorting out the materials received on the barge, so they would be easily accessible after the snow and the dark period began.

WINTER CLEANUP

A trial was made during the fall of 1976, to test the economic feasibility of a winter cleanup. Winter was defined as lasting from November 1 to January 31. For the winter work it was necessary to provide a self-sustaining camp for the 18-person crew. Skull Cliff, an abandoned LORAN navigational site about 38 km (24 mi) south-southwest of Barrow was selected for this operation. The site consisted of abandoned buildings and supplies, debris, and a collapsed 190-m (625-ft) tower, all scattered over an area of approximately 15 km^2 (6 mi^2). Work was carried on from October 26 to December 15, and during this period 2,280 drums and 900 kg (2,000 lb) of debris were picked up. The subzero temperatures were not as much of a problem as the lack of daylight. Hard-packed snow and reduced light made much of the debris impossible to locate or difficult to retrieve. Furthermore, the contents of the barrels were frozen, making them impossible to empty and very heavy. This problem, coupled with the long mobilization period, helped to increase the cost per unit of work accomplished to the point that it was decided to abandon winter cleanup.

SOUTH HARRISON BAY TEST WELL NO. 1

During the summer, the barges could not reach the South Harrison Bay site because the water was too shallow, and they had to return to Lonely to unload. As soon as the tundra conditions allowed, a small construction group left Lonely to install the piling and pile caps at the South Harrison Bay site. The rolligons began operating on the tundra on October 18. While the earth auger was working, the Twin Otter strip was cleared and was ready for operation by October 19. Work began immediately on clearing the ice of Harrison Bay just north of the drill site for a Hercules C-130 airstrip. The sand strip was used by the Twin Otter while the ice on the bay thickened sufficiently to support the Hercules C-130's.

Rig mobilization began on October 28. The rig (Parco No. 128) was stacked at East Teshekpuk and was moved by CATCO rolligons on the winter trail connecting the two locations. The rig move (129 loads) took 19 days. Weather conditions were generally good during this period; however, a brief period of warm temperatures (−12 to −9 °C, or +10 to +15 °F) and high winds (30-35 knots) at the end of the first week in November disrupted operations and broke up the ice strip on Harrison Bay. Because it was feared that the ice would not thicken fast enough to have the C-130 strip ready by spud date, it was decided to build the strip on the frozen mud flats near the mouth of the Kalikpik River about 10.4 km (6.5 mi) to the west along the shore of the bay. An ice road was cleared near the shore to connect the strip to the wellsite.

Rig-up operations began on November 10 and were completed in 11 days. The well was spudded at 3:00 p.m. on November 21 and was drilled to a total depth of 3,440 m (11,290 ft). The primary objective of the well was to reach the Sadlerochit Group, with secondary interests focused on the Kuparuk Formation and the basal sand of the Torok Formation. At the conclusion of the drilling and evaluation operations the well was abandoned, leaving cement plugs at selected intervals.

Rig-down began on February 8, and the rig was moved to Deadhorse. The pad was cleaned and graded to serve for summer stack-out of the Parco No. 95 after drilling was finished at Atigaru Point.

SOUTH BARROW NO. 13

South Barrow Well No. 13 is located in the South Barrow Gas Field approximately 8 km (5 mi) southeast of the city of Barrow. The pad for the well had been constructed earlier by the Navy, and the Cardwell Model H rig, owned by the Navy, was stacked out on the pad.

Field operations began on November 16, 1976, camp units moving from the Naval Arctic Research Laboratory to the well location. Considerable time was then spent in overhauling and repairing the rig components. Actual rig-up began on December 1, and the well was spudded at 10:00 a.m. on December 17, 1976.

The well was drilled to a depth of 772 m (2,534 ft) into the Jurassic gas sands above the argillite basement. After evaluation, the well was judged to be only a marginal producer. On January 16, the rig was taken down and moved to the South Barrow Well No. 14. The drilling pad was cleaned and leveled, and a shelter was placed over the wellhead.

SOUTH BARROW NO. 14

South Barrow Well No. 14 was located 19 km (12 mi) east-southeast of the city of Barrow and represented a step-out of approximately 11 km (7 mi) from the South Barrow Gas Field. Construction crews for the building of the pad were mobilized on November 20, 1976. Rig-up operations began on January 18, 1977, and the well was spudded at 1:30 a.m. on January 28. The rig used was the Navy-owned Cardwell Model H.

The well was drilled to a total depth of 688 m (2,257 ft). The primary objective of the well was to reach the Jurassic gas sands and the Triassic Sag River Sandstone. After evaluation, the well was completed as a gas well. It was cleaned up and lubricated with alcohol through the tubing and annulus to prevent freezing, and the wellhead tree was nippled up and tested. The rig was released on March 3, 1977, and moved to storage. The pad was cleaned and leveled, and a wellhead shelter was installed.

W.T. FORAN TEST WELL NO. 1

Lt. W.T. Foran, a Naval Reserve officer and a geologist in civilian life, was a strong proponent of the petroleum possibilities of Pet-4. In 1924 he led a USGS field party across the western part of the reserve, up the Utokuk River, across the Brooks Range, and down the Noatak River to Kotzebue. It was his memorandum for the Bureau of the Budget written in March of 1943, outlining the reasons to explore the Pet-4, that was largely responsible for the early exploration program. Appropriately, he was named to head a reconnaissance party to the reserve in 1944 and was very active in the geologic exploration throughout the early part of the program.

On November 23, 1976, an AS/AG construction train left Camp Lonely for the W.T. Foran No. 1 drill site located at lat 70°49.5′ N., long 152°18′ W. The borrow sites for this pad were located 10, 11, and 14 km (6, 7, and 9 mi) from the site, to the west along the coast. The first two sites were quite small, and so, to minimize disturbance, all of the material was taken from the most distant site (near Cameron Point). Care was taken to avoid the Esook trading post nearby, and material was extracted only to within 30 cm (1 ft) of sea-ice level. The drill pad and the airstrip on the nearby lake to the west were constructed in a month, and the construction train moved back to Lonely for equipment repair. On January 1, 1977, this crew moved on to the South Simpson wellsite.

Rig move-in to W.T. Foran No. 1 began on January 31, 1977, by air. The rig, Nabors Drilling Company No. 23, had been stacked at Deadhorse.

In 20 days, 110 Hercules C-130 loads brought in the rig, cement, and other miscellaneous equipment. Rig-up began on February 12 and was completed in 21 days. Weather conditions during the move and rig-up were generally good, but intermittent winds of 25-35 knots with blowing snow hampered flying on three days. The well was spudded at 12:00 midnight on March 6, 1977.

The W.T. Foran well was drilled to a total depth of 2,702 m (8,864 ft). The primary objective was to reach the Sadlerochit Group and the Lisburne Group, the secondary objective being the Kuparuk Formation. After cement and mechanical plugs were set at selected intervals, the well was abandoned and finally terminated on April 24, and the rig was stacked out for the summer at the W.T. Foran site. All personnel left the site on April 30, 1977.

ATIGARU TEST WELL NO. 1

A second construction train left Lonely on December 3, 1976, for the overland move to Atigaru Point. The Atigaru Point wellsite was located approximately at lat 70°33.3′ N., long 151°43.0′W. The material to build the pad came from a number of small deposits along the beach to the west of the wellsite. All were within 10 km (6 mi) of the site, and all were of relatively poor quality—containing a large amount of organic material and clay. The poor quality caused no immediate trouble in the frozen state, but it caused numerous problems during rehabilitation and revegetation. The pad was designed to leave undisturbed a LORAN tower that was already on the site. An ice runway oriented northeast-southwest was cleared in the mud-flat areas of Harrison Bay, behind the protection of Atigaru Point and numerous exposed mud-sand bars. Construction was completed on January 1, 1977, and the next day the train moved on to the West Fish Creek site.

The first drilling personnel arrived at Atigaru Point on December 15, 1976, and rig move-in operations began on December 17 by Hercules C–130's. The rig (Parco 95) had previously been used by Mobil Oil Company in the vicinity of Prudhoe Bay. The rig move was completed in 11 days and 99 loads. Other drilling supplies arrived from Lonely via rolligon. Rig-up began on December 31 and was completed in 13 days. The well was spudded at 4:00 p.m. on January 12, 1977.

The Atigaru Point well was drilled to a depth of 3,515 m (11,535 ft). The primary objective of the well was to reach the Kuparuk Formation, the Sadlerochit Group, and the Lisburne Group, the secondary objective being the Sag River Sandstone and the basal sand of the Torok Formation. The well was abandoned, with mechanical and cement plugs left at selected intervals. Operations were terminated on March 29, 1977, and the rig was moved over the ice of Harrison Bay to be stacked out for the summer on the South Harrison Bay drilling pad.

SOUTH SIMPSON TEST WELL NO. 1

A construction train left Lonely on January 1, 1977, and moved overland to the South Simpson No. 1 location. The trail followed the edge of the ice of Smith Bay and then the Piasuk River. Deep snow along the banks of the river and frequent high winds and blowing snow slowed the operation. The site was located approximately at lat 70°48.3′ N., long 154°58.9′ W.

FIGURE 2.15.—Spraying water to build ice road at South Simpson, January 1977.

FIGURE 2.16.—Truck hauling gravel over ice road at South Simpson, February 1977.

The material for construction of the pad was taken from a high sand bank on the Piasuk River about 8 km (5 mi) east of the site. However, because the ice road for the haul followed the lakes and streams wherever possible, the haul distance was over 10.5 km (6.5 mi) (figs. 2.15 and 2.16). The construction material was a well-drained sand, and excavation was relatively easy. An ice strip was cleared on an unnamed lake about 1 km (0.6 mi) directly west of the wellsite. The road connecting the site to the airstrip followed a frozen streambed. Construction was finished on February 13, and the construction train retraced its trail back to Camp Lonely, where it remained for the summer season.

Rig move-in operations commenced on February 12, 1977. Portions of the rig (Nabors No. 1) had been moved to Lonely by barge during the summer of 1976, and other portions remained at Deadhorse. Those parts of the rig at Lonely were transported to South Simpson by rolligon (fig. 2.17), and the components at Deadhorse were flown in by Hercules C-130 aircraft. Fifty-seven Hercules loads and 15 rolligon loads were required to move the rig to the wellsite. Rig-up began on February 20 and required 17 days. The well was spudded at 8:00 a.m. on March 9, 1977.

The well was drilled to a total depth of 2,680 km (8,795 ft). The primary objective was to reach the sandstones of the Kingak Shale and the Sadlerochit Group, the secondary objective being sandstones in the Okpikruak Formation. The well was abandoned and left with cement and mechanical plugs. The abandonment marker was set, and the rig was released at 3:00 p.m. on April 30, 1977. The rig was taken down and stacked out on location for the summer season.

WEST FISH CREEK TEST WELL NO. 1

On the second day of the new year (1977), a construction train left the Atigaru Point drill site to travel over the ice of Harrison Bay to the mouth of the Kalikpik River, then up the Kalikpik to the West Fish Creek drill site. The drill site was located at lat 70°19.6′ N., long 152°03.6′ W., approximately 7 km (4.5 mi) west-northwest of the Fish Creek Test Well drilled in 1949.

The weather was good for the overland move, but while traveling along the western shore of Harrison Bay, approximately 4 km (2.5 mi) from the mouth of the Kalikpik, a D-8 Cat fell through the ice. Fortunately the water was not deep, and the Cat went down, tipped to the right side, in about 1.5 m (5 ft) of water and mud. The operator was not hurt. The ice was evidently thin because of a strong current at that point. The surrounding ice was also quite thin, so the Cat was left for retrieval at a later time. The construction train finally arrived at the site on the afternoon of January 4. The Cat was extricated the first week of May with an auger and four flatbed trucks with gin poles rigged over their rear wheels.

Work began immediately on the excavation of the reserve pit. Borrow material for the pad was taken from a 6-m-high (20-ft) sand bank on an unnamed lake 3.5 km (2.2 mi) west-northwest of the site. The material was well-drained dune sand, so excavation was relatively easy. An ice runway was cleared on the unnamed lake 1.5 km (1 mi) east of the drill site. Construction was virtually complete by January 29, but another week was spent readying some of the equipment for summer stack-out on the site, so that it would be available for the North Kalikpik work the following season. The construction personnel left the site on February 6 with that portion of the equipment that was to be taken overland to Camp Lonely.

Rig move-in operations were begun on January 20, 1977. The rig (Parco No. 96) had been used by Mobil Oil at the West Staines location and was at Deadhorse. It was moved from Deadhorse by Hercules C-130 aircraft in 105 loads in 14 days. Weather conditions during rig move and rig-up were good, only three days being lost because of blowing snow. The well was spudded at 9:00 a.m. on February 14, St. Valentine's Day.

The objective of the well was to reach the Kuparuk Formation, the Sadlerochit Group, and the basal sand of the Torok Formation. The well was drilled to a total depth of 3,483 m (11,427 ft). It was plugged and abandoned, and the rig released on April 27, 1977. The rig was taken down and prepared for moving but was stacked on the location for the summer. Operations ceased May 4, 1977.

SEISMIC PROGRAM—SPRING 1977

The goal for the spring seismic program was to acquire 4,530 km (2,830 line mi) of seismic data. To do this, five seismic trains were mobilized in January 1977; two trains (Nos. 1182 and 1186) started out from Icy Cape, and three trains (Nos. 1173, 1184, and 1195) started out from Umiat. Work was scheduled in the western sector and in the Colville, Utukok, and Ikpikpuk basins, and it included more than 2,400 km (1,500 line mi) of reconnaissance in the Foothills province. From the onset, poor weather with whiteout conditions, blowing snow, and cold temperatures hampered operations. At the end of March everyone concerned was guessing that they would be lucky to accomplish 4,000 km (2,500 mi). However, extremely careful planning and some deeper and longer lasting snow cover allowed later operations in some areas. Party 1182 finished up in Barrow on May 11. Party 1186 finished some experimental work

FIGURE 2.17.—Rolligon transporting outsize rig component over tundra south of Lake Teshekpuk, winter 1977.

and then stacked their equipment at Brady on May 25. Parties 1173, 1184, and 1195 all arrived at Umiat by May 20 and there stacked equipment for the summer. A total of 4,222 km (2,639 line mi) was obtained.

CLEANUP—SPRING 1977

During 1977, the cleanup program was concentrated at three sites: POW A, a former DEW Line site; Simpson Test Well, drilled during the 1947 program; and the Topogaruk Test Wells from the 1951 program. It was decided to pick up the debris from the Simpson and Topogaruk sites and take everything back to POW A. The final plans for the disposition of the debris had still not been decided, but locating the debris at POW A allowed the additional option of a backhaul to the lower 48 States via barge. A portable drum crusher was used to consolidate the bulk.

Operations were begun February 10, and were halted at the end of the first week of May, when the camp and rolligons were returned to Camp Lonely. A total of 159 t (175 tons) of debris was retrieved, 9,718 drums were collected, and 12,233 drums were crushed. Although drums were often found filled with snow, covered, and frozen as in the fall, the spring phase of cleanup was more productive because of the increased amount of daylight and the greater dependability and speed of the CATCO rolligons. In addition, many of the drums at these sites were on top of the frozen tundra and therefore more accessible.

CAMP LONELY

Early in 1977, the Navy, recognizing the great need for fuel and the difficulty of bringing it north by barge, let a contract to build storage tanks at Lonely. The design included two tanks, each with a 4,770,000-L (30,000 bbl) capacity, and four tanks of 1,590,000-L (10,000 bbl) capacity, for a total capacity of 15,900,000 L (100,000 bbl or 4,200,000 gal). A fixed-price contract was issued by the Naval Facilities Engineering Command of San Bruno, California, to Arctic Slope/Alaska General (AS/AG), the successful bidder. Gravel placement began in late March. Construction of the tanks was started in early May, and final inspection and acceptance of the tanks was on July 20, 1977, just in time for fuel delivery on the 1977 barge.

NATIONAL PETROLEUM RESERVES PRODUCTION ACT OF 1976

The National Petroleum Reserves Production Act (Public Law 94-258) was passed by Congress as a result of the 1975 shortage of gasoline and heating oil. The act called for the production of petroleum, by the Navy, from Naval Petroleum Reserves 1 (Elk Hills, California), 2 (Buena Vista, California), and 3 (Teapot Dome, Wyoming). It called for the transfer of all of Petroleum Reserve 4, except for the Naval Arctic Research Laboratory, from the Navy to the Department of the Interior effective June 1, 1977. It charged the Secretary of the Interior with the continuation of the exploration program in Pet-4 and the continuation of the supply of natural gas to the community of Barrow. The act also changed the name of Pet-4 to the National Petroleum Reserve in Alaska (NPRA).

In addition, PL 94-258 charged the Secretary of the Interior with two studies that came to be known by their paragraph designations in the law. The 105b study was to investigate and recommend the best overall procedures to be followed in the development, production, transportation, and distribution of petroleum from the NPRA. Furthermore, the study was to include the economic and environmental consequences of this development. The 105c study was to determine the value of the lands of the NPRA and make appropriate recommendations for their best use. The law also required that special attention be given to the environmental problems of Teshekpuk Lake for nesting wildfowl and of the Utukok Uplands for caribou calving. It further authorized the Secretary to designate other areas that might require special environmental protection.

The Navy had restricted its studies to Zone A when they were writing the overall environmental impact statement (EIS). Consequently, Zone A was the only area considered by the EIS produced in October 1975. The Navy, although now relieved of responsibility for the program, felt, because of their many years of involvement and the start they had made, that they were morally obligated to finish the overall final EIS. This work was given high priority in the spring of 1977.

The draft EIS was submitted to the Council on Environmental Quality in February, and notice of its availability was published in the Federal Register in March. Distribution of copies was made to State, Federal, and local Government offices throughout Alaska, and approximately 230 additional copies were distributed to private industry, organizations, and individuals. Public hearings were held in Barrow, Fairbanks, and Anchorage. The record was kept open to receive written comments until April 18, and then a concerted effort was made to respond to all questions, pertinent points, and objections. The final EIS was presented to the President's Council on Environmental Quality on May 27, 1977.

About this same time, the Navy, in cooperation with the USGS, drew up a set of stipulations concerning winter road and trail construction and use within the NPRA. These stipulations were included in the final EIS and provided a detailed set of guidelines similar to those for the winter seismic program published in the EIS for Zone A.

To carry out the responsibilities specified in PL 94-258, the Secretary of the Interior delegated to the Bureau of Land Management (BLM) the surface management of the reserve and the protection of the surface values from environmental degradation. To the USGS, he delegated the management of the continuing exploration program, the enforcement of stipulations related to the petroleum exploration, and the operation of the Barrow gas fields as specified in the act. A memorandum of understanding was drawn up to identify the procedures to be followed to facilitate the interfacing of the two agencies.

The memorandum called for an annual plan of operations to be written jointly each year, describing the proposed exploration program. This plan was circulated to all cognizant Federal, State, and local Governments, private organizations, and individuals. Such wide distribution helped to bring up any concerns or reservations a Government agency or individual might hold about exploration in a specific area.

After the annual plan was written, the next step was to complete the summer field work at each drilling site so that a site-specific environmental assessment could be written. This assessment would address such items as location of the drill site in relation to special areas, local topography and drainage, water resources, fisheries resources, cultural and socioeconomic resources, clean-air degradation, noise pollution and human presence, degradation of scenic and wilderness values, and the presence of rare or endangered species and (or) archaeological sites. These assessments were made for each wellsite and its associated winter trails, as well as any additions to the planned seismographic program for the coming spring.

USGS/HUSKY OPERATIONS: THIRD SESSION— JUNE 1977 TO MAY 1978

SUMMER OPERATIONS

The summer survey in 1977 was extensive because not all of the subsurface data had been analyzed in time to decide on final well locations before the summer began. Therefore, four survey crews were mobilized to survey ten possible test well sites. These sites were:

Site	*N. latitude*	*W. longitude*
Inigok	70°00′	153°06′
Key River	69°53′	153°40′
Ikpikpuk	70°27′	154°20′
East Simpson	70°55′	154°37′
Tunalik	70°12′	161°04′
Kugrua	70°35′	158°40′
Maguriak	70°24′	159°15′
South Meade	70°37′	156°53′
Drew Point	70°53′	153°54′
North Kalikpik	70°31′	152°22′

Of these sites, Key River, East Simpson, and Maguriak were ultimately dropped from the program.

Improvements continued at Camp Lonely to cope with the increased number of personnel and attendant logistic needs of the large program. A heat-recovery system was installed on the power-generation plant. An extended aeration wastewater treatment plant of much larger capacity was installed. A four-unit extension on piling was added to the camp, and shelves and bins were added to the warehouse. Plans were also made to build increased shop and warehouse space.

The barges for that year's sealift left Seattle on June 29, with the season's resupply of 10,851,331 kg (23,872,928 lb) of pipe, chemicals, cement, muds, lumber, and piling and 20,574,427 L (5,435,780 gal) of fuel. Ice conditions were good that year, and unloading operations went smoothly. Lateral moves that summer included 359,000 kg (790,000 lb) of equipment to Peard Bay (the old DEW Line Station LIZ C—the "LIZ" is from Cape Lisburne) to prepare for mobilization that fall.

CLEANUP

The cleanup program for the 1977 summer included the sites of the exploratory wells that had been drilled during the 1976-77 season. Each site was visited to remove the piling caps and to cut off the piling below ground level. All the debris that was buried under the snow during the winter operation was picked up, and all combustibles were burned. The sites included: (1) East Teshekpuk (from the 1975-76 season), (2) South Harrison Bay, (3) W.T. Foran, (4) Atigaru Point, (5) South Simpson, and (6) West Fish Creek. In late August, Cape Halkett was seeded with a mix of northern grasses and fertilized, and debris and piling cleanup was completed at South Barrow Gas Wells Nos. 13 and 14 and also in the Camp Lonely area.

Cleanup of old Navy sites was limited to crushing the drums at POW A and POW B that had been stockpiled there that spring and during the previous summer. In addition, LIZ C was cleaned up to prepare the site for use as a logistics base during the coming season.

A total of 14,875 drums were retrieved; 16,743 were crushed, some of these having been retrieved previously; and 440 t (485 tons) of debris was collected and burned or stockpiled.

WESTERN SECTOR STAGING— SUMMER 1977

Mobilization of the construction crews for the wells to be drilled in the western sector required that a temporary staging area be located on the gravel base of the old DEW Line Station at Peard Bay (LIZ C).

The facility had served during the summer as a receiving depot for barge deliveries from Seattle, Anchorage, and Lonely. Lateral barge moves delivered 358 t (395 tons) of material, which included some operating equipment and two complete construction Cat trains. In addition, two 64,000-L (17,000-gal) double-walled steel tanks and two 37,900-L (10,000-gal) bladders were brought in for fuel storage. Personnel and supplies to assemble the trains and support the initial move arrived from Lonely and Barrow by Twin Otter aircraft, landing on the existing gravel strip. The unvegetated gravel spit along the ocean was to be leveled to allow a C-130 to land after freezeup, in order to deliver supplies and fuel for the camp and for the overland trip to the Kugrua and South Meade wellsites in December. Delivery to the wellsites was by land until the ice strips became operational.

In addition to the Peard Bay (LIZ C) site, quantities of drill pipe and crated drill muds were offloaded and stored on a point of gravel (called Husky Point) in Kasegaluk Lagoon just south of Nokotlek Point at lat 76°18.5′ N., long 161°04.5′ W. Supplies and materials from this site were moved inland to the proposed Tunalik Borrow Site No. 2, a little more than 1 km (3/4 mi) distant, and then over the prepared snow route to the drill site.

Late in September 1977, work was begun at Peard Bay to construct a temporary airstrip on the unvegetated gravel beach immediately to the west of the DEW Line site in preparation for the move to Kugrua and South Meade. Also in September, improvements continued in Camp Lonely, two 250-kW generators being installed to provide more dependable and increased power. Runway lights and weather shacks had been purchased early in the summer, and these began to arrive.

Early in November, Husky Oil NPR Operations, Inc., negotiated contracts for the use of Brinkerhoff-Signal Rig No. 31 in the Barrow gas fields.

The 1977-78 construction and drilling program was ambitious, and schedules were tight. As soon as the snow became deep enough to protect the surface of the tundra and the depth of freezing was sufficient to support heavy equipment, the season got underway. Construction trains were mobilized from Lonely to Drew Point (December 1, 1977) and from Lonely to North Kalikpik (December 4, 1977). The North Kalikpik train was supplemented on December 6 by the parts of a train that had been stacked out for the summer at West Fish Creek. In addition, two trains left Peard Bay (LIZ C)—one for Kugrua (December 2, 1977) and one for South Meade (December 5, 1977). All moves were overland and followed trails that had been staked and approved during the previous summer.

DREW POINT TEST WELL NO. 1

Field operations for Drew Point commenced when the construction train left Camp Lonely on December 1, 1977. The site was located at lat 70°53′ N., long 153°55′ W., on the eastern shore of Smith Bay about 29 km (18 mi) west of Camp Lonely. The sea ice near shore was followed wherever possible, because travel there was much smoother and caused less environmental degradation. Material for the drill pad was taken from a partially drained lake basin about 10 km (6 mi) south of the wellsite. Access to the borrow site was mainly over the ice along the edge of Smith Bay, and less than 2 km of overland ice road was required. An ice strip was cleared on a lake 5.5 km (3.5 mi) to the east of the site. The water source was a lake 5 km (3 mi) to the southeast. Construction was completed on January 5, 1978, and the train moved on to the Ikpikpuk site.

The rig (Nabors No. 25) was to be moved from the W.T. Foran drill site and was originally scheduled to be moved by air. An airstrip was cleared at the W.T. Foran site, because the ice on that shallow lake froze to the bottom early in the season. However, the ice strip at Drew Point was much slower to freeze. This, combined with some bad weather and aircraft-scheduling problems, made it expedient to move the entire rig by rolligon. Rig-moving operations began on December 20, 1977, and were completed on January 1, 1978. Rig-up began on January 2 and was completed in 11 days. The well was spudded at 4:00 p.m. on January 13.

The Drew Point well was drilled to a total depth of 2,422 m (7,946 ft). The primary objectives of the well were to reach the Sadlerochit and Lisburne Groups, and a secondary interest was in the possible presence of the Kuparuk Formation. Although minor oil shows were encountered, the potential reservoir zones were thin and (or) had low porosity and permeability. At the conclusion of the drilling and evaluation process, the well was abandoned, cement and mechanical plugs being placed at selected intervals. The rig was released at 2:00 p.m. on March 13, 1978.

KUGRUA TEST WELL NO. 1

The airstrip at Peard Bay (LIZ C) was ready by November 10, 1977, and the strip was checked and approved by a C-130 captain. Mobilization of the construction equipment began in mid-November, and approximately two weeks were spent putting the train together, checking generators and equipment, and making other preparations for the overland move. The first train departed LIZ C November 30 and arrived at the Kugrua site late in the evening of December 1. The Kugrua Test Well No. 1 was located at lat 70°35′ N., long 158°40′ W. Construction was begun the next morning on the reserve pit, the pad, the ice airstrip, and the ice roads. The airstrip was located on a lake about 1.5 km (1 mi) southwest of the well. This lake also served as a water source. The material for the pad was obtained from a slightly elevated sand dune about 2 km (1.25 mi) southeast of the wellsite. Construction was completed on January 7, but a ruptured fuel bladder delayed the overland move to Tunalik. Also, blowing snow hampered the crew cleaning the fuel pit and salvaging the fuel, so the train did not move out until January 29.

The rig (Parco No. 95) was moved from the South Harrison Bay wellsite by air and by rolligon. The ice runway was cleared again on the shallow mud flats at the west end of Harrison Bay. Move-in operations began on January 17 and were completed in 25 days. The well was spudded at 3:00 p.m. on February 12, 1978.

The Kugrua well was drilled to a total depth of 3,837 m (12,588 ft). The purpose of the well was to test an interpreted closure noted on seismic data within the basal part of the Lisburne Group or the Devonian sequence. The primary zones of interest included the Sadlerochit Group, the upper part of the Lisburne Group, and possibly the Kuparuk Formation. Drilling was uneventful except for repeated problems with sloughing shale.

The well was drilled to test a seismic anomaly in Paleozoic strata in an onlap sequence along the Arctic coast. The anomaly was penetrated, but an explanation for it was not obvious. The seismic interpretations may have been related to an unanticipated sequence of Pennsylvanian-Mississippian limestone exceeding 425 m (1,400 ft) in thickness encountered during the drilling. The projected depth of the Kugrua well was argillite basement at 3,725 m (12,220 ft), but the caving shale and the unanticipated sequence of limestone at the bottom of the hole slowed drilling considerably and the well bottomed in the Lisburne Group at a depth of 3,837 m (12,588 ft), still short of the argillite.

At the conclusion of the drilling and evaluating process, cement and mechanical plugs were set at selected intervals and diesel was left in the top 550 m (1,800 ft) of the well bore. The abandonment marker was set and the rig released at 9:00 p.m. on May 29. Fortunately, there was still a good snow cover on the tundra, and the rig was quickly broken down and moved by rolligon to Peard Bay, where it was stacked to await the barges that summer.

NORTH KALIKPIK TEST WELL NO. 1

The North Kalikpik drill site was located at lat 70°31′ N., long 152°22′ W. The construction train was mobilized in part from Camp Lonely on December 2, 1977, and in part from West Fish Creek on December 5. Both moves were overland. Construction actually started on December 4. The material for the pad was obtained from a high sand bank along a small unnamed tributary of the Kalikpik River approximately 6.5 km (4 mi) to the southeast. The C-130 strip was on the ice of a lake about 2.5 km (1.5 mi) to the northwest of the site, and the principal water source was a small lake one-half kilometer (one-quarter mi) directly south. Construction work was completed on January 25, but the crew remained on site until the drilling crew was established. The construction train left for the Inigok location on January 31, 1978.

Rig move-in began on January 29. The rig (Parco No. 96) was moved from West Fish Creek to North Kalikpik by rolligon—110 loads in 8 days. The ice of the air-strip lake was not thick enough to support heavy aircraft at the time of the move. Rig-up began on February 6 and was completed in 22 days. The well was spudded at 10:00 a.m. on February 28, 1978.

The well was drilled to a total depth of 2,254 m (7,395 ft). The purpose of the well was to test a stratigraphic erosional remnant of the Kuparuk Formation. No possible reservoir rocks were encountered, although the rocks of the target interval contained much organic material and traces of bitumen and gas.

After drilling and evaluation, the well was abandoned, cement and mechanical plugs being used to separate the formations. The abandonment marker was set, and the drilling rig released at 2:00 p.m. on April 14, 1978. The rig was then broken down for moving to the lkpikpuk location.

SOUTH MEADE TEST WELL NO. 1

On December 5, 1977, the second construction train left Peard Bay (LIZ C) enroute to the South Meade site at lat 70°37′ N., long 156°53′ W. Construction began immediately upon its arrival. Clearance for some of the borrow sites was not obtained because archaeological materials were involved. Where possible, such a borrow area was excavated by professional archaeologists. If time did not permit, the site was not used. The well location itself was moved about a hundred meters so as to be near one of the acceptable borrow sites. This move significantly reduced both the amount of work and the amount of tundra disturbed during the building. A number of borrow sites were approved but not used. The reserve pit at the relocated wellsite was pure sand, so no additional borrow was necessary. An airstrip was cleared on the ice of a lake located about 1.5 km (1 mi) west of the drill site. The primary water source was a lake located an equal distance south of the site. Ready access to the airstrip was provided by a convenient water channel that, when frozen, formed an ideal road. Construction was completed on January 6, 1978, and the train departed on the morning of January 8 for the Tunalik location.

The move of the rig (Nabors No. 1) from South Simpson No. 1 was made completely by rolligon and was efficient and uneventful. The operation began on January 6 and was completed January 19. Rig-up operations began on January 18 and were completed in 21 days. The well was spudded on February 7, 1978.

The target depth for the well was estimated at 2,995 m (9,825 ft). It later became evident that tight-hole problems, and a "fishing job" in severely sloughing shales, had delayed progress sufficiently that the target depth could not be reached in one season. After casing was set and the well plugged at an appropriate depth, the tree was nippled up and the well secured for the summer. The rig was released on May 17, the mast lowered, and the camp and rig prepared for summer suspension. The well was scheduled for reentry in the fall. Operations were suspended on May 20, 1978.

IKPIKPUK TEST WELL NO. 1

The construction train left Drew Point on January 5, 1978, and proceeded to the Ikpikpuk well site located at lat 70°27′ N., long 154°20′ W. It was planned to build the drilling pad in the spring, move the rig to the site, and get partially rigged up in order to get as early a start as possible in the fall. It was hoped that by starting early the drilling operations could reach the target depth of 4,625 m (15,175 ft) in one season.

Construction began immediately upon arrival. An ice runway was cleared on an interconnected complex of lakes immediately northwest of the site. One of these lakes also served as a water source. Access to the closest lake required only a hundred meters or so of ice-road construction. Borrow material for the drilling pad was taken from two higher dunelike areas: the first was about 1.5 km (1 mi) to the south, and the second was an equal distance to the west of the wellsite. Construction was completed on February 7, 1978.

Rig move-in operations began April 14. Ninety-one Hercules loads and 51 rolligon loads were required to move the rig (Parco Rig No. 96) from North Kalikpik to Ikpikpuk. The move was completed on May 2, 1978. Operations were suspended for the summer on May 6 with the rig-up 85 percent complete.

INIGOK TEST WELL NO. 1

The first contingent of the construction crew arrived at the Inigok site from North Kalikpik on January 25, 1978. The rest of the men and equipment arrived from Ikpikpuk on February 13, 1978.

The Inigok Test Well, located at lat 70°01′ N., long 153°06′ W., was the first deep test well on the reserve; it was scheduled to reach 6,020 m (19,750 ft) in depth. It was planned to continue the drilling operations through the summer, because three and possibly four reentries could prove very costly. A year-round runway, although expensive, was more economical when measured against rig costs. The plan was to build an ice airstrip on a nearby lake to serve during the spring construction season, while the all-season runway was being built. The pad, runway, and connecting road were all partially built of local materials, mostly obtained from leveling the ridgetop runway site. The cut-and-fill operation produced the sand subgrade. Over this material was placed 7.5 cm (3 in.) of Styrofoam insulation, which was in turn covered by 45 cm (18 in.) of gravel to serve as a protective and load-bearing surface (fig. 2.18) The design reduced the gravel requirements from about 230,000 m^3 (300,000 yd^3) to about 67,000 m^3 (88,000 yd^3). The Styrofoam insulation was an economical design choice. Gravel sources were searched for in every direction. Although many small deposits were found, their use would have meant the expense of numerous short ice roads and extensive disturbance of the tundra. A sufficient quantity of gravel was eventually found at the mouth of the Kikiakrorak River, where it joined the Colville River about 60 km (37.5 mi) to the east of the site. Ice-road construction began on February 1, taking advantage of the frozen surface of every lake, pond, and river on the route. Construction of the ice road was a round-the-clock operation from February 1 until March 8, when the gravel haul began. The gravel was hauled each day in two 10-hour shifts; the remaining 4 hours were spent repairing cracks in the ice road and servicing the equipment. In the 38 days of the gravel haul, approximately 120,000 t (132,000 tons) of gravel (67,000 m^3 or 88,000 yd^3) was hauled. More than 130,000 L (35,000,000 gal) of water was frozen to form the ice road. Construction was completed on the drilling pad on May 2, 1978. Some of the construction equipment was demobilized via airlift to South Meade on May 14, for use in the building of the ice airstrip at that site in the fall. A full construction train left Inigok on May 15 for the summer stack-out location at Wolf Creek. This site was chosen because it was central to many possible 1979 locations. The remaining construction equipment worked over the surface of the all-season airstrip until it was ready to receive a strip check and certification on the first of June.

Nabors Rig No. 25 was moved earlier via air from Drew Point, using the Inigok temporary ice runway, and was stacked at the site to await the completion of the gravel runway. Rig-up began on April 25, and was virtually complete by May 22 when the ice airstrip was closed. Final rig-up was delayed until the completion of the all-season gravel airstrip. The well was spudded on June 7, 1978.

BARROW GAS FIELDS

The construction and drilling operations in the Barrow area during 1977-78 were planned to center around two general locations. A lake for an ice strip and two small borrow sites were selected for South Barrow No. 16, and ice-strip locations and a larger borrow site were selected for South Barrow Nos. 17 and 19. However, at the last minute the local residents of Barrow objected to the two borrow sites located east of Tekegakrok Point, and they consented only to the larger borrow site north of South Barrow No. 19 on the condition that the gravel be replaced. The condition was extremely difficult to meet, but not impossible, and it was adhered to stringently. Some of the gravel from the South Barrow No. 16 pad was retrieved and used for South Barrow No. 17; part of the gravel from South Barrow No. 17 was retrieved and used again at South Barrow No. 19. This reuse of gravel reduced the amount taken from the borrow site. The ice strip for South Barrow No. 16 was constructed on an unnamed estuary known locally as Wohlschlag Slough. The ice strip for South Barrow Nos. 17 and 19 was constructed on the edge of Elson Lagoon immediately north of the drill sites. Because of the increased work planned for the Barrow area and the need for better housing in the field, an ATCO Drilling Camp was purchased in October 1977 and flown from Fairbanks to Barrow in C-130 aircraft.

SOUTH BARROW NO. 16

South Barrow No. 16 was located 10 km (6 mi) east of Barrow, approximately 3 km (2 mi) east-northeast of the nearest producing wells in the South Barrow Gas Field. Pad construction started on December 15, 1977; rig-up began on January 8, 1978, and the well was spudded on January 28. South Barrow No. 16 was drilled to explore a structure similar to that into which Barrow No. 14 had been drilled, in an attempt to locate a new gas field to supplement the diminishing reserves of the South Barrow field. The rig used was a National T-20, Brinkerhoff Signal No. 31. The well drilled directly from Cretaceous sediments into the argillite basement. Small shows of gas were noted, but the primary objective, the Jurassic Barrow sandstone (informal term), appeared to have been removed by Early Cretaceous erosion. The Sag River Sandstone, another potential oil reservoir, was also missing. The well reached a total depth of 730 m (2,400 ft), and after evaluation of the logs, South Barrow No. 16 was considered a dry hole and was plugged and abandoned. The rig was released on February 17 and partially rigged down for the move to the South Barrow No. 17 location.

SOUTH BARROW NO. 17

Barrow No. 17 was located approximately 20 km (13 mi) east-southeast of Barrow. The rig employed was Brinkerhoff-Signal No. 31. Installation of the piling for the rig began on January 8, 1978; rig move and rig-up began on February 19, and the well was spudded at 6:00 a.m. on March 3, 1978. South Barrow No. 17 was drilled in an attempt to learn more about the East Barrow field. The Barrow sandstone was the primary objective, but secondary objectives were the Sag River Sandstone and several thin but persistent sandstones in the pebble shale unit. The well was drilled to a total depth of 726 m

FIGURE 2.18.—Installing insulation on the Inigok runway, April 1978.

(2,382 ft), penetrated sediments of Holocene to Triassic age, and terminated in argillite of pre-Carboniferous age. After evaluation the well was suspended in the production mode because it produced considerable water with its gas. The rig was released on April 13, 1978, and partially rigged down for the move to the South Barrow No. 19 location.

SOUTH BARROW NO. 19

South Barrow No. 19 was another attempt to learn more about the East Barrow gas field; the well was located about 17.5 km (11 mi) east-southeast of Barrow and about 3 km (2 mi) west and north of South Barrow No. 17. Installation of the piling for the rig began on January 27, 1978; rig-up began on April 14, and the well was spudded at 5:00 a.m. on April 18, 1978.

The well was drilled to a total depth of 700 km (2,300 ft), the Barrow sandstone being the primary objective and the Sag River Sandstone a secondary objective. At the conclusion of testing, the well was completed as a gas well in the upper Barrow sandstone and left suspended in a production mode. Production tests in the Barrow sandstone showed a calculated absolute open-flow potential of 7.2 million ft^3/d of gas with no water. Tests for oil in the Sag River Sandstone were negative. The drill rig was released at midnight on May 16, 1978, and rig-down commenced immediately. The rig components were stacked on the South Barrow No. 6 well pad, and the camp and support units were moved to storage at the NARL facility.

TUNALIK TEST WELL NO. 1

The construction train from South Meade arrived at the Kuk River crossing, approximately 40 km (25 mi) south of Wainwright, on January 15, 1978. Thin ice coupled with blowing snow delayed the train until a timber-reinforced ice crossing could be constructed (fig. 2.19).

The first units of the train crossed the Kuk River on January 29, and the last units crossed on the 31st. The train arrived at Tunalik on February 2. The second construction train left Kugrua on January 29, arrived at the Kuk River on February 1, and crossed the same day. This train arrived at Tunalik on February 4, 1978. Although many difficulties were encountered during the overland trip, once at the site, operations proceeded efficiently during a long period of relatively mild temperatures (about −23 °C or −10 °F) and little wind. Tunalik is located at lat 70°12′ N., long 161°04′ W.

Tunalik was the second deep well (target depth 6,090 m or 19,980 ft) scheduled for year-round drilling and therefore required an all-season runway. The borrow site selected was located approximately 7 km (4.5 mi) directly west of the wellsite. However, the ice road that connected the wellsite, the all-season runway construction site, the Twin Otter strip, the material site, and the Hercules ice strip totaled about 13 km (8 mi) in length.

The borrow site was located on a westward-facing knoll and contained an archeological site in a section of the area referred to as Aliquot A. Permission had been obtained from the State Archaeologist to excavate the archaeological materials, so that the site could be used. This excavation had been completed the previous summer under the supervision of a BLM archaeologist at the same time the topographic survey was made.

Material was removed from Aliquots A and B to build the runway, the gravel access road from the airstrip to the drill site, and the drill pad itself. Insulation was employed in the design of all three to reduce the amount of gravel needed. Construction was completed by May 1.

On April 9, a loader, generator, grader, and survival shack were flown from Tunalik to Betty Lake for the proposed Etivluk well. The original landings were made on an ice airstrip cleared by GSI. This airstrip was improved, and the remainder of the entire construction train was flown in to Betty Lake for summer stackout. The camp was to be used during the summer as a

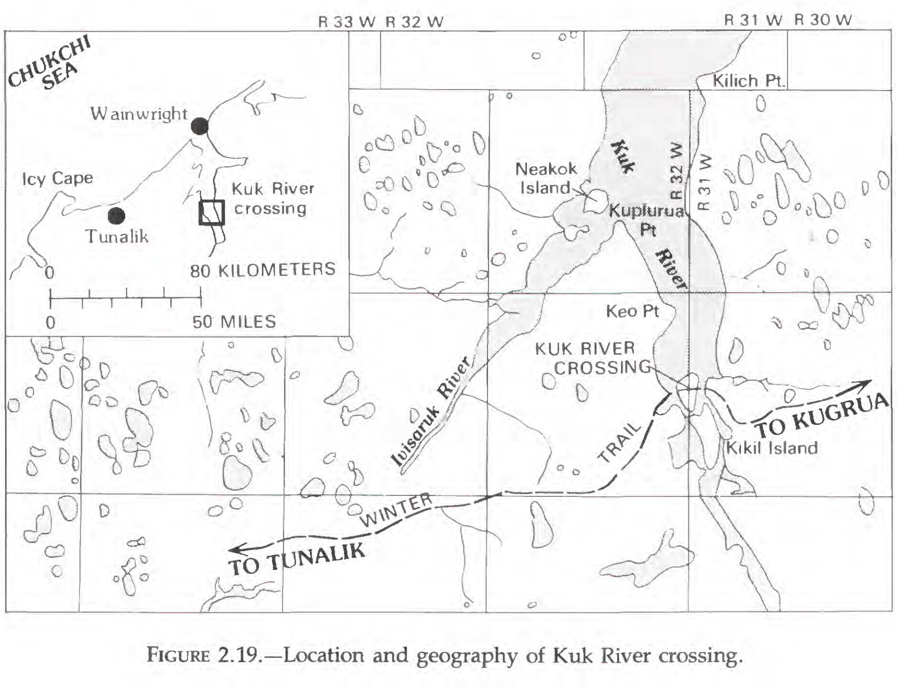

FIGURE 2.19.—Location and geography of Kuk River crossing.

base camp for the survey work. Betty Lake is located at lat 68°29′ N., long 156°30′ W.

The second construction train was moved from Tunalik overland to Husky Point on May 5. It was placed near the beach so that the barges could move it up to LIZ C in preparation for the Peard Bay wellsite construction in the fall and on their return move the Parco No. 95 rig from LIZ C to Husky Point.

In addition, a few pieces of equipment were flown from Tunalik to Barrow on May 7, 1978, to assist in construction there. A small camp and two pieces of equipment were left at the Tunalik site to work the runway and gravel road in order to remove excess moisture during the spring thaw.

CAMP LONELY—FEBRUARY 1978

On February 23, 1978, a fatal accident occurred at Camp Lonely. Steve Rusnak, a truck driver, was driving the water-haul vehicle, a large rubber-tired ARDCO all-terrain vehicle from Okalik Lake to Camp Lonely. He pulled up to the water-treatment unit behind the camp kitchen and jumped down, presumably to connect the hoses. Somehow, the vehicle was moving slightly, and he slipped or fell and became caught under one of the front tires. The vehicle was then up against the building and could not creep any farther. Although not crushed by the tire, he could not move or call out, and the weight of the vehicle restricted his breathing. When found by co-workers, he was carried to the camp medical station. Oxygen and cardiopulmonary resuscitation were administered by the medic, and a doctor was dispatched from Prudhoe. However, all efforts to revive him were in vain.

SEISMIC PROGRAM—SPRING 1978

The spring geophysical program was an ambitious one. It included work in the southern foothills, the Brooks Range, and some over-ice work on Smith Bay. Four crews were mobilized—three in the south and one in the north. They were blessed with exceptionally good weather and a minimum of blowing snow. Consequently 3,065 km (1,916 line mi) of survey were run despite difficult drilling conditions in the Brooks Range and southern foothills region. Three of the seismic trains were stacked for the summer at Umiat, and the fourth was stacked at the Kiligwa airstrip near Brady. It was a favorable season, and all assigned miles were completed.

The plan of operations for 1978-79 was to extend the NPRA regional geophysical surveys out of the reserve and across the Brooks Range by way of Howard Pass. No part of the Brooks Range had previously been crossed by seismic surveys, and the results of the proposed seismic and gravity investigations were of intense interest to both Government and industry. It was hoped to obtain information that would assist in understanding the orogeny of the Brooks Range and therefore provide a better understanding of the subsurface geology of the foothills province on the North Slope, including the NPRA. If, as many geologists had suggested, the foothills province were comparable to the foothills belt of the Canadian Rockies, an extensive exploration program for major hydrocarbon reserves would be warranted. If, on the other hand, the structures of the Brooks Range were fundamentally different from those in the Canadian Rockies, it would suggest a major difference in the hydrocarbon potential of the area.

Two generally parallel geophysical traverses, referred to as a doublet, were planned for this study. However, the survey in the southern portion of Howard Pass had to cross a small section of D(2) lands, that is, lands that had been proposed for parks, wildlife reserves, or similar uses under the Alaska Native Claims Settlement Act but had not yet been selected. Because of this, permission was not granted, even though the environmental assessment demonstrated that any effects of the study would be minor and transitory.

CLEANUP—SPRING 1978

The spring cleanup of old abandoned sites focused on the Skull Cliff Air Force Tower site and the Navy's Topagoruk and East Topagoruk test-well sites. Working out of Cat trains from April 1 through May 15, the cleanup crews stockpiled 964,000 kg (2,120,000 lb) of debris on the beach at Skull Cliff. This debris included the 107,000 kg (236,000 lb) of tower parts, 90,000 kg (200,000 lb) of crushed drums, 627,000 kg (1,380,000 lb) of cement and mud canisters, and about 136,000 kg (300,000 lb) of miscellaneous debris. Favorable weather helped make it a productive season.

DRILLING SITE REHABILITATION—SPRING 1978

The rehabilitation plan called for using Caterpillar tractors to lower the drill pads and to obliterate the straight edges that indicated their manmade origin. To prepare for this work at recently abandoned drill sites, D-8 tractors with blades and two drums of fuel were positioned before spring breakup at the Atigaru, West Fish Creek, South Harrison, East Teshekpuk, W.T. Foran, and South Simpson wellsites.

These Cats were to be used at various times during the summer to rework the pads and fill in the reserve pits. The Cat that was scheduled to be left at W.T. Foran finished the rehabilitation of Halkett before proceeding to W.T. Foran.

USGS/HUSKY OPERATIONS: FOURTH SEASON— JUNE 1978 TO MAY 1979

SUMMER OPERATIONS

The 1978 summer survey was a very active one, because many drill sites were still being considered, and final decisions had been reached on only three sites out of the five proposed. The schedule was to complete the two deep exploratory wells, Inigok and Tunalik, that had been started the previous season; reenter and complete South Meade and Ikpikpuk; drill three newly selected medium-depth wells; and prepare pads for two deeper drilling sites. One wellsite in the Barrow area was moved from Nuwuk Point first to Tapkaluk Island, then to Tulageak Point, to south of Tangent Point, and finally back to Nuwuk before being dropped from consideration. The Tangent site was actually surveyed since it was the popular choice during the field season. Because of archaeological discoveries, peregrine nesting locations, and other reasons, selecting the Lisburne wellsite involved making separate topographic surveys and taking soil samples at three possible runway locations and two possible well locations before a final site selection was made.

Survey crews operated out of Lonely and Barrow as well as out of the Betty Lake and Wolf Creek construction trains. Borrow sources were located and sampled where necessary; archaeological clearances and rare and endangered species clearances were obtained; water sources were found; and runway designs and pad locations were proposed. The following sites were actually surveyed during the 1978 summer season:

Site	*N. latitude*	*W. longitude*
Lisburne	68°29′	155°41′
Seabee	69°22′	152°10′
Peard	70°43′	159°00′
East Simpson	70°55′	154°37′
Tangent	71°07′	155°04′
J.W. Dalton	70°55′	153°08′
Carbon	69°29′	160°20′
Carbon Alternate	69°29′	160°36′
Kungok	70°24′	159°12′
Kigalik	69°28′	157°22′
Etivluk	68°24′	156°52′

The following three additional wells were planned in the East Barrow field, and their locations were also surveyed:

Site	*N. latitude*	*W. longitude*
Barrow No. 15	71°14′	156°21′
Barrow No. 18	71°14′	156°17′
Barrow No. 20	71°14′	156°20′

Of the surveyed wellsites, Tangent, Carbon, Carbon Alternate, Kungok, Kigalik, Etivluk and the Barrow wells were deferred for fiscal, logistical, or geophysical reasons.

An unusual amount of rain and cloud during the summer plagued workers all over the North Slope, but most operations were completed despite the adverse conditions. The Lonely airstrip parking apron was enlarged by 20,000 m^2 (220,000 ft^2). Work continued on the Inigok and Tunalik airstrips to compact and consolidate the gravel and work the moisture to the surface.

The warm rainy weather caused the ice in the Arctic Ocean to break up early in the season, and consequently the Operation Cool Barge deliveries at Lonely were completed unusually early. By July 19, 10,851,340 kg (23,872,950 lb) of dry cargo had been delivered to the camp plus 21,174,425 L (5,594,300 gal) of petroleum, oil, and lubricants (POL) products. In early August, 5,900,000 kg (13,000,000 lb) of lateral transfer was completed. The Nabors No. 17 drill rig arrived at Lonely, and the construction train was moved from Husky Point to LIZ C. The Parco No. 95 rig was moved from LIZ C to Husky Point. Totals to Seattle that year were 393,000 kg (864,000 lb).

Summer cleanup of the recently utilized drill sites began on June 8, 1978, and by the end of July the trash that was hidden by the winter snows was picked up at Ikpikpuk, Drew Point, Kugrua, South Meade, and the Inigok ice-road camp. The cleanup at the old Navy sites continued concurrently—one crew working out of Skull Cliff and a second crew stationed at Wolf Creek. The old sites (fig. 2.20) cleaned up that season included the following:

Skull Cliff Tower Site
Topagoruk and East Topagoruk
Wolf Creek Test Wells 1, 2, and 3
Weasel Creek Test Well
Square Lake Test Well
Knife Blade Test Wells 1, 2, and 2A
Mona Lisa Seismic Camp
East Oumalik Test Well
The explosives cache discovered in the Ikpikpuk area

The summer's cleanup may be summarized as follows:

	Amount	
Material	*Kilograms*	*Pounds*
Drums retrieved (uncrushed)	85,050	187,100
Drums crushed	323,966	712,725
Combustible debris stockpiled	171,523	377,350
Combustible debris burned	294,310	133,777
Other debris	122,923	270,430
Total	837,234	1,841,915

More than 835 t (920 tons) of material and debris was burned or stockpiled.

REHABILITATION AND REVEGETATION OPERATIONS

The revegetation program for 1978 was to include the six sites previously drilled by Husky Oil NPR Operations, Inc., and one site drilled earlier by the Navy. These sites were Cape Halkett No. 1 (Navy), East Teshekpuk No. 1, South Harrison Bay No. 1, W.T. Foran No. 1, Atigaru No. 1, West Fish Creek No. 1, and South Simpson No. 1. After cleanup of miscellaneous debris, it was planned to use the D-8 Cats that had been positioned on the sites the previous spring to push as much of the pad as possible into the reserve pit. The object was to reduce the height of the pad as much as possible in order to bring the surface closer to the moisture table and thus facilitate revegetation and obliterate man's effects on the landscape. Attempts were made to pump out the reserve pits and fill them with pad material. This operation was only partially successful. The water would percolate back into the pit almost as fast as it was pumped out.

Because of the very wet summer, much difficulty was encountered with the rehabilitation work. The pads were very wet, and the tractors continually bogged down. It was decided to delay this work as long as possible and then to sow dormant grass seeds in the fall. This delay allowed the pads to dry out

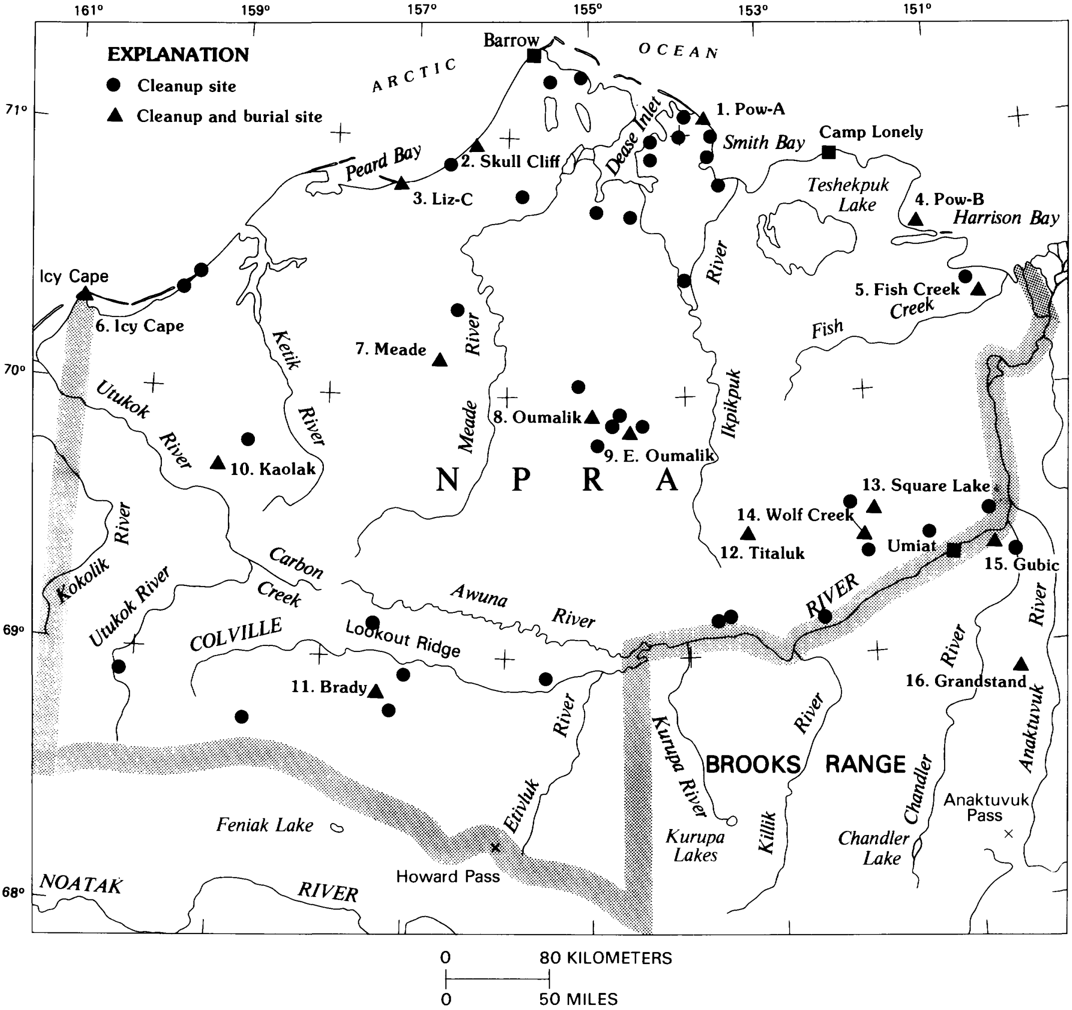

FIGURE 2.20.—Burial sites, identified by number and name, and other cleanup sites of the rehabilitation program for the NPRA.

as much as possible, even to crust over with the first frosts, and thus provide better trafficability. The aim of the work was to obliterate the straight edges of the pads and to leave the land looking as natural as possible. Some work was done in July and the first week of August. Then the decision was made to await better weather conditions. At that point, South Harrison Bay, Atigaru Point, and East Teshekpuk were ready to seed. The remainder of the program was then completed between September 1 and 22. A gravity-feed, helicopter-transportable hopper/spreader was fabricated for distributing the seed and fertilizer. After spreading, the seed was pressed into the surface by the onsite tractor, if conditions permitted.

Reseeding and fertilizing was completed at the following sites on the dates listed:

September 14, 1978—Tunalik Borrow Site, Aliquots A and B and the Delta-3 track that paralleled the road (fertilizer only on the track).

September 16, 1978—W.T. Foran No. 1 and Atigaru Point No. 1.

September 21, 1978—W. Fish Creek No. 1 and South Harrison Bay No. 1.

September 22, 1978—Cape Halkett No. 1, East Teshekpuk No. 1, and South Simpson No. 1.

In addition, the borrow area at Inigok (the area of cut along the runway from which the primary fill was obtained) was dormant seeded in the fall of 1978. Two types of seed were used—Tundra Bluegrass (*Poa glauca*) was spread on the area northeast of the taxiway, and Alyeska Northern mixture was spread on the area southwest of the taxiway.

CAMP LONELY

During the fall of 1978, a subcontractor erected a fabricated-steel aircraft hangar at Lonely on the newly enlarged apron. This 40×40 m (130×130 ft) structure greatly reduced the problems of aircraft maintenance and provided a warm storage area for the aircraft. Although it was not known at that time how long the exploration program would continue, the time saved in maintenance, the greatly reduced ferry costs to mobilize and demobilize exchange aircraft for periodic maintenance, and the greatly increased safety factor made the project worthwhile. This expansion at Lonely proved to be cost effective, as the exploration program continued at full pace for three more winter seasons (fig. 2.21).

CHANGES IN OPERATIONAL DESIGN

Two design changes in operational methods were made during the summer of 1978 that had a significant impact on the ensuing program. The construction department designed a double-walled fuel-storage tank that was completely self-contained, held 87,000 L (23,000 gal), had a safety catchment basin to contain any valve leaks, and was transportable by Hercules aircraft. Before this, single-wall fuel tanks or fabric storage bladders were used for fuel storage within gravel or timber-diked areas lined with impermeable membranes. These liners were expensive, and because of the cold weather and the need to retrieve them, often before breakup, they were seldom used more than one season. The double-walled steel tanks eliminated the need for the membranes and containment berms that were otherwise required under State regulations. The concept was discussed with the Alaska Department of Environmental Conservation, and after approval was received a number of tanks were ordered. The tanks proved their worth, as they were safe, conveniently transportable, and easily adapted to the needs of the program.

The second change of operational methods that had considerable effect on the program was the decision to employ the so-called thin-pad concept in the design of all one-season wells. It was reasoned that if the drilling-pad surface was to be used for only one winter season and would always be frozen during use, then the stabilization of the surface was a product of the weather and the ice/moisture content of the pad material was irrelevant. By following this concept, it was possible to use the material obtained from excavating the reserve pit to build the drilling pad no matter what its ice content or thaw characteristics. The reserve pit was designed to contain all of the anticipated volume of fluids below the original tundra level. The drill rig, however, was still placed on piling to prevent any settlement during the drilling.

When the wellsite was abandoned, rehabilitation of the drill pad consisted of removing the piling and sills below surface level. Usually, the ice content of the pad material was high, and the slumping of the surface during the thaw caused all the change in profile that was necessary. The thin pads had two other environmental advantages. Since no "imported" material from a borrow pit was needed, the overall area of environmental impact was reduced by the size of the borrow pit and any associated roads. In addition, the resulting scar of the drill pad had a lower profile and was closer to the natural water table of the tundra so that revegetation was easier. The reserve pit was always cleaned of any petroleum residue, and the edges quickly thawed to assume an appearance difficult to distinguish from the many thousands of natural ponds of the tundra. Thus the thin-pad design was less expensive to build, less expensive to rehabilitate, and had less environmental impact. If oil or gas was discovered at a thin-pad exploratory well, the well could be suspended for the melt season and the pad rebuilt with a more permanent surface the following winter season.

INIGOK TEST WELL NO. 1

Drilling the deep well at Inigok continued throughout the summer and fall of 1978. Numerous cores were taken and the usual problems were encountered—such as "iron-in-the-hole" and "fishing". In December, while the crew were circulating and conditioning the hole to run intermediate logs at 5,410 m (17,750 ft), the mud brought up high-pressure hydrogen sulfide gas and native sulfur. The sulfur and gas were controlled, and drilling continued, but the hydrogen sulfide problem impeded the rest of the drilling operation.

On January 5, 1979, the Great Northern Airlines contract Electra N403GN was on route from Anchorage to Inigok. Weather was clear and cold, with visibility more than 11 km (7 mi). On approaching the runway, the left main landing gear of the aircraft contacted the ground about 2.5 m (8 ft) short of the runway and 20 cm (8 in.) below the runway's face. The left wing assembly, with the attached gear,

FIGURE 2.21.—Camp Lonely, the exploration base camp, near Pitt Point on shore of Beaufort Sea, July 1979. Photograph by J. Haugh.

separated from the fuselage when the gear hit the runway threshold. The wing and gear continued down the runway about 320 m (1,050 ft), stopping on the left side, and immediately caught fire. The main fuselage continued straight down the runway for about 275 m (900 ft), then veered left, coming to rest, upside down, about 150 m (500 ft) off the runway. Nine passengers and six crew were on board, all strapped in their seats and badly shaken. With help from ground personnel, they quickly released themselves and each other from their inverted dangling positions and evacuated the aircraft. The wreckage caught fire almost immediately. Attempts were made to put out the fire, but no proper equipment was available at the site. Minor explosions began to occur from emergency survival ammunition and other materials on board the aircraft, forcing the firefighters to retreat. A medic flew down from Camp Lonely in case first aid was necessary, and all passengers and crew were evacuated to Lonely for further examination. Luckily, all injuries were minor.

FIGURE 2.22.—Montage of scenes of drilling at Inigok No. 1 test well, 1978-1979.

The Inigok well (fig. 2.22) was drilled to a depth of 6,127 m (20,102 ft), reaching that depth on May 16, 1979. The true vertical depth was calculated at 6,097.45 m (20,004.76 ft). The well was drilled to test a deeply buried east-trending faulted anticline separating the Umiat and Ikpikpuk basins. The primary zones of interest included the Sadlerochit and Lisburne Groups and possibly the Kuparuk Formation. Minor shows of gas were encountered in several zones, but no good reservoirs were found. Although argillite was not penetrated, the drilling was terminated because of excessive drift of the borehole. However, the 6,127 m (20,102 ft) was a new depth record at that time for an Alaskan well. The well was plugged and abandoned at 1:10 a.m. on May 21, 1979. The rig was released at noon on May 22. On May 31, the ninth day of rig-down, preparations were underway to airlift the rig to the Seabee location.

TUNALIK TEST WELL NO. 1

The move of Parco Rig No. 95 from Husky Point to Tunalik began on October 11, 1978, when the crews arrived at Tunalik. The move took 97 rolligon loads and was completed in 10 days, finishing up on the evening of the 20th. Rig-up began on October 18, along with several major rig modifications that were accomplished concurrently. The mast was raised on November 4. Rig-up and winterization continued, including the tie-in of the new equipment. The 107-cm (42-in.) conductor pipe was cemented in with 450 sacks of Permafrost II cement. The well was spudded on November 10, 1978 and drilling operations continued for the next 420 days.

IKPIKPUK TEST WELL NO. 1

Skeleton crews of Parco and Kodiak Oilfield Haulers (KOH) arrived on location November 2, 1978, to activate the Ikpikpuk rig camp and support the ice-runway construction crew. A Twin Otter strip was prepared, and the camp was placed in full operation. A Delta-Commander and two Delta-3 all-terrain vehicles arrived at the drill site on November 6, after an overland trip from Camp Lonely. Construction of the ice-on-tundra runway began on November 7. Because of the target depth of the well, it was decided to build an ice strip on tundra because it would be operational long before the lake ice would freeze to the 120-cm (48-in.) thickness required by the Hercules aircraft. It was hoped that an early start would allow completion within one winter season. The ice strip was completed and checked on November 21, 1978.

During this time, rig-up had begun and maintenance work was being conducted on the rig. Rig-up with a full crew began on November 22. The derrick was raised on November 23. The 76-cm (30-in.) conductor was cemented in place with 305 sacks of Permafrost II cement on November 26. Rig-up was completed and the well was spudded at 3:00 p.m. on November 28.

Almost immediately, downhole problems with sloughing shales and lost mud were encountered. Numerous cores were requested to try to understand the stratigraphy, and each trip, even short trips, required reaming to reach bottom. It became obvious that, even though the target depth was less than 450 m (1,500 ft) away, it could not be reached that season. Consequently, at 4,331 m (14,210 ft), casing was set, and Arctic pack was placed in the annulus. The well was secured and the rig released on April 17, 1979. The derrick was laid down, and the rig and camp were shut down for the summer. All personnel were off location by April 21, 1979.

SOUTH MEADE TEST WELL NO. 1

Skeleton crews from Nabors and KOH arrived on location on November 11, 1978. They opened the rig camp for the support of the construction group that was scheduled to rebuild the ice airstrip on the shallow lake used the first season. It was hoped to get an early start, finish early, and free the rig for use on another location. On November 13, the airstrip construction got underway. A Twin Otter strip was cleared on a nearby lake for interim use, and it was ready on the 14th. The rig mast was raised on November 21, and preparations got underway while awaiting completion of the airstrip. The airstrip was ready on the 27th and checked for use on the 29th. Reentry of the well began December 3.

South Meade was drilled to the argillite basement at 3,031 m (9,945 ft). The purpose of the well was to test for a possible oil and gas accumulation in some truncated onlap strata on the southern flank of the Barrow arch. Minor gas shows were noted from many zones, but none was judged to be commercially significant. The well was plugged and abandoned and the rig released on January 22, 1979. Rig-down began immediately and the move of Nabors No. 1 to the East Simpson No. 1 site got underway on January 26, 1979.

BARROW GAS FIELDS

The program for Barrow for fiscal year 1979 included no additional wells but considerable construction and rehabilitation work to utilize more efficiently the resources already discovered.

That season's schedule called for reentry and rehabilitation of South Barrow No. 6 to cure a rattle that had been observed during a blowdown. This work involved killing the well with calcium chloride mud and pulling the tubing, then deepening the well about 9 m (30 ft) and anchoring the tubing to the bottom. Work at South Barrow Nos. 14, 17, and 19 prepared the wells for production. A cement plug was set at the bottom of No. 17 in an attempt to seal off the water.

Overall, construction of 7.5-cm (3-in.) gathering lines was planned for the East Barrow field and a 15-cm (6-in.) transmission line to connect the eastern portion with the South Barrow field to the west. A connecting road and powerline were also planned. An all-weather road was necessary for the round-the-clock attendance required to operate the fields. The pipeline was to be 90-cm (3 ft) above ground on wooden pilings placed 10 m (35 ft) apart and set 3 m (10 ft) into the ground. To allow traffic to reach the other side of the pipeline, gravel ramps were to be built across the line. A pole every 32 m (105 ft), or every third pole that supported the pipeline, was to be tall enough to carry the proposed powerline.

The schedule of construction for the 1978-79 season included completing the 3.8-km (2.4-mi) extension of road to serve the South Barrow operating field and the 15-cm (6-in.) transmission line from the east field. This section of road became known as Cake Eater Road after an earlier Air Force project of that name that was located along the right-of-way. The following season, 1979-80, the Government planned to continue the road to connect with the newer East Barrow gas field. Spur roads would eventually connect each well to the main road. Spur roads were designed to be 4.25 m (14 ft) wide, main roads were to be 5.5 m (18 ft) wide, and both were to be constructed of 1.5 m (5 ft) of gravel fill. The source of the gravel for all this construction was to be the borrow pit located on Barrow townsite land in the beach bluff area southwest of the city.

A construction Cat train arrived from Peard Bay on January 8, and Hercules C-130 flights began bringing equipment from Tunalik at the same time. Work began immediately on the ice road from the borrow source southwest of the city to the work site in the South Barrow field. Gravel was also hauled to rebuild the pad at South Barrow No. 14. The first portion of the construction plans—the Cake Eater Road—was completed that season, and South Barrow Nos. 6, 14, 17, and 19 were worked over.

PEARD TEST WELL NO. 1

The construction crew mobilized at LIZ C in early November, 1978. They departed on November 22 and traveled overland following the previously staked trail to the Peard site at lat 70°43′ N., long 159°00′ W. An additional small construction crew came overland from the South Meade site, arriving at the Peard site on December 3.

Construction of the drilling pad at Peard consisted of excavating a reserve pit and using the material to build the pad. Borrow sites were not used, but were located in case it became necessary to build a pad to stack out for the summer or drill for another season. These sites could provide material to build a pad with a more permanent surface. The airstrip was cleared on a shallow lake southwest of the drill site. A small extension of the strip was made on the tundra because the lake was not the required 1,500 m (5,000 ft) in length. The rig pilings were in place and the ice road finished to the water source by December 29. After a few days of repairs, preparations, and delays because of bad weather, the construction train left for the overland trip to Barrow on January 7, 1979.

On December 19, 1978, Nabors, Kodiak, and Husky personnel started the air move of the Nabors Rig No. 17 components from Lonely. Support equipment was moved between the 19th and the 21st, the flying of the actual rig components starting on the 22nd. By January 1, 1979, 98 Hercules loads of rig components and 13 loads of Kodiak equipment had been received. Rig-up and assembly of the camp began on January 2. The 50-cm (20-in.) conductor was cemented in place by the 20th, and rig-up continued until the well was spudded at 4:30 p.m. on January 27, 1979.

Peard Test Well No. 1 was drilled to test for possible oil and gas in Cretaceous, Jurassic, and Carboniferous rocks along the northern flank of the Meade basin. Minor gas shows were noted in several zones, but no potential reservoirs were found. No trace was found of the 425 m (1,400 ft) of Lisburne limestone that was present in the Kugrua well only 19 km (12 mi) to the southeast. The well was plugged and abandoned after reaching a depth of 3,117 m (10,225 ft), and the rig released on April 13, 1979. Rig-down began immediately, and the components were stacked in Hercules-size loads to await the completion of the Ivotuk airstrip at Lisburne. It became a race against time and the melt of the ice strip at Peard, but all of the rig was airlifted out by May 18, 1979.

J.W. DALTON TEST WELL NO. 1

The construction crew arrived at the J.W. Dalton site, 5.6 km (3.5 mi) east of Lonely, on December 11, 1978. The site is located on high ground just east of the Smith River at lat 70°55′ N., long 153°08′ W. Because efficient use of rig time dictated that this well be drilled after East Simpson No. 1, the pad for J.W. Dalton was the conventional thick design. The gravel was taken from a source just behind the beach about 3 km (2 mi) to the east of the drill site. The thickness of the drill pad and its accessibility to the Lonely airstrip via the beach would allow drilling to continue into the summer months. The construction was finished on December 29, and the crews moved back to Lonely and then on to the East Simpson No. 1 site.

Rig move-in operations were over the sea ice from the East Simpson No. 1 location. The moving operation began on April 11. It took 69 truck loads and 11 rolligon loads to move the Nabors No. 1 rig. Rig-up began on April 16 and took 21 days. A rather large modification and maintenance program on the rig and the camp took place concurrently with rig-up. The well was spudded at noon on May 7, 1979.

On May 30, a group of dignitaries gathered at the site to formally dedicate the well to James W. Dalton, who had died two years earlier, almost to the day. Dalton pioneered much of the early work north of the Arctic Circle, and his reports on the petroleum potential of the North Slope greatly influenced Alaska's decision to select land in the Prudhoe area. At the ceremonies were his widow, Kathleen (Mike) Dalton and his children, George and Elizabeth.

The J.W. Dalton well was drilled to test for oil and gas accumulations on the southern flank of the

Barrow-Prudhoe high. Oil shows had been found in a nearby well (W.T. Foran) located farther down this structure. At the J.W. Dalton location, heavy residual oils and (or) tars were encountered, and tests of several zones showed small amounts of gas and heavy asphaltic oil. The occurrence of heavy oil and salt water may indicate that the well penetrated a reservoir just below the oil-water contact. If gas or oil is present in the reservoir, it may lie offshore. The well was drilled to argillite basement at 2,855 m (9,367 ft) and was plugged and abandoned.

The rig was released at midnight August 1 and was taken down and moved to Camp Lonely. Because the Nabors No. 1 rig consisted of many loads that were too large for the Hercules, it was decided to move the rig by barge. The rig was loaded on the barges on August 8 and hauled to Cape Simpson (POW A) to be close to the proposed East Simpson No. 2 well site.

EAST SIMPSON TEST WELL NO. 1

On January 2, 1979, the construction train that built the J.W. Dalton drill pad set out for the East Simpson No. 1 site located at lat 70°55′ N., long 154°37′ W. It was an easy trip, following the relatively smooth coastal ice most of the way. The well was located about half a kilometer (a quarter of a mile) inland from Smith Bay on the Simpson Peninsula—the site of the numerous oil seeps that sparked the Executive Order in 1923 creating Naval Petroleum Reserve No. 4.

East Simpson No. 1 used the thin-pad concept, the drill pad consisting only of material excavated from the reserve pit. Borrow sites were identified but not utilized. Water was drawn from a lake 7 km (4.5 mi) to the west, and a C-130 runway was cleared on a lake 3 km (2 mi) to the west. Access to both was over a common ice road. Construction went smoothly with no weather delays and was finished on January 22. However, the construction camp was needed until the drill camp was in place, and blowing snow and poor weather compounded delays until February 10.

Nabors Rig No. 1 was airlifted from South Meade beginning January 28, 1979, and the move took 89 Hercules loads. Outsize pieces were delivered overland in 2 Magnum vehicle loads and 23 rolligon loads. Rig-up began on February 7 and was completed in 12 days. The well was spudded at 8:00 a.m. on February 19, 1979.

East Simpson No. 1 was drilled as a test of possible stratigraphic traps, especially in the Sadlerochit Group of Permian and Triassic age. Shows of oil and gas and residual oil were noted in several zones, but no significant reservoirs were found. Potential reservoir zones had low to moderate porosity and permeability. Structural and stratigraphic relations indicated that the location was structurally too low. The well reached a total depth of 2,359 m (7,739 ft) on April 3 and was logged, plugged, and abandoned by April 10, 1979. The rig was released at midnight and the abandonment marker set. Beginning on April 11, the rig was moved overland to the J.W. Dalton site.

SEABEE TEST WELL NO. 1

Part of the construction crew that built the Inigok all-season runway in the spring of 1978 spent that summer at the old Wolf Creek site established by the Navy in the early 1950's. The location was central to a number of wellsites that were being considered, and it served as a base camp for the 1978 summer survey. Late in the year a train was prepared for overland travel, and in January 1979 it left Wolf Creek for Umiat, arriving on the 21st. Work began immediately to rehabilitate the Umiat airstrip and construct the Seabee drilling pad. An agreement had been reached with the State of Alaska for the use of the runway, and a major rehabilitation was scheduled to bring the Umiat gravel strip up to satisfactory operating condition. During the next month, as equipment was freed from other uses at various sites, it was flown to Umiat, when runway conditions would allow, to be used in the construction. The runway surface was improved by filling in the low areas and placing a 15-cm (6-in.) lift of crushed rock on the level surface. This operation was followed by grading and compaction of the surface, plus the addition of a new lighting system for improved winter operations. An NDB (nondirectional beacon) was added off the west end of the runway as required by the increased amount of air traffic, and the approach pattern for landing was altered to avoid disturbing any nesting peregrine falcons.

The wellsite was located to the north and west of the Umiat runway at lat 69°23′ N., long 152°10′ W. Access to the site was over an improved gravel road that followed approximately the same course as a trail established by the Navy in 1951. Construction included a low-water crossing of Seabee Creek and the summer placement of oversize culverts to provide a stable roadway surface during normal water flow. If early spring or late fall flooding did occur, only the roadway across the creek would be washed out, and this section could easily be replaced. Such an arrangement would cause the least permanent environmental impact.

Construction was finished on April 2, 1979, and the equipment and trains were stacked near the runway apron for the summer. It was planned to demobilize these construction trains overland to Service City in the spring of 1980.

LISBURNE TEST WELL NO. 1

The design and construction of the Lisburne test well, located at lat 68°29′ N., long 155°41′ W., near the eastern edge of the southern portion of the reserve, was a challenge to scheduling as well as to engineering skill. It was anticipated that reaching the target depth of 4,570 m (15,000 ft) would take 200 days of drilling. Because the rocks in this area are all steeply dipping and harder than those encountered elsewhere in the reserve, it was considered impossible to complete the well in one season.

The small construction train, which had been stacked at Betty Lake, in Howard Pass to serve as a base camp for a summer survey, was mobilized in early February 1979. A Hercules airstrip was cleared on Betty Lake, and 80 Hercules loads of additional equipment and camp units were flown in from Camp Lonely, East Simpson, Inigok, and other sites. Traveling overland along the staked trail, the enlarged train arrived at the Lisburne site on February 21, 1979.

Upon the train's arrival, the camp was established on stable ground and work began. Water for the 140-man camp was hauled over a winter trail from a nearby lake about 4 km (2.5 mi) to the northwest using low-ground-pressure rubber-tired vehicles.

The first phase of the C-130 airstrip construction was to remove the snow from the airstrip site and compact the tundra surface by repeated passes of the heavy equipment. Then approximately 15 cm (6 in.) of gravel was added, graded, and cemented in place with water that froze to ice. After this first phase, the heavy airlift began in order to build up fuel and supplies and to add some equipment. Then the airstrip was closed to heavy traffic, and the second phase of construction was initiated. Only half the length of the runway was worked on at one time, with the other half reserved for the use of the Twin Otter aircraft in resupply and emergency operations.

A 6.3-cm (2.5-in.) thickness of high-density Styrofoam insulation was installed in two overlapping layers of 3.8-cm and 2.5-cm (1.5-in. and 1.0-in.) thickness and covered with Visqueen. A layer of pit-run gravel 45 cm (18 in.) thick was then installed followed by a 15-cm (6-in.) layer of crushed gravel. The use of insulation confined the thaw zone to the top 60 cm (2 ft) of surface.

An insulated apron-storage area approximately 90×180 m (300×600 ft) was connected to the airstrip by an insulated 120×30-m (400×100-ft) taxiway. An all-season road, 2.7 km (1.7 mi) long, connected the airstrip to the drill site.

The gravel access road and the drilling pad also posed special design problems. The road was 6 m (20 ft) wide, with five turnouts spaced along its length. Each turnout was 30 m (100 ft) long and 3.6 m (12 ft) wide. The road bed was built of 1.2 m (4 ft) of pit-run gravel topped with 23 cm (9 in.) of graded gravel. Although it was not anticipated that this thickness would be sufficient to prevent melting of the underlying permafrost, it was felt that the expected subsidence could be easily repaired and did not constitute a real safety hazard such as it would on the airstrip. Culverts were added where necessary. Otuk Creek was crossed with a wooden-deck bridge 30 m (100 ft) long and with 15-m (50-ft) spans on glulams (beams built of laminated wood strips glued together). The bridge was supported by a pile-and-timber box abutment on the west end and a pile-and-timber wing wall on the east end. The edge of the roadway fill on each side of the abutments was protected from erosion by the installation of gabions (rock-filled wire baskets). The barriers prevented the fast-moving waters at flood stage from eroding the abutments.

The drilling site was located on a north-facing slope of the Ivotuk Hills. Because of the slope, the pad was divided into three sections with differences in elevation of 5-6 m (17-20 ft). The uppermost (south) area was for the camp and storage; the middle area was for the rig and drilling activity; and the lowest area consisted of the dikes and berms for the reserve and flare pits. The lowest portion of the reserve pit was about 3 m (10 ft) below the crowns of the adjacent dikes. The upper layer of the drill pad had 6 cm (2.5 in.) of Styrofoam installed, and the central section had 15 cm (6 in.). The rig was supported on 220 wooden pilings augered and frozen in to a depth of 7.5-8.5 m (25-28 ft) below the finished grade. The 15 piles immediately beneath the rig were frozen in to a depth of 14 m (45 ft) below finished grade.

The size of the reserve pit was sufficient to contain all of the anticipated fluids below the original tundra surface. Special care was taken with the dikes to ensure their integrity. Gabions were used to protect the eastern edge of the reserve and flare pits, in case spring or fall runoff swelled the nearby intermittent creeks.

Borrow material for the runway, apron, road, and drilling pad was taken from two sources located in the flood plain of Otuk Creek. Overburden in these areas ranged from about 10 cm (a few inches) to as much as 45 cm (1.5 ft) of organic silts. This overburden was removed and stockpiled. After the borrow material was removed, the areas were contoured to blend in with the surroundings, and the overburden was spread on the surface to aid in the rehabilitation and revegetation. An undisturbed area 7.5 m (25 ft) wide was maintained along the existing banks of Otuk Creek.

The rig scheduled to drill the Lisburne well was Nabors Rig No. 17, which was finishing up at the Peard site. The rig move from Peard to Lisburne actually began on May 1 and required a total of 30 days because of poor weather and difficult runway conditions at Ivotuk. Because the ice airstrip at Peard was deteriorating in the warm weather, the rig had to be temporarily staged at Tunalik and Lonely. The distance from Peard to Tunalik was considerably less, so more cargo could be moved in a shorter time. Early in May the airlift was augmented by three rolligons to ensure that all of the rig components were located at permanent strips before breakup. Rig move-in operations to Lisburne required a total of 220 Hercules C-130 loads. Rig-up began on May 19 and took 23 days. The well was spudded at 8:00 a.m. on June 11, 1979.

There is some confusion concerning the name of the Lisburne wellsite. The air-freight handlers used the symbol IVO (Ivotuk Hills) to designate freight for Lisburne in order to avoid confusion with the Lisburne DEW Line sites along the western Alaska Arctic coast. Because of this designation, the airstrip was often called Ivotuk, but the official name of the drilling operation was Lisburne Test Well No. 1.

SEISMIC PROGRAM—SPRING 1979

Approximately 2,500 km (1,600 line miles) of common-depth-point seismic surveys was originally scheduled for the mid-January to mid-May 1979 season. Of this total, approximately 1,600 km (1,000 mi) was to be additional fill-in reconnaissance, and the remaining 900 km (600 mi) was to be fill-in detail surveys. Three parties were fielded that season. One worked on the coastal plain in the area between Wainwright Village on the west and Smith Bay on the east. The two other parties worked in the foothills area of the reserve between Umiat and the western boundary near Icy Cape; one of those parties used the vibroseis method of imparting energy to the underlying formations, and the second used conventional explosives. Vibroseis transmits energy into the ground by the repeated impact of a heavy weight on the frozen tundra instead of by explosive energy.

The transecting couplet seismic survey through Howard Pass in the Brooks Range was proposed again, this time using the vibroseis method of survey. On June 30, 1978, the National Park Service gave permission to conduct a survey through Howard Pass to the Noatak River subject to archaeological clearances, but the actual departmental authorization for a seismic survey was not given, and the work was not done.

By late April 1979, because of a somewhat early breakup, the two parties working in the southern foothills region were forced to terminate their operations, and the third party working on the Simpson Peninsula pulled off the tundra in early May. Despite the shortened season, 3,042 km (1,901 mi) of seismic survey data was obtained.

DRILLING SITE REHABILITATION–SPRING 1979

The work of filling in the reserve pits and obliterating straight-line outlines was not cost effective in the summer of 1978 because of excessive precipitation, which bogged down the Cats in the deep mud. However, through diligence and persistence, and a careful weather watch, six sites were ready for seeding when the fall freeze-up began. These were South Harrison Bay, Atigaru Point, East Teshekpuk, West Fish Creek, W.T. Foran, and South Simpson.

In January 1979 a small party was sent to Drew Point, about 29 km (18 mi) east of Camp Lonely, to try to rehabilitate the area under winter conditions. The work went better than expected. The frozen pads ripped rather easily, and the material was pushed into the reserve pit and the pad lowered. Using the lessons learned at Drew Point and considering the costs, a program was initiated to rehabilitate South Meade, Kugrua, and North Kalikpik. A small train left Lonely in mid-April and completed the work at North Kalikpik with no difficulty. A second train left Barrow at about the same time. It completed the work at South Meade and was on the way to Kugrua when the work had to be postponed. Unusually warm temperatures around the first of May and a very sparse snow cover made the risk of damage to the tundra too great.

In anticipation of a summer program to clean up old sites, an attempt was made to stockpile fuel at Oumalik. A rolligon tried twice to reach Oumalik but was stopped by deep soft snow. The load of fuel was finally left at North Kalikpik, partially completing the plan. These spring programs provided excellent lessons in operating on varying snow depths and in varying surface conditions throughout the reserve.

USGS/HUSKY OPERATIONS: FIFTH SEASON— JUNE 1979 TO MAY 1980

SUMMER OPERATIONS

The drilling program for 1979-80 included the completion of Tunalik, Seabee, Lisburne, and Ikpikpuk, the drilling of three new Barrow wells (Nos. 15, 18, and 20) and three new exploratory wells, and the initiation of a fourth exploratory well and possibly a fifth if time allowed. Although this was an extremely ambitious program, the amount of field survey work required was not as great as during the previous season. Most locations were decided upon before the field season, and only five new sites were surveyed. These included a site near the Rogers-Post monument, 19 km (12 mi) southwest of Barrow; a site on the west side of Dease Inlet; a site on the Simpson Peninsula; a proposed deep well just north of Lookout Ridge; and a site near the confluence of the Ikpikpuk and Price Rivers. This season, in addition to conventional survey methods, an autosurvey system was used that speeded the work and shortened the field-crew time.

The cleanup program to rehabilitate old Government sites began at the Old Brady site on the Kiligwa River with concurrent programs at Driftwood and Liberator Lake. Work was then concentrated in the southeastern part of the reserve. Combustibles that had been stockpiled in 1978 were burned at Wolf Creek, Square Lake, Titaluk, and East Oumalik. Cleanup was completed at Fish Creek, Oumalik, Grandstand, and Gubik. The Navy had drilled these latter two sites off the reserve in 1951-52. The area around the Gubik test wells proved to have much more debris than was originally estimated, and the crews worked in this area for 32 days, or more than one-third of the total time. More than 900,000 kg (20 million lb) of debris was handled, and a final 1,900,000 kg (4,200,000 lb) was stockpiled for burial at a later time.

The policing of recent wellsites and subsequent seeding and fertilizing to revegetate those sites was accomplished on a split schedule during the summer of 1979. Because of wet and somewhat warmer-than-usual weather, an intermittent schedule of pickups was followed throughout the summer. It was a rush to get to the sites while they were dry enough to walk on and before the next rain. Seeding and fertilizing was done later in the fall, after the first frost. This dormant seeding had proved successful in the past, and it appeared to be the only way to cope with the wet weather.

Miscellaneous debris was collected and the pile caps cut and burned at the following sites: W.T. Foran No. 1, South Simpson No. 1, Atigaru Point No. 1, East Teshekpuk No. 1, Drew Point Test Well No. 1, Halkett No. 1, North Kalikpik Test Well No. 1, West Fish Creek No. 1, South Harrison Bay No. 1, and South Meade Test Well No. 1.

In 1978, seed germination was successful at East Teshekpuk, South Harrison Bay, South Simpson, and West Fish Creek. It was partially successful at W.T. Foran, Atigaru Point, and Halkett. South Meade, Kugrua, East Simpson No. 1, Peard, and North Kalikpik were seeded and fertilized this season. Halkett, Atigaru Point, and W.T. Foran were refertilized.

The barges arrived at Camp Lonely on August 1 and unloaded a total of 9,330,000 kg (20,530,000 lb) of dry cargo and 20,217,555 L (5,341,494 gal) of petroleum products. Nabors Rig No. 1 was loaded on the barges for transport to POW A. Construction-train units were picked up at Barrow and Lonely and delivered to the abandoned DEW Line site POW A in preparation for the construction of the East Simpson No. 2 drill site. POW A is only about 10 km (6 mi) from the drilling location. All told, there was a lateral movement of 3,700,598 kg (8,141,315 lb) of dry cargo and 353,965 L (93,518 gal) of fuel.

TUNALIK TEST WELL NO. 1

The primary objective of the Tunalik well was to test a seismically defined, structurally closed anticlinal trap in the Sadlerochit and Lisburne Groups. Secondary interest was in the pebble shale unit and the sandstones of the Kingak Shale. Numerous gas shows were encountered at both shallow and moderate depths in sandstones with low porosity. High-pressure gas, which was encountered at about 3,825 and 4,488 m (12,550 and 14,725 ft), created severe drilling problems. The heavy drilling mud and barite used to control the high-pressure gas precluded the successful testing of the sands. An unexpected and geologically significant sequence of igneous rock was found within the sedimentary rocks. Most stratigraphic units penetrated by this well were found to be thicker than strata of the same age in wells to the east. The well was drilled to a depth of 6,198 m (20,335 ft) or a true vertical depth of 6,160.3 m (20,211.1 ft)—a new depth record in Alaska. This depth was reached on December 22, 1980. After cementing, reversing out, nippling down, and cleaning up, the hole was pulled out for the last time on January 4, 1980. Following the laying down of the kelly, the rigging down of the iron roughneck, and the cleaning of the mud pits, the rig was released on January 7. As rigdown was accomplished the components were segregated into Hercules-size loads to await the completion of the Awuna airstrip. The air move to Awuna was begun on January 24, 1980.

SEABEE TEST WELL NO. 1

The rig to drill Seabee Test Well No. 1 was Nabors No. 25; it was airlifted from Inigok between June 14 and June 24, 1979. The all-season runways at each site allowed for a flexibility of schedules. Rig-up operations began on June 15 and were completed in 18 days. The well was spudded at 2:30 p.m. on July 1, 1979. About six weeks later a dispute arose between the drilling subcontractor and the labor union, forcing suspension of the drilling operations on August 21 at a depth of 1,997 m (6,551 ft). Reentry was made on October 16, after the labor dispute had been settled.

The Seabee test well (fig. 2.23) reached the Lower Cretaceous pebble shale unit, at a total depth of 4,758 m (15,611 ft), in early April 1980. The well was drilled on the flank of the Umiat anticline—the structure that contains the Umiat oil field discovered in 1950. The objective was to test for possible deeper hydrocarbon reservoirs in Lower Cretaceous (Fortress Mountain Formation) strata. Oil and gas shows were encountered in the shallow Umiat oil zone, but testing was not possible because of the large size of the borehole. Minor oil and gas shows were found at 1,655 m (5,430 ft) in the Torok Formation. Tests of this zone gave flows of 2 to 6 million ft^3/d but detailed analyses of the test data indicate a limited and depleting reservoir. Minor gas shows were found in deeper, thin, nonporous sandstones.

After testing and evaluation, the hole was plugged back with cement and the cement string pulled and reversed out. The mud was replaced with water, and the water with diesel, to a depth of 402 m (1,320 ft). The blowout preventers were nippled down, and the abandonment marker set. The rig was released on April 15, 1980, and rig-down and demobilization of the rig and drill camp began. The rig components themselves were stacked on the pad, because the rig was scheduled for use in the 1980-81 winter season.

LISBURNE TEST WELL NO. 1

The labor dispute that suspended drilling activities at Seabee also affected the operations at Lisburne. Drilling was suspended on August 23 at 2,064 m (6,773 ft). Reentry was made two months later on October 24, 1979.

Lisburne Test Well No. 1 was completed on June 2, 1980, at 5,180 m (17,000 ft) in the fifth penetration of limestone of the Lisburne Group. The well was located on a seismic closure in the disturbed-belt play—a structure that borders the Brooks Range and is at least somewhat analogous to the overthrust play in the Western United States. The well drilled through about 2,100 m (7,000 ft) of highly deformed rocks before reaching the Jurassic to Mississippian section exposed at the surface immediately south of the wellsite. Ubiquitous dead-oil occurrences indicated the generation of hydrocarbons. Tests in two different Lisburne thrust plates recovered only small volumes of gas and some relatively fresh formation water. A test in the Shublik Formation flowed gas at a calculated rate of 213,000 ft^3/d but indicated a depleting reservoir. The rocks are porous locally to at least 3,660 m (12,000 ft), and maturation analyses indicate promising source rocks for the total depth. This well will provide fundamental information in future disturbed-belt exploration.

The well was plugged and abandoned; cement and mechanical plugs were set at selected intervals. The rig was released at midnight on June 2, 1980. The abandonment head was installed, and the derrick laid down. The rig was partially broken down and stacked to await use in 1980-81.

IKPIKPUK TEST WELL NO. 1

Personnel returned to the Ikpikpuk location on November 20, 1979, to open the camp. The crew had trouble starting the generator, so they returned to Camp Lonely for the night and tried again, this time successfully, on the 21st. They rigged up the camp, started the support equipment, set the sewer plant, worked on the ice road to the water source, laid out the Twin Otter strip, and began work on the C-130 ice-on-tundra airstrip. While the mast was being raised, the A-frame legs were damaged and required repair, but otherwise rig-up proceeded smoothly. Reentry was made on December 25, 1979.

The Ikpikpuk Test Well No. 1 reached a total depth of 4,719 m (15,481 ft) in the Kekiktuk Con-

FIGURE 2.23.—Drilling Seabee No. 1 test well near Umiat on the Colville River, July 1979. Photograph by J. Haugh.

glomerate of Mississippian age. The well was drilled to test the Lisburne and pre-Lisburne plays at their wedgeout on the north flank of the Ikpikpuk basin. Nearly 1,200 m (4,000 ft) of tight, unpromising Lisburne and Endicott beds were drilled, producing only scattered minor gas shows. Two of the shallow sands, the basal pebble shale unit sand and a sand in the Torok Formation, were tested primarily for productive capacity and fluid content. Some gas was recovered on each test. The well was abandoned, and cement and mechanical plugs were set at selected intervals. The rig (Parco No. 96) was released at midnight on February 28, 1980. Rig-down began on March 1, and by March 10 all components had been demobilized from the reserve to Deadhorse by C-130 airlift.

WALAKPA TEST WELL NO. 1

The construction train left Barrow for Walakpa on November 25, 1979, arriving at the site, 24 km (15 mi) southwest of Barrow, the following day. Travel was very slow because the tundra along the coast was quite hummocky and the trail was frequently intersected by small streams draining to the ocean. Walakpa No. 1 is located at lat 71°06′ N., long 156°53′ W., about 9 km (5.5 mi) from the coast. The pad was built in a fairly flat, wet meadow of sedge. Construction of the thin pad, the associated ice road, and the Hercules strip on a nearby lake proceeded on schedule. Construction was completed in two weeks, and the train returned to Barrow on December 11, 1979.

The move of the Brinkerhoff-Signal Rig No. 31 from the South Barrow No. 6 site began on December 2 and was completed by December 17. Rig-up began immediately, and the well was spudded on Christmas Day. The well was drilled to a total depth of 1,117 m (3,666 ft), bottoming in argillite of pre-Carboniferous age. The objective of the well was to explore a stratigraphic trap in the Jurassic Simpson sandstone (informal term). The Jurassic sandstone was not present, but gas was found in a basal Cretaceous sandstone. This gas discovery may have important implications as a future Barrow gas supply. At the conclusion of the drilling operations, casing and a cased-hole drill-stem test were run. The rig was released on February 7, 1980, and preparations were begun for moving the rig to the West Dease Test Well No. 1 site.

EAST SIMPSON TEST WELL NO. 2

The construction Cat train that was stacked at POW A the previous summer was activated the first week of December and set out for the East Simpson No. 2 site on the morning of the 18th, arriving late that afternoon. The site was located at lat 70°58′ N., long 154°40′ W. Travel was relatively easy because 8 km (5 mi) of the 10-km (6-mi) route was on the flat ice of shallow lakes and ponds. Snow cover was deep but was easy to clear from the flat ice. The drilling location was within one-half kilometer (one-quarter mile) of the edge of the lake upon which the C-130 airstrip was located. The water source, although 8 km (5 mi) distant, was so located that only about 1.5 km (1 mi) of ice road had to be constructed. Construction started immediately and was completed by January 11, 1980. The construction train was airlifted to Barrow on January 18 to help in the construction of the West Dease site. The rig to be used was Nabors Rig No. 1, which had been positioned by barge the previous summer at POW A. Rig move-in operations began on the 13th, rig-up commenced concurrently, and the well was spudded on January 29, 1980.

The East Simpson Test Well No. 2 was drilled into the argillite basement at a depth of 2,288 m (7,505 ft) on March 15, 1980. The primary objective of the well was to test sandstone of the Ivishak Formation of Permian and Triassic age as it onlaps the pre-Devonian basement rock. This sandstone was believed to be present as a thickened section of the porous and oil-stained rocks of the Sadlerochit Group that were found in the East Simpson No. 1 well 6.5 km (4 mi) away. Minor oil and gas shows were found in the Torok Formation and Sag River Sandstone. A thin section of the Sadlerochit had a good oil show, but a test of the sand recovered 161 bbl of formation water with only a sheen of oil. Small-scale faulting was noted between the wells, and this may account for the thin Sadlerochit section. Sandstones of probable Endicott Group age had poor to fair porosity and dead-oil shows.

The crew pulled the drill out of the hole for the last time on the 15th of March, laid down the drill pipe, and began nippling down the blowout preventer. The rig was released on the 15th, and rig-down commenced on the 16th, in preparation for the demobilization of the rig to Lonely. The move was accomplished over the ice of Smith Bay and then over the trail from Drew Point to Lonely, the last units arriving in the camp on the evening of March 25, 1980.

WEST DEASE TEST WELL NO. 1

The construction train that was airlifted from East Simpson No. 2 to Barrow on January 18, 1980, left Barrow a few days later for the West Dease wellsite located at lat 71°09′ N., long 155°37′ W., approximately 45 km (28 mi) east-southeast of Barrow. Conditions allowed travel over the ice of Elson Lagoon, and the move was made uneventfully. Plans called for the construction of an ice airstrip on a lake about three-quarters of a kilometer (half a mile) south of the wellsite. By connecting this lake with the proposed water source 1.5 km (1 mi) to the west, only 2.5 km (1.5 mi) of ice road was needed. The drilling pad itself was located partly on an area of high-center polygons and partly on a low swampy area. The thin-pad design was used. Construction was somewhat hampered by a period of high winds and blowing snow, but otherwise all went well. The pad was completed, and the train started back over the ice for Barrow on February 18, 1980.

Also on February 18, around 2:30 in the afternoon, the Umiat Enterprises Pilatus Porter took off from the ice runway at West Dease intending to go to Camp Lonely. People on the ground reported that the takeoff appeared normal until the plane reached about 60 m (200 ft) in the air, when it abruptly and inexplicably dove and crashed at the side of the runway. The aircraft exploded into flames and was quickly consumed. The pilot, Charles Guesford (UEI), and his two passengers, William Frey and James Bowlin (both of Husky NPR), were killed instantly. The accident was investigated by the National Transportation Safety Board, but the exact cause was not ascertained.

The Brinkerhoff-Signal Rig No. 31 that drilled the Walakpa No. 1 well was used for West Dease and arrived overland via Barrow and the Elson Lagoon ice road by the 15th of February. Rig-up ran concurrently with the arrivals, and the well was spudded on February 19, 1980.

The primary objective of the well was to reach an updip stratigraphic pinchout of the upper Sag River Sandstone onto the Barrow arch. The Jurassic Barrow sandstone and the Triassic Sag River Sandstone were cored and contained oil and gas shows, but the test of the Barrow sandstone showed only mud with an oil sheen. Minor amounts of gas and oil were found in the Torok Formation and in the pebble shale unit.

The well was completed as a dry hole at a depth of 1,271 m (4,170 ft) in the argillite basement of pre-Carboniferous age. The rig was released on March 26, 1980, and rig-down began in preparation for the move to Barrow.

BARROW CONSTRUCTION

The Barrow 1979-80 winter construction season started with the building of an ice road from the gravel borrow pit immediately southwest of the city to a point near the South Barrow gas field. Water was taken mostly from Ikroavik Lake. The plan was to extend the all-season gravel road from its previous year's terminus, at South Barrow Well No. 6, about 12 km (7.5 mi) eastward to the new pressure-reducing station and then on to the site proposed for South Barrow No. 18. Plans also called for spur roads from the main road to each of the two existing wells and to the two other wells (South Barrow Nos. 15 and 20) that were to be drilled during calendar 1980. The gravel road would allow drilling during the summer and fall season and also serve as a maintenance road during the operation of the field. The actual gravel haul began in early February and was completed by May 1. Pads were also built at the proposed locations of South Barrow Nos. 15, 18, and 20.

On March 3, 1980, the construction train that built the Seabee pad and had been stacked at Umiat was moved off the reserve. It was taken overland on approved trails across the Colville River and then to Service City at Prudhoe Bay.

SOUTH BARROW WELL NO. 20

The drilling pad for South Barrow No. 20 was finished by the end of March, and the Brinkerhoff Signal Rig No. 31 was moved in from the West Dease location. The move was by truck and low-boys over the sea ice of Elson Lagoon. Well No. 20 was located almost due south of Well No. 12—the East Barrow discovery well. Rig-up began on April 4 and proceeded without incident. The well was spudded on April 7 and drilled to a total depth of 718 m (2,356 ft) in 16 days.

The primary objectives of the well were to test the Early to Middle Jurassic lower Barrow sandstone interval, which was encountered between 629 and 635 m (2,064 to 2,082 ft) and the upper Barrow sandstone, which was encountered between 608 and 624 m (1,994 to 2,046 ft). The secondary objective was to test the Sag River Sandstone interval, which was encountered between 645 and 705 m (2,117 to 2,313 ft). A third objective of the well was to check the pebble shale interval, which was encountered at 475 to 480 m (1,558 to 1,574 ft), at 497 m (1,629 ft) and at 500 m (1,639 ft).

The secondary objective, the Sag River Sandstone, was cored and tested. The test indicated that it was a weak gas sand flowing at a rate of 12,000 ft^3/d of gas. The primary objective, the Barrow sandstone, was not cored, but electric-log analyses and sample evaluation revealed that it had typical reservoir characteristics. Because time was short, it was decided to set pipe through the sand and test it later through perforations. During cementing operations, no returns were observed at the surface, although 80 sacks of cement and 25 bbl of water (spacer) were pumped down the hole. The cementing operation was the same as had been used on previous wells, but the cement was obviously pumped into the Barrow sandstone. When the sand was perforated, it flowed only small volumes of gas, and tests showed extremely slow pressure build-up. The well was plugged back, and two sands within the Cretaceous pebble shale unit were perforated. The well was blown clear several times with gas from Well No. 19, and a total of approximately 15 to 20 bbl of oil cut with gas and water was recovered. The well was suspended as a questionable oil well, and the rig was released on May 10, 1980.

AWUNA TEST WELL NO. 1

The Awuna wellsite was located about 5 km (3 mi) north of Lookout Ridge at lat 69°09′ N., long 158°01′ W., 10 km (6 mi) inside the boundary of the Caribou Calving Grounds (Utokuk River Uplands) Special Area. The location was 120 km (75 mi) from Ivotuk (Lisburne drill site) by air, but about 175 km (110 mi) over the approved overland route. In mid-December 1979, a small construction crew activated the train that had been left at Ivotuk and set out over the staked trail for the Awuna site. They arrived on Christmas Eve, 1979. Work began immediately on clearing a runway on a shallow lake about 1.5 km (1 mi) southeast of the wellsite. The lake was only 1.4 km (0.9 mi) long, so the runway had to be extended by icing the tundra at the west end of the lake. As soon as the airstrip was operational, the rest of the construction equipment began arriving. The first Hercules C-130 arrived on January 22, 1980.

The Awuna well was planned with a target depth of 4,570 m (15,000 ft) to test the closure of a huge domelike structure 10-14 km (6-9 mi) wide and more than 160 km (100 mi) long. It was planned to drill in the spring and suspend operations in May before the caribou arrived. The well would be Arctic packed for reentry the next fall. The equipment and supplies for reentry were to be stored for the summer on a specially insulated area of the drill pad.

The reserve pit was excavated to a minimum depth of 2 m (6 ft) below the original tundra level. Before the second season of drilling, it was planned to enlarge the pit to contain the additional fluids and cuttings and to use the excavated material to fill areas of the pad that had settled during the summer thaw.

Construction of the pad and reserve pit began immediately after the airlift of the additional equipment in late January 1980. Construction was being completed as the first units of the drill rig and camp began arriving on February 12. When the construction was finished, the train, except for the equipment required to enlarge the reserve pit the next season, was flown out to Umiat and other locations, some pieces going to points off the reserve. It took 32 days and 152 Hercules loads to move the rig (Parco No. 95) from Tunalik. The weather did not cooperate, and many flights were delayed.

Rig-up began on February 10, and the well was spudded on February 29, 1980. Drilling was slow; for many days drilling was in a formation with a dip of approximately 30°, and deviation was troublesome. Stuck pipe and a "fishing" operation contributed to the problems, but the well had reached a depth of 1,615 m (5,300 ft) when operations were suspended on May 8. Preparations were made for the summer, and the drill crew left the site on May 11, 1980, well in advance of the arrival of the caribou.

KOLUKTAK TEST WELL NO. 1

It was originally planned to build the Koluktak wellsite during the winter of 1980, fly in the rig, drill the well, and then, if necessary, leave the rig on the site for the summer. However, the rig to be used was the Brinkerhoff Signal No. 31 which was used at Walakpa No. 1, West Dease, and South Barrow No. 20. Many unexpected delays, not the least of which was the unusual amount of snow and the attendant warm weather that slowed down the thickening of the ice airstrips, delayed the schedule, and only the construction of the Koluktak pad was completed in the spring of 1980.

A small advance train and some equipment were flown from Awuna to Umiat at the end of January 1980; they proceeded overland via the old trail from Umiat to Wolf Creek and then over newly staked and cleared trail to Koluktak. They arrived on site at lat 69°45′ N., long 154°37′ W., on February 6, 1980. Construction proceeded in good order, and the airstrip was ready in a few days. However, it could only accept light aircraft until the ice thickened. During the month of February, the decision was made not to move in the rig that spring, and the construction plans were adjusted accordingly. The reduced equipment needs meant a reduced number of Hercules trips and less time on the site, all contributing to considerable savings. The pad (of the thin-pad design), reserve pit, and flare pit were constructed, and the rig piling was installed. The ice road to the water-source lake was not built. The work was completed by March 19, and all construction gear was demobilized—some overland to Umiat and some airlifted off the reserve.

ENVIRONMENTAL REHABILITATION—SPRING 1980

In the fall of 1979, disposition of the consolidated and stockpiled debris from the cleanup of old sites was still undecided. At the two sites that were farthest from the ocean, burial was considered the best method of disposal, because it would be very expensive to transport the debris north for marine retrograding. These sites were Gubik (lat 69°26′ N., long 151°28′

W.) and Grandstand (lat 68°58′ N., long 152°05′ W.)—both just off the reserve to the east and southeast of Umiat. The sites were on selected lands, so the plan was discussed with the BLM and the Arctic Slope Regional Corp. After they had agreed to this method of disposal, the permission of the Alaska Department of Environmental Conservation was obtained. A contract was let early in March 1980 for a Cat train to do the burying. The plan was to strip away the organic overburden and stockpile it to one side, then to excavate the hole, push in the debris, compact it, and cover it to a depth of at least 60 cm (2 ft) with the excavated dirt. The overburden would then be spread over the site and seed and fertilizer distributed. The operation went very smoothly.

After completing the Gubik site, the contractor proceeded north to Inigok to perform some minor work on the pad and reserve pit. Because native sulfur and hydrogen sulfide had been encountered during the drilling, the reserve pit contained some strange compounds in addition to the usual drilling muds and clays. Consequently, the pit was carefully monitored for possible environmental problems. The outlines of the flare and fuel pits were changed, and the edges of the pad were feathered out to the tundra to blend some of the straight lines into more natural configurations. However, the integrity of the reserve pit was maintained. The Cat train traveled east over the old Inigok ice road and left the reserve on April 24, 1980.

An attempt was also made at Ikpikpuk to utilize the KOH (Kodiak Oilfield Haulers) equipment that was on site during rigdown to contour the drilling pad. However, the pad was frozen too hard to be ripped by the available equipment (a D-7 Cat), so a D-8 Cat traveled overland from Camp Lonely to do the work. This work was done in late March and early April, and, in spite of a long siege of blowing snow, it went smoothly.

In late April, after the Ikpikpuk rehabilitation work was completed, the Camp Lonely support crews began work on the gravel pad at J.W. Dalton. Much of this gravel was salvaged for use in the Lonely camp area and as cover for the sanitary land fill. The rest of the gravel was pushed into the reserve pit, and the pad area was leveled out.

SEISMIC PROGRAM—SPRING 1980

A total of 1,570 km (980 line miles) of common-depth-point seismic surveys was scheduled to be completed in the spring of 1980. The surveys were to be run in the Icy Cape area, the northern foothills area from the western border to just off the reserve east of Umiat, and in some isolated areas of the Brooks Range. Most of the surveys were for additional fill-in reconnaissance information, but some closely spaced detailed surveys were run near Tunalik, Meat Mountain, and the Lisburne wellsite. Only two crews were in the field that season, one working in the coastal area and the other in the foothills and the Brooks Range. Both parties used dynamite as an energy source. Snow conditions and weather were better than usual, and the parties finished up in April. A total of 1,754 km (1,096 mi) of seismic lines was run that season, including 214 km (134 mi) of a supplementary program.

USGS/HUSKY OPERATIONS: SIXTH SEASON—JUNE 1980 TO MAY 1981

SUMMER OPERATIONS

The summer survey for the 1980-81 season required the investigation of seven wellsites, three of which were alternates. These sites were the following:

Site	*N. latitude*	*W. longitude*
Kuyanak	70°55′	156°03′
Walakpa No. 2	71°03′	156°57′
Avgunum (alternate)	70°40′	159°16′
North Inigok	70°15′	152°45′
East Kealok (alternate)	70°22′	152°29′
Carbon (second alternate)	69°31′	160°18′
Tulageak	70°11′	155°44′

Because of the uncertainties resulting from the somewhat different positions taken by the Department of the Interior and the Congress, all seven sites were surveyed. The stated position of the Department of the Interior was to close out the NPRA exploration program in an orderly manner and to continue the exploration under a private leasing arrangement. However, Congressional hearings on the program indicated that Congress wished to continue the Government's exploration program until such time as a private leasing program was in effect. These uncertainties led to delays in the selection of potential wellsites and the refinement of the geophysical data. In preparation for possibly drilling four wells, seven sites were investigated—four primary and three alternates—and archaeological, environmental, and engineering studies were conducted at all sites. The completion work at Awuna and Koluktak scheduled for 1980-81 did not require additional field work.

The Cool Barge arrived at Lonely on August 15, 1980, and unloading of the piling, timber, dry cargo, drum stock, and bulk fuel continued around the clock until August 20. A total of 3,243,113 kg (7,134,848 lb) of dry cargo and 17,056,414 L (4,506,318 gal) of fuel was delivered. Lateral movements to Deadhorse, Cape Simpson, and Peard Bay included 479,769 kg (1,055,493 lb) of dry cargo and 108,312 L (28,616 gal) of fuel. In addition, 83,545 kg (183,800 lb) of miscellaneous items was retrograded to Seattle. The barges left Camp Lonely the evening of August 21 to proceed to Barrow and then on to Seattle.

The 1980 summer cleanup of old Navy sites and the cleanup and revegetation of the drill sites of the current exploration program were combined under one contractor. The operations got underway when equipment and personnel arrived at Camp Lonely during the last week of May. An 18-man tent camp was set up at Oumalik and, utilizing a Bell 205 helicopter for lifting power (fig. 2.24), began the cleanup of Oumalik, East Oumalik, Brady, Mona Lisa, Lisburne (the current drill site), and a number of new finds and explosive caches. The term "new finds" was used to designate any considerable amount of debris encountered locally within 8 km (5 mi) or so of the site—debris that was not originally scheduled in the work plan. The disposal of the explosives was coordinated with the Alaska Department of Environmental Conservation, the USGS, and other Government authorities. By July 24, the tent camp was moved to the Old Meade site; the crews helped with the pickup at Tunalik during the move.

Demobilization of the cleanup camp at Old Meade began on August 20, and the operation was out of the field by August 25. Although this was early, according to the schedule maintained in previous years, during the last days of operation the camp was plagued by freezing water pipes and condensation of moisture in the tents. This season a total of 1,203,463 kg (2,647,620 lb) of debris was stockpiled for burial; 826,045 kg (1,817,300 lb) consolidated at Oumalik; and 377,418 kg (830,320 lb) consolidated at Old Meade. New finds at Oumalik (figs. 2.25-2.27) totaled an estimated 177,000 kg (389,000 lb), and at Old Meade approximately 23,000 kg (51,000 lb).

REVEGETATION OPERATIONS

The revegetation crew of 10 was based at Camp Lonely and used a Bell 205 helicopter for transportation. The plan was to seed and fertilize as many pads as possible before July 4, then go back and begin the cleanup at each site. Research and experience had shown that any seed planted after the beginning of July did not have sufficient time to germinate and establish adequate roots to survive the winter. Those sites not seeded in the spring were sown with dormant seeds in late August after the first frosts.

FIGURE 2.24.—Helicopter transporting debris to the burial location, Grandstand site, July 1979.

The following sites were worked over during the 1980 season:

1. Drew Point—policed pad, cut piling, applied seed and fertilizer; seeded in spring.
2. J.W. Dalton—policed pad, cut piling, applied seed and fertilizer; seeded in spring.
3. W.T. Foran—reseeded and fertilized; seeded in spring.
4. Atigaru Point—reseeded and fertilized; seeded in spring.
5. East Simpson No. 1—reseeded and fertilized; seeded in spring.
6. South Simpson—cut piling, policed pad; last season's seed had germinated successfully.
7. South Harrison Bay—reseeded and fertilized; seeded in spring.
8. North Kalikpik—policed pad, cut piling, applied seed and fertilizer; seeded in spring.
9. East Simpson No. 2—policed pad, cut piling, and applied seed and fertilizer; seeded in spring.
10. Ikpikpuk—policed pad and airstrip, cut piling, applied seed and fertilizer; seeded in spring.
11. Inigok—applied seed and fertilizer to pad and runway edges; seeded in spring.
12. Grandstand and Gubik—applied seed and fertilizer; seeded in spring.
13. Seabee—applied seed and fertilizer to the borrow site and the construction camp site; seeded in spring.
14. West Dease—policed pad, cut piling, applied seed and fertilizer to pad; seeded in spring.
15. POW A (Cape Simpson)—picked up debris where construc-

tion train and drilling rig had been stacked the previous season.

16. Walakpa No. 1—policed pad, cut piling, applied seed and fertilizer; seeded in spring.

17. Peard—policed pad, cut piling, applied seed and fertilizer; seeded in fall.

18. Kugrua—policed pad, cut piling, applied seed and fertilizer; seeded in fall.

19. Tunalik—policed pad and airstrip, applied seed and fertilizer to pad and edges of runway; seeded in fall.

20. South Meade—policed pad, cut piling, applied seed and fertilizer; seeded in fall.

The East Teshekpuk and West Fish Creek sites were inspected during the summer. Germination of the seed spread the previous season was deemed successful, and no further work was done. On days when the helicopter was restricted from flying, the revegetation crews collected about 13,500 kg (30,000 lb) of miscellaneous debris from the gravel and tundra areas around Camp Lonely. In addition, the Lisburne site was visited and cleared of loose debris.

The 1980 summer season was not a good one for grass germination, because it was exceptionally wet and foggy, and almost all grasses had fungus and mold. Although the fungus infestation of the native species used in the revegetation did not appear to be fatal to the stand, the so-called Alyeska mixture did not fare as well. This raises the questions of winter survival and of how many seasons of followup will be necessary to insure adequate stands of grasses.

CAMP LONELY

Upgrading of the facilities continued at Camp Lonely, largely to bring the camp into compliance with the safety standards of OSHA (Occupational Safety and Health Administration) and the Alaska Department of Labor. Climbing cages were added to the ladders on the sides of the Mogas tanks. An exhaust-vent hose system was installed in the mechanic's shop to remove fumes from the immediate vicinity of the welder. In addition, the old incinerator was removed and a new one installed that could handle all the garbage, sewer-plant sludge, and waste oil generated by the program.

BARROW GAS FIELDS

The work to upgrade the Barrow gas facility continued during the summer of 1980. The Barrow Gas Field Power Generation Facility was built; the new road to the field was bladed and compacted during the

FIGURE 2.25.—Drum pile at Oumalik site before cleanup, June 1980.

FIGURE 2.26.—Drum-crushing operation at Oumalik site, June 1980.

entire month of June and most of July; and a culvert that had washed out during the spring breakup was replaced by one with larger capacity.

SOUTH BARROW NO. 15

The pad for South Barrow No. 15 had been constructed the previous March, but the rig (Brinkerhoff-Signal No. 31) was still at South Barrow No. 20. The rig move and rig-up for South Barrow No. 15 began on August 12 and was completed in 11 days. The well was spudded on August 23, 1980.

The sandstone that was the objective of the well was found much lower than expected, indicating either a very steep north flank of the structure or faulting. Total depth of the well was 694 m (2,278 ft) in Jurassic sedimentary rocks. The upper Barrow sandstone was cored, and an open-hole drill-stem test recovered gas. A test in the lower Barrow sandstone recovered water. Minor oil and gas shows were found in the Torok Formation and the pebble shale unit of Cretaceous age. Casing was set through the upper Barrow sandstone and perforated from 626 to 629 m (2,054-2,064 ft) and from 643 to 656 m (2,110-2,151 ft). On a production test, the well flowed gas at a rate of 1 million ft^3/d. The well was completed on September 18, 1980.

SOUTH BARROW NO. 18

The pad for South Barrow No. 18, like that for South Barrow No. 15, was constructed in March of 1980. When the Brinkerhoff-Signal rig finished drilling at South Barrow No. 15 in early September, it was moved over the gravel roads to the new location. Rig-up began on September 19, and the well was spudded on September 22, 1980.

South Barrow No. 18 was drilled on the east flank of the east Barrow structure, reaching a total depth of 651 m (2,135 ft), about 15 m (50 ft) below the Barrow sandstone—the objective of the well. Minor oil and gas shows were found in thin sand stringers in the Torok Formation and the pebble shale unit. The upper and lower Barrow sandstones were cored, and casing was set through the sandstones. The entire lower Barrow sandstone was perforated and tested; the maximum flow rate was 1.4 million ft^3/d. The well was completed and the rig released on October 14, 1980. The rig was stacked out temporarily on the pad.

FIGURE 2.27.—Site of drum pile at Oumalik after cleanup, July 1980.

AWUNA TEST WELL NO. 1

The drilling camp at Awuna was reopened in mid-October of 1980. It was discovered that the camp had sustained much water damage over the summer. Floors, ceilings, and insulation had to be repaired, delaying construction by about one week. By the end of the month the construction crew was on the site, assembling the insulated pipe necessary to build a Hercules ice airstrip on the tundra and servicing the equipment needed to enlarge the reserve pit.

During the month of November, more than 22,700,000 L (6,000,000 gal) of water was frozen to form the Awuna airstrip, the reserve pit was enlarged, and the connecting ice roads from the pad to the airstrip and the water source were constructed. Operations were hindered by high winds, blowing snow, and warm temperatures, but the airstrip was operational on December 5. Mobilization of drilling equipment had begun, and the well was reentered immediately.

The Awuna Test Well No. 1 was drilled to test for possible oil and gas accumulations on one of the highest structural positions along the Carbon Creek-Awuna anticline—a structure that extends across much of the reserve. The well was drilled to test sandstones of the Torok and Fortress Mountain Formations of Cretaceous age. Its total depth was 3,414 m (11,200 ft). The well was spudded in the Torok and reached the top of the Fortress Mountain at 2,404 m (7,886 ft). The Torok was mainly shale with some thin nonporous sandstones, many of which had gas shows. The upper part of the Fortress Mountain

Formation was more sandy than the Torok, but the sandstones were fine grained, calcareous, and argillaceous and generally had low porosity. Gas shows were noted by the mud logger in many of the sands. A drill-stem test near the top of the Fortress Mountain showed a water flow rate of 2,057 bbl/d. There was evidence of fracturing in some of the sands, and the high water flow was probably due to the fractures. Minor amounts of asphaltic material were found in the lower part of the well.

The rig was released at 2:00 a.m. on April 20, 1981, and demobilization began immediately. The weather shack, beacons, communications gear, and a few miscellaneous pieces of equipment were demobilized to Lonely, and the camp and drill rig were returned to Deadhorse and Fairbanks. Demobilization required 132 Hercules C-130 loads. All the equipment was off the site by April 28, 1981.

WALAKPA TEST WELL NO. 2

The construction crews left Barrow early on December 8, 1980, and arrived on location that night. Construction began the next day. Walakpa No. 2 was located at lat 71°03′ N., long 156°57′ W., about 6.5 km (4 mi) south and 2.5 km (1.5 mi) west of Walakpa No. 1 and 12 km (7.5 mi) south and east of the Rogers-Post monument. Walakpa No. 2 was constructed in a low marshy tundra area, and the thin-pad design was used. To speed up the schedule, an unnamed lake of 60-cm (2-ft) depth south of the wellsite was selected for the ice airstrip. The lake immediately east of the site served as the water source. Using the shallow frozen-to-bottom lake for the airstrip meant there was no waiting for the ice to reach sufficient thickness to support the Hercules aircraft. Construction was completed by December 23, and the Cat train departed for the Kuyanak site.

The drilling camp was opened December 11, and the crew was used in the Barrow gas field while the rig was being prepared for the move. Also during this time the trail to the drill site was worked on to smooth out unusually rough spots. The camp was moved to the drill site and was operational by December 22. The rig (Brinkerhoff-Signal No. 31) was on location by December 25. During rig-up a derrick leg buckled, but repairs were made concurrently with the completion of rig-up. The well was spudded at 7:00 p.m. on January 3, 1981.

The Walakpa Test Well No. 2 was drilled to a total depth of 1,329 m (4,360 ft) and, after testing, was completed on February 15, 1981. The well was drilled to confirm the gas accumulation in the Lower Cretaceous sandstone (informally termed Walakpa sandstone), which had tested gas in the Walakpa No. 1 well. The well was spudded in the Torok Formation, which was mainly shale with thin sand streaks containing minor shows of gas. Below the Torok, a normal sequence of the Lower Cretaceous pebble shale unit, Jurassic Kingak Shale, Triassic Sag River Sandstone and Shublik Formation shale, sandstone, and limestone beds was penetrated. The drilling terminated in argillite basement. The Lower Cretaceous Walakpa sandstone, found 162 m (532 ft) lower than in the Walakpa No. 1 well, was cored from 796 to 805 m (2,611-2,640 ft). Fine-grained glauconitic sandstone was recovered, which had poor to good porosity and a show of hydrocarbons. A drill-stem test of the sandstone recovered gas at the rate of 2.3 million ft^3/d. The sandstone was 10 m (32 ft) thick versus 5.5 m (18 ft) in Walakpa No. 1 and had a minimum gas column of 168 m (550 ft). Walakpa No. 2 was temporarily abandoned and the rig released the evening of February 14. Preparations began immediately for the move to the Tulageak site.

NORTH INIGOK TEST WELL NO. 1

The construction train to prepare the North Inigok drill site was moved from Barrow to Lonely by air during the early part of December 1980. The train left Lonely on December 18 and arrived on site December 21, 1980. The North Inigok site was located at lat 70°15′ N., long 152°45′ W., about 77 km (48 mi) south-southeast of Camp Lonely.

It was decided that the drilling pad would be of the thin-pad type—a decision that brought with it a couple of fortuitous advantages that were peculiar to the site. The well was so located that a shallow nearby pond could be the site of the reserve pit. This pond was excavated to a depth approximately 1.7 m (5.5 ft) below the original elevation of the water surface. The drilling pad was located on two low sandy knolls, one in the middle of the pad and one in the southwest corner. The leveling of these knolls provided the additional material necessary for the pad and reserve-pit dikes. The airstrip was located on a lake about 3 km (1.75 mi) northwest of the drill site. The water source was a lake one-half kilometer (one-quarter mile) north of the pad.

Construction of the airstrip was finished by January 1, but the ice still was too thin to support the fully loaded Hercules aircraft. Thus landing restrictions were imposed until the 15th of the month. Site construction was completed by the first week in January, and the contractor prepared to demobilize his equipment by air to Deadhorse.

Beginning January 7, the Nabors Rig No. 25 was moved from Seabee to North Inigok by air. The insufficient thickness of the ice on the North Inigok airstrip and a few days of bad weather hampered the move. The entire 152 loads were flown in 18 days despite of the ice and weather problems.

North Inigok Test Well No. 1 was spudded on February 13, 1981, and was drilled to a total depth of 3,100 m (10,170 ft) in the Triassic Shublik Formation. Seismic records indicated an anomaly at the Upper Jurassic seismic datum level, which was interpreted as being an offshore bar. In addition, the anomaly was correlated seismically with the Walakpa gas sand tested in the Walakpa No. 1 well. The test began drilling in Tertiary (Paleocene) beds, then penetrated the Cretaceous Colville Group, Nanushuk Group, and Torok Formation shales, siltstones, and sandstones, and the pebble shale unit. No sandstones were found in the Jurassic section, although a silty zone, perhaps representing the seismic anomaly, was drilled from 2,483 to about 2,560 m (8,145 to about 8,400 ft). A thin siltstone of the Triassic Sag River Sandstone was drilled, and the well then reached its final depth in limestone of the Shublik Formation. Gas shows were encountered only in the lowermost part of the Torok Formation, and a single show was indicated in the Jurassic siltstone. Surprisingly, a drill-stem test of this siltstone zone produced gas at an estimated rate of 30 million ft^3/d and recovered 94 m (310 ft) of gas-cut mud. The gas was quite rich, analyzing 73 percent methane, 12.8 percent ethane, 7.3 percent propane, 3.2 percent butane, and 3.7 percent pentanes and heavier hydrocarbons. Such an analysis has important implications for a possible oil column downdip.

The well reached a total depth of 3,100 m (10,170 ft), and the rig was released at 11:00 a.m. on April 4, 1981. The Hercules aircraft started the demobilization of the Nabors Rig No. 25 on April 6; with some flights shared with Chevron, 140 loads were flown to Cobblestone (a Chevron strip), Lonely, and Deadhorse. The demobilization move was completed by April 17, 1981.

KUYANAK TEST WELL NO. 1

The construction crews left the Walakpa No. 2 site on December 23, 1980, for Kuyanak at lat 70°55′ N., long 156°03′ W. The location was on the edge of a drained lake basin, about 1.5 km (1 mi) north of Kuyanak Bay—an arm of Admiralty Bay. Construction was hampered during the last week of December by extreme cold and wind. On two occasions windchill factors of −110 °F were experienced.

The thin-pad design was used, and, except for delays caused by bad weather, construction of the drilling pad proceeded on schedule. Both a water source and a satisfactory Twin Otter strip were provided by a lake a mile southwest of the site. The heavy-aircraft airstrip was located on a lake 6.5 km (4 mi) north of the site. The connecting road followed the edges of lakes and ponds, and, although it was 8 km (5 mi) in length, only 3 km (2 mi) of overland ice-road had to be constructed. The construction crew finished in mid-January, but their departure was delayed so that they could help the drilling crews get established. Also, the rig move was off schedule because the ice of the Hercules strip was too thin. The construction train finally moved to Tulageak on January 26, 1981.

Rolligons began moving Nabors Rig No. 1 from Lonely to Kuyanak on January 17. The drilling camp was in operation by January 24, and the rig move was completed by January 27. Rig-up was hampered by bad weather but was finally completed and the well spudded on February 13.

The Kuyanak test well reached its total depth of 2,039 m (6,690 ft) on March 31, 1981. Located 35 km (22 mi) southeast of Walakpa No. 2, the well was drilled to explore primarily for the Simpson sandstone within the Jurassic Kingak Shale. This sandstone had been found in wells to the southeast, south, and southwest and had good reservoir characteristics. It had been noted in the Kugrua No. 1 test well, and seismic information indicated similar conditions could be expected at the Kuyanak location. A trap was postulated because of the truncation of the sandstone layer against the Barrow arch by the basal Cretaceous unconformity and by a facies change to the northwest. A secondary objective was to reach the Sag River Sandstone of Triassic age. Drilling was begun in the Cretaceous Nanushuk Group, and a normal sequence of Cretaceous Torok Formation and pebble shale unit, Jurassic Kingak Shale, and Triassic Sag River Sandstone and Shublik Formation was penetrated before drilling terminated in argillite basement. A sandstone, tentatively correlated with the Walakpa sandstone, was found at 1,552 m (5,092 ft) and cored from 1,552.5 to 1,581 m (5,093-5,186 ft). There were no hydrocarbon shows in the sand, but porosity determined from core analyses ranged from 15 to 22 percent, and permeabilities as high as 318 millidarcies were measured. The Walakpa sandstone thus occurs more than 762 m (2,500 ft) structurally lower than in the Walakpa No. 2 well, which possibly indicates a continuous sandstone with good reservoir characteristics below a proven gas column. A possible equivalent of the Simpson sandstone occurs in the Kuyanak well from 1,639 to 1,724 m (5,378-5,656 ft) and consists mostly of a siltstone with minor shows of gas near the top. Possible equivalents of the Jurassic Barrow sandstone and Triassic Sag River Sandstone of the East Barrow field were cored; the Sag River had a minor show of gas. The rig was released at 6:00 p.m. on March 31, 1981.

The rig was demobilized overland by rolligon to Lonely for later shipment by barge. The camp was demobilized by air off the reserve to Deadhorse.

TULAGEAK TEST WELL NO. 1

The construction train moved overland from Kuyanak to the Tulageak site on January 26, 1981. The wellsite was located at lat 71°11′ N., long 155°44′ W., about one-half kilometer (one-quarter mile) south of Tulageak Point and 3 km (2 mi) north of Reindeer Lake. The wellsite was on relatively flat coastal tundra with an indistinct polygon pattern. Reindeer Lake provided the platform for the ice runway and also served as a water source until the ice became too thick and the water undrinkable. The alternate water source was an unnamed lake 3 km (2 mi) west of Reindeer Lake.

Construction was completed in early February, but the crews remained at the site until the drilling camp was in place and habitable. Demobilization of the construction equipment was overland by rolligon to Barrow and then by Hercules off the reserve to Deadhorse. The move was completed by March 5, 1981.

The move of the drilling camp and the Brinkerhoff-Signal Rig No. 31 was overland from Walakpa No. 2 to Tulageak. It took 30 rolligon loads from February 15 to February 20. Rig-up proceeded without snags, and the well was spudded at 3:00 p.m. on February 26, 1981.

The Tulageak Test Well was drilled to a depth of 1,224 m (4,015 ft) to test a combination structural-stratigraphic prospect. Detailed seismic studies indicated an east-west-trending graben north of the West Dease No. 1 well and separated from it by faulting. The structure was closed to the west by cross-faulting and stratigraphic pinchout; regional dip was maintained to the northeast. It was believed that Simpson sandstone equivalents and older sandstones would be preserved in the structural low. Five objectives were considered: the pebble shale unit, the Walakpa sandstone, the Simpson sandstone, the Barrow sandstone, and the Sag River Sandstone. The well was spudded in probable Torok Formation claystone and penetrated mostly shale with thin sandstone and some limestone streaks before reaching the pebble shale unit. The Early Cretaceous unconformity was reached at approximately 900 m (2,950 ft). From that point, the well was drilled through the Cretaceous and Jurassic Kingak Shale and the Triassic Sag River Sandstone and Shublik Formation sandstone and shale sequence until an unconformity was reached at 1,203 m (3,947 ft). Argillite was cored from this unconformity to a total depth of 1,224 m (4,015 ft). No sandstone was found in the pebble shale unit or at the Jurassic Simpson sandstone level. The Barrow sandstone appeared to be present, as well as the Sag River Sandstone and some thin Shublik sandstones. The Sag River Sandstone contained the only hydrocarbon show, and a drill-stem test recovered slightly water-cut drilling mud but no evidence of hydrocarbons.

The rig was released at 6:00 p.m. on March 31, 1981. The drilling camp was moved by rolligon to the South Barrow gas field, and the rig was demobilized to Fairbanks in 32 Hercules loads. Demobilization was completed by April 8, 1981.

KOLUKTAK TEST WELL NO. 1

The Koluktak drilling pad was built in the spring of 1980, and at that time the well was scheduled to be drilled with Brinkerhoff-Signal Rig No. 31. When other needs made this impractical, Nabors Rig No. 17 was substituted. To accommodate the new rig configuration, 170 additional piles had to be set in the pad.

The construction crew traveled overland on January 5, 1981, from outside the reserve to Inigok by way of the trail of the former Inigok ice road and from Inigok to Koluktak over a new staked trail. Work began immediately to install the needed piling and to rebuild the ice runway and connecting ice road. Weather was unfavorably warm that season, slowing the freezing of the lake ice. In early January, ice on the Hercules strip was less than 75 cm (30 in.) thick, and with temperatures around +20 °F the ice was not thickening. The contractor had to flood the lake surface artificially to build ice, and even with this method, the Hercules strip was not ready until late February. Once ready, the airlift of Nabors Rig No. 17 began. A total of 180 Hercules loads were flown in February and March between Ivotuk (Lisburne) and Koluktak. During March, after the drilling camp was in place, the construction contractor demobilized by rolligon on a backhaul arrangement. Rig-up began during the air move, and the well was spudded on March 23, 1981.

The primary objective of the well was the sandstone of the Nanushuk Group, which had produced good gas and oil shows in several of the wells drilled during the Pet-4 program. Reservoir conditions were believed to be good at the east end of the Oumalik anticlinal trend, where a low-velocity seismic anomaly had been interpreted as being a possible gas accumulation. From the surface to about 1,280 m (4,200 ft) the well was drilled through a Nanushuk-age sequence. The upper two-thirds of this section was predominantly sandstone, but with thin shale, siltstone, limestone, and coal beds, many minor gas shows, and a few oil shows. The lower one-third was much more shaly and had only a few gas shows. The top of the Torok was reached at about 1,280 km (4,200 ft), and from this point the well was drilled mostly through shale with minor amounts of sandstone and siltstone. Only one minor gas show was noted. The well was completed as a dry hole on April 19, 1981, after reaching a total depth of 1,793 m (5,882 ft).

The demobilization of the rig by air was started on April 16 and consisted of 162 loads flown to Deadhorse, Lonely, and Fairbanks. The move was completed by April 28, 1981.

BARROW CONSTRUCTION—SPRING 1981

The major construction at Barrow during the spring of 1981 was the completion of the 1980 program. The Barrow gas-field generating facility was completed, and its performance tested. The gathering lines for wells 12, 15, and 18 in the East Barrow field were completed and connected to a newly constructed pressure-reducing station. Crossarms and powerlines were added to the power poles placed the previous year. The power poles were 32 m (105 ft) apart, and the system was so designed that it could also carry the gas line on a special support at its base. The gasline supports were 11 m (35 ft) apart. All this work was part of the overall design to integrate the East Barrow field into the gas-delivery system.

SEISMIC PROGRAM—SPRING 1981

Early in the 1980-81 season, on the assumption that Congress would mandate a continued geophysical exploration program, it was planned that four crews would run approximately 2,900 km (1,800 line miles) of seismic exploration. However, when it became evident that Congress intended to open the reserve for private exploration as soon as possible, this plan was drastically changed. Also, the reserve was opened that spring to allow industry to acquire its own field data. Consequently, the Government's seismic program that year consisted of only 946 km (591 line mi). Of these, 160 km (100 mi) was refraction data obtained in the vicinity of the Brady anticline. This area had intrigued petroleum geologists for more than 30 years, but reflection techniques had yielded no returns. In addition, nearshore lines on the Beaufort Sea coast were run to serve the dual purpose of providing information required for the leasing program and of tying the data from the Outer Continental Shelf program to the land-based data.

The 1981 geophysical program was carried out by the Government through its contractor for technical services, not through its contractor for general exploration.

BURIAL PROGRAM—SPRING 1981

The 1980 spring burial program was so successful that the decision was made to bury all the stockpiled debris. During the last few days of February, the contractor moved his Cat train and equipment to Koluktak by rolligon, using previously cleared trails. Koluktak was chosen for a starting point because the ongoing drilling operation there, complete with camp and runway, was near the first burial site. The program got underway on March 9.

The contractor's task was to travel overland to the sites where the debris from previous cleanup programs had been stockpiled. Locations for burial were designated, and archaeological and environmental clearances had already been obtained. The procedure was to strip the tundra overburden and stockpile it to one side, then excavate the pit, push in the metallic debris, compact it as much as possible, and cover it to a depth of 60 cm (2 ft) or more. The tundra overburden was then spread over the burial site, and seed and fertilizer were distributed and worked in with a Cat. Burial of debris was completed at the East Oumalik, Square Lake, Oumalik, Old Fish Creek, Old Meade, POW B (Kogru), Titaluk, Wolf Creek, and POW A (Cape Simpson) sites.

Because deep snow prevented the train from reaching the Brady site, POW A was substituted for it. The program was finished by April 19, and the contractor demobilized the train overland to Deadhorse.

USGS/HUSKY OPERATIONS: SEVENTH SEASON—JUNE 1981 TO MAY 1982

SUMMER OPERATIONS

No drilling was planned for the 1981-82 season because the first oil lease sale in the reserve was scheduled for December 1981. Therefore, no surveying was required that summer.

The summer work focused on environmental rehabilitation and preparing Camp Lonely for closure. Decisions had to be reached and carried out concerning the disposition of equipment, supplies, the communications system, and the camp itself.

Since this season was possibly the last opportunity to do any environmental work under the exploration program, it was planned to accomplish as much as time and weather would allow. Cleanup began at the recent drilling sites on June 18. Removal of the pile caps and the pile tops below pad level was the primary aim, because such work was easier to do before the summer thaw had melted the frozen pads.

High winds and fog in the western part of the reserve slowed down the establishment of the cleanup tent camp at Icy Cape, but the operation was finally begun on July 2. A second period of winds as high as 25 m/s (50 knots) hampered work for another week. Icy Cape was finished by July 28, and the camp was moved to the Kaolik site. The old sites cleaned that season were Icy Cape (LIZ B), Peard Bay (LIZ C), Kaolik, and numerous smaller finds.

REVEGETATION OPERATIONS

The following recent drill sites were cleaned up and seeded with native grasses: Walakpa No. 2, Tulageak, North Inigok, Koluktak, Kuyanak, and Awuna.

Further cleanup work was also completed at Seabee (Umiat) and Lisburne (Ivotuk).

The decision was made to use fixed-wing planes to spread fertilizer on trails and pads, because the distances to be covered were great and aerial application was much less costly. Consequently, two Cessna AgWagons were procured by contract; the first arrived at Lonely on July 10 and the second on July 23. Fertilizer was applied aerially to the following trails:

- Lonely to Drew Point—29 km (18 mi)
- Drew Point to Ikpikpuk—58 km (36 mi)
- Ikpikpuk to Inigok—93 km (58 mi)
- Inigok to North Kalikpik—80 km (50 mi)
- North Kalikpik to West Fish Creek—27 km (17 mi)
- North Kalikpik to South Harrison Bay—14 km (9 mi)
- North Kalikpik to Atigaru Point—24 km (15 mi)
- North Kalikpik to W.T. Foran—38 km (24 mi)
- W.T. Foran to Lonely—51 km (32 mi)
- North Kalikpik to Lonely—67 km (42 mi)
- Drew Point to South Simpson—40 km (25 mi)
- South Simpson to East Simpson No. 2—53 km (33 mi)
- Barrow to Walakpa No. 1—22 km (14 mi)

Many trails were rather wide and required two or three passes of the aircraft to ensure complete coverage.

The following abandoned drill pads were fertilized:

Drew Point	Kugrua
Ikpikpuk (plus on tundra ice-runway area)	East Teshekpuk
	Peard
Inigok (plus road and air strip edges)	Tunalik (plus road and airstrip edges)
North Kalikpik	Walakpa No. 1
West Fish Creek	West Dease
South Harrison Bay	Koluktak
Atigaru Point	Tulageak
W.T. Foran	Walakpa No. 2
Cape Halkett	Awuna
South Simpson	Lisburne (plus road and airstrip edges)
East Simpson No. 1	
East Simpson No. 2	Kuyanak
South Meade	North Inigok

Personnel at the Camp Lonely Control Center provided communications for all the cleanup and revegetation operations as well as for the USGS field parties.

Although the level of field activity for the summer of 1981 was less than half that of previous summers, Camp Lonely was a busy place. The Skyvan aircraft and four helicopters were flying in support of the Barrow gas-field work, the cleanup, and the Technical Services Contractor, and the Hercules aircraft made lateral shuttles, moving material between Lonely and Barrow. The operations at NARL were greatly reduced because of the decreased Navy interest and the planned closure of that facility. To fulfill the Secretary of the Interior's requirements to operate and maintain the Barrow gas fields, the USGS moved the Camp Lonely exploration equipment to Barrow because the exploration program was over.

All of the sorting, crating, and transfer of equipment for an orderly closure of Camp Lonely consumed much time and effort. USGS and Husky property-management personnel inventoried all the materials and equipment, particularly the communications gear, and identified items for lateral barge movement to Barrow. The Nabors Rig No. 1 was readied for shipment to Seattle.

In late July, the construction of the heater buildings in the East Barrow gas field was begun, and the radiographic inspection of the gasline gathering system got underway. A telephone line between the East and South Barrow gas fields was installed on the gasline itself. In Camp Lonely, work was started to add urethane to the roofs of the camp units to seal and insulate them before closing them up. Generators were overhauled, some on site and others at Fairbanks and Anchorage. The 87,000-L (23,000-gal) double-walled fuel tanks were drained and cleaned in preparation for painting and shipping to Barrow.

In August, the barges arrived (figs. 2.28-2.30), and fuel deliveries and lateral movements immediately got underway. At Lonely, 3,036,775 L (801,500 gal) of Arctic diesel was offloaded, and another 1,133,600 L (299,500 gal) was received at Barrow. Three barge loads of equipment were shipped from Lonely to Barrow in August and two more in September. Also in September, Lonely received 18,170 L (4,800 gal) of MoGas and 242,250 L (64,000 gal) of Arctic diesel for the DEW Line and stored it in the USGS tanks.

INIGOK RESERVE PIT

After Inigok Test Well No. 1 was abandoned in May of 1979, the spring runoff added considerable fluid to the reserve pit. The resulting increased head pressure allowed some of the fluid in the reserve pit to seep through the sands of the retaining berm. During the growing season, an area of dead vegetation developed around the toe of the berm along the western edge. Samples were collected to evaluate potential toxicity. Chemical analysis was extremely difficult because of the complex nature of the fluids. Tests indicated that the material had high-oxygen-demand characteristics but was only mildly toxic. Containment within the existing berm was believed to be the best way to solve the problem. The reserve pit was again tested during the summer of 1980, but this examination was only cursory and indicated only limited change. In the early summer of 1981 a full analysis was made to update the record. It was discovered that a number of significant chemical changes had occurred. A radical downward shift in pH was noted, as well as a substantial decrease in organic strength.

FIGURE 2.28.—Sealift in Elson Lagoon, off Point Barrow, waiting for ice to clear for trip eastward, August 1976.

FIGURE 2.29.—Barge being towed in sealift operation off Cape Simpson, August 1980. Photograph by S. Krogstad.

When first examined in June of 1979, the reserve-pit material was found to have a pH of 9.0. During that summer, the pH dropped slowly into the 8.2-8.3 range. The cursory examination in 1980 indicated that the pH remained relatively unchanged. In September of 1981, the pH was found to be 3.3. At that time a program was begun to neutralize the material. Laboratory tests indicated that it was possible to neutralize the fluids with sodium hydroxide (NaOH). Consequently, approximately 2,300 kg (5,000 lb) of solid NaOH was added to the reserve-pit fluid through the ice cover on October 2 and 3, 1981. Plans were made to test the pit during the 1982 season.

CLOSURE OF CAMP LONELY

After the barges had departed from Lonely, the materials to be stored on the camp pad were rearranged and restacked to make the best use of space and minimize the snow-drifting problems. All of the equipment and supplies that had been stored along the road to the summer water-supply lake were brought in and stored either in the warehouse or on the pad. Vehicles and other equipment were shipped to Barrow by C-130 Hercules aircraft. The 87,000-L (23,000-gal) double-walled steel tanks were also moved to Barrow, where the sanding and painting would be completed. Industrial gases, the manlift, and miscellaneous files were backhauled to Anchorage. A new hookup of the runway lights and beacon to the DEW Line electrical system was completed to keep them operational after the Camp

Lonely power plant was closed down.

Camp Lonely was completely shut down on December 5, 1981. The camp was left in excellent condition and well secured. All windows were boarded up, locks secured on all doors and fuel valves, and no-trespassing signs were placed on all doors and on the drill pipe, mud products, and other items stored on the pad. The USGS made arrangements with the DEW Line personnel for periodic surveillance of the camp.

CONSTRUCTION IN THE BARROW GAS FIELDS—WINTER 1981-1982

Modernization and modifications of the gas-field structures continued throughout the winter, although progress was frequently hampered by blowing snow in the period from October through February. Electric power for the East Field was supplied, as of November 1981, by the new generating facility in the South Field. The East Field was started up and was turned over to the gas-field operator in December. Construction continued throughout the spring and included a building over the metering and regulation bypass facility, the installation of instrument panels in both fields, of ratio control valves, and of emergency fuel tanks and generators (on piling) in the East Field.

BURIAL PROGRAM—SPRING 1982

The last major cleanup and burial program was scheduled for the spring of 1982. The contractor used two Cat trains of equipment—the larger one doing the work at Skull Cliff and Peard Bay, and the smaller, more mobile train working briefly at Skull Cliff and then at Brady, Kaolik, and Icy Cape. The Skull Cliff operation was a major one, because the estimated 1,977,000 kg (4,350,000 lb) of debris that had been stockpiled on the beach in hopes of marine removal had to be moved about 1.5 km (1 mi) inland to the burial site. However, despite the size of the task, the work proceeded on schedule.

After the second train departed Skull Cliff for Brady, it encountered some deep snow, but the snow did not nearly reach the depths that had thwarted the efforts to reach Brady a year earlier.

The contractor was in the field, working with both crews at the Skull Cliff site, on March 15. The program was completed and all equipment began moving off the reserve on April 17. Seed and fertilizer were spread before the work crews left the sites.

CAMP LONELY—SPRING 1982

On June 2 the DEW Line personnel, acting as caretakers and watchmen for Camp Lonely, reported that the center section of roof over the recreation area had collapsed. Apparently, a 2-m (6-ft) snow drift had formed on the roof, downwind of the weather observation tower, and the weight of this densely packed snow collapsed the roof. Cleanup of the debris and repair of the roof were completed late that summer to keep the camp weather-tight.

SUMMER OPERATIONS—1982

The revegetation and cleanup crews finished the final cleanup of miscellaneous debris at the recent drill sites during the summer of 1982. During the summer, many abandoned drums, both full and empty, were found along the old Navy trails throughout the reserve. The cleanup crews had concentrated on abandoned wellsites and their immediate vicinity, and the trails had not been surveyed until this year. The number of drums found was a surprise even to those people who had often flown over the reserve; therefore, after the drill sites were given a final policing, attention was turned to cleaning up as many drums as possible. In addition, considerable time was spent in the Barrow and Lonely areas, where work had been going on after freeze-up in the fall of 1981. As usual, the snow had concealed a considerable amount of debris. Cleanup ceased on September 28,

FIGURE 2.30.—Anchoring the sealift barge with a Caterpillar tractor at Camp Lonely, September 1981. Photograph by S. Krogstad.

1982. No one claimed that the NPRA was completely clean, but more than 6,350 t (7,000 tons) of debris had been picked up, burned or consolidated, and buried. The entire area was in much better environmental condition than it was before 1975.

Samples of fluid were again taken from the Inigok reserve pit on June 29, 1982, and the results indicated that the pit had nearly attained stabilization and neutralization. Samples taken around the inside perimeter of the pit yielded pH values of 6.4 and 6.5. Color was pronounced because of the fulvic and humic acids that are naturally occurring polymers—the products of biological degradation. More samples for analysis were taken on September 23, 1982. The pH values measured in three samples were 7.4, 7.6, and 7.6. These compared favorably with the 7.4 and 7.5 measured in the natural lake waters nearby. The conductivity of the pit was still somewhat high (7,600 $\mu\Omega$/cm), but the alkalinity, measured as calcium carbonate, was quite low (120 mg/L). All these measurements were taken when there was a few centimeters (about an inch) of ice on the surface. The differences in the measurements were somewhat surprising, because it was expected that the spring values would decrease as they had the previous season. However, the earlier values represented the pit under well-mixed conditions after a summer of wind, and the June 25 samples were obtained when the fluids were probably still winter stratified.

SUMMARY

The modern exploration program of the National Petroleum Reserve in Alaska was initiated in the spring of 1975 with the drilling of Cape Halkett No. 1 well and continued in the spring of 1976 with the drilling of East Teshekpuk No. 1. The program reached full operational status in the winter of 1976-1977 when five exploratory wells were drilled (South Harrison Bay, Atigaru Point, West Fish Creek, South Simpson, and W.T. Foran), Camp Lonely was enlarged, construction trains were assembled, and overland trails were established. During the program, a total of 28 exploratory wells were drilled—7 under the direction of the U.S. Navy and 21 under the direction of the U.S. Department of the Interior, Geological Survey. In addition, as an adjunct to the exploration program, 10 test wells were drilled in the Barrow gas district, 4 by the Navy and 6 by the USGS. Over the seven-year life of the program, a total of 23,632 km (14,770 line mi) of seismic survey was completed and interpreted.

GEOLOGIC FINDINGS

The NPRA program discovered a natural gas field (Walakpa) about 24 km (15 mi) south of Barrow. The gas found in the Walakpa Test Well No. 1 is in a Lower Cretaceous sandstone reservoir with a gross thickness of about 5.5 m (18 ft) at a depth of about 630 m (2,070 ft). Original gas in place was calculated to be 428,000 ft^3/acre-ft of reservoir, on the basis of an engineering study of drill-stem tests and core-analysis data. The areal extent of this field was not determined, but it may be fairly large. Gas was found in a correlative sandstone in Walakpa Test Well No. 2, located about 6.5 km (4 mi) to the south-southwest of the discovery well. In Well No. 2, the gas-bearing sandstone has a gross thickness of 10 m (32 ft) and is 159 m (523 ft) structurally lower than in Well No. 1. A cased-hole drill-stem test of the sandstone in Well No. 2 gave a maximum flow rate of 2.293 million ft^3/d. However, the test-flow rates were not considered stable because there was evidence that gas hydrates formed in the wellbore during all the flow periods.

Most other exploratory wells drilled during the program found gas shows, and several wells had oil shows. These shows were generally evaluated as they were encountered on the basis of sample analysis, mudlogger gas shows, and cores. When feasible, the better shows were further evaluated with drill-stem tests after electric-log interpretations, if available, had indicated possible reservoir conditions.

The Seabee Test Well No. 1, located near Umiat in the southeastern part of the reserve, tested gas from a thin (net thickness 4.3 m, or 14 ft) Cretaceous sandstone at a depth of 1,636 m (5,366 ft). According to an analysis of the test data by H.J. Gruy and Associates, Inc., the gas reservoir is small and closed, and the total gas originally in place is estimated to be only about 330 million ft^3.

Several gas shows were encountered in Cretaceous rocks in the Tunalik Test Well No. 1, which was drilled in the northwest part of the reserve about 65 km (40 mi) southwest of Wainwright. The most significant show was from an overpressured sequence of interbedded sandstone and shale at depths between 3,825 and 3,840 m (12,550-12,600 ft). This zone required prolonged well-control procedures, which caused barite to plug much of the porosity of the sandstone. Because of the formation damage, a conventional drill-stem test was not attempted; wireline tests to obtain pressures and fluid samples were unsuccessful.

Many gas shows were noted in drilling the Awuna Test Well No. 1, located in the south-central part of the reserve about 243 km (152 mi) south of Barrow. This test of Cretaceous rocks had severe drilling problems, and it did not reach the planned total depth of 4,570 m (15,000 ft). The only drill-stem test, between 2,529 and 2,564 m (8,297-8,412 ft), recovered salty water at the rate of 2,057 bbl/d. This flow was probably from fracture porosity in the tested rocks.

The Inigok No. 1 was a deep exploratory test well in the eastern part of the reserve, about 100 km (60 mi) south of Lonely. The well had numerous small gas shows, but none was tested. At a depth of 5,355 m (17,570 ft) the Inigok well encountered a considerable amount of hydrogen sulfide gas and sulfur while drilling through Mississippian carbonate rocks of the Lisburne Group. This unexpected occurrence of hydrogen sulfide, one of the very few known occurrences on the North Slope, caused a major delay in the drilling of the Inigok well.

In the northeastern part of the reserve, near the coast, most wells had at least some shows of oil and (or) gas. The South Simpson Well No. 1, a U.S. Navy well (1977), recovered small amounts of gas on drill-stem tests of Lower Cretaceous and Jurassic sandstones between depths of 1,770 and 2,002 m (5,807-6,568 ft). The East Simpson Test Well No. 2 flowed formation water at a rate of 24 bbl/h and showed traces of oil and gas from a drill-stem test of Triassic and Permian sandstone between 2,180 and 2,194 m (7,152-7,197 ft). Tests of another Navy well (1977), W.T. Foran No. 1, recovered formation water with a trace of oil from Lower Cretaceous rocks at 2,290-2,292 m (7,512-7,520 ft), slightly gas-cut water from Triassic and Permian rocks at 2,313-2,340 m (7,587-7,676 ft), and some slightly oil-cut water from Pennsylvanian carbonate beds of the Lisburne Group at 2,501-2,525 m (8,206-8,283 ft). In the J.W. Dalton Test Well No. 1, the Lisburne carbonates yielded five bbl of asphalt on one test at 2,618-2,641 m (8,588-8,665 ft) and five bbl of asphalt and water emulsion on another test at 2,585-2,602 m (8,482-8,538 ft). Saltwater was produced on both tests. A test of Triassic and Permian rocks at 2,381-2,481 m (7,812-8,140 ft) in the J.W. Dalton well flowed saltwater, with a light sheen of oil, at a rate of 1,218 bbl/d.

ENVIRONMENTAL REHABILITATION

The 1975-82 exploration program included cleanup work to some degree throughout its seven-year history, the major efforts being in the later years. All of the major wellsites from the 1944-53 Navy exploration program were cleaned up, along with the sites from the recent program. Four abandoned DEW Line intermediate sites were also cleaned up, as well as the Skull Cliff Communication Site, and many of the incidental operational locations such as fuel and explosive caches and seismic and Cat train mechanic's campsites. Combustible debris was burned, and noncombustible debris was collected, consolidated, and buried. The entire reserve was left in much better environmental condition at the end of the program than it was at the beginning.

In the 95,800-km^2 (23,680,000-acre) reserve, an estimated 2.2 km^2 (545 acres) of surface was subjected to more than transient disturbance from the program. This disturbed area can be classified as follows: wellpads, 1.01 km^2 (250 acres); borrow sites, 0.69 km^2 (170 acres); debris burials, 0.064 km^2 (16 acres); roads, 0.016 km^2 (4 acres); and aircraft runways, 0.425 km^2 (105 acres). Revegetation of all disturbed areas, except for the permanent aircraft runways, was attempted. Of the 1.78 km^2 (440 acres) seeded, the vegetation on an estimated 1.6 km^2 (395 acres) was well established at the end of the program. Recovery of the remaining 0.18 km^2 (45 acres), which was mostly coastal sites with high salt content from ocean spray, was taking place at a much slower rate. However, even these sites were rapidly blending with the surroundings.

The exploration program spanned seven years. At the peak of activity, more than 700 Government personnel and industrial contractors and subcontractors were employed. Their work provided the U.S. domestic petroleum industry with a wealth of information about the hydrocarbon potential of the Arctic Slope and the National Petroleum Reserve in Alaska. All of the knowledge gained is now publicly available and helps provide a sound basis for additional exploration in the NPRA and adjacent areas.

REFERENCES CITED AND UNPUBLISHED REPORTS

REFERENCES CITED

Black, R.F., 1954, Permafrost—A review: Geological Society of America Bulletin, v. 65, p. 839-856.

Britton, M.E., 1957, Vegetation of the Arctic tundra, *in* Hasen, H.P., ed., Arctic biology: Corvallis, Oregon State University Press, p. 26-61.

Brooks, A.H., 1906, The geography and geology of Alaska: U.S. Geological Survey Professional Paper 45, 327 p.

Carson, C.E., and Hussey, K.M., 1962, The oriented lakes of Arctic Alaska: Journal of Geology, v. 70, no. 4, p. 417-439.

Croft, Andrew, 1939, Polar exploration: London, Adams and Black, 269 p.

Hultén, Eric, 1968, Flora of Alaska and neighboring territories: Stanford, Calif., Stanford University Press, 1008 p.

Lachenbruch, A.H., 1962, Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost: Geological Society of America Special Paper 70, 69 p.

Leffingwell, E. de K., 1915, Ground-ice wedges, the dominant form of ground-ice on the north coast of Alaska: Journal of Geology, v. 23, no. 7, p. 635-654.

National Oceanic and Atmospheric Administration, 1979: Environmental data service, local climatological data.

Reed, J.C., 1958, Exploration of Naval Petroleum Reserve No. 4 and adjacent areas, northern Alaska, 1944-53, part 1, History of the exploration: U.S. Geological Survey Professional Paper 301, 192 p.

Riverain, Jean, 1966, Concise encyclopedia of explorations: Chicago, Follett, 279 p.

Sage, B.L., 1970, Oil and Alaskan ecology: New York, New Scientists Publications, 137 p.

Schindler, J.F., 1983, Solid waste disposal, National Petroleum Reserve, Alaska, Fourth International Conference on Permafrost, Proceedings: Washington, National Academy Press, p. 1111-1116.

Spencer, Robert, 1959, The north Alaskan Eskimo: Smithsonian Institution, Bureau of American Ethnology Bulletin 171, 490 p.

Stefansson, Vilhjáimur, 1924, The northward course of empire: New York, McMillan, 274 p., 9 pls.

UNPUBLISHED REPORTS OF HUSKY OIL NPR OPERATIONS INC.

Copies of these reports are available for purchase from the National Geophysical and Solar-Terrestrial Data Center, NOAA, Boulder, CO 80303.

HISTORY OF EXPLORATION

Schindler, J.F., 1983, The second exploration, 1975-1982, National Petroleum Reserve in Alaska: Husky Oil NPR Operations, Inc., 89 p.

HISTORY OF DRILLING OPERATIONS

Hewitt, S.L., 1982, East Simpson Test Well No. 2: Husky Oil NPR Operations, Inc., 51 p. and appendix.

——— 1982, East Teshekpuk No. 1: Husky Oil NPR Operations, Inc., 56 p. and appendix.

——— 1982, Inigok Test Well No. 1: Husky Oil NPR Operations, Inc., 170 p. and appendix.

——— 1982, North Kalikpik Test Well No. 1: Husky Oil NPR Operations, Inc., 47 p. and appendix.

——— 1982, South Meade Test Well No. 1: Husky Oil NPR Operations, Inc., 97 p. and appendix.

——— 1982, Walakpa Test Well No. 1: Husky Oil NPR Operations, Inc., 53 p. and appendix.

——— 1982, U.S. Navy, West Fish Creek No. 1: Husky Oil NPR Operations, Inc., 56 p. and appendix.

——— 1983, West Dease Test Well No. 1: Husky Oil NPR Operations, Inc., 10 p. and appendix.

Hewitt, S.L., and Brockway, R.G., 1982, Tulageak Test Well No. 1: Husky Oil NPR Operations, Inc., 36 p. and appendix.

——— 1983, U.S. Navy, Atigaru Point No. 1: Husky Oil NPR Operations, Inc., 50 p. and appendix.

——— 1983, Drew Point Test Well No. 1: Husky Oil NPR Operations, Inc., 60 p. and appendix.

——— 1983, Ikpikpuk Test Well No. 1: Husky Oil NPR Operations, Inc., 124 p. and appendix.

——— 1983, Koluktak Test Well No. 1: Husky Oil NPR Operations, Inc., 36 p. and appendix.

——— 1983, Kuyanak Test Well No. 1: Husky Oil NPR Operations, Inc., 50 p. and appendix.

——— 1983, Lisburne Test Well No. 1: Husky Oil NPR Operations, Inc., 130 p. and appendix.

——— 1983, Seabee Test Well No. 1: Husky Oil NPR Operations, Inc., 134 p. and appendix.

——— 1983, U.S. Navy, South Harrison Bay No. 1: Husky Oil NPR Operations, Inc., 45 p. and appendix.

——— 1983, Tunalik Test Well No. 1: Husky Oil NPR Operations, Inc., 189 p. and appendix.

——— 1983, U.S. Navy, W.T. Foran No. 1: Husky Oil NPR Operations, Inc., 11 p. and appendix.

Hewitt, S.L., and Legg, G.W., 1982, South Barrow Well No. 15 (East Area): Husky Oil NPR Operations, Inc., 43 p. and appendix.

——— 1982, South Barrow Well No. 16 (North Area): Husky Oil NPR Operations, Inc., 34 p. and appendix.

——— 1982, South Barrow Well No. 17 (East Area): Husky Oil NPR Operations, Inc., 51 p. and appendix.

——— 1983, East Simpson Test Well No. 1: Husky Oil NPR Operations, Inc., 56 p. and appendix.

——— 1983, J.W. Dalton Test Well No. 1: Husky Oil NPR Operations, Inc., 83 p. and appendix.

——— 1983, South Barrow Well No. 13: Husky Oil NPR Operations, Inc., 44 p. and appendix.

——— 1983, South Barrow Well No. 14 (East Area): Husky Oil NPR Operations, Inc., 41 p. and appendix.

——— 1983, South Barrow Well No. 18 (East Area): Husky Oil NPR Operations, Inc., 37 p. and appendix.

——— 1983, South Barrow Well No. 19 (East Area): Husky Oil NPR Operations, Inc., 47 p. and appendix.

——— 1983, South Barrow Well No. 20 (East Area): Husky Oil NPR Operations, Inc., 48 p. and appendix.

Hewitt, S.L., Legg, G.W., and Brockway, R.G., 1983, U.S. Navy, South Simpson No. 1: Husky Oil NPR Operations, Inc., 43 p. and appendix.

Hewitt, S.L., and Livingston, C.C., 1982, Kugrua Test Well No. 1: Husky Oil NPR Operations, Inc., 76 p. and appendix.

——— 1982, North Inigok Test Well No. 1: Husky Oil NPR Operations, Inc., 53 p. and appendix.

——— 1982, Peard Test Well No. 1: Husky Oil NPR Operations, Inc., 63 p. and appendix.

——— 1982, Walakpa Test Well No. 2: Husky Oil NPR Operations, Inc., 52 p. and appendix.

Livingston, C.C., and Legg, G.W., 1983, Awuna Test Well No. 1: Husky Oil NPR Operations, Inc., 106 p. and appendix.

GEOLOGIC REPORTS

Brockway, R.G., 1983, Ikpikpuk Test Well No. 1: Husky Oil NPR Operations, Inc., 17 p. and appendix.

——— 1983, South Barrow Well No. 15 (East Area): Husky Oil NPR Operations, Inc., 12 p. and appendix.

——— 1983, South Barrow Well No. 18 (East Area): Husky Oil NPR Operations, Inc., 12 p. and appendix.

——— 1983, South Barrow Well No. 19 (East Area): Husky Oil NPR Operations, Inc., 13 p. and appendix.

——— 1983, U.S. Navy, South Simpson Test Well No. 1: Husky Oil NPR Operations, Inc., 11 p. and appendix.

Brockway, R.G., and Legg, G.W., 1983, Koluktak Test Well No. 1: Husky Oil NPR Operations, Inc., 11 p. and appendix.

——— 1983, South Barrow Well No. 13: Husky Oil NPR Operations, Inc., 10 p. and appendix.

——— 1983, U.S. Navy, South Harrison Bay No. 1: Husky Oil NPR Operations, Inc., 12 p. and appendix.

Geology Department, 1982, Peard Test Well No. 1: Husky Oil NPR Operations, Inc., 18 p. and appendix.

——— 1982, South Meade Test Well No. 1: Husky Oil NPR Operations, Inc., 18 p. and appendix.

Haywood, H., and Brockway, R.G., 1982, West Dease Test Well No. 1: Husky Oil NPR Operations, Inc., 43 p. and appendix.

——— 1983, East Simpson Test Well No. 1: Husky Oil NPR Operations, Inc., 15 p. and appendix.

——— 1983, East Simpson Test Well No. 2:

Husky Oil NPR Operations, Inc., 14 p. and appendix.

——— 1983, Inigok Test Well No. 1: Husky Oil NPR Operations, Inc., 19 p. and appendix.

Haywood, H., and Legg, G.W., 1983, J. W. Dalton Test Well No. 1: Husky Oil NPR Operations, Inc., 11 p. and appendix.

——— 1983, Tunalik Test Well No. 1: Husky Oil NPR Operations, Inc., 18 p. and appendix.

Haywood, H., Legg, G.W., and Brockway, R.G., 1983, Walakpa Test Well No. 1: Husky Oil NPR Operations, Inc., 9 p. and appendix.

Hewitt, S.L., and Legg, G.W., 1983, Drew Point Test Well No. 1: Husky Oil NPR Operations, Inc., 16 p. and appendix.

Legg, G.W., 1983, U.S. Navy, Atigaru Point No. 1: Husky Oil NPR Operations, Inc., 10 p. and appendix.

——— 1983, Awuna Test Well No. 1: Husky Oil NPR Operations, Inc., 10 p. and appendix.

——— 1983, U.S. Navy, East Teshekpuk No. 1: Husky Oil NPR Operations, Inc., 10 p. and appendix.

——— 1983, Kugrua Test Well No. 1: Husky Oil NPR Operations, Inc., 14 p. and appendix.

——— 1983, Lisburne Test Well No. 1: Husky Oil NPR Operations, Inc., 17 p. and appendix.

——— 1983, South Barrow Well No. 14 (East Area): Husky Oil NPR Operations, Inc., 10 p. and appendix.

——— 1983, South Barrow Well No. 16 (North Area): Husky Oil NPR Operations, Inc., 9 p. and appendix.

——— 1983, South Barrow Well No. 17 (East Area): Husky Oil NPR Operations, Inc., 14 p. and appendix.

——— 1983, South Barrow Well No. 20 (East Area): Husky Oil NPR Operations, Inc., 10 p. and appendix.

——— 1983, U.S. Navy, W.T. Foran No. 1: Husky Oil NPR Operations, Inc., 46 p. and appendix.

Legg, G.W., and Brockway, R.G., 1983, North Kalikpik Test Well No. 1: Husky Oil NPR Operations, Inc., 14 p. and appendix.

——— 1983, Seabee Test Well No. 1: Husky Oil NPR Operations, Inc., 16 p. and appendix.

——— 1983, U.S. Navy, West Fish Creek No. 1: Husky Oil NPR Operations, Inc., 13 p. and appendix.

DESIGN AND CONSTRUCTION

Brooks, T.E., 1983, Design and construction of the Awuna wellsite: Husky Oil NPR Operations, Inc., 13 p. and appendix.

——— 1983, Design and construction of the Lisburne wellsite: Husky Oil NPR Operations, Inc., 26 p. and appendix.

——— 1983, Winter drilling pads, 1976-1978: Husky Oil NPR Operations, Inc., 9 p. and appendix.

Mitchell, D.W., 1983, Design and construction of the Inigok wellsite: Husky Oil NPR Operations, Inc., 18 p. and appendix.

——— 1983, Design and construction of the North Inigok wellsite: Husky Oil NPR Operations, Inc., 10 p. and appendix.

——— 1983, Design and construction of the Seabee wellsite: Husky Oil NPR Operations, Inc., 14 p. and appendix.

——— 1983, Design and construction of the Tunalik wellsite: Husky Oil NPR Operations, Inc., 20 p. and appendix.

——— 1983, Design of NPRA winter drilling pads, 1979-1981: Husky Oil NPR Operations, Inc., 9 p.

——— 1983, On-tundra ice airstrips: Husky Oil NPR Operations, Inc., 22 p. and appendix.

Mitchell, D.W., and Brooks, T.E., 1983, NPRA construction cost estimating system: Husky Oil NPR Operations, Inc., 24 p. and appendix.

MISCELLANEOUS REPORTS

Anderson, J.D., DeSpain, C.H., and Schindler, J.F., 1983, Operations, report for transportation and communications for fiscal years 1976-1982: Husky Oil NPR Operations, Inc., 190 p. and appendix.

Lee, C.K., and Schindler, J.F., 1983, Camp Lonely, support services, 1975-1981: Husky Oil NPR Operations, Inc., 32 p. and appendix.

Parsons, L. E., 1982, Communications and engineering: Husky Oil NPR Operations, Inc., 372 p. and appendix.

Schindler, J.F., 1983, Environmental rehabilitation, 1975-1982: Husky Oil NPR Operations, Inc., 31 p. and appendix.

Schindler, J.F., and Mitchell, D.W., 1983, Cost summary of exploratory wells, 1976-1981: Husky Oil NPR Operations, Inc., 112 p.

UNPUBLISHED REPORTS OF TETRA TECH INC.

Copies of these reports are available for purchase from the National Geophysical and Solar-Terrestrial Data Center, NOAA, Boulder, CO 80303.

Bruynzeel, J.W., Guldenzopf, E.C., and Pickard, J.E., 1982, Petroleum exploration of NPRA, 1974-1981, final report: Tetra Tech, Inc., v. 1, 183 p., v. 2, fig. 29-84, v. 3, fig. 85-132, Box 1-5, geophysical maps.

Patterson, S.O., Sullivan, D.A., Trunz, J.P., Jr., Aerthur, S.R., Allard, B.R., Mangus, M.D., and Palenske, A., 1982, Technical services contract, 1981 exploration program, Volume II, Drilling, geological, and geophysical reports: Tetra Tech, Inc.

Patterson, S.O., Sullivan, D.A., Trunz, J.P., Jr., Andrews, J.K., Cox, W.J., Jr., and Miller, N.H., 1982, Technical services contract, 1981 exploration program, Volume I, Interpretation report: Tetra Tech, Inc., 79 p., Box 1-5, geophysical maps.

Tetra Tech, Inc., 1983, Environmental monitoring report, National Petroleum Reserve-Alaska, oil and gas exploration program, fiscal year 1981: 7 sections, 97 p.

——— 1984, Construction monitoring report, National Petroleum Reserve-Alaska, oil and gas exploration program, fiscal year 1981: 5 sections, 97 p.

APPENDIX 2.1—GLOSSARY OF SELECTED TERMS AND ABBREVIATIONS

Arctic Slope. Area north of the drainage divide of the Brooks Range; also known as the North Slope.

ATV. All-terrain vehicle.

Beaver (or **Single-Engine Beaver**). A single-engine turboprop aircraft with STOL (short takeoff or landing) characteristics used to transport passengers and light cargo, often on a ski-wheel configuration. Manufactured by the DeHaviland Corporation of Canada.

BLM. Bureau of Land Management, U.S. Department of the Interior.

Blowdown. Periodic flowing of a well at a high rate to remove the accumulation of dirt, rocks, water, and ice (and oil in a gas well) that tend to reduce the flow.

Bottoms up. Circulation of the drilling mud in a well, with returns to the surface, indicating that the hole is sealed by the mud, thus helping prevent cave-ins.

C-130 (or **Hercules C-130**). A multiengine turboprop aircraft for freight transport manufactured by the Martin Marietta Corporation of Marietta, Georgia.

Calculated depth (or **true vertical depth**). The calculated distance from the surface to the bottom of the hole, taking into consideration the angle of drift from the vertical.

D-8 Cat. A large tractor-type vehicle for support work or hauling heavy loads, manufactured by the Caterpillar Corporation.

Delta. An all-terrain vehicle used to haul freight or heavy loads, manufactured by the Foremost Manufacturing Company, Calgary, Canada. Models include the Delta-3, Delta-Commander, and Delta-Magnum.

DOI. United States Department of the Interior.

Joint. A length of pipe or tubing.

Kelly. A long steel forging that makes the torque connection from the drill rig to the top joint of the drill stem in the drill string.

LCC. Abbreviation for the Camp Lonely Control Center. The staff of the Center was responsible for the coordination of all freight and passenger movements to, from, and within the reserve.

Lowboy. A trailer on tires, built very low to the ground, usually used to transport tracked vehicles or other large equipment.

Measured depth. The depth as indicated by the length of the drill stem or of a wire line lowered to reach the bottom of the hole.

Mobilization. All activity associated with the assembly and moving of equipment and personnel for an operation at a site; sometimes called move-in. Demobilization (or move-out) is all activity associated with withdrawal from a site.

Mouse hole (see also **rat hole**). A second, usually smaller or shallower hole, in addition to a rat hole, used for the temporary placement of tools.

NARL. Naval Arctic Research Laboratory.

NDB. Non-directional beacon—a navigation aid at each airstrip that provides a pulsating radio frequency that aircraft can home in on.

NPRA. National Petroleum Reserve in Alaska; the name given to Naval Petroleum Reserve No. 4 by Public Law 94-258 in 1976 upon the transfer of jurisdiction from the Secretary of the Navy to the Secretary of the Interior.

Open hole. The portion of the well bore without casing.

Perforate. To make holes in the casing (and cement, if present) in a well to allow formation fluids to enter the well bore.

Permafrost. Any naturally occurring material that has been below the freezing point of fresh water (0 °C or 32 °F) for two years or more.

Permeability. A measure of the resistance offered by a rock or other porous material to the movement of fluid through it.

Pet-4 (also **NPR-4** and **NPR No. 4**). Naval Petroleum Reserve No. 4, or the Navy's exploration program in Pet-4 and the adjacent areas; later renamed the NPRA.

Polygons. The surface manifestation of a pattern of ice wedges below the surface. High-center polygons form in areas where surface drainage is present; low-center polygons form in areas of poor surface drainage.

Porosity. Of the total volume of a rock or soil, the percentage of pore space between the mineral grains.

Rat hole. A shallow hole drilled adjacent to a well hole for the temporary placement of certain tools or parts of the drilling-rig equipment during rig operation.

Retrograde. To return or go backwards—here it means to return materials or equipment to their source; from the NPRA it has been usually by barge to Seattle, Washington.

Rig-up and rig-down. General terms used to refer to the assembly and disassembly of the entire drill-rig equipment complex.

Rolligon. An all-terrain vehicle on large balloonlike tires used to transport heavy loads yet causing little damage to the environment.

Sno-cat. An all-terrain vehicle for carrying personnel. Manufactured by the Tucker Corporation in Medford, Oregon.

Spud. The initial boring of the hole at the surface in the drilling of a well.

Stack-out. A term used to refer to the orderly storage of mobile equipment during a period of nonuse.

String shot. An explosive device used to loosen a tool joint for downhole backoff (unscrewing) of a stuck pipe.

Strip check. The inspection and resulting certification of an airstrip by a qualified pilot of the airline planning to use the airstrip.

TD. Usually the target depth of a well; also used to mean the total depth reached.

Twin Otter. A two-engine turboprop aircraft used for personnel and cargo transport. Manufactured by the DeHaviland Corporation of Canada.

USGS. The United States Geological Survey, Department of the Interior.

APPENDIX 2.2—STIPULATIONS CONCERNING WINTER SEISMIC AND RELATED GEOPHYSICAL OPERATIONS WITHIN NAVAL PETROLEUM RESERVE NO. 4

(U.S. Navy, 1975)

[These stipulations were written by the U.S. Navy as guidelines to winter operators and were appended to all contracts issued by the Navy and its contractors. This allowed the Navy to maintain operational and environmental control of all activities on the Naval Petroleum Reserve No. 4.]

The conditions listed below are those which successful bidders will be required to follow in order to minimize damage to the surface of the land, to the surface waters, and to the fish and wildlife on NPR-4.

1. Seismic survey operations are to begin only after the seasonal frost in the tundra and underlying mineral soils has reached a depth of 12 inches, the average snow cover a depth of 6 in. Normally these conditions will not prevail until about 15 October, occasionally not until 1 November.

2. Seismic operations will cease when the spring melt of snow begins, which is approximately 5 May in the foothill areas exceeding 300 ft in elevation, and approximately 15 May in the northern coastal areas.

3. No bulldozing of tundra areas, trails, or seismic lines will be allowed. This stipulation, however, does not prohibit the clearing of drifted snow along a trail or seismic line nor in a camp, if the tundra mat is not disturbed. Also, it does not prohibit the clearing of snow from the surface of lake or river ice in order to prepare an aircraft runway.

4. Camps will be situated on gravel bars, sand, or other stable lands. Where leveling for trailers or modules is required and the surface has a vegetative mat, leveling will be with blocking rather than leveling with a bulldozer.

5. Camps will not be located on frozen lakes or on river ice. Locating camps on river sand or gravel bars is allowed and, where feasible, encouraged.

6. Exploration activities will employ low-ground-pressure vehicles of the rolligon, ARDCO, Trackmaster, Nodwell, or similar type. The limited use of tractors, equipped with wide tracks or "shoes," will be allowed for the ploughing of snow or to pull the camp trailers. Any exceptions to this stipulation will require the written approval of the Officer in Charge, NPR-4.

7. All operations will be conducted with due regard for good resource management and in such a manner as not to block any stream or drainage system, or change the character or course of a stream, or cause the pollution or siltation of any stream or lake.

8. Crossing of waterway courses will be made by using a low-angle approach in order not to disrupt the natural banks of the stream or lake.

9. All operations will be conducted in such a manner as not to cause damage or disturbance to any fish or wildlife resource. This includes, but is not limited to, the following:

a. No seismic shooting or vehicle operations within half a mile of any denning barren ground grizzly (in the upland area) or of any denning polar bear (near the sea coast, in the lower reaches of major rivers, or in the estuaries).

b. No chasing by vehicles or buzzing by aircraft of any wildlife. Particular attention will be paid to the caribou.

c. Shot holes must be a minimum of 300 feet from any designated anadromous stream except where such waters, at the time of seismic shooting, may be frozen to the bottom and the underlying gravels or sands also are frozen. Where required for the completion of critical surveys or tie-ins, variances may be requested (through the Officer in Charge, NPR-4) from the appropriate regulatory authority.

10. No hunting will be allowed within a radius of 5 miles from a geophysical camp, explosives cache, fuel cache, or seismic operation.

11. All oil spills will be reported to the Officer in Charge, NPR-4, at the time of the first solid radio contact or other communication occurring after the incident. Additional fuel handling requirements are:

a. All fuel spills will be cleaned up immediately, taking precedence over all other matters except the health and safety of personnel.

b. Oil spills will be incinerated in approved receptacles but not on lake or river ice.

c. Although fuels may be off-loaded from aircraft on the ice, there will be no storage of fuels on lake or river ice, even on a temporary basis.

12. All fuel containers used, including barrels, must be marked with the contractor's name and date.

13. All combustible solid waste, including seismic cartons, drilling-mud sacks, and used lubricating oils will be incinerated or returned to the base of operations for approved disposal. All noncombustible solid waste, including fuel drums, will be returned to the base of operations for approved disposal. An exception would be incinerated ash which may be deposited in a seismic hole which has vented. There will be no burial of garbage or dozing up of any area for the burial of any matter or thing.

14. All retrievable shot hole wire will be picked up and returned to the base of operations for approved disposal. Records shall be kept of the amount of shot-hole wire used and of the amount returned for disposal.

15. Shot lines will be left clean of all foreign debris. Such debris includes, but is not limited to, shot wire, explosive boxes, and drilling mud sacks.

16. A snow-melter system will be present at each mobile camp to provide potable water at dry camp sites. In addition, a tank or tanks capable of storing 1,000 gallons of potable water for camp use shall be a part of each camp's equipment, together with the necessary hoses, fittings, and water pumps.

17. Waste water will receive treatment conforming to Federal requirements for secondary treatment, if Arctic-tested package-treatment facilities are used. If chemical-recirculating sewage facilities are employed, they will be kept separate from the gray wash water and the kitchen waste water. The chemical effluent may be drained into a shot hole that has vented or into a land-drilled hole. The liquid level should not be less than 5 ft from the surface of the ground and, after freezing, will be filled with cuttings or other clean fill to the surface. Gray wash water and kitchen waste water may be filtered to remove the solids and the liquid discharged to the land surface. All solids and sludges will be incinerated.

18. The contractor will protect all survey monuments, witness corners, and reference monuments against destruction, obliteration, or damage. He will, at his expense, reestablish damaged, destroyed, or obliterated monuments and corners in their exact original position. A record of the reestablishment shall be submitted to the Officer in Charge, NPR-4.

19. The Antiquities Act of June 8, 1906 (34 Stat. 225; 16 U.S.C. 431-433) prohibits the appropriation, excavation, injury, or destruction of any historic or prehistoric ruin or monument, or any other object of antiquity situated on lands owned or controlled by the United States. No historic site, archaeological site, or camp, either active or abandoned, will be disturbed in any manner, nor will any item be removed therefrom. Should such sites be discovered during the course of field operations, the Officer in Charge, NPR-4, will be promptly notified.

20. The contractor will report the location and depths, and enter on the appropriate seismic log, any occurrences of water found in seismic drill holes. Samples will be tested for brine content and, when feasible, a small sample will be taken for delivery to the Officer in Charge, NPR-4.

21. The foregoing provisions do not relieve the contractor or his subcontractors of any responsibilities or provisions required by any applicable laws or regulations.

22. A copy of these stipulations will be posted in a conspicuous place in each camp site established for the purpose of geophysical exploration within NPR-4.

APPENDIX 2.3—STIPULATIONS CONCERNING WINTER ROAD AND TRAIL CONSTRUCTION AND USE WITHIN THE NATIONAL PETROLEUM RESERVE IN ALASKA (U.S. DEPARTMENT OF INTERIOR, GEOLOGICAL SURVEY)

[These stipulations (Appendix 2.3) were written by the U.S. Geological Survey as guidelines to winter operators and were appended to all contracts issued by the Geological Survey and its contractors. This allowed the Geological Survey to maintain operational and environmental control of all activities on the National Petroleum Reserve in Alaska.]

The conditions listed below are those which contractors or subcontractors, at any tier, will be required to follow in order to minimize damage to the surface of the land, to the surface waters, and to the fish and wildlife on the National Petroleum Reserve in Alaska (NPRA).

1. Winter road or trail construction and use, involving heavy equipment, are to begin only after the seasonal frost in the tundra and in the underlying mineral soils over the route has reached a depth of 12 inches, the average snow cover a thickness of 6 inches. Normally this condition will not prevail until about October 15, occasionally not until November 1. These requirements may be modified by the Chief of Operations, ONPRA, for the use of light-weight equipment specialized for use in tundra environments. Such modification, for specific uses, shall be in writing with a copy provided to the contractor or subcontractor and to the Bureau of Land Management.

2. Winter road or trail use, involving heavy equipment, will cease when the daytime spring melt of snow begins approximately May 5 in the foothill areas exceeding 300 feet in elevation, approximately May 15 in the northern coastal areas.

3. No bulldozing of tundra areas for roads or trails will be allowed. This prohibition against the bulldozing of tundra areas includes the organic ridges outlining low-centered polygonal areas. This stipulation, however, does not prohibit the clearing of drifted snow along a trail or road nor in a camp, to the extent that the tundra mat is not disturbed. Also, it does not prohibit the clearing of snow on a lake or on a river ice surface, or on an unvegetated gravel bar or beach, in order to prepare an aircraft runway.

4. Camps used for road construction will be situated on gravel bars, sand, or other stable lands. Where leveling for trailers or modules is required and the surface has a vegetative mat, leveling will be accomplished by blocking rather than by leveling with a bulldozer.

5. Camps may be located on pond or lake ice which is determined to be frozen to the bottom provided that no sewage effluent, filtered waste water, toxic or hazardous materials, petroleum products, or solid wastes are allowed to be dumped onto the ice. Such locations will be specifically approved in writing by the Chief of Operations, ONPRA, with a copy of the approval provided to the contractor or subcontractor and to the Bureau of Land Management.

6. Exploration activities will employ low-

ground-pressure vehicles of the Rolligon, ARDCO, Trackmaster, Nodwell, Flextrac, or similar types. The limited use of tractors, equipped with wide snow tracks, will be allowed for the plowing of snow or to pull heavy camp equipment and drilling rigs. Blades may be used to plow unusually deep snow, but, when used, must be kept sufficiently high so that they do not ''clip'' the tops of tussocks or polygonal ridges. Blade ''shoes'' or similar elevation-guide-type blade attachments are not required. Experience has shown that such ''guides'' concentrate pressures on the tundra and tend to clip off tussock tops, especially in the drier tundra-type areas. Any exceptions to this stipulation, which could result in damage to the tundra, will require the written approval of the Chief of Operations, ONPRA. Should true ice roads be used, their construction shall be sufficiently substantial, for the specific use intended, that there is no breaking through the ice, by wheel or track, to the underlying tundra surface.

7. All operations shall be conducted with due regard for good resource management and in such a manner so as to not block any stream, or drainage system, or change the character or course of a stream, or cause the pollution or siltation of any stream or lake.

8. Crossing of waterway courses shall be made using a low-angle approach in order not to disrupt the natural stream or lake banks. There will be no bulldozing of stream or lake banks.

9. All operations shall be conducted in such a manner as to cause no damage or disturbance to any fish or wildlife resource. This stipulation includes, but is not limited to the following:

a. No vehicle operations within one-half mile of any denning barren ground grizzly (in the upland area) or of any denning polar bear (near the sea coast or in the lower reaches of major rivers, or in the estuaries).

b. No chasing by vehicles or buzzing by aircraft of any wildlife. Particular attention will be given to not disturbing caribou. In this regard, it is assumed, and experience has shown, that small groups of caribou, which habitually hang around airstrips and airstrip approaches, are not unduly disturbed by normal aircraft operation.

c. There will be no feeding of wildlife. Camps will be so managed that no garbage is left uncovered while awaiting incineration.

10. No hunting will be allowed within a radius of 5 miles from a mobile construction camp, fuel cache, drilling operation, or from a road or trail under construction or use.

11. All oil spills will be reported to the Chief of Operations, ONPRA, at the time of the first solid radio contact or other communication occurring after the oil spill incident. The Chief of Operations, ONPRA, will inform the respective agencies having cognizant jurisdiction in such matters. Additional fuel-handling requirements are:

a. All fuel spills will be cleaned up immediately, taking precedence over all other matters, except the health and safety of personnel.

b. Oil spills will be incinerated in approved receptacles but not on lake or river ice.

c. Although fuels may be off-loaded from aircraft on the ice, there will be no storage of fuels on lake or river ice, even on a temporary basis.

12. All fuel containers used, including drums, shall be marked with the contractor's name and date.

13. All combustible solid waste, including cartons, dunnage, drilling-mud sacks, if any, and used lubricating oils, will be incinerated or returned to the base of operations for approved disposal. All noncombustible solid waste, including fuel drums, will be returned to the base of operations for approved disposal. An exception would be incinerated ash which may be deposited as part of a drill ing pad or gravel road. There will be no burial of garbage or the dozing up of any area for the burial of any matter or thing.

14. Waste water from any mobile camp used during road construction will receive treatment conforming to Federal requirements for secondary treatment, if Arctic-tested package-treatment facilities are used. If chemical recirculating sewage facilities are employed, they will be kept separate from the gray wash and kitchen waste water. The chemical effluent will be carried until an approved waste-disposal facility is reached. Gray wash water and kitchen waste water will be filtered to remove the solids and grease after which the liquid may be discharged to the land surface. All solids and sludges will be incinerated.

15. The contractor will protect all survey monuments, witness corners, and reference monuments against destruction, obliteration, or damage. He will, at his expense, reestablish damaged, destroyed, or obliterated monuments and corners in their original exact position. A record of the reestablishment will be submitted to the Chief of Operations, ONPRA, who in turn will inform the respective agencies having cognizant jurisdiction.

16. The Antiquities Act of June 8, 1906, (34 Stat. 225; 16 U.S.C. 431-433), prohibits the appropriation, excavation, injury, or destruction of any historic or prehistoric ruin or monument, or any other object of antiquity, situated on lands owned or controlled by the United States. No historic site, archaeological site, or camp, either active or abandoned, will be disturbed in any manner nor will any item be removed therefrom. Should such sites be discovered during the course of field operations, the Chief of Operations, ONPRA, will be promptly notified. The Chief of Operations, ONPRA, in turn will promptly notify the BLM of such discovery.

17. Should gravel borrow be required for the construction of a winter road or trail, or for any portion thereof, a plan for both the borrow of the gravel and for the subsequent rehabilitation of the borrow area, with a time schedule for the rehabilitation, will be submitted to the Chief of Operations, ONPRA.

18. The foregoing provisions do not relieve the contractor or his subcontractors of any responsibilities or provisions required by any applicable laws or regulations.

19. A copy of these stipulations shall be posted in a conspicuous place in any mobile site established for the purpose of winter road construction and at all base camps within the National Petroleum Reserve in Alaska.

Lisburne No. 1 well, 1979-1980.
Photograph by Charles Mayfield.

Lisburne well site.
Photograph by John Schindler.

View up the tower, Lisburne drilling rig.
Photograph by Charles Mayfield.

Drilling at Inigok No. 1 well, 1978-1979.
Photograph by Jeep Johnson.

Pumping oil at Umiat No. 5 well, 1951.
Photograph by George Gryc.

Barrow well site.
Photograph by Jeep Johnson.

Fish Creek No. 1 well site, summer 1949.
Photograph by George Gryc.

Computer room, Inigok No. 1 well.
Photograph by Jeep Johnson.

RESOURCE ASSESSMENT

The Naval Petroleum Reserves Production Act of 1976 directed the Secretary of the Interior to "*** commence further petroleum exploration of the reserve as of the date of transfer ***" (Section 104d) and also to "establish a task force to conduct a study to determine the values of, and best uses for, the lands contained in the reserve ***" (Section 105c(2)), and it mandated another study (Section 105b) "*** to determine the best overall procedures to be used in the development, production, transportation, and distribution of petroleum resources in the reserve." Satisfying the provisions of these sections required not only an assessment of the petroleum resources, but also an evaluation of alternative management procedures and of the economic and environmental consequences of such procedures.

The methods traditionally used by the U.S. Geological Survey (USGS) for estimating petroleum resources involved volumetric analyses, analogs based on subjective judgments, statistical analyses of drilling histories, or combinations of these. Such methods had long been used in assessing the Nation's resources, but they were difficult to reproduce and did not provide the details required by an economic model.

In our studies of the National Petroleum Reserve in Alaska (NPRA) we needed an assessment method suitable for economic modeling and an exploration strategy suitable for longer range planning. The USGS therefore decided to use the "play" approach, a well-established industry technique. Individual plays were identified, assessed, and then integrated with development and economic submodels using a Monte Carlo simulation. The chapters in this section define and discuss the plays and the methods and procedures used to generate economic models and resource assessments on which to base policy and administrative decisions.

3. COMPARISON OF SIX ASSESSMENTS OF THE HYDROCARBON RESOURCES OF THE NATIONAL PETROLEUM RESERVE IN ALASKA

By KENNETH J. BIRD and RICHARD B. POWERS

INTRODUCTION

During the period 1968-1980, six assessments of the undiscovered petroleum resources in the National Petroleum Reserve in Alaska (NPRA) were commissioned by various U.S. Government agencies (U.S. Department of the Interior, 1979, p. 20). Five of these assessments have already been reported in Government intra-agency or interagency documents; the most recent assessment is referred to by Bird (chapter 4), Miller (chapter 5), and Bugg and others (chapter 6) in this volume.

In this chapter, each of the six assessments is summarized, and the resulting estimates are compared to answer the following questions: (1) How do hydrocarbon resource estimates from the latest assessment, which employs the recently developed U.S. Department of the Interior play-analysis method, compare with the previous estimates? (2) What, if anything, can be learned from this comparison?

Selected for inclusion in this chapter are those Government estimates that were based on systematic analyses of the data and that have been documented in a report. Not included are estimates that appeared in trade journals or in the popular press, such as the 400-billion-barrel estimate reported in the Anchorage *Daily News* (Dec., 1974).

These six assessments all postdate the discovery of the Prudhoe Bay field in 1968 and can be considered an indirect result of that discovery—the largest known hydrocarbon accumulation in North America. Because of the proximity of the NPRA to the Prudhoe Bay field (about 60 mi or 100 km) and the size of the reserve (37,000 mi^2, or nearly half of the North Slope petroleum province), Government interest in the petroleum potential of the reserve was renewed. Initially, only two independent resource estimates were requested—one to be made by the Department of the Interior (U.S. Geological Survey) and the other by the Department of the Navy (Office of Naval Petroleum and Oil Shale Reserves). Government exploration of the reserve resumed in 1974, after a 21-yr hiatus, and legislation of 1975 and 1976 authorized an evaluation and economic analysis of the petroleum potential of the reserve. The other four of the six assessments are the results of this legislation.

This chapter describes each assessment—the assessor, the available data, and the assessment method. The results of the assessments are then summarized, compared, and discussed.

ASSESSMENTS

U.S. GEOLOGICAL SURVEY, 1969

This study was summarized in an unpublished report by A.A. Wanek in 1969 utilizing the data from the 1944-53 Government exploration program of Naval Petroleum Reserve No. 4 (Pet 4), in addition to sketchy geologic details from the Prudhoe Bay discovery.

Two methods were employed. The first was the areal-yield method of Hendricks (1965), in which geologic characteristics are compared with those of certain areas in the conterminous United States—areas that have been divided into four general categories according to relative hydrocarbon yield. Each of these categories carries a value for average petroleum yield per 1,000 mi^2 of surface area. The reserve was judged by this method to have a petroleum potential between category 2 (the midcontinent region) and category 3 (the Rocky Mountains region). The values for the two categories are shown below, but they are not included in the summary (table 3.1) or plots (fig. 3.1) because the estimate is not specific, whereas the second method (described below) deals more directly with the data and yields a specific estimate.

Estimated recoverable petroleum resources in the NPRA (Hendricks method)

	Oil and Natural Gas Liquids (billion bbl)	Gas (trillion ft^3)
Category 2	10.7	55
Category 3	2.7	9.3

The second method, a volumetric yield method, incorporated the available geologic data from the Arctic Foothills and Arctic Coastal Plain physiographic provinces but not from the Brooks Range province, an area considered unfavorable for petroleum because of its complex structure (for location of these physiographic provinces, see Kirschner and Rycerski, chapter 9, fig. 9.1). For the provinces considered, data were analyzed for each of six major

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stratigraphic intervals. By this method, estimates of undiscovered recoverable hydrocarbon resources (table 3.1, fig. 3.1) are the product of the following five variables: (1) the area of the reservoir rock, (2) the average thickness of the reservoir rock, (3) the volume of hydrocarbons in the reservoir rock, (4) the percentage of the hydrocarbons that are recoverable, and (5) the percentage of the area that is potentially productive. In table 3.1 the estimated volume of oil includes natural-gas liquids, and the estimated volume of natural gas results from calculations at an assumed reservoir pressure of 3.45 MPa (500 psi).

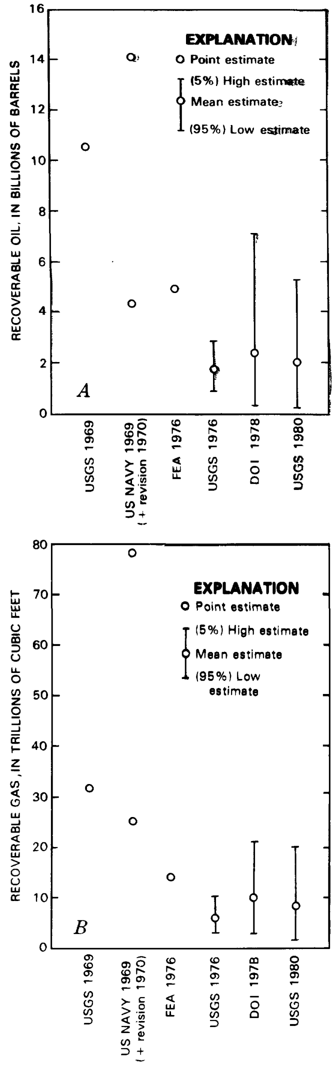

FIGURE 3.1.—Comparison of selected estimates of oil and gas resources in the NPRA. *A*, Undiscovered recoverable oil. *B*, Undiscovered recoverable gas.

DEPARTMENT OF THE NAVY, 1969

This assessment, commissioned by the U.S. Navy, was conducted by J.C. Reed (1969) and published by the Arctic Institute of North America. New data for the study consisted of a set of maps compiled by the USGS that summarized geologic data for eight rock divisions. These maps were used extensively, and each of the rock divisions was assessed by the same volumetric method employed in the 1969 USGS assessment. As in that assessment, the Brooks Range was excluded. This Navy assessment generated two sets of estimates of undiscovered recoverable resources—an initial set presented in the 1969 Reed report and a revised set issued informally the following year. Both sets are included in table 3.1 and figure 3.1.

FEDERAL ENERGY ADMINISTRATION, 1976

This project was undertaken by a committee of scientists from Resource Planning Associates, Inc., under contract to the Federal Energy Administration (Resource Planning Associates, 1976). New data, all from the northern and eastern areas of the reserve, were obtained from the renewed Government exploration program, which included two new wells, 3,500 line-miles of interpreted seismic data, and a set of maps showing prospect size and vertical closure. In addition, information was available from industry wells drilled adjacent to the reserve and from the Prudhoe Bay field.

A modification of the volumetric method of Jones (1975) was employed for the assessment. This modification, like the original method, utilizes the identified structures as the basic units of the assessment. By this method, estimates of undiscovered recoverable hydrocarbon resources are the product of the following four variables: (1) the volume of rock in the structures, (2) the fraction of the structures considered as net pay, (3) the fraction of the reservoir volume containing petroleum, and (4) the hydrocarbon recovery factor. The rocks in the reserve with petroleum prospects were divided into five stratigraphic intervals, each assessed separately. For the first time, the Brooks Range was included in the assessment. Extrapolation was necessary to include those areas of the reserve not covered by seismic surveys, and additional resources were estimated for potential stratigraphic traps.

This study produced single-value (point) estimates for oil and for gas as shown in table 3.1 and in figure 3.1.

U.S. GEOLOGICAL SURVEY, 1976

This assessment, summarized in an unpublished 1976 administrative report by R.B. Powers, was conducted by a committee of six USGS scientists who were familiar with both North Slope geology and resource appraisal methods. The available data consisted of the Pet-4 program data, information from the Prudhoe region, and a limited amount of information from the reactivated Government exploration program.

The delphi method of assessment was employed. As described by White and Gehman (1979, p. 2185), this procedure is named after the ancient Grecian oracle, but experts replace the priestesses and proph-

TABLE 3.1.—*Summary of six Government-commissioned petroleum reserve appraisals of the National Petroleum Reserve in Alaska*

Year	Agency	Method	Estimated recoverable hydrocarbon resources							
			Oil (billion bbl)				Gas (trillion ft^3)			
			95 percent	5 percent	Mean	Point	95 percent	5 percent	Mean	Point
1969	U.S. Geological Survey	Volumetric	-	-	-	10.7	-	-	-	31.9
1969	Department of the Navy	Volumetric	-	-	-	4.5	-	-	-	25.3
1970	Department of the Navy (revision of 1969 appraisal)	Volumetric	-	-	-	14.3	-	-	-	78.7
1976	Federal Energy Administration	Volumetric	-	-	-	5.0	-	-	-	14.3
1976	U.S. Geological Survey	Delphi	1.0	3.0	1.9	-	3.2	10.6	6.3	-
1978	Department of the Interior	Play analysis	.4	7.2	2.5	-	3.2	21.5	10.3	-
1980	U.S. Geological Survey	Play analysis	.3	5.4	2.1	-	1.8	20.4	8.5	-

ets. The delphi approach takes the average of several expert opinions of the probability distribution of potential resources. This is a method extensively used by the USGS to assess the Nation's resources (Miller and others, 1975; Dolton and others, 1981). For the assessment, the reserve was divided into three physiographic provinces (coastal plain, northern foothills, and southern foothills-Brooks Range). Each committee member estimated the following three values for recoverable gas and recoverable oil in each province: low resources (95 percent probability of being exceeded), high resources (5 percent probability of being exceeded), and most likely resources. After group review and some modification of individual estimates, single sets of these three values—the committee consensus—were obtained. Monte Carlo procedures were then used to aggregate the province estimates to a single set of estimates for the entire reserve. The estimates selected for inclusion in table 3.1 are the 95-percent, 5-percent, and mean values. The mean value is the mean of the derived probability distribution and differs from the most likely estimate, a model value.

DEPARTMENT OF THE INTERIOR, 1978

A committee of scientists from Tetra Tech, Inc., under contract to the U.S. Department of the Interior, conducted this assessment using new data from 9,700 line-miles of seismic surveys, 10 wells, and some preliminary source-rock chemical analyses.

A newly developed play-analysis method was employed in this assessment. In this method geologic parameters are analysed and evaluated, and a computer program generates the estimates. These estimates are reported as full probability distributions of undiscovered, in-place hydrocarbons. However, only the 95-percent, 5-percent, and mean values are shown below.

Estimated in-place hydrocarbon resources for NPRA by play-analysis method—U.S. Department of the Interior, 1978

	95 percent	5 percent	Mean
Oil (billion bbl)	1.1	20.5	7.0
Gas (trillion ft^3)	4.2	28.7	13.7

For comparison with other assessments, the in-place values of this and the 1980 USGS assessment were converted to recoverable values (table 3.1). This conversion was made by utilizing recovery factors of 35 percent for oil and 75 percent for gas (Office of Minerals Policy and Research Analysis, written commun., 1980).

U.S. GEOLOGICAL SURVEY, 1980

This assessment was made by a group of USGS scientists, most of whom had participated in the 1976 assessment. New data consisted of 22 wells, 11,500 line-miles of seismic surveys, numerous new geologic summaries and interpretations, and, for the first time, a comprehensive set of source-rock geochemical analyses.

The play-analysis method was again employed. Compared to the 1978 Tetra Tech assessment, which used the same method, this assessment involved fewer plays, and the plays were defined differently. In addition, the computer program had been modified between the 1978 and 1980 assessments.

Four separate appraisals were carried out over a two-year period, concurrent with the exploration program; however, only the results of the latest (May 1980) assessment are reported here.

Estimated in-place hydrocarbon resources for NPRA by play-analysis method—U.S. Geological Survey, 1980

	95 percent	5 percent	Mean
Oil (billion bbl)	0.8	15.4	6.0
Gas (trillion ft^3)	2.4	27.2	11.3

Conversion from in-place resources to estimated recoverable resources was made in the same manner as for the 1978 Department of the Interior assessment. These converted values are shown in table 3.1 and figure 3.1.

RESULTS

Six Government-sponsored resource appraisals conducted during the period 1968-80 are summarized in table 3.1 and compared graphically in figure 3.1. The earlier three appraisals are single-value (point) estimates based on areal and volumetric methods. The other three are estimates expressed as full probability distributions obtained by delphi or play-analysis methods.

The comparative plots (fig. 3.1) show a marked and generally progressive decrease in estimates from 1969 to 1980. However, the reader is cautioned against comparing these estimates because they are not strictly comparable. As already noted, different hydrocarbon recovery factors were employed. In addition, plays were defined differently for each of the two play-analysis assessments, and the computer program had been modified between assessments. Finally, fundamental to the problem of comparison is this question: At what point within a range can, or should, a single-value estimate be placed? The answer usually reflects the degree of optimism or pessimism of the single-value estimator, but this is a factor not provided for in subjective assessment procedures.

CONCLUSIONS

Conducted during a time characterized by ever-increasing amounts of new data and correspondingly more sophisticated assessment methods, the six NPRA hydrocarbon resource estimates demonstrate a downward trend. This trend appears to reflect the dynamic nature of resource assessment in response to changes in data, methods used, and appraisal personnel.

When new data are scarce or inconclusive, subjective factors can greatly influence the outcome of a study. Such influence seems to be illustrated in the first four of these six assessments. These four assessments were conducted with the realization that the hydrocarbon-producing formations at the Prudhoe Bay field were present in the reserve, but the assessments were completed with no significant new data on the rocks in the reserve. Influenced by the supergiant Prudhoe Bay discovery, these earlier assessments were unduly optimistic. However, in the USGS assessment of 1976, this optimism was tempered by the results of a simple analysis of regional relationships, subsequently reported by Carter and others (1977a, b), which indicated little chance for the combination of structural and stratigraphic features in the reserve that would produce hydrocarbon accumulations like those at Prudhoe Bay. The last two of the six assessments were based on significant new data from an exploration program which was specifically focused on evaluation of these formations. The evaluation results confirmed the earlier 1976 USGS pessimism for Prudhoe Bay-type accumulations in the reserve.

REFERENCES CITED

Carter, R.D., Mull, C.G., and Bird, K.J., 1977a, Any Prudhoe Bays in Naval Petroleum Reserve No. 4?, *in* Blean, K.M., ed., The United States Geological Survey in Alaska—accomplishments during 1976: U.S. Geological Survey Circular 751-B, p. B14-B15.

Carter, R.D., Mull, C.G., Bird, K.J., and Powers, R.B., 1977b, The petroleum geology and hydrocarbon potential of Naval Petroleum Reserve No. 4, North Slope, Alaska: U.S. Geological Survey Open-File Report 77-475, 61 p.

Dolton, G.L., Carlson, K.H., Charpentier, R.R., Coury, A.B., Crovelli, R.A., Frezon, S.E., Khan, A.S., Lister, J.H., McMullin, R.H., Pike, R.S., Powers, R.B., Scott, E.W., and Varnes, K.L., 1981, Estimates of undiscovered conventional resources of oil and gas in the United States: U.S. Geological Survey Circular 860, 87 p.

Hendricks, T.A., 1965, Resources of oil, gas, and natural gas liquids in the United States and the world: U.S. Geological Survey Circular 572, 20 p.

Jones, R.W., 1975, A quantitative geologic approach to the prediction of petroleum resources, *in* Haun, J.D., ed., Methods of estimating the volume of undiscovered oil and gas resources: American Association of Petroleum Geologists Studies in Geology 1, p. 186-195.

Miller, B.M., Thomsen, H.L., Dolton, G.L., Coury, A.B., Hendricks, T.A., Lennartz, F.E., Powers, R.B., Sable, E.G., and Varnes, K.L., 1975, Geological estimates of undiscovered recoverable oil and gas resources in the United States: U.S. Geological Survey Circular 725, 78 p.

Reed, J.C., 1969, Oil and gas values in Naval Petroleum Reserve No. 4: report prepared for Arctic Institute of North America, 30 p.

Resource Planning Associates, 1976, The exploration, development, and production of Naval Petroleum Reserve No. 4: report prepared for Federal Energy Administration, 2 v.

U.S. Department of the Interior, Office of Minerals Policy and Research Analysis, 1979, Final report of the 105(b) economic and policy analysis: Alternative overall procedures for the exploration, development, production, transportation and distribution of the petroleum resources of the National Petroleum Reserve in Alaska (NPRA): Washington, U.S. Government Printing Office, 145 p.

White, D.A., and Gehman, H.M., 1979, Methods of estimating oil and gas resources: American Association of Petroleum Geologists Bulletin, v. 63, no. 12, p. 2183-2192.

4. THE GEOLOGIC BASIS FOR APPRAISING UNDISCOVERED HYDROCARBON RESOURCES IN THE NATIONAL PETROLEUM RESERVE OF ALASKA BY THE PLAY-APPRAISAL METHOD

By KENNETH J. BIRD

INTRODUCTION

The Naval Petroleum Reserves Production Act of 1976 provided for a Government study to determine the best general procedure for the development, production, transportation, and distribution of the hydrocarbon resources in the National Petroleum Reserve in Alaska (NPRA). An essential and distinguishing feature of this study was the development of a resource-appraisal method that would furnish the estimates of undiscovered oil and gas resources in a form compatible with the sophisticated computer model demanded by the economic and policy-analysis portion of the study.

Existing resource-appraisal methods, reviewed by Bugg and others (chapter 6), failed to meet these demands. Therefore, a new method was developed—the play-analysis method—based on the resource-appraisal method of the Geological Survey of Canada (Roy and others, 1975; Canada Department of Energy, Mines, and Resources, 1977). The new play-analysis method was developed by the Office of Minerals Policy and Research Analysis, U.S. Department of the Interior, utilizing as contractors the Aerospace Corp. and Tetra Tech, Inc. As the method was developed, it was monitored and periodically reviewed by the U.S. Geological Survey (USGS). Although the method defines the term "play" rather broadly—one or more prospects in a fairly homogeneous setting—in practice all the plays assessed in the NPRA are stratigraphic intervals except for the structural play in the disturbed belt.

This appraisal represents the first use of the newly developed play method and is the latest in a series of hydrocarbon-resource appraisals of the NPRA (see Bird and Powers, chapter 3). As the most recent of the series, it is based on a larger number of data.

In the NPRA, the play method was first used by the USGS in November 1979. At intervals averaging 6 months, as new information was gained from the ongoing drilling program, the original assessment was reviewed and updated. Miller (chapter 5) provides a brief narrative of each assessment meeting, as well as the estimates of total NPRA resources that resulted from each meeting. This chapter gives the estimated resources for each play on the basis of the last update (May 1980).

By the time of the final update of the NPRA appraisal, the play method was being employed in another Government resource assessment, this time in the Arctic National Wildlife Refuge. That appraisal was documented by Mast and others (1980).

Other publications describing the use of the play method include those by Bird (1981), Miller (1981, 1982), and White (1981). The final report on the NPRA economic and policy study as required in the Act has also been published (U.S. Department of the Interior, 1979).

Three chapters in this volume pertain to the NPRA appraisal and the ensuing economic and policy study: This chapter presents the geologic basis for the resource appraisal; the chapter by Miller (chapter 5) explains the assessment procedures and the details of the computer model that generates the resource estimates; and the chapter by Bugg and others (chapter 6) provides background information on the analytic approach itself and describes the methods used in the economic and policy study.

This chapter was prepared to document the petroleum geology for each assessed play and thus serve as a basis for further assessments. In addition, it provides information about the assessment personnel, the data base, and analogous formations; for each play, it includes a petroleum geology summary, an outline map, a completed assessment form, and resource estimates. A glossary of terms used in the assessment may be found at the end of this chapter.

ASSESSMENT PERSONNEL

Two committees of ten scientists were appointed by the USGS to make this resource assessment. The Geologic Assessment Committee[1] met to review the geology, evaluation methods, and terms; they then defined the plays and assessed the

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Manuscript received for publication on April 21, 1983.

[1] Geologic Assessment Committee: K.J. Bird (chairman), W.P. Brosgé, J.K. Kienzle, L.B. Magoon, C.G. Mull, R.B. Powers, E.W. Scott.

play parameters. The Resource Appraisal Review Committee[2] met to consider the assessments made by the Geologic Assessment Committee, and they changed the assessed parameters or definitions as deemed necessary.

Representatives from the Office of Minerals Policy and Research Analysis, U.S. Department of the Interior[3], who had developed the play and economic evaluation program, were available to the committee members for consultation. They also entered the geologic information into the computer play by play as it was made available by the committees. Thus, processing of the data was immediate, and the resource appraisals were generated on the spot.

Although this was the first authorized play-method assessment by USGS scientists, 7 of the 10 committee members had had some previous experience with this method of appraisal: As members of the Geological Survey Review Committee, they had been responsible for monitoring the development of the method by the U.S. Department of the Interior (in cooperation with a private contractor). Two of the committee members were also experienced in the evaluation procedures for leases on the Outer Continental Shelf—a method similar to the play method—used by the Minerals Management Service.

At the time of the assessment in May 1980, the committee members possessed in aggregate approximately 60 man-years of North Slope geologic experience and more than 100 man-years of oil industry experience. Most committee members had also been involved with the direct assessments of U.S. petroleum resources (Miller and others, 1975; Dolton and others, 1981).

The knowledge and experience of noncommittee scientists were actively sought and utilized to ensure that the most recent data and interpretations were incorporated into the assessments.

DATA BASE

Resource appraisals are conspicuously time dependent; results change as data accumulate and (or) methods are modified. Three updates of the original November 1978 appraisal were made at approximately 6-month intervals. However, each data sheet was revised only when new data required modification of our geologic estimates, and so the latest update recorded on a data sheet might date from any previous assessment meeting. The regular updates reflected our recognition of the dynamic nature of resource appraisals, the necessity to test and refine the newly developed play method, and the requirement that we incorporate into the project the great amount of new information being obtained from the active exploration program. The varied results of the four appraisals, as given by Miller (chapter 5), validated our decision to employ these updates.

The data base at the time of the initial November 1978 appraisal consisted of: (1) geologic and geophysical data from the Pet-4 program (summarized or referenced by Collins and Robinson, 1967; Brosgé and Tailleur, 1971; and Carter and others, 1977); (2) data from the adjacent Prudhoe Bay region (summarized or referenced by Tailleur and others, 1978); and (3) newly gathered information on the NPRA from 11,207 line-miles of reflection seismic surveys and 16 new exploratory wells.

During each winter season after the initial assessment, 1,000 or more line-miles of seismic-reflection data were acquired, and several new wells were drilled. The analysis and synthesis of these basic data were provided by the USGS and contractor personnel.

At the time of the last assessment update (May 1980), the data base had increased to 14,189 line-miles of seismic-reflection data and 22 exploratory wells. Information from each well includes a complete suite of modern wireline logs, lithologic descriptions, porosity and permeability measurements, petrographic descriptions (see Bartsch-Winkler and Huffman, chapter 35; van de Kamp, chapter 36), a systematic analysis of the micropaleontology (Witmer and others, 1981), and the organic geochemistry (see Magoon and Bird, chapter 17; Baylis and Magoon, chapter 20; Magoon and Claypool, chapter 21). Preliminary results were available from new geologic field studies of the Cretaceous rocks (Ahlbrandt, 1979) and from surveys designed to detect leaking hydrocarbons—a helium survey by Roberts and Cunningham (chapter 24) and a low-level aeromagnetic survey by Donovan and others (chapter 26). The seismic data were summarized in a series of isopach and structure-contour maps. Gravity and conventional aeromagnetic data were also available, but they were of limited usefulness because other, more definitive data, such as seismic data, were available.

A set of maps was maintained for each play and consisted of (1) a structure-contour map, (2) an isopach map, (3) a net reservoir-thickness map, (4) an isoporosity map, (5) a source-rock map, and (6) a migration-path map. These maps, originally compiled by a contractor (Tetra Tech, Inc.) for the U.S. Department of the Interior, were modified as new data became available.

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[2] Resource Appraisal Review Committee: B.M. Miller (chairman), K.J. Bird, G.L. Dolton, J.K. Kienzle, R.H. McMullin, C.G. Mull, R.B. Powers, E.W. Scott.

[3] Office of Minerals Policy and Research Analysis: Roger Anderson, Paul Bugg, Stanley Miller, Tod Huffman, L.P. White.

TABLE 4.1.—*Reservoir rock units in the NPRA and suggested analogs in other areas*

[References: 1, Lane and Jackson (1980); 2, Mills (1968); 3, Barlow and Haun (1966); 4, McCubbin and Brady (1969); 5, Asquith (1970); 6, Exxon Alaska State A-1 well; 7, MacPherson (1978); 8, Berg and Powers (1981); 9, Berg and Tedford (1978); 10, Williamson (1980); 11, Detterman and others (1975); 12, Newman and others (1977); 13, Jamison and others (1980); 14, McIntosh (1977); 15, McCoy and Moritz (1982); 16, Sabins (1972); 17, Carman and Hardwick (1982); 18, Jones and Speers (1976); 19, Oil and Gas Journal (1981); 20, Eckelmann and others (1976); 21, Bird and Jordan (1977); 22, Kerns and Traut (1979); 23, Asquith (1979); 24, Harris and others (1966); 25, Bradley (1975); 26, Williams (1982); 27, Kirschner and Lyon (1973); 28, Magoon and Claypool (1981). Do., ditto]

NPRA rock unit	Analog				
	Rock unit	Basin	Region	Oil or gas fields	References
Colville and Nanushuk Groups.	Upper Cretaceous and Tertiary sandstones.	Beaufort-MacKenzie Basin.	Canada	Adgo	1
	Cardium Sandstone	Alberta Basin	do	Pembina	2
	Frontier Sandstone	Powder River Basin	Wyoming	Salt Creek	3
	Almond Formation	Washakie and Great Divide Basins.	do	Patrick Draw	4, 5
Torok and Fortress Mountain Formations.	Tertiary deep-marine sandstones.	North Slope	Alaska	Flaxman Island	6
	Stevens Sandstone	San Joaquin Valley	California	Ten Section	7
	Hackberry Sandstone	Gulf Coast	Louisiana	Hildebrandt Bayou	8
	Wilcox sandstones of local usage, Gulf Coast (deep part), Texas.	do	Texas	Northeast Thompsonville.	9
	Bell Canyon Formation	Delaware Basin	Texas and New Mexico.	More than 100	10
Sandstone of the pebble shale unit.	Thomson sand	North Slope	Alaska	Point Thompson	11, 12
	Put River Sandstone	do	do	Prudhoe Bay	13, 14
	Cretaceous sandstones	Alberta Basin	Canada	Countess	15
	Tocito Sandstone Lentil of the Mancos Shale.	San Juan Basin	New Mexico	Bisti and Horseshoe Canyon.	16
Sandstone of the Kingak Shale and Sag River Sandstone.	Kuparuk River Formation	North Slope	Alaska	Kuparuk River	13, 17
	Sag River Formation	do	do	Prudhoe Bay	18
	Lower Cretaceous glauconitic sandstones..	Alberta Basin	Canada	Hoadley	19
Sadlerochit Group	Sadlerochit Group	North Slope	Alaska	Prudhoe Bay	18, 20
Lisburne Group	Lisburne Group	do	do	do	13, 21
	Mission Canyon Formation	Williston Basin	Montana and North Dakota.	Mondak and Truro	22, 23, 24
	Leadville Limestone	Paradox Basin	Utah	Lisbon	25
Endicott Group	Endicott Group	North Slope	Alaska	Endicott	26
	Tertiary sandstones	Cook Inlet Basin	do	Swanson River	27, 28

Unpublished information on trap fill for western Canadian oil and gas fields was generously provided by the Canadian Geological Survey. Trap fill is one of the assessed hydrocarbon volume parameters for which there are few North Slope data. When the Canadian trap-fill information was incorporated into analogous NPRA plays in the last assessment, the resulting resource estimates were lower because our earlier trap-fill estimates had been optimistic.

The NPRA exploration program has continued since May 1980, and an additional 5 wells and 581 line-miles of seismic data have been added to the data base. Analysis, synthesis, and interpretation of these data continue to be done by USGS and contractor personnel, but the information has not been included in the assessment.

ANALOGS

When information is limited, a basin or play may be more confidently assessed through the use of analogs. At the November 1978 assessment meeting, the Geologic Assessment Committee compiled a list of hydrocarbon-producing formations that could serve as analogs for rock units assessed in the NPRA. This list of NPRA rock units and their suggested analogs, updated and with references added, is given in table 4.1. Except for North Slope analogs, which were used extensively, the assessment schedule did not allow time to gather and synthesize data for the analogs.

PLAYS

A "play" is defined as one or more prospects with similar or related geologic characteristics. By definition, therefore, a play may be established in several different ways (see Miller, chapter 5). In this assessment of the NPRA, plays were defined for each stratigraphic interval considered to be a potential hydrocarbon reservoir; if the data warranted, more than one play was created within a single interval. Establishing the plays in this manner greatly facilitated assessment of the geologic parameters.

A total of 17 plays were identified and assessed; 16 were named for the reservoir rock unit and the geographic area, and 1 for the tectonic characteristics. One new play (Tunalik) was added after the original (November 1978) assessment. These plays are shown in relation to the generalized stratigraphy of the NPRA in figure 4.1. Of the 17 plays, 9 are in Ellesmerian sedimentary rocks derived from a northern source (Lerand, 1973); 7 are in Brookian sedimentary rocks derived from a southern source; and 1, the Disturbed belt play, is a tectonic unit composed of structurally deformed sedimentary rocks of both northern and southern derivation. For each play, the following section gives a map, a summary of the petroleum geology, the assessment parameters, and the resource estimates.

The objective of the program was to assess the oil and gas resources of the entire NPRA. The strategy followed was first to identify all plays and then to test, by drilling, at least one prospect (that is, potential hydrocarbon accumulation) within each play. Drilling is required to gain information on reservoir characteristics under actual trap conditions, on the mode and history of entrapment, and on the distribution and characteristics of oil and gas accumulations. In our analysis of plays and in the prospects tested, we included the results from the earlier government program (Pet-4). The information is summarized in figure 4.2. It shows that the Pet-4 program wells tested prospects predominantly in plays in the Brookian sequence, whereas the subsequent wells in the NPRA program concentrated on plays in the Ellesmerian sequence. This figure also shows that most plays have been tested in at least one prospect. By using the data available to us, we were unable to identify any prospects worthy of drilling for 2 of the 17 plays (Colville I and Tunalik), even though gas was penetrated in the Tunalik play. The locations of the wells listed in figure 4.2 are shown in figure 4.3.

An ideal appraisal would predict location as well as quantity of hydrocarbons. For predicting location, the play method is less precise than the prospect-evaluation method, in which each and every prospect is assessed, because in the play method not all the prospects are known, and the resources are simply assumed to be located some-

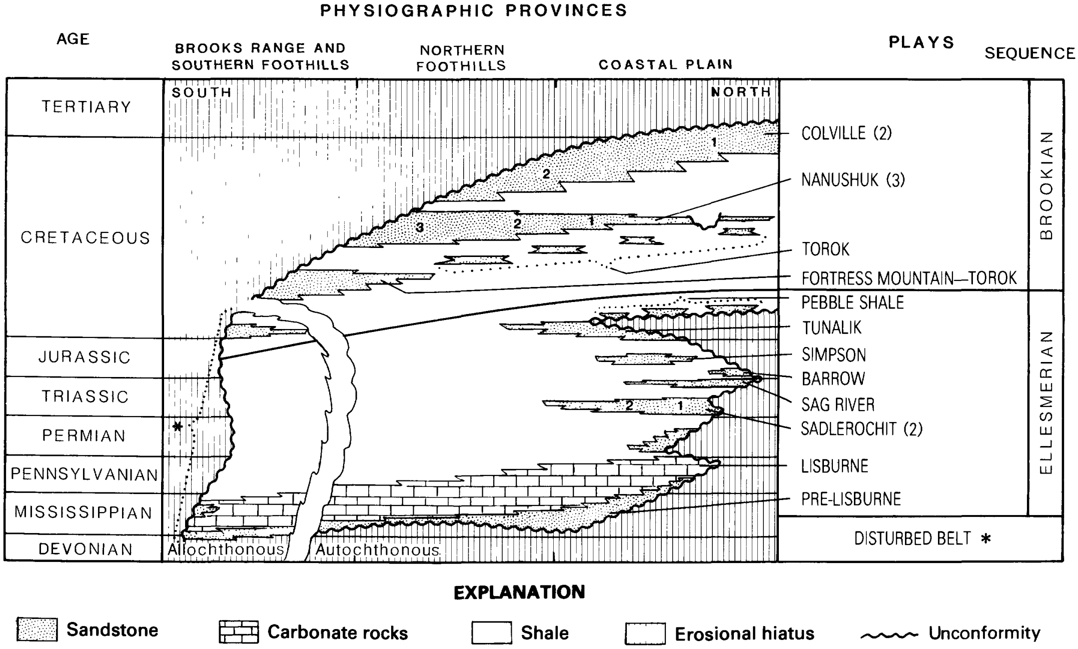


FIGURE 4.1.—Assessed plays in relation to generalized stratigraphy in the NPRA. Numbers refer to different plays within the same stratigraphic unit.

where within the defined plays. In this assessment, an effort was made to improve the predictability of hydrocarbon location by the play method. Accordingly, after assessing each play, the Geologic Assessment Committee then judged the geographic distribution of hydrocarbons within each play area. If hydrocarbons were thought to be unevenly distributed, this was indicated by partitioning the play into two or more areas, giving an estimate of the percentage of resources thought likely to be present in each area. Partitions and percentages are shown on the play maps (figs. 4.4–4.20). Partitions of plays should not be confused with activity areas, those 15 land blocks arbitrarily established by the Office of Minerals Policy and Research Analysis 105(b) study team to facilitate the economic analysis of the NPRA (see Bugg and others, chapter 6; U.S. Department of the Interior, 1979).

PLAY DESCRIPTIONS AND ASSESSMENTS

COLVILLE PLAYS

The Colville plays, in sandstone reservoirs of Late Cretaceous and Tertiary age having stratigraphic and structural traps, are in the Colville Group and Sagavanirktok Formation. The Colville Group conformably overlies the Nanushuk Group. These rocks, which are present only in the east third of the NPRA, consist of marine to nonmarine shale, sandstone, conglomerate, and coal. They have a maximum thickness in the NPRA of 1,500 m (5,000 ft) along the east edge of the reserve (see Bird, chapter 16) and thin westward to 0 at an erosional edge that forms the west play boundary. Colville play I is distinguished from play II by its absence of structural traps. Their common boundary marks the north limit of anticlinal folds (figs. 4.4, 4.5).

Reservoir rocks—sandstone and conglomerate—may total several hundred feet in thickness, but few individual beds exceed 15 m (50 ft). Marked facies changes over short distances are expected. Porosity is expected to range generally from 4 to 25 percent but to reach 35 percent locally. Sandstone in the lower part of the Colville Group, unlike most other North Slope sandstone, is rich in volcanic-rock fragments and pore-plugging clay (Fox and others, 1979).

Potential source rocks include coal and marine shale. Limited geochemical data (Magoon and Claypool, 1979) indicate that these rocks are immature, average about 1.0 weight percent organic carbon, and are gas prone. East of the NPRA, the equivalent marine shale is expected to increase in thickness and organic content and to become

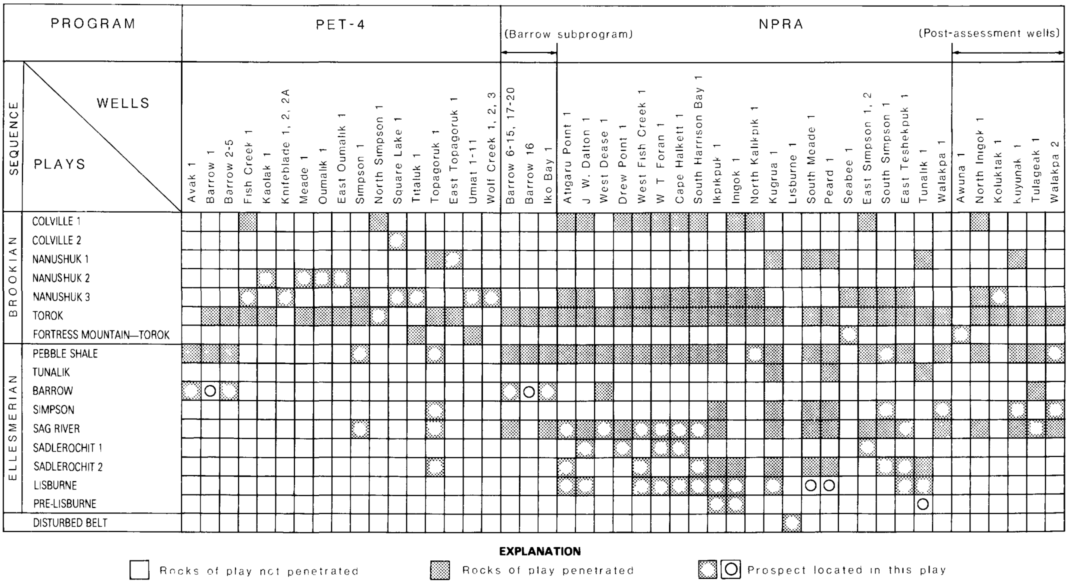


FIGURE 4.2.—Plays penetrated and prospects tested by all exploratory and development wells drilled during the Naval Petroleum Reserve No. 4 (Pet-4) and NPRA exploration programs. Plays are those developed during the NPRA program. Not included are 44 shallow core tests drilled during the Pet-4 program. Wells listed here are located in figure 4.3.

mature where it is buried to depths of 3,000 m (10,000 ft) or more (Pessel and others, 1978). Gas shows are encountered in these rocks in most wells, and gas accumulations are present in the Square Lake No. 1 well (Collins, 1959) and immediately east of the NPRA at Gubik (Robinson, 1958). Surface oil seeps are known in these rocks at Fish Creek and on the Simpson peninsula (Collins and Robinson, 1967).

Postulated traps in play I, all stratigraphic, are related to facies changes and include sandstone enclosed in shale-filled Simpson Canyon. Play II includes anticlinal traps and postulated updip facies changes. In both plays, interbedded shale is expected to provide adequate seals.

Only play I is partitioned. In the east half of the play area, reservoir rocks are expected to be more abundant and more deeply buried than in the west half.

NANUSHUK PLAYS

The Nanushuk plays, in sandstone reservoirs of mid-Cretaceous (Albian and Cenomanian) age having stratigraphic and structural traps, are in the Nanushuk Group. This group comprises nonmarine to shallow-marine shale, sandstone, conglomerate, and, locally, abundant coal. The thickness of the group ranges from about 2,700 m (9,000 ft) in the southwestern part of the NPRA to 300 m (1,000 ft) in the northeastern part of the NPRA (see Bird, chapter 16; Molenaar, chapter 25). The group thins to zero thickness at erosional edges at the latitude of the headwaters of the

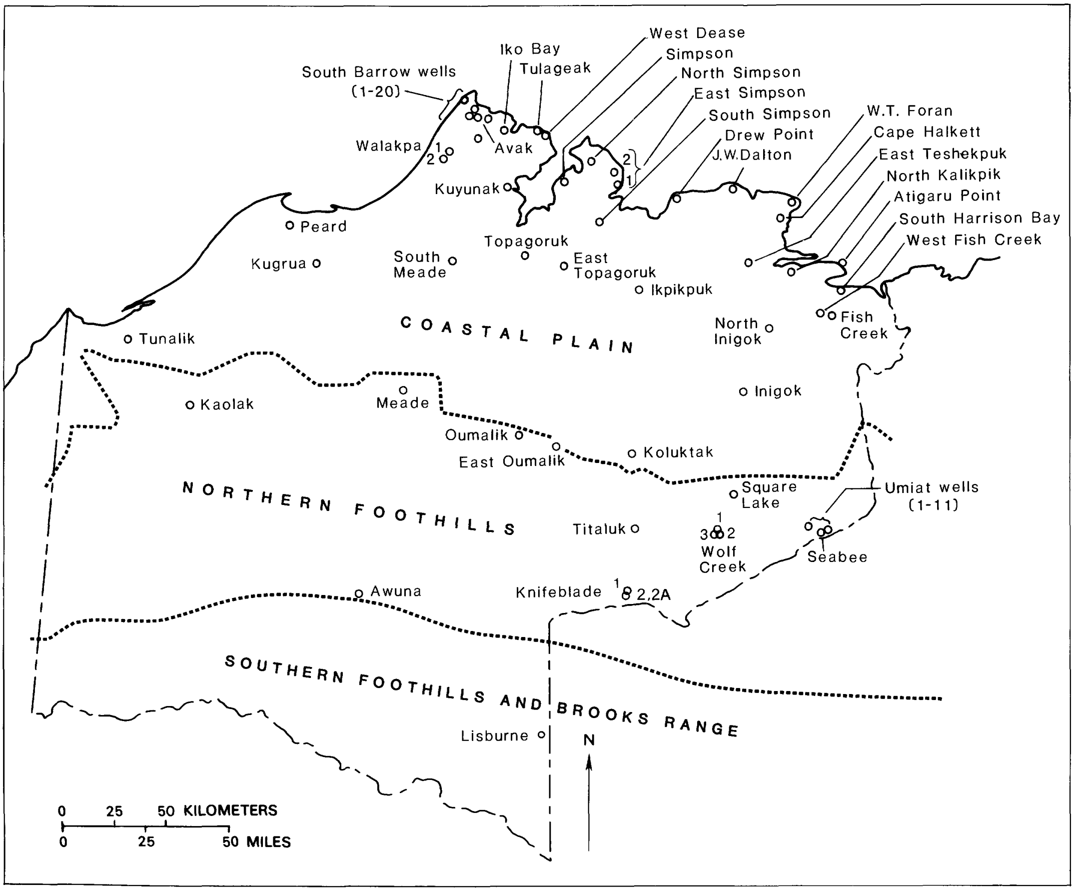
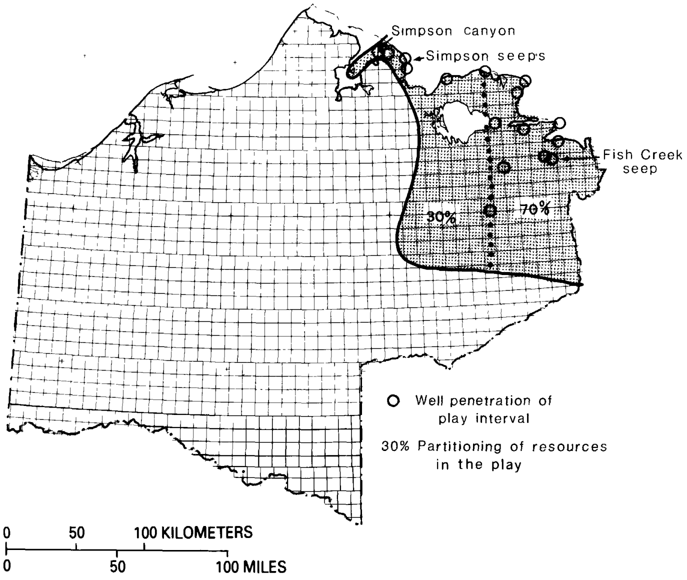


FIGURE 4.3.—Physiographic provinces and exploration wells in the NPRA. Wells are those listed in figure 4.2 and shown on the play maps in figures 4.4–4.20.

OIL AND GAS APPRAISAL DATA FORM

EVALUATOR: U.S. Geological Survey PLAY NAME: Colville 1
DATE EVALUATED: 11/78 REVISED: 11/78, 9/79

	ATTRIBUTE		PROB. OF FAVORABLE							COMMENTS
PLAY ATTRIBUTES	HYDROCARBON SOURCE (S)		1.0							
	TIMING (T)		0.9							
	MIGRATION (M)		0.8							
	POTENTIAL RESERVOIR FACIES (R)		1.0							
	PLAY PROBABILITY (SxTxMxR=MP)		0.72							
PROSPECT ATTRIBUTES	TRAP OCCURRENCE (TM)		0.08							Stratigraphic
	EFFECTIVE POROSITY (≥3%) (P)		0.9							
	HYDROCARBON ACCUMULATION (C)		0.7							
	PROSPECT PROBABILITY (TMxPxC=CP)		0.05							
HYDROCARBON VOLUME PARAMETERS	RESERVOIR LITHOLOGY	SAND	1.0							
		CARBONATE	0							
	HYDROCARBON MIX	GAS	0.5							Gas shows in wells; oil seeps at Fish Creek and Simpson Peninsula
		OIL	0.5							
	FRACTILES / ATTRIBUTES		PROB. OF EQUAL TO OR GREATER THAN							
			100	95	75	50	25	5	0	
	AREA OF CLOSURE (x10³ ACRES)		0.6	0.8	1	1.5	2	3	6	
	RESERVOIR THICKNESS (FT)		100	125	150	200	250	300	400	No sand more than about 50' thick
	EFFECTIVE POROSITY (%)		3	4	7	12	18	25	35	
	TRAP FILL (%)		1	5	10	15	20	25	90	
	RESERVOIR DEPTH (x10³ FT)		0.1	0.5	1	1.5	2	2.5	3.5	
	NUMBER OF DRILLABLE PROSPECTS		0	2	6	10	14	19	25	
PROVED RESERVES (x10⁶ BBLS; 10¹² ft³)			0							



PROBABILITY OF EQUAL TO OR GREATER THAN	ESTIMATED RESOURCES IN PLACE: OIL (MILLIONS OF BBLS)	GAS (BILLIONS OF CU FT)	BOE (MILLIONS OF BBLS)	ESTIMATED POOL SIZE (ASSUMING 100% OIL) (MILLIONS OF BBLS)
.95	0.00	0.00	0.00	0.00
.90	0.00	0.00	0.00	0.00
.75	0.00	0.00	0.00	0.00
.50	0.00	0.00	0.00	0.00
.25	0.00	.09	.13	0.00
.10	17.34	6.36	18.97	0.00
.05	45.18	14.65	47.24	0.00
.01	149.70	45.98	152.01	44.58
AVERAGE VALUES	8.35	2.67	8.82	1.58

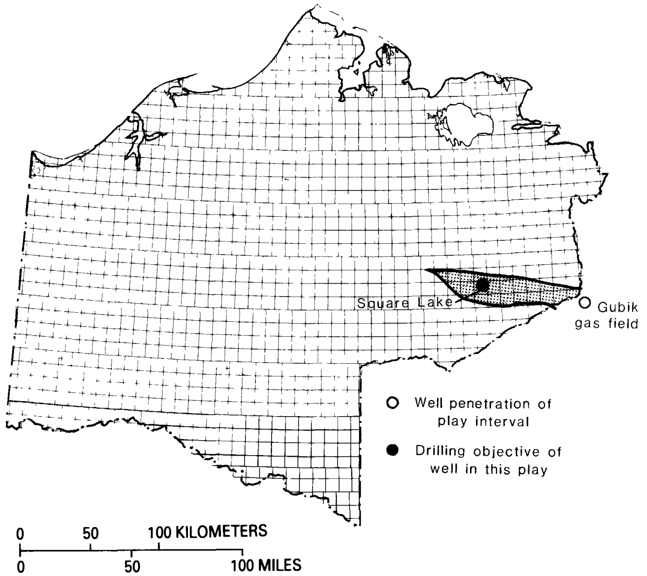
FIGURE 4.4.—Colville I play (shaded area) within the NPRA.

OIL AND GAS APPRAISAL DATA FORM

EVALUATOR: U.S. Geological Survey PLAY NAME: Colville 2
DATE EVALUATED: 11/76 REVISED: 9/79

	ATTRIBUTE		PROB. OF FAVORABLE	COMMENTS
PLAY ATTRIBUTES	HYDROCARBON SOURCE (S)		1.0	
	TIMING (T)		1.0	
	MIGRATION (M)		1.0	
	POTENTIAL RESERVOIR FACIES (R)		1.0	
	PLAY PROBABILITY (SxTxMxR=MP)		1.0	Proven reserves at Square Lake and Gubik
PROSPECT ATTRIBUTES	TRAP OCCURRENCE (TM)		0.9	
	EFFECTIVE POROSITY (≥3%) (P)		0.9	
	HYDROCARBON ACCUMULATION (C)		0.7	
	PROSPECT PROBABILITY (TMxPxC=CP)		0.6	
HYDROCARBON VOLUME PARAMETERS	RESERVOIR LITHOLOGY	SAND	1.0	
		CARBONATE	0	
	HYDROCARBON MIX	GAS	0.6	
		OIL	0.2	

	ATTRIBUTES \ FRACTILES	PROB. OF EQUAL TO OR GREATER THAN							
		100	95	75	50	25	5	0	
HYDROCARBON VOLUME PARAMETERS	AREA OF CLOSURE ($\times 10^3$ ACRES)	0.6	1	2	6	16	23	55	
	RESERVOIR THICKNESS (FT)	100	150	200	300	370	400	500	No sand more than about 50′ thick
	EFFECTIVE POROSITY (%)	3	5	8	10	15	25	30	
	TRAP FILL (%)	1	5	10	15	20	25	90	
	RESERVOIR DEPTH ($\times 10^3$ FT)	0.1	0.5	1	1.5	2.5	3	4	
NUMBER OF DRILLABLE PROSPECTS		5	5	5	6	7	10	15	
PROVED RESERVES ($\times 10^6$ BBLS; 10^{12} ft^3)		0.033-0.058 0.022-0.295							Square Lake gas field Gubik gaa field



PROBABILITY OF EQUAL TO OR GREATER THAN	ESTIMATED RESOURCES IN PLACE OIL (MILLIONS OF BBLS)	GAS (BILLIONS OF CU FT)	BOE (MILLIONS OF BBLS)	ESTIMATED POOL SIZE (ASSUMING 100% OIL) (MILLIONS OF BBLS)
.95	0.00	10.73	5.11	0.00
.90	0.00	29.65	11.67	0.00
.75	0.00	87.98	36.52	0.00
.50	11.42	225.34	103.36	20.02
.25	239.19	460.57	323.29	181.63
.10	714.26	816.52	792.30	546.68
.05	1179.21	1144.18	1248.15	893.07
.01	2803.15	2034.81	2850.18	2198.41
AVERAGE VALUES	244.58	356.65	307.15	193.67

FIGURE 4.5.—Colville II play (shaded area) within the NPRA.

Colville River in the south and in the Barrow area in the north. Recent investigations indicate that the Nanushuk Group was deposited in two separate delta systems: a western sand-poor delta complex (Corwin delta) and an eastern sand-rich delta complex (Umiat delta) (Huffman and Ahlbrandt, 1979). The partly time equivalent Torok Formation underlies the Nanushuk Group and comprises prodelta shelf, slope, and basinal deposits (see Molenaar, chapter 25). The Colville Group conformably overlies the Nanushuk. As a result of differential uplift and erosion, the Nanushuk is exposed on the surface in the west two-thirds of the NPRA and is overlapped by the Colville Group in the east third of the NPRA. Three plays were established: Play I is distinguished from play II by better reservoir characteristics and an absence of structural traps; play III is distinguished from the other two plays by the presence of the overlying Colville Group (figs. 4.6-4.8).

The reservoir rocks are multiple sandstone beds. Each bed is expected to be less than 30 m (100 ft) thick and to exhibit marked facies change over short distances. Sandstone increases in proportion and porosity in a northeasterly direction. Plays I and II are both expected to include about 20 percent sandstone; however, the average expected porosity in play II is 8 percent, whereas in play I it is 20 percent. In play III, the percentage of sandstone may reach 50 percent, and the average expected porosity 16 percent.

Potential source rocks include coal and shale in the Nanushuk Group and marine shale in the adjacent Torok Formation and Colville Group (Stadnichenko, 1929; Webber, 1947; Magoon and Claypool, 1979). Shale in the Nanushuk and Torok is gas prone and averages 1 to 2 weight percent organic carbon. The Nanushuk is mature in the southwestern part of the NPRA but immature elsewhere (see Magoon and Bird, chapter 17). Oil and gas indications are common. Play I includes gas shows in most wells and the Skull Cliff oil seep (Webber, 1947). Play II includes oil and gas shows in wells, the subcommercial gas accumulation in the Meade No. 1 well, the Pahron gas seep and gas in nearby seismic shot holes (Whittington and Keller, 1950), and oil-stained sandstone in the Carbon anticline area (Chapman and Sable, 1960; Roehler and Stricker, 1979). Play III includes gas seeps at North Colville and Aupuk (Chapman and others, 1964); subcommercial gas accumulations at Wolf Creek and at Gubik and East Umiat (adjacent to the reserve); and subcommercial oil accumulations at Simpson, Fish Creek, and Umiat. The East Umiat No. 1 well, with 10 separate gas-bearing sandstone reservoirs, demonstrates the capacity of the source rocks to fill multiple reservoirs.

Postulated traps in play I include stratigraphic traps related to facies change and, possibly, low-amplitude structures smaller than the seismic grid. Play II contains anticlinal and, possibly, facies-change traps. Play III includes anticlinal traps in the southern part of the play area and stratigraphic traps in the northern part. Stratigraphic traps include those caused by facies change and those formed against the sides of shale-filled canyons or channels, such as Simpson Canyon (Collins and Robinson, 1967).

TOROK PLAY

The Torok play, in deep-marine sandstone reservoirs of Early Cretaceous age having structural and stratigraphic traps, is in the Torok Formation. This formation is the deeper marine equivalent of the Nanushuk Group and conformably overlies the pebble shale unit (see Molenaar, chapter 25). The Torok Formation ranges in thickness from a minimum of 365 m (1,200 ft) at Barrow to 3,000 m (10,000 ft) at the south play margin (see Bird, chapter 16). The south play boundary (fig. 4.9) is arbitrarily determined at the north onlap limit of seismic reflectors FM_3, FM_4, and FM_5 mapped by Miller and Peterson (1978, pl. 2). South of this limit, all strata above the pebble shale unit and below the Nanushuk Group compose the Fortress Mountain-Torok play.

Reservoir rocks (fine-grained sandstone) may occur anywhere in the formation, but they are most common in the lower quarter of the unit as toe-of-slope or basin-plain turbidites. Depths to the top of this part of the formation range from 300 m (1,000 ft) at Barrow to 2,700 m (9,000 ft) at the south play boundary. The sandstone bodies are laterally discontinuous and may have an aggregate thickness of 60 m (200 ft) or more, but few individual beds are more than 10 m (30 ft) thick. A submarine fan or canyon that might have concentrated sandstone deposition and thus localize the search for better reservoir rocks in this play has yet to be identified.

Potential source rocks (marine shale in the Torok Formation and in the pebble shale unit) surround the sandstone reservoirs. Preliminary geochemical analyses show 1 to 2 weight percent organic carbon in the Torok and 1 to 3 weight percent in the pebble shale unit (see Magoon and Bird, chapter 17). The Torok is relatively gas prone. These potential source rocks are immature in the northern part of the play area; they become mature southward, and at the south play boundary the lower part of the Torok is overmature. Gas shows in Torok sandstone are common; oil shows are fewer.

Stratigraphic traps related to facies change or to channeling are ex-

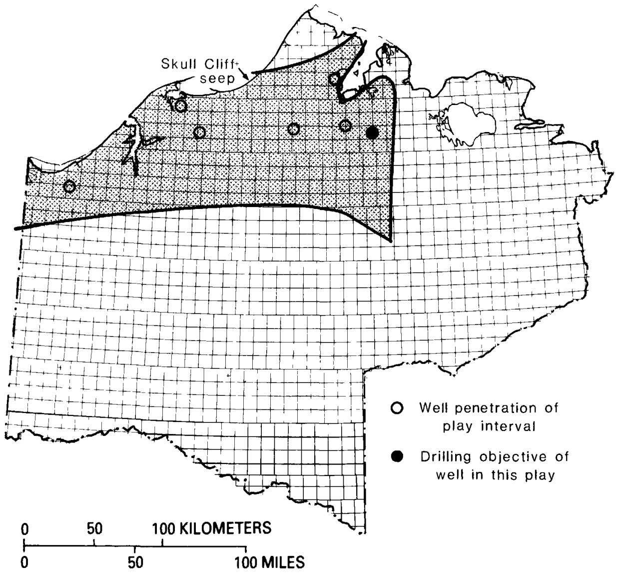
OIL AND GAS APPRAISAL DATA FORM

EVALUATOR: U.S. Geological Survey PLAY NAME: Nanushuk 1

DATE EVALUATED: 11/78 REVISED: 11/78, 5/79, 9/79

	ATTRIBUTE		PROB. OF FAVORABLE	COMMENTS
PLAY ATTRIBUTES	HYDROCARBON SOURCE (S)		1.0	Skull Cliff oil seep
	TIMING (T)		1.0	
	MIGRATION (M)		0.7	
	POTENTIAL RESERVOIR FACIES (R)		1.0	
	PLAY PROBABILITY (SxTxMxR=MP)		0.7	
PROSPECT ATTRIBUTES	TRAP OCCURRENCE (TM)		0.1	Stratigraphic
	EFFECTIVE POROSITY (≥3%) (P)		0.9	
	HYDROCARBON ACCUMULATION (C)		0.7	
	PROSPECT PROBABILITY (TMxPxC=CP)		0.063	
HYDROCARBON VOLUME PARAMETERS	RESERVOIR LITHOLOGY	SAND	1.0	
		CARBONATE	0	
	HYDROCARBON MIX	GAS	0.5	
		OIL	0.5	

	FRACTILES / ATTRIBUTES	PROB. OF EQUAL TO OR GREATER THAN 100	95	75	50	25	5	0	COMMENTS
HYDROCARBON VOLUME PARAMETERS	AREA OF CLOSURE (x10³ ACRES)	0.6	1.0	2	3.2	10	25	90	Few structures, possibility of large strat. traps
	RESERVOIR THICKNESS (FT)	5	50	300	350	400	550	800	Individual sands less than 100' thick
	EFFECTIVE POROSITY (%)	3	7	15	20	24	28	35	
	TRAP FILL (%)	1	5	10	15	20	25	90	
	RESERVOIR DEPTH (x10³ FT)	0.1	1.5	2.5	3.7	4.5	6	8	
	NUMBER OF DRILLABLE PROSPECTS	0	3	7	12	18	25	45	
	PROVED RESERVES (x10⁶ BBLS; 10¹² ft³)	NONE							



PROBABILITY OF EQUAL TO OR GREATER THAN	ESTIMATED RESOURCES IN PLACE OIL (MILLIONS OF BBLS)	GAS (BILLIONS OF CU FT)	BOE (MILLIONS OF BBLS)	ESTIMATED POOL SIZE (ASSUMING 100% OIL) (MILLIONS OF BBLS)
.95	0.00	0.00	0.00	0.00
.90	0.00	0.00	0.00	0.00
.75	0.00	0.00	0.00	0.00
.50	0.00	0.00	0.00	0.00
.25	0.00	42.73	40.44	0.00
.10	257.88	292.94	354.66	0.00
.05	709.53	628.01	813.91	0.00
.01	2556.14	2626.86	2692.01	523.28
AVERAGE VALUES	132.81	142.87	157.88	21.76

FIGURE 4.6.—Nanushuk I play (shaded area) within the NPRA.

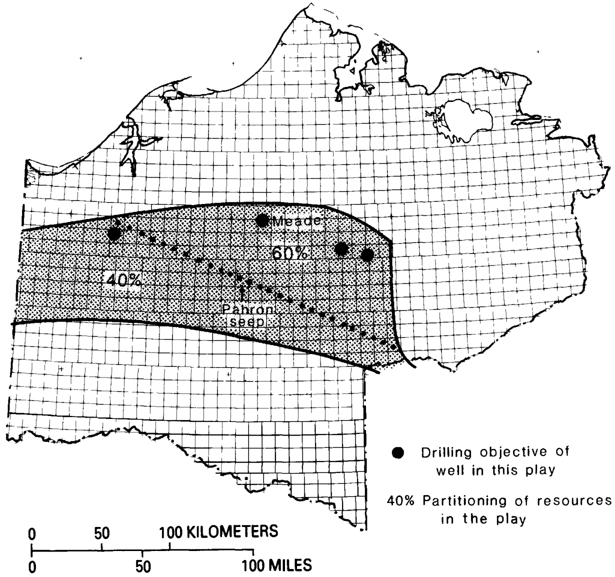
OIL AND GAS APPRAISAL DATA FORM

EVALUATOR: U.S. Geological Survey PLAY NAME: Nanushuk 2
DATE EVALUATED: 11/78 REVISED: 11/78, 5/79, 9/79

	ATTRIBUTE		PROB. OF FAVORABLE	COMMENTS
PLAY ATTRIBUTES	HYDROCARBON SOURCE (S)		1.0	Gas at Meade test well and Pahron seep
	TIMING (T)		1.0	
	MIGRATION (M)		0.7	
	POTENTIAL RESERVOIR FACIES (R)		0.7	
	PLAY PROBABILITY (SxTxMxR=MP)		0.49	
PROSPECT ATTRIBUTES	TRAP OCCURRENCE (TM)		0.9	Mostly structural
	EFFECTIVE POROSITY (≥3%) (P)		0.5	
	HYDROCARBON ACCUMULATION (C)		0.7	
	PROSPECT PROBABILITY (TMxPxC=CP)		0.315	
HYDROCARBON VOLUME PARAMETERS	RESERVOIR LITHOLOGY	SAND	1.0	
		CARBONATE	0	
	HYDROCARBON MIX	GAS	0.7	Dry gas at Meade
		OIL	0.3	

	FRACTILES / ATTRIBUTES	PROB. OF EQUAL TO OR GREATER THAN 100	95	75	50	25	5	0	COMMENTS
HYDROCARBON VOLUME PARAMETERS	AREA OF CLOSURE ($\times 10^3$ ACRES)	0.6	2	6	14	22	53	73	
	RESERVOIR THICKNESS (FT)	5	25	75	150	250	350	500	Individual sands generally less than 100' thick
	EFFECTIVE POROSITY (%)	3	4	6	8	10	14	20	
	TRAP FILL (%)	1	3	6	10	15	20	90	
	RESERVOIR DEPTH ($\times 10^3$ FT)	0.1	2	3	4	5	7	9	
	NUMBER OF DRILLABLE PROSPECTS	32	35	37	40	45	50	60	

PROVED RESERVES ($\times 10^6$ BBLS; 10^{12} ft^3)	est. 0.196	Recoverable gas at Meade



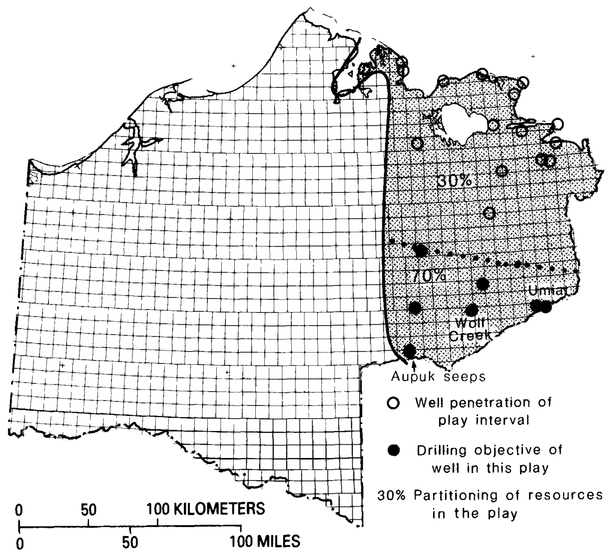
PROBABILITY (OF EQUAL TO OR GREATER THAN)	ESTIMATED RESOURCES IN PLACE OIL (MILLIONS OF BBLS)	GAS (BILLIONS OF CU FT)	BOE (MILLIONS OF BBLS)	ESTIMATED POOL SIZE (ASSUMING 100% OIL) (MILLIONS OF BBLS)
.95	0.00	0.00	0.00	0.00
.90	0.00	0.00	0.00	0.00
.75	0.00	0.00	0.00	0.00
.50	0.00	0.00	0.00	0.00
.25	394.38	1125.06	646.59	0.00
.10	1004.56	2030.72	1325.37	27.64
.05	1525.49	2776.66	1857.21	112.15
.01	2839.81	4923.56	3150.90	542.48
AVERAGE VALUES	324.93	714.62	450.30	25.24

FIGURE 4.7.—Nanushuk II play (shaded area) within the NPRA.

OIL AND GAS APPRAISAL DATA FORM

EVALUATOR: U.S. Geological Survey PLAY NAME: Nanushuk 3
DATE EVALUATED: 11/78 REVISED: 5/79, 9/79

	ATTRIBUTE		100	95	75	50	25	5	0	PROB. OF FAVORABLE	COMMENTS
PLAY ATTRIBUTES	HYDROCARBON SOURCE (S)									1.0	Wolf Cr., Simpson, and Umiat oils are similar, may have same source
	TIMING (T)									1.0	
	MIGRATION (M)									1.0	
	POTENTIAL RESERVOIR FACIES (R)									1.0	
	PLAY PROBABILITY (SxTxMxR=MP)									1.0	Produces at Umiat
PROSPECT ATTRIBUTES	TRAP OCCURRENCE (TM)									0.5	Structural and stratigraphic
	EFFECTIVE POROSITY (≥3%) (P)									0.7	
	HYDROCARBON ACCUMULATION (C)									0.9	
	PROSPECT PROBABILITY (TMxPxC=CP)									0.315	
HYDROCARBON VOLUME PARAMETERS	RESERVOIR LITHOLOGY	SAND								1.0	
		CARBONATE								0	
	HYDROCARBON MIX	GAS								0.3	
		OIL								0.7	
	ATTRIBUTES \ FRACTILES	PROB. OF EQUAL TO OR GREATER THAN	100	95	75	50	25	5	0		
	AREA OF CLOSURE ($\times 10^3$ ACRES)		0.6	1	2	8	16	23	55		
	RESERVOIR THICKNESS (FT)		5	50	200	450	675	850	1,000		Individual sands less than 150' thick
	EFFECTIVE POROSITY (%)		3	8	12	16	22	28	35		
	TRAP FILL (%)		1	5	12	30	35	40	90		
	RESERVOIR DEPTH ($\times 10^3$ FT)		0.1	1	3	4	5	6	7		
NUMBER OF DRILLABLE PROSPECTS			10	12	14	16	20	30	40		
PROVED RESERVES ($\times 10^6$ BBLS; 10^{12} ft^3)										19-122	Umiat oil field



PROBABILITY (OF EQUAL TO OR GREATER THAN)	ESTIMATED RESOURCES IN PLACE OIL (MILLIONS OF BBLS)	GAS (BILLIONS OF CU FT)	BOE (MILLIONS OF BBLS)	ESTIMATED POOL SIZE (ASSUMING 100% OIL) (MILLIONS OF BBLS)
.95	94.29	118.58	232.72	0.00
.90	317.91	220.00	538.78	0.00
.75	1125.40	629.32	1407.74	0.00
.50	2903.23	1496.81	3260.35	0.00
.25	5918.02	3042.77	6377.37	76.29
.10	9939.76	5538.10	10643.25	839.90
.05	13208.33	7306.66	14002.90	1921.73
.01	21237.68	11789.07	22051.27	5613.88
AVERAGE VALUES	4271.14	2320.74	4678.29	334.98

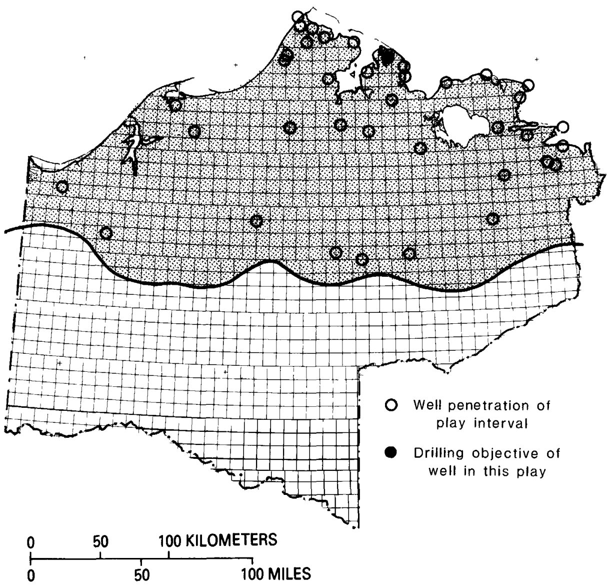
FIGURE 4.8.—Nanushuk III play (shaded area) within the NPRA.

OIL AND GAS APPRAISAL DATA FORM

EVALUATOR: U.S. Geological Survey PLAY NAME: Torok
DATE EVALUATED: 11/78 REVISED: 11/78, 9/79, 5,80

	ATTRIBUTE		PROB. OF FAVORABLE	COMMENTS
PLAY ATTRIBUTES	HYDROCARBON SOURCE (S)		1.0	Abundant gas shows
	TIMING (T)		1.0	
	MIGRATION (M)		0.8	
	POTENTIAL RESERVOIR FACIES (R)		0.5	
	PLAY PROBABILITY (SxTxMxR=MP)		0.40	
PROSPECT ATTRIBUTES	TRAP OCCURRENCE (TM)		0.3	Problem of finding stratigraphic traps
	EFFECTIVE POROSITY (≥3%) (P)		0.5	
	HYDROCARBON ACCUMULATION (C)		0.9	
	PROSPECT PROBABILITY (TMxPxC=CP)		0.135	
HYDROCARBON VOLUME PARAMETERS	RESERVOIR LITHOLOGY	SAND	1.0	
		CARBONATE	0	
	HYDROCARBON MIX	GAS	0.8	
		OIL	0.2	

	FRACTILES / ATTRIBUTES	PROB. OF EQUAL TO OR GREATER THAN							COMMENTS
		100	95	75	50	25	5	0	
HYDROCARBON VOLUME PARAMETERS	AREA OF CLOSURE (x10³ ACRES)	0.6	1	2	2.5	5	10	23	
	RESERVOIR THICKNESS (FT)	10	50	100	150	175	200	225	Individual sands generally less than 30' thick
	EFFECTIVE POROSITY (%)	3	6	9	12	15	18	22	
	TRAP FILL (%)	1	3	6	10	15	20	90	
	RESERVOIR DEPTH (x10³ FT)	0.1	4	6.5	7.5	8.5	10	12	
	NUMBER OF DRILLABLE PROSPECTS	20	22	25	30	35	45	85	
	PROVED RESERVES (x10⁶ BBLS; 10¹² ft³)							0	



PROBABILITY (OF EQUAL TO OR GREATER THAN)	ESTIMATED RESOURCES IN PLACE OIL (MILLIONS OF BBLS)	ESTIMATED RESOURCES IN PLACE GAS (BILLIONS OF CU FT)	ESTIMATED RESOURCES IN PLACE BOE (MILLIONS OF BBLS)	ESTIMATED POOL SIZE (ASSUMING 100% OIL) (MILLIONS OF BBLS)
.95	0.00	0.00	0.00	0.00
.90	0.00	0.00	0.00	0.00
.75	0.00	0.00	0.00	0.00
.50	0.00	0.00	0.00	0.00
.25	0.00	100.97	29.86	0.00
.10	32.29	286.23	85.18	0.00
.05	68.89	426.92	132.59	3.26
.01	208.57	823.51	306.31	51.42
AVERAGE VALUES	12.72	86.29	27.86	2.01

FIGURE 4.9.—Torok play (shaded area) within the NPRA.

pected to be most common. Structural traps are rare except in the southern part of the play.

FORTRESS MOUNTAIN-TOROK PLAY

The Fortress Mountain-Torok play is in sandstone reservoirs having structural and stratigraphic traps in the interval of strata below the Nanushuk Group and above the pebble shale unit. These strata range in thickness from 3,000 m (10,000 ft) in the northern part of the play to 7,600 m (25,000 ft) in the southern part (see Bird, chapter 16). They consist of shale, graywacke sandstone, and conglomerate derived from the south and deposited in deep marine environments. At the time of this assessment, these strata were referred to as the Fortress Mountain and Torok Formations. Within the play area (fig. 4.10), these formations are lithologically indistinguishable, an observation that led Molenaar and others (chapter 12) to restrict the term "Fortress Mountain Formation" to outcrops. The rocks in this play, therefore, are now considered as all Torok Formation. The south boundary of this play area is marked by the north outcrop limit of the Fortress Mountain Formation (see Bird, chapter 15). Its north boundary, shared with the contiguous Torok play, is defined by the north limit of seismic horizons FM_3 through FM_5 as mapped by Miller and Peterson (1978, pl. 2). Information on the Torok and Fortress Mountain Formations comes mostly from surface geologic studies (see Molenaar and others, chapter 12; Patton, 1956; Chapman and Sable, 1960; Patton and Tailleur, 1964; Hunter and Fox, 1976) and a few wells.

The reservoir rock consists of deep-marine turbidite sandstone that is distributed irregularly and with little lateral continuity. It may aggregate several hundred feet in thickness, but individual beds are expected to be less than 30 m (100 ft) thick. Depth to reservoir rock ranges from 0 (at the surface) to more than 7,600 m (25,000 ft). Porosity is generally 3 to 9 percent, although some sandstone has as much as 15 percent porosity, as does that in the Seabee No. 1 well at 1,615 m (5,300 ft) depth.

The potential source rock is marine shale both in the pebble shale unit and in the Torok and Fortress Mountain Formations. Limited geochemical data indicate that the organic richness and kerogen types should be similar to those in the Torok play, that is, 1 to 2 percent gas-prone organic carbon (see Magoon and Bird, chapter 17). The upper 300 m (1,000 ft) of the Torok is immature in the eastern part of the play. In the rest of the play area these rocks are mature to overmature. Indications of gas are more common than of oil in this play. Gas was tested at rates up to 6.7 million ft^3/d from 1,615 m (5,300 ft) in the Seabee-1 well. Gas was tested at a rate of 10 million ft^3/d from these same rocks just outside the NPRA in the East Kurupa No. 1 well. Patton and Tailleur (1964, p. 496) reported seams of asphaltic hydrocarbons along bedding planes and filling fractures in surface exposures of the Torok, Fortress Mountain, and Okpikruak Formations.

Both structural and stratigraphic traps are expected. Numerous long, linear anticlines complicated by faulting have been seismically mapped within the play area. Interbedded shale is expected to provide adequate seals.

PEBBLE SHALE PLAY

The pebble shale play, in sandstone reservoirs having structural and stratigraphic traps, is in the Lower Cretaceous (Neocomian) informally named pebble shale unit (see Bird, chapter 15). The pebble shale unit, 60 to 150 m (200-500 ft) of dark-gray marine shale, derives its name from the presence of a small but distinctive amount (max 1 percent) of well-rounded chert pebbles and sand-size quartz grains that are scattered through and supported by the clay matrix. A zone of intense gamma radiation, probably related indirectly to an increase in organic content of the rock, characterizes the upper part of this rock unit. The pebble shale unit overlies a regional unconformity and is conformably overlain by the Torok Formation. The north play boundary is the coastline, and the south boundary is a line arbitrarily drawn beyond the southernmost expected occurrence of sandstone (fig. 4.11).

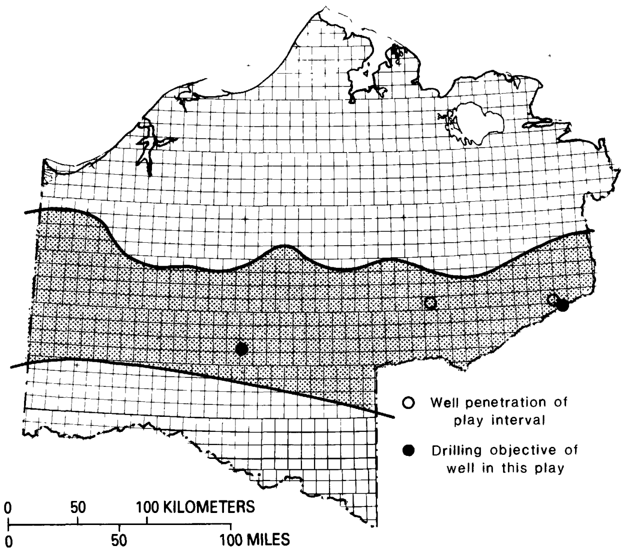
The reservoir rock is a fine-grained, well-sorted quartzose sandstone with an average expected porosity of 15 percent. Two types of sandstone are expected. The first type is limited to the Barrow area and consists of as many as eight sandstone beds, 1.5 to 3 m (5-10 ft) thick, scattered throughout the pebble shale interval. The second type, which may occur anywhere in the play area, is a basal sandstone. This sandstone, which overlies the unconformity, may be as much as 14 m (45 ft) thick, but it is discontinuous; many wells have penetrated no sandstone. This sandstone is not seismically detectable, and its distribution is unpredictable. Reservoir depth ranges from 400 m (1,300 ft) in the northern play area to 2,750 m (9,000 ft) in the southern.

Potential source rocks include marine shale in the pebble shale unit, the overlying Torok Formation, and the underlying Kingak Shale and Shublik Formation. Geochemical data indicate that the pebble shale unit contains an average of 2 to 3 weight percent organic carbon that is oil prone (see Magoon and Bird, chapter 17). The pebble shale unit is immature in the north half of the play area and mature in the south half. The sandstone of the

OIL AND GAS APPRAISAL DATA FORM

EVALUATOR: U.S. Geological Survey PLAY NAME: Fortress Mountain-Torok
DATE EVALUATED: 11/78 REVISED: 11/78, 9/79, 5/80

	ATTRIBUTE		100	95	75	50	25	5	0	PROB. OF FAVORABLE	COMMENTS
PLAY ATTRIBUTES	HYDROCARBON SOURCE (S)									1.0	Good gas shows reported in Seabee and Kurupa wells
	TIMING (T)									1.0	
	MIGRATION (M)									0.8	
	POTENTIAL RESERVOIR FACIES (R)									0.3	
	PLAY PROBABILITY (SxTxMxR=MP)									0.24	
PROSPECT ATTRIBUTES	TRAP OCCURRENCE (TM)									0.7	Numerous large structures
	EFFECTIVE POROSITY (≥3%) (P)									0.1	
	HYDROCARBON ACCUMULATION (C)									0.9	
	PROSPECT PROBABILITY (TMxPxC=CP)									0.063	
HYDROCARBON VOLUME PARAMETERS	RESERVOIR LITHOLOGY	SAND								1.0	Reservoir generally below 10,000′
		CARBONATE								0	
	HYDROCARBON MIX	GAS								0.9	
		OIL								0.1	
	ATTRIBUTES / FRACTILES	PROB. OF EQUAL TO OR GREATER THAN	100	95	75	50	25	5	0		
	AREA OF CLOSURE ($\times 10^3$ ACRES)		0.6	7	13	20	30	40	55		
	RESERVOIR THICKNESS (FT)		5	15	75	150	475	735	800		Assume 10% sandstone, scattered throughout section. Individual sands up to 100′ thick
	EFFECTIVE POROSITY (%)		3	3.2	4	5	7	9	16		
	TRAP FILL (%)		1	2	8	15	45	69	75		
	RESERVOIR DEPTH ($\times 10^3$ FT)		0.1	1.2	8	12	21	28	30		
	NUMBER OF DRILLABLE PROSPECTS		25	26	30	35	47	57	60		
	PROVED RESERVES ($\times 10^6$ BBLS; 10^{12} ft^3)									0	



PROBABILITY (OF EQUAL TO OR GREATER THAN)	ESTIMATED RESOURCES IN PLACE OIL (MILLIONS OF BBLS)	GAS (BILLIONS OF CU FT)	BOE (MILLIONS OF BBLS)	ESTIMATED POOL SIZE (ASSUMING 100% OIL) (MILLIONS OF BBLS)
.95	0.00	0.00	0.00	0.00
.90	0.00	0.00	0.00	0.00
.75	0.00	0.00	0.00	0.00
.50	0.00	0.00	0.00	0.00
.25	0.00	0.00	0.00	0.00
.10	0.00	841.49	168.31	0.00
.05	0.00	2196.62	453.74	0.00
.01	306.16	6549.02	1264.11	27.32
AVERAGE VALUES	11.50	339.33	71.03	4.30

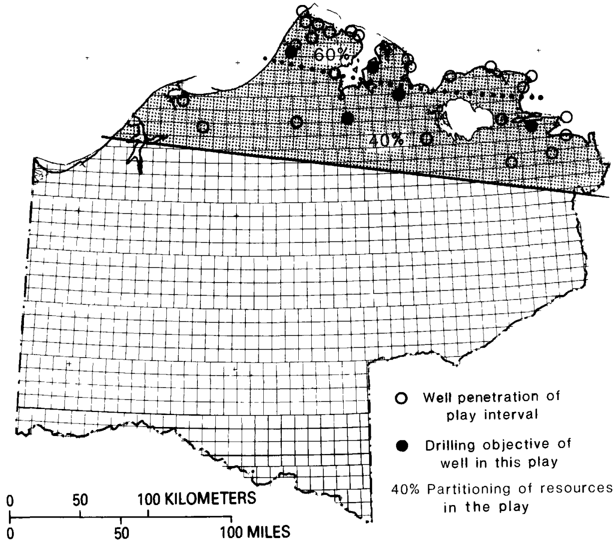
FIGURE 4.10.—Fortress Mountain-Torok play (shaded area) within the NPRA.

OIL AND GAS APPRAISAL DATA FORM

EVALUATOR: U.S. Geological Survey PLAY NAME: Pebble shale
DATE EVALUATED: 11/78 REVISED: 11/78, 5/79, 9/79, 5/80

	ATTRIBUTE		PROB. OF FAVORABLE	COMMENTS
PLAY ATTRIBUTES	HYDROCARBON SOURCE (S)		1.0	Immature on Barrow Arch
	TIMING (T)		1.0	
	MIGRATION (M)		1.0	
	POTENTIAL RESERVOIR FACIES (R)		1.0	
	PLAY PROBABILITY (SxTxMxR=MP)		1.0	Gas discovery at Walakpa
PROSPECT ATTRIBUTES	TRAP OCCURRENCE (TM)		0.1	Problem indentifying traps; discontinuous sandstone bodies
	EFFECTIVE POROSITY (≥3%) (P)		0.9	
	HYDROCARBON ACCUMULATION (C)		0.9	
	PROSPECT PROBABILITY (TMxPxC=CP)		0.081	
HYDROCARBON VOLUME PARAMETERS	RESERVOIR LITHOLOGY	SAND	1.0	
		CARBONATE	0	
	HYDROCARBON MIX	GAS	0.5	Torok Fm.,pebble shale unit,and Kingak Sh are mature downdip to the south Gas at Walakpa; oil in Barrow #20
		OIL	0.5	

	ATTRIBUTES \ FRACTILES	PROB. OF EQUAL TO OR GREATER THAN							
		100	95	75	50	25	5	0	
HYDROCARBON VOLUME PARAMETERS	AREA OF CLOSURE (x10³ ACRES)	0.6	1	4	8	13	25	50	
	RESERVOIR THICKNESS (FT)	5	5	10	20	30	35	40	
	EFFECTIVE POROSITY (%)	3	5	10	15	17	20	25	
	TRAP FILL (%)	1	5	23	45	67	85	90	
	RESERVOIR DEPTH (x10³ FT)	1.3	2	4	6	7	8	9	
	NUMBER OF DRILLABLE PROSPECTS	10	12	18	20	25	35	50	
	PROVED RESERVES ($\times 10^6$ BBLS; 10^{12} ft³)	?							



○ Well penetration of play interval

● Drilling objective of well in this play

40% Partitioning of resources in the play

PROBABILITY (OF EQUAL TO OR GREATER THAN)	ESTIMATED RESOURCES IN PLACE OIL (MILLIONS OF BBLS)	GAS (BILLIONS OF CU FT)	BOE (MILLIONS OF BBLS)	ESTIMATED POOL SIZE (ASSUMING 100% OIL) (MILLIONS OF BBLS)
.95	0.00	0.00	0.00	0.00
.90	0.00	0.00	0.00	0.00
.75	0.00	2.86	2.56	0.00
.50	5.76	33.04	23.00	0.00
.25	60.46	106.83	83.85	0.00
.10	176.33	216.89	203.51	0.00
.05	281.88	347.32	305.40	16.83
.01	617.12	659.65	658.36	137.56
AVERAGE VALUES	57.83	82.55	72.31	5.20

FIGURE 4.11.—Pebble shale play (shaded area) within the NPRA.

pebble shale unit is stained with oil in most wells in the Barrow area, and small amounts of oil were recovered from the Barrow No. 20 and Cape Halkett No. 1 wells. Gas was discovered in the Walakpa No. 1 well and, after the last assessment, was confirmed in the Walakpa No. 2 well, 5 km (3 mi) away and 200 m (600 ft) downdip from the discovery well.

Structural traps are rare in the play area; however, the discontinuous occurrence of the sandstone favors the presence of stratigraphic traps. The surrounding shale is expected to provide excellent seals.

TUNALIK PLAY

The Tunalik play, in sandstone reservoirs of Late Jurassic and earliest Cretaceous age having stratigraphic traps, encompasses the interval of the Kingak Shale above the Simpson sandstone of local usage and below the pebble shale unconformity. This interval of the Kingak ranges in thickness from 0 near Barrow, where it is completely truncated by the unconformity, to more than 900 m (3,000 ft) near the Tunalik No. 1 well. Sandstone in this part of the Kingak is apparently restricted to the northwest corner of the NPRA, as indicated by the play boundaries. Information from the Tunalik No. 1 well indicates that the upper part of the Kingak is distinct from the lower part containing the Simpson sandstone. Therefore, the Jurassic II play of former assessments was split into the new Tunalik and Simpson plays (figs. 4.12, 4.13).

Reservoirs, in three separate intervals, reach a total thickness of at least 105 m (350 ft) in the Tunalik No. 1 well; however, much less sandstone is present in wells to the north. Preliminary observations indicate that the sandstone is marine and is more quartzose and less glauconitic than the Simpson sandstone. Porosity is 8 to 15 percent, and reservoir depth ranges from 1,800 m (6,000 ft) to 4,900 m (16,000 ft).

Geochemical data indicate that the Kingak and the overlying pebble shale unit in the play area are fair to good source rocks, mature in the northern part of the play and overmature in the southern part (see Magoon and Bird, chapter 17). High-pressure, low-volume gas was penetrated in the Tunalik No. 1 well but was not tested.

No anticlinal prospects are known in this play area, but seismic data reveal numerous strong reflectors gently inclined southward that may represent sandstone bodies. The abundant shale in this interval should provide excellent seals for these potential stratigraphic traps.

SIMPSON PLAY

The Simpson play, in sandstone reservoirs of Early and Middle Jurassic age having structural and stratigraphic traps, encompasses the interval in the Kingak Shale from the top of the Simpson sandstone of local usage to the top of the Sag River Sandstone. This part of the Kingak is composed of marine shale and sandstone and is about 300 m (1,000 ft) thick along the northeast play boundary. That boundary is defined by the unconformity truncation edge of the Simpson sandstone. The Kingak thins southward to the south boundary of the play area, which is placed at the estimated downdip limit of sandstone (fig. 4.13).

Reservoir rocks consist of the widespread Simpson sandstone, which is as much as 50 m (160 ft) thick, and at least two other unnamed sandstones 15 to 24 m (50-80 ft) thick in the South Meade No. 1 well. These sandstones are generally fine grained, argillaceous, and rich in glauconite. Porosities are as much as 25 percent, but measured permeabilities of 1 millidarcy or less suggest that the pores are plugged by clay or glauconite. Reservoir depth ranges from 460 to 4,600 m (1,500-15,000 ft).

Geochemical data indicate that the Kingak Shale and the overlying pebble shale unit in the play area are fair to good source rocks. These rocks are immature in the northern part of the play and become mature to overmature in the southern part (see Magoon and Bird, chapter 17). Gas was tested at a rate of 75,000 ft^3/d from the Simpson sandstone in the South Simpson No. 1 well.

Structural traps in the play area are rare. A postulated stratigraphic trap of great areal extent was tested by the Walakpa No. 1 well. This well shows that a facies change has occurred—the Simpson sandstone has changed to a siltstone lithology—and that the postulated trap, if present, is reduced in size.

BARROW PLAY

The Barrow play, in sandstone reservoirs of Early Jurassic age having structural and stratigraphic traps, consists of the interval of the Kingak Shale from the top of the Sag River Sandstone to the top of the Barrow sandstone of local usage. This play, the smallest of all the ones considered, encompasses the areal limits of the Barrow sandstone. It consists of marine shale and sandstone that is about 90 m (300 ft) thick over most of the play area. The north play boundary coincides with the truncation edge of the Barrow sandstone along the pebble shale unconformity (fig. 4.14).

The reservoir rock is the Barrow sandstone, a very fine grained, argillaceous, bioturbated sandstone, probably deposited as a series of offshore bars (R.J. Weimer, oral commun., 1977). Numerous well penetrations indicate the presence of two sandstone intervals, totaling about 12 m (40 ft) in thickness and having a porosity in the 20-percent

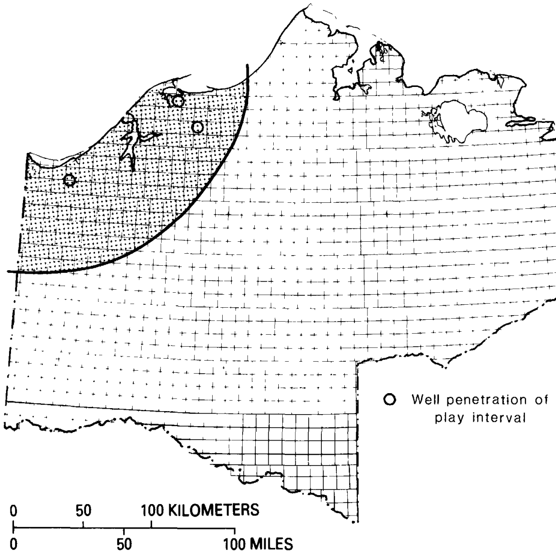
OIL AND GAS APPRAISAL DATA FORM

EVALUATOR: U.S. Geological Survey PLAY NAME. Tunalik

DATE EVALUATED: 9/79 REVISED: 5/80

	ATTRIBUTE		PROB. OF FAVORABLE	COMMENTS
PLAY ATTRIBUTES	HYDROCARBON SOURCE (S)		1.0	
	TIMING (T)		1.0	
	MIGRATION (M)		1.0	
	POTENTIAL RESERVOIR FACIES (R)		0.9	Possibly of limited areal extent
	PLAY PROBABILITY (SxTxMxR=MP)		0.9	
PROSPECT ATTRIBUTES	TRAP OCCURRENCE (TM)		0.3	Stratigraphic
	EFFECTIVE POROSITY (≥3%) (P)		0.9	
	HYDROCARBON ACCUMULATION (C)		0.9	
	PROSPECT PROBABILITY (TMxPxC=CP)		0.243	
HYDROCARBON VOLUME PARAMETERS	RESERVOIR LITHOLOGY	SAND	1.0	
		CARBONATE	0	
	HYDROCARBON MIX	GAS	0.7	Possible condensate in Tunalik
		OIL	0.3	

	FRACTILES / ATTRIBUTES	PROB. OF EQUAL TO OR GREATER THAN 100	95	75	50	25	5	0	COMMENTS
HYDROCARBON VOLUME PARAMETERS	AREA OF CLOSURE (x10^3 ACRES)	0.6	10	20	40	60	100	150	Mostly stratigraphic traps
	RESERVOIR THICKNESS (FT)	5	50	75	150	300	400	500	350' in Tunalik in three separate intervals
	EFFECTIVE POROSITY (%)	3	5	8	10	15	20	30	
	TRAP FILL (%)	1	9	20	30	45	75	100	Canadian data
	RESERVOIR DEPTH (x10^3 FT)	6	7	8.5	11	13.5	15	16	
	NUMBER OF DRILLABLE PROSPECTS	1	3	5	8	12	15	20	
	PROVED RESERVES (x10^6 BBLS; 10^{12} ft^3)							0	



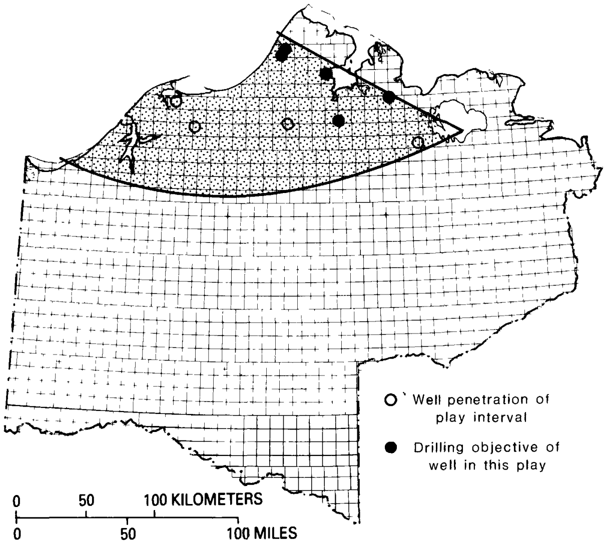
PROBABILITY (OF EQUAL TO OR GREATER THAN)	ESTIMATED RESOURCES IN PLACE OIL (MILLIONS OF BBLS)	GAS (BILLIONS OF CU FT)	BOE (MILLIONS OF BBLS)	ESTIMATED POOL SIZE (ASSUMING 100% OIL) (MILLIONS OF BBLS)
.95	0.00	0.00	0.00	0.00
.90	0.00	0.00	0.00	0.00
.75	0.00	0.00	0.00	0.00
.50	0.00	1621.97	482.81	0.00
.25	389.41	5515.94	1653.81	0.00
.10	1801.86	12495.56	3798.61	559.11
.05	3296.98	17640.94	5492.02	1384.51
.01	7781.40	31074.29	11214.90	4702.51
AVERAGE VALUES	612.20	4337.31	1373.13	253.30

FIGURE 4.12.—Tunalik play (shaded area) within the NPRA.

OIL AND GAS APPRAISAL DATA FORM

EVALUATOR: U.S. Geological Survey PLAY NAME: Simpson
DATE EVALUATED: 11/76 REVISED: 9/79, 5/80

	ATTRIBUTE		PROB. OF FAVORABLE							COMMENTS
PLAY ATTRIBUTES	HYDROCARBON SOURCE (S)		1.0							
	TIMING (T)		1.0							
	MIGRATION (M)		1.0							
	POTENTIAL RESERVOIR FACIES (R)		0.6							Poor permeability
	PLAY PROBABILITY (SxTxMxR=MP)		0.6							
PROSPECT ATTRIBUTES	TRAP OCCURRENCE (TM)		0.2							
	EFFECTIVE POROSITY (≥3%) (P)		0.9							
	HYDROCARBON ACCUMULATION (C)		0.9							
	PROSPECT PROBABILITY (TMxPxC=CP)		0.162							
HYDROCARBON VOLUME PARAMETERS	RESERVOIR LITHOLOGY	SAND	1.0							
		CARBONATE	0							
	HYDROCARBON MIX	GAS	0.4							Gas in So.Simpson. Geochemistry suggests oil-prone source
		OIL	0.6							
	FRACTILES / ATTRIBUTES		PROB. OF EQUAL TO OR GREATER THAN							
			100	95	75	50	25	5	0	
	AREA OF CLOSURE ($x10^3$ ACRES)		0.6	20	40	80	100	150	250	One large stratigraphic trap and potential for several smaller ones
	RESERVOIR THICKNESS (FT)		5	50	75	90	100	120	150	
	EFFECTIVE POROSITY (%)		3	5	8	10	15	20	25	
	TRAP FILL (%)		1	10	20	30	45	75	100	Canadian data
	RESERVOIR DEPTH ($x10^3$ FT)		1.5	2	4	6	8	10	15	
NUMBER OF DRILLABLE PROSPECTS			1	1	1	2	3	4	6	Structural closure at So. Simpson
PROVED RESERVES ($x10^6$ BBLS; 10^{12} ft^3)			0							



PROBABILITY (OF EQUAL TO OR GREATER THAN)	ESTIMATED RESOURCES IN PLACE OIL (MILLIONS OF BBLS)	GAS (BILLIONS OF CU FT)	BOE (MILLIONS OF BBLS)	ESTIMATED POOL SIZE (ASSUMING 100% OIL) (MILLIONS OF BBLS)
.95	0.00	0.00	0.00	0.00
.90	0.00	0.00	0.00	0.00
.75	0.00	0.00	0.00	0.00
.50	0.00	0.00	0.00	0.00
.25	0.00	0.00	0.00	0.00
.10	0.00	313.30	252.50	0.00
.05	879.92	938.48	1058.41	673.52
.01	2997.71	3068.42	3213.70	2641.00
AVERAGE VALUES	130.25	161.69	158.62	114.52

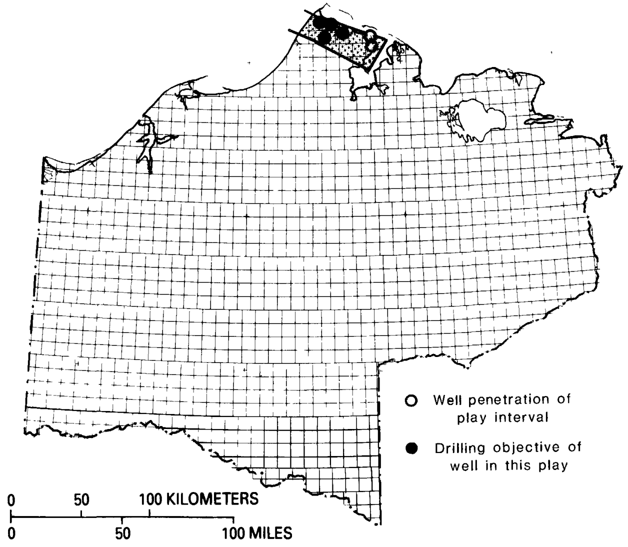
FIGURE 4.13.—Simpson play (shaded area) within the NPRA.

OIL AND GAS APPRAISAL DATA FORM

EVALUATOR: U.S. Geological Survey PLAY NAME: Barrow (Jurassic 1)
DATE EVALUATED: 11/78 REVISED: 11/78, 5/79, 9/79

	ATTRIBUTE		PROB. OF FAVORABLE	COMMENTS
PLAY ATTRIBUTES	HYDROCARBON SOURCE (S)		1.0	
	TIMING (T)		1.0	
	MIGRATION (M)		1.0	
	POTENTIAL RESERVOIR FACIES (R)		1.0	
	PLAY PROBABILITY (SxTxMxR=MP)		1.0	Barrow gas fields
PROSPECT ATTRIBUTES	TRAP OCCURRENCE (TM)		0.9	
	EFFECTIVE POROSITY (≥3%) (P)		0.9	
	HYDROCARBON ACCUMULATION (C)		0.8	
	PROSPECT PROBABILITY (TMxPxC=CP)		0.648	
HYDROCARBON VOLUME PARAMETERS	RESERVOIR LITHOLOGY	SAND	1.0	
		CARBONATE	0	
	HYDROCARBON MIX	GAS	0.9	
		OIL	0.1	

	FRACTILES / ATTRIBUTES	PROB. OF EQUAL TO OR GREATER THAN 100	95	75	50	25	5	0	COMMENTS
HYDROCARBON VOLUME PARAMETERS	AREA OF CLOSURE ($\times 10^3$ ACRES)	0.6	0.7	1	1.5	2	2.8	3	Utilized Tetra Tech numbers
	RESERVOIR THICKNESS (FT)	5	8	12	18	25	30	40	
	EFFECTIVE POROSITY (%)	10	11	15	20	25	29	30	
	TRAP FILL (%)	1	5	23	45	67	65	90	
	RESERVOIR DEPTH ($\times 10^3$ FT)	2	2.1	2.3	2.6	2.9	3.3	4	
	NUMBER OF DRILLABLE PROSPECTS	6	7	8	9	11	13	15	
	PROVED RESERVES (10^{12} ft^3)						remaining:	0.014 0.012	South Barrow East Barrow



PROBABILITY (OF EQUAL TO OR GREATER THAN)	ESTIMATED RESOURCES IN PLACE OIL (MILLIONS OF BBLS)	GAS (BILLIONS OF CU FT)	BOE (MILLIONS OF BBLS)	ESTIMATED POOL SIZE (ASSUMING 100% OIL) (MILLIONS OF BBLS)
.95	0.00	11.12	2.86	0.00
.90	0.00	15.87	3.83	0.00
.75	0.00	25.35	6.41	0.00
.50	0.00	39.50	10.78	3.89
.25	10.27	58.10	18.90	12.78
.10	27.17	77.90	35.08	26.09
.05	39.92	90.03	49.06	37.36
.01	73.82	119.11	78.91	65.31
AVERAGE VALUES	8.26	43.92	15.96	9.27

FIGURE 4.14.—Barrow play (shaded area) within the NPRA.

range. Reservoir depth in the play ranges from 600 to 1,200 m (2,000-4,000 ft).

Geochemical data indicate that the Kingak and the unconformably overlying pebble shale unit are fair to good source rocks but are immature (see Magoon and Bird, chapter 17). The South Barrow and East Barrow gas fields are in this play (Lantz, 1981). Carbon-isotope data seem to indicate that these accumulations are thermal gas, and not biogenic gas, as expected from the surrounding immature shale.

Most traps are structural and consist of low-amplitude domes surrounding the so-called disturbed zone—a circular area southeast of Barrow village in which seismic reflections are poor or nonexistent. Other structures in this play are associated with faults.

SAG RIVER PLAY

The Sag River play, in sandstone reservoirs of latest Triassic age having stratigraphic and structural traps, is in the Sag River Sandstone. This formation, a marine blanket sandstone situated between the Kingak Shale and the Shublik Formation, ranges in thickness from 90 m (300 ft) in the northern part of the play area to 0 in the southern part (see Bird, chapter 16). East of Barrow, the coastline approximates the truncation edge of the Sag River along the pebble shale unconformity. The south boundary of the play area is the estimated downdip limit of sandstone (fig. 4.15).

The reservoir sandstone is as much as 45 m (150 ft) thick and consists of fine-grained, glauconitic quartz sand. Both porosity, which is as high as 25 percent, and thickness are greatest in the northeastern part of the play; they decrease to the south. Reservoir depths range from 610 m (2,000 ft) in the north to 4,000 m (13,000 ft) in the south.

Geochemical data indicate that the overlying Kingak Shale and the underlying Shublik Formation are fair to good source rocks. They are immature in the north half of the play but mature in the south half (see Magoon and Bird, chapter 17). Low-gravity asphaltic oil is present in most Barrow-area wells that penetrate the Sag River Sandstone. This formation is part of the productive interval in the Prudhoe Bay field.

Structural traps in this play are fairly rare except at Barrow. Stratigraphic traps may be present along the truncation edge, but traps related to facies changes are considered unlikely because of the blanketlike nature of this formation. The overlying Kingak and pebble shale unit are expected to provide adequate seals.

SADLEROCHIT PLAYS

The Sadlerochit plays, in sandstone reservoirs of Triassic age having structural and stratigraphic traps, are in the Ivishak Formation of the Sadlerochit Group. The Ivishak Formation consists of nonmarine sandstone, conglomerate, and shale in its northernmost occurrences; it grades southward into marine sandstone and shale. The Sadlerochit Group overlaps the Lisburne and Endicott Groups to the north and lies on the basement south of Barrow along its onlap edge. This onlap edge trends northeast through the Simpson peninsula. Offshore, the onlap edge is apparently truncated by the pebble shale unconformity. Two plays were established in the Sadlerochit on the basis of the relations of source rocks to reservoir rocks. In play I, the Sadlerochit is in contact with the pebble shale unit (offshore). In play II, the Sadlerochit is downdip from play I and not in contact with the pebble shale unit. The south boundary of play II is the estimated downdip limit of sandstone deposition (figs. 4.16, 4.17).

Reservoir rocks include fluvial to shallow-marine quartzose sandstone and minor amounts of conglomerate. The reservoir sandstone may be as much as 120 m (400 ft) thick. Porosity ranges from 4 to 15 percent in play I and from 4 to 20 percent in play II. A 12-m (40-ft) interval at 3,960 m (13,000 ft) in the Inigok No. 1 well has a 20-percent porosity, anomalously high for that depth. Reservoir depth ranges from 1,980 to 2,590 m (6,500-8,500 ft) in play I and from 2,590 to 6,000 m (8,500-20,000 ft) in play II. The main producing reservoir in the Prudhoe Bay field is the Ivishak Formation.

Potential source rocks in play I include the pebble shale unit (offshore), the Shublik Formation, and the Kavik Member of the Ivishak. In play II, only the latter two units are potential source rocks. Geochemical data indicate that the pebble shale unit and Shublik Formation are fair to good source rocks and that the Kavik is a poor source rock (see Magoon and Bird, chapter 17). The pebble shale unit is immature in play I and, presumably, offshore. The Shublik and Kavik are mature in play I and mature to overmature in play II. Oil-stained sandstone occurs in several wells in play I, and a small amount of oil was recovered from the Dalton No. 1 well. Oil and gas indications are rare in play II.

Structural traps are uncommon in both plays. Wells drilled on the Simpson peninsula (play I) for a stratigraphic trap were unsuccessful in locating a significant hydrocarbon accumulation.

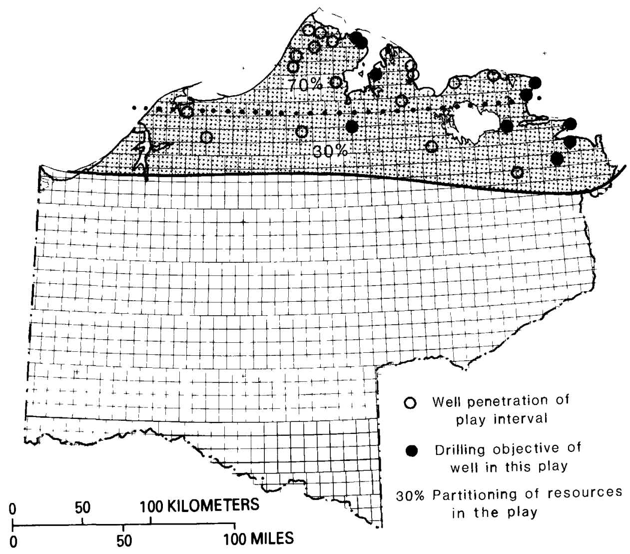
LISBURNE PLAY

The Lisburne play, in carbonate or clastic reservoirs of Mississippian to Permian age having structural and stratigraphic traps, includes the autochthonous Lisburne Group in the NPRA. The allochthonous Lisburne, in the Brooks Range and

OIL AND GAS APPRAISAL DATA FORM

EVALUATOR: U.S. Geological Survey PLAY NAME: Sag River
DATE EVALUATED: 11/78 REVISED: 11/78, 5/79, 9/79

	ATTRIBUTE		PROB. OF FAVORABLE	100	95	75	50	25	5	0	COMMENTS
PLAY ATTRIBUTES	HYDROCARBON SOURCE (S)		1.0								Oil shows in Barrow 12, 17, 19, and Iko
	TIMING (T)		1.0								
	MIGRATION (M)		1.0								
	POTENTIAL RESERVOIR FACIES (R)		0.7								New core data shows low perm.
	PLAY PROBABILITY (SxTxMxR=MP)		0.7								
PROSPECT ATTRIBUTES	TRAP OCCURRENCE (TM)		0.3								
	EFFECTIVE POROSITY (≥3%) (P)		0.9								
	HYDROCARBON ACCUMULATION (C)		0.9								
	PROSPECT PROBABILITY (TMxPxC=CP)		0.243								
HYDROCARBON VOLUME PARAMETERS	RESERVOIR LITHOLOGY	SAND	1.0								
		CARBONATE	0								
	HYDROCARBON MIX	GAS	0.2								
		OIL	0.8								
	ATTRIBUTES / FRACTILES	PROB. OF EQUAL TO OR GREATER THAN		100	95	75	50	25	5	0	
	AREA OF CLOSURE ($x10^3$ ACRES)			0.6	1	3	6	8	10	25	
	RESERVOIR THICKNESS (FT)			5	30	60	90	120	140	170	
	EFFECTIVE POROSITY (%)			3	8	10	12	15	20	25	Glauconitic ss: standard porosity vs. permeability relations may not hold
	TRAP FILL (%)			1	15	30	45	55	70	95	
	RESERVOIR DEPTH ($x10^3$ FT)			2	5	8	9	10	11	13	
NUMBER OF DRILLABLE PROSPECTS				4	5	6	8	12	15	20	
PROVED RESERVES ($x10^8$ BBLS; 10^{12} ft^3)			0								



PROBABILITY (OF EQUAL TO OR GREATER THAN)	ESTIMATED RESOURCES IN PLACE OIL (MILLIONS OF BBLS)	GAS (BILLIONS OF CU FT)	BOE (MILLIONS OF BBLS)	ESTIMATED POOL SIZE (ASSUMING 100% OIL) (MILLIONS OF BBLS)
.95	0.00	0.00	0.00	0.00
.90	0.00	0.00	0.00	0.00
.75	0.00	0.00	0.00	0.00
.50	28.20	55.01	52.55	0.00
.25	190.20	251.33	240.13	0.00
.10	398.54	481.31	477.80	54.56
.05	553.65	669.51	657.04	130.99
.01	960.35	1216.22	1103.59	334.50
AVERAGE VALUES	133.00	169.10	162.67	19.50

FIGURE 4.15.—Sag River play (shaded area) within the NPRA.

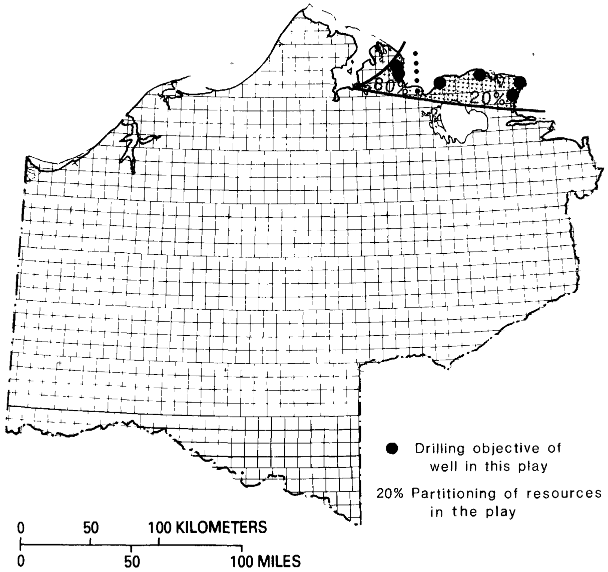
OIL AND GAS APPRAISAL DATA FORM

EVALUATOR: U.S. Geological Survey PLAY NAME: Sadlerochit 1

DATE EVALUATED: 11/78 REVISED: 11/78, 5/79, 9/79, 5/80

	ATTRIBUTE		PROB. OF FAVORABLE	COMMENTS
PLAY ATTRIBUTES	HYDROCARBON SOURCE (S)		1.0	
	TIMING (T)		0.7	
	MIGRATION (M)		1.0	Immature pebble shale unit overlying truncation
	POTENTIAL RESERVOIR FACIES (R)		0.8	
	PLAY PROBABILITY (SxTxMxR=MP)		0.56	
PROSPECT ATTRIBUTES	TRAP OCCURRENCE (TM)		0.4	Stratigraphic trap by onlap/truncation
	EFFECTIVE POROSITY (≥3%) (P)		0.9	
	HYDROCARBON ACCUMULATION (C)		0.5	See migration above
	PROSPECT PROBABILITY (TMxPxC=CP)		0.18	
HYDROCARBON VOLUME PARAMETERS	RESERVOIR LITHOLOGY	SAND	1.0	
		CARBONATE	0.0	
	HYDROCARBON MIX	GAS	0.2	Oil shows in Drew Pt., East Simpson, Foran, and Dalton
		OIL	0.8	

	FRACTILES / ATTRIBUTES	PROB. OF EQUAL TO OR GREATER THAN							COMMENTS
		100	95	75	50	25	5	0	
HYDROCARBON VOLUME PARAMETERS	AREA OF CLOSURE (x10^3 ACRES)	0.8	5	18	35	60	70	90	
	RESERVOIR THICKNESS (FT)	5	100	200	250	300	350	400	
	EFFECTIVE POROSITY (%)	3	4	6	8	10	15	22	
	TRAP FILL (%)	1	5	22	45	55	70	95	
	RESERVOIR DEPTH (x10^3 FT)	6.5	6.6	7.0	7.5	8.0	8.4	8.5	
	NUMBER OF DRILLABLE PROSPECTS	0	0	0	1	1	1	2	
	PROVED RESERVES (x10^6 BBLS; 10^{12} ft^3)								



PROBABILITY (OF EQUAL TO OR GREATER THAN)	ESTIMATED RESOURCES IN PLACE OIL (MILLIONS OF BBLS)	ESTIMATED RESOURCES IN PLACE GAS (BILLIONS OF CU FT)	ESTIMATED RESOURCES IN PLACE BOE (MILLIONS OF BBLS)	ESTIMATED POOL SIZE (ASSUMING 100% OIL) (MILLIONS OF BBLS)
.95	0.00	0.00	0.00	0.00
.90	0.00	0.00	0.00	0.00
.75	0.00	0.00	0.00	0.00
.50	0.00	0.00	0.00	0.00
.25	0.00	0.00	0.00	0.00
.10	0.00	19.57	21.87	30.02
.05	529.11	647.55	646.45	868.20
.01	3312.63	2834.94	3670.77	3717.26
AVERAGE VALUES	121.59	120.27	142.69	149.09

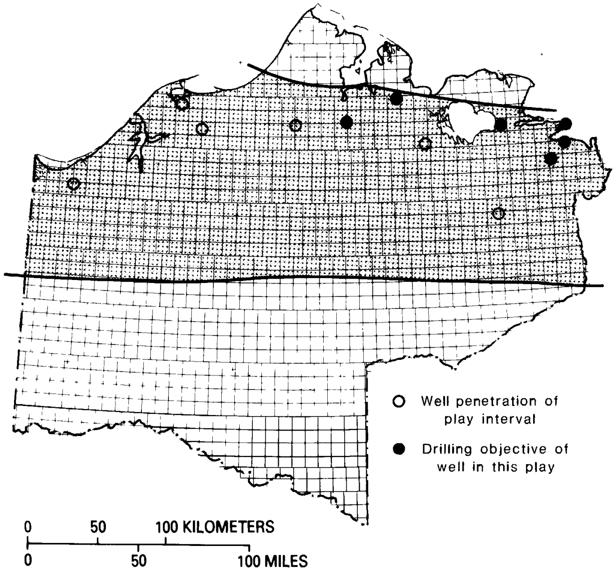
FIGURE 4.16.—Sadlerochit I play (shaded area) within the NPRA.

OIL AND GAS APPRAISAL DATA FORM

EVALUATOR: U.S. Geological Survey
PLAY NAME: Sadlerochit 2
DATE EVALUATED: 11/78
REVISED: 11/78, 5/79, 9/79

	ATTRIBUTE		PROB. OF FAVORABLE	COMMENTS
PLAY ATTRIBUTES	HYDROCARBON SOURCE (S)		0.8	
	TIMING (T)		1.0	
	MIGRATION (M)		1.0	
	POTENTIAL RESERVOIR FACIES (R)		0.7	
	PLAY PROBABILITY (SxTxMxR=MP)		0.56	
PROSPECT ATTRIBUTES	TRAP OCCURRENCE (TM)		0.5	
	EFFECTIVE POROSITY (≥3%) (P)		0.4	
	HYDROCARBON ACCUMULATION (C)		0.4	
	PROSPECT PROBABILITY (TMxPxC=CP)		0.08	
HYDROCARBON VOLUME PARAMETERS	RESERVOIR LITHOLOGY	SAND	1.0	
		CARBONATE	0.0	
	HYDROCARBON MIX	GAS	0.7	
		OIL	0.3	

	FRACTILES / ATTRIBUTES	PROB. OF EQUAL TO OR GREATER THAN 100	95	75	50	25	5	0	COMMENTS
HYDROCARBON VOLUME PARAMETERS	AREA OF CLOSURE ($\times 10^3$ ACRES)	0.6	0.7	1	1.8	4.6	6	10	
	RESERVOIR THICKNESS (FT)	5	25	50	75	100	200	400	
	EFFECTIVE POROSITY (%)	3	4	5	6	12	20	25	20% porosity at 13,000 ft in Inigok
	TRAP FILL (%)	1	3	6	10	15	20	90	Similar to Torok play because of low φ
	RESERVOIR DEPTH ($\times 10^3$ FT)	8.5	8.7	9.8	11	14	17	20	
NUMBER OF DRILLABLE PROSPECTS		8	9	10	12	14	16	25	
PROVED RESERVES ($\times 10^6$ BBLS; 10^{12} ft^3)		NONE							



PROBABILITY (OF EQUAL TO OR GREATER THAN)	ESTIMATED RESOURCES IN PLACE OIL (MILLIONS OF BBLS)	GAS (BILLIONS OF CU FT)	BOE (MILLIONS OF BBLS)	ESTIMATED POOL SIZE (ASSUMING 100% OIL) (MILLIONS OF BBLS)
.95	0.00	0.00	0.00	0.00
.90	0.00	0.00	0.00	0.00
.75	0.00	0.00	0.00	0.00
.50	0.00	0.00	0.00	0.00
.25	0.00	5.69	1.40	0.00
.10	.48	29.94	7.62	0.00
.05	4.87	61.02	16.17	0.00
.01	29.02	187.48	49.40	9.48
AVERAGE VALUES	1.11	12.47	3.29	.41

FIGURE 4.17.—Sadlerochit II play (shaded area) within the NPRA.

foothills, is assessed in the disturbed-belt play. The area of the Lisburne play extends from the onlap limit or coastline in the north to the NPRA boundary in the south (fig. 4.18). The Lisburne Group is partly a lateral equivalent of the autochthonous Endicott Group and becomes younger to the north and west. The Lisburne either onlaps the basement or grades laterally into a clastic facies (Endicott Group) along the line marking the north play boundary. It is overlain by the Sadlerochit Group. The Lisburne is composed of shallow-marine limestone and dolomite and minor amounts of shale and sandstone. Its thickness varies; the maximum is about 1,200 m (4,000 ft).

Potential reservoir rocks include dolomite, limestone, and sandstone. Dolomite, the most important reservoir rock, is expected to be most abundant in the Upper Mississippian part of the Lisburne, as at Prudhoe Bay (Bird and Jordan, 1977). This expectation has been confirmed in several wells in the eastern part of the NPRA, and porosity there ranges from 10 to 15 percent. Dolomite of this age is not expected in the northernmost or western parts of the NPRA because the Lisburne is onlapping. Porous limestone is very rare in the Lisburne and is unlikely to be present in the play. Sandstone may be common along the onlap edge, but much of it is partially to completely cemented with calcite and thus becomes a questionable reservoir. Depth to the top of the Lisburne in this play ranges from 2,500 m (8,300 ft) to about 10,700 m (35,000 ft). The Lisburne is oil bearing at Prudhoe Bay.

Potential source rocks include marine shale in the overlying Sadlerochit Group, marine shale and limestone within the Lisburne, and marine shale and coal in the underlying Endicott Group. Limited geochemical data seem to indicate that all are fair to poor, gas-prone source rocks that are mature in the north quarter of the play area and, by projection, overmature in the south three-quarters (see Magoon and Bird, chapter 17). A few barrels of low-gravity asphaltic oil was recovered from interbedded sandstone and limestone in the Dalton No. 1 well. Black oil residue is common in porous dolomite in the Lisburne. Hydrogen sulfide gas, from interbedded limestone and shale at the base of the Lisburne, was encountered in the Inigok No. 1 well.

Stratigraphic traps related to the onlap edge and to facies changes are expected in the northern part of the play area. Structural traps, fairly rare in the north, are much more common in the southern part, but generally deeper than 4,600 m (15,000 ft). Interbedded shale and impermeable limestone are expected to provide adequate seals.

PRE-LISBURNE PLAY

The pre-Lisburne play is in sandstone, conglomerate, and, possibly, dolomite and limestone reservoirs of Mississippian and Pennsylvanian age (see Bird, chapter 15), which have stratigraphic and structural traps, that are assigned to the autochthonous Endicott Group (fig. 4.19). The allochthonous Endicott Group is assessed in the disturbed-belt play. The pre-Lisburne play was established and named before any wells in the play area had penetrated these rocks. Drilling of the Inigok No. 1 and Ikpikpuk No. 1 wells led to the belief that the rocks of this interval are typical Endicott Group. They consist of a lower, nonmarine, coal-bearing sequence of sandstone, conglomerate, and shale (Kekiktuk Conglomerate) gradationally overlain by marine shale containing interbedded sandstone at the base and limestone at the top (Kayak Shale). The irregular north play boundary outlines the basinal areas where the Endicott is supposed to be thickest. Seismic-reflection data indicate that the Endicott ranges in thickness from near 0 at the basin margins to nearly 3,000 m (10,000 ft) in the basin center (see Bird, chapter 16).

Potential reservoir rocks include sandstone, conglomerate, dolomite, and limestone. Sandstone and conglomerate with low (max 10 percent) porosity are expected to be the most common reservoir rock types. Dolomite and limestone, also probably with low porosity, are expected to make up a small, but unknown, amount of the basin fill. Depth to the top of the Endicott Group ranges from 3,350 m (11,000 ft) to more than 9,100 m (30,000 ft).

Potential source rocks, all overmature and apparently gas prone, are coal and marine shale (see Magoon and Bird, chapter 17). Except for gas associated with coal beds, no hydrocarbon shows are known. Hydrogen sulfide gas was encountered at the Lisburne-Endicott transition in the Inigok No. 1 well.

Numerous large structures have been mapped seismically, and the Inigok No. 1 well was a test of one of these. Stratigraphic traps related to facies changes may also be present.

DISTURBED-BELT PLAY

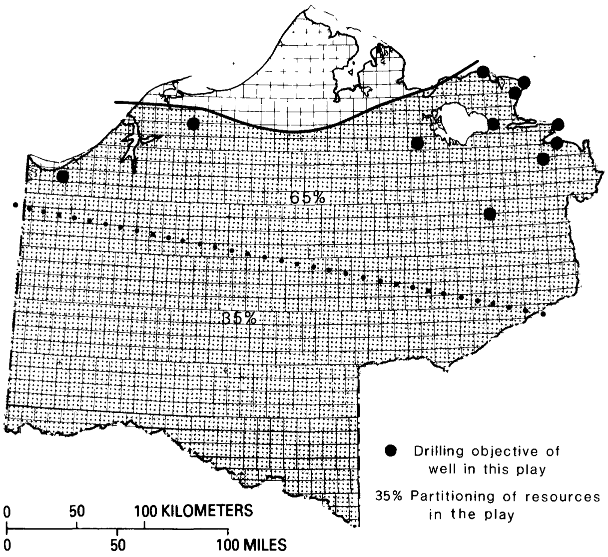
The disturbed-belt play consists of stratigraphic and structural traps in clastic, carbonate, and siliceous rocks of Devonian to Cretaceous age that include all the allochthonous rocks in the Brooks Range and adjacent foothills. This play area is characterized by extreme structural complexity related to low-angle, northward-directed thrust faults. The north boundary of the play area is drawn north of outcropping allochthonous rocks, and the south boundary is the south border of the NPRA (fig. 4.20). The thickness of the alloch-

OIL AND GAS APPRAISAL DATA FORM

EVALUATOR: U.S. Geological Survey PLAY NAME: Lisburne
DATE EVALUATED: 11/78 REVISED: 11/78, 5/79, 9/79, 5/80

	ATTRIBUTE		PROB. OF FAVORABLE	COMMENTS
PLAY ATTRIBUTES	HYDROCARBON SOURCE (S)		0.8	
	TIMING (T)		1.0	
	MIGRATION (M)		1.0	
	POTENTIAL RESERVOIR FACIES (R)		0.8	
	PLAY PROBABILITY (SxTxMxR=MP)		0.64	
PROSPECT ATTRIBUTES	TRAP OCCURRENCE (TM)		0.8	
	EFFECTIVE POROSITY (≥3%) (P)		0.1	
	HYDROCARBON ACCUMULATION (C)		0.6	
	PROSPECT PROBABILITY (TMxPxC=CP)		0.048	
HYDROCARBON VOLUME PARAMETERS	RESERVOIR LITHOLOGY	SAND	0.0	10% chance of sandstone reservoir anywhere in section
		CARBONATE	1.0	
	HYDROCARBON MIX	GAS	0.9	Recovered 5 bbls heavy oil from Dalton
		OIL	0.1	

	ATTRIBUTES / FRACTILES	PROB. OF EQUAL TO OR GREATER THAN							COMMENTS
		100	95	75	50	25	5	0	
HYDROCARBON VOLUME PARAMETERS	AREA OF CLOSURE ($\times 10^3$ ACRES)	0.6	15	30	40	80	90	100	
	RESERVOIR THICKNESS (FT)	5	40	100	200	300	500	1,500	Multiple dolomite reservoirs maximum thickness ~100′
	EFFECTIVE POROSITY (%)	3	3.2	4	5	6	7	12	Fracture porosity included
	TRAP FILL (%)	1	3	8	12	18	38	100	Canadian data
	RESERVOIR DEPTH ($\times 10^3$ FT)	8.3	9.5	12	16	26	33	35	
	NUMBER OF DRILLABLE PROSPECTS	50	55	60	70	80	90	110	
	PROVED RESERVES ($\times 10^6$ BBLS; 10^{12} ft^3)	NONE							



PROBABILITY (OF EQUAL TO OR GREATER THAN)	ESTIMATED RESOURCES IN PLACE OIL (MILLIONS OF BBLS)	GAS (BILLIONS OF CU FT)	BOE (MILLIONS OF BBLS)	ESTIMATED POOL SIZE (ASSUMING 100% OIL) (MILLIONS OF BBLS)
.95	0.00	0.00	0.00	0.00
.90	0.00	0.00	0.00	0.00
.75	0.00	0.00	0.00	0.00
.50	0.00	795.92	148.68	0.00
.25	0.00	2684.83	507.94	0.00
.10	0.00	5585.66	1095.10	0.00
.05	122.89	8070.76	1606.79	0.00
.01	856.85	15912.81	3200.43	195.17
AVERAGE VALUES	36.85	2032.78	393.48	7.77

FIGURE 4.18.—Lisburne play (shaded area) within the NPRA.

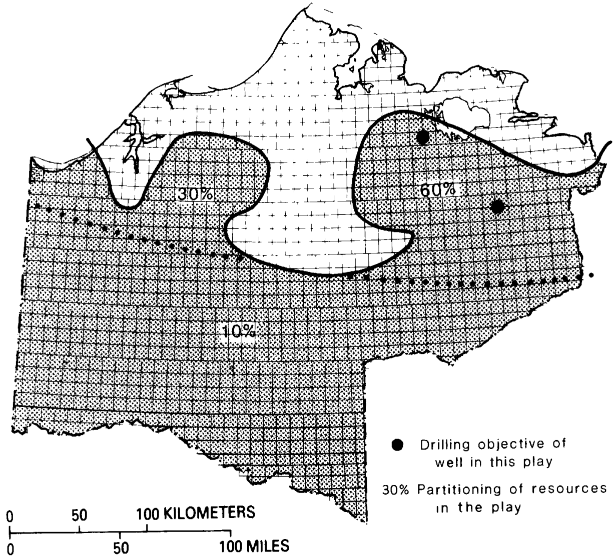
OIL AND GAS APPRAISAL DATA FORM

EVALUATOR: U.S. Geological Survey PLAY NAME: Pre-Lisburne

DATE EVALUATED: 11/78 REVISED: 11/78, 5/79

	ATTRIBUTE		PROB. OF FAVORABLE	COMMENTS
PLAY ATTRIBUTES	HYDROCARBON SOURCE (S)		1.0	Coal in Inigok well
	TIMING (T)		0.6	
	MIGRATION (M)		0.6	
	POTENTIAL RESERVOIR FACIES (R)		0.5	
	PLAY PROBABILITY (SxTxMxR=MP)		0.18	
PROSPECT ATTRIBUTES	TRAP OCCURRENCE (TM)		0.8	
	EFFECTIVE POROSITY (≥3%) (P)		0.05	
	HYDROCARBON ACCUMULATION (C)		0.25	
	PROSPECT PROBABILITY (TMxPxC=CP)		0.01	
HYDROCARBON VOLUME PARAMETERS	RESERVOIR LITHOLOGY	SAND	1.0	Possibly 10% carbonate rocks
		CARBONATE	0.0	
	HYDROCARBON MIX	GAS	1.0	
		OIL	0.0	

	ATTRIBUTES \ FRACTILES	PROB. OF EQUAL TO OR GREATER THAN 100	95	75	50	25	5	0	COMMENTS
HYDROCARBON VOLUME PARAMETERS	AREA OF CLOSURE ($x10^3$ ACRES)	0.6	5	15	25	60	120	130	
	RESERVOIR THICKNESS (FT)	5	10	50	100	200	300	900	
	EFFECTIVE POROSITY (%)	3	3.2	4	5	6	7	10	
	TRAP FILL (%)	1	3	10	20	55	83	90	
	RESERVOIR DEPTH ($x10^3$ FT)	11	12	15	18	29	38	40	
	NUMBER OF DRILLABLE PROSPECTS	47	52	66	84	105	122	126	
	PROVED RESERVES ($x10^6$ BBLS; 10^{12} ft^3)	NONE							



● Drilling objective of well in this play

30% Partitioning of resources in the play

PROBABILITY (OF EQUAL TO OR GREATER THAN)	ESTIMATED RESOURCES IN PLACE OIL (MILLIONS OF BBLS)	GAS (BILLIONS OF CU FT)	BOE (MILLIONS OF BBLS)	ESTIMATED POOL SIZE (ASSUMING 100% OIL) (MILLIONS OF BBLS)
.95	0.00	0.00	0.00	0.00
.90	0.00	0.00	0.00	0.00
.75	0.00	0.00	0.00	0.00
.50	0.00	0.00	0.00	0.00
.25	0.00	0.00	0.00	0.00
.10	0.00	0.00	0.00	0.00
.05	0.00	414.42	72.71	0.00
.01	0.00	3790.10	664.93	0.00
AVERAGE VALUES	0.00	144.66	25.38	.41

FIGURE 4.19.—Pre-Lisburne play (shaded area) within the NPRA.

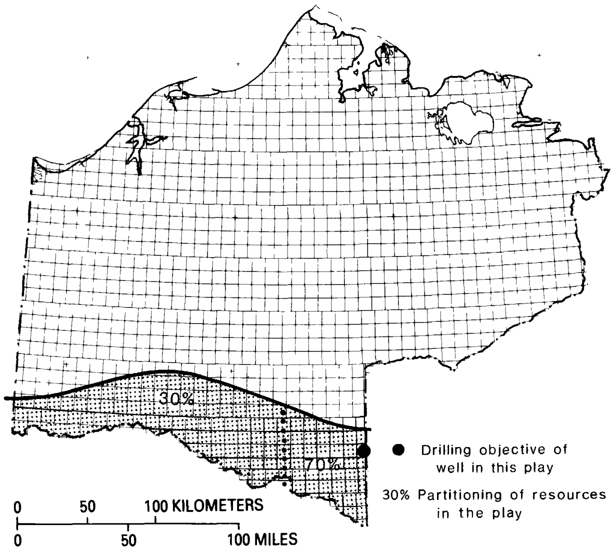
OIL AND GAS APPRAISAL DATA FORM

EVALUATOR: U.S. Geological Survey PLAY NAME: Disturbed belt

DATE EVALUATED: 11/78 REVISED: 11/78, 9/79, 5/80

	ATTRIBUTE		PROB. OF FAVORABLE	COMMENTS
PLAY ATTRIBUTES	HYDROCARBON SOURCE (S)		1.0	
	TIMING (T)		0.5	
	MIGRATION (M)		1.0	
	POTENTIAL RESERVOIR FACIES (R)		0.5	
	PLAY PROBABILITY (SxTxMxR=MP)		0.25	
PROSPECT ATTRIBUTES	TRAP OCCURRENCE (TM)		0.4	
	EFFECTIVE POROSITY (≥3%) (P)		0.7	
	HYDROCARBON ACCUMULATION (C)		0.7	
	PROSPECT PROBABILITY (TMxPxC=CP)		0.196	
HYDROCARBON VOLUME PARAMETERS	RESERVOIR LITHOLOGY	SAND	0.0	Up to 5% sandstone possible
		CARBONATE	1.0	
	HYDROCARBON MIX	GAS	0.7	
		OIL	0.3	

	ATTRIBUTES \ FRACTILES	PROB. OF EQUAL TO OR GREATER THAN 100	95	75	50	25	5	0	COMMENTS
HYDROCARBON VOLUME PARAMETERS	AREA OF CLOSURE ($\times 10^3$ ACRES)	1	9	17	25	33	41	49	Numbers directly from Tetra Tech "Lisburne thrust belt" form
	RESERVOIR THICKNESS (FT)	5	25	175	250	350	500	1,000	
	EFFECTIVE POROSITY (%)	3	3.2	4	6	8	12	20	
	TRAP FILL (%)	1	3	8	12	18	38	100	Canadian data
	RESERVOIR DEPTH ($\times 10^3$ FT)	1	4	7	10	15	27	35	See note above
	NUMBER OF DRILLABLE PROSPECTS	3	4	7	10	13	16	20	See note above
	PROVED RESERVES ($\times 10^6$ BBLS; 10^{12} ft^3)	NONE							



PROBABILITY (OF EQUAL TO OR GREATER THAN)	ESTIMATED RESOURCES IN PLACE OIL (MILLIONS OF BBLS)	GAS (BILLIONS OF CU FT)	BOE (MILLIONS OF BBLS)	ESTIMATED POOL SIZE (ASSUMING 100% OIL) (MILLIONS OF BBLS)
.95	0.00	0.00	0.00	0.00
.90	0.00	0.00	0.00	0.00
.75	0.00	0.00	0.00	0.00
.50	0.00	0.00	0.00	0.00
.25	0.00	0.00	0.00	0.00
.10	0.00	764.96	208.38	0.00
.05	136.46	1632.59	460.28	0.00
.01	979.76	4731.89	1416.28	384.53
AVERAGE VALUES	34.60	267.89	81.60	14.41

FIGURE 4.20.—Disturbed-belt play (shaded area) within the NPRA.

thonous-rock interval is expected to be 0 along the north play boundary and to increase southward. The Lisburne No. 1 well, 5,181 m (17,000 ft) deep, incompletely penetrated the allochthonous section. Thrust faulting is believed to have telescoped different rock facies and to have juxtaposed these allochthonous rocks with autochthonous marine sedimentary rocks of Cretaceous age.

Potential reservoir rocks include various rock types. The types with greatest potential are dolomite and recrystallized limestone of the Lisburne Group (Armstrong, 1970). Other rocks with less potential include Devonian and Triassic limestone; Devonian, Mississippian, and Cretaceous sandstone; and, possibly, fractured chert and siliceous shale of Mississippian to Jurassic age. The Lisburne No. 1 well penetrated five thrust repetitions of the Lisburne Group. Each repetition is about 360 m (1,200 ft) thick; in some intervals, the porosity ranges from 10 to 15 percent. Depth to the Lisburne Group ranges from 0 to probably more than 6,000 m (20,000 ft).

Potential source rocks include marine shale of Mississippian to Cretaceous age. Some oil shales are known from this play (Tailleur, 1964), although they are considered to be small, abnormally rich local occurrences, not characteristic of the entire allochthonous section. Preliminary data from the Lisburne No. 1 well indicate that the Triassic rocks are fair to good source rocks that are mature to overmature. Most source rocks in this play are expected to be mature to overmature. However, the data are sparse, and the geology complex. Both structural and stratigraphic traps are expected.

RESULTS

The computer program described by Miller (chapter 5) generated resource estimates from the assessed geologic parameters recorded on the data forms. These estimates, all fully risked, are for inplace, undiscovered oil and gas and for a combination of both oil and gas defined as barrels-of-oil equivalent (BOE). Also provided are estimated hydrocarbon-pool sizes expressed in terms of barrels of oil. These resource and pool-size estimates are reported at seven probability levels (fractiles) and are presented for each play (figs. 4.4-4.20). Total resources for the NPRA (aggregated play estimates) are presented by Miller (chapter 5).

To facilitate comparison of the plays, the mean values for estimated resources and pool sizes are compiled in figure 4.21. They show estimated inplace resources of 200 million BOE or less for most plays. To convert the values for inplace hydrocarbons to estimates of economically recoverable hydrocarbons, one should consider the following: In 1979, for the NPRA, the minimum commercial pool sizes were estimated to be approximately 80 million bbl for recoverable oil and 1.1 trillion ft^3 for recoverable gas (U.S. Department of the Interior, 1979, table 1.2). Assuming 30-percent recovery for oil and 80-percent recovery for gas, these minimum commercial pool-size estimates convert to inplace pool sizes of 267 million bbl of oil and 1.38 trillion ft^3 of gas. The 1.38 trillion ft^3 of gas represents 242 million BOE, using the conversion factor of 1 bbl oil equals 5,700 ft^3 gas. According to these values, therefore, only 3 of the 17 plays would be expected to have commercially recoverable oil, and only 3 to have commercially recoverable gas. If the same comparison is made using the resources estimated at the 5-percent-probability level (5th fractile), then 9 of the 17 plays might be expected to have commercial oil and 6 to have commercial gas.

SUMMARY

The play method of resource appraisal was used to estimate the undiscovered hydrocarbon resources of the NPRA. After the initial assessment, three subsequent updates were made to incorporate new data and results that had been obtained during the ongoing drilling program. This report summarizes for each of 17 plays the geologic information and estimated resources from the third and most recent update (May 1980). The total estimated resources for the NPRA (the aggregate resources from all plays) is given by Miller (chapter 5).

The play method of resource appraisal has been judged successful on the basis of these features: (1) It can incorporate large numbers of objective data, (2) it provides a record of judgments concerning these data, and (3) it provides a means of modifying these judgments as new data are acquired.

GLOSSARY OF TERMS USED IN THE NPRA APPRAISAL

This glossary includes the terms used on the "Oil and Gas Appraisal Data Form" that was developed to appraise the undiscovered hydrocarbon resources of large frontier areas and was utilized in the assessment of the NPRA from 1978 to 1980. The terms are arranged alphabetically, and those terms printed in bold type in the definitions are themselves included in this glossary. Since the last appraisal (May 1980), I have modified the definitions, but the modifications are in style, not substance. The original definitions were by Mast and others (1980).

Area of closure. This **hydrocarbon-volume parameter** is an estimate of the possible range for the number of acres within a trap above the spill point. This parameter is evaluated by entering on the data form estimates for size of closure at seven probability levels (fractiles) ranging from 100 percent (total certainty that at least this value will be attained) to 0 percent (total certainty that this value will not be exceeded). Intermediate fractiles indicate the relative confidence (subjective probability) that the area of closure is at least as large as the recorded fractile value. **A minimum threshold value** of 600 acres is used at the 100th fractile, and the probability that this minimum value is achieved is incorporated in the **trap occurrence** (TM) judgment (**prospect attribute**). Data that can be used in the evaluation of this parameter include seismic mapping, surface geologic mapping, and analog comparison.

Effective porosity (percent). This **hydrocarbon-volume parameter** is an estimate of the possible range of values for the amount of interconnected void space of the reservoir rock in a randomly selected prospect. This parameter is evaluated by entering on the data form porosity estimates at seven probability levels (fractiles) ranging from 100 percent (total certainty that at least this value will be attained) to 0 percent (total certainty that this value will not be exceeded). Intermediate fractiles indicate the relative confidence (subjective probability) that the **effective porosity** (percent) is at least as large as the recorded fractile value. A **minimum threshold value** of 3 percent is used at the 100th fractile, and the probability that this minimum value is achieved is incorporated in the **effective porosity** (*P*) judgment (**prospect attribute**). Data used in the evaluation of this parameter are derived from measurement, calculation, projection, or analog comparison.

Effective porosity (*P*). This **prospect attribute** is an estimate of the probability of significant interconnected void space of a **potential reservoir facies** (*R*) capable of holding hydrocarbons. This at-

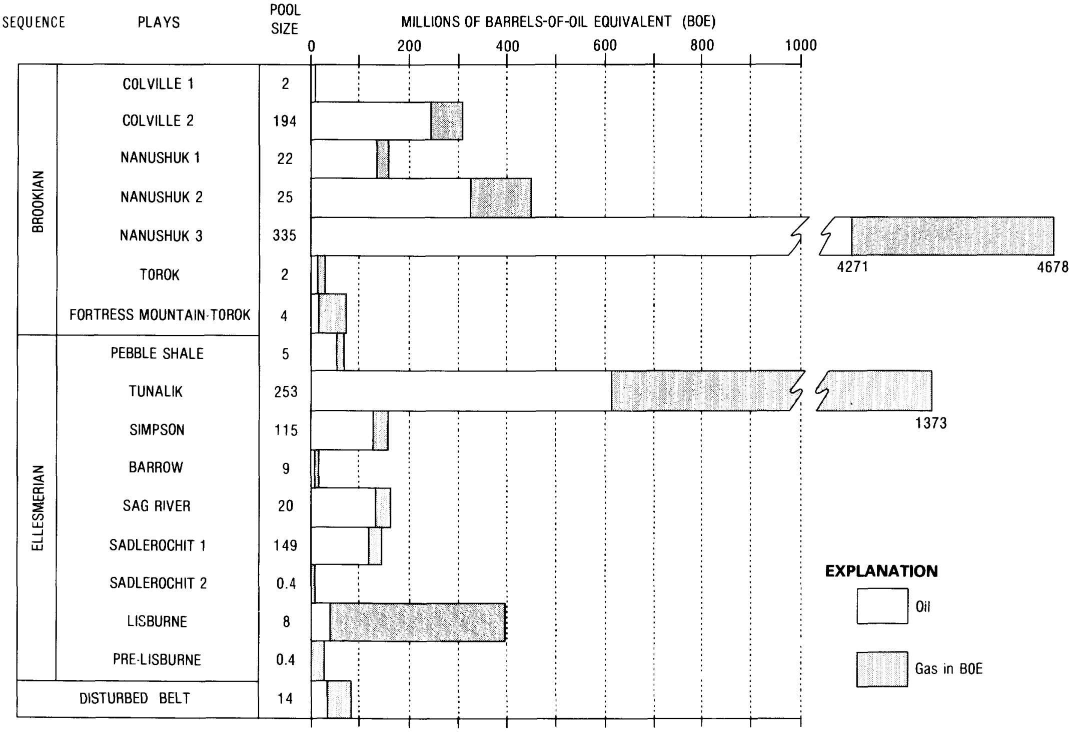


FIGURE 4.21.—Comparison of mean-value estimates of undiscovered inplace hydrocarbon resources and of pool sizes for plays in the NPRA. Mean values are from May 1980 appraisal. Oil and pool sizes are expressed in millions of barrels; gas, in barrels-of-oil equivalent (BOE), by converting on an energy-equivalent basis: 5,700 ft^3 of gas equals 1 bbl of oil.

tribute is evaluated by recording a single value between 0 (total certainty that the attribute is absent) and 1 (total certainty that the attribute is present) for the probability that a porosity equal to or greater than 3 percent will be found in any randomly selected **prospect** within the **play** area. In the evaluation of this attribute, it is assumed that the **play attributes** are favorable. Data used in the evaluation of this parameter are based on the porosity of the potential reservoir rocks as determined by measurement, calculation, projection, or analog comparison.

Hydrocarbon accumulation (*C*). This **prospect attribute** is an estimate of the probability of the combination of **hydrocarbon source** (*S*), **timing** (*T*), and **migration** (*M*) necessary for the formation of hydrocarbon accumulations. This attribute is evaluated by recording a single value between 0 (total certainty that the attribute is absent) and 1 (total certainty that the attribute is present) for the probability that hydrocarbons will be found to occupy at least 1 percent of any randomly selected **prospect** within the **play** area. In the evaluation of this attribute, it is assumed that the **play attributes** are favorable. Data used in the evaluation of this parameter are based on the structural, stratigraphic, and thermal history of the **play** area.

Hydrocarbon mix. This **play attribute** is an estimate of the tendency of accumulations in the play to be either all oil or all nonassociated gas. The computer program used in this method can be set (1) to consider hydrocarbon accumulations to be either all oil (with solution gas) or all nonassociated gas, and not the mixture of oil and gas which is commonly found in nature; or (2) to make an allocation of each accumulation in the proportion of the **hydrocarbon mix** attribute. This attribute is evaluated by estimating two values that sum to one (gas+oil =1.0). For example, a mix of 0.8 gas and 0.2 oil would indicate an 80-percent chance that a randomly selected accumulation in the play would be nonassociated gas and a 20-percent chance that the accumulation would be oil. Data used in the evaluation of this parameter are based on concepts of thermal maturity, the type of organic material in the source rock, and the type of hydrocarbon observed in wells and seeps.

Hydrocarbon source (*S*). This **play attribute** is an estimate of the probability of occurrence of rocks that have generated and expelled oil or gas. This attribute is evaluated by recording a single value between 0 (total certainty that the attribute is absent) and 1 (total certainty that the attribute is present) for the probability that oil or gas has been generated and expelled from source rocks in sufficient quantity to form an accumulation within the play. The evaluation of this parameter is based on a set of minimum source-rock criteria that includes organic richness, kerogen type, and thermal maturity. As used in this study, minimum organic-richness values are 0.5 weight percent for clastic source rocks and 0.35 weight percent for carbonate source rocks. Kerogen types favorable for oil are amorphous and herbaceous; for gas, herbaceous and coaly. Minimum requirements for thermal maturity are vitrinite-reflectance values of 0.65 percent for oil and 1.2 percent for condensate and gas. When known hydrocarbon accumulations occur in the **play** area, this attribute probability is 1.

Hydrocarbon-volume parameters. The five hydrocarbon-volume parameters are: (1) **area of closure**, (2) **reservoir thickness**, (3) **effective porosity**, (4) **trap fill**, and (5) **reservoir depth**; the distribution for a sixth parameter, connate-water saturation, is selected by the choice of **reservoir lithology**. They indicate the range of possible generic reservoir characteristics that determine the volume of hydrocarbons present in an individual accumulation within the play. These parameters are evaluated by recording judgmental values at seven probability levels (fractiles) ranging from 100 percent (total certainty that at least this estimated value will be attained) to 0 percent (total certainty that this estimated value will not be exceeded). **Minimum threshold values** may be recorded at the 100th fractile. When the hydrocarbon-volume parameters are being assessed, it is assumed that both the **play probability** and the **prospect probability** are 1. Thus, the hydrocarbon-volume-parameter judgments are conditional on the **play attributes** and the **prospect attributes** being favorable.

Migration (*M*). This **play attribute** is an estimate of the probability of effective movement of hydrocarbons through a conduit, which may be a permeable clastic or carbonate rock, a joint, or a fault. This attribute is evaluated by recording a single value between 0 (total certainty that the attribute is absent) and 1 (total certainty that the attribute is present) for the probability that oil or gas has migrated in sufficient quantity to form an accumulation somewhere in the **play** area. Evaluation of this parameter is based on structural and stratigraphic information from which inferences can be drawn concerning the presence of a geologically favorable conduit. When known hydrocarbon accumulations occur in the play area, this attribute probability is 1.

Minimum threshold values. The following minimum values apply to the five **hydrocarbon-volume parameters**: **area of closure**—600 acres; **reservoir thickness**—1.5 m (5 ft); **effective porosity**—3 percent; **trap fill**—1 percent; **reservoir depth**—30 m (100 ft). These minimum values are used at the 100th fractile, unless a higher value is selected. The probabilities that these threshold values are achieved are incorporated in the **prospect attributes** judgments and the **number of drillable prospects** distribution. The **minimum threshold values** are selected to be less than any reasonable economic limit to prevent economic considerations from influencing the evaluation procedure.

Number of drillable prospects. This **play attribute** describes the range of possible values of the valid targets that would be considered for drilling if the play were to be fully explored. This attribute is evaluated by recording the estimated number of prospects at seven probability levels (fractiles) ranging from 100 percent (total certainty that at least this value will be attained) to 0 percent (total certainty that this value will not be exceeded). Fractiles indicate the relative confidence (subjective probability) that the number of drillable prospects is at least as great as the recorded fractile value. Only prospects having **area of closure** of 600 acres or greater, **reservoir thickness** or vertical closure of at least 5 ft, and **reservoir depth** of 100 ft or greater are considered. The distribution of drillable prospects also takes into account the probability that the reservoir formation may be absent in parts of the **play** area. The absence of a reservoir within some parts of the play area results in a reduced number of drillable prospects. Data used in the evaluation of this parameter may include seismic mapping, surface and subsurface geologic mapping, and projection from nearby areas. Based on these data, additional prospects may be added to allow for the presence of stratigraphic traps.

Oil and gas appraisal data form. A form has been designed for the systematic recording of geologic judgments pertaining to the occurrence of oil and gas. The form is organized into three main categories: (1) **play attributes**, (2) **prospect attributes**, and (3) **hydrocarbon-volume parameters**. Judgments recorded on this form are used in a computer simulation of the petroleum geology of the **play** under consideration. This simulation yields a probabilistic resource appraisal and pool-size distribution of the **play**. For multiple **plays**, it yields an appraisal for the region as a whole.

Play. A **play** area consists of one or more **prospects** in a common or fairly homogeneous geologic setting, the **prospects** of which can be explored by geologic, geochemical, and geophysical techniques.

Play attributes. The seven regional characteristics that describe a given **play** are: (1) **hydrocarbon source** (S), (2) **timing** (T), (3) **migration** (M), (4) **potential reservoir** facies (R), (5) **reservoir lithology**, (6) **hydrocarbon mix**, and (7) **number of drillable prospects**.

Play probability (MP). This term, also known as the marginal play probability, expresses the probability that all of the first four **play attributes** are concurrently favorable somewhere in the **play**. Because each **play attribute** is assumed to be statistically independent of the others, this probability is the product of the four separate play-attribute probabilities ($MP=S\times T\times M\times R$, where S is the **hydrocarbon source**, T is the **timing**, M is the **migration**; and R is the **potential reservoir facies**). An oil or natural gas deposit discovered in the **play** is an indication that all four **play attributes** are concurrently favorable, and therefore the **play probability** is 1.

Potential reservoir facies (R): This **play attribute** estimates the probability of occurrence of a rock with porosity and permeability such that it can contain producible hydrocarbons. This attribute is evaluated by recording a single value between 0 (total certainty that the attribute is absent) and 1 (total certainty that the attribute is present) for the probability that favorable reservoir rocks occur somewhere in the **play** area. Data used in the evaluation of this attribute may include reservoir data from the **play** area, projections from adjacent areas, or analog comparisons. When known hydrocarbon accumulations occur in the **play area**, this **play attribute** probability R is 1.

Prospect: A **prospect** requires an inferred potential **hydrocarbon accumulation** with (1) at least 600 acres **area of closure**, (2) **effective porosity** of at least 3 percent, (3) **reservoir thickness** or vertical closure of at least 1.5 m (5 ft), (4) **reservoir depth** of at least 30 m (100 ft), and (5) **trap fill** of at least 1 percent.

Prospect attributes: Three local characteristics describe the **prospects** within a **play**: **trap occurrence** (TM), **effective porosity** (P), and **hydrocarbon accumulation** (C). These attributes are evaluated by recording a single value between 0 (total certainty that the attribute is absent) and 1 (total certainty that the attribute is present) for the probability that the attribute is generally favorable in a randomly selected **prospect** within the **play** area. When the **pros-**

pect attribute judgments are being made, it is assumed that all four components of the **play probability** are favorable. Thus, the probability judgments are conditional on the **play attributes** being favorable. If the regional characteristics are all favorable, the existence of a hydrocarbon accumulation at any particular prospect is determined by the simultaneously favorable occurrence of the three **prospect attributes**.

Prospect probability (*CP*). This term, also known as the conditional deposit probability, expresses the probability that any randomly selected **prospect** is an accumulation, provided that all the **play attributes** are favorable. Because each **prospect attribute** is assumed to be statistically independent of the others, this probability is the product of three **prospect attribute** probabilities ($CP=TM \times P \times C$, where TM is the **trap occurrence**, P is the **effective porosity**, and C is the **hydrocarbon accumulation**).

Proved reserves. The **proved reserves** consist of a compilation of all recoverable hydrocarbon accumulations that have been found to date within a given **play**. The presence of **proved reserves** indicates that at some time and place within the play, all **play attributes** were present. Therefore, the marginal play probability is 1.

Reservoir depth. This **hydrocarbon-volume parameter** represents the possible range for the depth that must be drilled to penetrate the **potential reservoir facies** (*R*). This parameter is evaluated by entering depth estimates at seven probability levels (fractiles) ranging from 100 percent (total certainty that at least this value will be attained) to 0 percent (total certainty that this value will not be exceeded). Intermediate fractile values indicate the relative confidence (subjective probability) that the reservoir is at least as deep as the recorded fractile value. A **minimum threshold value** of 30 m (100 ft) is used at the 100th fractile. The probability that this minimum value is achieved is incorporated in the judgments of the **trap occurrence** (*TM*) (**prospect attribute**). Data used in the evaluation of this parameter may include seismic mapping, projection from nearby areas, or analog comparison.

Reservoir lithology. This **play attribute** describes the most common reservoir rock type expected in the play. The attribute is evaluated by selecting either sandstone or carbonate rocks; no probabilities are expressed. The computer program is currently set up so that **reservoir lithology**, besides describing the reservoir rock type, determines which of two distributions for water saturation will be selected. Values for water saturation are negatively correlated ($r=-0.9$) with the estimated distribution for the hydrocarbon volume parameter **effective porosity** (in percent).

Reservoir thickness. This **hydrocarbon volume parameter** indicates the possible range for the thickness of the reservoir, or the amount of vertical closure in a situation where structural amplitude is less than reservoir thickness. This parameter is evaluated by entering estimates of reservoir thickness or vertical closure (whichever value is less) at seven probability levels (fractiles) ranging from 100 percent (total certainty that at least this value will be attained) to 0 percent (total certainty that this value will not be exceeded). Intermediate fractile values indicate the relative confidence (subjective probability) that the reservoir thickness or vertical closure is at least as great as the recorded fractile value. Thickness values in the fractiles describe the maximum reservoir thickness (single reservoir or stacked multiple reservoirs) with **effective porosity** of 3 percent or more. Thus these judgments assess the net thickness of reservoir rather than the total thickness of the structure. A **minimum threshold value** of 1.5 m (5 ft) is used at the 100th fractile. The probability that this minimum value is achieved is incorporated in the **trap occurrence** (*TM*) judgment (**prospect attribute**). Data used in the evaluation of this parameter may include seismic mapping, surface and subsurface geologic measurements, projection from nearby areas, or analog comparison.

Timing (*T*). This **play attribute** indicates the probability of occurrence of a suitable relation between the time of trap formation and the time of hydrocarbon movement into or through the area. The attribute is evaluated by recording a single value between 0 (total certainty that the attribute is absent) and 1 (total certainty that the attribute is present) for the probability that favorable timing occurred somewhere in the **play** area. Evaluation of this attribute is based on knowledge of the time of trap formation and on estimates of the time of maturity of the source rocks. When known hydrocarbon accumulations occur in the **play** area, this **play attribute** probability is 1.

Trap fill. This **hydrocarbon-volume parameter** represents the possible range for volume of trapped hydrocarbons as a percentage of the total porous volume under closure. The parameter is evaluated by recording percentage values at seven probability levels (fractiles) ranging from 100 percent (total certainty that at least this value will be attained) to 0 percent (total certainty that this value will not be exceeded). Intermediate fractile values indicate the relative confidence that the trap is at least as full as the recorded fractile value. A **minimum threshold value** of 1 percent is used at the 100th fractile. The probability that this minimum value has been achieved is incorporated in the **hydrocarbon accumulation** (*C*) (**prospect attribute**). Evaluation of this parameter is based on: (1) source-rock richness and thermal maturation, (2) hydrocarbon drainage area, (3) size of structure, (4) porosity and permeability of reservoir rock, and (5) analog comparison.

Trap occurrence (*TM*). This **prospect attribute** indicates the probability of occurrence of reservoir facies in a structural or stratigraphic configuration that provides a trap for migrating hydrocarbons. This attribute is evaluated by recording a single value between 0 (total certainty that the attribute is absent) and 1 (total certainty that the attribute is present) for the probability that a trap having an **area of closure** of at least 600 acres, a **reservoir thickness** or vertical closure of at least 5 ft (1.5 m), and a **reservoir depth** of at least 30 m (100 ft) is present in a randomly selected **prospect** within the **play** area. In the evaluation of this attribute, it is assumed that the **play attributes** are favorable. Data used in the evaluation of this attribute are based on seismic or geologic mapping, projection from nearby areas, or analog comparison.

REFERENCES CITED

Ahlbrandt, T.S., ed., 1979, Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, 163 p.

Armstrong, A.K., 1970, Mississippian dolomites from Lisburne Group, Killik River, Mount Bupto Region, Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 54, no. 2, p. 251-264.

Asquith, D.O., 1970, Depositional topography and major marine environments, Late Cretaceous, Wyoming: American Association of Petroleum Geologists Bulletin, v. 54, no. 7, p. 1184-1224.

Asquith, G.B., 1979, Subsurface carbonate depositional models: a concise review: Tulsa, Okla., Petroleum Publishing Co., 121 p.

Barlow, J.A., Jr., and Haun, J.D., 1966, Regional stratigraphy of Frontier Formation and relation to Salt Creek field, Wyoming: American Association of Petroleum Geologists Bulletin, v. 50, no. 10, p. 2185-2196.

Berg, R.R., and Powers, B.K., 1981, Morphology of turbidite channel reservoirs, lower Hackberry Oligocene, southeast Texas: Oil and Gas Journal, v. 79, no. 16, p. 184-188.

Berg, R.R., and Tedford, F.J., 1978, Wilcox gas-reservoir characteristics in Northeast Thompsonville field: Oil and Gas Journal, v. 76, no. 6, p. 96-102.

Bird, K.J., 1981, Petroleum exploration of the North Slope, Alaska, *in* Mason, J.F., ed., Petroleum geology in China: Tulsa, Okla., PennWell, p. 233-248.

Bird, K.J., and Jordan, C.F., 1977, Lisburne Group (Mississippian and Pennsylvanian), potential major hydrocarbon objective of Arctic Slope, Alaska: American Association of Petroleum Geologists Bulletin, v. 61, no. 9, p. 1493-1512.

Bradley, G.A., 1975, Lisbon field, Utah, *in* Fassett, J.E., ed., Canyonlands country: Durango, Colo., Four Corners Geological Society Guidebook, p. 277-278.

Brosgé, W.P., and Tailleur, I.L., 1971, Northern Alaska petroleum province, *in* Cram, I.H., ed., Future petroleum provinces of the United States—their geology and potential: American Association of Petroleum Geologists Memoir 15, p. 69-99.

Canada Department of Energy, Mines and Resources, 1977, Oil and natural gas resources of Canada: Report EP 77-1, 76 p.

Carman, G.J., and Hardwick, Peter, 1982, Geology and regional setting of the Kuparuk oil field, Alaska: Oil and Gas Journal, v. 80, no. 47, p. 153-158.

Carter, R.D., Mull, C.G., Bird, K.J., and Powers, R.B., 1977, The petroleum geology and hydrocarbon potential of Naval Petroleum Reserve No. 4, North Slope, Alaska: U.S. Geological Survey Open-File Report 77-475, 61 p.

Chapman, R.M., Detterman, R.L., and Mangus, M.D., 1964, Geology of the Killik-Etivluk Rivers region, Alaska: U.S. Geological Survey Professional Paper 303-F, p. 325-407.

Chapman, R.M., and Sable, E.G., 1960, Geology of the Utukok-Corwin region, northwestern Alaska: U.S. Geological Survey Professional Paper 303-C, p. 47-167.

Collins, F.R., 1959, Test wells, Square Lake and Wolf Creek areas, Alaska: U.S. Geological Survey Professional Paper 305-H, p. 423-484.

Collins, F.R., and Robinson, R.M., 1967, Subsurface stratigraphic, structural, and economic geology, northern Alaska: U.S. Geological Survey open-file report, 252 p.

Detterman, R.L., Reiser, H.N., Brosgé, W.P., and Dutro, J.T., Jr., 1975, Post-Carboniferous stratigraphy, northeastern Alaska: U.S. Geological Survey Professional Paper 886, 46 p.

Dolton, G.L., Carlson, K.H., Charpentier, R.R., Coury, A.B., Crovelli, R.A., Frezon, S.E., Khan, A.S., Lister, J.H., McMullin, R.H., Pike, R.S., Powers, R.B., Scott, E.W., and Varnes, K.L., 1981, Estimates of undiscovered recoverable conventional resources of oil and gas in the United States: U.S. Geological Survey Circular 860, 87 p.

Eckelmann, W.R., Fisher, W.L., and DeWitt, R.J., 1976, Prediction of fluvial-deltaic reservoir geometry, Prudhoe Bay field, Alaska, *in* Miller, T.P., ed., Recent and ancient sedimentary environments in Alaska: Alaska Geological Society Symposium, Anchorage, 1976, Proceedings, p. B1-B8.

Fox, J.E., Lambert, P.W., Pitman, J.K., and Wu, C.H., 1979, A study of reservoir characteristics of the Nanushuk and Colville Groups, Umiat test well 11, National Petroleum Reserve in Alaska: U.S. Geological Survey Circular 820, 47 p.

Harris, S.H., Land, C.B., and McKeever, J.H., 1966, Relation of Mission Canyon stratigraphy to oil production in north-central North Dakota: American Association of Petroleum Geologists Bulletin, v. 50, no. 10, p. 2269-2276.

Huffman, A.C., and Ahlbrandt, T.S., 1979, The Cretaceous Nanushuk Group of the western and central North Slope, Alaska, *in* Johnson, K.M., and Williams, J.R., eds., The United States Geological Survey in Alaska: Accomplishments during 1978: U.S. Geological Survey Circular 804–B, p. B46-B50.

Hunter, R.E., and Fox, J.E., 1976, Interpretation of depositional environments in the Fortress Mountain Formation, central Arctic Slope: U.S. Geological Survey Circular 733, p. 30-31.

Jamison, H.C., Brockett, L.D., and McIntosh, R.A., 1980, Prudhoe Bay—a 10-year perspective, *in* Halbouty, M.T., ed., Giant oil and gas fields of the decade 1968-1978: American Association of Petroleum Geologists Memoir 30, p. 289-314.

Jones, H.P., and Speers, R.G., 1976, Permo-Triassic reservoirs of Prudhoe Bay field, North Slope, Alaska, *in* Braunstein, J., ed., North American oil and gas fields: American Association of Petroleum Geologists Memoir 24, p. 23-50.

Kerns, J.R., and Traut, J.D., 1979, Mississippian discoveries revive the Williston Basin: World Oil, v. 188, no. 6, p. 52-57.

Kirschner, C.E., and Lyon, C.A., 1973, Stratigraphic and tectonic development of Cook Inlet petroleum province, *in* Pitcher, M.G., ed., Arctic geology: American Association of Petroleum Geologists Memoir 19, p. 396-407.

Lane, F.H., and Jackson, K.S., 1980, Controls on occurrence of oil and gas in the Beaufort-MacKenzie basin, *in* Miall, A.D., ed., Facts and principles of world petroleum occurrence: Canadian Society of Petroleum Geologists Memoir 6, p. 489-507.

Lantz, R.J., 1981, Barrow gas fields—North Slope, Alaska: Oil and Gas Journal, v. 79, no. 13, p. 197-200.

Lerand, Monti, 1973, Beaufort Sea, *in* McCrossan, R.G., ed., The future petroleum provinces of Canada—their geology and potential: Canadian Society of Petroleum Geologists Memoir 1, p. 315-386.

Magoon, L.B., and Claypool, G.E., 1979, Hydrocarbon source potential of the Nanushuk Group and the Torok Formation, a preliminary report, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 54-60.

——— 1981, Petroleum geology of Cook Inlet Basin—an exploration model: American Association of Petroleum Geologists Bulletin, v. 65, no. 6, p.1043-1061.

Mast, R.F., McMullin, R.H., Bird, K.J., and Brosgé, W.P., 1980, Resource appraisal of undiscovered oil and gas resources in the William O. Douglas Arctic Wildlife Range: U.S. Geological Survey Open-File Report 80-916, 62 p.

MacPherson, B.A., 1978, Sedimentation and trapping mechanism in Upper Miocene Stevens and older turbidite fans of southeastern San Joaquin Valley, California: American Association of Petroleum Geologists Bulletin, v. 62, no. 11, p. 2243-2274.

McCoy, A.W., and Moritz, C.A., 1982, Countess oil field, south-central Alberta—case history in finding a stratigraphic trap: Oil and Gas Journal, v. 80, no. 44, p. 95-98.

McCubbin, D.G., and Brady, M.J., 1969, Depositional environment of the Almond reservoirs, Patrick Draw field, Wyoming: Mountain Geologist, v. 6, no. 1, p. 3-26.

McIntosh, R.A., 1977, Prudhoe Bay unit operating plan, reservoir description: Alaska Oil and Gas Conservation Commission, May 5 Conservation Hearing 145, Exhibit 8, 9 p.

Miller, B.M., 1981, Methods of estimating potential hydrocarbon resources by the U.S. Geological Survey—case studies in resource assessment in the National Petroleum Reserve in Alaska and the William O. Douglas Arctic Wildlife Range: Southwestern Legal Foundation Proceedings, Exploration and Economics of the Petroleum Industry, v. 19, p. 57-95.

——— 1982, Application of exploration play-analysis techniques to the assessment of conventional petroleum resources by the U.S. Geological Survey: Journal of Petroleum Technology, v. 34, no. 1, p. 55-64.

Miller, B.M., Thomsen, H.L., Dolton, G.L., Coury, A.B., Hendricks, T.A., Lennartz, F.E., Powers, R.B., Sable, E.G., and Varnes, K.L., 1975, Geological estimates of undiscovered recoverable oil and gas resources in the United States: U.S. Geological Survey Circular 725, 78 p.

Miller, C.C., and Peterson, D.H., 1978, Summary geophysical report FY '78, prepared for Husky Oil NPR Operations, Inc., National Petroleum Reserve-Alaska: Houston, Tetra Tech, Inc., 33 p.

Mills, B.A., 1968, Solution-gas reserves in Pembina Cardium oil field, Alberta, Canada, *in* Beebe, B.W., ed., Natural gases of North America: American Association of Petroleum Geologists Memoir 9, p. 698-704.

Newman, G.W., Mull, C.G., and Watkins, N.D., 1977, Northern Alaska paleomagnetism, plate rotation, and tectonics [abs.]: Alaska Geological Society Symposium on the Relationship of Plate Tectonics to Alaskan Geology and Resources, Anchorage, 1977, Program and Abstracts, p. 16-19.

Oil and Gas Journal, 1981, Huge new gas area seen developing in Alberta: v. 79, no. 18, p. 118.

Patton, W.W., Jr., 1956, New and redefined formations of Early Cretaceous age, *in* Gryc, George, and others, Mesozoic sequence in Colville River region, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 40, no. 2, p. 219-223.

Patton, W.W., Jr., and Tailleur, I.L., 1964, Geology of the Killik-Itkillik region: U.S. Geological Survey Professional Paper 303-G, p. 409-500.

Pessel, G.H., Tailleur, I.L., and Bird, K.J., 1978, Generalized isopach map of the Colville Group, eastern North Slope petroleum province, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-928-F, scale 1:500,000.

Robinson, F.M., 1958, Test wells, Gubik area, Alaska: U.S. Geological Survey Professional Paper 305-C, 264 p.

Roehler, H.W., and Stricker, G.D., 1979, Stratigraphy and sedimentation of the Torok, Kukpowruk, and Corwin Formations of Cretaceous age in the Kokolik-Utukok Rivers region, NPRA: U.S. Geological Survey Open-File Report 79-995, 80 p.

Roy, K.J., Proctor, R.N., and McCrossan, R.G., 1975, Hydrocarbon assessment using subjective probability, *in* Davis, J.C., and others, conveners, Probability methods in oil exploration: American Association of Petroleum Geologists Research Symposium, Stanford, Calif., 1975, Notes, p. 56-60.

Sabins, F.F., Jr., 1972, Comparison of Bisti and Horseshoe Canyon stratigraphic traps, San Juan Basin, New Mexico, *in* King, R.E., ed., Stratigraphic oil and gas fields—classification, exploration methods, and case histories: American Association of Petroleum Geologists Memoir 16, p. 610-622.

Stadnichenko, Taisia, 1929, Microthermal studies of some "mother rocks" of petroleum from Alaska: American Association of Petroleum Geologists Bulletin, v. 13, no. 7, p. 823-848.

Tailleur, I.L., 1964, Rich oil shale from northern Alaska, art. 148 *of* Short papers in geology and hydrology: U.S. Geological Survey Professional Paper 475-D, p. 131-133.

Tailleur, I.L., Pessel, G.H., and Engwicht, S.E., 1978, Maps showing land status and well locations, and tables of well data, eastern North Slope petroleum province, Alaska, *with a section on* Exploration, by H.C. Jamison: U.S. Geological Survey Miscellaneous Field Studies Map MF-928-F, scale 1:500,000.

U.S. Department of the Interior, Office of Minerals Policy and Research Analysis, 1979, Final report of the 105(b) economic and policy analysis: Alternative overall procedures for the exploration, development, production, transportation and distribution of the petroleum resources of the National Petroleum Reserve in Alaska (NPRA): Washington, U.S. Government Printing Office, 145 p.

Webber, E.J., 1947, Stratigraphy and structure of the area of the Meade and Kuk Rivers and Point Barrow, Alaska: U.S. Geological Survey report, 14 p.

White, L.P., 1981, A play approach to hydrocarbon resource assessment and evaluation, *in* Ramsey, J.B., Economics of exploration for energy resources: Contemporary studies in economic and financial analysis: Greenwich, Conn., JAI Press, v. 26, p. 51-67.

Whittington, C.L., and Keller, A.S., 1950, Stratigraphy and structure of the area of the upper Meade River, Alaska: U.S. Geological Survey Geological Investigations, Naval Petroleum Reserve No. 4, Alaska, Report 36, 8 p.

Williams, Bob, 1982, U.S. Beaufort Sea development eyed: Oil and Gas Journal, v. 80, no. 25, p. 80-81.

Williamson, C.R., 1980, Sedimentology of Guadelupian deep-water clastic facies, Delaware Basin, New Mexico and West Texas, *in* Dickerson, P.W., ed., Trans-Pecos region; southeastern New Mexico and West Texas: Socorro, New Mexico Geological Society Guidebook 31, p. 195-204.

Witmer, R.J., Haga, Hideyo, and Mickey, M.B., 1981, Biostratigraphic report of thirty-three wells drilled from 1975 to 1981 in National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 81-1166, 47 p.

5. METHODS FOR ASSESSING THE PETROLEUM RESOURCES IN THE NATIONAL PETROLEUM RESERVE IN ALASKA

By Betty M. Miller

INTRODUCTION

The methods and procedures described in this chapter were used by the U.S. Geological Survey's Geologic Assessment Committee and Resource Appraisal Review Committee in assessing the petroleum resources of the National Petroleum Reserve in Alaska (NPRA), an area of approximately 95,830 km^2 (37,000 mi^2) on the North Slope of Alaska. A Monte Carlo simulation model is explained that is based upon the exploration play-analysis approach and produces an appraisal of the conventional petroleum resources, and the application of this method and the results of the subsequent assessment studies are described.

Various exploration play-analysis methods have been designed for identification of conceptual exploration plays within a basin or province in order to assess conventional petroleum resources. The basic definition of an exploration play is as follows: a practical and meaningful planning unit around which an integrated exploration program can be constructed. A play has geographic and stratigraphic limits and is confined to a formation or a group of formations that are closely related by lithology, depositional environment, or structural history (Miller, 1981). However, many variations of this definition and of the basic assumptions applied to play concepts have been accepted by different estimators using play-analysis techniques.

Play-analysis methods have usually been applied to the appraisal of fairly small areas, such as a geologic trend consisting of a reef play, a channel, or a bar sand (McCrossan, 1973; Bois, 1975; Roadifer, 1975; White and Gehman, 1979). However, the play-analysis procedure has sometimes been applied to entire geologic horizons or stratigraphic units for the appraisal of a total basin or province; for example, the total potential within the Cretaceous sedimentary sequence of a basin, or the potential of an entire basin (Jones, 1975; Roy and others, 1975; White and others, 1975). Although the estimator may still call the procedure a "play analysis," the basic concepts in these examples are obviously no longer those of the original definition. Thus, there are extreme variations in this method and in the respective assumptions from one estimator to another. Exploration play-analysis techniques have in recent years been applied to frontier areas, where geologic and geophysical data are limited; the geologic variables have been described by subjectively derived probability functions based on the judgment of the estimators or by selected analogs (Canada Department of Energy, Mines and Resources, 1977; Mast and others, 1980). This chapter describes the application of such a method to assessing the petroleum potential of the NPRA.

The simulation model designed for this study was developed in the U.S. Department of the Interior, Office of Minerals Policy and Research Analysis (DOI/OMPRA), in response to a directive in the Naval Petroleum Reserves Production Act of 1976. This act required that a study be conducted to determine the best overall procedures to be used in the development, production, transportation, and distribution of any petroleum resources in the reserve and to assess the economic and environmental consequences of alternative procedures (U.S. Department of the Interior, 1979). The integrated computer model simulates the exploration, development, production, transportation, and distribution activities for oil and gas on the basis of the results of the play-analysis approach in the geologic submodel. Only the geologic and exploration submodels are discussed in this chapter. The remaining activities and the economic evaluations performed by the models are discussed by Bugg and others (chapter 6).

The basic concepts in the geologic submodel, designed by DOI/OMPRA, were patterned after one of the most publicized applications of the play-analysis method by the Geological Survey of Canada (Canada Department of Energy, Mines and Resources, 1977). The basic resource appraisal method described here is not an original one. Various modified versions similar to the Canadian version are being used by the petroleum industry and by other research groups (Bois, 1975; Roadifer, 1975; White and others, 1975; White and Gehman, 1979).

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Minerals Policy and Research Analysis (DOI/OMPRA), who was instrumental in the development of the computer models.

THE EXPLORATION PLAY-ANALYSIS METHOD

In the exploration play-analysis method used in the NPRA, the oil and gas resource base is simulated by the integration of two independent submodels: (1) a geologic submodel based on a probabilistic assessment of the most important geologic variables or attributes in a province that relate to the occurrence of hydrocarbons; and (2) an exploration submodel that simulates the search for oil and gas in the province, producing a sequence of discoveries that provide an inventory of pools for subsequent evaluation with the development submodels. The geologic submodel produces a list of prospects (potential drilling targets) and a resource appraisal of the oil and gas in place by using subjective probability distributions for the values of the geologic variables that were estimated by experts familiar with the geology of the area. Most of the explanation of the geologic submodel used for the NPRA is from White (1979).

The geologic submodel is integrated with the submodels for petroleum-development activity and economic decisions by using a Monte Carlo simulation of these activities and decisions over an extended simulated time period. Each Monte Carlo pass begins with the geologic submodel and samples from probability distributions for each of the important geologic variables for each play to simulate a possible so-called state of geologic nature, which consists of one possible size distribution of the oil and gas deposits for the province. This state of geologic nature is composed of a particular number of prospects, some of which are simulated as actual deposits of oil and (or) gas and the rest as dry. After simulating the expected size of these prospects, the program ranks them according to expected volume to form a simulated target list for the discovery process.

The discovery process is then simulated on a mock year-by-year basis in the form of sequential evaluation of the prospects on the target list. The simulated explorer does not know which prospects are simulated discoveries (successes) and which are dry (failures). If the expected economic value of a particular prospect justifies drilling an exploratory well, the simulated decision is to test it and to determine whether it contains hydrocarbons. This procedure continues for each mock year in the Monte Carlo pass or until all prospects have been tested. The learning process in an exploration program is simulated by using the drilling results from each mock year to revise the simulated explorer's perceived state of geologic nature. The output of the exploration submodel each mock year is a list of dry wells and discovered deposits of oil and gas. The discovered deposits are added to an inventory of pools to be considered for development. Many Monte Carlo passes, commonly 3,000 to 5,000, are made to produce frequency distributions for the important variables, such as production and discovered reserves, and the total oil and gas resources in place.

GEOLOGIC MODEL BASED ON THE PLAY-ANALYSIS APPROACH

The geologic-assessment procedure devised specifically for application to the NPRA resource assessment focuses on the play. A play is an area in which the geology and geophysics indicate that any prospects present may have similar combinations of the major assessable geologic attributes: hydrocarbon sources, reservoir beds, and traps. Equally important but more difficult to assess are the attributes of thermal history and the relative timing of oil generation, migration, and entrapment. In brief, a play consists of one or more prospects in a common or fairly homogeneous geologic setting that can be explored for with geologic, geochemical, and geophysical techniques. A prospect, as defined for this study, is a potential hydrocarbon accumulation having an area of at least 600 acres.

The play is a useful analytical concept that allows the analysis to be sensitive to the physical processes actually involved in the entrapment of oil and gas and in the discovery of oil and gas accumulations. A fundamental assumption is that the geologic characteristics are significantly related within a play but show substantially less correlation between plays. Thus, if all the regional geologic characteristics necessary for the occurrence of trapped hydrocarbons are present within the play area, the play probably will contain accumulations of oil or gas or both; however, if one or more of the significant geologic characteristics is missing or unfavorable, all the prospects within the play probably will be unsuccessful. The primary output for the geologic submodel is a probabilistic appraisal of resources in place for each play.

The play-analysis approach classifies each geologic characteristic of a potential play as either play-specific, prospect-specific, or reservoir-specific. Therefore, for each play, three corresponding sets of probabilistic judgments were elicited from experts familiar with the local geology. Figure 5.1 is a sample of the data form for recording these judgments.

Oil and Gas Appraisal Data Form

Evaluator: ____________________ Play Name ____________________

Date Evaluated: ____________________

Attribute			Probability of Favorable or Present	Comments
Play Attributes	Hydrocarbon Source			
	Timing			
	Migration			
	Potential Reservoir Facies			
	Marginal Play Probability			
Prospect Attributes	Trapping Mechanism			
	Effective Porosity (>3%)			
	Hydrocarbon Accumulation			
	Conditional Deposit Probability			
Hydrocarbon Volume Attributes	Reservoir Lithology	Sand		
		Carbonate		
	Hydrocarbon	Gas		
		Oil		

	Fractiles Attribute	Probability of equal to or greater than							
		100	95	75	50	25	5	0	
Hydrocarbon Volume Attributes	Area of Closure (x10^3 Acres)								
	Reservoir Thickness/vertical closure (Ft)								
	Effective Porosity %								
	Trap Fill (%)								
	Reservoir Depth (x10^3 Ft)								
No. of drillable prospects (a play characteristic)									
Proved Reserves (x10^6 Bbl; TCF) (If known production)									

FIGURE 5.1.—Form for recording oil and gas appraisal data.

The first set of subjective judgments concerns the individual probabilities that each of four regional geologic characteristics (or attributes) common to the play area is favorable for the existence of petroleum accumulations. These regional characteristics are (1) existence of a hydrocarbon source, (2) favorable timing for migration from source to trap, (3) potential migration paths, and (4) presence of potential reservoir facies. The product of these single-value probability estimates is termed the marginal-play probability—the joint probability that all the regional geologic characteristics necessary for the accumulation of petroleum in the play area are simultaneously favorable. Each play characteristic is a necessary but not sufficient condition for the existence of oil or gas deposits in the play. The marginal-play probability requires, in addition, probability judgments on the number of potentially drillable prospects in the play area, the type of reservoir lithology, and the petroleum mix (proportion of deposits within the play that contain oil rather than nonassociated gas).

The second set of single-value subjective judgments elicited is a set of probabilities concerning the presence or absence of three geologic characteristics common to each of the individual prospects within each play: (1) trapping mechanism, (2) effective porosity, and (3) hydrocarbon accumulation. The probability judgment of the presence or absence of these geologic characteristics is made conditional on the favorable existence of all four play attributes. The product of the three prospect-attribute probabilities is termed the conditional-deposit probability—the probability that a particular prospect is an actual accumulation of oil or gas, given that all the play attributes are favorable.

The third type of subjective probability judgment involves probability distributions for each of the reservoir-volume attributes that define the size of a deposit. These reservoir characteristics are area of closure, reservoir thickness, effective porosity, trap fill, and reservoir depth. The reservoir-volume characteristics jointly determine the size of a reservoir (pool) for a simulated deposit.

These three basic sets of subjective judgments (play-specific, prospect-specific, and reservoir-specific) are made for each of the identified plays and constitute the basic geologic data entered in the geologic submodel.

At the beginning of each pass in the Monte Carlo procedures, the geologic submodel samples the probability distributions for each play to simulate one possible state of nature. For each play, the submodel samples the number of potentially drillable prospects from the probability distribution to determine the number of prospects that will be simulated during the particular pass. The marginal-play probability is then sampled to determine whether the play will be simulated as unproductive or potentially productive during the pass.

For each prospect in a productive play, the conditional-deposit probability is sampled to determine whether that prospect will be simulated as an actual deposit or as dry. The petroleum-mix probability is sampled for each simulated deposit to determine whether the deposit contains oil or gas. All prospects in an unproductive play are automatically simulated as dry. Each probability distribution for the reservoir-volume attributes is then sampled for each of the prospects (both dry prospects and deposits) to simulate their volume and reservoir characteristics.

Finally, the geologic submodel allocates the prospects from each play to the appropriate overlying surface area or areas, called ''activity areas.'' The model allows partitioning of the surface area for the basins or provinces into delineated surface areas of arbitrary size, shape, and number; the allocation of the prospects to these activity areas is based on an arbitrary judgment regarding the areal distribution of the resources because the specific location of each of the prospects is not defined by the geologists.

The result of this allocation is a projection of the three-dimensional geologic column, in which plays are vertically stacked into a two-dimensional delineation at the surface, with each activity area being assigned the total number of prospects estimated to occur within it.

The primary output of the geologic submodel is the prospect list for each activity area, which is used in the remaining submodels for the exploration, production, transportation, and economic analysis in the system (U.S. Department of the Interior, 1979). A second major output, with the completion of all the Monte Carlo passes, is an appraisal of the total oil and gas resources within the NPRA. This resource appraisal is prepared by (1) aggregating the simulated deposits for each Monte Carlo pass and (2) using a large number of passes to produce a probability distribution for in-place oil and natural-gas resources. A flow chart of the geology model is shown in figure 5.2.

SUBJECTIVE PROBABILITY PROCEDURES USED FOR ASSESSING INDIVIDUAL PLAYS

The data bases used for the preliminary petroleum-resource estimates within the NPRA were the geologic, geophysical, and petroleum-resource data available from the research programs of the U.S. Geological Survey (USGS) and the U.S. Navy, as well as the data base prepared by Tetra Tech, Inc.

A review panel of USGS geologists analyzed the Tetra Tech data, compiled the geologic and geophysical data base necessary for an NPRA resource evaluation, reviewed all new well data from the Survey's ongoing exploration program, conducted appropriate background analyses, and estimated the values for key geologic and geophysical variables needed for the resource assessments. Two USGS committees, the Geologic Assessment Committee and the Resource Appraisal Review Committee, in successive meetings during 1978 and 1979, identified 17 petroleum plays in the Reserve and prepared a set of subjective probabilistic estimates of the geologic characteristics for each play.

Bird (chapter 4) describes in detail the geologic basis used in the play-analysis method of petroleum resource appraisal for the NPRA. The Geologic Assessment Committee reviewed and developed the geologic data and geologic rationale for defining the plays, establishing the play boundaries, and supplying the geologic background for the appraisal forms and for presentations to the Resource Appraisal Review Committee. The Resource Appraisal Review Committee, composed in part of members from the Geologic Assessment Committee and in part of members with expertise in resource-appraisal methods, reviewed all the revised information presented by the Geologic Assessment Committee that would have impact on the resource-appraisal methods. This information included revised definitions, data formats, plays and play boundaries, updated data bases, and probability estimates for each of the play and reservoir attributes. The Resource Appraisal Review Committee conducted the final resource-appraisal meetings for additional revisions in definitions and interpretations and a review of all the probability estimates for each play.

The subjective probability procedures used by the two committees consisted of team input, team participation in the subjective estimating of the play, prospect, and reservoir attributes, and a team consensus of the final subjective probability estimates for each of the attributes documented on the final appraisal form. The subjective estimates were based on the geologic and geophysical data, when available, and on the experience and expertise of the geologists in using analog data and geologic extrapolations when specific data were unavailable. For some plays, analog estimates were used for the reservoir-volume attributes in the absence of reservoir-engineering measurements.

EXAMPLE OF AN INDIVIDUAL PLAY ASSESSMENT

An example of a completed data form for an individual play is shown in figure 5.3. The Monte Carlo procedures and the input attributes used can be traced in the flow chart of the geology model in figure 5.2. The attributes on the data form are identified by code letters shown also on the flow chart for the reader's convenience: A single play is selected at A in the geology model and proceeds through the system until it reaches X on the flow chart. If additional plays remain to be simulated, the program returns to the selection of a new play and repeats the procedure. When there are no additional plays left to process, the

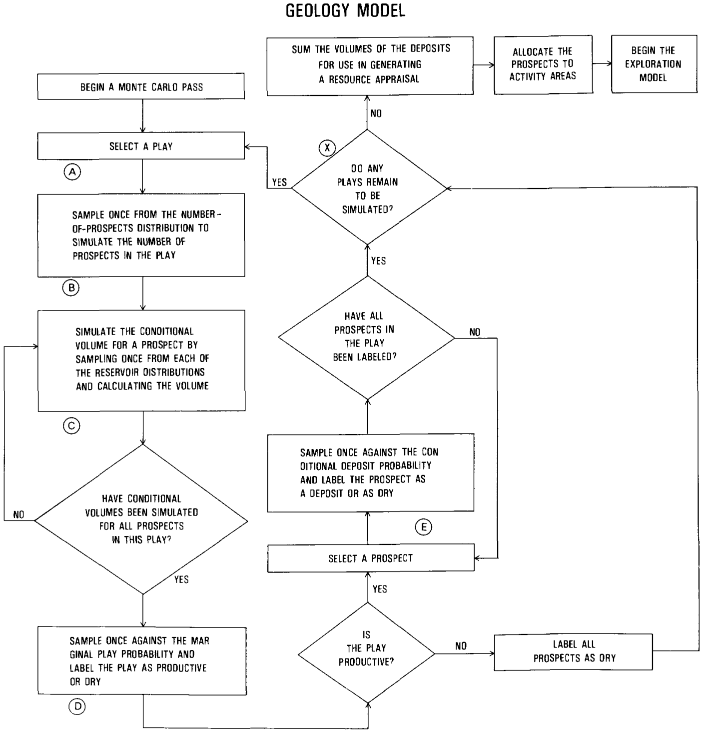

FIGURE 5.2.—Flow chart of geology model in play-analysis method of hydrocarbon resource appraisal (after White, 1979).

Oil and Gas Appraisal Data Form

Evaluator: Resource Appraisal Team

Play Name Ⓐ Play #1

Date Evaluated: November 8, 1978

Attribute			Probability of Favorable or Present	Comments
Play Attributes	Hydrocarbon Source	(S)	1.0	
	Timing	(T)	1.0	
	Migration	(M)	1.0	
	Potential Reservoir Facies	(R)	1.0	
	Ⓓ Marginal Play Probability	(SxTxMxR =MP)	1.0	Produces at Umiat
Prospect Attributes	Trapping Mechanism	(TM)	.5	Structural and Stratigraphic
	Effective Porosity (>3%)	(P)	.7	
	Hydrocarbon Accumulation	(C)	.9	
	Ⓔ Conditional Deposit Probability (TMxPxC = CP)		.315	

Ⓒ Hydrocarbon Volume Attributes			
Reservoir Lithology	Sand	1.0	
	Carbonate	0	
Hydrocarbon	Gas	.3	
	Oil	.7	

Attribute \ Fractiles	Probability of equal to or greater than							Comments
	100	95	75	50	25	5	0	
Area of Closure ($x10^3$ Acres)	.6	1	2	8	16	23	55	
Reservoir Thick-ness/vertical closure (Ft)	5	50	200	450	675	850	1000	Individual sands less than 150′ thick
Effective Porosity %	3	8	12	16	22	28	35	
Trap Fill (%)	1	5	12	30	35	40	90	
Reservoir Depth ($x10^3$ Ft)	.1	1	3	4	5	6	7	
Ⓑ No. of drillable prospects (a play characteristic)	10	12	14	16	20	30	40	

Proved Reserves ($x10^6$ Bbl; TCF)	19–122	Umiat Oil Field

FIGURE 5.3.—Example of appraisal form filled out by resource-appraisal team.

TABLE 5.1.—*Estimated conditional resources in place for play No. 1*

[Estimates of BOE (barrels-of-oil equivalent) determined separately for each pass during Monte Carlo simulation procedure and not derived by converting gas in place to energy equivalent in oil and adding to oil in place at same probability level]

Probability that quantity is at least given value (percent)	Oil (10^6 bbl)	Gas (10^9 ft^3)	BOE (10^6 bbl)
100-------------	0	0	0
95-------------	310	154	340
75-------------	1,541	786	1,692
50-------------	3,209	1,751	3,555
25-------------	5,791	3,277	6,370
5-------------	11,902	7,023	12,982
Statistical mean--	4,208	2,421	4,632

TABLE 5.2.—*Distribution of estimated in-place pool sizes in the NPRA from a 1979 study*

[Read as follows: There is, for example, a 95-percent probability that a pool of at least $2x10^6$ bbl of oil in place occurs, 10 percent for a pool of at least $1x10^9$ bbl]

Probability that pool size is at least given value (percent)	Pool size (10^6 bbl of oil in place)
100-------------	0
95-------------	2
90-------------	4
75-------------	13
50-------------	56
25-------------	275
10-------------	1,007
5-------------	2,043
1-------------	6,581
Statistical mean--	484

volumes of the deposits generated in the Monte Carlo procedure are summed and used in generating a total resource appraisal.

The values recorded on the data form, for play no. 1 in the example given, were used as the basic data for estimating the presence and volumes of oil and gas in the play. Table 5.1 lists conditional estimates of the petroleum resources in place in play no. 1. The estimates indicate, for example, that there is a 95-percent probability that the conditional oil in place will be equal to or greater than 310 million bbl, and a 5-percent probability that the conditional oil in place will be equal to or greater than 11.9 billion bbl. Similarly, there is a 95-percent probability of at least 154 billion ft^3 of gas and a 5-percent probability of at least 7.02 trillion ft^3 of gas.

TOTAL POOL SIZES

Within any Monte Carlo pass, the computed resources in place are the total of the simulated deposits of oil and gas summed over all of the plays analyzed in the NPRA. Similar total quantities, however, can result from a large number of small reservoirs or pools, or a smaller number of large pools. An analysis of 16 plays, taken from a 1979 study that included play no. 1 from the above discussion, yielded the in-place pool-size distribution shown in table 5.2. For purposes of obtaining this distribution, all petroleum in place is assumed by the computer model to be oil. The smallest single pool is at least a 3,000-bbl pool at the 100-percent probability level, whose size is shown here as zero because of rounding, and the largest pool reported, at the 1-percent probability level, has at least 6.6 billion bbl in place.

RESOURCE ASSESSMENT FOR THE NPRA

HISTORY OF THE 105(b) NPRA RESOURCE ASSESSMENTS

The first meetings of the two USGS committees (the Geologic Assessment Committee and the Resource Appraisal Review Committee) to review all of the geologic and geophysical data necessary for an NPRA resource evaluation took place in November 1978 in Menlo Park, Calif., and Denver, Colo. The first NPRA resource estimates were based on the identification and evaluation of 16 plays. At the time of the November 1978 evaluation there were 43 test wells drilled in the NPRA.

The second full-scale evaluation of the available information took place in Menlo Park in May 1979. New information for review included data from two wells being drilled at the time and an additional five wells that had been suspended or abandoned. There were minor modifications on 10 of the 16 plays, but the most significant changes involved only 3 plays. The total number of plays remained at 16. With the updated revisions made to the plays as input to the Monte Carlo model, the second resource evaluation was made in May 1979.

Meetings for the third update of the resource evaluation of the NPRA were held in Menlo Park in September 1979. New information for this update included well data, analyses, and interpretations. New data were available from one well then being drilled and three additional wells that had been recently suspended or abandoned. In this update, as in the original resource appraisal, each play was reviewed and discussed by the full committees. Changes were made on the play-appraisal forms by team consensus. The most important change was the separation of the Jurassic II play into 2 new and separate plays,

TABLE 5.3.—*Resource assessments for the National Petroleum Reserve in Alaska conducted from 1978 through 1980*

[Sources for resource assessments: November 1978, B.M. Miller and K.J. Bird, A preliminary report on the appraisal of oil and gas resources in National Petroleum Reserve in Alaska by the U.S. Geological Survey, unpublished USGS administrative report, December 1978, 63 p.; May 1979, Miller (1979); September 1979, K.J. Bird, Update No. 3, preliminary report on the reappraisal of oil and gas resources in the National Petroleum Reserve in Alaska by the U.S. Geological Survey, unpublished USGS administrative report, November 1979, 61 p.; May 1980, U.S. Department of the Interior, Office of Minerals Policy and Research Analysis, unpublished computer results on the fourth resource assessment of NPRA, 1980, 2 p. Estimates of barrels of oil equivalent (BOE) are made independently, therefore oil and gas estimates at given percentage do not add up to barrels of oil equivalent. n.d., not determined]

Probability that quantity is at least given value (percent)	Resource assessment			
	November 1978	May 1979	September 1979	May 1980
Conditional estimates for oil in place (10^9 bbl)				
95	0.65	1.58	0.99	0.82
90	.86	2.26	1.61	1.27
75	1.40	3.73	3.10	2.44
50	2.44	6.24	5.57	4.69
25	4.24	10.05	9.50	7.95
10	6.63	15.59	14.62	12.35
5	8.55	20.56	18.42	15.42
1	12.80	38.26	26.17	22.96
Statistical mean	3.24	8.19	7.12	5.97
Conditional estimates for natural gas in place (10^{12} ft^3)				
95	.80	2.30	2.88	2.41
90	1.16	3.02	4.02	3.43
75	2.14	5.09	7.25	5.59
50	4.30	8.48	11.81	9.15
25	8.53	14.34	19.68	14.46
10	16.00	21.73	28.92	21.70
5	22.30	30.29	35.75	27.20
1	39.30	54.58	54.80	45.06
Statistical mean	7.04	11.50	14.90	11.31
Conditional estimates for BOE in place (10^9 bbl)				
95	n.d.	2.28	2.36	1.90
90	n.d.	3.15	3.20	2.51
75	n.d.	4.94	5.10	4.10
50	n.d.	7.82	8.11	6.69
25	n.d.	12.29	12.60	10.39
10	n.d.	18.97	18.17	14.91
5	n.d.	24.73	22.56	18.42
1	n.d.	47.02	31.31	25.62
Statistical mean	n.d.	10.21	9.73	7.95
Conditional estimates for in-place pool sizes (10^9 bbl)				
95	n.d.	.002	.002	.002
90	n.d.	.004	.005	.005
75	n.d.	.013	.014	.014
50	n.d.	.056	.064	.058
25	n.d.	.275	.304	.252
10	n.d.	1.007	1.092	.855
5	n.d.	2.043	2.113	1.729
1	n.d.	6.581	5.967	5.022
Statistical mean	n.d.	.484	.448	.369

making a total now of 17 plays. This separation had been anticipated in the second update, but there had been insufficient information at that time to justify the change. Numerous minor changes were also made in the estimates of some of the reservoir attributes.

In May 1980 the fourth and, at the time of this report, last review and update of the resource evaluation of the NPRA was conducted by the two USGS committees in Menlo Park. New information for review included data from an additional nine wells; the most significant information affecting the resource evaluations came from the Walakpa No. 1 well. There were minor modifications on most of the 17 plays. The most significant modification was made in the resource appraisals for the Simpson play because the earlier extrapolations for the Jurassic reservoirs were now found to be of a poorer quality siltstone in the Walakpa No. 1 well. This modification resulted in a reduction of the estimated resources for the Simpson play and for the total estimated resource potential in the NPRA when processed by DOI/OMPRA in the Monte Carlo model.

RESULTS OF THE ASSESSMENTS

The results of the four successive resource assessments for the NPRA, as generated by the Monte Carlo model using the USGS estimates of the geologic attributes, are listed in table 5.3. The assessments are reported as probability distributions for oil in place, natural gas in place, barrels-of-oil equivalent (BOE) in place, and in-place distribution of pool sizes. These assessments are also shown graphically for comparative purposes as probability distributions in figures 5.4 through 5.7.

All of the resource-appraisal estimates reported in this chapter are based on a computer simulation of approximately 3,000 passes of random sampling from the USGS geologic-attribute estimates. This number of passes is in contrast to the September 1979 results reported by DOI/OMPRA in the Final Report of the 105(b) Economic and Policy

Analysis (U.S. Department of the Interior, 1979) and in the DOI 1980 press release on the updated petroleum resources of NPRA taken from the May 1980 study (U.S. Department of the Interior, 1980). The results reported by OMPRA of the estimated resources in these two releases were based on a computer simulation of only 150 passes. A comparison of resource estimates made using 3,000 passes versus 150 passes shows significantly different results and attests the need for consistency in the number of passes selected for different runs of a computer simulation.

Review and comparison of the results of the four separate resource assessments as recorded in table 5.3 lead to the following comments regarding some apparent relations between the assessments:

(1) There is a significant increase in the estimated petroleum potential between the November 1978 assessment and the May 1979 assessment. This increase is noted, in particular, for the assessment of the oil resources in place. The difference may be explained by the geologists' interpretations of new information from seven wells (two wells being drilled and five wells that were either suspended or abandoned at the time of the May 1979 assessment) and a reevaluation of the preexisting data, which tended to support a higher estimate for petroleum potential than the November 1978 assessment.

(2) The September 1979 assessment for oil-resource potential was not significantly different from the May 1979 assessment. However, the resource potential for natural gas was assessed as being somewhat higher in the September 1979 assessment. There were four additional wells at the time of the September 1979 review (one well being drilled and three either suspended or abandoned). The most important change was the separation of the Jurassic II play into 2 new and separate plays (Simpson and Tunalik)—making a total of 17 plays, 1 more than in the previous assessment.

(3) The May 1980 assessment resulted in a significant reduction in the estimates of the petroleum resource potential for the NPRA from the previous two assessments made in May and September of 1979. This reduction may be explained by the information from the Walakpa No. 1 well that the Jurassic sandstone reservoir section, thought previously to have a high potential, was found to be siltstone in the Walakpa area. This information caused major revisions in the geologic interpretations of the extent of the Simpson play.

CONCLUSION

A play-analysis approach to resource assessment and evaluation for large basins or provinces such as the NPRA was selected by DOI/OMPRA for several reasons. First, it provided a direct assessment and record of the numerous

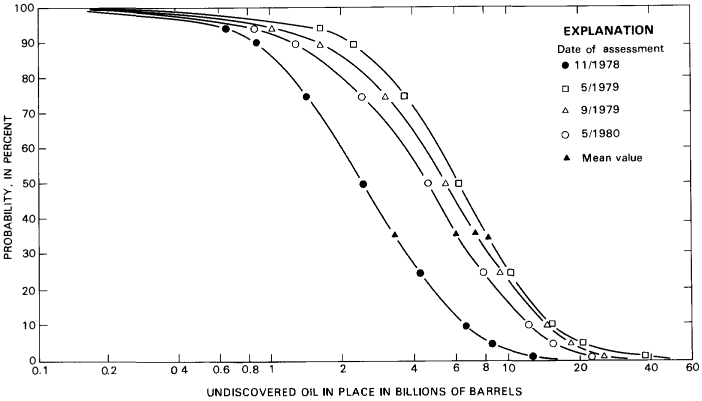

FIGURE 5.4.—Probability distributions of undiscovered oil in place in the NPRA.

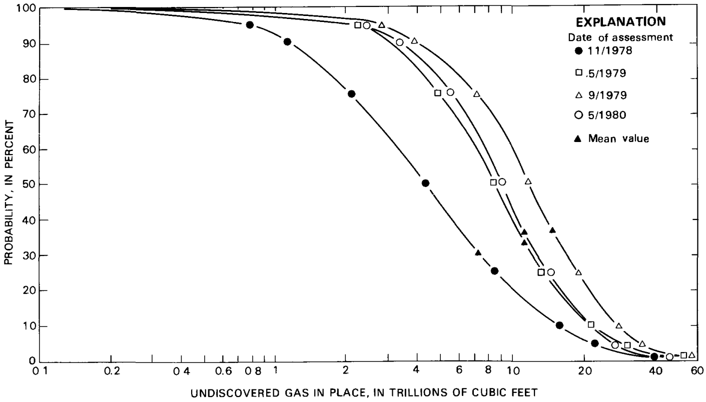

FIGURE 5.5.—Probability distributions of undiscovered gas in place in the NPRA.

geologic characteristics and their uncertainties. Although analogs are of value to the geologist in evaluating a geologic province, the final judgments must be tailored explicitly to the information and perceptions of the study area, that is, the play. Secondly, the level of geologic detail provided by the play-analysis approach was thought to be comprehensive enough, assuming a comparable level of available information, to support a resource assessment and an economic analysis as provided by the Monte Carlo model for a large area, although under conditions of substantial uncertainty. Furthermore, the results of future exploration in an area can easily be incorporated into the play format for updating. Thirdly, although the play-analysis approach treats exploration as a process of prospect evaluation and decision, it does not require explicit identification, specific location, or substantial detail for each prospect. Fourthly, the play-analysis approach recognizes a regional component to the geology within a play, which allows prospects to be geologically correlated. In essence, the play-analysis approach divides the traditional dry-hole risk factor into two components. The first component is the geologic risk common to all prospects in the play because they share a common potential for source, migration, timing, and reservoir rock. The second component is the risk that an individual prospect may be lacking in one or more essential geologic attributes in a way specific to it and independent of the other prospects in the play. Finally, the approach does not require actual discoveries in a play for assessment purposes; subjective judgments may be based on whatever data exist, and therefore the method explicitly reflects the uncertainty in the data (White, 1979).

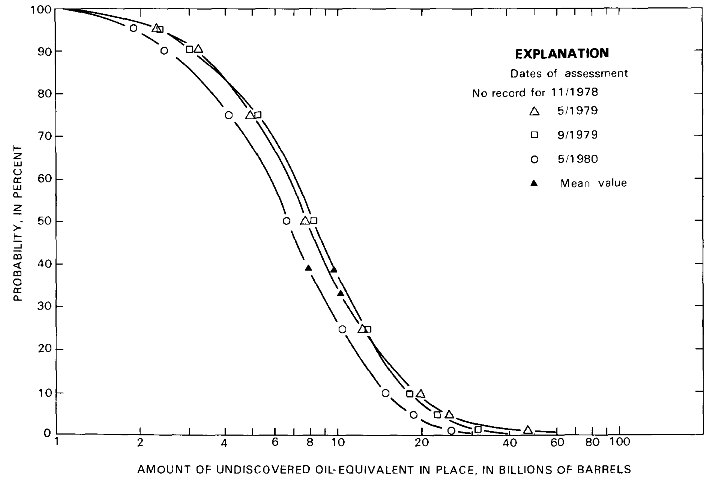

FIGURE 5.6.—Probability distributions of undiscovered oil-equivalent in place in the NPRA.

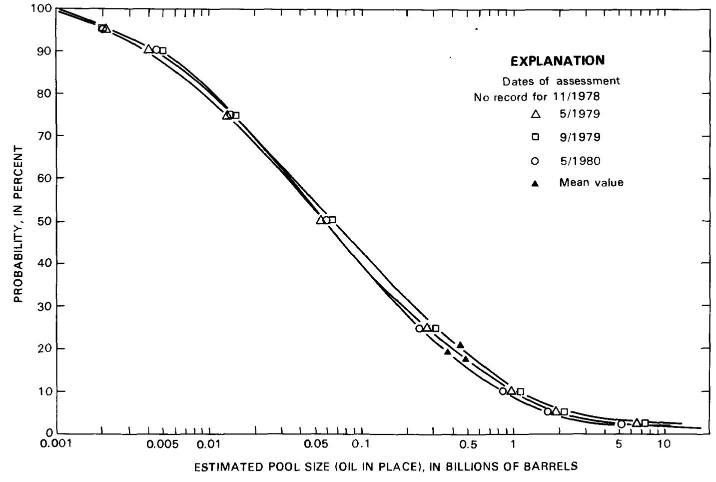

FIGURE 5.7.—Probability distribution of estimated pool sizes for oil in place in the NPRA.

However, problems inherent in the application of the exploration play-analysis approach to petroleum-resource appraisal should not be overlooked. One problem concerns the amount and kind of available data necessary for credible input by the geologists making the subjective evaluations for each of the attribute values. In frontier areas where few data are available, the geologists must base their subjective evaluations for the attributes on comparisons with analogs. The resulting resource assessment is only as good as the geologic analogs selected by the geologists, which may or may not match the frontier basin. When the play-analysis method is used, all the potential plays are assumed to have been identified and adequately described. However, exploration often discovers unexpected resources in unidentified plays, even in well-explored basins. The Michigan basin provides a classic example, namely, the significant resources recently discovered in the northern Niagaran reef play after nearly 40,000 wells had been drilled in the basin. In frontier areas, where knowledge of the subsurface geology is highly speculative, it is difficult to identify and describe adequately all the probable plays (Miller, 1979, 1981; Mast and others, 1980).

Another problem is that many geologists lack the training or experience required to understand the basic principles of probability distributions, let alone the specific probability distributions they produce for the individual attributes in the model. Briefing sessions on the use of probability distributions should be emphasized for the geologic teams that are to provide the information on the data forms.

The many assumptions that must be made in models of this type are cause for concern. One weakness in such play-analysis and prospect-analysis models is the assumption that all the attributes assessed, as used in the Monte Carlo simulations, are independent; in fact, many of the geologic and reservoir attributes are interrelated. This can lead to confusion as geologists mentally try to juggle the assignments of values for each attribute, the likelihood of occurrence of a favorable play, and the favorableness of the prospects in that play.

In addition, serious concerns develop in comparing the results of resource estimates from separate Monte Carlo runs when these estimates are generated by computer simulations that vary from run to run in the number of passes or samplings. There are significant differences in the results of a resource assessment when a run of 3,000 passes is compared to a run of 150 passes. It is strongly recommended for consistency and for robust statistical credibility that the same number of passes (2,000-3,000) be used when making comparative studies.

One apparent advantage of the play-analysis approach is that it simplifies, or appears to simplify, the geologist's task in documenting the geologic information used to evaluate the resources of an area by providing a fixed format for the attributes evaluated and a systematized procedure for the geologist to follow; the actual resource estimate is determined by statistical and mathematical methods through the use of computer models. This method may also reduce the time necessary to evaluate an area, provided ample data are readily available. It also provides the geologist with a checklist that highlights those areas in which information and knowledge are available and those areas in which information is not available.

However, the application of such sophisticated computerized procedures does not mean that these resource assessments are necessarily any more accurate than assessments made using other resource-appraisal methods. Geologists should be aware of and concerned over the assumptions and mathematical manipulations involved in the programs for these computer systems, which are designed by computer programmers not always familiar with basic concepts of petroleum geology (Miller, 1979).

One of the most publicized of the play-analysis methods has been that used by the Geological Survey of Canada (Canada Department of Energy, Mines and Resources, 1977). Several modified versions of the Canadian approach and some others used by industry are currently under study by the USGS. An ideal computerized procedure similar to that used in the play-analysis approach may be the ultimate goal for assessing resources. We have yet to achieve that goal.

REFERENCES CITED

Bois, Christian, 1975, Petroleum-zone concept and the similarity analysis—contribution to resource appraisal, *in* Haun, J.D., ed., Methods of estimating the volume of undiscovered oil and gas resources: American Association of Petroleum Geologists Studies in Geology, no. 1, p. 87-89.

Canada Department of Energy, Mines and Resources, 1977, Oil and natural gas resources of Canada, 1976: Canada Department of Energy, Mines and Resources, Report EP 77-1, 76 p.

Jones, R.W., 1975, A quantitative geologic approach to prediction of petroleum resources, *in* Haun, J.D., ed., Methods of estimating the volume of undiscovered oil and gas resources: American Association of Petroleum Geologists Studies in Geology, No. 1, p. 186-195.

Mast, R.F., McMullin, R.H., Bird, K.J., and Brosgé, W.P., 1980, Resource appraisal of undiscovered oil and gas resources in the William O. Douglas Arctic Wildlife Range: U.S. Geological Survey Open-File Report 80-916, 62 p.

McCrossan, R.G., ed., 1973, The future petroleum provinces of Canada—their geology and potential: Canadian Society of Petroleum Geologists Memoir 1, 720 p.

Miller, B.M., 1979, The evolution in the development of the petroleum resource appraisal procedures in the U.S. Geological Survey and a summary of current assessments for the United States: Society of Petroleum Engineers of the American Institute of Mining Engineers Hydrocarbon Economics and Evaluation Symposium, 8th, Dallas, Tex., 1979, report SPE 7720, p. 79-90.

——— 1981, Application of exploration play-analysis techniques to the assessment of conventional petroleum resources by the U.S. Geological Survey: Society of Petroleum Engineers of the American Institute of Mining Engineers Economics and Evaluation Symposium, Dallas, Tex., 1981, report SPE 9561, 9 p.

Roadifer, R., 1975, A probability approach to estimate volumes of undiscovered oil and gas, *in* Davis, J.C., and others, conveners, Probability methods in oil exploration: American Association of

Petroleum Geologists Research Symposium, Stanford, Calif., 1975, Notes, 18 p.

Roy, K.J., Procter, R.M., and McCrossan, R.G., 1975, Hydrocarbon assessment using subjective probability, *in* Davis, J.C., and others, conveners, Probability methods in oil exploration: American Association of Petroleum Geologists Research Symposium, Stanford, Calif., 1975, Notes, p. 55-60.

U.S. Department of the Interior, 1980, Interior updates Alaska petroleum reserve data: Office of the Secretary, News Release, July 17, 1980, 3 p.

U.S. Department of the Interior, Office of Minerals Policy and Research Analysis, 1979, Final report of the 105(b) economic and policy analysis; Alternative overall procedures for the exploration, development, production, transportation and distribution of the petroleum resources of the National Petroleum Reserve in Alaska (NPRA): Washington, D.C., U.S. Government Printing Office, 145 p.

White, D.A., Garrett, R.W., Jr., Marsh, G.R., Baker, R.A., and Gehman, H.M., 1975, Assessing regional oil and gas potential, *in* Haun, J.D., ed., Methods of estimating the volume of undiscovered oil and gas resources: American Association of Petroleum Geologists Studies in Geology, no. 1, p. 143-159.

White, D.A., and Gehman, H.M., 1979, Methods of estimating oil and gas resources: American Association of Petroleum Geologists Bulletin, v. 63, no. 12, p. 2183-2192.

White, L.P., 1979, A play approach to hydrocarbon resource assessment and evaluation: Conference on the Economics of Exploration for Energy Resources, New York University, N.Y., May 17-18, 1979.

6. POLICY ANALYSES OF THE NATIONAL PETROLEUM RESERVE IN ALASKA—METHODS AND APPLICATIONS

By Paul Bugg, Stanley Miller, and Loring P. White[1]

INTRODUCTION

Frontier regions in the United States, Canada, and elsewhere may contain important domestic fuel and nonfuel mineral resources, yet little exploration has taken place in many of these regions. Even when mineral resources are discovered, the costs of development and production in harsh environments like that of the Arctic and of transportation to distant major markets frequently exceed any obtainable price. Furthermore, development of fuel and nonfuel mineral resources may have a significant impact on wildlife and wilderness areas, as well as on indigenous populations. An example of one such frontier is the National Petroleum Reserve in Alaska (NPRA), an area covering 23 million acres on the North Slope of Alaska. In addition to having petroleum prospects, this area has wildlife and wilderness values that are important especially to the large indigenous Inupiat (Eskimo) population.

In response to a legislative request for a report to help Congress decide on the best use of the NPRA, a method was developed to estimate (1) the economic values of the petroleum resources and (2) the impacts on these values of various price, cost, transportation, leasing, and land-use alternatives. Because of its potential value to geologists, petroleum engineers, economists, and policy analysts facing similar problems in other frontier regions, we provide here a general description of the technique used and its application to North Slope policy decisions.

ACKNOWLEDGMENTS

The work reported in this chapter results from the efforts of many individuals and organizations, including Hermann Enzer, the other members of the 105(b) study team (Roger Anderson, Patricia Devine, Larry Harms, Tod Huffman, Ron Hurdelbrink, Ronald Prishivalko, and Max Taves), the contractors and consultants to the study, and the members of the NPRA Geologic and Resource Appraisal Committees of the U.S. Geological Survey.

Our selection of the play as the appropriate geologic unit was in large part the result of the work of, and discussions with, the Energy Subdivision, Institute of Sedimentary and Petroleum Geology of the Geological Survey of Canada. In particular, the NPRA study team is much indebted to Robert McCrossan and Richard Procter (see Roy and others, 1975). The importance of modeling of regional geologic correlation was brought to our attention by Charles G. Mull of the Division of Geological and Geophysical Surveys, Alaska Department of Natural Resources.

POLICY ISSUES

Because the U.S. Congress believed it had insufficient knowledge to make land-use decisions in the NPRA, it passed Title I of the Naval Petroleum Reserves Production Act of 1976, designed to provide data and analyses upon which national decisions could be based regarding the disposition of these lands. In addition to the continuation of a petroleum exploration program, the Act required a study to determine the best overall procedures for the development, production, transportation, and distribution of the NPRA's petroleum resources and a separate study to determine the best use of the lands, were the oil and gas potential not developed. The first study is known as the NPRA economic and policy analysis, or simply the 105(b) study, after the section of the law requiring it.

The team assigned to the 105(b) study was confronted with the problem of having limited data with which to analyze the economic consequences of alternative policies and procedures for managing petroleum activities in a large area where conflicts existed between petroleum exploration and other land uses. Before decisions were made regarding the appropriate analytical approaches to be used in the analysis, the following major issues related to the management of the NPRA petroleum resources were identified:

1. Is there a reasonable likelihood that commercially attractive oil or gas deposits will be found? If so, how much oil and gas are likely to be recovered?
2. What would be the effects on oil and gas development if alternative land uses are recommended?

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If specific areas of the reserve are excluded from use for development or transportation, what would be the economic consequences of such exclusions on the petroleum activities?

3. What would be the economic consequences of alternative transportation routes?

4. When, at what rate, and in what geographical sequence should the NPRA be developed?

5. What would be the fiscal impacts of petroleum development on the Federal Government, the State of Alaska, and the North Slope Borough?

6. What would be the appropriate leasing systems and terms to use if petroleum resources were transferred from the public to the private sector?

7. What would be the economic consequences of private versus public management of petroleum exploration, development, and production?

To evaluate the analysis of these and other policy issues, the following five resource-management considerations were used as criteria:

1. Economic benefit to the Nation.
2. Reduced dependence on imported oil and gas because of deliveries of NPRA oil and gas.
3. Return to the public, as measured by income to the Federal Government from leasing and taxation.
4. Equitable treatment for Alaska, as measured by revenues to the State of Alaska and the North Slope Borough from petroleum development.
5. Protection of the environment and mitigation of the socioeconomic impacts resulting from development.

The development of a comprehensive approach to managing NPRA's petroleum resources was found to be a complex task that required sorting and selecting from a range of options. It became apparent that no single management approach could simultaneously satisfy all criteria. Therefore, instead of choosing a best-management approach or a unique solution from the many different ways of combining policy options, we initially selected five management approaches that represent the range of available choices and reflect the varying perspectives of Congress, the State of Alaska, the North Slope Borough, and other elements of the public. Two such approaches are outlined below in the section entitled "Selected Policy Analyses."

DEVELOPMENT OF AN ANALYTICAL APPROACH

Before we could address policy issues, we needed an estimate of the petroleum resource base. Therefore, we examined the existing appraisal techniques in order to assess their applicability to the NPRA economic and policy study.

Most approaches to regional resource appraisal and exploration modeling fall into one of three categories: (1) volumetric analysis, (2) prospect analysis, or (3) geomathematical analysis. Historically, volumetric analysis has been the usual procedure applied to a large province. First, an area that has been extensively explored and developed and that is geologically analogous to the area of interest is identified. Then the known hydrocarbon resources in the analog area per unit of sedimentary volume are used as a surrogate for the hydrocarbon potential per unit volume in the area of interest. An example of the use of the volumetric approach maybe found in Jones (1975).

Two problems would exist if this approach were used to estimate the economic value of the potential resources of a frontier province. First, the geologic information developed in a volumetric analysis is too limited to be useful for economic analysis. Many of the geologic characteristics, such as the number and sizes of deposits, which are critical in determining economic value, are not identified. Secondly, because the degree to which the analog area matches the target area is poorly known, it is difficult to estimate quantitatively the geologic uncertainty and, in turn, the economic uncertainty for the area of interest.

The volumetric-analysis approach to petroleum resource appraisal can be extended by incorporating subjective probability assessments that express the geologist's degree of confidence in the estimates. Such subjective assessments attempt to account for the geologic uncertainty of the approach. However, because these appraisals are generally not designed to support economic and policy analysis, they do not provide the geologic characteristics most needed for estimating economic value. A good example of an extended volumetric analysis may be found in Miller and others (1975).

Prospect analysis is another way to assess an area. It involves identifying and making a rather detailed evaluation of all the potential targets for exploratory drilling in the area. This approach is widely used and well developed. Examples of its use may be found in Newendorp (1975) and Eppler and others (1976).

The prospect analysis technique has two shortcomings when applied to a frontier area. First, the data required for a prospect analysis are substantial and are generally not available for an initial economic evaluation. Secondly, prospect analysis typically treats each prospect independently and ignores any regional correlation of geologic characteristics from one prospect to another. The probability that a particular prospect is actually a deposit—the complement of the dry-hole risk factor—is commonly used to assess the risk of each prospect. In essence, this implies that the presence of oil or gas in one prospect is totally independent of its presence in other prospects, even though the prospects may exist in a fairly homogeneous geologic setting. Therefore, although prospect analysis may be appropriate for certain applications, it is inappropriate for the assessment of a frontier area like the NPRA because acquiring the amount of information necessary for its application is generally time consuming and costly. Furthermore, it ignores regional geologic correlations and so makes inefficient use of the geologic information that is available.

A more recent approach to modeling the exploration process relies on geomathematical analysis and makes use of the early results of exploration to estimate the returns from future drilling. In general, initial discoveries are used to estimate the parameters in a statistical model of the discovery process. Two examples of this approach may be found in papers by Attanasi and others (1981) and Kaufman and others (1981). A shortcoming of this approach, in its present state of development, is that it requires information that is not available until some actual discoveries have been made in the area.

PLAY ANALYSIS

For the reasons discussed above, all of these approaches were found to be inappropriate for evaluating the economic consequences of alternative management uses for a large frontier area like the NPRA that has a limited geologic and economic data base. What was needed was an analytical system that would provide information essential to Congressional decisionmakers and could explicitly incorporate the uncertainties in both the inputs (such as the size of the resource base) and the outputs (such as the amount of oil and gas production).

Therefore, a fourth type of appraisal system, play analysis, was adapted over a two-year period by the Office of Minerals Policy and Research Analysis (OMPRA) of the U.S. Department of the Interior to provide petroleum resource estimates in a format that can be used for economic and policy analyses. In this system a play is defined as an area in which one or more prospects occur in a common or fairly homogeneous geologic setting, and the prospects can be explored by using geological, geochemical, and geophysical techniques. Play analysis is based on a resource-appraisal method developed by the Geological Survey of Canada (see Roy and others, 1975), but it involves several modifications of their method. It assesses the probability of petroleum being present, and its quantity, by estimating the likelihood of occurrence of the individual geological characteristics that are necessary for the formation of petroleum deposits. By use of an explicit genetic model of the formation of a deposit, the estimated probabilities for the occurrence of these individual geological characteristics are combined to yield probability distributions of the number, size, and total potential of the petroleum deposits in the play. In yielding such detail for multiple plays, the play approach provides sufficient information to permit economic and policy analyses for the petroleum resources of the region. In addition to permitting an economic analysis, the Canadian system includes the ability to update assessments rapidly while incorporating the uncertainties inherent in the petroleum-appraisal process.

As in the Canadian approach, the OMPRA resource-appraisal technique focuses on the play as a basic unit of geologic analysis. The principal change is the division of the traditional dry-hole risk factor into two parts—a regional component and a prospect-specific component—in order to reflect regional geologic correlation. A fundamental assumption is that the geologic characteristics are significantly correlated within the play but show substantially less correlation across plays. In particular, if all the regional geologic characteristics necessary for the occurrence of trapped hydrocarbons are present in the play area, it is likely that the play will contain one or more deposits of oil or gas. However, if one or more of these regional characteristics is missing or unfavorable, it is likely that all the prospects within the play will turn out to be dry.

The play approach divides the geologic characteristics of a potential deposit into three categories: play-specific, prospect-specific, and reservoir-specific attributes (see Eckbo and others, 1978).

Play-specific attributes consist of geologic characteristics common to the play as a unit and include favorable lithology, hydrocarbon source, timing, migration, reservoir rock, and number of prospects. The occurrence of these attributes is a necessary condition for the existence of oil or gas deposits in the play.

Prospect-specific attributes are the geologic characteristics common to the individual prospects within the play and include the existence of a trapping mechanism, minimum effective porosity, and hydrocarbon accumulation or charge. If the necessary play-specific characteristics exist, the simultaneous occurrence of these three prospect attributes results in the presence of oil or gas in a prospect.

Reservoir-specific attributes are the reservoir characteristics of an individual deposit of oil or gas in the play and include the area of closure, reservoir thickness, effective porosity, trap fill, reservoir depth, water saturation (currently estimated with typical distributions for sandstone or carbonate rock), and hydrocarbon type (that is, oil or dry gas). These attributes determine the volume of oil or gas present in a deposit.

Probability judgments about these three sets of characteristics for the play are developed by experts familiar with the geology of the area of interest. For example, the U.S. Geological Survey (USGS) is responsible for the probability judgments for the National Petroleum Reserve in Alaska (see Bird, chapter 4; Miller, chapter 5). Major plays are first identified within the basin or province, all existing data relevant to the evaluation are next reviewed, and then subjective probability judgments are made for the three sets of attributes for each identified play.

This play approach to estimating petroleum potential was selected for several reasons. First, it is based on an explicit geologic model of petroleum occurrence and provides a direct assessment of the geological characteristics and uncertainties for the area of interest. Although analogs are of great use to the geologist in developing judgments concerning an area, by using the play approach, judgments, as well as the degree of confidence in these judgments, are more precisely structured and tailored explictly to the information and perceptions of the target area.

Secondly, because this approach provides sufficient geologic detail to support economic analysis, it obviates the need for geologists to make implicit or explicit economic judgments. This level of detail includes the modeling of both oil and gas potentials, the number of prospects and deposits, and their field sizes and flow rates. Futhermore, new information derived from additional exploration in an area is quite easily incorporated into the play format.

Thirdly, although the play approach treats exploration as a process of prospect evaluation and drilling decisionmaking, it does not require explicit identification or substantial detail for each prospect (see Kaufman and others, 1975).

Fourthly, by dividing the traditional dry-hole risk factor into two components, the OMPRA approach recognizes a regional geologic component within a play that results in correlation of the geological prospects. The first component is the risk that is common to all prospects in the play because they share a common potential for source material, migration, timing, and reservoir rock. The second component is the risk that an individual prospect may have a geologic flaw specific to itself which is independent of other prospects in the play.

Finally, the approach does not require actual discoveries in a play for assessment purposes; judgments are based on existing data and explicitly reflect the uncertainty in those data.

DEVELOPMENT OF THE PETROLEUM-ACTIVITY AND DECISION-SIMULATION MODEL

Using the play approach, OMPRA designed a Monte Carlo simulation model of the process of petroleum exploration, development, production, and transportation in order to assess the economic potential of the NPRA as an oil and gas province. This model explicitly recognizes the major uncertainties inherent in petroleum estimates by using subjective probability assessments, and it provides a consistent method for estimating the principal economic consequences of a specified set of management alternatives. When the inputs of public policy, economics, and petroleum resource base are specified, the model can be used to estimate various measures of value, including deliveries of oil and gas, under alternative scenarios of frontier-area development.

Oil and gas exploration, development, production, and transportation are highly complex and interdependent activities. Therefore, a model for petroleum activity and decision simulation (PADS) was developed in an attempt to portray these activities under various conditions of uncertainty. Oil and gas activities are simulated for an extended period of time (for example, 40 years), each year's activity being dependent on the simulated results of previous years. Such a year-by-year simulation represents one pass of the model. A large number of passes are run and their results aggregated as frequency distributions to evaluate a policy option.

One set of policies is evaluated repeatedly under varying geologic and economic conditions in each model run, and a large number of passes are made. For each pass, a randomly selected combination of values for the uncertain components, including both the oil and gas resource base and the cost, is selected to simulate one possible state under which oil and gas activities might be economic. The economic consequences of the selected combination are evaluated for each pass. At the end of the model run, the range over all the passes is presented as a probability distribution. A simplified logic diagram of PADS is shown in figure 6.1.

The NPRA has been arbitrarily partitioned into 15 geographic activity areas, which serve as the basic units for analyzing petroleum or other land uses and constitute the lowest level of geographic detail in PADS (fig. 6.2). We note that these activity areas are not necessarily related to the geologic plays used to assess the petroleum potential of the area. The size, shape, number, land-use classification, and transportation corridors of such activity areas and the timing and sequence of their development may be changed in analyses of alternative policies. For example, the region under study may be divided into two sets of activity areas, one set closed to petroleum activity and the other set to be opened for petroleum activity according to a particular schedule. The economic consequences of closing areas to petroleum activity may then be tested.

The model, given the uncertainty about the petroleum resource base, simulates a sequence of decisions regarding potential oil and gas activity over an extended period of time. The making of decisions is simulated explicitly: Choices are determined within the model according to an internal economic-decision rule and are not provided as inputs to the model. The major decisions treated in this manner are (1) the decision to test a petroleum prospect with an exploratory well, (2) the decision to develop, produce, and transport to market the oil and gas in a discovered deposit or combination of deposits, and (3) the decision to abandon a producing pool. When these decisions are being made, the model explicitly differentiates between expectations and after-the-fact outcomes.

STRUCTURE OF THE MODEL

The PADS model is composed of an integrated set of process-oriented submodels. Each of the major elements of petroleum activity is represented in a detailed submodel that attempts to capture the major characteristics of a particular process. The submodels are:

1. *Geology*. The geology submodel simulates a particular resource base for each pass of the model.

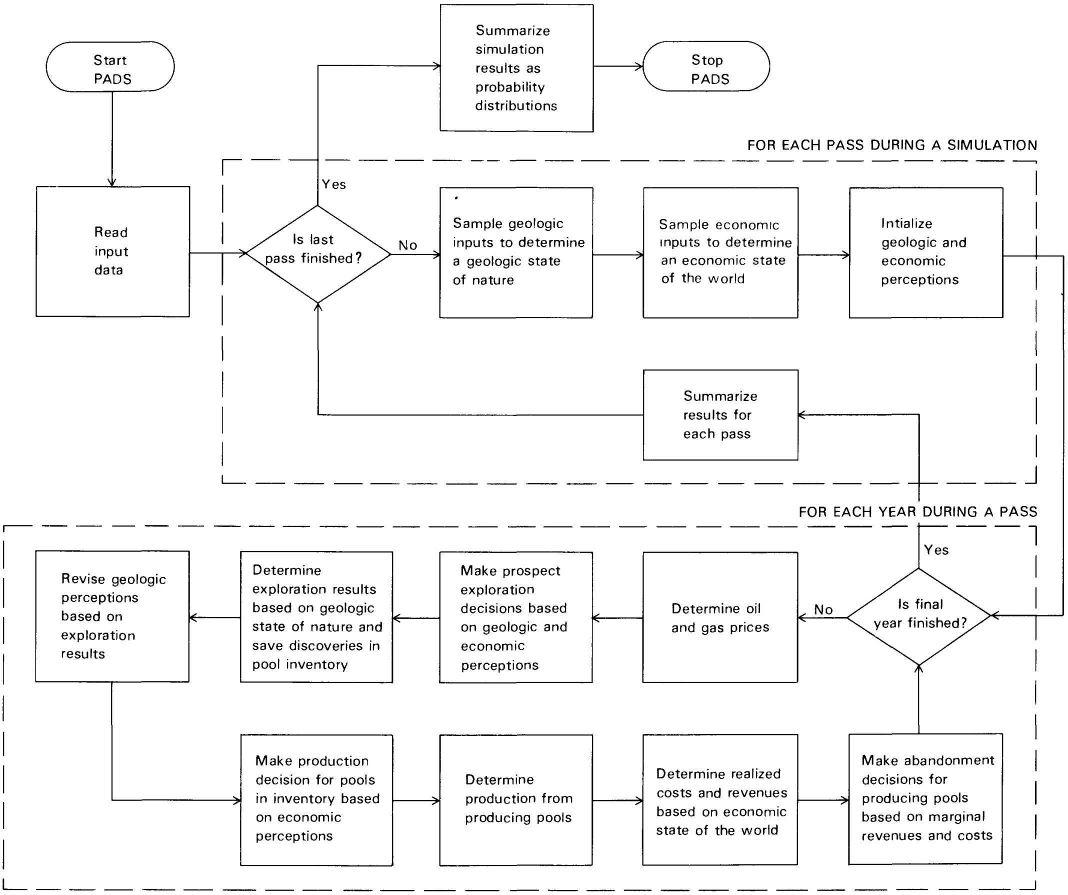

FIGURE 6.1.—Outline of the petroleum activity and decision simulation (PADS) model.

2. *Exploration*. The exploration submodel simulates the search for oil and gas in a frontier basin.

3. *Development and production*. This model simulates the development and production of oil and gas discoveries.

4. *NPRA transportation*. The NPRA transportation submodel simulates the development of pipeline networks for moving oil and gas out of the NPRA.

5. *Alaska transportation*. The Alaska transportation submodel simulates pipeline systems for moving oil and gas from the NPRA to a point outside Alaska.

6. *Distribution*. The distribution submodel simulates marine or overland transportation systems for moving oil and gas from Alaska to the conterminous United States or to export markets.

7. *Economic*. The economic submodel interacts with all other submodels except the geology submodel to estimate the major economic implications of petroleum activity in the NPRA.

Through the integrated application of these submodels, several different economic measures of petroleum activity (for example, costs and revenues) can be computed for each model pass and a distribution for each developed by aggregating the results for all the passes in the model run. Similarly, different physical measures of activity (for example, number of wells

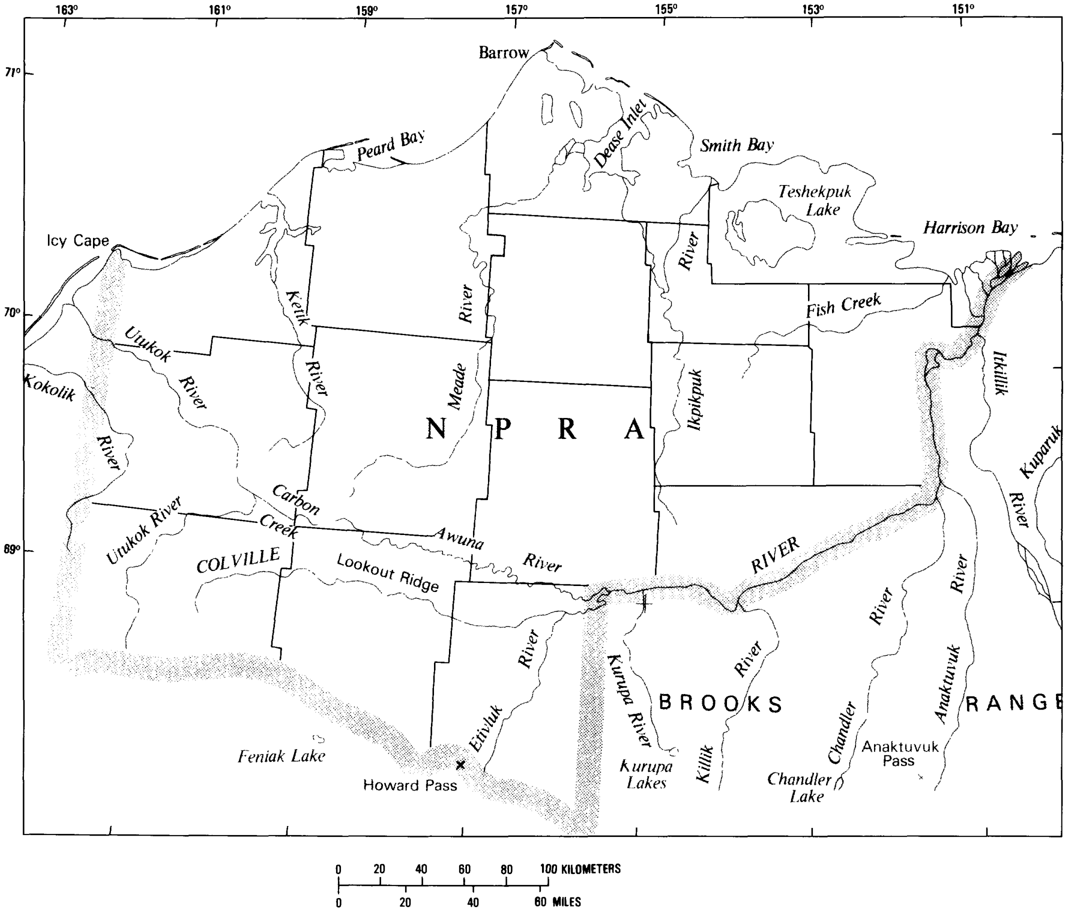

FIGURE 6.2.—Partitioning of the NPRA surface into geographic units (activity areas) along township borders to provide a spatial dimension for evaluating economic and policy alternatives.

TABLE 6.1.—*Distribution of estimated oil and gas resources in place in the NPRA according to appraisals of September 1979 and May 1980*

Probability that quantity is at least given value (percent)	Oil (billion bbl)		Gas (trillion ft^3)	
	May 1980	September 1979	May 1980	September 1979
95-----------	0.8	1.0	2.4	2.9
90-----------	1.3	1.6	3.4	4.0
50-----------	4.7	5.6	9.2	11.8
10-----------	12.4	14.6	21.7	28.9
5-----------	15.4	18.4	27.2	35.8
1-----------	23.0	26.2	45.1	54.8
Average---	6.0	7.1	11.3	14.9

TABLE 6.2.—*Estimated pool-size distribution of NPRA hydrocarbon resources in place*

[Based on resource appraisal of May 1980; estimated gas pools converted to oil equivalent]

Probability that quantity is at least given value (percent)	Pool size (million bbl)
95-----------	2
90-----------	5
50-----------	58
10-----------	855
5-----------	1,729
1-----------	5,022
Average---	369

drilled and miles of pipeline simulated) can be determined and their distributions developed. The relative performance of alternative public-policy options may then be evaluated by comparing their respective distributions. More detailed descriptions of the PADS model may be found in a U.S. Department of the Interior report (1979) and in White (1981b).

SELECTED POLICY ANALYSES

In order to demonstrate the resource-appraisal and updating capabilities of the PADS model, two assessments of the NPRA petroleum resources in place, made in September 1979 and May 1980, are given in table 6.1. The May 1980 petroleum resource appraisal, based on the most current geological and geophysical data available at the time, indicated that the average estimate of total resources in place for all of the NPRA was approximately 6.0 billion barrels of oil and 11.3 trillion cubic feet of gas. Table 6.1 shows that on the basis of the May assessment there is a 5 percent chance that at least 15.4 billion barrels of oil is in place in the NPRA. Also, there is a 50-percent chance for at least 9.2 trillion cubic feet of natural gas. The mean estimate of oil in place declined more than 15 percent, and that for gas declined more than 24 percent since the previous resource evaluation in September 1979. These declines in petroleum estimates resulted from new information obtained by the NPRA drilling program since the September 1979 assessment. Table 6.2 lists the estimated distribution of pool sizes for oil, based on the May 1980 appraisal. For the purposes of obtaining this distribution, all simulated deposits are assumed to be oil accumulations. Given the number of simulated deposits in the NPRA, table 6.2 indicates a 5-percent chance that one of them is a field containing 1.7 billion barrels or more of oil in place.

The PADS model results described below were calculated on the basis of the September 1979 NPRA resource assessment data. Had the May 1980 resource assessment data been available, these results would have reflected the decrease in estimated inplace resources. We note that the complexity of the PADS model relative to the resource appraisal model results in use of a smaller set of simulated resource bases to estimate the distribution of inplace resources. Therefore, the distribution of inplace resources for the PADS model runs was quite similar to, but not identical with, that generated in the September 1979 resource assessment.

To indicate how the PADS model produces output distributions under alternative inputs, selected assumptions and results of two different management approaches are listed in tables 6.3 and 6.4. Table 6.3 lists selected assumptions in a management approach based on traditional procedures for leasing and development on the U.S. Outer Continental Shelf and in an approach with major attention given to environmental values. Because in the environmentally oriented approach development and transportation activities are prohibited in selected areas and the pace of petroleum development is more restrained, it is not surprising to find (table 6.4) that significantly lower values in oil and gas deliveries, national benefits, and Federal and State revenues result.

SENSITIVITY ANALYSES

In addition to an analysis of five basic management approaches for the reserve, sensitivity analyses were performed in which alternative economic and policy assumptions concerning oil and gas prices, land-use management procedures, transportation routes, and the role of the Federal Government were evaluated.

TABLE 6.3.—*Key assumptions of two NPRA management approaches*

Approach 2 (Traditional approach)	Approach 4 (Major attention to environment)
Private-sector exploration and development	Federal Government exploration; private-sector development
No activity prohibitions	Prohibition of petroleum activities and transportation in selected areas
Lease sales	Lease sales
1983-1990 development period	1995-2013 development period

TABLE 6.4.—*Selected estimated results of petroleum activities in the NPRA under management approaches 2 and 4*

[Figures in 5-percent columns indicate that there is a 5-percent chance quantity is at least given value. All dollar values in billions of 1978 dollars, undiscounted unless otherwise noted. See table 6.3 for assumptions in the two approaches]

	Approach 2		Approach 4	
	Mean	5 percent	Mean	5 percent
Total barrels-of-oil equivalent delivered (billion bbl).	2.5	5.9	1.2	3.7
Net national economic benefit ($, discounted at 7 percent).	17.5	43.3	3.6	12.6
Total lease payments ($)---	22.1	43.6	12.9	40.4
Federal corporate income taxes from production ($).	11.5	29.8	4.0	12.2
Total severance-tax payments to Alaska ($).	7.5	18.1	4.0	11.8

Specific areas within the NPRA or any similar frontier region may be withdrawn or otherwise restricted from petroleum development to enhance protection of the wildlife and other resource values. Because this designation requires that protection and enhancement of wildlife or other nonpetroleum values take precedence over all other land uses and activities, it was assumed for the sensitivity analysis that exploration, development, production, and transportation activities would be prohibited within areas designated for wilderness withdrawal. Table 6.5 indicates what society will forego in petroleum deliveries if alternative wilderness designations are assumed for six environmentally sensitive areas in the reserve.

Withdrawal of all six environmentally sensitive areas reduces the estimated probability of commercial production in the NPRA from 97 to 31 percent, and the average values of oil and gas delivered from 1.9 to 0.3 billion barrels and from 3.7 to 0.3 trillion cubic feet, respectively. Such analyses have provided policy makers with explicit estimates of the costs of prohibiting development when making decisions concerning wilderness areas.

In response to a request made in 1980 by staff members of the U.S. House of Representatives Appropriations Subcommittee on Interior, a direct comparison was made of the results of development by the Federal Government versus the private sector. This comparison assumed similar conditions with regard to the initiation and duration of exploration, environmental protection, and other individual policy elements that constitute each management approach.

Despite greater exploratory activity, simulation of the Federal Government's management resulted in considerably lower estimates of oil and gas delivered and of net national economic benefits than simulated development of the NPRA by the private sector. This difference results because the cost savings of the Federal Government's nonpayment of taxes are unable to overcome the results of assuming that exploration, development, and production by any single prospector or explorer, such as the Federal Government, would generate only 40 percent of the discoveries that would be expected under multiple prospectors (White, 1981a). In addition, the Federal Government's expenditures for exploration, development, and production activities were assumed to be 10 percent higher than those of the private sector because of differences in operating efficiency and administrative costs.

THE ARCTIC NATIONAL WILDLIFE REFUGE ANALYSIS

The U.S. Senate Energy and Natural Resources Committee requested in May 1980 that an initial petroleum resource appraisal be made of the Arctic National Wildlife

TABLE 6.5.—*Implications of alternative wilderness designations*

[Figures in 5-percent columns indicate that there is a 5-percent chance quantity is at least designated value; base case assumes resource development by approach 2]

Alternative	Resources in place: Average oil (billion bbl)		Resources in place: Average gas (trillion ft^3)		Probability of commercial production in the NPRA (percent)	Total NPRA oil delivered (billion bbl)		Total NPRA gas delivered (trillion ft^3)	
	Areas open to development	Areas withdrawn	Areas open to development	Areas withdrawn		Average	5 percent	Average	5 percent
Base case: Total NPRA.	7.1	---	14.1	---	97.3	1.9	4.8	3.7	12.9
Case 1: All six areas withdrawn.	1.6	5.5	4.7	9.4	30.7	.3	1.6	.3	2.7
Case 2: Teshekpuk Lake and Utukok River Uplands Areas withdrawn.	5.6	1.5	10.7	3.4	93.3	1.5	4.4	2.9	10.8
Case 3: Colville River Valley withdrawn.	5.4	1.7	12.2	1.9	92.7	1.4	4.4	3.2	12.4
Case 4: De Long Mountains/ Arctic Foothills withdrawn.	7.1	0	13.5	.6	97.3	1.9	4.8	3.6	12.9
Case 5: Ikpikpuk River withdrawn.	5.6	1.5	12.2	1.9	92.7	1.5	4.1	3.1	11.0
Case 6: Kasegaluk withdrawn.	6.2	.9	11.7	2.4	96.7	1.6	4.4	3.1	10.8

TABLE 6.6.—*Preliminary oil and gas estimates for the Arctic National Wildlife Refuge (ANWR) from the petroleum resource appraisal of June 2, 1980*

Probability that quantity is at least given value (percent)	Total ANWR oil in place (billion bbl)	Total ANWR gas in place (trillion ft^3)
95------------	0.2	1.4
90------------	.4	2.2
50------------	2.7	8.4
10------------	11.3	25.2
5------------	17.0	33.9
1------------	32.0	61.7
Average----	4.9	11.9

TABLE 6.7.—*Preliminary estimates of the pool-size distribution for the Arctic National Wildlife Refuge (ANWR)*

[Based on resource appraisal of June 2, 1980; estimated gas pools converted to oil equivalent]

Probability that quantity is at least given value (percent)	Total ANWR pool size (million bbl)
95-----------	6
90-----------	14
50-----------	216
10-----------	2,102
5-----------	3,811
1-----------	10,804
Average---	892

Refuge on the basis of the methods developed for the 105(b) Economic and Policy Analysis (U.S. Department of the Interior, 1979). Staff members of the Office of Minerals Policy and Research Analysis, working with geologists of the USGS and the State of Alaska, derived distributions of oil and gas for the coastal plain of the refuge as well as the distribution of field sizes (tables 6.6, 6.7). The results indicate that the estimated average oil-pool size within the coastal plain of the refuge is nearly 900 million barrels, more than twice the estimated average pool size within the NPRA. These data played a pivotal role in the negotiations that took place in the U.S. Congress regarding the future land status of the refuge as reflected in Section 1002 of the Alaska National Interest Lands Conservation Act.

CONCLUSION

A primary advantage of the PADS model is that it transforms the resource assessments of geologic experts into a format that can be used for testing a range of alternative policies. Once geologic data regarding petroleum occurrences are provided by the experts, they can be combined with economic and engineering data and evaluated by the PADS technique to provide estimated economic consequences. The model directly reflects the risks inherent in alternative decisions by incorporating uncertainty in the data base, processing, and outputs.

The PADS method provides an approach that has been successfully applied in analyses of the petroleum potential of frontier areas like the NPRA and the Arctic National Wildlife Refuge. The results of these studies have had an impact on North Slope legislative developments. The 105(b) study results are reflected in the Presidential bill to lease the NPRA to the private sector. They have also served as background for the NPRA lease-sale decisions made by the U.S. Department of the Interior. Because of its applicability to other frontier areas, the PADS model has generated considerable interest outside the U.S. Department of the Interior. The Canadian Department of Energy, Mines, and Resources and the Alaska Department of Natural Resources have developed the ability to use this analytical technique. The model has also been used by the U.S. Department of Energy in the development of leasing policies.

The PADS model continues to be modified and refined. In order to provide secure energy supplies, geologists, petroleum engineers, economists, and policy analysts should continue to work together to improve such techniques. To this end, meetings of working groups have been held at selected intervals. The groups included technicians from the former Office of Minerals Policy and Research Analysis of the U.S. Department of the Interior, the Canadian Department of Energy, Mines and Resources, Statistics Canada, the State of Alabama, the State of Alaska, the U.S. National Petroleum Council, and major oil corporations and petroleum industry service companies. Similar technical interchanges with representatives of other public and private organizations are needed and will be welcomed.

REFERENCES CITED

Attanasi, E.D., Drew, L.J., and Root, D.H., 1981, Physical variables and the petroleum discovery process, *in* Ramsey, J.B., ed., The economics of exploration for energy resources: Greenwich, Conn., JAI Press (Contemporary Studies in Economic and Financial Analysis, v. 26), p. 3-18.

Eckbo, P., Jacoby, H., and Smith, J., 1978, Oil supply forecasting—a disaggregated approach: Bell Journal of Economics, v. 9, no. 1, p. 218-235.

Eppler, J.L., Price, E.R., and Wansbrough, R.S., 1976, Evaluation of dry hole probability associated with exploration projects: Society of Petroleum Engineers of AIME Annual Fall Technical Meeting, 51st, New Orleans, 1976, Preprint SPE-6081, 16 p.

Jones, R.W., 1975, A quantitative geologic approach to prediction of petroleum resources: American Association of Petroleum Geologists Studies in Geology 1, p. 186-195.

Kaufman, G.M., Balcer, Y., and Kruyt, D., 1975, A probabilistic model of oil and gas discovery: American Association of Petroleum Geologists Studies in Geology 1, p. 113-142.

Kaufman, G.M., Runggaldier, W., and Livne, Z., 1981, Predicting the time rate of supply from a petroleum play, *in* Ramsey, J.B., ed., The economics of exploration for energy resources: Greenwich, Conn., JAI Press (Contemporary Studies in Economic and Financial Analysis, v. 26), p. 69-102.

Miller, B.M., Thomsen, H.L., Dolton, G.L., Coury, A.B., Hendricks, T.A., Lennartz, F.E., Powers, R.B., Sable, E.G., and Varnes, K.L., 1975, Geological estimates of undiscovered recoverable oil and gas resources in the United States: U.S. Geological Survey Circular 725, 78 p.

Newendorp, P.D., 1975, Decision analysis for petroleum exploration: Tulsa, Okla., Petroleum Publishing Co., 668 p.

Roy, K.J., Procter, R.M., and McCrossan, R.G., 1975, Hydrocarbon assessment using subjective probability, *in* Probability methods in oil exploration: American Association of Petroleum Geologists Research Symposium, Stanford, Calif., 1975, Proceedings, p. 56-60.

U.S. Department of the Interior, Office of Minerals Policy and Research Analysis, 1979, Final report of the 105(b) economic and policy analysis: Alternative overall procedures for the exploration, development, production, transportation and distribution of the petroleum resources of the National Petroleum Reserve in Alaska (NPRA): Washington, U.S. Government Printing Office, 145 p.

White, L.P., 1981a, Estimating the value of multiple perspectives in exploration: Institute of Gas Technology Symposium, Energy Modeling III; Dealing with Energy Uncertainty, Chicago, 1980, Papers, p. 261-265.

——— 1981b, A play approach to hydrocarbon resource assessment and evaluation, *in* Ramsey, J.B., ed., The economics of exploration for energy resources: Greenwich, Conn., JAI Press (Contemporary Studies in Economic and Financial Analysis, v. 26), p. 51-67.

Lisburne No. 1 well, with Otuk Creek in foreground. Overturned anticline in background exposes Lisburne Formation and forms Ivotuk Ridge. Photograph by Irvin Tailleur.

GEOLOGIC FRAMEWORK

Planning a systematic petroleum-exploration program or assessing the petroleum potential of a given region involves applying a reference model to the geologic framework. That framework is assembled from many detailed studies that are compiled, synthesized, and interpreted. As more information is added to the framework, the validity of both the detail and the framework is tested. The several studies completed under the NPRA program that are included here both add to and test our knowledge of the region's geology.

The geologic framework for northern Alaska and the NPRA has been pieced together largely from the exploration and development of the petroleum resources. Systematic geologic studies and mapping by the USGS began in the region in the early 1900's and continue today. A series of USGS publications describe the geology and record the evolution of geologic-framework concepts. The chapters that follow add to these interpretations and bring them into accordance with current plate-tectonic models.

7. STRATIGRAPHY, STRUCTURE, AND PALINSPASTIC SYNTHESIS OF THE WESTERN BROOKS RANGE, NORTHWESTERN ALASKA

By Charles F. Mayfield, Irvin L. Tailleur, and Inyo Ellersieck

INTRODUCTION

The western Brooks Range is situated at the northwest end of the Cordilleran orogenic belt of North America. As in its counterparts to the south in the Canadian Rockies and the thrust belts of Idaho, Montana, and Wyoming, the Mesozoic orogeny in the Brooks Range was characterized by a period of intense compression in which large panels of shelf deposits were thrust onto what had been a stable continental platform. In the Brooks Range, this process also involved the obduction of an extensive sheet of ophiolite and is here viewed as the underthrusting of a continental margin below an oceanic plate to the south. The western part of the Brooks Range is a good place to study the effects of this process, because erosion has stripped away just enough of the major thrust sheets to permit a comprehensive three-dimensional view of the juxtaposed sequences. This unusually complete preservation and exposure of the structure and stratigraphy of a region makes it possible to gain added insight into orogenic processes and to reconstruct a detailed picture of the depositional history of the continental edge before the orogeny.

This chapter describes the stratigraphy and structure of the western Brooks Range. During the orogeny that created the Brooks Range in Jurassic and Cretaceous time, a stable continental shelf containing Devonian to Lower and Middle(?) Jurassic sediments was broken up and telescoped by numerous thrust faults, the combined displacement measuring hundreds of kilometers. In the first section of this report a tectonostratigraphic scheme is outlined in an attempt to simplify and catalog the thrust-faulted stratigraphy. This section is followed by a palinspastic synthesis in which the rock units are restored to their original basins of deposition. The report concludes with a plate-tectonic model that seems to explain the principal orogenic processes which created the Brooks Range.

The palinspastic synthesis of the western Brooks Range concentrates on a 300-m.y. period from Devonian to Cretaceous time. This period includes the time of deposition of most of the regional sedimentary rocks units that crop out in the northern and western parts of the western Brooks Range. In the southeastern part, Precambrian and lower Paleozoic rocks are exposed, but much of their geologic history was obscured by regional metamorphism during the Brooks Range orogeny in Jurassic and Cretaceous time.

The tectonostratigraphic scheme presented in this report is based on 12,000 km^2 of geologic field mapping at a scale of 1:63,360 (1 in. = 1 mi). Field work was done during the summer months of 1978, 1979, and 1981. This mapping project, undertaken in order to achieve a better understanding of the complex structure and stratigraphy of the western Brooks Range, was carried out in connection with the exploration program of the National Petroleum Reserve in Alaska. Seven open-file maps or Miscellaneous Field Investigations Maps of this area are currently available, and others are being prepared for publication. Areas shown on geologic maps already published are being reinterpreted using the scheme presented in this report.

We consider the western Brooks Range to consist of the area bounded on the east by long 156° W. and on the west by the Chukchi Sea. The area includes the Howard Pass, Ambler River, Misheguk Mountain, Baird Mountains, De Long Mountains, Noatak, and Point Hope 1:250,000-scale quadrangles (fig. 7.1). We have extended this region a short distance north and south of the Brooks Range—north through the northern foothills and south to the Arctic Circle—to show important geologic details in adjacent provinces that relate to the Brooks Range orogeny.

The present concepts of how the Brooks Range was formed and how the rocks were distributed before the orogeny are based upon numerous geologic studies. Reports that have presented a generalized stratigraphic and structural synthesis of this region include those by Tailleur and others (1966), Tailleur and others (1967), Snelson and Tailleur (1968), Tailleur (1969a, b), Brosgé and Tailleur (1970), Martin (1970), Tailleur and Brosgé, (1970), Mayfield and others (1978a), Churkin and others (1979a), Ellersieck and others (1979), and Mull (1979, 1982). Differences in nomenclature and in interpretation found in these reports reflect the fact that the stratigraphic

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and structural synthesis has been, and still is, in a process of evolution. This report confirms, documents, and refines many of the ideas reported earlier; where possible, the same concepts and terms are used. Details of the stratigraphic sequences and allochthons can be checked in the field, using either the allochthon-sequence map included in this report or the more detailed geologic maps on which the current interpretations are based. Important differences from previous stratigraphic and structural interpretations are discussed under the appropriate subject headings.

GEOLOGIC SETTING

Discussion of the general geology of the western Brooks Range and adjacent areas can be simplified by dividing this region into four geologic provinces: (1) the Colville basin; (2) the De Long Mountains allochthon belt; (3) the Schwatka Mountains province; and (4) the Yukon-Koyukuk province (fig. 7.2). The rocks in these provinces have a related geologic history that provides a comprehensive picture of the evolution of the Brooks Range.

The Colville basin, sometimes called the Colville geosyncline (Payne, 1955) or the Colville trough, consists of a thick series of Lower and Upper Cretaceous clastic rocks along the north side of the Brooks Range. The rocks are predominantly immature to moderately mature sandstone, mudstone, and conglomerate—clastic materials that were shed from the developing Brooks Range orogen. The basin sequence is more than 6,500 m (20,000 ft) thick near the northern edge of the study area and thins gradually to the south, where it onlaps Lower Cretaceous and older rocks of the De Long Mountains allochthon belt. Under the Colville basin, a succession of Lower Cretaceous (Neocomian) and older sedimentary rocks dips gently to the south. The stratigraphy is inferred from seismic traces that extend to equivalent strata in exploration wells farther to the north. Carboniferous and Permian strata under the Colville basin correlate in age and lithology with rocks exposed in the Schwatka Mountains province in the southwestern Brooks Range (Mull, 1982).

Important rock units in this part of the Colville basin are the Lower Cretaceous (Albian) Torok and Fortress Mountain Formations—mostly of flyschoid marine turbidites deposited at the close of the period of major thrusting in the Brooks Range. These rocks are succeeded by the Lower and Upper Cretaceous Nanushuk and Upper Cretaceous Colville Groups—Albian to Maestrichtian marine and deltaic sandstone, shale, conglomerate, and coal deposited during the culmination and waning stage of the orogenic uplift.

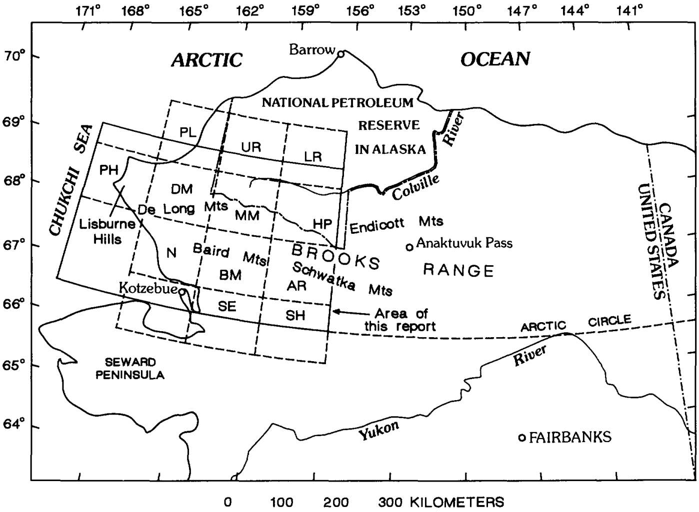


FIGURE 7.1.—Central and northern Alaska, showing area of western Brooks Range covered in this report. Letters identify 1:250,000 quadrangles outlined by dashed lines: PL, Point Lay; UR, Utukok River; LR, Lookout Ridge; PH, Point Hope; DM, De Long Mountains; MM, Misheguk Mountain; HP, Howard Pass; N, Noatak; BM, Baird Mountains; AR, Ambler River; SE, Selawik; SH, Shungnak. Also shown are the principal mountain belts within the western Brooks Range.

The rocks of this province have been gently folded into broad anticlines and synclines with fold axes that generally trend east-west. Deformation gradually decreases from south to north in the Colville basin; within the Fortress Mountain and Torok Formations, it decreases from lower to higher in the section. In some places along the southern margin of the province, thrust faults and northward overturned folds in the lower strata of the Fortress Mountain and Torok Formations are overlain by gently folded and sparsely faulted strata of the the upper parts of the same rock units. These structural relations show that the period of most intense deformation had ended before late-Fortress Mountain and Torok time.

The De Long Mountains allochthon belt includes the Endicott Mountains, De Long Mountains, Lisburne Hills, and the northern and western parts of the Baird Mountains (fig. 7.1). In this region the bedrock is composed of sedimentary and, to a lesser extent, igneous rocks that range in age from Ordovician to Early Cretaceous in the Lisburne Hills and Baird Mountains (fig. 7.2) and Devonian to Early Cretaceous in the De Long and Endicott Mountains. The rocks occur in a series of stacked thrust sheets that have been gently folded and then eroded to form numerous klippen and fensters. The strata of this province are thought to make up a large synclinorium, dipping south or southeast along the north front of the De Long and Endicott Mountains and north or northwest along the southern boundary with the Schwatka Mountains province.

Although many folds have divergent orientations, most axes in the De Long and Endicott Mountains are generally parallel to the west or southwest physiographic trend of the mountain ranges and are thought to be at right angles to the principal thrust direction. Incompetent rocks such as shale and chert have been deformed intensely, and in some places there are numerous complex disharmonic folds. Anticlinal folds are commonly overturned toward the north in the Endicott Mountains and eastern De Long Mountains and overturned toward the northwest in the western parts of the De Long and Baird Mountains. In the Lisburne Hills, fold axes generally trend north-south and appear to transect the westward structural trends of the foothills north of the Brooks Range.

The Schwatka Mountains province occupies the southern and eastern part of the Baird Mountains quadrangle and the central part of the Ambler River quadrangle. In general, this province is an internally complex anticlinorium. Its northern edge dips north, under a series of thrust sheets that form the base of the De Long Mountains allochthon belt, and its southern edge dips south under thrust-faulted mafic igneous rocks that are partly covered by middle Cretaceous clastic rocks. This part of the Brooks Range is believed to be autochthonous or parautochthonous, because the Upper Paleozoic metasediments are closer to the crustal rocks on which they were deposited than are the coeval rocks in the De Long Mountains allochthon belt, where the sedimentary and igneous rocks are widely separated from the crustal rocks on which they were formed.

The autochthonous or parautochthonous rocks of the Schwatka Mountains province also are considered to have moved relatively little with respect to rocks in the Colville basin. Upper Paleozoic rocks are believed to be linked in the subsurface to the north with coeval and lithologically similar rocks that occur under the Colville basin and have been found in exploration wells drilled under the North Slope (Mull, 1982).

Most rocks of the Schwatka Mountains province were isoclinally folded and regionally metamorphosed to a greenschist metamorphic facies during Cretaceous time. Consequently, the older part of the sedimentary sequence that makes up the protolith is neither well dated nor well understood. On the basis of lithologic correlations and sporadic fossils, the youngest parts of the stratigraphic section in the Schwatka Mountains province are considered to be Devonian, Carboniferous, and locally Permian(?) (Mull and Tailleur, 1977; Mayfield and Tailleur, 1978). Thus they are partly coeval with the allochthonous sedimentary sequences in the De Long Mountains allochthon belt. Mississippian rocks in this province rest upon Devonian and older rocks along a regional angular unconformity. This relation is in sharp contrast to most (all but the lowest) allochthonous sedimentary

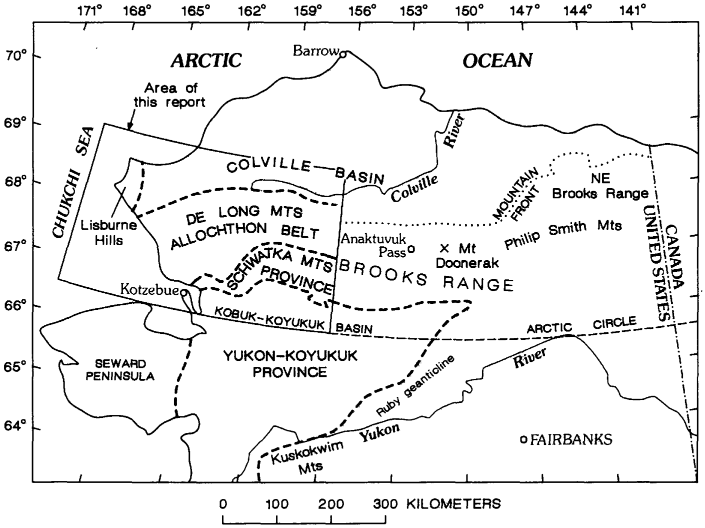


FIGURE 7.2.—Central and northern Alaska, showing the four principal geologic provinces of the western Brooks Range and selected geographic features. Bold dashed lines mark geologic province boundaries.

sequences in the allochthon belt, which record relatively unbroken sedimentation from Devonian into Mississippian time. The protolith for the autochthonous pre-Mississippian rocks appears to have been a thick succession of sedimentary and igneous rocks of early Paleozoic and late Precambrian age.

Within the area covered by this report, the Yukon-Koyukuk province (fig. 7.2), described in detail by Patton (1973), includes the rocks south of the Brooks Range in the Selawik, Shungnak, and southern Ambler River quadrangles (fig. 7.1). The bedrock is composed chiefly of orogenic clastic rocks and volcanogenic sedimentary and andesitic rocks of Cretaceous age. Locally, these rocks are intruded by plutons of Late Cretaceous and earliest Tertiary age.

Immediately south of the Brooks Range, the Yukon-Koyukuk province is underlain by sandstone, conglomerate, coal, and shale that form a basin called the Kobuk-Koyukuk basin (Patton, 1973). Clastic materials were shed into this east-trending troughlike basin from andesitic rocks to the south and from the Brooks Range to the north. Unlike the Colville basin, into which a continuous flood of detritus was shed from the Brooks Range during Early Cretaceous (late Neocomian) to Tertiary time, the Kobuk-Koyukuk basin appears to record a fairly short episode of deposition in middle Cretaceous (Albian and Cenomanian) time (Patton, 1973). In some places along the northern margin of the basin, the clastic rocks rest on south-dipping, thin, and discontinuous thrust sheets of mafic and ultramafic rocks that are thought to be the root zone for similar igneous rocks in the De Long Mountains allochthon belt (Tailleur, 1969a, b; Patton and others, 1977; Roeder and Mull, 1978; Gealey, 1980). In other places, the Cretaceous rocks lap onto low-grade metamorphosed Devonian limestone and pelitic schist that are part of the Schwatka Mountains province.

South of the Kobuk-Koyukuk basin is an extensive area of slightly older andesitic volcanic rocks, which probably underlie most of the sedimentary rocks in the Yukon-Koyukuk province. The volcanic assemblage is composed predominantly of volcaniclastic rocks, flows, and hypabyssal intrusive rocks. Fossils from volcaniclastic beds are Early Cretaceous (Neocomian) in age, and K-Ar ages from andesitic volcanic rocks range from 134 to 117 Ma. Some tuff beds are considered to be middle Cretaceous in age. Late Cretaceous granitic plutons having K-Ar ages of approximately 100 to 80 Ma intrude the older rocks in the province. Local felsic extrusive, tuffaceous, and hypabyssal rocks that are probably related to the plutonic activity have Late Cretaceous to early Tertiary K-Ar ages that range from 85 to 58 Ma (Patton, 1973).

DEFINITIONS OF SEQUENCES AND ALLOCHTHONS

The hundreds of thrust sheets that are present in the De Long Mountains allochthon belt and the Schwatka Mountains province contain parts of structurally overlapping sequences that are composed of sedimentary, metasedimentary, and (or) igneous rocks. On the allochthon map (pl. 7.1), 15 sedimentary and 2 igneous sequences are named in the De Long Mountains allochthon belt. All the rocks in the Schwatka Mountains province have been assigned to one sequence. The sedimentary sequences are mostly coeval. Each is characterized by having a distinctive column of sedimentary rocks that have slightly different lithologic facies compared to coeval rocks of other sequences. The rocks of each sequence are believed to have been deposited contiguously. Depositional contiguity is inferred on the basis of similarity of stratigraphic sections, present geographic proximity of outcrops, and a regional occurrence at the same structural level. Igneous sequences are predominantly composed of distinctive igneous rocks that cover a wide geographic area.

Sequences are distinguished by lithologic differences in certain coeval rock units. Both igneous sequences and a few of the sedimentary sequences have certain unique rock units that serve to distinguish them from all other sequences. The other sedimentary sequences do not have a single unique rock unit and must be distinguished by differences in the succession of rock units. Sediments deposited during Late Mississippian time have the greatest variety of lithologic types and so are most useful for distinguishing the various sedimentary sequences. Where Mississippian rocks in different sequences have similar lithologies, the sequences most commonly can be distinguished on the basis of a comparison of their Upper Devonian rocks. Pennsylvanian to Early Cretaceous rocks are generally more similar, and they have been used only sparingly to help distinguish certain sequences.

In the De Long Mountains allochthon belt, thrust sheets containing the same or similar sequences almost always occur at the same structural level. If this were not the case, then the paleogeographic basins of deposition for the rock units would be much more difficult to reconstruct. Fortunately the structural levels of sequences seem to be consistent, with few exceptions, over hundreds of square kilometers in the western Brooks Range, and a reasonable pattern of paleogragraphic stratigraphy results when allochthons are unstacked sequentially.

The smallest division of a structural level is a thrust sheet, but because there are hundreds of thrust sheets, often poorly exposed, we cannot describe each of them. Therefore, in order to provide a simple structural scheme for this large region, multiple thrust sheets that contain similar sequences and occur at approximately the same structural level are grouped into seven structural units called "allochthons." Allochthons are sequentially numbered, allochthon number one, the Brooks Range allochthon, being at the bottom of the stack and allochthon number seven, the Misheguk Mountain allochthon, at the top. Autochthonous or parautochthonous metasedimentary rocks in the Schwatka Mountains province are not numbered.

Many previous studies that recognized major structural dislocations in the western Brooks Range did not distinguish between the structural units and the sedimentary sequences within them, but used the same names for both. Most of these names correspond to the structural units that are here called allochthons. Mapping over a large area, however, shows that there are significant stratigraphic changes from place to place within most of the allochthons. The facies differences within allochthons generally are not as pronounced as the facies differences between different allochthons. Thus, the allochthons also can be used as generalized tectonostratigraphic units. This simplification is most useful in correlations across hundreds of kilometers or for mapping at regional scales.

Our scheme of seven allochthons provides for simplicity when structural units are unstacked on a palinspastic map. The designation of 18 sedimentary and igneous sequences emphasizes facies changes between and within allochthons. Distinguishing minor differences in sequences permits a more accurate view of the limits that can be placed on structural interpretations as well as a more complete palinspastic view of the original basins of deposition.

Detailed study of some areas should provide data for further division of some of the sequences used in this report. There is commonly some degree of facies change between some of the coeval rocks in any two thrust sheets, or even within the same sheet. Different observers might decide to define their sequences in different ways, because of differences between the areas where they have worked, or because they may base their interpretations on different units within the sequences. Undoubtedly the system presented here will undergo expansion, and the units will undergo subdivision as additional regional and detailed studies are made.

SUCCESSION OF ALLOCHTHONS COMPARED TO EQUIVALENT STRUCTURAL UNITS OF PREVIOUS STUDIES

From the bottom to the top, the stack of allochthons that are differentiated in the De Long Mountains allochthon belt are: (1) the Brooks Range allochthon; (2) the Picnic Creek allochthon; (3) the Kelly River allochthon; (4) the Ipnavik River allochthon; (5) the Nuka Ridge allochthon; (6) the Copter Peak allochthon; and (7) the Misheguk Mountain allochthon. The first five are composed mostly of coeval sedimentary sequences. The base of the sequences is Ordovician, Devonian, or Mississippian, and the top is Early Cretaceous in age. The top two allochthons are composed of distinctive igneous sequences that are Triassic and (or) Jurassic in age. Each allochthon is named for a prominent geographic feature where the structural position of one or more sequences in the allochthon is well exposed. Allochthon names are taken from previous publications. Because other authors commonly have used different names for equivalent structural units, table 7.1 is included to correlate the presently used structural nomenclature with that of previous reports.

The process of naming and mapping sequences and structural units in the western Brooks Range began with the publication of geologic maps from the northern part of the Howard Pass and Misheguk Mountain quadrangles by Tailleur and others (1966). Their report represents the first significant step toward understanding and mapping the distribution of thrust-juxtaposed sequences. By 1970, six of the seven presently distinguished structural units (equivalent to the allochthons of present usage) had been described in one or more reports on the regional geology. These were by Tailleur and others (1967); Snelson and Tailleur (1968); Tailleur (1969a, b); Tailleur and Brosgé (1970); and Martin (1970). By that time most of the allochthons had been named, even though different names were sometimes given to equivalent structural units.

In these earlier reports, the structural position of the Nuka Ridge allochthon was one of the least understood of the tectonostratigraphic relations. For example, Tailleur and others (1966) thought the Nuka Ridge allochthon was on top of the Ipnavik and Brooks Range allochthons. However, a few years later Tailleur (1969a, b) and Tailleur and Brosgé (1970) reported that the Nuka Ridge allochthon was either on the top or on the bottom of the

TABLE 7.1.—*Comparison of allochthons described in this report with equivalent structural units used in earlier works*

(n.d., not distinguished)

This report	Curtis and others (1982, 1983) Ellersieck and others (1982, 1983) Mayfield and others (1982a, 1983a)	Mull (1982)	Ellersieck and others (1979)	Mull (1979)	Churkin and others (1979a) Churkin and Trexler (1981)	Mayfield and others (1978a)	Martin (1970)	Snelson and Tailleur (1968) Tailleur and Brosge (1970)	Tailleur and others (1966)
Misheguk Mountain allochthon	Misheguk Mountain allochthon	Misheguk Mountain allochthon	Misheguk Mountain thrust sequence	Misheguk sequence	n.d.	Misheguk Mountain thrust sequence	Ultrabasic pluton sequence	Misheguk thrust tectonic unit	n.d.
Copter Peak allochthon	Copter Peak allochthon	Copter Peak allochthon	Copter Peak thrust sequence	Misheguk sequence	n.d.	Misheguk Mountain thrust sequence	Ultrabasic pluton sequence	Misheguk thrust tectonic unit	n.d.
Nuka Ridge allochthon	Nuka Ridge allochthon	Nuka Ridge allochthon	Nuka Ridge thrust sequence	Nuka sequence	n.d.	Nuka Ridge thrust sequence	Nuka Ridge sequence	Nuka Ridge thrust tectonic unit	Nuka Ridge sequence
Ipnavik River allochthon	Ipnavik River allochthon	Ipnavik River allochthon	Ipnavik River thrust sequence	Ipnavik sequence	n.d.	Ipnavik River thrust sequence	Ipnavik sequence	Ipnavik thrust tectonic unit	Ipnavik sequence
Kelly River allochthon	Kelly River allochthon	Kelly River allochthon	Kelly River thrust sequence	Kelly sequence	n.d.	Kelly River thrust sequence	De Long sequence	Kelly thrust tectonic unit	n.d.
Picnic Creek allochthon	Picnic Creek allochthon	n.d.	Picnic Creek thrust sequence	n.d.	n.d.	Northwestern Brooks Range thrust sequences	n.d.	Wulik thrust tectonic unit	Sequence at Kiligwa River
Brooks Range allochthon	Brooks Range allochthon	Endicott Mountains allochthon	Brooks Range thrust sequence	Endicott sequence	Kagvik structural sequence	Northwestern Brooks Range thrust sequences North Central Brooks Range thrust sequence	Brooks Range sequence Ivotuk Hills sequence	Foothills thrust tectonic unit	Foothills sequence Assemblages on Drenchwater Creek Sequence at Mount Bupto

stack of allochthons. Martin (1970) thought it was near the bottom of the stack and mapped it over a wide area, over much of which those rocks are presently known to be parts of the Brooks Range or Picnic Creek allochthons. The problem in understanding this allochthon was due partly to poor dating of the rocks and partly to misinterpretation of the structural positions of isolated tectonic blocks of the Nuka Formation. These blocks are widely scattered in areas of low relief and poor exposure in the foothills north of the Brooks Range. The Nuka Ridge allochthon is presently considered to be the fifth allochthon in the stack of seven. This conclusion was reached after detailed mapping in the mountainous areas where structural relationships are well exposed (Ellersieck and others, 1979; Mull, 1979; Curtis and others, 1982, 1984; Ellersieck and others, 1982, 1984; Mayfield and others, 1982a, 1984a). It is structurally the highest allochthon of those that contain the sedimentary sequences.

Evidence for the allochthonous character of the Brooks Range allochthon relative to the Schwatka Mountains province was not published until the latter half of the 1970's by Mull and others (1976), Dutro and others (1976), and Mull and Tailleur (1977). These reports contain descriptions of the Upper Paleozoic part of the sequence of rocks in the Schwatka Mountains province. Subsequent maps of the Baird and Schwatka Mountains (Mayfield and Tailleur, 1978; Turner and others, 1978; Nelson and Grybeck, 1980) show the general distribution of the northern part of the Schwatka sequence based on the location of outcrops of the Lower Mississippian to Permian sequence composed of the Kekiktuk Conglomerate, Kayak Shale, Lisburne Group, and Sadlerochit Group.

DESCRIPTION OF ALLOCHTHONS AND SEQUENCES

In order to understand the evidence for the palinspastic synthesis and the tectonic implications, it is first necessary to become familiar with the stratigraphic and structural subdivisions in the western Brooks Range. Therefore, the 18 sequences and 7 allochthons (pl. 7.1) that are differentiated in this report are described briefly in this section. The autochthonous or parautochthonous Schwatka sequence is described first, then the allochthons and the sequences of rocks that occur in each allochthon. Generalized stratigraphic columns (figs. 7.3–7.21) are given for the sequences along with descriptions of the most distinctive characteristics and areas where the best exposures of the sequences and allochthons are to be found. Because the structural deformation is complex and paleontologic ages are sparse, the estimates of original depositional thickness and age for the various rock units are often approximate.

THE SCHWATKA SEQUENCE

The late Paleozoic and older parts of the Schwatka sequence (fig. 7.3) are exposed in the southern part of the Brooks Range, here called the Schwatka Mountains province. This sequence is the least understood of those in the western Brooks Range, because it was regionally metamorphosed during the Cretaceous (Turner and others, 1978; Turner and others, 1979; Dillon and others, 1980) and, in some areas, during the Precambrian (Turner and others, 1979; Mayfield and others, 1982b). The protolith is believed to range in age from Precambrian to Mississippian or Permian(?) (Mull and Tailleur, 1977). The sequence probably consists of hundreds, or even thousands, of meters of Precambrian and lower Paleozoic metasedimentary rocks. Because the older rocks of the protolith are largely undated and their structure is complex, the stratigraphic column is partly speculative; it is composed of a composite of rock units from a wide geographic area.

Upper Paleozoic rocks, mostly of Mississippian age, make up less than 2 percent of the geographic area of this province. They occur in a discontinuous narrow belt that extends from east and north of Shishakshinovik Pass to Nanielik Creek near Hub Mountain (pl. 7.1; Mull and Tailleur, 1977; Pessel and Brosgé, 1977; Tailleur and others, 1977; Mayfield and Tailleur, 1978). In the Schwatka Mountains, these metasediments consist of Upper Mississippian carbonate rocks of the Lisburne Group underlain by the Lower Mississippian Kayak Shale and Kekiktuk Conglomerate. The conglomerate unconformably overlies older metamorphic rocks. In the vicinity of Shishakshinovik Pass, siltstone and slate appear to overlie the Lisburne and may correlate with the Permian part of the Sadlerochit Group (Mull and Tailleur, 1977). The same stratigraphic sequence also occurs at Mount Doonerak (fig. 7.2) in the central Brooks Range (Dutro and others, 1976).

Upper Paleozoic strata in the Schwatka sequence are believed to correlate with autochthonous rocks under the Colville basin. Oil exploration wells show that the foundation for the north part of the Colville basin consists of deformed Devonian and older sedimentary rocks and granite unconformably overlain by the Lower Mississippian to Lower Cretaceous sequence composed of Kekiktuk Conglomerate, Kayak Shale, Lisburne Group, Sadlerochit Group, Shublik Formation, Kingak Shale, and pebble shale unit. Seismic profiles in the National Petroleum Reserve in Alaska (NPRA) (Bruynzeel and others, 1982) show that these strata extend southward from the wells to at least the latitude of the Colville River, where they lie beneath 5 to 7 km of middle Cretaceous basin fill and dip gently south. Similar Mississippian to Permian(?) strata reappear in the Schwatka and Baird Mountains (Mull and Tailleur, 1977), and similar Mississippian to Triassic strata reappear in the southern Endicott Mountains (Dutro and others, 1976). Intense deformation of Cretaceous sediments south of the Colville River makes seismic records nearly uninterpretable, but gently south-dipping seismic reflectors at inferred depths of approximately 7 to 10 km under the mountain fronts of the De Long and Endicott Mountains probably represent continuity between autochthonous rocks to the north and those in the Schwatka sequence to the south. A representative section of rocks under the Colville basin is shown in figure 7.4.

Below the angular unconformity at the base of the Kekiktuk Conglomerate in the southern Brooks Range is a succession of intensely deformed lithologic units including marble, phyllite, calcareous schist, schistose wacke, quartz-mica schist, greenstone, and gneissic granitic rocks. Most of the thick and widespread metamorphosed limestone and dolomite is correlative with the Silurian to Upper Devonian Skajit Limestone. In a few places, slate and marble of Ordovician and Silurian age have been dated by fossils (U.S. Geological Survey, 1975; Mayfield and Tailleur, 1978; Mayfield and others, 1983b). Most other rocks in this sequence are too recrystallized to preserve identifiable fossils, although lithologic correlations to the widely spaced areas that have fossil control or radiogenic ages indicate that the protolith probably ranges in age from the early Paleozoic into the Precambrian.

The stratigraphy of the Schwatka sequence differs in a few important respects from the allochthonous sequences structurally above it. The predominantly shaly Permian and Triassic Sadlerochit Group and, at Mount Doonerak in the central Brooks Range, the Triassic Shublik Formation occur only in this sequence. These units are lithologically distinct from, and in part the same age as, the predominantly cherty Etivluk Group in the allochthonous sequences. The pre-Mississippian angular unconformity at the base of the Kekiktuk Conglomerate is in contrast to the continuous succession of Devonian through Mississippian rocks in all the allochthonous sedimentary sequences, except for the sequence of rocks in the Lisburne Hills. In the Lisburne Hills, there is a pre-Mississippian unconformity similar to the one in the Schwatka sequence, but post-Mississippian rocks are much more like those in other allochthonous sequences.

BROOKS RANGE ALLOCHTHON (1)

The Brooks Range allochthon is the most extensive and the lowest in the stack of allochthons in the western Brooks Range (pl. 7.1). It was named by Martin (1970), who called it the Brooks Range sequence because of its widespread occurrence throughout the northern and western parts of the Brooks Range. It is exposed in the Lisburne Hills, Mulgrave Hills, Endicott Mountains, northern and western parts of the Baird Mountains, and in numerous fensters in the De Long Mountains. This allochthon is the only one in the western Brooks Range that crops out nearly continuously from the Chukchi Sea in the west to the Philip Smith Mountains in the east. It makes up a quarter to a third of all the exposures in the Brooks Range. The estimated aggregate thickness of the thrust sheets in this allochthon, measured approximately normal to the upper and lower fault surfaces, totals 5 to 10 km in the foothills and under the De Long and Endicott Mountains.

Sequences in the Brooks Range allochthon have certain characteristics that can be used to distinguish them from sequences in other allochthons. This allochthon contains the thickest and most widespread exposures of Upper Devonian and Lower Mississippian sandstone, shale, and conglomerate of the Endicott Group. The Etivluk Group is generally more shaly and less cherty and Upper Triassic rocks have a greater proportion of limestone than in other allochthonous sequences.

The Brooks Range allochthon includes the Ivotuk, Key Creek, and Lisburne Hills sequences. They are grouped into the same allochthon because they have lithologic similarities and occur at approximately the same structural level. In the foothills north of the Endicott Mountains, the Ivotuk sequence occurs in a series of thrust sheets that are structurally below the Key Creek sequence. West of long 158° W., the distinctive Mississippian carbonate rocks in the Ivotuk sequence appear to grade laterally into rocks characteristic of the Key Creek sequence. The Lisburne Hills sequence is only exposed on the Lisburne Peninsula. It is thought to be structurally below the Key Creek sequence, but the sequences are separated by a belt of Cretaceous orogenic clastic rocks that makes direct structural relations uncertain.

THE IVOTUK SEQUENCE

The Ivotuk sequence (fig. 7.5) was described by Martin (1970),

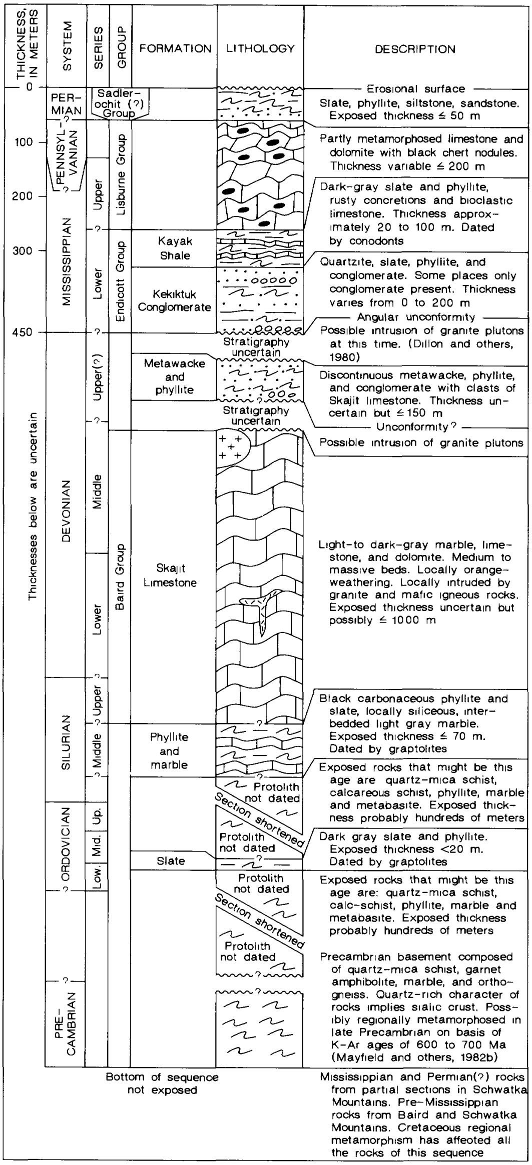


FIGURE 7.3.—Columnar section of the Schwatka sequence. For explanation of lithologic symbols, see figure 7.5.

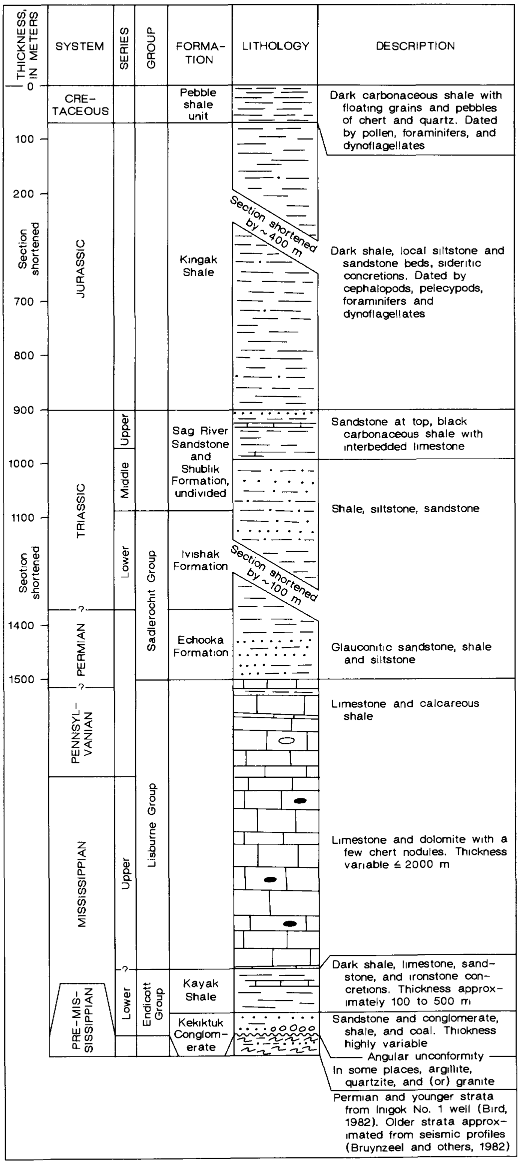


FIGURE 7.4.—Columnar section of rocks under the Colville basin. For explanation of lithologic symbols, see figure 7.5.

who named it for exposures at Ivotuk Ridge in the Killik River quadrangle east of the area covered by this report. Outcrops are present in a fairly limited area in the foothills north of the Endicott Mountains. Best exposures occur at Lisburne Ridge and at Mount Bupto in the Howard Pass quadrangle (pl. 7.1). This sequence is composed of Mississippian to Lower Cretaceous sedimentary rocks. The pre-Cretaceous rocks are approximately 600 m thick.

The Ivotuk sequence is distinguished from the Key Creek sequence by differences in the Upper Mississippian rocks. In the Ivotuk sequence, a fairly thin black, carbonaceous, shaly part of the Kuna Formation overlies several hundred meters of light-gray-weathering dolomite and limestone containing black chert nodules and lenses. The upper part of the shaly strata contains a phosphatic zone that is believed to be correlative with phosphatic beds in the upper part of the Alapah Limestone in the foothills and mountains of the north-central Brooks Range (Patton and Matzko, 1959) and with phosphatic shale of the Kuna Formation in the Key Creek sequence.

Rocks older than the Lower Mississippian Kayak Shale have not been identified and must have been structurally detached from most of the Ivotuk sequence. Like the other sequences in allochthon 1, the Ivotuk sequence probably was deposited upon Lower Mississippian and possibly Upper Devonian sandstone of the Endicott Group. In the Lisburne No. 1 well, which was drilled to a depth of about 5,580 m (17,000 ft) in the southern part of the NPRA, at least five partly repeated sections (Mickey, 1980) of the Ivotuk sequence were encountered, but no coarse clastic rocks of the Endicott Group were found. The older rocks on which the Ivotuk sequence was deposited may have been the northern part of a thick clastic wedge of Late Devonian and Early Mississippian age, similar to the Key Creek sequence, or they may have been paralic coaly sandstone and shale on a pre-Mississippian unconformity, similar to the Lisburne Hills sequence.

THE KEY CREEK SEQUENCE

The Key Creek sequence (fig. 7.6) was named by Curtis and others (1982, 1984) for exposures at Key Creek in the De Long Mountains A-1 quadrangle (Curtis and others, 1983). This sequence is the most extensively exposed in the western Brooks Range. It crops out from the southwestern edge of the Mulgrave Hills at the seacoast in the Noatak quadrangle to the Endicott Mountains in the Howard Pass quadrangle. Parts of this sequence are well exposed in numerous places, but in no place is there a complete unbroken succession of strata. The Mississippian to Cretaceous part is well exposed at Key Creek; the Late Devonian to Mississippian part is well exposed along the northern mountain front of the Endicott Mountains; the lower part of the sequence is exposed along the north

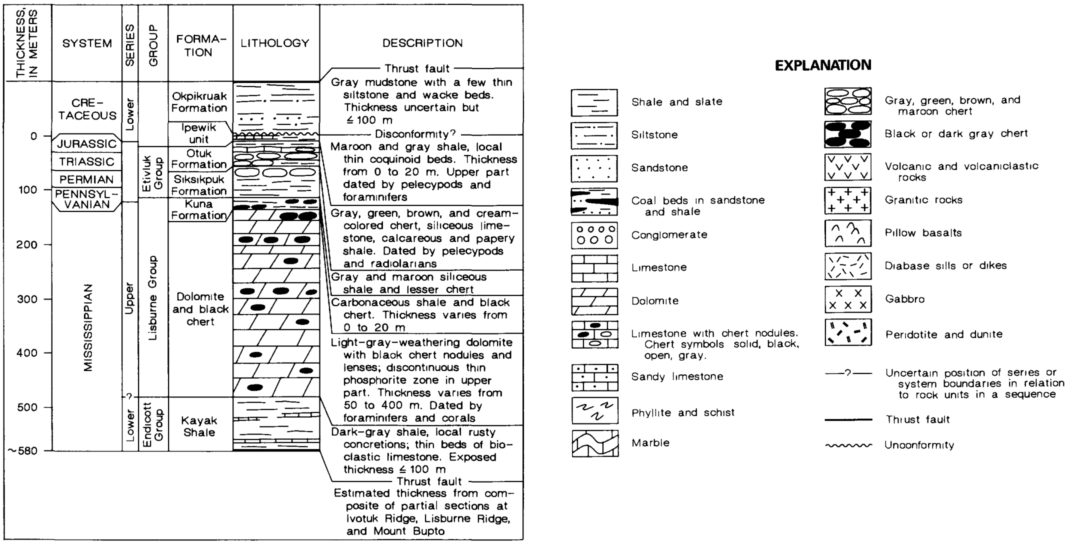


FIGURE 7.5.—Columnar section of the Ivotuk sequence of allochthon 1.

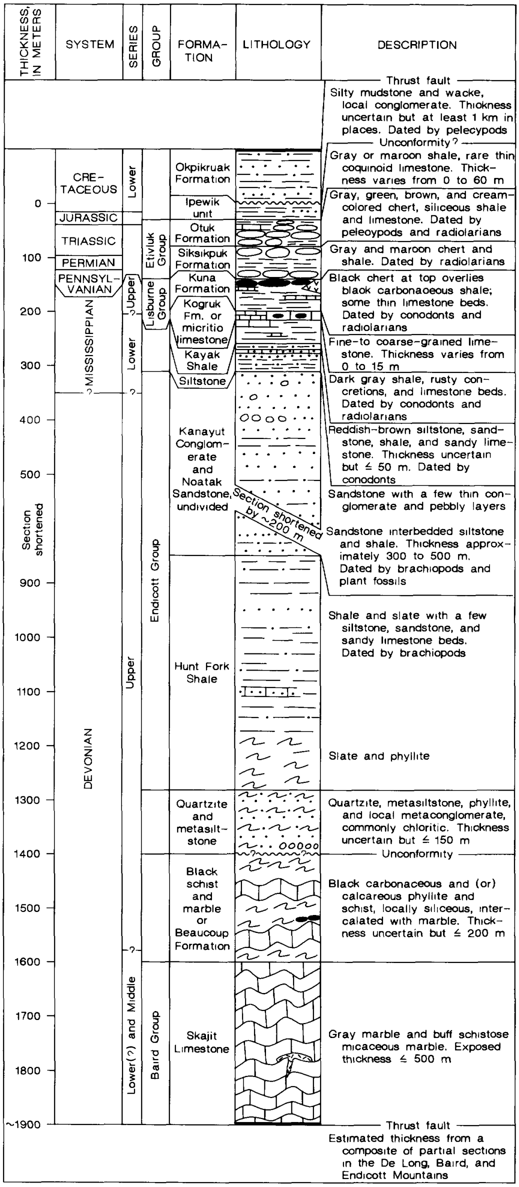


FIGURE 7.6.—Columnar section of the Key Creek sequence of allochthon 1. For explanation of lithologic symbols, see figure 7.5.

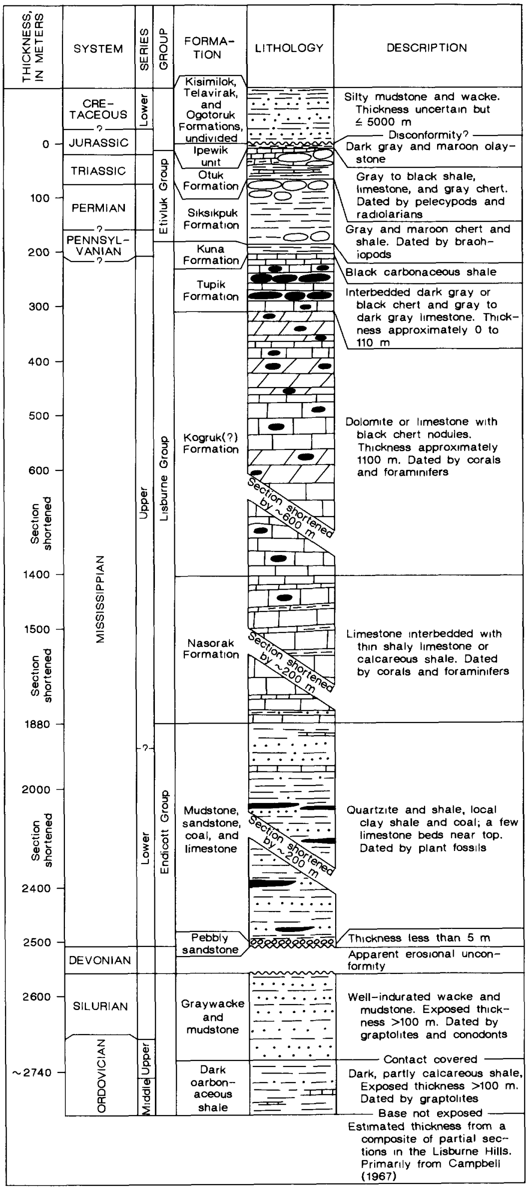


FIGURE 7.7.—Columnar section of the Lisburne Hills sequence of allochthon 1. For explanation of lithologic symbols, see figure 7.5.

and west edge of the Baird and Schwatka Mountains. The pre-Cretaceous rocks are approximately 1,900 m thick.

The Key Creek sequence differs from the other two sequences in allochthon 1, the Ivotuk and Lisburne Hills sequences, by having a thick section of Upper Mississippian and Lower Pennsylvanian black shale and chert of the Kuna Formation (Mull and others, 1982) that overlies a thin (less than 20 m) and discontinuous light-gray-weathering limestone containing black chert nodules. The pre-Mississippian part of the Key Creek sequence differs from all other sequences in the western Brooks Range, because it is composed of a 1,000-m-thick clastic wedge of Late Devonian and Early Mississippian age called the Endicott Group (Tailleur and others, 1967; Nilsen, 1981).

THE LISBURNE HILLS SEQUENCE

The Lisburne Hills sequence (fig. 7.7) is named for exposures along the seacliffs in the southern part of the Lisburne Hills (pl. 7.1; Campbell, 1967). Exposures are confined to the Lisburne Hills. The base of the section is Ordovician (U.S. Geological Survey, 1972; Grantz and others, 1983), and the uppermost part is Early Cretaceous. The composite depositional thickness is more than 2,700 m.

Because the Lisburne Hills sequence does not have any exposed contacts with the other sequences in the western Brooks Range, its structural and stratigraphic position is uncertain. It is assigned to allochthon 1 because the Carboniferous and younger rocks are similar to other sequences in this allochthon, and the stratigraphy shows the same Neocomian tectonic history during the Brooks Range orogeny.

In the past, this sequence has been included in allochthon 3, primarily because the Upper Mississippian carbonate beds in the Lisburne Hills and De Long Mountains are similar in lithology and thickness (Tailleur, 1969a, b; Mull, 1979). Although the Upper Mississippian dolomitic carbonate rocks, mapped as the Kogruk(?) Formation by Campbell (1967), are similar in thickness to the Kogruk Formation in the sequences of allochthon 3, the overall Mississippian to Lower Cretaceous stratigraphic section is also similar to coeval beds in sequences of allochthon 1. For example, the upper part of the Triassic and Jurassic Otuk Formation in the Lisburne Hills contains numerous distinctive limestone beds, and its general lithologic character is more like correlative beds in the Key Creek and Ivotuk sequences than like those in any of the sequences in allochthon 3. The Siksikpuk Formation and the lower part of the Otuk Formation are more shaly in the Lisburne Hills sequence than they are in sequences of allochthon 3. These shaly beds are most like coeval beds in the Ivotuk and Key Creek sequences. The Upper Mississippian dolomitic carbonate beds in the Lisburne Hills are thicker but lithologically similar to correlative beds in the Ivotuk sequence. Outside the Lisburne Hills, coal beds in a similar stratigraphic setting are known in only a few places in the lower, sandy part of the Kayak Shale, in the Key Creek sequence, and in autochthonous rocks under the Colville basin.

Lower Mississippian rocks in the Lisburne Hills rest unconformably on black, graptolitic Ordovician and Silurian wacke and shale (Grantz and others, 1983). This stratigraphic relationship is similar to that at the basal Mississippian unconformity in the Schwatka sequence and in the succession of Neocomian and older rocks under the northern part of the Colville basin. However, in the Lisburne Hills sequence rocks of Pennsylvanian to Early Cretaceous age are markedly different in lithology from coeval rocks under the Colville basin and from suspected Permian rocks in the Schwatka sequence (compare figs. 7.3, 7.4, and 7.7).

Thus, the pre-Mississippian stratigraphy of the Lisburne Hills is similar to the sequences in the Schwatka Mountains and under the Colville basin, and the Pennsylvanian to Lower Cretaceous stratigraphy is similar to sequences in allochthon 1. On the basis of these stratigraphic relations, it is inferred that before the Brooks Range orogeny the Lisburne Hills sequence was in the northern part of the region occupied by the sequences in allochthon 1 and south of the Schwatka sequence. For structural simplicity, the Lisburne Hills sequence and other exposures of allochthonous rocks with no sequence designation in the foothills north of the De Long Mountains (pl. 7.1) are included as part of allochthon 1.

PICNIC CREEK ALLOCHTHON (2)

The Picnic Creek allochthon is the second allochthonous structural level in the western Brooks Range. It was named by Ellersieck and others (1979) for exposures in the Picnic Creek fenster in the Misheguk Mountain quadrangle (Mayfield and others, 1982a). Exposures extend from the hills southeast of Cape Seppings to the foothills along the northern margin of the Endicott Mountains. The Picnic Creek allochthon is exposed discontinuously between allochthon 1 and allochthon 3 or 4. The structural relation to allochthons 1 and 3 is best exposed in the mountains drained by the Wulik River, north of the Avan Hills along the Kuruk Creek valley, in the Picnic Creek fenster, and in the Cutaway fenster (pl. 7.1). This allochthon probably does not exceed 1,000 m in thickness, and in most areas it is less than 500 m thick.

Sequences in the Picnic Creek allochthon differ lithologically from most other sequences by having a section of well-bedded black chert with subordinate interbedded fine-grained carbonate rock of Late Mississippian age. In sequences of allochthon 4, coeval sedimentary rocks are lithologically similar but locally contain many diabase sills. In allochthon 2, Mississippian rocks appear to have been deposited on Upper Devonian and (or) lowest Mississippian sandy rocks of the Endicott Group. In one sequence of allochthon 2, these sandy beds interfinger with latest Devonian (Famennian) carbonate beds that are here correlated by age and lithology with part of the Baird Group. This sequence contrasts with allochthon 4, in which Missisipian rocks appear to have been deposited only on Middle and Upper Devonian carbonate rocks of the Baird Group.

Four sequences in the Picnic Creek allochthon are distinguished in this report. They are exposed in an east-trending outcrop belt from the foothills of the Endicott Mountains through the De Long Mountains and are called, from west to east, the Amaruk sequence, the Wulik sequence, the Picnic sequence, and the Nigu sequence. The sequences are usually found in adjacent geographic areas and are believed to have been deposited contiguously. Border areas between these sequences either have gradational lithologies or are thought to be separated by thrust faults having fairly minor displacements.

THE AMARUK SEQUENCE

The Amaruk sequence (fig. 7.8) was named by Mayfield and others (1983a) for exposures at the headwaters of the Amaruk River in the De Long Mountains quadrangle. This sequence extends from the western De Long Mountains to the hills southeast of Cape Seppings (Mayfield and others, 1984b). Best exposures are found along the northeast and northwest margins of the Wulik Peaks (pl. 7.1). The sequence is composed of Upper Devonian or Lower Mississippian to Lower Cretaceous sedimentary rocks. The pre-Cretaceous rocks are approximately 350 m thick.

Structurally the Amaruk sequence occurs below the Kelly sequence of allochthon 3 and above the Key Creek sequence of allochthon 1. Upper Mississippian rocks are distinguished from bordering sequences in higher and lower allochthons by being composed predominantly of black chert.

Within the Picnic Creek allochthon, the Amaruk sequence grades eastward into the Wulik sequence. Unlike the Wulik sequence, the Amaruk sequence contains only a few shaly rocks that correlate with the Kuna Formation and only a small amount of noncherty micritic limestone. The oldest rocks in the Amaruk sequence are exposed in the hills southeast of Cape Seppings. Here the Kayak Shale grades downward into increasingly sandier beds that are poorly exposed and are thought to be correlative either with the Upper Devonian and Lower Mississippian Noatak Sandstone or with the sandstone member of the Lower Mississippian Kayak Shale. These sandy beds are similar to coeval clastic beds at the base of the Wulik and Nigu sequences.

THE WULIK SEQUENCE

The Wulik sequence (fig. 7.9) was named by Snelson and Tailleur (1968) for exposures in the Wulik River area of the De Long Mountains quadrangle. Discontinuous outcrops are found throughout the De Long Mountains and in the foothills north of the range. Best exposures are in the Wulik knot, on the south side of Inaccessible Ridge, and in the Kuruk Creek valley about 5 km north of the Avan Hills (pl. 7.1). This sequence is composed of Upper Devonian to Lower Cretaceous sedimentary rocks. The pre-Cretaceous rocks are approximately 400 m thick.

The Wulik sequence is structurally overlain by the Amphitheatre and Kelly sequences of allochthon 3 and is underlain by the Key Creek sequence of allochthon 1. It consists of a fairly thick section of Upper Mississippian black chert, locally interbedded with limestone. This contrasts with coeval limestone of the Kogruk Formation in sequences of allochthon 3 and with black carbonaceous shale and chert of the Kuna Formation in the Key Creek sequence. Upper Devonian (Famennian) rocks in this sequence are exposed only in Kuruk Creek valley. Here, limestone correlated with part of the Baird Group is interbedded with sandstone and shale correlated with part of the Endicott Group. In contrast, Upper Devonian rocks in the overlying sequences in allochthon 3 are mostly carbonate rocks of the Baird Group, and Upper Devonian rocks in the underlying Key Creek sequence of allochthon 1 are entirely sandstone and shale that are part of the Endicott Group.

Within the Picnic Creek allochthon, the Wulik sequence grades eastward and westward into the Picnic and Amaruk sequences, respectively. It is distinguished from them by having a persistent micritic limestone unit beneath Upper Mississippian black chert. In the De Long Mountains quadrangle, the Wulik sequence crops out in the foothills north of the Amaruk sequence, implying that part of the Wulik sequence occurs in structurally lower thrust sheets. North of Inaccessible Ridge, Upper Mississippian rocks of this sequence contain more shale and less limestone, like the rocks in the Key Creek sequence (Curtis and others, 1983).

THE PICNIC SEQUENCE

The Picnic sequence (fig. 7.10) was named by Ellersieck and others (1979) for exposures in the Picnic Creek fenster in the Misheguk Mountain quadrangle. This sequence is exposed throughout the eastern De Long Mountains in an outcrop belt that extends from the Kuna River in the Howard Pass quadrangle westward to the headwaters of the Kugururok and Utukok Rivers in the Misheguk Mountain quadrangle. The best exposures of this sequence are found in the Cutaway fenster, on the north side of the Picnic fenster, and southeast of the Drenchwater fenster (pl. 7.1). The lowermost part of the sequence is Early Mississippian in age, and the uppermost part is Early Cretaceous. The pre-Cretaceous rocks are approximately 270 m thick.

Structurally, the Picnic sequence overlies the Key Creek sequence and, in most places, is overlain by discontinuous thrust slices of the Kelly sequence of allochthon 3 or the Ipnavik and Nachralik Pass sequences of allochthon 4. Most of the Upper Mississippian rocks are well-bedded black chert. Sedimentary rocks in the Picnic, Nachralik Pass, and Ipnavik sequences are lithologically similar. Mafic igneous rocks are common in the Ipnavik sequence and uncommon in the Nachralik Pass and Picnic sequences. In general, the Picnic sequence contains less limestone in the Lisburne Group and a smaller percentage of maroon chert in the Etivluk Group as compared to the Nachralik Pass and Ipnavik sequences.

Within the Picnic Creek allochthon, the Picnic sequence grades eastward and westward into the Nigu and Wulik sequences, respectively. In the foothills of the northwestern De Long Mountains, the Picnic sequence appears to grade westward into the Wulik sequence. The Picnic sequence is distinguished from the Wulik sequence by having more chert and less limestone in the Lisburne Group.

THE NIGU SEQUENCE

The Nigu sequence (fig. 7.11) is named for exposures at Nigu Bluff, in the foothills north of the Endicott Mountains, which were described by Murchey and others (1981). The outcrop area of this sequence is confined to the low rolling hills with rubble slopes in the foothills north of the Endicott Mountains. The best exposures are along stream cuts, the most prominent being the one at Nigu Bluff (pl. 7.1). The lowermost part of the sequence is Late Devonian or Early Mississippian in age, and the uppermost part is Early Cretaceous. The pre-Cretaceous rocks are approximately 220 m thick—an approximation based on isolated exposures of different parts of the section.

Structurally the Nigu sequence lies above the Ivotuk and Key Creek sequences of allochthon 1 and below the Ipnavik sequence of allochthon 4. Sequences in allochthon 3 do not extend as far east as the outcrop belt of the Nigu sequence. The Nigu sequence is distinguished from the Key Creek and Ivotuk sequences by having Upper Mississippian well-bedded black chert overlying a thin micritic limestone unit. The cherty part of the section is similar to coeval rocks in the Ipnavik sequence except that the cherts in the Ipnavik sequence contain numerous brown-weathering diabase sills.

Within the Picnic Creek allochthon, the Nigu sequence appears to grade westward into the Picnic sequence. In contrast to the Picnic sequence, the Nigu sequence contains fine-grained limestone of middle Mississippian age that is overlain by dark-gray and black chert. On the allochthon map (pl. 7.1), an arbitrary boundary between the Nigu and Picnic sequences was placed in the area of discontinuous exposures between the Ipnavik and Etivluk Rivers.

KELLY RIVER ALLOCHTHON (3)

The Kelly River allochthon is the third allochthonous structural level in the western Brooks Range. It is extended from what was named the Kelly tectonic unit by Snelson and Tailleur (1968) for excellent exposures in the mountains at the head of the Kelly River in the De Long Mountains quadrangle. The sequences in this allochthon are well exposed throughout the De Long Mountains and in a southwest-trending belt in the western Baird Mountains. The greatest aggregate thickness of thrust sheets is probably more than 2 km and is found in the Wulik Peaks area (pl. 7.1) and in the hills southeast of Cape Seppings. East of Misheguk Mountain, this allochthon becomes much thinner and more discontinuous. In the Nimiuktuk River drainage and the Picnic Creek fenster, it is probably no more than 200 m thick. East of long 159° W. it is absent, except possibly for a few thin thrust slivers of Devonian and Mississippian carbonate rocks at the south margin of the Drenchwater fenster and on the north side of the Pupik Hills (pl. 7.1).

Except for two sequences in allochthon 1, the sequences in allochthon 3 are distinguished from sequences in other allochthons of the western Brooks Range in that they contain a thick section of Upper Mississippian bioclastic limestone assigned to the Kogruk Formation. The Lisburne Hills and

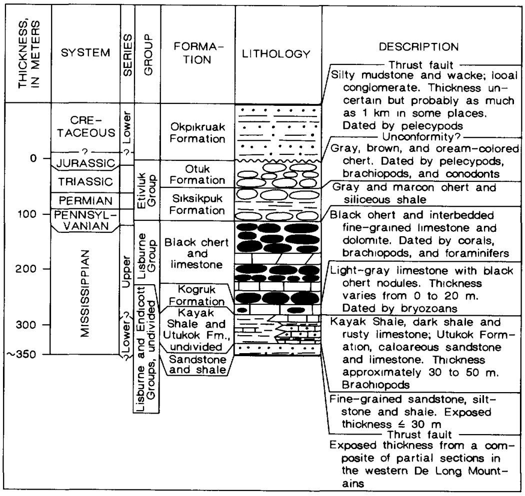


FIGURE 7.8.—Columnar section of the Amaruk sequence of allochthon 2. For explanation of lithologic symbols, see figure 7.5.

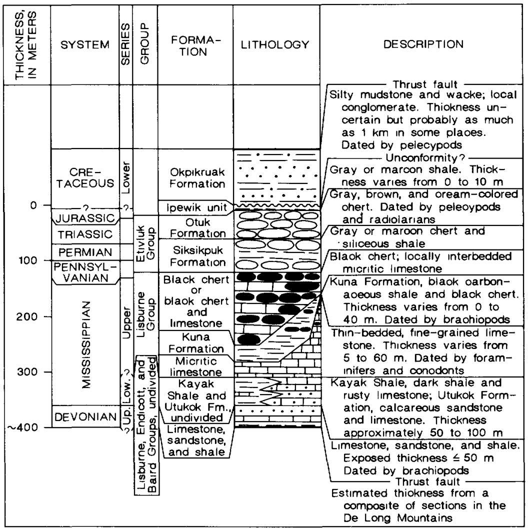


FIGURE 7.9.—Columnar section of the Wulik sequence of allochthon 2. For explanation of lithologic symbols, see figure 7.5.

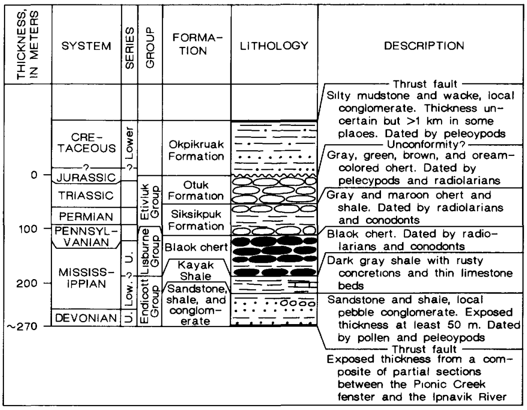


FIGURE 7.10.—Columnar section of the Picnic sequence of allochthon 2. For explanation of lithologic symbols, see figure 7.5.

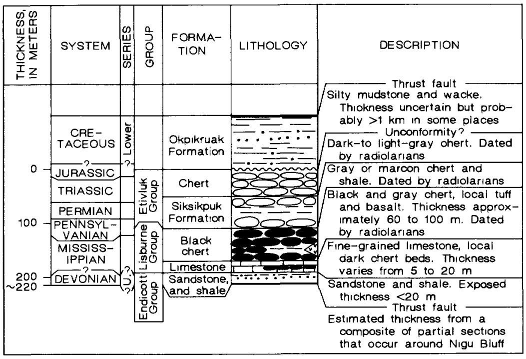


FIGURE 7.11.—Columnar section of the Nigu sequence of allochthon 2. For explanation of lithologic symbols, see figure 7.5.

Ivotuk sequences of allochthon 1 have similar Upper Mississippian carbonate sections. In sequences of the Kelly River allochthon, the Etivluk Group has a higher proportion of chert and less Triassic limestone than in either the Lisburne Hills or Ivotuk sequence. Also, the Ipewik unit has not been recognized from sequences in the Kelly River allochthon.

There are three sequences in the Kelly River allochthon: the Amphitheatre sequence, the Kelly sequence, and the Eli sequence. They generally have thrust-fault contacts, the Amphitheatre sequence being structurally the lowest, the Kelly sequence in the middle, and the Eli sequence structurally the highest.

THE AMPHITHEATRE SEQUENCE

The Amphitheatre sequence (fig. 7.12) was named by Curtis and others (1983) for exposures around Amphitheatre Mountain in the eastern part of the De Long Mountains quadrangle. Exposures are found in the mountains at the headwaters of the Kelly River (pl. 7.1) in the De Long Mountains quadrangle and at the mountain front southeast of Cape Seppings (Mayfield and others, 1984b). This sequence consists of sedimentary rocks that range in age from Late Devonian to Early Cretaceous. Pre-Cretaceous rocks range in thickness from approximately 500 m in the hills southeast of Cape Seppings to about 900 m in the De Long Mountains.

The Amphitheatre sequence overlies the Wulik and Amaruk sequences of allochthon 2 and the Key Creek sequence of allochthon 1. It is distinguished from all other sequences by having several hundred meters of light-gray bioclastic limestone containing black chert nodules (the Kogruk Formation) that is underlain by more than 100 m of buff-weathering, noncherty, micritic limestone that commonly weathers to form platy and flaggy talus slopes. At its southern boundary, this sequence is structurally overlain by imbricated thrust sheets of the Kelly sequence. At the southwest end of Inaccessible Ridge, the Amphitheatre sequence appears to grade laterally into the Kelly sequence. In the hills southeast of Cape Seppings, the cherty zone at the top of the Kogruk Formation in the Amphitheatre sequence becomes much thicker; at this location, the Mississippian part of the Amphitheatre sequence is similar to parts of the Wulik sequence in overall lithology.

THE KELLY SEQUENCE

The Kelly sequence (fig. 7.13) was named the Kelly tectonic unit by Snelson and Tailleur (1968) for exposures in the mountains west of the Kelly River in the De Long Mountains. Its outcrop area extends from the Picnic fenster (pl. 7.1) west to the seacoast south of Cape Seppings. East of the Picnic fenster, the Kelly sequence occurs as a few thrust slices at the mountain front south of the Drenchwater fenster and possibly along the north side of the Pupik Hills. The thickness of the Mississippian part of the Kelly sequence decreases from west to east in the De Long Mountains: in the west, it is at least 800 m thick; in the east, it is less than 75 m thick. The Kelly sequence probably was not deposited at the longitude of the eastern part of the area shown on pl. 7.1. This sequence ranges in age from Late Devonian to Early Cretaceous. Pre-Cretaceous rocks are approximately 600 to 1,000 m thick west of long 162° W. and less than 300 m thick east of long 160° W.

In the western De Long Mountains, thrust sheets that contain the Kelly sequence are at a structural middle level in the Kelly River allochthon. They overlie the Amphitheatre sequence wherever the two sequences are in contact, and they underlie the Eli sequence. Where the Amphitheatre sequence is missing they directly overlie the Picnic, Wulik, and Amaruk sequences of allochthon 2 and the Key Creek sequence of allochthon 1. In many places they are structurally overlain by sequences in allochthon 4.

The Kelly sequence is distinguished from the Amphitheatre and Eli sequences by the character of the Lower and Upper Mississippian Utukok Formation. The Utukok has not been recognized in the Amphitheatre sequence. In the Eli sequence the Utukok is thin and discontinuous, generally not more than 50 m thick, in contrast to the Kelly sequence, where thicknesses of 300 m or more are common.

THE ELI SEQUENCE

The Eli sequence (fig. 7.14) was named by Curtis and others (1982, 1984) for exposures in the mountains around the Eli River in the Baird Mountains and Noatak quadrangles. This sequence also is exposed west of the Mulgrave Hills in the Noatak quadrangle and discontinuously in the southern part of the De Long Mountains. Best exposures occur along a southwest-trending mountainous belt extending along the east side of the Avan Hills to the east side of Maiyumerak Mountain and Asik Mountain (pl. 7.1). The lowermost part of this sequence is at least as old as Middle Devonian and the uppermost part is Early Cretaceous. Pre-Cretaceous rocks are approximately 1,300 to 1,500 m thick—an approximation based on a composite of sections in the western Baird Mountains.

Structurally the Eli sequence lies below the Ipnavik and Nachralik Pass sequences and above the Kelly, Wulik, and Key Creek se-

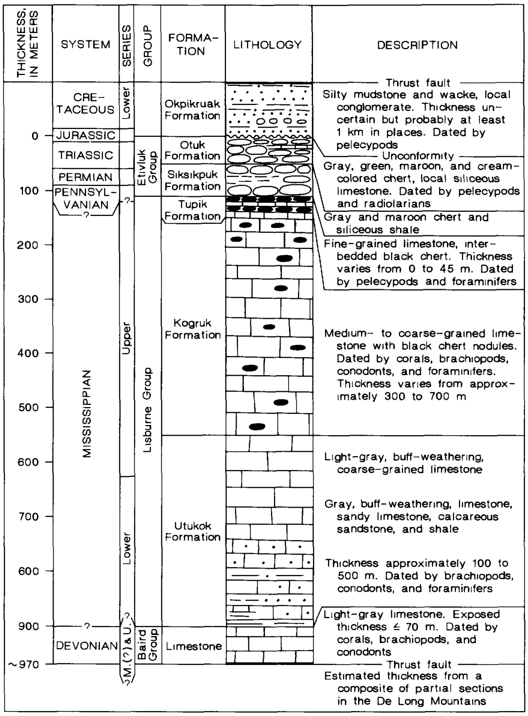


FIGURE 7.12.—Columnar section of the Amphitheatre sequence of allochthon 3. For explanation of lithologic symbols, see figure 7.5.

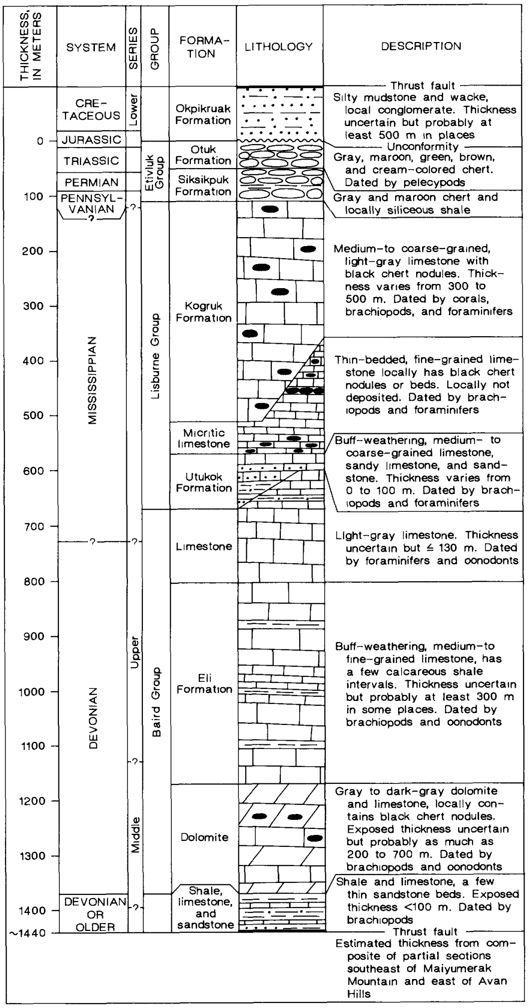


FIGURE 7.14.—Columnar section of the Eli sequence of allochthon 3. For explanation of lithologic symbols, see figure 7.5.

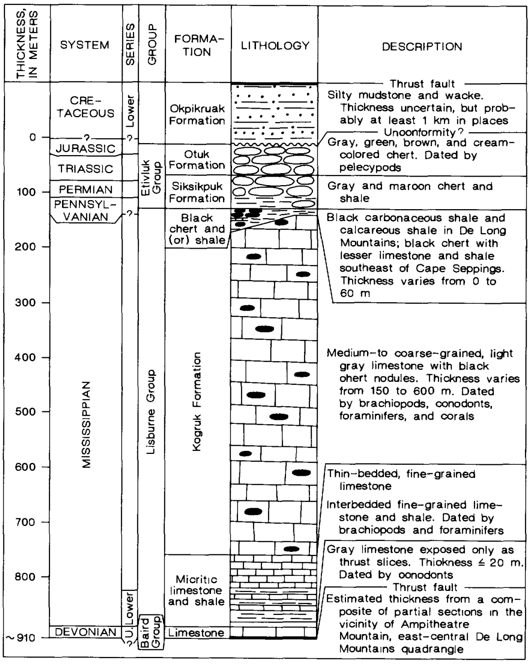


FIGURE 7.13.—Columnar section of the Kelly sequence of allochthon 3. For explanation of lithologic symbols, see figure 7.5.

sequences. It is distinguished from sequences in other allochthons by having a thick section of carbonate rocks assigned to the Kogruk Formation and Baird Group. The Utukok Formation is thin or locally absent in the Eli sequence in contrast to the other sequences in the Kelly River allochthon. In a few places, such as east and west of the Kugururok River, the Kogruk Formation appears to rest directly on the Baird Group. This sequence contains the most extensive exposures of the Baird Group carbonate rocks that have been found in any of the sequences in the De Long Mountains allochthon belt.

IPNAVIK RIVER ALLOCHTHON (4)

The Ipnavik River allochthon is the fourth allochthonous structural level in the western Brooks Range. It was first named the Ipnavik tectonic unit by Snelson and Tailleur (1968) for exposures in the foothills of the Endicott Mountains west of the Ipnavik River. The sequences that constitute this allochthon are well exposed in the foothills of the Endicott Mountains and throughout the eastern part of the De Long Mountains. More limited exposures are found to the west and southwest in the western Baird Mountains, south of the Wulik Peaks, and west of Iyikrok Mountain. The best areas for determining the structural level of this allochthon, compared to the higher and lower allochthons, are between Nuka Ridge and the Picnic fenster, at the Cutaway fenster, southeast of the mafic and ultramafic complex of Misheguk Mountain, and in the mountains around the upper Kugururok River drainage. In some places between Mount Bastille and the Drenchwater fenster (pl. 7.1), this allochthon is composed of as many as three or four thrust sheets that probably reach an aggregate thickness of more than 2 km. In some places farther to the west in the hills southeast of Cape Seppings, this allochthon is discontinuous and appears to be missing between allochthons 3 and 5.

Sequences in the Ipnavik River allochthon can be distinguished from sequences in most other allochthons because they have Upper Mississippian black chert or interbedded black chert and fine-grained limestone. However, with the exception of distinctive diabase sills that are common in some places and rare in others, the Mississippian to Cretaceous sedimentary rocks in sequences of the Ipnavik River allochthon are similar to the rocks in allochthon 2. One way to distinguish sequences in these allochthons in the absence of diabase sills is to determine the lithology of the Devonian rocks of the questionable sequence. If the Upper Devonian rocks consist of sandstone and shale of the Endicott Group, then they belong to a sequence in allochthon 2. If they are limestone and dolomite of the Baird Group, then the sequence belongs to the Ipnavik River allochthon. Devonian rocks are, however, commonly missing from the thrust sheets of these allochthons; where they do occur at the base of the section, they form thin and discontinuous thrust slices. In areas where it is difficult to find Devonian rocks or diabase sills, the structural position in relation to known allochthons has been used to determine if a sequence is in the Ipnavik River allochthon or in allochthon 2.

There are three sequences in the Ipnavik River allochthon. They are the Nachralik Pass sequence, the Puzzle Creek sequence, and the Ipnavik sequence. The Nachralik Pass sequence is structurally overlain by the Ipnavik sequence. Outcrops of the Puzzle Creek sequence are isolated geographically to the north and west of the Nachralik Pass and Ipnavik sequences.

THE NACHRALIK PASS SEQUENCE

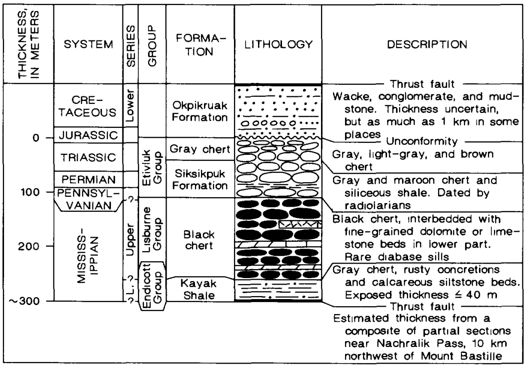
The Nachralik Pass sequence (fig. 7.15) was named by Curtis and others (1982, 1984) for exposures in the mountains east and west of Nachralik Pass, a few kilometers northeast of Copter Peak (pl. 7.1). Exposures of this sequence are found as isolated outcrop areas in the central and southern parts of the Misheguk Mountain quadrangle. The section is composed almost entirely of sedimentary rocks that range in age from Early Mississippian to Early Cretaceous. Pre-Cretaceous rocks are approximately 300 m thick.

In most places, the Nachralik Pass sequence overlies the Kelly and Eli sequences; in a few places, it appears to overlie the Picnic and Key Creek sequences. It underlies the Ipnavik sequence throughout most of its outcrop belt.

The coeval sedimentary rocks in the Nachralik Pass, Puzzle Creek, and Ipnavik sequences are generally similar in lithology. There are few mafic sills and dikes in the Nachralik Pass and Puzzle Creek sequences as compared to their abundance in the Ipnavik sequence. Because the Nachralik Pass and Puzzle Creek sequences are structurally lower, they are believed to have been deposited to the north of the Ipnavik sequence in a part of the depositional basin not reached by most of the mafic intrusions. Mississippian to Cretaceous rocks in the Nachralik Pass and Puzzle Creek sequences are similar. However, Devonian rocks are not exposed at the base of the Nachralik Pass sequence.

THE PUZZLE CREEK SEQUENCE

The Puzzle Creek sequence (fig. 7.16) was named by Mayfield and others (1983a) for exposures in the hills around Puzzle Creek, south of the Wulik Peaks in the De Long



Thrust fault

Wacke, conglomerate, and mudstone. Thickness uncertain, but as much as 1 km in some places

Unconformity

Gray, light-gray, and brown chert

Gray and maroon chert and siliceous shale. Dated by radiolarians

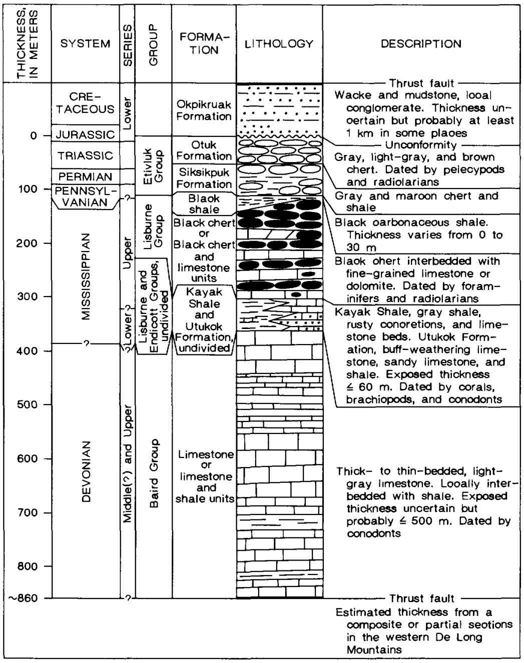
Black chert, interbedded with fine-grained dolomite or limestone beds in lower part. Rare diabase sills

Gray chert, rusty concretions and calcareous siltstone beds. Exposed thickness ≦ 40 m

Thrust fault

Estimated thickness from a composite of partial sections near Nachralik Pass, 10 km northwest of Mount Bastille

FIGURE 7.15.—Columnar section of the Nachralik Pass sequence of allochthon 4. For explanation of lithologic symbols, see figure 7.5.



Thrust fault

Wacke and mudstone, local conglomerate. Thickness uncertain but probably at least 1 km in some places

Unconformity

Gray, light-gray, and brown chert. Dated by pelecypods and radiolarians

Gray and maroon chert and shale

Black carbonaceous shale. Thickness varies from 0 to 30 m

Black chert interbedded with fine-grained limestone or dolomite. Dated by foraminifers and radiolarians

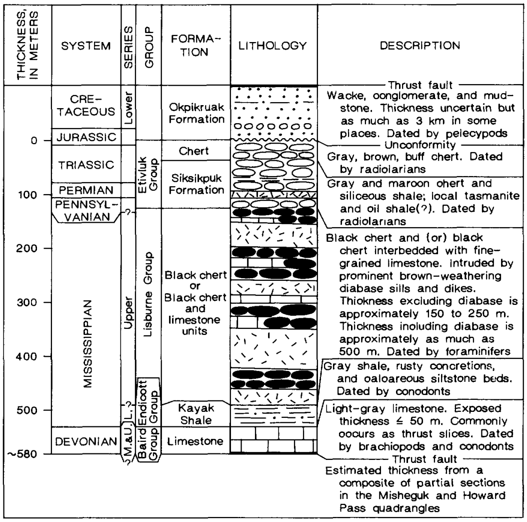
Kayak Shale, gray shale, rusty concretions, and limestone beds. Utukok Formation, buff-weathering limestone, sandy limestone, and shale. Exposed thickness ≦ 60 m. Dated by corals, brachiopods, and conodonts

Thick- to thin-bedded, light-gray limestone. Locally interbedded with shale. Exposed thickness uncertain but probably ≦ 500 m. Dated by conodonts

Thrust fault

Estimated thickness from a composite or partial sections in the western De Long Mountains

FIGURE 7.16.—Columnar section of the Puzzle Creek sequence of allochthon 4. For explanation of lithologic symbols, see figure 7.5.



Thrust fault

Wacke, conglomerate, and mudstone. Thickness uncertain but as much as 3 km in some places. Dated by pelecypods

Unconformity

Gray, brown, buff chert. Dated by radiolarians

Gray and maroon chert and siliceous shale; local tasmanite and oil shale(?). Dated by radiolarians

Black chert and (or) black chert interbedded with fine-grained limestone. Intruded by prominent brown-weathering diabase sills and dikes. Thickness excluding diabase is approximately 150 to 250 m. Thickness including diabase is approximately as much as 500 m. Dated by foraminifers

Gray shale, rusty concretions, and calcareous siltstone beds. Dated by conodonts

Light-gray limestone. Exposed thickness ≦ 50 m. Commonly occurs as thrust slices. Dated by brachiopods and conodonts

Thrust fault

Estimated thickness from a composite of partial sections in the Misheguk and Howard Pass quadrangles

FIGURE 7.17.—Columnar section of the Ipnavik sequence of allochthon 4. For explanation of lithologic symbols, see figure 7.5.

Mountains quadrangle (pl. 7.1). Exposures are limited to the Puzzle Creek area, where the sequence is composed of sedimentary rocks that range in age from Middle or Late Devonian to Early Cretaceous. Pre-Cretaceous rocks are approximately 800 to 900 m thick. The greater thickness of the Puzzle Creek sequence compared to other sequences in the Ipnavik River allochthon is due to a greater thickness of the Baird Group at the base of this sequence.

Mississippian to Jurassic sedimentary rocks of the Puzzle Creek sequence are similar to coeval rocks in the Ipnavik and Nachralik Pass sequences. However, only a few mafic igneous rocks are found in the Puzzle Creek sequence in contrast to their abundance in the Ipnavik sequence. The Nachralik Pass sequence is both lithologically and structurally similar to the Puzzle Creek sequence. If the outcrop belt of these sequences were continuous across the De Long Mountains, the two sequences could probably be mapped under a single name. The two separate names are retained in this report so that the allochthon-sequence map (pl. 7.1) will conform to terminology used previously on more detailed maps of this region (Curtis and others, 1982; Mayfield and others, 1983a) and so that greater flexibility will be provided for discussions concerning their structural relations.

THE IPNAVIK SEQUENCE

The Ipnavik sequence (fig. 7.17) was named and described by Tailleur and others (1966) for exposures in the foothills of the Endicott Mountains in the vicinity of the Ipnavik River. This sequence is exposed discontinuously from the lower Kivalina River area in the west to the east edge of the study area in the foothills of the Endicott Mountains. Some of the best exposures are found in the mountains around the Picnic, Drenchwater, and Cutaway fensters (pl. 7.1). The rocks in this sequence range in age from Devonian to Early Cretaceous. Pre-Cretaceous rocks range in thickness from 400 to more than 600 m, depending upon the thickness and number of the mafic igneous sills.

In different places, the Ipnavik sequence structurally overlies most of the sequences in allochthons 3, 2, and 1. Within the Ipnavik River allochthon, this sequence overlies the Nachralik Pass and Puzzle Creek sequences. It can be distinguished from all other sequences by having numerous mafic igneous sills and dikes that intrude rocks of the Lisburne and Etivluk Groups. The prominent brown weathering color of the igneous rocks and light weathering color of the limestone and bleached chert make this sequence readily distinguishable from all other sequences, even when viewed from a distance.

NUKA RIDGE ALLOCHTHON (5)

The Nuka Ridge allochthon is the fifth allochthonous structural level in the western Brooks Range. Structurally it is the highest in the stack of allochthons that are composed predominantly of sedimentary rocks. It was first mapped and described by Tailleur and others (1966) from exposures at Nuka Ridge in the Misheguk Mountain quadrangle. Outcrops of this allochthon also are found as isolated thrust slivers extending from the hills southeast of Cape Seppings to the foothills north of the Endicott Mountains. Outcrops that best show the structural relations between this allochthon and the adjacent allochthons are in the hills around Nuka Ridge and in the mountains along the upper Kugururok River valley (pl. 7.1). The allochthon is thickest at Nuka Ridge, where at least five stacked thrust sheets are folded into an overturned syncline that reaches a depth from the surface of approximately 1 to 1.5 km. In most other places, this allochthon is less than 200 m thick; it is commonly missing at the thrust-fault contact between allochthons 4 and 6.

There are two sequences in the Nuka Ridge allochthon: the Bastille sequence and the Bogie sequence. The structural and stratigraphic relation between these two sequences is uncertain; both sequences structurally overlie allochthon 4 and underlie allochton 6. The lithologic difference between the two sequences appears to be that Carboniferous(?) rocks in the Bastille sequence are thin-bedded, fine-grained limestone, whereas correlative rocks in the Bogie sequence are arkosic limestone of the Upper Mississippian and Lower Pennsylvanian(?) Nuka Formation overlying shale and siltstone of the Kayak Shale. The uncertainty involves the stratigraphic position and age of the Carboniferous(?) limestone in the Bastille sequence. The upper part of this limestone section in the Bastille sequence has thus far proved to be unfossiliferous. Because this limestone crops out beneath a nearly unfaulted section of Etivluk Group chert, it seems likely that it is in part Carboniferous in age and therefore correlative in part with, though lithologically distinct from, the Nuka Formation. However, if future fossil collections establish that these limestone beds are instead Devonian in age and in fault contact with the overlying Etivluk Group, then the Bastille sequence would no longer need to have a spearate designation, because its upper and lower parts could be assigned to the Etivluk Group and Baird Group, respectively, of the Bogie sequence. If future study can show that there is an unconformity between the Etivluk Group and Baird Group that cuts out Carboniferous rocks, the Bastille sequence would remain distinct.

THE BASTILLE SEQUENCE

The Bastille sequence (fig. 7.18) was named by Curtis and others (1982, 1984) and Ellersieck and others (1982, 1984) for exposures in the upper Kugururok River valley and at Mount Bastille in the De Long Mountains (pl. 7.1). Known outcrops of this sequence, as shown on plate 7.1, are confined to the area where the structural position of this sequence in relation to other sequences above and below is well exposed. The sequence is composed of sedimentary rocks that range in age from Devonian to Early Cretaceous. Pre-Cretaceous rocks are approximately 500 to 600 m thick.

At numerous other places in the western Brooks Range, thrust slices of Devonian limestone similar to those in the Bastille sequence overlie allochthon 4 and either underlie or occur within allochthon 6. Many of these isolated limestone outcrops have been tentatively correlated with allochthon 5 without being given a sequence designation. On the allochthon map (pl. 7.1) some of the larger limestone outcrops are labeled with the numeral 5 to signify a probable correlation with the Nuka Ridge allochthon.

THE BOGIE SEQUENCE

The Bogie sequence (fig. 7.19) was named by Mayfield and others (1982a, 1984a) for exposures along Bogie Creek at the southeast end of Nuka Ridge. This sequence crops out discontinuously in the hills southeast of Cape Seppings, in the southern and eastern DeLong Mountains, in the western Baird Mountains, and in the foothills of the Endicott Mountains (pl. 7.1). The best exposures are at Nuka Ridge. The age of the Bogie sequence is Early Mississippian to Early Cretaceous. No unfaulted and (or) uncovered stratigraphic contact of the Upper Devonian limestone below the Lower Mississippian Kayak Shale has been found. Some and perhaps all of the isolated Devonian limestone outcrops present at this structural level may belong in this stratigraphic interval. The original thickness of pre-Cretaceous rocks in the Bogie sequence probably exceeded 500 m, but because of thrust faulting, no unfaulted section more than 200 m thick has been found.

The Upper Mississippian and Lower Pennsylvanian(?) part of the Bogie sequence, designated as the Nuka Formation, has the most distinctive lithology of all the sedimentary sequences in the western Brooks Range. It consists of coarse-grained arkose, arkosic limestone, and glauconitic or hematitic limestone. These rock types contrast with the limestone, chert, and shale that characterize coeval parts of the sedimentary sequences in other allochthons. The Bogie sequence commonly crops out as small discontinuous thrust slices or blocks that structurally overlie the Ipnavik sequence and underlie the Copter igneous sequence. Some outcrops are believed to be olistoliths that have slid onto structurally lower allochthons and were subsequently engulfed in Lower Cretaceous flyschoid sediment.

COPTER PEAK ALLOCHTHON (6)

The Copter Peak allochthon is the sixth allochthonous structural level in the western Brooks Range. It was named by Ellersieck and others (1979) for exposures at Copter Peak in the western part of the Misheguk Mountain quadrangle. The most extensive exposures of this allochthon are preserved as erosional remnants of large synforms and are commonly best seen around the margins of the klippen of allochthon 7. Extensive exposures also are present in the Pupik Hills in the Endicott Mountains, in outcrops that follow a northeastward linear trend through Maiyumerak Mountain in the western Baird Mountains, and in mountaintop klippen in the Copter Peak and Mount Bastille areas of the eastern De Long Mountains. Poorly exposed rubbly outcrops are found in the low hills around Iyikrok Mountain and the lower Kivalina River in the southwestern De Long Mountains (pl. 7.1). Similar outcrops, thought to be structurally equivalent to the Copter Peak allochthon, are present along the southern edge of the Brooks Range through the Jade Mountains and Cosmos Hills. The thickness of this allochthon varies greatly throughout the outcrop belt. In most areas, however, it is at least 650 m thick; in some areas such as at Maiyumerak Mountain (pl. 7.1), the thickness may be as much as 1 or 2 km.

The one sequence in this allochthon is called the Copter igneous sequence. In most places, it lies structurally above sequences in allochthons 4 and 5 and below allochthon 7.

THE COPTER IGNEOUS SEQUENCE

The Copter igneous sequence (fig. 7.20) was named by Curtis and others (1982, 1984) for excellent exposures at the top of Copter Peak in the Misheguk Mountain quadrangle. This sequence is predominantly composed of pillow basalt and, to a lesser extent, andesite. A small granitic dike cuts the basalt northeast of Misheguk Mountain, and small granitic dikes or stocks are also found in the lowlands south and west of Maiyumerak Mountain. Areas of andesitic volcanic and intrusive rocks intercalated with basalt are found in the lower Kugururok River valley and north of Asik Mountain (pl. 7.1). Similar rocks of uncertain structural position are mapped tentatively as part of this sequence northwest of Siniktanneyak Mountain (pl. 7.1). At this location, it is possible that some intermediate volcanic rocks and basalts may have formed at the top of the Misheguk igneous sequence in allochthon 7.

Gray, green, and maroon chert and gray or maroon shale appear to be interbedded with the basalt in some areas. Triassic and indefinitely dated Mesozoic radiolarians have been found in the chert beds intercalated with pillow basalt at several widely scattered localities in the De Long Mountains (Ellersieck and others, 1982, 1984) and in the Anguyucham Mountains east of the Cosmos Hills (Plafker and others, 1978). On the basis of this fossil evidence and the possible correlation of some of the basalts with the Jurassic gabbroic rocks in the Misheguk igneous sequence, the pillow basalts and andesite are currently thought to be Triassic and Jurassic(?) in age.

Widely scattered outcrops of fossiliferous shallow-water Devonian limestone are intercalated with the basalt in some areas. Some of these limestone blocks are close to the basal thrust fault of the Copter Peak allochthon or along fault planes parallel to the basal thrust and so are thought to be thrust slivers (Ellersieck and others, 1982, 1984). The stratigraphic significance of these dated Devonian carbonate rocks is debatable; they may be thrust slices of the Baird Group from sedimentary sequences in lower allochthons, or they may be rocks upon which the volcanic rocks were extruded.

MISHEGUK MOUNTAIN ALLOCHTHON (7)

The Misheguk Mountain allochthon is the seventh and highest allochthonous structural level in the western Brooks Range. It was first named the Misheguk tectonic unit by Snelson and Tailleur (1968) for exposures in the mafic and ultramafic complex at Misheguk Mountain. This allochthon occurs as large synformal erosional remnants in the igneous complexes around Iyikrok Mountain, Asik Mountain, Avan Hills, Misheguk Mountain, and Siniktanneyak Mountain (pl. 7.1). Correlative rocks thought to be at this structural level, composed of serpentinite and partly serpentinized peridotite, also are found at the southern margin of the Brooks Range in the Jade Mountains, in the Cosmos Hills, and elsewhere in small isolated outcrops at the southern edge of the Baird Mountains. Erosion has stripped away much of the original thickness of the Misheguk Mountain allochthon. At most of these exposures, the allochthon is probably no more than 1 or 2 km thick.

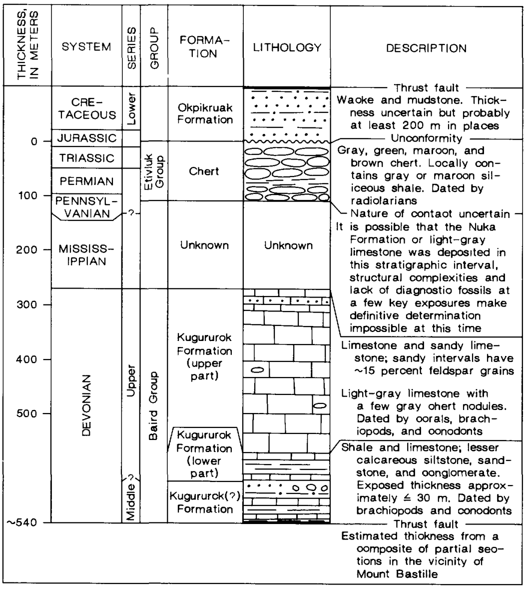
The Misheguk Mountain allochthon is thought to be part of an ophiolite (Tailleur and Brosgé, 1970; Tailleur, 1973; Patton and others, 1977; Roeder and Mull, 1978; Nelson and others, 1979; Zimmerman and Soustek, 1979; Gealey, 1980). It is thought to be the remnants of a series of thrust sheets that overlay at least three-fourths of the western Brooks Range and dipped south under the Yukon-Koyukuk province.

The one sequence in this allochthon is called the Misheguk igneous sequence. In different places, it lies directly on sequences of allochthons 1, 2, 3, 4, and 6. In some places below the basal thrust contact, this sequence rests directly on thin zones of well-foliated metasedimentary and mafic metaigneous rocks. North of the igneous complexes of the Avan Hills and Asik Mountain, metabasite and (or) meta-andesitic rocks of the underlying Copter igneous sequence are metamorphosed to garnetiferous amphibolite that, at the Asik Mountain locality, grades into nonfoliated and unmetamorphosed basalt and andesite thought to be part of the Copter igneous sequence. North and west of Misheguk Mountain, metabasites, metapelites, and marble are inferred to be metamorphosed igneous and sedimentary rocks from structurally lower sequences. These discontinuous thin zones are interpreted to have been formed by contact metamorphic effects from residual heat in the gabbro and peridotite during ophiolite obduction (Ellersieck and others, 1982, 1984; Zimmerman and Frank, 1982; Boak and others, 1985).

THE MISHEGUK IGNEOUS SEQUENCE

The Misheguk igneous sequence (fig. 7.21) is named for excellent exposures at the igneous complex around Misheguk Mountain (Ellersieck and others, 1984). The sequence is composed predominantly of a wide variety of gabbroic and peridotite-related rocks (Roeder and Mull, 1978; Nelson and others, 1979; Zimmerman and Soustek, 1979; Zimmerman and others, 1981; Frank and Zimmerman, 1982; Nelson and Nelson, 1982). Dioritic and granitoid plutonic rocks are present locally in the igneous complexes at the Avan Hills and Siniktanneyak Mountain (pl. 7.1). They are thought to have been late-stage differentiates (Frank and Zimmerman, 1982) or felsic plutons produced by anatexis of wallrocks during ophiolite obduction (Roeder and Mull, 1978).

These rocks are the lower part of a classic ophiolite sequence. The layers of basalt and oceanic sediment above the gabbroic and ultramafic rocks have not been reported and presumably were stripped away by erosion. The bottom of the sequence is a zone of olivine-rich peridotite and dunite with both tectonite and cumulate characteristics. Above this is a transitional zone that contains alternating layers of peridotite, pyroxenite, and gabbroic rocks. The top of the sequence consists mainly of gabbroic rocks that tend to display cumulate layering of



Thrust fault

Wacke and mudstone. Thickness uncertain but probably at least 200 m in places

Unconformity

Gray, green, maroon, and brown chert. Locally contains gray or maroon siliceous shale. Dated by radiolarians

Nature of contact uncertain

It is possible that the Nuka Formation or light-gray limestone was deposited in this stratigraphic interval, structural complexities and lack of diagnostic fossils at a few key exposures make definitive determination impossible at this time

Limestone and sandy limestone; sandy intervals have ~15 percent feldspar grains

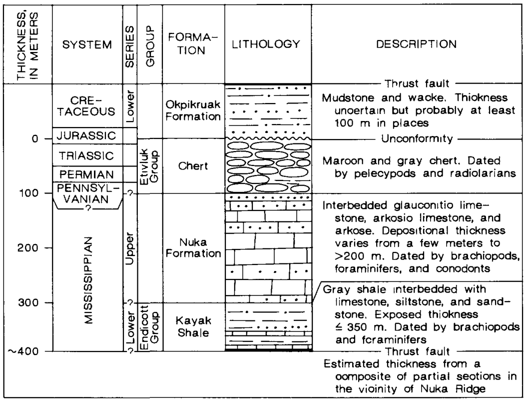
Light-gray limestone with a few gray chert nodules. Dated by corals, brachiopods, and conodonts

Shale and limestone; lesser calcareous siltstone, sandstone, and conglomerate. Exposed thickness approximately ≦ 30 m. Dated by brachiopods and conodonts

Thrust fault

Estimated thickness from a composite of partial sections in the vicinity of Mount Bastille

FIGURE 7.18.—Columnar section of the Bastille sequence of allochthon 5. For explanation of lithologic symbols, see figure 7.5.



Thrust fault

Mudstone and wacke. Thickness uncertain but probably at least 100 m in places

Unconformity

Maroon and gray chert. Dated by pelecypods and radiolarians

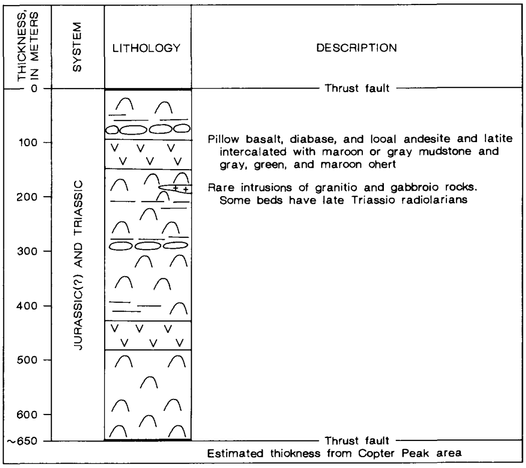
Interbedded glauconitic limestone, arkosic limestone, and arkose. Depositional thickness varies from a few meters to >200 m. Dated by brachiopods, foraminifers, and conodonts

Gray shale interbedded with limestone, siltstone, and sandstone. Exposed thickness ≦ 350 m. Dated by brachiopods and foraminifers

Thrust fault

Estimated thickness from a composite of partial sections in the vicinity of Nuka Ridge

FIGURE 7.19.—Columnar section of the Bogie sequence of allochthon 5. For explanation of lithologic symbols, see figure 7.5.



Thrust fault

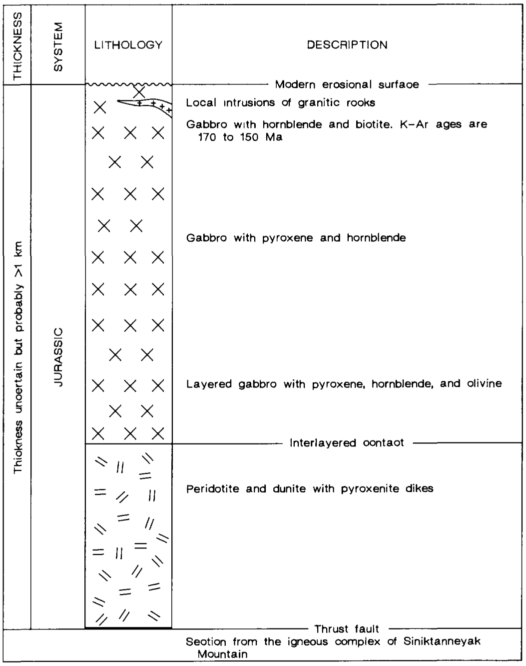
Pillow basalt, diabase, and local andesite and latite intercalated with maroon or gray mudstone and gray, green, and maroon chert

Rare intrusions of granitic and gabbroic rocks. Some beds have late Triassic radiolarians

Thrust fault

Estimated thickness from Copter Peak area

FIGURE 7.20.—Columnar section of the Copter igneous sequence of allochthon 6. For explanation of lithologic symbols, see figure 7.5.



Modern erosional surface

Local intrusions of granitic rocks

Gabbro with hornblende and biotite. K-Ar ages are 170 to 150 Ma

Gabbro with pyroxene and hornblende

Layered gabbro with pyroxene, hornblende, and olivine

Interlayered contact

Peridotite and dunite with pyroxenite dikes

Thrust fault

Section from the igneous complex of Siniktanneyak Mountain

FIGURE 7.21.—Columnar section of the Misheguk igneous sequence of allochthon 7. For explanation of lithologic symbols, see figure 7.5.

pyroxene- and plagioclase-rich layers in the lower part; in the upper part, they are not layered and are more leucocratic. Granitoid rocks are locally present, more common in the upper part; they seem to form both layers and crosscutting dikes in the gabbro (Roeder and Mull, 1978; Nelson and others, 1979; Zimmerman and others, 1981).

Biotite from granitoid rocks and hornblende from gabbro pegmatites collected from igneous complexes at Misheguk Mountain and Siniktanneyak Mountain have been dated as 170 to 150 Ma by the K-Ar method (Patton and others, 1977; Ellersieck and others, 1982; Boak and others, 1985). These Middle Jurassic ages record the cooling of this sequence, thought to coincide with the process of ophiolite obduction.

SUMMARY OF DIFFERENCES IN STRATIGRAPHY BETWEEN ALLOCHTHONS

Certain generalizations can be made about coeval sedimentary rocks that occur in the different allochthons. For example, Upper Devonian rocks do not occur in the Lisburne Hills sequence of allochthon 1 and appear to be thin and discontinuous in the Schwatka sequence. In these sequences, most of Late Devonian time is thought to be represented by an erosional interval. In the Key Creek sequence of allochthon 1, Upper Devonian rocks consist of a thick succession of sandstone, shale, and conglomerate of the Endicott Group, whereas coeval rocks in allochthons 3, 4, and 5 consist of limestone and dolomite of the Baird Group (Tailleur and others, 1967). North of the Avan Hills (pl. 7.1) in the Wulik sequence of allochthon 2, interlayered clastic and carbonate rocks containing latest Devonian (Famennian) fossils appear to be a transitional facies between the Endicott Group and the upper parts of the Baird Group.

Lower Mississippian rocks consist of interfingering shale, limestone, and sandstone of the Kayak Shale and the Utukok Formation. These formations contain similar rock types in different allochthons. Thus, isolated exposures of these rock units are not very useful for distinguishing the allochthons.

Upper Mississippian rocks include a variety of types in different allochthons. The few exposures of Upper Mississippian rocks in the Schwatka sequence consist of limestone and dolomite with black chert nodules. In allochthons 1 and 2, black carbonaceous shale and (or) black chert are underlain by thick to thin or discontinuous limestone. Sequences in allochthon 3 contain mostly limestone with black chert nodules. Sequences in allochthon 4 contain well-bedded black chert or interbedded black chert and limestone, and sequences in allochthon 5 contain noncherty limestone and (or) arkose.

Pennsylvanian to Lower Jurassic rocks generally show only minor lithologic differences in different allochthons. These rocks consist mainly of radiolarian chert and siliceous shale of the Etivluk Group (Mull and others, 1982). The lithologic differences are illustrated by the Otuk Formation, which has more Upper Triassic limestone in sequences of allochthon 1 than it does in higher allochthons. Also, the Etivluk Group generally has a greater proportion of chert and maroon-weathering beds in higher allochthons. These differences are usually not distinctive enough to differentiate individual sequences; in areas of poor exposure, however, they can be used as guides to approximate the structural level.

The Ipewik unit of Jurassic to Early Cretaceous age (Crane and Wiggins, 1976) is exposed most prominently in sequences of allochthon 1 and in the Wulik sequence of allochthon 2. In most places in the De Long Mountains, this formation consists of maroon and gray clay beds and papery carbonaceous shale. However, in a few of the lower thrust sheets of allochthon 1, this formation also contains distinctive coquinoid limestone beds and (or) quartzose sandstone beds of the Tingmerkpuk member (Curtis and others, 1983).

The top of each allochthonous sedimentary sequence consists of rocks of Late Jurassic and (or) Early Cretaceous age that are mainly shale, wacke, and local conglomerate—rocks that in most sequences are assigned to the Lower Cretaceous Okpikruak Formation. In a few places, variations in the proportions of shale and wacke can be used to help differentiate allochthons, but in larger geographic areas these variations are not consistent enough to be used as criteria. The lowermost part of the Okpikruak Formation, as dated by sparse pelecypod fossils, appears to be older in higher-numbered allochthons and younger in lower-numbered allochthons. The base appears to be at least as old as Late Jurassic in allochthons 4 and 5 and Neocomian in allochthons 1, 2, and possibly 3 (Mayfield and others, 1983a). At the Surprise and Brady anticlines in the farthest north exposures of allochthon 1 (pl. 7.1), the base of similar wacke and mudstone is no older than latest Valanginian and probably no older than Albian. Because there are few fossils in these rocks, this diachronous characteristic has not been useful for distinguishing sequences in most places.

APPROXIMATE TIMING OF MAJOR TECTONISM IN THE WESTERN BROOKS RANGE

The tectonic event that created most of the Brooks Range orogen is believed to have begun during the

Middle Jurassic, about 170-150 Ma (Tailleur and Brosgé, 1970). Stratigraphic evidence for the time the orogeny began comes from study of the sedimentary record in the allochthonous sequences. During Early or Middle Jurassic time, the period of slow deposition of siliceous sediments in the southern part of northern Alaska came to an end and was followed by rapid deposition of sediments composed of flyschoid mudstone and wacke. In allochthon 4, the uppermost cherty beds of the Etivluk Group are dated by radiolarian fossils that range from Toarcian to Late Pleinsbachian in age (Mayfield and others, 1983a); in allochthon 1, siliceous shale in the uppermost part of the Etivluk Group contains the pelecypods *Otapiria tailleuri* and *Inoceramus lucifer* Eichwald (Imlay, 1955, 1967) that are considered to be Bajocian in age (Mull and others, 1982). Although dated only by sparse pelecypods, the flyschoid sediments that overlie the Etivluk Group appear to have begun to be deposited in sequences of upper allochthons during Middle and Late Jurassic time. The oldest identified megafossil reported from the flyschoid deposits in the western Brooks Range is the pelecypod *Buchia fischeriana* d'Orbigny of Tithonian age (Curtis and others, 1982). This fossil was collected from the middle of a section of graywacke and mudstone more than 150 m thick, so it is possible that the lowermost Brookian orogenic sediments are older than Tithonian in this region. Upper Jurassic turbidites and olistostrome units also have been reported by Kleist and others (1983). In the north-central Brooks Range, fragments of the pelecypod *Inoceramus* sp., similar in appearance to immature forms of *Inoceramus lucifer* found elsewhere in northern Alaska in beds of Bajocian age, and the ammonite *Arkelloceras* cf. *A. tozeri* Frebold, also of Bajocian age, have been found in tuffaceous graywacke (Jones and Grantz, 1964).

Radiometric evidence for the initiation of thrusting comes from K-Ar ages on the ophiolite of allochthon 7. The ophiolite cooled to argon-retention temperatures at about the same time as northern Alaska changed from a stable to a tectonic depositional regime. This strongly implies, though it does not prove, that the obduction of the ophiolite also occurred at the same time. Additional indication that the ophiolite was hotter than argon-retentive temperatures during the early stages of the obduction process comes from the basal thrust contact of the peridotite and gabbro in allochthon 7. At Asik Mountain, Misheguk Mountain, the Avan Hills, and north of Iyikrok Mountain (pl. 7.1), discontinuous thin zones of metamorphic rocks consist of garnet amphibolite, dark-gray phyllite or schist, fine-grained quartzite, and marble. These metamorphic rocks are believed to have been basalt, shale, chert, and limestone in the sequences of lower allochthons that were recrystallized by residual heat from the overlying panel of peridotite and gabbro in allochthon 7. This interpretation is supported by K-Ar ages of 154 and 153 Ma from hornblende in amphibolite and garnet-bearing biotite-hornblende gneiss collected from north of Iyikrok Mountain (Boak and others, 1985).

Evidence for the time the major thrusting ceased comes from fossil ages in the nearly autochthonous Fortress Mountain Formation that crops out in the foothills of the Endicott and De Long Mountains. The Fortress Mountain Formation, which contains Albian pelecypods and ammonites (Imlay, 1961), is the oldest rock unit in the Brooks Range that has not undergone significant thrust transport. This relation is particularly well displayed at Ekakevik Mountain (pl. 7.1) in the foothills north of the Endicott Mountains (Tailleur and Kent, 1951; Mull, 1982). Here, gently folded and faulted sedimentary rocks of the upper part of the Fortress Mountain Formation unconformably overlie allochthon 4, which is composed of highly deformed and faulted Neocomian sedimentary rocks of the Okpikruak Formation and of older rock units.

After the major thrusting period had come to an end, the metamorphic welt in the southern Brooks Range isostatically rebounded during middle and Late Cretaceous time. Evidence for this period of epeirogeny comes from the cooling of metamorphic minerals to argon-retention temperatures in the Schwatka Mountains province (Turner and others, 1979) and from the concurrent deposition of large volumes of clastic detritus in the successor basins north and south of the Brooks Range.

At a late stage in the Brooks Range orogeny, the allochthons, whose internal strata were highly deformed during the thrusting period, probably underwent another period of deformation in which they were folded into complex-shaped broad anticlines and synclines. Broad folds with west-trending axes are also found in the Upper Cretaceous clastic rocks in the foothills north and south of the Brooks Range. This period of deformation appears to have been accompanied by local small-scale thrust faulting in middle and Upper Cretaceous rocks in the northern foothills; it may have been contemporaneous with some small-scale late thrust faulting in the mountains. In the foothills north of the Brooks Range, Late Cretaceous or younger high-angle normal faults, commonly with no more than a few tens of meters displacement, cut both the flat thrust sheets and the broadly folded Upper Cretaceous rocks. In the Baird and De Long

Mountains, some east-trending high-angle faults with apparent displacements of as much as a few hundred meters cut the major thrust sheets and may correspond to this or other episodes of late-stage deformation.

The Lisburne Hills also appear to have undergone a late-stage deformational event, which has been termed the Tigara uplift (Payne, 1955). The structural grain of the Lisburne Hills trends north-south, and some eastward-verging folds and westward-dipping thrust faults are present along the east side. The deformed rocks in the Lisburne Hills are believed to connect with the west end of the De Long Mountains in the subsurface, and marine seismic evidence indicates they continue offshore to the northwest (Grantz and others, 1975). Subparallel folds and faults also have affected Albian and Cenomanian(?) clastic rocks northeast of the Lisburne Hills. From this evidence, previous researchers of the regional geology have concluded that the Tigara uplift was caused by eastward-directed tectonic forces during post-late Albian(?) time (Campbell, 1967; Grantz and others, 1975) or during Late Cretaceous or Tertiary time (Chapman and Sable, 1960; Martin, 1970). However, these previous estimates for the age of tectonism in this region provide no explanation for the fact that Paleozoic and Lower Mesozoic rocks are overlain by Neocomian flysch. The Neocomian flysch and the underlying pre-Cretaceous rocks in the Lisburne Hills are exposed in major thrust sheets in the same style of intra-allochthon deformation as in the De Long Mountains. Nonorogenic deposits of early Mesozoic time were overlain by a sudden influx of orogenic sediments during Neocomian time. These tectonostratigraphic relations are the same as found in comparable thrust sheets in the De Long Mountains. Though fold evidence for a Neocomian period of northward-directed thrust dislocation has not been cited in regional geologic reports on the Lisburne Hills, the overall history of orogeny from stratigraphic evidence is the same as for the rest of the western Brooks Range. It is therefore probable that large thrust dislocations also occurred in the rocks in the Lisburne Hills during Neocomian time just as they did in structurally higher allochthons in other parts of the western Brooks Range. Subsequent deformation of the older allochthonous sheets during the Tigara uplift in post-middle Cretaceous time has produced folds with northward-trending axial planes and thrust faults that have displaced upper thrust sheets to the east along the east side of the Lisburne Hills (Chapman and Sable, 1960; Campbell, 1967; and Martin, 1970).

The tectonic origin of the Tigara uplift is uncertain. Tailleur (1969a, b) and Tailleur and Brosgé (1970) observed that the Cordilleran fold trends of the western Brooks Range, Seward Peninsula, and Lisburne Hills formed a series of deflections, called the Chukchi syntaxis, that they believed were caused by eastward-directed compression between Siberia and northwestern Alaska. Patton and Tailleur (1977) believed that the deflections were formed by a giant southward-looping oroclinal flexure. Grantz and others (1975) argued that the deflections may have formed when the westward structural trends of the western Brooks Range were refolded during late-stage deformation along the offshore Herald fault zone and its extension through the Lisburne Hills and were not necessarily caused by oroclinal bending. In any case, it seems likely that the average southwest structural bend of the western De Long and Baird Mountains, which approximately parallels the fold axes in the southern Lisburne Hills, was caused by a late deformational event.

CROSS SECTIONS TO THE ALLOCHTHON MAP

Cross sections for the western Brooks Range allochthon map (pl. 7.1) are shown on plate 7.2. Despite an attempt to keep the vertical and horizontal scale the same, the thickness of allochthons had to be exaggerated slightly in some places so that they could be traced on the sections. This exaggeration applies especially to allochthons 2, 4, and 5, which in many places are less than 500 m thick.

The depth of the boundary fault at the base of allochthon 1 is not well defined by geologic or currently available geophysical evidence under the De Long and Endicott Mountains. The approximate upper boundary of the succession of rocks under the Colville basin that correlates with the Schwatka sequence is considered here to be the top of the Lower Cretaceous pebble shale unit. This stratigraphic horizon is derived from seismic maps in the southern part of the NPRA (Bruynzeel and others, 1982). The northern limit of allochthon 1 is approximated on plate 7.1 and corresponds to the southern limit of the seismically traceable and only gently folded Neocomian to Albian strata in the Colville basin. The leading edges of the thrust sheets in allochthon 1 probably were moved by reverse faults of progressively diminishing displacement in shale and sandstone of Early Cretaceous age.

The northern boundary of the Schwatka Mountains province is difficult to map in many areas. The rocks in the boundary zone in the Baird and Schwatka Mountains are low-grade metamorphic rocks of the greenschist metamorphic facies. As a consequence, the stratigraphic units in the Schwatka sequence and at the base of the Key Creek sequence of allochthon 1 have been difficult to date. The stratigraphy of these sequences is therefore not completely understood, and the precise contact between them is difficult to locate in many areas. Carboniferous sedimentary rocks of the Schwatka sequence are exposed north of Hub Mountain and in the northern part of the Schwatka Mountains. The contact between the Schwatka sequence and allochthon 1 has been approximated north of these exposures; elsewhere this boundary is even more speculative. In many and perhaps most areas, it is likely that the contacts as shown on the allochthon map (pl. 7.1) and the cross sections (pl. 7.2) will be changed somewhat as the lower Paleozoic metasedimentary rocks are studied in greater detail.

The southern part of section lines *A–A′* and *B–B′* (pl. 7.2) reflect the uncertainty of whether the exposures of Ordovician to Devonian carbonate rocks that extend from the southwest Baird Mountains to the Igichuk Hills are part of allochthon 1 or allochthon 3. This area needs better paleontologic dating before the stratigraphic section can be fully understood. If the upper part of this carbonate section is Late Devonian (Famennian) or younger, then it is probably the lower part of a sequence in allochthon 3. If the upper part of the carbonate section is Late Devonian (early Frasnian) or older, then these rocks could be the lower part of a sequence in allochthon 1 that has been juxtaposed in many places by intrasequence thrust faults.

PALINSPASTIC SYNTHESIS

Two assumptions have been made about the movement of the thrust faults and of northern Alaska. Both were used in constructing the palinspastic map (pl. 7.3). The first assumption concerns the direction of movement along any thrust fault relative to the rocks that border it. The second assumption concerns the movement of the Arctic Alaska plate (Sweeney and others, 1978) relative to the North American craton.

Assumption 1.—The relative movement of the thrust sheets is north under south. This assumption is based on three observations and (or) interpretations: (1) The overall fold style of the De Long and Endicott Mountains is that of anticlines and synclines overturned to the north, and the leading or northern edges of the thrust sheets commonly are rolled over into northward-vergent anticlinal folds (Curtis and others, 1982, 1983, 1984; Ellersieck and others, 1982, 1983, 1984; Mayfield and others, 1982a, 1983a, 1984a, b). (2) The root zone for the ophiolite suite in allochthon 7 and for the pillow basalt in allochthon 6 appears to be in the southward-dipping thrust sheets at the southern edge of the Brooks Range (Tailleur and Brosgé, 1970; Patton and others, 1977; Roeder and Mull, 1978). (3) A simple and reasonable reconstruction of sedimentary facies patterns in allochthons 1 through 5 and the autochthonous or parautochthonous rocks in the Schwatka sequence (discussed later) results when the Schwatka sequence is restored to a position farthest to the north, and the sequences in allochthon 5 are restored to a position farthest to the south.

Assumption 2.—Relative to the north American craton, the Arctic Alaska plate has rotated counterclockwise in a southward direction out of the Beaufort Sea and collided with another crustal plate in a southward-dipping subduction zone along the south side of the Brooks Range. This assumption is based upon the proposals of Carey (1958), Tailleur (1969a, b; 1973), Rickwood (1970), Freeland and Dietz (1973), Mull and others (1976), Patton and others (1977), Roeder and Mull (1978), Grantz and others (1981), and Mull (1982) that the continental shelf of northern Alaska is a rifted, Atlantic-type margin that began to move away from another continental plate at its northern margin sometime between Early Jurassic and Early Cretaceous (Neocomian), that is, at about the same time that thrusting occurred in the Brooks Range. There is no evidence that overthrusting was a component of the process of major thrust dislocation in the Brooks Range orogeny, because the movement of the oceanic crust south of the Brooks Range relative to the North American craton is not known. For simplicity, therefore, it is assumed that the ophiolite klippen of allochthon 7, represented by Iyikrok Mountain, Avan Hills, Asik Mountain, Misheguk Mountain, and Siniktanneyak Mountain, have remained fixed relative to the North American craton. Thus, the thrusting process is viewed here as being the underthrusting of northern rocks beneath more southern rocks, as first proposed by Tailleur and Snelson (1969).

The pole of rotation for the counterclockwise motion of northern Alaska is assumed to be in the area of the Mackenzie River Delta (Tailleur, 1969a, b; Rickwood, 1970; Newman and others, 1979). However, the evidence for the location of this pole of rotation is not conclusive. If northern Alaska moved in a southerly direction without a significant amount of rotation, as implied by the scheme proposed by Dutro (1981), the relative palinspastic position of the allochthons and the minimum estimated foreshortening would not be changed significantly through the central part of the palinspastic map. However, somewhat larger gaps and therefore greater displacement distances would be measured between allochthons at the eastern edge of the palinspastic map. We have chosen the Mackenzie Delta as the pole of rotation, because this model seems to be the best explanation for the origin of the Canada Basin. Also, the outcrop pattern of allochthons on the palinspastic map fits together better when the allochthons are unstacked using the rotational model.

THE PALINSPASTIC MAP

The palinspastic map of the western Brooks Range (pl. 7.3) was constructed by using the outcrop areas shown on the allochthon map (pl. 7.1). Allochthon 7 has been held in a fixed position, and each lower numbered allochthon (allochthons 1 through 6 and the parautochthonous rocks of the Schwatka Mountains province) has been restored to a position north of the allochthon structurally above it.

The method that we have used to unstack the allochthons does not take into account several factors that act in some cases to lengthen and in other cases to shorten the estimated thrust displacement. Most allochthons vary in thickness from place to place. In some exposures, a sequence may be thickened significantly by imbricated thrust sheets that duplicate parts of the sequence; in other exposures, the same sequence may be thinned by the omission of the upper or lower parts of the stratigraphic section. In many areas of poor exposure, it has not been possible to determine which condition exists. Multiple sheets within allochthons have not been unstacked on the palinspastic map; if they were, the north-south width of some of the outcrop areas would be increased, and thus the minimum thrust displacement would be increased. In other areas, the width of some of the outcrop areas on the palinspastic map would be reduced if some thrust sheets, composed of the upper part of a sequence, were restored above other thrust sheets composed of the lower part of the same sequence. If complex folds (common within thrust sheets) were unfolded, the allochthon outcrop areas probably would be widened and the total thrust displacement increased. Because allochthons pinch and swell in the thrusting direction, it is difficult to estimate accurately the amount of foreshortening within a single allochthon in areas between outcrops. Erosion also has stripped away an undetermined amount of the actual depositional width of each sequence. In most cases, the depositional width was probably significantly broader than is shown by the present outcrop distribution. All these factors make it difficult to arrive at an accurate figure for the total thrust displacement in the western Brooks Range.

Another potentially important factor in the construction of a palinspastic model is the possible oroclinal flexure in the western Brooks Range and the eastward thrusting on the Lisburne Peninsula—thrusting thought to have occurred after the period of major northward foreshortening in the Brooks Range (Tailleur, 1969a, b; Patton and Tailleur, 1977). For purposes of simplicity, the hypothetical orocline has not been taken into account on the palinspastic map. If the southwestward structural trends in the western De Long Mountains were bent back to their possible pre-oroclinal westward or northwestward trends, the relative palinspastic positions of the allochthons in the western Brooks Range would not change appreciably, but the rocks in the Lisburne Hills would move to a position as much as about 150 km west or northwest of their position on the palinspastic map (Tailleur and Brosgé, 1970).

THRUST DISPLACEMENT

The thrust displacement for any allochthon in the western Brooks Range is the distance between its present geographic location and its palinspastic location. Because the amount of pull-apart of allochthons on the palinspastic map (pl. 7.3) probably errs on the conservative side, the amount of thrust displacement inferred from this map is here considered to be a minimum estimate. The two areas labeled AH and SM on plate 7.3 are the present positions of the klippen of allochthon 7 at Avan Hills and Siniktanneyak Mountain unmoved with respect to the Schwatka Mountains province. The minimum thrust displacement of the Avan Hills is the length of the arc between area AH and the palinspastic position of the Avan Hills. This distance is about 800 km. Measured in the same way, but closer to the pole of rotation, the minimum thrust displacement of Siniktanneyak Mountain is about 700 km. These numbers are significantly greater than most estimates published previously.

To give an idea of how thrust-displacement estimates have increased as detailed geologic maps in the western Brooks Range have progressively encompassed a larger part of this region, a sample of these estimates is given as follows: 80 km minimum and 160 km reasonable (Tailleur and others, 1966); 32 km minimum, 160 km reasonable (Snelson and Tailleur, 1968); 130 km minimum (Martin, 1970); 240 km minimum, 500 km reasonable (Tailleur, 1973); 250 km minimum, 600 km reasonable (Ellersieck and others, 1979); 500 km minimum (Mull, 1980); 580 km minimum (Mull, 1982). Many of these estimates were based on studies of smaller geographic areas within the western Brooks Range, but most previous estimates, especially the earliest reports, represent the minimum amount of thrust displacement that could be inferred at the time they were published.

An estimate of the minimum rate of plate convergence can be made by dividing the distance moved by the duration of the thrusting event. If it is assumed that the minimum thrust displacement in the western Brooks Range was 700 to 800 km and the duration of thrusting was 50 m.y. (between the middle Jurassic and middle Cretaceous, 160 and 110 Ma), then the average minimum rate of plate movement would be 1.4 to 1.6 cm/yr.

Another estimate of the minimum rate of convergence can be made by comparing two areas that should have been displaced by a much lesser amount. For example, the minimum foreshortened distance between the Schwatka sequence and the Surprise anticline located in the northeastern part of the De Long Mountains quadrangle (pl. 7.1) is about 230 km. The lower part of the sequence exposed at the Surprise anticline is composed of chert and carbonaceous shale that is Triassic, Jurassic, and Early Cretaceous (Valanginian) in age. These sedimentary rocks record slow rates of deposition and their clastic components have distal or nonorogenic sources. Orogenic turbidite deposits, composed of silty mudstone and graywacke, overlie the Valanginian beds and are younger than similar orogenic sediments in sequences farther to the south. This evidence implies that rocks in the Surprise anticline were some of the last rocks to become involved in the orogeny and that thrusting did not affect them until at least late Valanginian time (about 125 Ma). Because the major thrusting episode had ceased by Albian time (about 110 Ma), there was a period of approximately 15 m.y. during which the rocks of the Surprise anticline might have been affected by thrust movement. Based on these assumptions, the rate of convergence between the Schwatka Mountains province and the Surprise anticline is approximately 1.5 cm/yr. When these estimates of plate movement are compared to the average half rate of about 2 cm/yr for spreading centers in the world today, they show that, even with moderate rates of convergence, thrust displacement in the western Brooks Range could have exceeded 1,000 km.

It is also possible to test the feasibility of the estimated thrust displacement in the western Brooks Range by using a counterclockwise rotational model for the Arctic Alaska plate. On the palinspastic map, the minimum angular convergence between the Schwatka Mountains province and allochthon 7, measured about a pole of rotation in the Mackenzie River Delta, is about 40° (pl. 7.3). The amount of rotation necessary to restore northern Alaska against the Canadian Arctic islands, shown on figure 7.22, is about 67° (Rickwood, 1970). The minimum amount of thrust displacement given above for Siniktanneyak Mountain is 700 km. The distance between the continental edges of northern Alaska and the Canadian Arctic islands measured along an arc that projects through Siniktanneyak Mountain is 1,150 km. These measurements show that the minimum amount of thrust displacement currently estimated in the western Brooks Range supplies only about 60 percent of the distance required to open the Canada Basin using the most extreme rotational hypothesis possible.

THE ARCTIC ALASKA BASIN

The palinspastic map (pl. 7.3) outlines a small part of an extensive epicontinental sedimentary platform that existed across northern Alaska and part of northeastern Siberia before the Brooks Range orogeny.

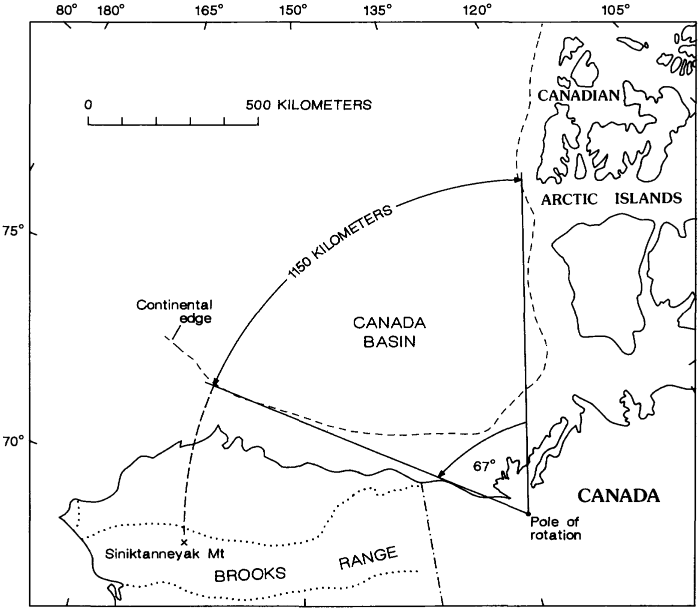


FIGURE 7.22.—Angle of rotation and distance of movement required to open the Canada Basin by rotating northern Alaska about a pole near the Mackenzie River Delta. The distance measured along an arc of 67° that projects through Siniktanneyak Mountain is 1,150 km.

This area has been termed the Arctic Alaska basin by Tailleur (1969a). A generalized geologic history of the Arctic Alaska basin is given below. Details of the reconstructed stratigraphy within the basin and reasons for specific interpretations about its geologic history are based on analysis of the palinspastic stratigraphy, which is discussed in more detail in the next section.

Although the Arctic Alaska basin was an area where sediments were deposited during most of middle Paleozoic to early Mesozoic time, deposition did not take place in a simple basin. During Middle Devonian to Mississippian time, land areas existed in the region presently occupied by the Schwatka sequence and by rocks in the subsurface under the Colville basin. By late Carboniferous time, the emergent rocks were planed by erosion, and the northern shoreline of the Arctic Alaska basin shifted north toward the Barrow area. Land also probably existed south of sequences that are now part of allochthon 5. This southern land area appears to have periodically shed clastic detritus into the southern edge of the basin during Devonian and Mississippian time. After that time, the southern emergent area apparently disappeared, because its distinctive arkosic detritus is not observed in the later sedimentary record. Through much of late Paleozoic and early Mesozoic time, the northern land area shed clastic detritus south onto the Schwatka sequence. South of the area underlain by the Schwatka sequence lay a depositional area in which strata accumulated with only minor interruption on an ensialic platform during Devonian and early Carboniferous time. During late Carboniferous to Jurassic time, northern Alaska seems to have become an extensive continental shelf more than 800 km wide. Remnants of the most seaward 400 km of this depositional area are presently exposed in the sequences in allochthons 1 through 5.

Areas of similar depositional facies (see the palinspastic map, pl. 7.3) appear to follow fairly narrow belts having approximately east-west trends. To some extent this may be a product of the minimal pullapart in the procedure by which the map was constructed. In other words, the original north-south depositional width of these facies could have been much greater than is indicated by their palinspastic outcrop distribution. To show the principal stratigraphic changes, schematic cross sections *X–X′* (figs. 7.23, 7.24) and *Y–Y′* (figs. 7.25, 7.26) have been made approximately normal to the allochthon boundaries from the Schwatka Mountains province through allochthon 6. Each section is drawn twice to show both the principal stratigraphic units and the lithologies. Above each section, the allochthons and their associated sequences are labeled.

IMPORTANT FEATURES OF RESTORED NORTHERN ALASKA STRATIGRAPHY

During Middle Devonian time, marine limestone of the Baird Group appears to have been deposited in most, if not all, of the sedimentary sequences of western Alaska (figs. 7.23-7.26). In the Key Creek and Schwatka sequences, these strata have been assigned to the Skajit Limestone in the southern part of the Endicott Mountains and in the Schwatka Mountains (Pessel and Brosgé, 1977; Mayfield and Tailleur, 1978; Nelson and Grybeck, 1980). In sequences south of the Key Creek sequence, the Baird Group consists of the Upper Devonian Kugururok Formation and other unnamed carbonate rock units. At the base of the carbonate section in the southern sequences, there is shale, limestone, and conglomerate.

During Late Devonian time, carbonate rocks of the Baird Group, including the upper part of the Eli Limestone and the Kugururok Formation, continued to be deposited in the sequences that later became parts of allochthons 3, 4, and 5. To the north in the Key Creek sequence, which later became part of allochthon 1, a complex interval of clastic and carbonate rocks that partly correlates regionally with the Upper Devonian Beaucoup Formation graded upward into a thick clastic wedge of Frasnian and Fammenian age. The clastic wedge is a mostly marine but partly nonmarine fluvial-deltaic accumulation of sandstone, shale, and conglomerate called the Endicott Group (Tailleur and others, 1967). Important rock units in the Endicott Group are the Upper Devonian Hunt Fork Shale, the Upper Devonian and Lower Mississippian Noatak Sandstone, the Upper Devonian and Lower Mississippian(?) Kanayut Conglomerate, and the Lower Mississippian Kayak Shale. The source area was located to the north and northeast (Tailleur and others, 1967; Donovan and Tailleur, 1975; Nilsen, 1981), presumably in the Schwatka sequence and in rocks now under the Colville basin. The clastic wedge seems to have interfingered southward with the Baird Group carbonate rocks in the Wulik sequence that became part of allochthon 2.

While the clastic wedge was being deposited, rocks in the Schwatka sequence that are presently under the Colville basin appear to have been deformed and uplifted at the south side of an extensive orogen that extended north to Barrow and beyond. Granite plutons were intruded into the Schwatka sequence exposed in the southern Brooks Range (Dillon and others, 1980), in the northeast Brooks Range (Reiser and others, 1980), and possibly at the base of the East

Teshekpuk exploration well 150 km southeast of Barrow (Bird and others, 1978). Faulting and folding in the Precambrian and lower Paleozoic sedimentary rocks accompanied the uplift, and later erosional planation resulted in an extensive pre-Mississippian angular unconformity. This period of tectonism is called the Ellesmerian orogeny (Lerand, 1973).

During Early Mississippian time, the Kekiktuk Conglomerate and Kayak Shale were deposited over the old erosional surface developed within the Schwatka sequence and in the area presently underlying the Colville basin. Coal is interbedded with Lower Mississippian sandstone above a major unconformity in the Lisburne Hills sequence (fig. 7.7), indicating that nearshore conditions existed in the western part of the sequences in allochthon 1 (Collier, 1906; Tailleur, 1965). South of the area underlain by the Schwatka sequence, shale, limestone, and sandstone were deposited—generally assigned either to the Kayak Shale or Utukok Formation. Clastic detritus forming the shale and sandstone in sequences that are now part of allochthons 1 and 2 probably were derived from a land area to the north. In sequences that are now part of allochthons 3, 4, and 5, Lower Mississippian sandstone is more prevalent to the west than to the east. Thus, it is possible that sand also was being shed from a western and (or) southern source during this time.

The sediments that were deposited across the Arctic Alaska basin during Late Mississippian and Early Pennsylvanian time show many pronounced facies changes. Limestone and dolomite of the Lisburne Group were deposited as part of the Schwatka sequence and as strata presently underlying the Colville basin. These carbonate rocks probably graded and interfingered southward with the Key Creek sequence, in which thin and discontinuous carbonate beds are overlain by basinal black carbonaceous shale and chert of the Kuna Formation. The KunaFormation graded southward into what appears to have been mostly low-energy sediments composed of discontinuous local micritic limestone overlain by well-bedded black chert and subordinate amounts of black shale in the Amaruk, Wulik, Picnic, and Nigu sequences. Upper Mississippian rocks of the Wulik and Amaruk sequences graded to the south into the Amphitheatre and Kelly sequences that are now part of allochthon 3. Here, limestone and nodular to bedded black chert make up the rock units called micritic limestone and the Kogruk and Tupik Formations. Most strata in these sequences were deposited as part of a bioclastic carbonate buildup. A large part of the Kogruk Formation is composed of coarse-grained limestone containing corals, echinoderms, and other biogenic debris indicative of normal marine and shoaling-water depositional environments (Armstrong, 1970). The sequences of allochthon 3 thin rapidly to the east and are not shown on the east margin of the palinspastic map (pl. 7.3). Comparison of sections *X–X′* and *Y–Y′* (figs. 7.23–7.26) shows that the Kogruk and underlying Utukok Formations were hundreds of meters thicker in the western part of the area than they were to the east. Farther to the south and gradational into the Eli and Kelly sequences, interbedded black chert and fine-grained limestone formed in the Puzzle Creek, Nachralik Pass, and Ipnavik sequences (now part of allochthon 4) during Late Mississippian time. These strata were deposited in a low-energy setting, perhaps in a submarine trough between sediments deposited in higher energy settings to the north and south.

A sharp break exists in the sedimentary facies of the Upper Mississippian and Lower Pennsylvanian parts of the Ipnavik sequence and sequences in allochthon 5. Black chert is common in Upper Mississippian rocks in sequences of allochthon 4 but missing in the coeval rocks in the sequences of allochthon 5. On the other hand, Upper Mississippian siliciclastic rocks are common in the Bogie sequence of allochthon 5 but are very rare in coeval rocks of the lower allochthons. It is not known if this apparently sharp facies change represents an abrupt change in depositional setting or if it is the result of the incomplete preservation of what might have been a gradational boundary.

During Upper Mississippan (Chesterian) and Early Pennsylvanian(?) time, arkose and arkosic limestone were deposited to form the Nuka Formation of the Bogie sequence. These rocks are preserved in thin, discontinuous thrust sheets and olistoliths from the Chukchi seacoast to at least as far east as the central Brooks Range. Coarse-grained arkose, indicative of a nearby source, is interbedded with arkosic limestone in many places. Red beds, glauconite, and numerous brachiopod and crinoid fossils indicate deposition in shallow water (Tailleur and Sable, 1963). An unrecognized granitic source area for the Nuka Formation is believed to have existed south of the area underlain by the sequences that are now part of allochthon 5.

We call the hypothetical source area for the arkose of the Nuka Formation "Nukaland." During Late Mississippian and Early Pennsylvanian(?) time, large areas of granitic rocks must have been exposed, because the clastic components for the arkose—quartz, microcline, and plagioclase—are nearly uniform for as much as 500 km along the east-west outcrop belt of the Nuka For-

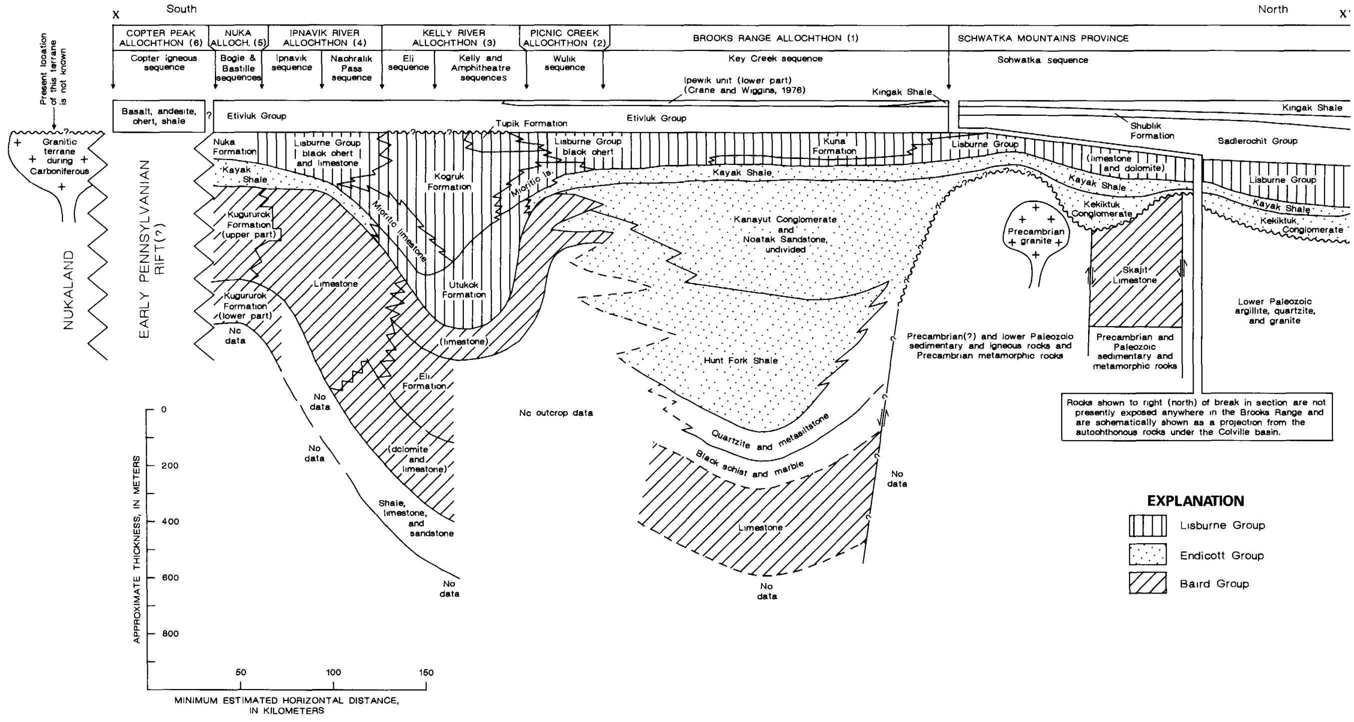


FIGURE 7.23.—Schematic reconstructed north-south cross section X-X′ across area of western Brooks Range in Middle Jurassic time, showing important rock units. Line of section indicated on palinspastic map, plate 7.3; allochthons and sequences shown in inferred original geographic positions and relations.

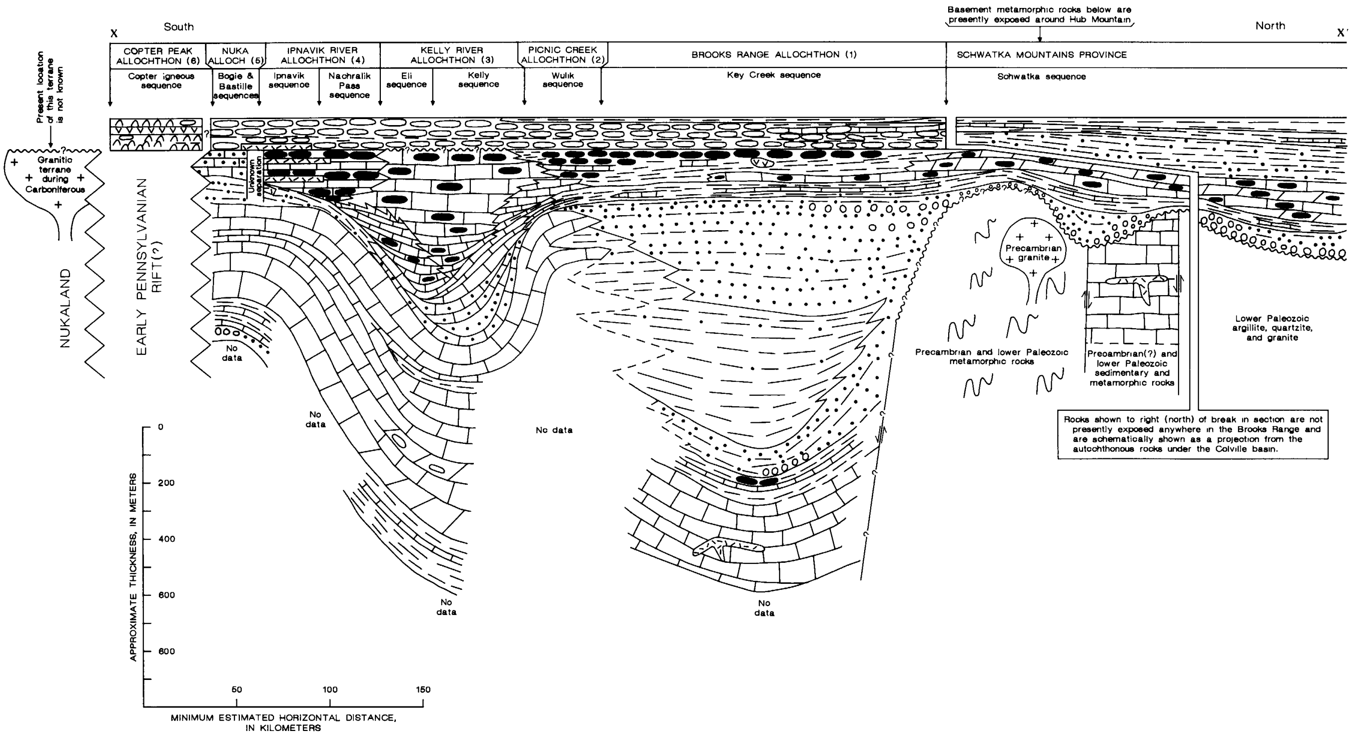


FIGURE 7.24.—Schematic reconstructed north-south cross section *X-X′* across area of western Brooks Range in Middle Jurassic time, showing important rock types. Line of section indicated on palinspastic map, plate 7.3; allochthons and sequences shown in inferred original geographic positions and relations. For explanation of lithologic symbols, see figure 7.5.

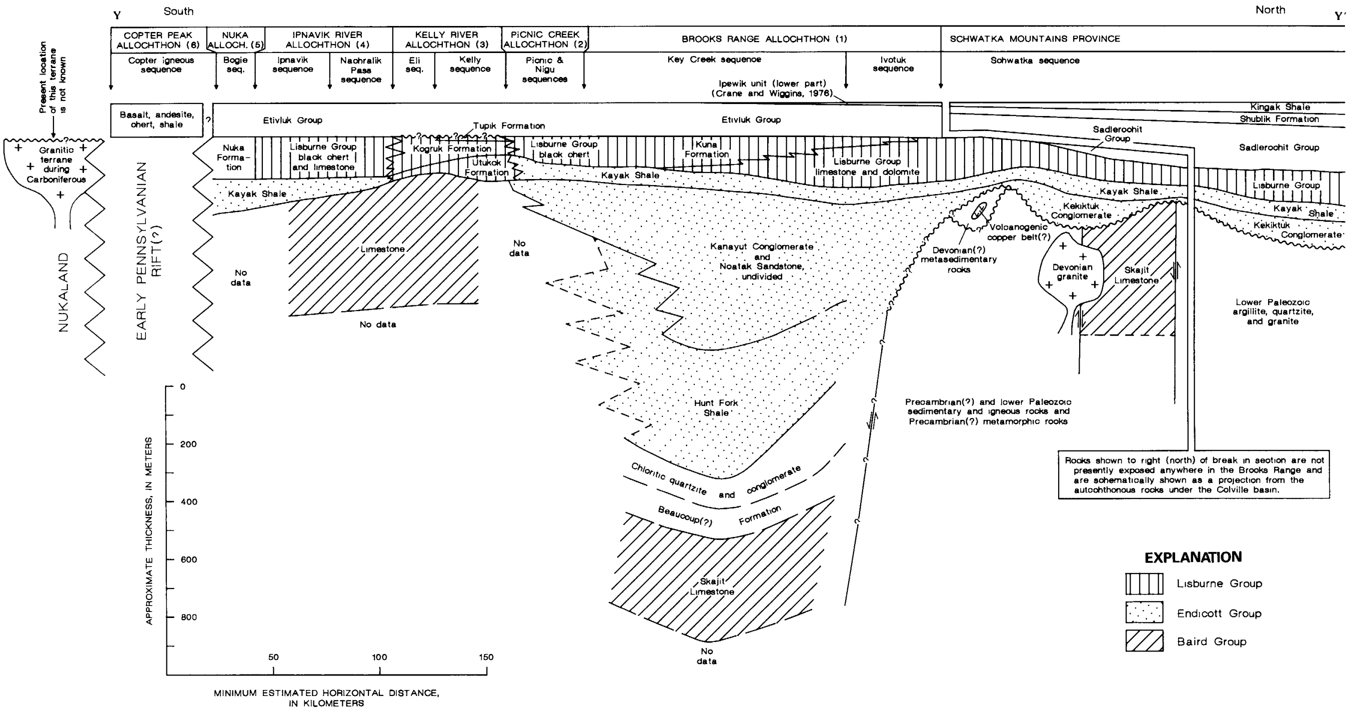


FIGURE 7.25.—Schematic reconstructed north-south cross section Y-Y′ across area of western Brooks Range in Middle Jurassic time, showing important rock units. Line of section indicated on palinspastic map, plate 7.3; allochthons and sequences shown in inferred original geographic positions and relations.

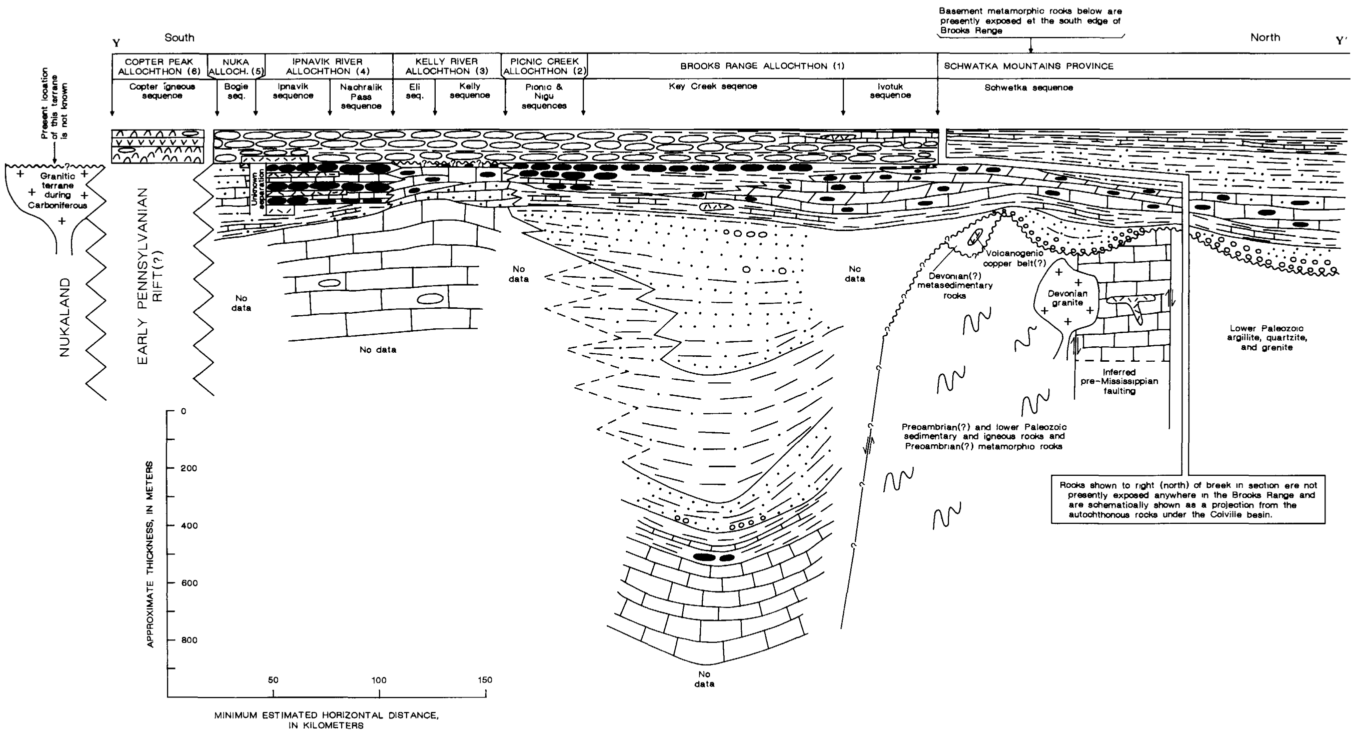


FIGURE 7.26.—Schematic reconstructed north-south cross section Y–Y′ across area of western Brooks Range in Middle Jurassic time, showing important rock types. Line of section indicated on palinspastic map, plate 7.3; allochthons and sequences shown in inferred original geographic positions and relations. For explanation of lithologic symbols, see figure 7.5.

mation. Nukaland also may have been emergent during Middle and Late Devonian time, because quartz, feldspar, and low-grade metamorphic rock fragments were shed into the Bastille sequence at that time. The Upper Devonian Kugururok Formation at Mount Bastille contains feldspathic limestone in the uppermost part of the section and shale associated with rare hematite-stained quartz conglomerate in the lowermost part. The same source area also could have contributed the shale and siltstone interbedded with Middle(?) Devonian limestone in the lowermost parts of the Eli and Puzzle Creek sequences in allochthons 3 and 4.

During Late Carboniferous time, a significant change took place in the lithology and depositional setting of the allochthonous sequences. Radiolarian chert and siliceous shale (the Etivluk Group) were deposited in all the sequences of allochthons 1 through 5 from Pennsylvanian to Early or Middle Jurassic (Toarcian to Bajocian) time. These rocks record a period of slow, low-energy sedimentation virtually unaffected by continental clastic detritus.

During Permian and Triassic time, the Sadlerochit Group was deposited in the area that later was covered by the Colville basin. As determined from subsurface well information and geologic studies in the northeastern Brooks Range, the clastic facies in the Sadlerochit under the Colville basin is generally coarser to the north and finer to the south (Detterman, 1974, 1976). In only two places in the southwestern and south-central Brooks Range is the Sadlerochit Group exposed. These are at Shishakshinovik Pass (pl. 7.1) in the east-central Ambler River quadrangle (Mull and Tailleur, 1977) and near Mount Doonerak (fig. 7.2) in the central Brooks Range (Dutro and others, 1976). At both locations, shale and siltstone have been recognized that are thought to be a distal facies of the Sadlerochit Group. Farther to the northeast, in the subsurface at Prudhoe Bay and in outcrops in the northeastern Brooks Range, nearshore marine and fluvial sandstone and conglomerate constitute much of the Sadlerochit. South of the area underlain by the Schwatka sequence in coeval rocks of the Etivluk Group, the proportion of shale to chert was generally greater in sequences deposited to the north than in those deposited to the south. Thus, the Sadlerochit Group and the age-equivalent part of the Etivluk Group are thought to have been a continuum of depositional clastic facies in which coarse-grained clastic rocks were deposited in a nearshore setting near the present coastline of northern Alaska and the deposits became progressively finer grained southward, grading to siliceous shale and radiolarian chert. This gradual facies gradient across hundreds of kilometers of northern Alaska indicates that the Arctic Alaska basin may have been a continental shelf with oceanic conditions south of the area underlain by the Bogie and Bastille sequences during Late Pennsylvanian to Jurassic time.

SPECULATIONS ABOUT ROCKS SOUTH OF THE ARCTIC ALASKA BASIN

During Devonian time and the first half of Carboniferous time, Nukaland appears to have shed clastic detritus into the southern part of the Arctic Alaska basin. After latest Mississippian or earliest Pennsylvanian time, this source area is not sensed in the sedimentary record. It seems unlikely that Nukaland was attached to the south edge of the sequences in allochthon 5 at the beginning of the Brooks Range orogeny, because no parts of a granitic terrane have been found between allochthons 5 and 6.

Nukaland may have become detached, possibly by rifting or strike-slip motion, from the south edge of northern Alaska during the Carboniferous, marking the end of deposition of the Nuka Formation and Lisburne Group throughout the allochthonous sequences. Upper Mississippian and Lower Pennsylvanian sediments in the allochthonous sequences appear to have been deposited on a sea floor, resulting in a complex pattern of high- and low-energy sediments. Before and after this time, sedimentologic conditions produced much more gradual lithologic changes. It is possible that rifting produced block faulting during Late Mississippian and Early Pennsylvanian time, resulting in a series of subparallel rises and troughs on the sea floor. Deposition of sediment on such a horst-and-graben submarine topography seems to be the most probable explanation for the many pronounced facies changes in the Upper Mississippian rock units of different allochthons. At the same time, Carboniferous sediments now underlying the Colville basin were deposited in several large, deepened fault-bounded basins, indicating that this may have been a period of regional extensional tectonics throughout northern Alaska. Such an extensional event also has been proposed to explain the tectonic setting for the Late Mississippian volcanism and lead-zinc mineral deposits in the Key Creek sequence (Metz and others, 1979, 1982; Moore and others, 1986). Perhaps, when Nukaland disappeared, the continental shelf of northern Alaska foundered, resulting in an open-marine environment distant from continental clastic sources that was favorable for radiolarians. Consequent deposition of sediment formed the chert and siliceous shale of the Etivluk Group.

The present location of Nukaland is problematical. A rifting event at the south edge of the Brooks Range has been proposed to explain the predominance of Cretaceous and younger rocks in the Yukon-Koyukuk province by W.W. Patton (Patton and others, 1977). According to that scheme, the metamorphic and granitic terrane south of the Yukon-Koyukuk province, called the Ruby geanticline (fig. 7.2) by Miller and others (1959), would have been rifted south from the Arctic Alaska basin during late Paleozoic time. However, extensive granitic source rocks for the arkose in the Nuka Formation have not yet been located. Most of the granitic rocks in the Ruby geanticline are thought to be Cretaceous in age (Silberman and others, 1979), whereas the source terrane for the Nuka Formation should contain considerable amounts of Carboniferous or older granitic rocks. Stratigraphic studies indicate that the Ruby geanticline contains pre-Permian (and probably pre-Ordovician) regional metamorphic rocks (Patton and Dutro, 1979), but no mineralogic evidence has been found from petrographic study of the Nuka arkose to suggest that there were extensive areas of metamorphic rocks in its source terrane. Conclusive evidence for the location of Nukaland is not at hand, and further clues to its location must wait until the geotectonic setting of the continental rocks in central and western Alaska and northeastern Siberia is better understood.

During early Mesozoic time in the area south of sequences that are now part of allochthon 5, pillow basalt with intercalated shale and chert formed in the Copter igneous sequence (figs. 7.23–7.26). Blocks of limestone, some of which contain Devonian fossils, also are found within and at the base of the basalt. The stratigraphic setting and tectonic history of the Copter igneous sequence are problematical. If the volcanic rocks were erupted upon a continuous layer of Devonian limestone, then they might have formed in a continental setting. If the limestone blocks are thrust slices from sequences below, then it is possible that the Copter igneous sequence erupted on oceanic crust south of the area underlain by the Bogie sequence. It has been suggested by Patton and others (1977) that the pillow basalt is part of a dismembered ophiolite sequence. However, the basalt consistently is present structurally below gabbro and peridotite of the ophiolite complex, and a comagmatic origin for these two suites of rocks is not a necessary conclusion, as discussed by Roeder and Mull (1978).

Intermediate and granitic rocks make up less than 10 percent of the exposures in the Copter igneous sequence. In some places granitic rocks intrude the pillow basalt. In other places, basalt and andesite are interlayered. The association of granitic rocks, which are mostly quartz diorite, with basalt and andesite implies the possibility that parts of the Copter igneous sequence have island-arc affinities. Detailed chemical and petrographic studies might provide more definitive evidence. Remnants of a hypothetical obducted arc may be preserved as the heretofore unexplained Jurassic igneous cobbles and boulders found in Lower Cretaceous conglomerate in flyschoid sediments along the northern foothills of the De Long and Endicott Mountains (Mayfield and others, 1978b).

THRUSTING MECHANISM—HYPOTHETICAL CONSIDERATIONS

A simple model that seems to explain the great amount of foreshortening in the western Brooks Range can be described as underthrusting (or subduction) of the Arctic Alaska plate beneath another crustal plate to the south (Tailleur, 1969a, b; Martin, 1970; Mull and others, 1976; Gealey, 1980; Mull, 1982). The underthrust plate consisted largely of continental rocks, and the upper plate consisted of oceanic crust in allochthon 7. Such a model had been proposed previously by Gealey (1980) as a likely mechanism for many other places around the world where ophiolites have been obducted onto continental crust.

According to this model, the Arctic Alaska plate began to move into a south-dipping subduction zone during about Middle Jurassic time (schematically illustrated on plate 7.4). When the ophiolite (allochthon 7) was underthrust by the less dense sialic crust, it was uplifted and cooled to argon-retentive temperatures between 170 and 150 Ma. At the subduction zone, the allochthons were detached from the lower part of the crust on which their sequences had been deposited. The process probably first started at the south edge of the continental shelf, where it involved allochthons 6 and then 5. At progressively later stages, allochthons 4, 3, 2, and finally allochthon 1 detached from their basement along shallow-angle thrust faults as each allochthon was tucked under the one previously detached. The sole thrusts for individual allochthons commonly are below Mississippian strata in the northern De Long Mountains and below Devonian strata in the southern De Long Mountains and in the Baird Mountains.

Evidence that the faults began to move at an earlier time in the south than in the north comes from comparison of the sporadic fossil ages in the orogenic flysch at the top of the allochthonous stratigraphic sequences. The basal part of the synorogenic flyschoid mudstone and graywacke, in most places called the Okpikruak Formation, appears to be at least as old as Late Jurassic in the higher allochthons and no older than Early Cretaceous (late Valanginian) in the lowest exposed thrust sheets of the lowest allochthon (Curtis and others, 1983; Ellersieck and others, 1983; Mayfield and others, 1983a). This fossil evidence for the diachronous nature of the flyschoid rocks is supported by the presence of lithologically distinct conglomerate clasts derived from structurally higher allochthons that are now found in the underthrust parts of the Okpikruak Formation in structurally lower allochthons. These relations suggest that lower allochthons were thrust beneath higher allochthons after the higher allochthons had been imbricated and partially eroded.

During the later stages of the underthrusting event, the southern part of the Schwatka sequence and the lower parts of allochthon 1, presently exposed in the Baird Mountains and Schwatka Mountains, were moved under more than 10 km of thrust sheets. The resulting increase in heat and pressure transformed the rocks into slate, schist, quartzite, and marble of the greenschist metamorphic facies (Nelson and Grybeck, 1979; Gealey, 1980; Mayfield and others, 1983b). In most places, there is a steady and continuous metamorphic gradient southward from unmetamorphosed rocks at the latitude of the Noatak River to mostly recrystallized rocks in the central Baird and Schwatka Mountains. This evidence indicates that a progressively greater amount of uplift and erosion have occurred from the latitude of the Noatak River south to the central Baird and Schwatka Mountains.

South of the Brooks Range in the Yukon-Koyukuk province, an extensive terrane of Early Cretaceous andesitic volcanic and intrusive rocks developed, and clastic detritus was shed into the surrounding sedimentary basins. K-Ar ages from andesitic volcanic rocks in the Yukon-Koyukuk province (Patton, 1973) show that they were formed during the major thrusting episode in the Brooks Range. For this reason, some geologists believe that they represent a volcanic arc generated from a subduction zone at the south edge of the Brooks Range (Gealey, 1980; Fisher and others, 1982).

The major thrusting process stopped in Early Cretaceous time, during or just before deposition of the sparsely fossiliferous Fortress Mountain Formation, which is Albian in age. The southern Brooks Range then began to rebound isostatically, erosion continued to strip away the allochthonous thrust sheets, and large quantities of clastic sediment were shed north into the Colville basin during middle and Late Cretaceous time. Most K-Ar ages from metamorphic micas in the southern Brooks Range are thought to date the uplift and cooling of these rocks between 110 and 80 Ma (Tailleur and Brosgé, 1970; Turner and others, 1978, 1979).

We assume that the sedimentary sequences of the western Brooks Range were deposited upon continental crust of unknown thickness. Middle Devonian to Carboniferous parts of the allochthonous sequences contain reefoid, bioclastic, and glauconitic limestone, carbonaceous shale, and quartzose clastic sedimentary rocks; such rocks are characteristically deposited near shorelines and in epicontinental marine basins. Because these rocks were deposited over a period of about 50 m.y. in periodically shallow-water environments, it is probable that the basement was composed of continental crust. Overlying these middle Paleozoic rocks are radiolarian chert and siliceous shale of the Etivluk Group—rocks that occur in the upper part of all the allochthonous sedimentary sequences.

This interpretation of the crustal setting for the siliceous rocks of the Etivluk Group differs from the conclusions reached during some previous studies. Churkin and others (1979a) named a succession of Mississippian to Lower Cretaceous rocks in the De Long Mountains the Kagvik sequence. Primarily on the basis of the siliceous character and fossils present in these rocks, they believed the sequence to be an oceanic deposit (Churkin and others, 1979b) or a continental margin deposit (Churkin and Trexler, 1981). The Kagvik sequence correlates with the upper part of the Key Creek sequence and possibly with some of the other sedimentary sequences described in this report. The lower part of the Key Creek sequence includes the Endicott Group, which contains fluvial quartzose clastic sedimentary rocks, coal beds, and other features indicating an epicontinental origin.

According to the palinspastic model outlined in this report, a panel of continental crust probably extended more than 400 km in a north-south direction under the sequences of allochthons 1 to 5 before the Brooks Range orogeny. The present location of the underthrust continental basement for the allochthonous sequences is a mystery. The subduction model outlined in this report requires that an unknown thickness of this crust be consumed at the south edge of the Brooks Range. At present, there is not much geological or geophysical evidence to restrict hypothetical models of the process of crustal consumption in northern Alaska. A simple solution might be that the excess crust was subducted into the mantle. If it is assumed that the sialic part of the crust is not dense enough to be returned to the mantle at a subduction zone, then at least some of the missing crust must be under the southern part of the Brooks Range and (or) extend an unknown distance to the south under the Yukon-Koyukuk province.

If some of the excess crust is under the Brooks Range, it might explain why gravity data indicate that the crust is thicker in the southern half of the Brooks Range than to the north or south (Barnes, 1976). Such crustal thickening (shown as basement thickening by Roeder and Mull, 1978) would also help to explain the greater amount of isostatic rebound that has occurred in the southern Brooks Range as compared to the adjacent geologic provinces to the north and south. If some of the excess crust followed a course of shallow subduction south of the Brooks Range, it might help to explain why gravity data indicate a crustal thickness of approximately 30 km in the Yukon-Koyukuk province. This thickness is more like that of a continental margin or an island arc than normal oceanic crust.

The thickness of the continental basement that once lay under the allochthonous sequences before the Brooks Range orogeny adds uncertainty and limits to developing a subduction model for the south edge of the Brooks Range. Future deep seismic studies of crustal thickness in the Brooks Range and the Yukon-Koyukuk province might provide some additional clues. Locations of the klippen in the Brooks Range and along the Ruby geanticline (Tailleur, 1969a; Patton and others, 1977; Roedder and Mull, 1978) indicate that the ophiolites are rooted in the Yukon-Koyukuk province, implying that a panel of oceanic crust underlies much, if not all, of the province. However, if the basement beneath the ophiolite slab contains some low-density continental crust, as seems possible from the gravity model of Barnes (1976), then an underthrust basement panel from the Brooks Range may underlie a signficant amount of west-central Alaska. Partial melting of a panel of attenuated sialic crust under the Yukon-Koyukuk province might account for some of the widespread Late Cretaceous granite plutonism south of the Brooks Range.

IMPLICATIONS FOR THE CENTRAL AND EASTERN BROOKS RANGE

Fewer allochthonous thrust sequences are known in the central and eastern Brooks Range than in the western Brooks Range (Tailleur and Brosgé, 1970). Part of the reason for this difference seems to be that the eastern two-thirds of the Brooks Range has been eroded to deeper structural levels than the western part, so there are fewer klippen of upper allochthons preserved. Most of the Endicott and Philip Smith Mountains are composed of rocks that correlate both lithologically and structurally with sequences in allochthon 1. Structurally higher allochthons have smaller outcrop areas with mainly rubble-covered exposures in the foothills north of the Endicott Mountains. As a consequence, many previous workers were reluctant to make palinspastic maps that restored these rocks to positions south of rocks that correlate with the autochthonous or parautochthonous Schwatka sequence in the southern Brooks Range.

The central and eastern Brooks Range underwent a significant compression during the Brooks Range orogeny. Numerous thrust faults and folds affect the rocks as far east as the Canadian border (Brosgé and others, 1976). Correlation of sedimentary rocks in allochthon 1 across the north-central Brooks Range, correlation of rocks in the Schwatka Mountains province across the south-central Brooks Range, and correlation of mafic igneous rocks along the south edge of the southwestern and south-central Brooks Range make it seem probable that most rocks exposed in the Endicott and Philip Smith Mountains could be restored south of the rocks currently in the southern Brooks Range on a palinspastic map of pre-Jurassic northern Alaska. If the pole of rotation for the Arctic Alaska plate that controlled most of the thrust dislocation in the Brooks Range was situated in the Mackenzie Delta, and if the leading edge of the plate boundary was along the south edge of the Brooks Range, then a minimum thrust displacement between an ophiolite sheet and the autochthon of about 500 km would be expected for the central Brooks Range and progressively less thrust displacement in the eastern Brooks Range. However, it seems unlikely that a pole of rotation in the Mackenzie Delta would be the sole determining factor for thrust displacement in the eastern Brooks Range, because significant thrust faulting with similar displacement configurations also occurred at about the same time farther south in the Canadian Cordillera.

IMPLICATIONS FOR THE SEWARD PENINSULA

It is probable that most, if not all, of the sedimentary and metasedimentary rocks in the Seward Peninsula can be correlated with rocks that are part of the Schwatka sequence and possibly with some rocks of the allochthonous sequences in the southwestern Brooks Range. Sainsbury (1969) described the rocks of the entire Seward Peninsula as being cut by imbricate thrust sheets and named this area the A.J. Collier thrust belt. He believed that the upper thrust plates were moved to the north in the western part of the Seward Peninsula and to the east along the eastern side. The time of thrusting is believed to have been during the Early Cretaceous. Similarities in metamorphic grade, mineralogy, structural trends, and Paleozoic stratigraphy between rocks in the Seward Peninsula and rocks in the southwestern Brooks Range have been noted by Tailleur and others (1967) and Patton and Tailleur (1977). These similarities suggest a similar late Paleozoic and Mesozoic geologic history for the Seward Peninsula and the western Brooks Range.

Late Cretaceous or early Tertiary tectonism in the Seward Peninsula may have been the result of an oroclinal flexure in the Bering Strait region (Tailleur, 1969a, b, 1973; Patton and Tailleur, 1977) or of folds that cut across the dominant westerly trends of the Brooks Range (Miller and others, 1959). Regardless of which of these (or other) tectonic deformations occurred in the Seward Peninsula, it is probable that this area was also affected by the same Jurassic and Early Cretaceous thrusting event that affected the Brooks Range. Any scheme that explains the Seward Peninsula on a pre-Jurassic palinspastic basis needs to take into account the dramatic effects of Brooks Range tectonism on western Alaska. For example, if most of the metamorphic rocks in the Seward Peninsula are correlated with rocks in the Schwatka sequence, as suggested by Patton and Tailleur (1977), then the Seward Peninsula would need to be restored hundreds of kilometers to the north in a position west or southwest of the Schwatka sequence on the palinspastic map (pl. 7.3).

CONCLUSIONS

The early part of the Brooks Range orogeny was a period of low-angle thrust faulting in which great panels of oceanic crust and continental-platform and shelf sediment were underthrust by the Arctic Alaska plate. This process is interpreted (in reference to the North American craton) as being the underthrusting of the Arctic Alaska plate southward, first beneath oceanic crust, represented by allochthon 7 and possibly allochthon 6, and later beneath the southern parts of its own sedimentary cover, represented by allochthons 1 to 5. The process appears to have been initiated at the southern edge of the Arctic Alaska plate by the obduction of an extensive ophiolite panel (allochthon 7) during the Middle Jurassic. Initial movement on the thrust faults appears to be progressively younger from higher to lower in the stack of thrust sheets, and the major thrust faults had stopped most of their movement by Albian time during the Early Cretaceous. The palinspastic model presented here shows the minimum thrust foreshortening between the highest structural level and the autochthon as 700 to 800 km. A total thrust foreshortening of more than 1,000 km is possible.

The underthrusting process moved the autochthonous or parautochthonous rocks that are presently exposed in the Schwatka Mountains beneath a substantial thickness of already imbricated allochthonous thrust sheets. Increased heat and pressure resulted in regional metamorphism in the Schwatka sequence and in the lower parts of the overlying lowest allochthon. During this period of underthrusting the continental crust in the southern Brooks Range appears to have thickened. After the compressional episode ceased, the southern Brooks Range isostatically rebounded, and the northern Brooks Range and Colville basin developed broad folds, high-angle faults, and small-scale thrust faults. These late tectonic processes probably continued from Late Cretaceous into Tertiary time and may have been part of the Laramide orogeny in the more southern regions of the Cordillera.

During Devonian and Mississippian time, the southern part of northern Alaska seems to have been an ensialic basin adjoined by land areas to the north and south. During late Carboniferous (probably Early Pennsylvanian) time, the southern granitic land area, here called Nukaland, disappeared. Stratigraphic and structural evidence indicates that Nukaland was moved away from the Arctic Alaska basin (during a widespread extensional tectonic event) by a rift or a strike-slip fault. During late Paleozoic and early Mesozoic time, before the Brooks Range orogeny, northern Alaska is believed to have been an extensive continental shelf having oceanic conditions to the south and a land area to the north. The stratigraphy of this old sedimentary basin and continental shelf has been reconstructed by systematically restoring lower allochthons to the north of higher allochthons. The palinspastic map resulting from this reconstruction provides a reasonable paleogeographic model for integrating future detailed studies of the Paleozoic and Mesozoic stratigraphy in the western Brooks Range.

The tectonostratigraphic model presented in this report provides a framework that will help in exploration for the energy and mineral resources of this region. In oil and gas exploration, it is crucial that there be some way to predict what rock units will be encountered in the subsurface and what facies trends will be found within key stratigraphic horizons. In contrast to the promising areas of petroleum potential in the thrust belts of the Rocky Mountains, which commonly are described as being composed of single stratigraphic sequences, prediction of facies trends in rocks of the Brooks Range is complicated by the presence of stacks of thrust sheets that contain multiple stratigraphic sequences. The stratigraphic sequences in the western Brooks Range show that in different allochthons there are many pronounced facies changes in Devonian and Mississippian rocks but only a few such changes in Pennsylvanian to Lower Cretaceous rocks. The tectonostratigraphic model of sequences and allochthons in this report provides a way to predict these important lithologic changes from one thrust sheet to the next in the subsurface. In mineral exploration, the large lead-zinc-silver and (or) barite deposits that are found within a wide area of the western Brooks Range are known to occur only in the Devonian and Mississippian rocks of allochthon 1. Therefore, the allochthon map and cross sections (pls. 7.1, 7.2) should aid in exploration by showing where such rocks occur at the surface and where favorable rocks are expected to occur in the subsurface.

The palinspastic synthesis of the western Brooks Range is a stratigraphic framework that should provide additional insight into the geologic history of adjacent regions in northern and central Alaska. In the central Brooks Range, where most rocks occur in thrust sheets that correlate with structurally lower allochthons in the western Brooks Range, hundreds of kilometers of thrust displacement should have occurred during Late Jurassic and Early Cretaceous time, and the palinspastic stratigraphy, though much of the section is now apparently eroded away, should have been similar to the stratigraphy described here. In the Seward Peninsula, where mostly Precambrian and lower Paleozoic rocks are exposed, important similarities of structural style and metamorphism to the southwestern Brooks Range indicate similar Late Jurassic and Early Cretaceous tectonic histories. Geologists working on models showing the origin of Cretaceous volcanic rocks and granitic plutons south of the Brooks Range in the Yukon-Koyukuk province will need to take into account the possibility that the Arctic Alaska plate underthrust that province.

Our tectonostratigraphic model leaves many important geologic problems unresolved. The early Paleozoic geologic history and the character and structural style of the Devonian Ellesmerian orogeny in northern Alaska are still poorly understood. The late Paleozoic geologic history of northern and central Alaska will be incomplete until we know what happened to the granitic rocks of Nukaland. Uncertainty about the character of the southern edge of the Arctic Alaska plate just before the Brooks Range orogeny could be resolved if the crustal setting of the pillow basalt in the Copter igneous sequence of allochthon 6 were known. If we knew the origin of this basalt, added insight into the origin and process of obduction of the Brooks Range ophiolites might be provided. The model for the tectonic evolution of the Brooks Range also will be incomplete until we have better evidence for what happened to the missing subducted(?) sialic crust in the Brooks Range, and until we know whether or not the deflection of the mountain trends at the east and west ends of the Brooks Range were formed by oroclinal bends. Answers to these questions would greatly improve our understanding of the tectonic processes that helped shape northern Alaska.

REFERENCES CITED

Armstrong, A.K., 1970, Carbonate facies and the lithostrotionid corals of the Mississippian Kogruk Formation, DeLong Mountains, northwestern Alaska: U.S. Geological Survey Professional Paper 664, 38 p.

Barnes, D.F., 1976, New gravity map of Alaska, *in* Cobb, E.H., ed., The United States Geological Survey in Alaska; accomplishments during 1975: U.S. Geological Survey Circular 733, p. 2-6.

Bird, K.J., 1982, Rock-unit reports of 228 wells drilled on the North Slope, Alaska: U.S. Geological Survey Open-File Report 82-278, 106 p.

Bird, K.J., Connor, C.L., Tailleur, I.L., Silberman, M.L., and Christie, J.L., 1978, Granite on the Barrow Arch, northeast NPRA, *in* Johnson, K. M., ed., The United States Geological Survey in Alaska; accomplishments during 1977: U.S. Geological Survey Circular 772-B, p. B24-B25.

Boak, J.L., Turner, D.L., Wallace, W.K., and Moore, T.E., 1985, K-Ar ages of allochthonous mafic and ultramafic complexes and their metamorphic aureoles, western Brooks Range, Alaska [abs.], *in* Alaskan and West Coast Geology and Energy Mineral Resources, American Association of Petroleum Geologists, Programs and Abstracts, Anchorage, Alaska, May 22-24, 1985, p. 37.

Brosgé, W.P., Reiser, H.N., Dutro, J.T., Jr., and Detterman, R.L., 1976, Reconnaissance geologic map of the Table Mountain quadrangle, Alaska: U.S. Geological Survey Open-File Report 76-546, 2 sheets, scale 1:200,000.

Brosgé, W.P., and Tailleur, I.L., 1970, Depositional history of northern Alaska, *in* Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska: Los Angeles, American Association of Petroleum Geologists, Pacific Section, p. D1-D17.

Bruynzeel, J.W., Guldenzopf, E.C., and Pickard, J.E., 1982, NPRA final report, 1974-1981: 183 p., 3 v., 71 maps, scale 1:500,000. [Available from National Geophysical Data Center, 325 Broadway, E/GC, Dept. CNP, Boulder, CO 80303]

Campbell, R.H., 1967, Areal geology in the vicinity of the Chariot site, Lisburne Peninsula, northwestern Alaska: U.S. Geological Survey Professional Paper 395, 71 p.

Carey, S.W., 1958, A tectonic approach to continental drift, *in* Carey, S.W., ed., Continental drift; a symposium: Hobart, Australia, Tasmania University Press, p. 177-355.

Chapman, R.M., and Sable, E.G., 1960, Geology of the Utukok-Corwin region, northwestern Alaska: U.S. Geological Survey Professional Paper 303-C, p. 47-167.

Churkin, Michael, Jr., Nokleberg, W.J., and Huie, Carl, 1979a, Collision-deformed Paleozoic continental margin, western Brooks Range, Alaska: Geology, v. 7, no. 8, p. 379-383.

——— 1979b, Tectonic model for the western Brooks Range, Alaska, *in* Johnson, K.M., and Williams, J.R., eds., The United States Geological Survey in Alaska; accomplishments during 1978: U.S. Geological Survey Circular 804–B, p. B22-B25.

Churkin, Michael, Jr., and Trexler, J.H., Jr., 1981, Continental plates and accreted oceanic terranes in the Arctic, *in* Nairn, A.E.M., Churkin, Michael, Jr., and Stehli, F.G., eds., The ocean basins and margins, v. 5, The Arctic Ocean: New York, Plenum Press, p. 1-20.

Collier, A.J., 1906, Geology and coal resources of the Cape Lisburne region, Alaska: U.S. Geological Survey Bulletin 278, 54 p.

Crane, R.C., and Wiggins, V.D., 1976, Ipewick Formation, significant Jurassic–Neocomian map unit in northern Brooks Range foldbelt [abs.]: American Association of Petroleum Geologists Bulletin, v. 60, no. 12, p. 2177.

Curtis, S.M., Ellersieck, Inyo, Mayfield, C.F., and Tailleur, I.L., 1982, Reconniassance geologic map of southwestern Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Open-File Report 82-611, 2 sheets, scale 1:63, 360.

—— 1983, Reconnaissance geologic map of the De Long Mountains A1, B1, and part of C1 quadrangles, Alaska: U.S. Geological Survey Open-File Report 83-185, 54 p., 2 sheets, scale 1:63,360.

—— 1984, Reconnaissance geologic map of the southwestern Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigation Series Map I–1502, 2 sheets, scale 1:63,360.

Detterman, R.L., 1974, Fence diagram showing lithologic facies of the Sadlerochit Formation (Permian and Lower Triassic), northeastern Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF–584, 1 sheet, scale 1:500,000.

—— 1976, Lithofacies fence diagram of Sadlerochit Group for Philip Smith Mountains quadrangle and adjacent areas, northeastern Alaska: U.S. Geological Survey Miscellaneous Field Study Map MF–744, 1 sheet, scale approx. 1:500,000.

Dillon, J.T., Pessel, G.H., Chen, J.H., and Veach, N.C., 1980, Middle Paleozoic magmatism and orogenesis in the Brooks Range, Alaska: Geology, v. 8, no. 7, p. 338-343.

Donovan, T.J., and Tailleur, I.L., 1975, Map showing paleocurrent and clast-size data from the Devonian-Mississippian Endicott Group, northern Alaska: U.S. Geological Survey Miscellaneous Geologic Field Studies Map MF-692, scale 1:7,500,000.

Dutro, J.T., Jr., 1981, Geology of Alaska bordering the Arctic Ocean, *in* Nairn, A.E.M., Churkin, Michael, Jr. and Stehli, F.G., eds., The ocean basins and margins, v. 5, The Arctic Ocean: New York, Plenum Press, p. 21-36.

Dutro, J.T., Jr., Brosgé, W.P., Lanphere, M.A., and Reiser, H.N., 1976, Geological significance of Doonerak structural high, central Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 60, no. 6, p. 952-961.

Ellersieck, Inyo, Curtis, S.M., Mayfield, C.F., and Tailleur, I.L., 1982, Reconnaissance geologic map of south-central Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Open-File Report 82-612, 38 p., 2 sheets, scale 1:63,360.

—— 1983, Reconnaissance geologic map of the De Long Mountains A2, B2, and part of C2 quadrangles, Alaska: U.S. Geological Survey Open-File Report 83-184, 54 p., 2 sheets, scale 1:63,360.

—— 1984, Reconnaissance geologic map of south-central Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigation Series Map I–1504, 2 sheets, scale 1:63,360.

Ellersieck, Inyo, Mayfield, C.F., Tailleur, I.L., and Curtis, S.M., 1979, Thrust sequences in the Misheguk Mountain quadrangle, Brooks Range, Alaska, *in* Johnson, K.M., and Williams, J.R., eds., The United States Geological Survey in Alaska; accomplishments during 1978: U.S. Geological Survey Circular 804–B, p. B8.

Fisher, M.A., Patton, W.W., Jr., and Holmes, M.L., 1982, Geology of Norton Basin and continental shelf beneath northwestern Bering Sea, Alaska: American Association of Petroleum Geologists Bulletin, v. 66, no. 3, p. 255-285.

Frank, C.O., and Zimmerman, Jay, 1982, Petrography of nonultramafic rocks from the Avan Hills complex, De Long Mountains, Alaska, *in* Coonrad, W.L., ed., The United States Geological Survey in Alaska; accomplishments during 1980: U.S. Geological Survey Circular 844, p. 22-27.

Freeland, G.L., and Dietz, R.S., 1973, Rotation history of Alaskan tectonic blocks: Tectonophysics, v. 18, p. 379-389.

Gealey, W.K., 1980, Ophiolite obduction mechanism, *in* Panayiotou, A., ed., Ophiolites; proceedings international ophiolite symposium: Cyprus Geological Survey Department, p. 228-243.

Grantz, Arthur, Eittreim, Stephen, and Whitney, O.T., 1981, Geology and physiography of the continental margin north of Alaska and implications for the origin of the Canada Basin, *in* Nairn, A.E.M., Churkin, Michael, Jr., and Stelhi, F. G., eds., The ocean basins and margins, v. 5, The Arctic Ocean: New York, Plenum Press, p. 439-492.

Grantz, Arthur, Holmes, M.L., and Kososki, B.A., 1975, Geologic framework of the Alaskan continental terrace in the Chukchi and Beaufort Seas: Canadian Society of Petroleum Geologists Memoir 4, p. 669-700.

Grantz, Arthur, Tailleur, I.L., and Carter, Claire, 1983, Tectonic significance of Silurian and Ordovician graptolites, Lisburne Hills, northwest Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 15, no. 5, p.274.

Imlay, R.W., 1955, Characteristic Jurassic mollusks from northern Alaska: U.S. Geological Survey Professional Paper 274–D, p. 69-96.

—— 1961, Characteristic Lower Cretaceous megafossils from northern Alaska: U.S. Geological Survey Professional Paper 335, 74 p.

—— 1967, The Mesozoic pelecypods *Otapiria* Marwick and *Lupherella* Imlay, new genus, in the United States: U.S. Geological Survey Professional Paper 573–B, 11 p.

Jones, D.L., and Grantz, Arthur, 1964, Stratigraphic and structural significance of Cretaceous fossils from Tiglukpuk Formation, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 48, no. 9, p. 1462-1474.

Kleist, J.R., Bard, T.R., Engstrom, D.B., Morrow, H.B., and Reber, S.J., 1983, Central Arctic foothills, Alaska; a unique challenge in frontier exploration [abs.]: American Association of Petroleum Geologists Bulletin, v. 67, no. 3, p. 495-496.

Lerand, Monti, 1973, Beaufort Sea, *in* McCrossan, R.G., ed., The future petroleum provinces of Canada; their geology and potential: Canadian Society of Petroleum Geologists Memoir 1, p. 315-386.

Martin, A.J., 1970, Structure and tectonic history of the western Brooks Range, De Long Mountains and Lisburne Hills, northern Alaska: Geological Society of America Bulletin, v. 81, no. 12, p. 3605-3621.

Mayfield, C.F., Curtis, S.M., Ellersieck, Inyo, and Tailleur, I.L., 1982a, Reconnaissance geologic map of southeastern Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Open-File Report 82-613, 40 p., 2 sheets, scale 1:63,360.

—— 1983a, Reconnaissance geologic map of the De Long Mountains A3, B3, and parts of A4, B4 quadrangles, Alaska: U.S. Geological Survey Open-File

Report 83-183, 60 p., 2 sheets, scale 1:63,360.

—— 1984a, Reconnaissance geologic map of southeastern Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigation Series Map I-1503, 2 sheets, scale 1:63,360.

Mayfield, C.F., Ellersieck, Inyo, and Tailleur, I.L., 1984b, Reconnaissance geologic map of the Noatak C5, D5, D6, and D7 quadrangles, Alaska: U.S. Geological Survey Open-File Report 84-396, 27 p., 1 sheet, scale 1:63,360.

Mayfield, C.F., Silberman, M.L., and Tailleur, I.L., 1982b, Precambrian metamorphic rocks from the Hub Mountain terrane, Baird Mountains quadrangle, Alaska, *in* Coonrad, W.L., ed., The United States Geological Survey in Alaska; accomplishments during 1980: U.S. Geological Survey Circular 844, p. 18-22.

Mayfield, C.F., and Tailleur, I.L., 1978, Bedrock geologic map of the Ambler River quadrangle, Alaska: U.S. Geological Survey Open-File Report 78-120A, 1 sheet, scale 1:250,000.

Mayfield, C.F., Tailleur, I.L., Albert, N.R.D., Ellersieck, Inyo, Grybeck, Donald, and Hackett, S.W., 1983b, The Alaskan mineral resource assessment program; background information to accompany folio of geologic and mineral resource maps of the Ambler River quadrangle, Alaska: U.S. Geological Survey Circular 793, 31 p.

Mayfield, C.F., Tailleur, I.L., Mull, C.G., and Sable, E.G., 1978a, Bedrock geologic map of the south half of National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 78-70B, 2 sheets, scale 1:500,000.

Mayfield, C.F., Tailleur, I.L., Mull, C.G., and Silberman, M.L., 1978b, Granitic clasts from Upper Cretaceous conglomerate in the northwestern Brooks Range, *in* Johnson, K.M., ed., The United States Geological Survey in Alaska; accomplishments during 1977: U.S. Geological Survey Circular 772-B, p. B11-B13.

Metz, P.A., Egan, Alyce, and Johanson, Otto, 1982, Landsat linear features, and incipient rift system model for the origin of base metal and petroleum resources of northern Alaska, *in* Embry, A.F., and Balkwill, H.R., eds, Arctic geology and geophysics: Canadian Society of Petroleum Geologists Memoir 8, p. 101-112.

Metz, P.A., Robinson, M.S., Pease, J.L., and Lueck, Larry, 1979, Carboniferous metallogeny of the northern Brooks Range, Alaska, *in* Alaska's mineral and energy resources, economics and land status: Alaska Geological Society Symposium Program and Abstracts, 1979, p. 41-42.

Mickey, M.B., 1980, Palynology/micropaleontology reports for 8 wells (1980 SE-CC): Data Set No. TGY-0060, 22 p. [Available from National Geophysical Data Center, 325 Broadway, E/GC, Dept. CNP, Boulder, Colorado 80303]

Miller, D.J., Payne, T.G., and Gryc, George, 1959, Geology of possible petroleum provinces in Alaska: U.S. Geological Survey Bulletin 1094, 131 p.

Moore, D.W., Young, L.E., Modene, J.S., and Plahuta, J.T., 1986, Geologic setting and genesis of the Red Dog zinc-lead-silver deposit, western Brooks Range, Alaska: Economic Geology, v. 81, no. 7, p. 1696-1727.

Mull, C.G., 1979, Nanushuk Group deposition and the late Mesozoic structural evolution of the central and western Brooks Range and Arctic Slope, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 5-13.

—— 1980, Evolution of Brooks Range thrust belt and Arctic Slope, Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 64, no. 5, p. 754-755.

—— 1982, Tectonic evolution and structural style of the Brooks Range, Alaska; an illustrated summary, *in* Powers R.B., ed., Geologic studies of the Cordilleran thrust belt: Denver, Colorado, Rocky Mountain Association of Geologists, v. 1, p. 1-45.

Mull, C.G., and Tailleur, I.L., 1977, Sadlerochit(?) Group in the Schwatka Mountains, south-central Brooks Range, *in* Blean, K.M., ed., The United States Geological Survey in Alaska; accomplishments during 1976: U.S. Geological Survey Circular 751-B, p. B27-B29.

Mull, C.G., Tailleur, I.L., Mayfield, C.F., Ellersieck, Inyo, and Curtis, Steven, 1982, New upper Paleozoic and lower Mesozoic stratigraphic units, central and western Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 66, no. 3, p. 348-362.

Mull, C.G., Tailleur, I.L., Mayfield, C.F., and Pessel, G.H., 1976, New structural and stratigraphic interpretations, central and western Brooks Range and Arctic Slope, *in* Cobb, E.H., ed., The United States Geological Survey in Alaska; accomplishments during 1975: U.S. Geological Survey Circular 733, p. 24-26.

Murchey, B.L., Swain, P.B., and Curtis, Steven, 1981, Late Mississippian to Pennsylvanian radiolarian assemblages in the Siksikpuk(?) Formation at Nigu Bluff, Howard Pass quadrangle, Alaska, *in* Albert, N.R.D., and Hudson, Travis, eds., The United States Geological Survey in Alaska; accomplishments during 1979: U.S. Geological Survey Circular 823-B, p. B17-B19.

Nelson, S.W., and Grybeck, Donald, 1979, Tectonic significance of metamorphic grade distribution, Survey Pass quadrangle, Alaska, *in* Johnson, K.M., and Williams, J.R., eds., The United States Geological Survey in Alaska; accomplishments during 1978: U.S. Geological Survey Circular 804-B, p. B16-B18.

—— 1980, Geologic map of the Survey Pass quadrangle, Brooks Range, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF 1176-A, 2 sheets, scale 1:250,000.

Nelson, S.W., and Nelson, W.H., 1982, Geology of the Siniktanneyak Mountain ophiolite, Howard Pass quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1441, 1 sheet, scale 1:63,360.

Nelson, S.W., Nokleberg, W.J., Miller-Hoare, Martha, and Mullen, M.W., 1979, Siniktanneyak Mountain ophiolite, *in* Johnson, K.M., and Williams, J.R., eds., The United States Geological Survey in Alaska; accomplishments during 1978: U.S. Geological Survey Circular 804-B, p. B14-B16.

Newman, G.W., Mull, C.G., and Watkins, N.D., 1979, Northern Alaska paleomagnetism, plate rotation, and tectonics, *in* Sisson, Alexander, ed., The relationship of plate tectonics to Alaskan geology and resources: Proceedings of Sixth Alaska Geological Society Symposium, p. C1-C7.

Nilsen, T.H., 1981, Upper Devonian and Lower Mississippian redbeds, Brooks Range, Alaska, *in* Miall, A.D., ed., Sedimentation and tectonics in alluvial basins: Geological Association of Canada Special Paper 23, p. 187-219.

Patton, W.W., Jr., 1973, Reconnaissance geology of the northern Yukon-Koyukuk province, Alaska: U.S. Geological Survey Professional Paper 774-A, p. A1-A17.

Patton, W.W., Jr., and Dutro, J.T., Jr., 1979, Age of the metamorphic complex in the northern Kuskokwim Mountains, west-central Alaska, *in* Johnson, K.M., and Williams, J.R., eds., The United States Geological Survey in Alaska; accomplishments during 1978: U.S. Geological Survey Circular 804-B, p. B61-B63.

Patton, W.W., Jr., and Matzko, J.J., 1959, Phosphate deposits in northern Alaska: U.S. Geological Survey Professional Paper 302-A, 17 p.

Patton, W.W., Jr., and Tailleur, I.L., 1977, Evidence in the Bering Strait region for differential movement between North America and Eurasia: Geological Society of America Bulletin, v. 88, no. 9, p. 1298-1304.

Patton, W.W., Jr., Tailleur, I.L., Brosgé, W.P., and Lanphere, M.A., 1977, Preliminary report on the ophiolites of northern and western Alaska, *in* Coleman, R.G., and Irwin, W.P., eds., North American ophiolites: Oregon Department of Geology and Mineral Industries Bulletin 95, p. 51-57.

Payne, T.G., 1955, Mesozoic and Cenozoic tectonic elements of Alaska: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-84, scale 1:500,000.

Pessel, G.H. and Brosgé, W.P., 1977, Preliminary reconnaissance geologic map of Ambler River quadrangle, Alaska: U.S. Geological Survey Open-File Report 77-28, 1 sheet, scale 1:250,000.

Plafker, George, Hudson, Travis, and Jones, D.L., 1978, Upper Triassic radiolarian chert from the Kobuk volcanic sequence in the southern Brooks Range, *in* Johnson, K.M., ed., The United States Geological Survey in Alaska; accomplishments during 1977: U.S. Geological Survey Circular 772-B, p. B45-B47.

Reiser, H.N., Brosgé, W.P., Dutro, J.T., Jr., and Detterman, R.L., 1980, Geologic map of the Demarcation Point quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1133, 1 sheet, scale 1:250,000.

Rickwood, F.K., 1970, The Prudhoe Bay field, *in* Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska: Los Angeles, American Association of Petroleum Geologists, Pacific Section, p. L1-L11.

Roeder, Dietrich, and Mull, C.G., 1978, Tectonics of Brooks Range ophiolites, Alaska: American Association of Petroleum Geologists Bulletin, v. 62, no.9, p. 1696-1702.

Sainsbury, C.L., 1969, The A.J. Collier thrust belt of the Seward Peninsula, Alaska: Geological Society of America Bulletin, v. 80, no. 12, p. 2595-2596.

Silberman, M.L., Moll, E.J., Chapman, R.M., Patton, W.W., Jr., and Connor, C.L., 1979, Potassium-argon age of granitic and volcanic rocks from the Ruby, Medfra, and adjacent quadrangles, west-central Alaska, *in* Johnson, K.M., and Williams, J.R., eds., The United States Geological Survey in Alaska; accomplishments during 1978: U.S. Geological Survey Circular 804-B, p. B63-B68.

Snelson, Sigmund, and Tailleur, I.L., 1968, Large-scale thrusting and migrating Cretaceous foredeeps in western Brooks Range and adjacent regions of northwestern Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 52, no. 3, p. 567.

Sweeney, J.F., Irving, E., and Geuer, J.W., 1978, Evolution of the Arctic Basin, *in* Sweeney, J.F., ed., Arctic geophysical review: Ottawa, Canada, Publications of the Earth Physics Branch, Department of Energy, Mines and Resources, v. 45, no. 4, p. 91-100.

Tailleur, I.L., 1965, Low-volatile bituminous coal of Mississippian age on the Lisburne Peninsula, northwestern Alaska, *in* Geological Survey research 1965: U.S. Geological Survey Professional Paper 525-B, p. B34-B38.

—— 1969a, Speculations on North Slope geology: Oil and Gas Journal, v. 67, no. 38 (September 22), p. 215-220, 225-226.

—— 1969b, Rifting speculation on the geology of Alaska's North Slope: Oil and Gas Journal, v. 67, no. 39 (September 29), p. 128-130.

—— 1973, Probable rift origin of the Canada Basin, Arctic Ocean; *in* Pitcher, M.G., ed., Arctic Geology: American Association of Petroleum Geologists Memoir 19, p. 526-535.

Tailleur, I.L., and Brosgé, W.P., 1970, Tectonic history of northern Alaska, *in* Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska: Los Angeles, American Association of Petroleum Geologists, Pacific Section, p. E1-E19.

Tailleur, I.L., Brosgé, W.P., and Reiser, H.N., 1967, Palinspastic analysis of Devonian rocks in northwestern Alaska, *in* Oswald, D.H., ed., International symposium on the Devonian System: Calgary, Alberta, Alberta Society of Petroleum Geologists, v. 2, p. 1345-1361.

Tailleur, I.L., and Kent, B.H., Jr., 1951, Stratigraphy and structure of the southern foothills section between the Etivluk and Kiligwa Rivers, Alaska: U.S. Geological Survey Investigations Naval Petroleum Reserve No. 4 and adjacent areas, Alaska, Regular Report 43, 28 p. [Available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey].

Tailleur, I.L., Kent, B.H., Jr., and Reiser, H.N., 1966, Outcrop/geologic maps of the Nuka-Etivluk region, northern Alaska: U.S. Geological Survey open-file report [66-128], 7 sheets, scale 1:63,360.

Tailleur, I.L., Mayfield, C.F., and Ellersieck, I.F., 1977, Late Paleozoic sedimentary sequence, southwestern Brooks Range, *in* Blean, K.M., ed., The United States Geological Survey in Alaska; accomplishments during 1976: U.S. Geological Survey Circular 751-B, p. B25-B27.

Tailleur, I.L., and Sable, E.G., 1963, Nuka Formation of Late Mississippian to Late Permian age, new formation in northern Alaska: American Association of Petroleum Geologists Bulletin, v. 47, no. 4, p. 632-642.

Tailleur, I.L., and Snelson, Sigmund, 1969, Large-scale thrusting in northwestern Alaska possibly related to rifting of the Arctic Ocean [abs.]: Geological Society of America Special Paper 121, p. 569.

Turner, D.L., Forbes, R.B., and Dillon, J.T., 1979, K-Ar geochronology of the southwestern Brooks Range, Alaska: Canadian Journal of Earth Sciences, v. 16, no. 9, p. 1789-1804.

Turner, D.L., Forbes, R.B., and Mayfield, C.F., 1978, K-Ar geochronology of the Survey Pass, Ambler River, and eastern Baird Mountains quadrangles, southwestern Brooks Range, Alaska: U.S. Geological Survey Open-File Report 78-254, 41 p., scale 1:250,000.

United States Geological Survey, 1972, Lisburne Peninsula, *in* Geological Survey research, 1972: Professional Paper 800-A, p. A50.

—— 1975, New graptolite discovery indicates Lower Ordovician rocks in southwestern Brooks Range, *in* Geological Survey research, 1975: Professional Paper 975, p. 64.

Zimmerman, Jay, and Frank, C.O., 1982, Possible ophiolite obduction-related metamorphic rocks at the base of the ultramafic zone, Avan Hills complex, De Long Mountains, *in* Coonrad, W.L., ed., The United States Geological Survey in Alaska; accomplishments during 1980: U.S. Geological Survey Circular 844, p. 27-28.

Zimmerman, Jay, Frank, C.O., and Bryn, Sean, 1981, Mafic rocks in the Avan Hills ultramafic complex, De Long Mountains, *in* Albert, N.R.D., and Hudson, Travis, eds., The United States Geological Survey in Alaska; accomplishments during 1979: U.S. Geological Survey Circular 823-B, p. B14-B15.

Zimmerman, Jay, and Soustek, P.G., 1979, The Avan Hills ultramafic complex, De Long Mountains, Alaska, *in* Johnson, K.M., and Williams, J.R., eds. The United States Geological Survey in Alaska; accomplishments during 1978: U.S. Geological Survey Circular 804-B, p. B8-B11.

8. BEDROCK GEOLOGIC MAP OF THE NATIONAL PETROLEUM RESERVE IN ALASKA

By Charles F. Mayfield, Irvin L. Tailleur, and Charles E. Kirschner

INTRODUCTION

This chapter is an introduction with background information to accompany the bedrock geologic map (pl. 8.1) and cross sections (pl. 8.2) of the National Petroleum Reserve in Alaska (NPRA). The surface geology of the northern part of the NPRA has been compiled with the aid of maps of northern Alaskan geology by Lathram (1965) and Payne and others (1951). The geology of the southern part was compiled largely from the geologic map by Mayfield and others (1978). These and more detailed sources of data are shown on the index map (pl. 8.1, map C). Unconsolidated Tertiary(?) and Quaternary sediments, principally those of the Pliocene(?) and Pleistocene Gubik Formation and the Holocene deposits, are omitted from the map in the northern part of the area in order to show the approximate subcrop contacts between consolidated rock units that are Tertiary and older in age. These contacts are approximated from information on the first consolidated rock unit drilled in oil exploration wells (Bird, 1982) and from maps of shallow seismic results in the northern and eastern parts of the NPRA.

Modifications to earlier geologic maps have been made where warranted by more recent geologic investigations. Previous geologic compilations of the southern part of the NPRA have been partly remapped to conform to the tectonostratigraphic units named by Ellersieck and others (1979) and Mayfield and others (chapter 7). In the northwestern part of the reserve, rocks previously mapped as part of the Colville Group are here reassigned to the Nanushuk Group. Reports of plant fossils on the Kuk and Kaolak Rivers (Smiley, 1969; Scott and Smiley, 1979) and micropaleontologic study of near-surface strata at the Tunalik No. 1 well indicate that the rocks west of the Meade River are probably all pre-Turonian in age and therefore older than any known rocks in the Colville Group. This revision is consistent with the sedimentology, because both the Nanushuk and Colville Groups consist of deltaic sediments that were prograded across the North Slope from southwest to northeast (Ahlbrandt, 1979). Though Colville deposition began with a significant marine transgression, it seems unlikely that this deposition reached as far west as the area in question.

GEOLOGIC SETTING

The NPRA has been divided into four physiographic regions (pl. 8.1, map D) called the Arctic coastal plain, northern foothills, southern foothills, and Brooks Range provinces (Wahrhaftig, 1965). Although each region contains some rocks that are the same age, the stratigraphy of the northern two regions is different from the coeval stratigraphy of the southern two regions. The rocks under the coastal plain and northern foothills are autochthonous or nearly so and have been divided into three principal sequences, discussed below. In the southern foothills and Brooks Range part of the pre-Albian section (at least 9 km thick) is allochthonous and has been divided into seven principal tectonostratigraphic sequences that have been superposed by numerous thrust faults.

ARCTIC COASTAL PLAN AND NORTHERN FOOTHILLS

The autochthonous rocks of the northern NPRA are subdivided into three parts called the Franklinian, Ellesmerian, and Brookian sequences (Lerand, 1973). The Franklinian sequence is composed of pre-Mississippian rocks that were deformed, uplifted, and eroded during the Late Devonian part of the Ellesmerian orogeny. These rocks are known to be composed of argillite, quartzite, and granite and are considered the basement for potential hydrocarbon resources. The Ellesmerian sequence consists of Lower Mississippian to Lower Cretaceous (pre-Albian) strata that were deposited in a sedimentary basin periodically receiving clastic detritus from a land area to the north. Lower Mississippian to Permian(?) strata consist of conglomerate, sandstone, and shale of the Endicott Group—clastic sediments deposited over the pre-Mississippian angular unconformity. Upper Mississippian to Lower Permian rocks are primarily carbonate strata of the Lisburne Group. Both these groups are

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younger to the north, indicating that their depositional settings followed a northward-transgressing shoreline. Middle Permian to Lower Cretaceous (pre-Albian) rocks are composed mostly of shale and sandstone whose constituents were shed primarily from a periodically emergent land area north of Barrow. The Brookian sequence in the northern foothills consists of Lower Cretaceous (Albian) and younger clastic rocks that had their source area to the south in the Brooks Range. The lower part of this sequence contains shaly distal marine deposits of the Torok Formation. The upper part contains molassic rocks composed primarily of two northeastward-prograded deltaic complexes called the Nanushuk and Colville Groups. Both complexes are characterized by shaly marine strata at their bases and grade upward into paralic and fluvial deposits. The uppermost part of the Brookian sequence consists of the Tertiary Sagavanirktok Formation, which represents the continued deposition of molassic sediments into the northeastern part of the NPRA.

The northern foothills region was deformed by the Late Cretaceous and possibly early Tertiary tectonism of the waning stages of the Brooks Range orogeny. East-trending, large-scale disharmonic folds are present throughout the area; they consist of shallowly dipping broad synclines separated by more steeply dipping anticlinal folds. In the southwestern part of the northern foothills, the synclines are generally composed of resistant sandstone of the Nanushuk Group, and the anticlinal folds have been breached to expose shale of the Torok Formation. Anticlines are commonly assymetric and have more steeply dipping beds on the north limbs. Most anticlines probably contain reverse faults related to the plastic flow of fine-grained sediments into the nose of the fold during deformation. Much of this movement, probably rooted to the south, occurred in a thick zone of deformation and multiple detachment surfaces in shaly sediments of the Torok Formation. In the southern part of the northern foothills, maximum foreshortening of rocks in the basal part of the Nanushuk Group with respect to the less deformed underlying Ellesmerian sequence is about 10 to 15 km. Deformation and foreshortening diminished to the north, and the coastal plain north of lat 70° N. is virtually undeformed.

SOUTHERN FOOTHILLS AND BROOKS RANGE

Surface rocks in the northern part of the southern foothills consist of Lower Cretaceous (Albian) flyschoid wacke, conglomerate, and mudstone of the Fortress Mountain and Torok Formations. These rocks unconformably lap onto older rocks in the southern part of the NPRA that consist of highly deformed and faulted allochthonous rocks of Devonian to Early Cretaceous (pre-Albian) age. The allochthonous rocks are grouped into seven major allochthons whose geographic distribution is plotted on the allochthon map (pl. 8.1, map A). Each allochthon is composed of a distinctive sequence of rocks. Allochthons six and seven are composed predominantly of Triassic and (or) Jurassic igneous rocks, and allochthons one through five are composed predominantly of Devonian to Cretaceous sedimentary rocks.

The allochthons are sequentially numbered, allochthon seven being on the top and allochthon one on the bottom of the stack. Allochthon seven is composed of gabbro and peridotite that are thought to be remnants of an extensive ophiolite sheet that once overlaid much of the southern part of the Brooks Range (Patton and others, 1977; Roeder and Mull, 1978). Allochthon six is composed predominantly of pillow basalt that has uncertain (oceanic or continental) affinities. Allochthons one through five are composed predominantly of sedimentary rocks. When higher allochthons are sequentially unstacked southward relative to lower allochthons, they describe a complex pre-Brookian sedimentary platform. Upper Devonian rocks in the northern part of this platform in allochthons one and two formed a clastic wedge, composed of the lower part of the Endicott Group, whose constituents were derived from rocks to the north in the Franklinian sequence. South of the clastic wedge on the platform in sequences of allochthons three, four, and five, coeval Upper Devonian rocks comprised predominantly limestone and dolomite of the Baird Group (Tailleur and others, 1967). Rocks of Late Mississippian and Early Pennsylvanian age range from shallow-water bioclastic limestone of the Lisburne Group, and arkosic limestone of the Nuka Formation (Upper Mississippian and Lower Pennsylvanian?), to basinal black shale and chert. Rapid changes between high- and low-energy facies suggest that deposition took place on a sea floor that had a complex series of rises and troughs. These complex sedimentary sequences are overlain by a continuous and fairly homogeneous layer of chert and siliceous shale of the Etivluk Group of Pennsylvanian to Early and Middle Jurassic age. The uppermost part of the sequence in each allochthon is composed of orogenic flyschoid rocks of the Lower Cretaceous (pre-Albian) Okpikruak Formation. These strata are thought to have been deposited in a northward-migrating foredeep during the major thrusting period of the Brooks Range orogeny, because sporadic fossil collections from the mountains southwest of the NPRA at the base of the synorogenic flyschoid rocks are at least as old as Late Jurassic (Tithonian) in upper thrust sheets and no older than Early Cretaceous (Valanginian) in the lowest thrust sheets (Mayfield and others, 1983; Curtis and others, 1984).

Clues to the tectonic process that superposed the seven major allochthons are found in the structural style of the Brooks Range and southern foothills. Numerous thrust faults and complex folds occur in all the allochthonous sequences. In general, fold axes have approximately east-west trends and commonly are overturned toward the north. The relative movement of thrust faults was south over north. We believe that with respect to the North American craton, this process can be best described as the underthrusting of more northerly rocks below those to the south, as first proposed by Tailleur and Snelson (1969). Thrusting probably began under allochthon seven with the obduction of ophiolite, as indicated by Middle Jurassic K-Ar ages that record the cooling of these rocks. During this early period of tectonism, the initial movement on the thrust faults occurred progressively later to the north and reached the lowest thrust sheets of allochthon one after Valanginian time. Minimum foreshortening between allochthon seven and the underlying and autochthonous Ellesmerian sequence is about 700 km. The major thrusting episode ceased before deposition of the nearly autochthonous Fortress Mountain Formation of Albian age (Tailleur and Brosgé, 1970; Mull, 1979). During middle and Late Cretaceous time, epeirogenic uplift affected the southern Brooks Range. Broad folds and high-angle faults in the allochthons and in the Cretaceous sedimentary rocks north of the Brooks Range are evidence for a later period of less intense deformation in northern Alaska.

REFERENCES CITED

Ahlbrandt, T.S., ed., 1979, Preliminary geologic, petrologic, and paleontologic results of the study of Nanshuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, 163 p.

Blanchard, D.C., and Tailleur, I.L., 1983, Pebble shale (Early Cretaceous) depositional environments in the National Petroleum Reserve in Alaska (NPRA) [abs.]: American Association of Petroleum Geologists Bulletin, v. 67, no. 3, p. 424-25.

Bird, K.J., 1978, New information on Lisburne Group (Carboniferous and Permian) in National Petroleum Reserve Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 62, no. 5, p. 880.

Bird, K.J., 1982, Rock-unit reports of 228 wells drilled on the North Slope, Alaska: U.S. Geological Survey Open-File Report 82-278, 105 p.

Bird, K.J., and Andrews, Jack, 1979, Subsurface studies of the Nanushuk Group, North Slope, Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 32-41.

Bird, K.J., Conner, C.L., Tailleur, I.L., Silberman, M.L., and Christie, J.L., 1978, Granite on the Barrow Arch, northeast NPRA, *in* Johnson, K.M., ed., the United States Geological Survey in Alaska; accomplishments during 1977: U.S. Geological Survey Circular 772-B, p. B24-25.

Brosgé, W.P., and Whittington, C.L., 1966, Geology of the Umiat-Maybe Creek region, Alaska: U.S. Geological Survey Professional Paper 303-H, p. 501-638.

Bruynzeel, J.W., Guldenzopf, E.C., and Pickard, J.E., 1982, NPRA final report, 1974-1981: 183 p., 3 v., 71 maps: scale 1:500,000. [Available from National Geophysical Data Center, 325 Broadway, E/GC, Dept. CNP, Boulder, Colorado 80303]

Carter, Claire, and Laufeld, Sven, 1975, Ordovician and Silurian fossils in well cores from North Slope of Alaska: American Association of Petroleum Geologists Bulletin, v. 59, no. 3, p. 457-464.

Carter, D.L., Repenning, C.A., Marincovich, L.N., Hazel, J.E., Hopkins, D.M., McDougall, Kristen, and Naeser, C.W., 1977, Gubik and pre-Gubik Cenozoic deposits along the Colville River near Ocean Point, North Slope, Alaska, *in* Blean, K.M., ed., The United States Geological Survey in Alaska; accomplishments during 1976: U.S. Geological Survey Circular 751-B, p. B12-B13.

Chapman, R.M., Detterman, R.L., and Mangus, M.D., 1964, Geology of the Killik-Etivluk Rivers region, Alaska: U.S. Geological Survey Professional Paper 303-F, p. 325-407.

Chapman, R.M., and Sable, E.G., 1960, Geology of the Utukok-Corwin region, northwestern Alaska: U.S. Geological Survey Professional Paper 303-C, 164 p.

Collins, F.R., 1958, Test wells, Topagoruk area, Alaska: U.S. Geological Survey Professional Paper 305-D, p. 265-316.

Crane, R.C., and Wiggins, V.D., 1976, Ipewick Formation, significant Jurassic-Neocomian map unit in northern Brooks Range foldbelt [abs.]: American Association of Petroeum Geologists Bulletin, v. 60, no. 12, p. 2177.

Curtis, S.M., Ellersieck, Inyo, Mayfield, C.F., and Tailleur, I.L., 1984, Reconnaissance geologic map of southwestern Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1502, scale 1:63,360.

Ellersieck, Inyo, Curtis, S.M., Mayfield, C.F., and Tailleur, I.L., 1984, Reconnaissance geologic map of south-central Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1504, scale 1:63,360.

Ellersieck, Inyo, Jansons, Uldis, Mayfield, C.F., and Tailleur, I.L., 1982, The Story Creek and Whoopee Creek lead-zinc-silver occurrences, western Brooks Range, Alaska, *in* Coonrad, W.L., ed., The United States Geological Survey in Alaska; accomplishments during 1980: U.S. Geological Survey Circular 844, p. 35-38.

Ellersieck, Inyo, Mayfield, C.F., Tailleur, I.L., and Curtis, S.M., 1979, Thrust sequences in the Misheguk Mountain quadrangle, Brooks Range, Alaska, *in* Johnson, K.M., and Williams, J.R., eds., The United States Geological Survey in Alaska; accomplishments during 1978: U.S. Geological Survey Circular 804-B, p. B8.

Jansons, Uldis, and Parke, Mary Ann, 1981, 1978 mineral investigations in the Misheguk Mountain and Howard Pass quadrangles, Alaska: U.S. Bureau of Mines Open-File Report 26-81, 195 p.

Lanphere, M.A., and Tailleur, I.L., 1983, K-Ar ages of bentonites in the Seabee Formation, northern Alaska; a Late Cretaceous (Turonian) time-scale point: Cretaceous Research, v. 4, p. 361-370.

Lathram, E.H., 1965, Preliminary geologic map of northern Alaska: U.S. Geological Survey open-file report [65-96], 2 sheets, scale 1:1,000,000.

Lerand, Monti, 1973, Beaufort Sea, *in* McCrossan, R.G., ed., The future petroleum provinces of Canada; their geology and potential: Canadian Society of Petroleum Geologists Memoir 1, p. 315-386.

Mayfield, C.F., Curtis, S.M., Ellersieck, Inyo, and Tailleur, I.L., 1983, Reconnaissance geologic map of the De Long Mountains A3, B3, and parts of A4, B4 quadrangles, Alaska: U.S. Geological Survey Open-File Report 83-183, 2 sheets, scale 1:63,360.

—— 1984, Reconnaissance geologic map of southeastern Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1503, scale 1:63,360.

Mayfield, C.F., Tailleur, I.L., Mull, C.G., and Sable, E.G., 1978, Bedrock geologic map of the south half of National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 78-70B, 2 sheets, scale 1:500,000.

Mull, C.G., 1979, Nanushuk Group deposition and the late Mesozoic structural evolution of the central and western Brooks Range and Arctic Slope, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 5-13.

Nokleberg, W.J., and Winkler, G.R., 1982, Stratiform zinc-lead deposits in the Drenchwater Creek area, Howard Pass quadrangle, northwestern Brooks Range, Alaska: U.S. Geological Survey Professional Paper 1209, 22 p.

Patton, W.W., Jr., Tailleur, I.L., Brosgé, W.P., and Lanphere, M.A., 1977, Preliminary report on the ophiolites of northern and western Alaska, *in* Coleman, R.G., and Irwin, W.P., eds., North American ophiolites: Oregon Department of Geology and Mineral Industries Bulletin 95, p. 51-57.

Payne, T.G., and others, 1951, Geology of the Arctic slope of Alaska: U.S. Geological Survey Oil and Gas Investigations Map OM-126, 3 sheets, scale 1:1,000,000.

Robinson, F.M., 1964, Core tests, Simpson area, Alaska: U.S. Geological Survey Professional Paper 305-L, p. 645-730.

Rockwell, D.W., 1981, Report on reinterpretation of seismic data pertaining to Mesozoic strata in the Cape Simpson region, National Petroleum Reserve in Alaska: Houston, Texas, Stewart Folk and Company Inc., 28 p. [Available from National Geophysical Data Center, 325 Broadway, E/GC1, Dept. CNP, Boulder, CO 80303]

Rockwell, D.W., and Folk, S.H., 1982, Analysis and reinterpretation of seismic and well data pertaining to Jurassic sandstone prospects in the northern part of the National Petroleum Reserve in Alaska: Houston, Texas, Stewart Folk and Company, Inc., 31 p. [Available from National Geophysical Data Center, 325 Broadway, E/GC1, Dept. CNP, Boulder, Colorado 80303]

Roeder, Dietrich, and Mull, C.G., 1978, Tectonics of Brooks Range ophiolites, Alaska: American Association of Petroleum Geologists Bulletin, v. 62, p. 1696-1702.

Sable, E.G., Chapman, R.M., and Tailleur, I.L., 1984a, Geological map of the western Kukpowruk-Nuka Rivers region, northwestern Alaska: U.S. Geological Survey Miscellaneous Field Investigations Map MF-1668, 2 sheets, scale 1:63,360.

—— 1984b, Geological map of the west-central Kukpowruk-Nuka Rivers region, northwestern Alaska: U.S. Geological Survey Miscellaneous Field Investigations Map MF-1669, 2 sheets, scale 1:63,360.

Sable, E.G., Dutro, J.T., Jr., Morris, R.H., and Tailleur, I.L., 1984c, Geologic map of the eastern Kukpowruk-Nuka Rivers region, northwestern Alaska: U.S. Geological Survey Miscellaneous Field Investigations Map MF-1671, 2 sheets, scale 1:63,360.

Sable, E.G., Mangus, M.D., Morris, R.H., and Dutro, J.T., Jr., 1984d, Geologic map of the east-central Kukpowruk-Nuka Rivers region, northwestern Alaska: U.S. Geological Survey Miscellaneous Field Investigations Map MF-1670, 2 sheets, scale 1:63,360.

Scott, R.A., and Smiley, C.J., 1979, Some Cretaceous plant megafossils and microfossils from the Nanushuk Group, northern Alaska; a preliminary report, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 89-111.

Smiley, C.J., 1969, Floral zones and correlations of Cretaceous Kukpowruk and Corwin Formations, northwestern Alaska: American Association of Petroleum Geologists Bulletin, v. 53, p. 2079-2093.

Stefansson, Karl, and Mangus, M.D., 1949, Stratigraphy and structure of the area of the Avalik and Ketik Rivers: U.S. Geological Survey Geological Investigations, Naval Petroleum Reserve No. 4 and adjacent areas, Alaska, Regular Report 28, 4 p. [Available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey]

Tailleur, I.L., and Brosgé, W.P., 1970, Tectonic history of northern Alaska: *in* Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska, Palo Alto, California, 1970: Los Angeles, American Association of Petroleum Geologists Pacific Section, p. E1-E19.

Tailleur, I.L., Brosgé, W.P., and Reiser, H.N., 1967, Palinspastic analysis of Devonian rocks in northwestern Alaska, *in* Oswald, D.H., ed., International Symposium on the Devonian System, Calgary, Alberta, 1967: Calgary, Alberta Society of Petroleum Geologists, v. 2, p. 1345-1361.

Tailleur, I.L., Kent, B.H., Jr., and Reiser, H.N., 1966, Outcrop/geologic maps of the Nuka-Etivluk region, northern Alaska: U.S. Geological Survey open-file report [66-128], 7 sheets, scale 1:63,360.

Tailleur, I.L., and Snelson, Sigmund, 1969, Large-scale thrusting in northwestern Alaska possibly related to rifting of the Arctic Ocean [abs.]: Geological Society of America Special Paper 121, p. 569.

Wahrhaftig, Clyde, 1965, Physiographic divisions of Alaska: U.S. Geological Survey Professional Paper 482, 52 p.

Webber, E.J., 1947, Stratigraphy and structure of the area of the Meade and Kuk Rivers and Point Barrow: U.S. Geological Survey Geological Investigations, Naval Petroleum Reserve No. 4 and adjacent areas, Alaska, Regular Report 6, 14 p. [Available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey]

Williams, J.R., 1983a, Engineering-geologic maps of northern Alaska, Meade River quadrangle: U.S. Geological Survey Open-File Report 83-294, 30 p., 1 sheet, scale 1:250,000.

—— 1983b, Engineering-geologic maps of northern Alaska, Wainwright quadrangle: U.S. Geological Survey Open-File Report 83-457, 28 p., 1 sheet, scale 1:250,000.

Woolson, J.R., and others, 1962, Seismic and gravity surveys of Naval Petroleum Reserve No. 4 and adjoining areas, Alaska: U.S. Geological Survey Professional Paper 304-A, 25 p.

Yeend, Warren, 1983, Engineering-geologic maps of northern Alaska, Lookout Ridge quadrangle: U.S. Geological Survey Open-File Report 83-279, 2 sheets, scale 1:250,000.

—— 1984, Engineering-geologic maps of northern Alaska, Utukok River quadrangle: U.S. Geological Survey Open-File Report 84-682, 2 sheets, scale 1:250,000.

9. PETROLEUM POTENTIAL OF REPRESENTATIVE STRATIGRAPHIC AND STRUCTURAL ELEMENTS IN THE NATIONAL PETROLEUM RESERVE IN ALASKA

By CHARLES E. KIRSCHNER and BARBARA A. RYCERSKI

INTRODUCTION

This chapter describes representative stratigraphic and structural elements in the National Petroleum Reserve in Alaska (NPRA) that have a bearing on the assessment of its petroleum potential (fig. 9.1). We summarize concepts developed during our three years (1981-84) with the Office of NPRA (ONPRA) and discussions held with numerous other U.S. Geological Survey (USGS) colleagues and contractors. The interpretations are based mainly on well, seismic, and geologic field data in the NPRA, including 45 shallow core tests, 50 exploratory test wells, and 31 field development wells (20 in the Barrow field and 11 in the Umiat field), in addition to about 26,323 line km (16,350 line mi) of seismic reflection profiles. Only part of this large volume of data has been examined in detail. Previous reports by the USGS and contractors to ONPRA, published literature, and selected independent studies have been relied on to develop interpretations (see list at end of chapter).

The NPRA covers about 93,240 km^2 (36,000 mi^2) of the west-central part of the Alaska North Slope. The stratigraphic section includes three Phanerozoic sequences: the Franklinian, Ellesmerian, and Brookian (fig. 9.2). Four distinct structural provinces, the Arctic platform, northern foothills, southern foothills, and Brooks Range, are present in the reserve area (fig. 9.1). These structural provinces correspond only approximately to the physiographic provinces defined by Wahrhaftig (1965) and Molenaar (1981). Carter and others (1977) summarized the petroleum geology and developed a play analysis for the NPRA. They subdivided petroleum prospects into three basic play types: the Prudhoe Bay type, conventional plays, and thrust-belt plays. Each type has several subtypes based on age. The observations in this chapter supplement the play analyses by Carter and others (1977). Those prospects here considered to be primarily stratigraphic are discussed in the next section, and those considered to be primarily structural in the section entitled "Stratigraphy." Nevertheless, we recognize that the major petroleum accumulations at the Prudhoe Bay (Jamieson and others, 1980) and Kuparuk (Carman and Hardwick, 1982) fields east of the NPRA and the smaller Walakpa gas field in the western NPRA are all in combination structural-stratigraphic traps. The oil and gas potential of each structural province is summarized at the end of this chapter.

Generalized structural and stratigraphic trends in the NPRA are shown on plate 9.1, and plate 9.2 displays selected structural and stratigraphic features interpreted from regional reflection seismic lines. Well-correlation sections across the northern part of the Arctic platform are shown in plates 9.3-9.7 and located on figure 9.3. The correlations were developed independently by the authors, and thus depths to specific horizons may not necessarily correspond to those of Bird (1982).

ACKNOWLEDGMENT

We are indebted to I.L. Tailleur for numerous informal discussions that helped us generate ideas and reach conclusions.

STRATIGRAPHY

A generalized stratigraphic section for the NPRA is shown in figure 9.2. For convenience in discussion, we follow Grantz and others (1979) in adopting Lerand's (1973) subdivision of the section into three sequences: the Franklinian, Ellesmerian, and Brookian. The Franklinian sequence consists mainly of pre-Mississippian, low-grade metamorphosed clastic sedimentary rocks locally intruded by granitic rocks (Brosgé and others, chapter 14). This sequence is considered to be the economic basement for petroleum exploration in the NPRA. Unconformably overlying the Franklinian rocks is the Ellesmerian sequence that consists of Mississippian through Lower Cretaceous (Neocomian) nonmarine and marine siliciclastic and carbonate sedimentary rocks. This sequence was largely derived from the hypothetical northern provenance terrane of Barrovia (Tailleur,

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1973); it is time transgressive northward on the Arctic platform. Initial deposition filled depressions in horst-and-graben structures; later deposition formed distinctive blanket and sheetlike sequences of rocks over the platform. The Ellesmerian sequence will be discussed as a succession of sedimentary packages, as illustrated in figure 9.2. Each package has its own lithologic and depositional characteristics that help to define the tectonic and stratigraphic development of the Arctic platform and also to define the potential for petroleum exploration. Overlying the Ellesmerian sequence is the Brookian sequence that consists of Lower Cretaceous through Quaternary marine and nonmarine clastic rocks derived from the Brooks Range.

FRANKLINIAN SEQUENCE

Franklinian rocks have been drilled and cored in most of the wells on the Barrow high and on the south flank of the Barrow arch (Brosgé and others, chapter 14). The most common rock type is dark-grey argillite or phyllite that is locally graphitic and dolomitic. Six wells encountered rocks other than argillite that are also considered to be part of the Franklinian sequence. The W.T. Foran No. 1, Cape Halkett No. 1, South Meade No. 1, and Topagoruk No. 1 wells drilled steeply dipping, nonmarine, metamorphosed clastic rocks consisting of coal-bearing argillite and metaquartzite containing Middle Devonian plant fossils (pls. 9.5, 9.6).

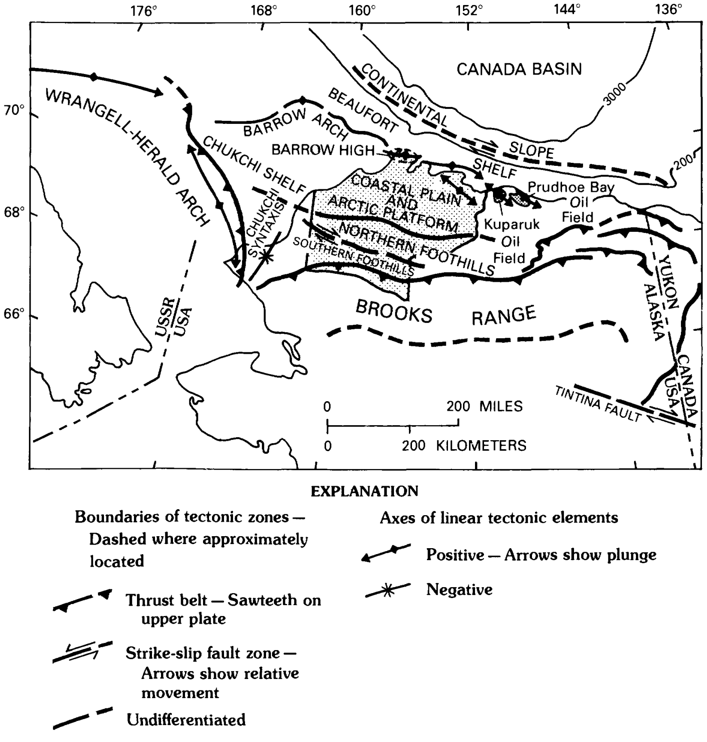


FIGURE 9.1.—Simplified tectonic map of northern Alaska showing location of National Petroleum Reserve in Alaska. Bathymetric contours are in meters.

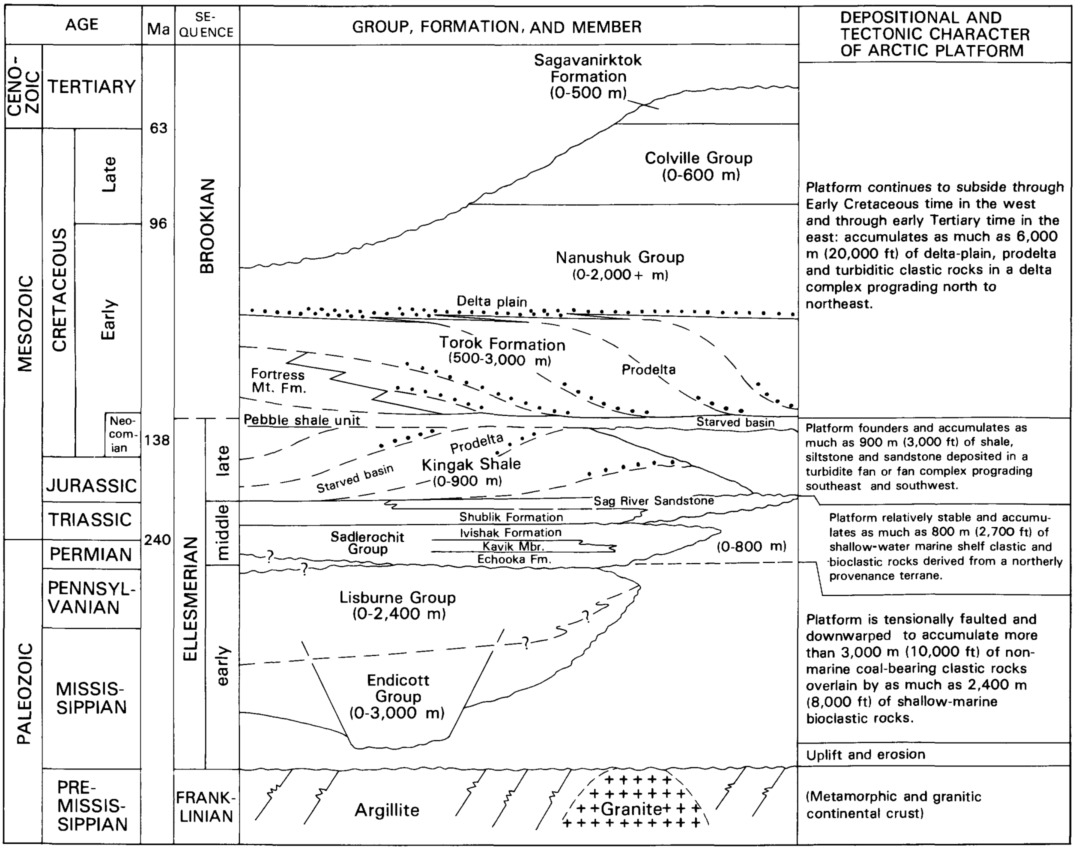
Steep to vertical dips in the nonmarine beds, contrasting with low dips in the basal Ellesmerian strata, document an unconformable relation between the Franklinian and Ellesmerian rocks in these and other wells that penetrated Franklinan beds. Weathered(?) argillite cored in the East Simpson No. 2 well also may indicate that the Franklinian rocks were locally subjected to subaerial erosion before deposition of the Ellesmerian rocks. The Ikpikpuk No. 1 well bottomed in metaquartzite, and the East Teshekpuk No. 1 well bottomed in granite (pl. 9.5; Bird and others, 1978) that is unconformably overlain by calcareous sandstone of the Lisburne Group. Carter and Laufield (1975) described Ordovician and Silurian fossils in the Franklinian sequence from well cores at Prudhoe Bay and the South Barrow gas field. In addition, Early to Middle Devonian leaf fossils have been reported from core samples in the Topagoruk No. 1 well (Collins, 1958b). These data indicate the sequence was probably deformed, metamorphosed, and intruded during a Late Devonian and Early Mississippian orogenic episode equivalent to the Antler orogeny, as previously described by Grantz and others (1979). Subsequently, these basement rocks were tensionally faulted and then subsided to provide a platform for the deposition of the basal Ellesmerian strata.

The Franklinian sequence is generally transparent seismically; bedding is rarely defined. However, faults commonly produce a diffraction wavelet and offset reflectors that originate at the Franklinian-Ellesmerian interface. This interface usually produces a strong reflection; it can be traced throughout the NPRA as far south as the Carbon Creek fault zone (fig. 9.4). It is less distinct farther south but is tentatively believed to continue dipping south at least to the north edge of the Brooks Range (plate 9.2).

ELLESMERIAN SEQUENCE

The Ellesmerian sequence (herein informally divided into early, middle, and late Ellesmerian segments), which rests unconformably on the Franklinian sequence on the Arctic platform, probably reaches a maximum thickness of about 6,100 m (20,000 ft) in the Umiat basin, a riftlike graben (pl. 9.2), and thins by basal onlap over the Meade and Wainwright arches and the Fish Creek and Umiat platforms (pls. 9.1, 9.2). On the Barrow arch and the Barrow high, the sequence thins as a result of onlap, wedgeout, disconformities, and unconformities within it. In north-south vertical profile the unconformities converge to the north on the Barrow arch and (to the northwest) on the Barrow high. These unconformities are associated with sandy intervals and indicate repetitive transgressive and regressive cycles related to episodic epeirogenic movements in the provenance terrane and possibly also to global sea-level changes.

The early Ellesmerian sequence comprises the Endicott and Lisburne Groups, which range from Early Mississippian to Early Permian in overall age in the NPRA, and consists of marine and nonmarine clastic and carbonate rocks. The sequence has irregular or lenticular east-west and north-south profiles (pl. 9.2) that result from graben filling and onlap of adjacent horsts. Sedimentation was initiated



Platform continues to subside through Early Cretaceous time in the west and through early Tertiary time in the east: accumulates as much as 6,000 m (20,000 ft) of delta-plain, prodelta and turbiditic clastic rocks in a delta complex prograding north to northeast.

Platform founders and accumulates as much as 900 m (3,000 ft) of shale, siltstone and sandstone deposited in a turbidite fan or fan complex prograding southeast and southwest.

Platform relatively stable and accumulates as much as 800 m (2,700 ft) of shallow-water marine shelf clastic and bioclastic rocks derived from a northerly provenance terrane.

Platform is tensionally faulted and downwarped to accumulate more than 3,000 m (10,000 ft) of nonmarine coal-bearing clastic rocks overlain by as much as 2,400 m (8,000 ft) of shallow-marine bioclastic rocks.

Uplift and erosion

(Metamorphic and granitic continental crust)

FIGURE 9.2—Generalized stratigraphy in National Petroleum Reserve in Alaska. Environments of deposition indicated for selected units. Lines of dots diagrammatically show location of some sandstone facies; dashed lines show progradation of deltas.

with a rapid deposition of nonmarine clastic strata of the Endicott Group that largely filled the riftlike basins. These tectonic features are interpreted on the basis of seismic data to be the result of a riftlike breakup and subsidence of the central Arctic platform probably beginning in Late Devonian or Early Mississippian time. The oldest beds belonging to the Endicott Group that have been drilled are Early Mississippian in age in the Inigok No. 1 well. Older beds are present in the deeper parts of the Umiat basin. Estimates of the rates of sedimentation indicate that the rapid deposition of the nonmarine strata was followed by slower deposition of shallow-marine sandy and shaly carbonate rocks of the Lisburne Group, which completed the basin filling and onlapped or overlapped highs to form a broad stable carbonate platform (Bird and Jordan, 1977). The Lisburne Group deposits are time transgressive on the Barrow arch and are as young as Early Permian in age near their zero edge (for example, in the W.T. Foran No. 1 well, pl. 9.5, sec. F-F′).

A thermal-alteration study conducted on the Inigok No. 1 well (Magoon and Claypool, 1981) indicates that the early Ellesmerian rocks are likely to be postmature and gas prone below about 3,700 m (12,000 ft) on the Arctic platform. The approximate onlap edge of the Lisburne Group trends generally westward across the northern part of the Arctic platform (pl. 9.1). The potential for stratigraphic entrapment along this trend is discussed below in the section entitled "Structure".

The middle Ellesmerian sequence consists of the Sadlerochit Group, Shublik Formation, and Sag River Sandstone, which are Permian and Triassic in overall age. It forms a sheetlike package of sandstone, shale, and carbonate rocks (pl. 9.2) on the Arctic platform that thins by onlap to the north on the Barrow arch (pl. 9.2; pl. 9.4, sec. D-D′). Seismic data indicate that it also thins to the south but maintains a fairly uniform thickness of about 460 m (1,500 ft) in east-west profile across the central part of the platform (pl. 9.2). The sandstones shale out southward and are virtually absent at the latitude of the Inigok No. 1 and Tunalik No. 1 wells (pls. 9.6, 9.7). Sedimentation was probably initiated by an epeirogenic uplift of the hypothetical northern provenance terrane of Barrovia (Tailleur, 1969). Coarse to fine clastic materials were shed southward over the Arctic platform during Early Permian to Early Triassic time to form the Sadlerochit Group. The platform and its provenance terrane were relatively quiescent in Middle and Late Triassic time during deposition of the Shublik Formation, which consists of sandy bioclastic limestone and shale deposited on a marine shelf. These strata form a characteristic high-amplitude seismic reflecting sequence that can be traced over the entire platform in the NPRA. A final epeirogenic uplift of Barrovia shed coarse to fine clastic materials southwestward over the northern part of the platform, forming the Sag River Sandstone. This epeirogenic episode may indicate continued rifting or a shift in the proximity of part of Barrovia as a provenance terrane for

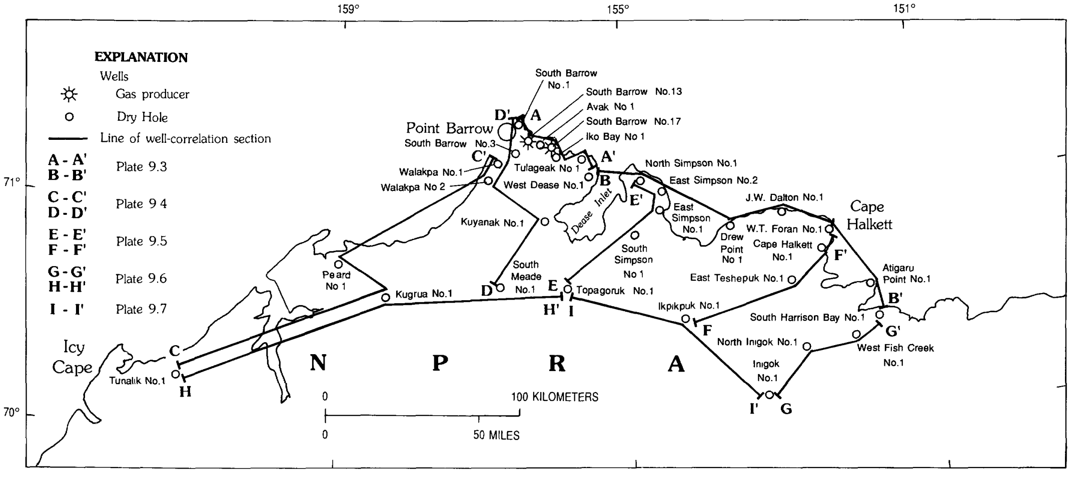


FIGURE 9.3—Outline map of northern part of National Petroleum Reserve in Alaska showing location of well-correlation sections on plates 9.3-9.7.

shelf sandstones on the Arctic platform in the NPRA; no similar platform deposits are present in the post-Triassic late Ellesmerian section.

Ellesmerian reservoirs, primarily in stratigraphic traps on the Arctic platform, have been considered to be potential prospects (Tetra Tech, Inc., 1982a, p. 117). Such reservoirs could include the wedge edges of the Endicott Group clastic beds, the Lisburne Group carbonate beds, and the sandstones of the Sadlerochit Group. If these reservoir targets are in part structurally controlled, their areal dimensions could be large because of the gentle structural relief on the platform. Reservoirs would require an overlying shale seal and, in the absence of structural closure, would also require horizontal permeability barriers. Although these conditions may be possible, a simple horizontal permeability barrier is unlikely, and an overlying shale seal is im-

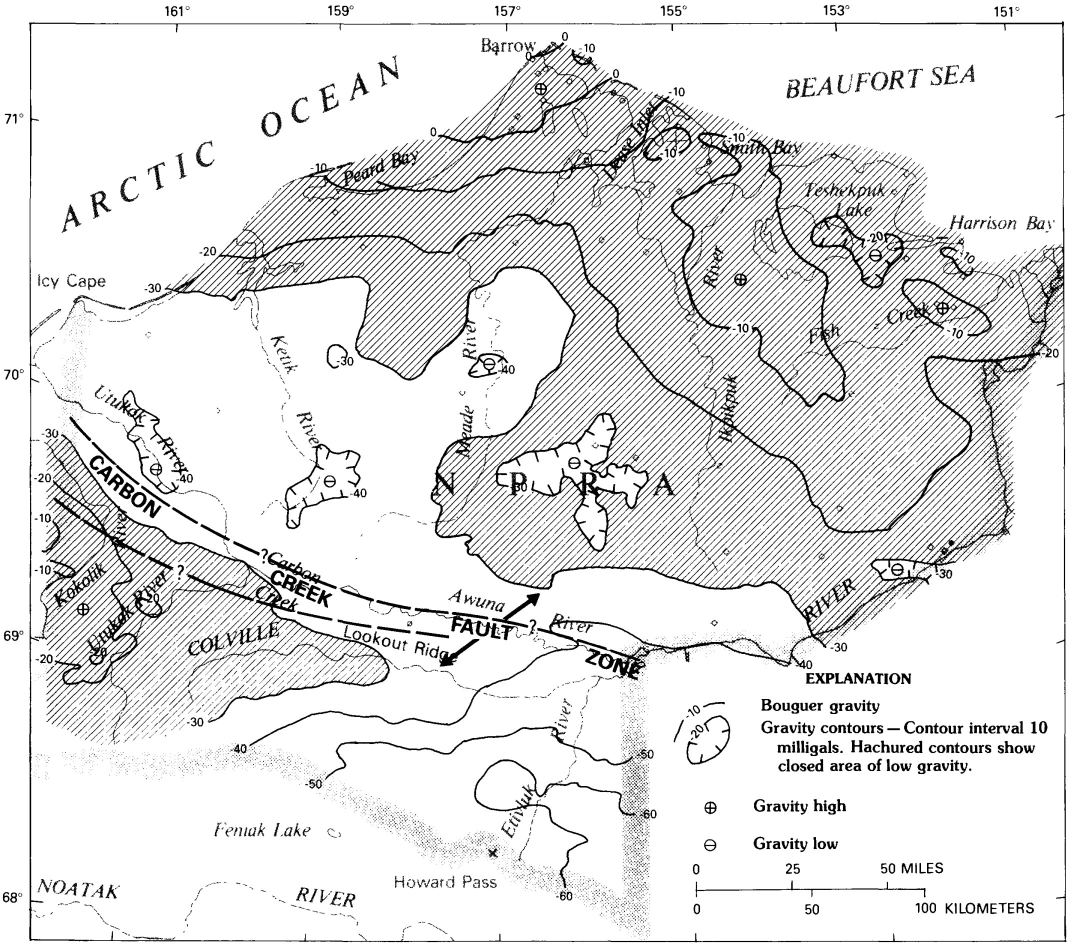


FIGURE 9.4—Bouguer gravity map of National Petroleum Reserve in Alaska showing Carbon Creek fault(?) zone (CCFZ). Arrows indicate possible northeast extension and dextral strike-slip displacement of blocks across the CCFZ, as shown by distribution of areas of Bouguer gravity greater than −30 milligals (lined). Adapted from Barnes (1977).

probable because the Ellesmerian sandstones are time transgressive. Strandline sand facies probably shifted generally northward, updip on the platform, so that hydrocarbons could continue to migrate updip until trapped by overlap of the Lower Cretaceous shales, as at the Prudhoe, Kuparuk, and Walakpa oil and gas fields. An attempt was made to test this type of stratigraphic prospect in the wedge edge of the Lisburne Group by drilling the Kugrua and Peard No. 1 wells. The Kugrua well was possibly too far downdip, and the Peard well was obviously too far updip, to test this model; the Peard well struck basement north of the Lisburne Group zero line. Neither of the wells had significant shows in either the Lisburne carbonate rocks or the Sadlerochit sandstones. Although these results may not rule out the potential of this type of prospect, they certainly indicate that careful seismic stratigraphic delineation will be required. Early and middle Ellesmerian reservoir targets in the NPRA are areally confined to a fairly narrow east-trending band on the north-central part of the platform. They are limited on the north by stratigraphic zero lines and on the south by sand shale-outs or depths beyond which source and reservoir beds may be postmature.

The late Ellesmerian sequence comprises the Kingak Shale and most of the pebble shale unit, which are Jurassic and Early Cretaceous (Neocomian) in overall age. It consists of a blanketlike package of shale, with minor amounts of sandstone and mudstone, about 825 m (2,700 ft) thick, extending across the central Arctic platform (pls. 9.2, 9.6). The sequence thins to the south, southwest, and southeast by progradational downlap (pl. 9.2). It also thins to the north, in the direction of its presumed Barrovian provenance terrane, by internal convergence, disconformities, and unconformities within the sequence, such as at the base of the Neocomian pebble shale unit (pl. 9.4, secs. C-C′, D-D′).

Late Ellesmerian sedimentation is transitional between the marine shelf deposits of middle Ellesmerian time, derived from a northern provenance terrane (Barrovia), and the deep basinal (bathyal to abyssal?) marine prodelta and turbidite deposits of early Brookian time (Barremian to Albian), which were derived from a southern provenance terrane (the Brooks Range). We speculate that the Arctic platform may have foundered rapidly in the Early and (or) Middle Jurassic and that the late Ellesmerian sediments were deposited, at least in part, in deep water by turbidity currents. Sandstone distribution patterns imply the presence of provenance terranes to the northeast and northwest of the Arctic platform through Jurassic and most of Neocomian time, and of a Brookian provenance terrane south of the platform in latest Neocomian and post-Neocomian time. Sandstones of the Neocomian Kuparuk Formation (Carmen and Hardwick, 1982) in the Prudhoe and Kuparuk oil fields east of the NPRA are interpreted as having been derived from a Barrovian provenance terrane to the northeast that was being displaced by rifting (Grantz and May, 1983).

Jurassic and Neocomian sandstones, which shale out southward in wells south and west of the Barrow high, indicate a Barrovian provenance in the vicinity of the Barrow arch northwest of the NPRA—an area that had not been displaced by rifting. The thick Jurassic and Neocomian turbidite sequence of the Okpikruak Formation, which consists of shale, graywacke, and conglomerate in the southern NPRA, was clearly derived from a southern or Brookian terrane (Molenaar, 1981). Haga and Mickey (1983b) and Blanchard and Tailleur (1983) recognized upper Neocomian (Barremian? and Barremian? to middle Albian?) rocks in the uppermost part of the pebble shale unit. They interpreted these rocks to be distal starved-basin deposits derived from the Brooks Range. The sequence is about 200 m (700 ft) thick in the Seabee No. 1 well and thins northward onto the Arctic platform, where it is generally less than 15 m (50 ft) thick, as in the Kuyanak No. 1 well (Haga and Mickey, 1983b). The interval lacks the conspicuous rounded, matrix-supported, frosted quartz and chert grains that are present in strata of the older pebble shale unit and are a lithologic characteristic of rocks derived from the northern provenance terrane. We interpret these data to indicate that the switch of provenance terranes for the Arctic platform took place during late Neocomian time.

The Kingak Shale and the lower part of the pebble shale unit in the north-south profile (pl. 9.2) appear to form a progradational delta sequence similar to the sigmoid reflection pattern of Mitchum and others (1977) and Sangree and Widmeir (1977) that is characteristic of low-energy, shale-prone deltas. Individual clinoform reflectors begin in the lower part of the pebble shale unit, dip southward, and flatten, downlapping pre-Kingak strata. Haga and Mickey (1983b, integrated correlation chart G-H) interpreted paleontologic bathymetric indicators as defining a middle and outer neritic (prodelta) to bathyal, starved-basin depositional environment for the Kingak Shale and a middle neritic to bathyal, starved-basin environment for the middle and lower parts of the pebble shale unit. We interpret these seismic, paleontologic, and lithologic data to indicate that the Arctic platform foundered during deposition of the

Kingak Shale and continued to founder during deposition of the pebble shale unit, while the northern source terranes had very low relief and (or) were being rifted away and not close to the site of deposition.

The "basal Neocomian unconformity" of other authors (for example, Grantz and May, 1983; Molenaar, 1981, p. 9), is interpreted as being a submarine unconformity that passes downdip (southward) into a disconformity and a surface of bypassed sedimentation that existed on the northern part of the Arctic platform during the progradational deposition of the Kingak Shale and the middle and lower parts of the pebble shale unit. This interpretation is uncertain because the updip flattening of the clinoform topset beds can only be inferred, not proved; the resolution of the seismic data is too coarse to delineate thin topset beds within the strata of the pebble shale unit. On the other hand, the interpretation has plausibility in two respects: (1) Both the Kingak Shale and the pebble shale unit are prodelta sequences and contain large quantities of hydrogen-rich organic matter (Franz and others, 1983). An unconformity that implies uplift, folding, and erosion is unlikely between two distal organic shale facies. (2) Sandstones and conglomeratic sandstones at the base of the pebble shale unit, such as those in the Walakpa No. 2 well at 790 m (2,600 ft) and in the Kuyanak No. 1 well at 1,550 m (5,080 ft), which might be thought to overlie the possible unconformity, are interpreted from seismic evidence to be at different stratigraphic levels (Rockwell, 1981a, p. 10). They are also interpreted to be different in age by paleontologic analysis (Haga and Mickey, 1983a). Such relations are characteristic of turbidite-fan sandstone bodies rather than of platform or shelf sandstones. Additionally, our studies of sandstone lithology and depositional structure inferred from cores and wire-line logs have shown that these characteristics are commonly associated with suspended-load sedimentation, such as occurs in turbidite channel and suprafan sandstone sequences. This type of sedimentation seems to be a logical depositional mechanism for sandstones in a distal prodelta environment.

Berg (1982) stated that the sigmoid reflection pattern is often seen adjacent to oblique and complex oblique progradational patterns which reflect higher energy sedimentation. If the Neocomian Kuparuk River sandstones east-northeast of the NPRA and the Neocomian sandstones in the Tunalik No. 1 well in the northwestern NPRA reflect the higher energy sedimentation in suprafan lobes, then the north-central and northeastern area of the Arctic platform in the NPRA may reflect the lower energy regime of an interlobe area. Molenaar (1981, p. 9) stated, "The rare chert and quartzite pebbles that are scattered throughout the pebble shale unit are an enigma," and speculated that they may be stones dropped from floating ice, kelp, or logs, or stomach stones from marine vertebrates. Such unusual sources for the large quartzite and chert grains seem unlikely; in a regime of suspended-load sedimentation and turbidite sand deposition, however, the presence of these grains as well as disorganized grain-flow and debris-flow beds (D.C. Blanchard, written commun., 1984) would be a normal characteristic.

Potential hydrocarbon plays in the late Ellesmerian rocks might include a combination of structural and stratigraphic traps, such as the truncation edges of lenticular sandstone reservoirs (Rockwell and Folk, 1982), and Upper Jurassic and lower Neocomian sandstones beneath the upper Neocomian pebble shale unit such as are found in the Walakpa gas-bearing sandstone at 790 m (2,600 ft) in the Walakpa No. 2 well. The Walakpa sandstone has a stratigraphic and structural setting similar to that of the petroliferous informally designated Kuparuk River sands and also has the reservoir capacity for gas production (Gruy Management Service Co., 1981), although the areal extent of the accumulation is not known. Significant gas shows were found in lower Neocomian sandstones below the upper Neocomian pebble shale unit in the Tunalik No. 1 well at 3,325 m (10,900 ft) and 3,810 m (12,500 ft) but were not tested. A study of the morphology of the Tunalik sandstones was conducted by geophysicists of Tetra Tech, Inc. (1982a). They interpreted the sandstones as having a limited areal extent compatible with the morphology of a sand lobe in a prograded submarine fan complex similar to the Winters Sandstone (Williamson and Hill, 1981) in the Sacramento Valley gas province of northern California. In addition, a core in Neocomian sandstone and shale in the Tunalik No. 1 well at 3,830-3,840 m (12,567-12,597 ft) has many of the depositional structures, associated with turbidite sequences, such as rip-up shale clasts in sandstone, thin-bedded sandstone-shale intervals, and complex soft-sediment deformation. Additional detailed study, drilling, and testing will be required to define the morphology and productive capability of the sandstones in these wells, but the turbidite fan model may prove useful in future petroleum exploration on the Arctic platform. Carmen and Hardwick (1982, p. 158) have also suggested that exploration plays of the Kuparuk type may be present on the flanks of the Barrow arch. The quartzites of the Ipewik Formation (Crane and Wiggins, 1976) and the sandstones of the Okpikruak Formation in the southern foothills province appear to be unpromising exploration reservoir targets, possibly because of diagenesis and absence of porosity related to strong structural deformation and probable deep burial.

BROOKIAN SEQUENCE

The Brookian sequence (herein informally divided into early, middle, and late Brookian segments) consists of thick Cretaceous and some Tertiary flysch and molasse deposits that were flushed from the rising Brooks Range orogen and dumped into the Colville foredeep. As the foredeep filled, the sequence prograded northeastward to overtop the present Barrow arch and also eastward across the Arctic platform south of the Barrow arch. In north-south profile the sequence is wedge shaped (pl. 9.2). On the south, the flysch and molasse deposits of the Lower Cretaceous Fortress Mountain Formation and the partly coeval Torok Formation probably exceed 6,000 m (20,000 ft) in thickness. To the north, the Torok Formation thins to 700 m (2,300 ft) over the Barrow high, where its original thickness has been reduced by erosion. The Brookian section thickens eastward down the plunge of the Barrow arch to about 2,500 m (8,200 ft) with the addition of the Lower and Upper Cretaceous Nanushuk Group, Upper Cretaceous Colville Group, and Tertiary deposits. The greatest thickness of Tertiary and Quaternary(?) beds encountered in the NPRA is about 460 m (1,500 ft) in the W.T. Foran No. 1 well (pl. 9.3, sec. B-B′). In east-west profile across the central part of the Arctic platform (pl. 9.2), the Torok Formation has a remarkably consistent thickness of about 1,500 m (5,000 ft), whereas the overlying Nanushuk Group thins over the Meade arch as the result of post-Nanushuk erosion, indicating post-Nanushuk uplift on the arch. Bird and Andrews (1979), Molenaar (1981), and Molenaar and others (1981) have reported on many stratigraphic details of the Lower Cretaceous rocks. Further comments here draw primarily on their data and address factors that may have particular significance to petroleum exploration.

The primary source for Brookian sedimentary materials, as defined by lithofacies, isopach, and paleocurrent data, was the ancestral Brooks Range and Herald arch (fig. 9.1). Deposition was in a shallow- to deep-water prograding delta system (pl. 9.2). The Torok Formation comprises the bottomset, the foreset, and the lower part of the topset sequence of the depositional system. Gas shows are common and oil shows fairly rare in the potential reservoir sandstones of this sequence. In general, both foreset and bottomset facies contain thin-bedded sandstone west of the Meade arch (pl. 9.6, sec. H-H′), where the dip of the foreset beds is low (pl. 9.2); however, the foreset beds are predominantly siltstone, and the bottomset beds contain thin-bedded sandstone east of the Meade arch (pl. 9.7), where the dip of the foreset beds is much steeper (pl. 9.2). Micropaleontologic data indicate deposition of the Torok Formation foreset-bottomset strata in neritic to bathyal depths and possibly also in abyssal depths below the calcium carbonate compensation depth (M.B. Mickey, written commun., 1984). These data are consistent with the water depth indicated by the vertical range of the suite of topset-foreset-bottomset beds. The bottomset beds are turbidites and can be expected to have the morphology characteristic of turbidite sandstones in an outer-fan setting. The most distal turbidites are starved-basin deposits that appear to merge tangentially with the top of the pebble shale unit and to include the topmost beds of Barremian to Albian age.

West of the Meade arch, foreset beds have low dips (1°-2°) but represent relatively high-energy depositional conditions; they have high proportions of sand and contain numerous gas shows in the Tunalik No. 1 well. By contrast, in the Inigok No. 1 well east of the Meade arch foreset beds are steeper but poor in sand (pl. 9.2; pl. 9.6, sec. H-H′; pl. 9.7). Similar progradational delta-facies relations were described by Sangree and Widmier (1977). The productivity of the sands in the Tunalik No. 1 well is untested. These Torok Formation sandstones penetrated in the NPRA wells are fine to very fine grained and thin bedded (Molenaar, 1981). A high-pressure, low-volume Torok foreset sandstone bed was tested in the Seabee No. 1 well. The gas sand at 1,600 m (5,300 ft) in the Seabee well occurs in a strongly folded and faulted (detached) anticline, whereas the gas sands in the Tunalik well are assumed to be stratigraphically trapped in an area of low structural relief and could have a fairly large areal extent.

The Torok Formation bottomset sandstones are present throughout the Arctic platform and may offer potential for petroleum reservoirs, although their porosity and permeability are usually low. Potential traps include sandstones truncated at the margin of the Simpson Canyon, as in the Simpson oil field, and sandstones truncated by a submarine paleolandslide on the northeast flank of the Fish Creek platform (Molenaar, 1981). Detailed mapping could possibly define an area of oil and gas potential where entrapment was caused by faulting that resulted from the landslide.

The Nanushuk Group forms the topset bed sequence of the delta system. The stratigraphic sequence is regressive and contains progressively more sandstone and coal-bearing beds in the upper part of the group. In the lower marine beds of the group in the eastern part of the NPRA, potential sand reservoirs are thick and have fair porosity and permeability because of the winnowing action of nearshore marine currents (Payne and others, 1952). T.G. Payne (written commun., 1984) and Bird and Andrews (1979) believed that the best reservoir conditions in the Nanushuk sandstones are in a ''fairway'' trending north-northwest between Umiat and Simpson. The Umiat (Collins, 1958a), Fish Creek (Robinson and Collins, 1959), and Simpson (Robinson, 1959a, 1964) oil accumulations are located in this fairway. Stratigraphic traps in the fairway might localize a large oil accumulation, but reservoir depths are fairly shallow and the oil is low gravity, as in the Fish Creek and Simpson reservoirs. The Umiat oil field is in an anticlinal trap, whereas the Fish Creek oil field, according to seismic interpretation and well-correlation studies, appears to be localized by a small listric fault. The Simpson oil accumulation is trapped by an updip seal at the east margin of the Simpson Canyon fill. The Fish Creek and Simpson accumulations appear to have leaky seals, as evidenced by the large surface oil seepages associated with these shallow oil accumulations. Stratigraphic traps such as river-channel stringer sands and offshore bar sands could localize larger accumulations without surface evidence of their presence.

STRUCTURE

For purposes of this discussion we delineate four major structural provinces in the NPRA. From north to south these are the Arctic platform, the northern foothills, the southern foothills, and the Brooks Range (pls. 9.1, 9.2). These structural subdivisions differ from physiographic subdivisions of previous authors, such as Wahrhaftig (1965) and Molenaar (1981).

ARCTIC PLATFORM

The Arctic platform is defined seismically beneath the Arctic Coastal Plain and the northern foothills (pls. 9.1, 9.2). The platform dips regionally south beneath the northern foothills and probably also dips south beneath the southern foothills at least as far as the north front of the Brooks Range. Along the trend of the Meade arch (pl. 9.2), the platform dips about 1° south to the northern limit of Cretaceous detachment folds in the northern foothills; farther south the dip increases to 4°-5°, presumably in response to the increased thickness (load) of Brookian rocks in the Colville foredeep. The dip and southward extent of the platform beneath the southern foothills province is uncertain, because the seismic data are poor in quality owing to the complex structure at shallow depths. In latitudinal profile the platform dips about 1°-2° east and west from the Meade arch (pl. 9.2). The west flank is interrupted at the level of the Franklinian basement by the half-graben structure of the Meade basin and the broad horst-block structure of the Wainwright arch. The Meade basin has no wells to indicate the presence or thickness of the Endicott Group sedimentary fill that is suspected to be present there. The basin also has not been fully delineated seismically, and so the area defined on plate 9.1 may not properly represent the extent or configuration of this basin. East of the Meade arch, the platform is interrupted by the complex horst-and-graben profile of the Ikpikpuk-Umiat basin. The faults that define the horst-and-graben structure of the platform die out upward in the lower part of the Lisburne Group and thus indicate Late Devonian(?) and (or) Early Mississippian extensional (riftlike) faulting. The Meade arch was a strong positive element from the Late Devonian to the Early Permian, as indicated by the overall time-transgressive onlap of the Endicott and Lisburne Groups. The arch stood in very low relief during Late Permian to Late Cretaceous time, as indicated by the essentially parallel contacts of the Permian to Lower Cretaceous rocks across it. Renewed uplift in post-Nanushuk time is indicated by thinning caused by erosion of the Nanushuk Group over the axis of the arch. The Wainwright arch had a tectonic history similar to that of the Meade arch until about the mid-Cretaceous; however, it was never as strongly positive and was not reactivated in the Late Cretaceous.

Two other major positive elements on the Arctic platform are the Barrow arch and the Barrow high. These features form the northern structural culmination along the northern coastline of the NPRA. It extends offshore to the northwest beneath the Chukchi Sea (Grantz and others, 1981) and southeast along the coast to Prudhoe Bay (Jones and Speers, 1976). The regional plunge and trend of the arch are interrupted by the Barrow high, a basement-controlled, east-trending, tensionally faulted anticline on the Barrow arch. Ellesmerian rocks thin northward onto the Barrow high by transgressive onlap, disconformities, and unconformities within the sequence. Basal Ellesmerian sandstone beds, which contain gas and oil accumulations in rocks of Late Triassic and Early Jurassic age, are overlapped by the pebble shale unit along the north flank of the high. It is possible that the pebble shale unit created an areally extensive seal and an accumulation of oil and gas on the Barrow arch before development of the Barrow high. As a result of further uplift, the apex of the Barrow high was disrupted to form what is known as the Avak structure. This structure is a subcircular area 10 km in diameter and about 0.75 km deep filled with complexly folded and faulted Jurassic and Lower Cretaceous rocks (pl. 9.3, sec. A-A′). The breach could have flushed out any existing gas or oil accumulation in reservoir beds in the vicinity of the Avak structure. The present south and east Barrow gas fields are Late Cretaceous to early Tertiary accumulations formed after the breach in Upper Triassic, Lower Jurassic, and Neocomian reservoirs trapped in part by anticlinal uplift of the Barrow high and in part by impermeable beds at the margin of the Avak structure. Detailed studies in this area (Rockwell, 1981b; Tetra Tech, Inc., 1982b) indicate that some additional small gas and possibly also oil accumulations may be found on the Barrow high adjacent to the south margin of the Avak structure—an area that has not been tested to date.

The Avak structure—called the Barrow disturbed zone in earlier reports—has been attributed to a meteorite impact, a volcanic gas explosion (Collins, 1961; Woolson and others, 1962), and slumping associated with canyon cutting (Rockwell, 1981b). A disruptive mechanism of major dimensions was certainly required to create the disturbed zone, uplifting Neocomian beds at least 460 m (1,500 ft) and disrupting the post- and pre-Neocomian beds in the core of the structure. Other mechanisms that have been considered are explosive disruption of a gas hydrate and free gas deposit (Kirschner, 1983) and a shale diapir. Future studies may consider these hypotheses in more detail.

Other possibly catastrophic structures on the Barrow arch are the Simpson paleocanyon (pls. 9.1, 9.2; Payne and others, 1951; Molenaar, 1981) and the Fish Creek paleolandslide (Molenaar, 1981). The Simpson paleocanyon was cut in prodelta strata of the Nanushuk Group and Torok Formation and was filled with Upper Cretaceous strata of the Colville Group. Offshore seismic data indicate that a submarine paleolandslide may have initiated and localized the headward erosion of the canyon. Beneath the Beaufort shelf, the canyon outline is generalized because of a limited amount of seismic control, and the extent of the canyon north of its outline on plate 9.1 has not been defined. One onshore well, North Simpson No. 1, of total depth 1,150 m (3,774 ft), was drilled through the canyon fill near the south edge of the canyon and penetrated 30 m (100 ft) of Pleistocene sands of the Gubik Formation, 814 m (2,671 ft) of Upper Cretaceous canyon-fill shale of the Colville Group, and 250 m (820 ft) of pre-fill shale of the Torok Formation; the well bottomed in the pebble shale unit (Robinson, 1964). Note, however, that in plate 9.2 the seismic line 6 passes north of the North Simpson well, where the canyon fill is thicker than at the well. Core-hole data in the Simpson Canyon area locally define sandy beds, steep dips, and slump structures in the base of the canyon fill overlying a homoclinal structure in strata of the Nanushuk Group and Torok Formation (Robinson 1964). S.H. Folk (written commun., 1984) has suggested that canyon-fill sandstones could trap oil; however, present data are inadequate to confirm this possibility. As previously described, the Simpson oil field is trapped at shallow levels on the east margin of the canyon in sandstone beds of the Nanushuk Group. The configuration of the sandstone beds and the canyon fill suggest that the canyon-fill shale provides an updip seal. The possibility that foreset or bottomset sandstones of the Torok Formation could trap oil or gas in a similar situation, that is, where the canyon fill produced an updip seal (Rockwell, 1981a), has not been tested by exploratory drilling.

The Fish Creek submarine paleolandslide disrupts the Neocomian pebble shale unit and the prodelta and turbidite strata in the lower part of the Torok Formation. Prodelta strata in the upper part of the Torok Formation prograde across the landslide. Seismic lines across the area of the landslide show a distinctive complex of diffractions. Tetra Tech, Inc. (1982b), interpreted the diffractions as having originated from sandstone bodies in a gas-charged turbidite channel. This interpretation may explain some of the diffractions. However, our studies have shown listric faults with associated rollover anticlines, confirmed by dipmeter data and cut-out stratigraphic intervals. These features are best interpreted as having resulted from a submarine landslide.

The Walakpa gas field on the southwest flank of the Barrow high has a stratigraphic and structural setting similar to that of the Kuparuk River oil field. Both accumulations are combination structural and stratigraphic traps in petroliferous sandstones overlapped by the pebble shale unit. The size of the Walakpa field and its well productivity have not been defined, but the accumulation is judged to be a viable source of gas for the local area (Gruy, 1981).

East of Simpson Canyon, near the northeastern coastline of the NPRA, the Barrow arch is a broad east- to southeast-trending offshore structure. The limited seismic data suggest that its structural and stratigraphic setting is analagous to that of the Prudhoe Bay anticline. Carter and others (1977) and T.G. Payne (oral commun., 1984) speculated that the oil shows and residual oil saturation in Ellesmerian strata in the J.W. Dalton No. 1 well may have resulted from a tilt of the oil column after accumulation and could be indicative of a present offshore accumulation.

In addition to the structural features along the Barrow arch, three other positive elements have been defined within the Arctic platform: the Fish Creek platform, the Oumalik platform, and the Utukok platform (pl. 9.1). All are caused by thinning as a result of nondeposition of part of the early Ellesmerian section over basement horst blocks. Ellesmerian and early Brookian reservoirs may be present on these structures.

The Fish Creek platform trends southeast, in echelon arrangement to the Kuparuk and Prudhoe Bay oil-field structures. Franklinian basement on the platform is intruded by a granitic body at the Teshekpuk No. 1 well (Bird and others, 1978). Basal Ellesmerian clastic rocks of the Endicott Group are missing on the crest of the platform because of onlap, erosion predating deposition of the Lisburne Group, or an Endicott-Lisburne facies change. Like the Barrow arch, the Fish Creek platform was a positive element during the early tectonic history of the Arctic platform. However, closure may have developed later (Cretaceous?), or the Lisburne Group may have lacked adequate reservoir beds, because no significant oil or gas accumulation was found in the Teshekpuk No. 1 well.

The Oumalik and Utukok platforms have east to northeast trends. The subparallel structure of these platforms and their spatial relation to the south-southwest trend of the Meade and Wainwright arches implies that they have a common origin. Ellesmerian and early Brookian reservoirs may be present on these platforms at depths in the ranges of 2,745-4,880 m (9,000-16,000 ft) on the Oumalik platform and 4,270-7,930 m (14,000-26,000 ft) on the Utukok platform. Early Brookian (lower part of the Torok Formation) sandstones, however, are thin and tight in the Oumalik No. 1 well, and Ellesmerian reservoirs may now be at depths below the optimum range of oil preservation, judging from Magoon and Claypool's (1981) study of the Inigok No. 1 well. However, the platforms are basement-controlled structures, and hydrocarbon accumulations there could have a large areal extent. Further study and evaluation of possible lower Ellesmerian reservoirs on these structures is warranted.

NORTHERN FOOTHILLS

The northern foothills province is underlain by a broad axelike wedge of Brookian strata, incorporating a pattern of detachment folds like a wrinkled carpet, that overlies the nearly planar, south-dipping homoclinal sequence of Ellesmerian formations of the Arctic platform province. The province is about 95 km (60 mi) wide and 385 km (240 mi) long within the NPRA and extends westward beneath the Chukchi Sea and eastward beneath the eastern North Slope (Grantz and May, 1983). Individual detachment folds trend east-west, but their axial traces are sinuous and commonly divergent. No geometric correlation seems to exist between the Franklinian basement horst-and-graben structures and the trend of the detachment folds. The structural relief and complexity in the folds generally, but not universally, increase southward. Detachment is in shales of the middle and upper parts of the Torok Formation, and it probably includes several anastamosing detachment planes in the south that die out progressively northward (pl. 9.2). The anticlines are fairly long, narrow, and asymmetric with the steep flank on the north. Their cores consist of Torok shale that is more complexly folded and faulted than the overlying more competent sandstone beds of the Nanushuk Group. Shortening of the Brookian section by folding and minor faulting is calculated to be approximately 11 km (7 mi) or 10 percent within the northern foothills province.

Potential reservoirs in sandstones of the Nanushuk Group and Torok Formation are present on many of the detachment anticlines. The Nanushuk Group reservoirs are generally at depths of less than 1,200 m (4,000 ft), as for example in the Oumalik No. 1 and Meade No. 1 wells (pl. 9.2). Potential Torok Formation reservoirs in thin foreset and bottomset sandstone beds are at greater depths, but these beds are generally complexly deformed by the detachment faulting. Examples are the Seabee No. 1 and Awuna No. 1 wells (pl. 9.2). Individual petroleum accumulations in the detachment folds are expected to be areally and volumetrically too small to be economically viable in an Arctic setting. Ten of these structures have been drilled, and most wells have gas and oil shows. The Umiat oil field, an anticlinal trap, has been partly delineated. Estimates of recoverable reserves range from 2 million to 122 million barrels, depending upon the recovery factors chosen (Brosgé and Whittington, 1966). The Seabee No. 1 well, also on the Umiat anticline, tested an 18-m-thick (60-ft) sandstone in the Torok Formation at 1,646 m (5,400 ft). Calculations indicate that the sand has 14 percent porosity, 58 percent water saturation, and open-flow potential of 400,000 m^3/d (14 million ft^3/d) of gas and about 8.5 million m^3 (300 million ft^3) of gas in place (H.J. Gruy and Associates, Inc., written commun., 1984). These results are probably indicative of the gas potential of similar sandstones of the Torok Formation at that depth. Numerous formation tests were made at depths less than 1,200 m (4,000 ft) in the older U.S. Navy wells at Titaluk and Knifeblade (Robinson, 1959b), Oumalik (Robinson, 1956), Meade and Kaolak (Collins, 1958c), Square Lake and Wolf Creek (Collins, 1959) and Umiat (Collins, 1958a). Some of the tests produced moderate gas flows, but no commercial productive capability or reservoir capacity was established. Reed (1958, p. 170-171) summarized the results of the oil and gas tests made during exploration by the U.S. Navy in the years 1944 through 1953. Although it can be assumed that newer drilling and testing techniques would produce more definitive results than those obtained in the older wells, the structural and stratigraphic conditions encountered in exploration to date make it difficult to anticipate commercial deposits in these rocks and structures.

The common boundary of the northern and the southern foothills is the Carbon Creek fault(?) zone. Several lines of evidence indicate the presence of a fault zone or an echelon series of faults at this boundary. No one line of evidence is definitive, but cumulatively the evidence is substantial. It includes the anomalous southeast bend in the Carbon anticline southwest of the Wainwright arch, the apparent western termination of west-trending anticlines in the southwestern area of the northern foothills province west of the Wainwright arch, and the transition from relatively simple detachment-fold structure north of the Carbon Creek fault(?) zone to more complex detachment structure south of it (pl. 9.2). Gravity data also support the existence of this fault zone (fig. 9.3; Brosgé and others, chapter 14). The fault zone could have been initially activated during the riftlike block faulting of the Arctic platform around Late Devonian time. If strike-slip movement on the postulated fault zone was responsible for the southeast bend of the Carbon anticline, movement could have continued episodically until, or been reactivated during, the Late Cretaceous. A large triangular positive gravity anomaly occupies the southwestern corner of the NPRA (fig. 9.3). The anomaly extends northwestward beneath the Chukchi Sea (Barnes, 1977). We suggest that this anomaly may represent a rifted fragment of the Arctic platform which was displaced relatively westward by oblique right-lateral extension across the Carbon Creek fault(?) zone. Such extension could have localized the position of the Colville foredeep.

SOUTHERN FOOTHILLS

The southern foothills province is defined as the area between the Carbon Creek fault(?) zone on the north and the Brooks Range province on the south (pl. 9.1). The province is as much as 112 km (70 mi) wide at the western boundary of the NPRA, where the Carbon Creek fault(?) zone arcs to the northwest and the Brooks Range thrust front arcs to the southwest, but narrows rapidly eastward to about 40 km (25 mi) at the northernmost salient of the Brooks Range thrust belt.

Different structural patterns characterize two subdivisions of the province. North of the Driftwood anticline and the Colville River, broad, ridge-forming, bathtub-shaped synclines are separated by long, narrow, diapiric anticlines in what Stille (1917; see also Goguel, 1962, p. 131) called the ejectif style (that is, where synclinal elements dominate), indicating deep erosion of a concentrically folded structural province. The sinuous traces of the anticlines suggest some mobility after folding; possibly the more competent synclines tended to float on their shale substrate in response to later deformation and development of the Chukchi syntaxis (Tailleur and Brosgé, 1970). Basal detachment probably occurs in the lower part of the Fortress Mountain and Torok Formations above relatively undisturbed Ellesmerian beds near the southern margin of the underlying Arctic platform (pl. 9.2). Chapman and Sable (1960) gave additional details based on field studies.

South of the Driftwood anticline and the Colville River, the structural style involves very complex bed crenulation, isoclinal folding, and thrust faulting. Structural symbols on plate 9.1 indicate the trend and general complexity of structural development, but they are only representative; the complexity is too great to be shown at the map scale of plate 9.1. The intensity of deformation in this area is presumed to be related to compression at the northern front of the Brooks Range thrust belt. The highly complex structure tends to be subparallel to the Brooks Range front but may also plunge beneath the bathtub-shaped synclines on the west in the Chukchi syntaxis and thus be indicative of complex structures within Brookian rocks at depth. Additional structural and stratigraphic details based on field studies were given by Sable and Mangus (1950a, b), Tailleur and Kent (1950), and Tailleur and others (1966).

Brookian reservoir beds in the subsurface of the southern foothills province might include thin Neocomian quartzose sandstone beds (Tingmerkpuk Member of the Ipewik Formation of Crane and Wiggins, 1976) and Lower Cretaceous graywacke sandstone beds in the Okpikruak and Fortress Mountain Formations (Carter and others, 1977). These beds are strongly folded, thrust faulted, and have undergone "dynamic eometamorphism" (Carter and others, 1977, p.

54). Source beds may be postmature. Because of these conditions, the Brookian hydrocarbon potential in the southern foothills is considered to be virtually nil. Potential in Ellesmerian reservoirs in the southern foothills analogous to that in the frontal thrust folds that are productive at Turner Valley in Alberta (Bally and others, 1966, pl. 5) or at the Painter Creek Reservoir in Wyoming (Lamb, 1980) was suggested by Tetra Tech, Inc. (1982a). We believe that this analogy may be misleading. Although the presence of Neocomian rocks that crop out at the Brady anticline (pl. 9.1; Mayfield and others, chapter 8) can be interpreted as indicating earlier Ellesmerian rocks at shallow to intermediate depths in the subsurface, there is little or no evidence in our seismic data for continuous high-velocity reflectors or aligned diffractions in the Ellesmerian carbonate rocks beneath the foothills comparable to those in the Rocky Mountain thrust belt (pls. 9.2, 9.3). Additionally, there is evidence that the Ellesmerian sequence lies beneath the thrust faults in the southern foothills and that detachment is within the overlying Brookian sequence.

Seismic surveys find coherent reflections in the Mississippian carbonate rocks in the Turner Valley area (Bally and others, 1966). Similarly, coherent reflections are also obtained in the Wyoming thrust belt (Petroleum Information Corp., 1981). The data are complex but can be interpreted and mapped. By comparison, the seismic-reflection data shot in 1977, 1978, and 1979 in the southern foothills north of the Lisburne Ridge area of the southern NPRA have much less coherence. The present surface and seismic data indicate a stronger degree of deformation in the Brooks Range and southern foothills provinces than in the Rocky Mountains province. If this is correct, overthrust-belt traps of Turner Valley type may be missing or very deep in the NPRA. We consider this interpretation to be tentative because more sophisticated seismic recording and processing techniques might improve the seismic data and well control is absent. If better seismic data could define frontal thrust folds similar to those in the Rocky Mountain thrust belt within reasonable drill depths, they could constitute viable exploration prospects. However, petroleum accumulations would probably be postmature and gas prone.

BROOKS RANGE

The southern margin of the NPRA includes a small segment of the northwest edge of the Brooks Range province. The province is characterized by imbricately stacked and folded thrust sheets, mainly in Ellesmerian rocks, that represent multiple deformational episodes (Brosgé and Tailleur, 1971; Mull and others, 1982). Ellersieck and others (1978) suggested that the thrust sequences have been involved in very large scale tectonic transport. Crustal shortening is thought to exceed 250 km (155 mi) and could be as much as 600 km (370 mi). Locally, in the Brooks Range and also in the southern foothills, broad, gently folded synclines developed in the Fortress Mountain Formation rest unconformably on complexly deformed strata of the lower part of the Torok and Okpikruak Formations (Tailleur and Kent, 1950, pl. 2), indicating that folding and thrusting must be at least earliest Cretaceous in age.

Form-line maps and structural interpretations of the Brooks Range province by Tetra Tech, Inc. (1982a), define a complex thrust-fold pattern of small structures that lack continuity in trend and indicate severe structural complications. Ellesmerian reservoirs in the province were tested in the Lisburne No. 1 well, where five thrust sheets are believed to have been penetrated (I.L. Tailleur and K.J. Bird, oral communs., 1984). The rocks are mainly postmature but probably gas prone (Carter and others, 1977; L.B. Magoon, oral commun., 1984).

The analogy between the Brooks Range and the Rocky Mountain thrust belt can be further examined in connection with vertical stacking above basement and horizontal tectonic transport. Vertical uplift by thrust stacking of Ellesmerian Paleozoic carbonate rocks at Mount Head in the Canadian Rockies thrust belt approximates 6,000 m (20,000 ft) (Bally and others, 1966, pl. 5). By comparison, vertical uplift of Ellesmerian Paleozoic carbonate strata at Lisburne Ridge is inferred to be at least 10,700 m (35,000 ft) and possibly more (pl. 9.2). Bally and others (1966) suggested that crustal shortening by detachment on decollement zones in the Rocky Mountain thrust belt is approximately 160 km (100 mi). Ellersieck and others (1978), as noted above, believed that crustal shortening in the Brooks Range is at least 250 km (155 mi) and may be as much as 600 km (370 mi). These comparisons indicate that both vertical uplift and subhorizontal tectonic transport of Ellesmerian beds in the western Brooks Range may be at least twice as large as in the Canadian Rockies west of Turner Valley. Such severe structural deformation does not favor significant oil or gas accumulations in this province.

SUMMARY OF OIL AND GAS POTENTIAL

ARCTIC PLATFORM

The Barrow gas fields are in structural traps at the crest of the Barrow high on the east and west margins of the Avak structure. The reservoir beds are thin sandstones of both Neocomian and Early Jurassic to Late Triassic ages. The primary potential is for additional gas production on the south margin of the Avak structure.

The Simpson oil field is in a truncation trap on the eastern, downdip margin of the Simpson paleocanyon. The reservoir beds are shallow, east-dipping sandstones of the Nanushuk Group. The field is partially delineated and is estimated to contain about 12 million barrels of recoverable 19° API gravity oil (Reed, 1958 p. 170) A leaky seal at the canyon margin accounts for the Simpson seeps. The possibility of a similar entrapment of oil in deeper foreset and bottomset (turbidite) sandstone reservoir beds of the Torok Formation has not been tested. We believe a similar potential may also be present adjacent to the Fish Creek paleolandslide area northwest of the Fish Creek platform. Reservoir sandstones of the lower part of the Torok could be terminated here by landslide faulting and covered by prodelta shale of the upper part of the Torok.

The Fish Creek, Oumalik, Utukok, and Umiat platforms are large basement-controlled structures. Only the Fish Creek platform has been tested, by the Teshekpuk well. In that well, Ellesmerian reservoir beds are tight, but oil migration could have occurred before the development of a structural closure. The Oumalik, Utukok, and Umiat platforms have not been tested. They have the potential for large accumulations in deep to very deep strata, but present data (Magoon and Claypool, 1981) suggest that the source beds may now be postmature and primarily gas prone. Regional stratigraphic trends also suggest that reservoir beds may not be present.

The Fish Creek oil accumulation is interpreted as having been trapped by a small listric fault updip to the west of the Fish Creek No. 1 test well. Reservoir beds are in shallow silty sandstone of the Nanushuk Group. The extent of the oil accumulation has not been defined, and the potential for additional similar traps is not known. Oil shows are also present in Nanushuk sandstone in other wells in this area, and oil and gas shows are common in sandstone of the Torok Formation, primarily in the eastward-prograding bottomset strata at deeper horizons. The oil may be indigenous to the interbedded Cretaceous shale strata. The numerous oil shows, the fault trap accumulation in the Fish Creek well, and the possibility for barsand and channel-sand reservoirs indicate a potential for oil accumulations in this area.

The Walakpa gas field is interpreted as being in a combination structural and stratigraphic trap, somewhat like that of the Kuparuk oil field, wherein the reservoir seal results from overlap of the Neocomian pebble shale unit. Significant gas shows were also encountered in Neocomian sandstone beneath the pebble shale unit in the Tunalik No. 1 well. The underlying Kingak Shale is a deep-water(?) prodelta deposit, and the overlying prodelta strata of the Torok Formation are even deeper water, turbidite deposits. The pebble shale unit is a highly organic starved-basin shale that we suspect could also have been deposited in fairly deep water. The data suggest that the Jurassic and Neocomian sandstone reservoirs (in the Kingak Shale) represent turbidite channel and suprafan deposits. This reservoir constitutes one of the most attractive prospects on the platform, but it will require detailed seismic interpretation to define, and it may be gas rather than oil prone.

The Peard and Kugrua wells tested the concept of a stratigraphic or combination structural and stratigraphic trap with the wedge edge of the Lisburne Group as the reservoir target. No significant oil or gas shows were encountered. The concept could also apply to potential stratigraphic or combination traps in the wedge edges of the Endicott Group and the Sadlerochit Group. The absence of significant oil or gas shows in numerous wells that have penetrated Ellesmerian transgressive sandstone led us to seek a basic reason for the failure. It may be that, because the early and middle Ellesmerian strata are time transgressive northward on the Arctic platform, their strandline sandstone facies marched progressively updip, allowing updip migration of any generated hydrocarbons. Under such conditions, entrapment of a significant volume of hydrocarbons is unlikely except when these beds are overlain by an overlapping shale seal, such as the Neocomian pebble shale unit. The potential for this type of play is therefore considered poor.

NORTHERN FOOTHILLS

The northern foothills province is primarily a structural-trap province within the context of this discussion. Primary reservoirs are in the sandstones of the Nanushuk Group; secondary reservoirs are in the foreset and bottomset beds of the Torok Formation. In general the latter beds are sand poor. West of the Meade arch, well data indicate that the sand-shale ratio is somewhat higher in the prodelta foreset beds and lower in the turbidite bottomset beds than east of the Meade arch (pls. 9.6, 9.7). The somewhat higher sand-shale ratio in the foreset beds west of the Meade arch may be related to the lower dips in those foreset beds (higher energy), whereas the lower sand-shale ratio east of the arch is related to the steeper dips in those foreset beds (lower energy), where the sands flowed down the foreset slope to accumulate as turbidite bottomset beds (pl. 9.2). Northern foothills structures have been tested by numerous wells, leading to the discovery of the noncommercial Umiat oil field and numerous oil and gas shows. However, no commercial oil or gas accumulation has been defined. The potential is limited by the combination of moderate to strong or complex structures and low porosity and permeability in relatively thin sandstone reservoirs at depth. The potential for several small oil and gas fields is fair to good, but the potential for a single large commercial reservoir is poor.

SOUTHERN FOOTHILLS

The southern foothills province has such complex structure in the Brookian rocks that large oil or gas accumulations are precluded. Additionally, potential reservoirs in Brookian sandstone are diagenetically altered and lack porosity and permeability. Since there are no wells in the province, evaluation of its potential relies on field observations and seismic data. The potential in the province centers on the concept that, as in the Rocky Mountain thrust belt, frontal thrust folds in Ellesmerian reservoirs are present within reasonable drill depths. Our seismic data do not define such thrust folds. If they are present, we expect any petroleum accumulation would be postmature and gas rather than oil prone.

BROOKS RANGE

The Brooks Range province includes multiple thrust sheets and folded thrust sheets of diverse lithology that are interpreted by others to have been juxtaposed or stacked by long-distance tectonic transport. Reservoirs would be in Ellesmerian clastic and carbonate strata. The only well drilled in this province, the Lisburne No. 1, is believed to have encountered five thrust sheets. Geochemical data indicate that the strata are postmature and probably gas prone. Seismic interpretation indicates that the structure is highly complex and does not delineate major structures or structural trends. We conclude from these data that the potential for commercial hydrocarbons is limited to small gas-prone reservoirs.

An overall assessment of the oil and gas potential of the NPRA on the basis of past exploration indicates that an easily defined giant oil or gas prospect may not be present. However, the reserve has only been partly explored, and evaluations may change in the light of new concepts. Detailed seismic stratigraphy will probably play a major role in defining any new prospects.

SELECTED BIBLIOGRAPHY

Alaska Geological Society, 1971, West to east stratigraphic correlation section, Point Barrow to Ignek Valley, Arctic North Slope, Alaska: Anchorage, Alaska Geological Society.

——— 1972, Northwest to southeast stratigraphic correlation section, Prudhoe Bay to Ignek Valley, Arctic North Slope, Alaska: Anchorage, Alaska Geological Society.

——— 1977, North to south stratigraphic correlation section, Beaufort Sea—Prudhoe Bay—Nora No. 1, Arctic Slope, Alaska: Anchorage, Alaska Geological Society.

ARCO Alaska, Inc., 1981, Kuparuk River field, North Slope, Alaska-field rules testimony before the Alaska Oil and Gas Conservation Commission: Anchorage, Alaska, Petroleum Institute Corp., 45 p., 20 exhibits.

Armstrong, A.K., and Bird, K.J., 1976, Facies and environments of deposition of carboniferous rocks, Arctic Alaska, *in* Miller, T.P., ed., Recent and ancient sedimentary environments in Alaska: Anchorage, Alaska Geological Society, p. A1-A16.

Bally, A.W., Gordy, P.L., and Stewart, G.A., 1966, Structure, seismic data, and orogenic evolution of southern Canadian Rocky Mountains: Bulletin of Canadian Petroleum Geology, v. 14, no. 3, p. 337-381.

Barnes, D.F., 1977, Bouguer gravity map of Alaska: U.S. Geological Survey Open-File Report 76-70, scale 1:2,500,000.

Berg, O.R., 1982, Seismic detection and evaluation of delta and turbidite sequences; their application to the exploration for the subtle trap, *in* Halbouty, M.T., ed., The deliberate search for the subtle trap: American Association of Petroleum Geologists Memoir 32, p. 57-75.

Bird, K.J., 1982, Rock-unit reports of 228 wells drilled on the North Slope, Alaska: U.S. Geological Survey Open-File Report 82-278, 106 p.

Bird, K.J., and Andrews, J.K., 1979, Subsurface studies of the Nanushuk Group, North Slope, Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 32-41.

Bird, K.J., Conner, C.L., Tailleur, I.L., Silberman, M.L., and Christie, J.L., 1978, Granite on the Barrow Arch, northeast NPRA, *in* Johnson, K.M., ed., The United States Geological Survey in Alaska; accomplishments during 1977: U.S. Geological Survey Circular 772-B, p. B24-B25.

Bird, K.J., and Jordon, C.F., 1977, Lisburne Group (Mississippian and Pennsylvanian), potential major hydrocarbon objective of Arctic Slope, Alaska: American Association of Petroleum Geologists Bulletin, v. 61, no. 9, p. 1493-1512.

Blanchard, D.C., and Tailleur, I.L., 1983, Pebble Shale (Early Cretaceous) depositional environments in National Petroleum Reserve in Alaska (NPRA) [abs.]: American Association of Petroleum Geologists Bulletin, v. 67, no. 3, p. 424-425.

Bouma, A.H., and Brouwer, Aart, eds., 1964, Turbidites: Amsterdam, Elsevier, 264 p.

Brosgé, W.P., and Tailleur, I.L., 1971, Northern Alaska petroleum province, *in* Cram, I.H., ed., Future petroleum provinces of the United States; their geology and potential: American Association of Petroleum Geologists Memoir 15, p. 68-99.

Brosgé, W.P., and Whittington, C.L., 1966, Geology of the Umiat—Maybe Creek region, Alaska: U.S. Geological Survey Professional Paper 303-H, p. 501-638.

Carman, G.J., and Hardwick, Peter, 1982, Geology and regional setting of the Kuparuk oil field, Alaska: Oil and Gas Journal, November 22, p. 153-158.

Carter, Claire, and Laufield, Sven, 1975, Ordovician and Silurian fossils in well cores from North Slope of Alaska: American

Association of Petroleum Geologists Bulletin, v. 59, no. 3, p. 457-464.

Carter, R.D., Mull, C.G., Bird, K.J., and Powers, R.B., 1977, The petroleum geology and hydrocarbon potential of Naval Petroleum Reserve No. 4, North Slope, Alaska: U.S. Geological Survey Open-File Report 77-475, 57 p.

Chapman, R.M., and Sable, E.G., 1960, Geology of the Utukok-Corwin region, northwestern Alaska: U.S. Geological Survey Professional Paper 303-C, p. 47-167.

Collins, F.R., 1958a, Test wells, Umiat area, Alaska: U.S. Geological Survey Professional Paper 305-B, p. 71-206.

——— 1958b, Test wells, Topagoruk area, Alaska: U.S. Geological Survey Professional Paper 305-D, p. 265-316.

——— 1958c, Test wells, Meade and Kaolak areas, Alaska: U.S. Geological Survey Professional Paper 305-F, p. 341-376.

——— 1959, Test wells, Square Lake and Wolf Creek areas, Alaska: U.S. Geological Survey Professional Paper 305-H, p. 423-484.

——— 1961, Core tests and test wells, Barrow area, Alaska: U.S. Geological Survey Professional Paper 305-K, p. 569-644.

Collins, F.R., and Robinson, F.M., 1967, Subsurface stratigraphic, structural and economic geology, northern Alaska: U.S. Geological Survey open-file report, 250 p.

Crane, R.C., and Wiggins, V.D., 1976, Ipewik Formation—Significance of Jurassic-Neocomian map unit, Brooks Range [abs.]: American Association of Petroleum Geologists Bulletin, v. 60, no. 12, p. 2177.

Crowell, J.C., 1957, Origin of pebbly mudstones: Geological Society of America Bulletin, v. 68, p. 993-1009.

Detterman, R.L., Reiser, H.N., Brosgé, W.P., and Dutro, J.T., Jr., 1975, Post-Carboniferous stratigraphy, northeastern Alaska: U.S. Geological Survey Professional Paper 886, 46 p.

Dietrich, R.V., Dutro, J.T., Jr., and Foose, R.M., 1982, AGI data sheets; for geology in the field, laboratory, and office: Falls Church, Virginia, American Geological Institute.

Ellersieck, Inyo, Mayfield, C.F., Tailleur, I.L., and Curtis, S.M., 1978, Thrust sequences in the Misheguk Mountain quadrangle, Brooks Range, Alaska, *in* Johnson, K.M., and Williams, J.R., eds., The United States Geological Survey in Alaska; accomplishments during 1978: U.S. Geological Survey Circular 804-B, p. B8.

Franz, U.A., Daly, A.R., and Brown, S.W., 1983, Organic facies of some Mesozoic source rocks on Alaskan North Slope [abs.]: American Association of Petroleum Geologists Bulletin, v. 67, no. 3, p. 463-464.

Galloway, W.E., and Brown, L.F., Jr., 1973, Depositional systems and shelf-slope relations on cratonic basin margin, uppermost Pennsylvanian of north-central Texas: American Association of Petroleum Geologists Bulletin, v. 57, p. 1185-1218.

Goguel, Jean, 1962, Tectonics [translated from the French edition of 1952 by Hans E. Thalmann]: San Francisco, Freeman and Co., 384 p.

Grantz, Arthur, Eittreim, Steve, and Dinter, D.A., 1979, Geology and tectonic development of the continental margin north of Alaska: Tectonophysics, v. 59, p. 263-291.

Grantz, Arthur, Eittreim, Steve, and Whitney, O.T., 1981, Geology and physiography of the continental margin north of Alaska and implications for origin of the Canada Basin, *in* Nairn, A.E.M., Churkin, Michael, Jr., and Stehli, F.G., eds., The ocean basins and margins, v. 5: New York, Plenum Press, p. 439-492.

Grantz, Arthur, and May, Steven, 1983, Rifting history and structural development of the continental margin north of Alaska, *in* Watkins, J.S., and Drake, C.L., eds., Studies in continental marine geology: American Association of Petroleum Geologists Memoir 34, p. 77-100.

Gruy Management Service Company, 1981, Preliminary conclusions of Walakpa Test Well No. 2: Dallas, Texas, Gruy Management Service Co, 3 p.

Haga, Hideyo, and Mickey, M.B., 1983a, South Barrow area, Neocomian biostratigraphy: *prepared under contract to* U.S. Geological Survey, v. 1, 12 p., v. 2, 36 p. [Available from National Oceanographic and Atmospheric Administration (E.D.S.), Mail Code D621, Boulder, Colorado 80303]

——— 1983b, Jurassic-Neocomian seismic stratigraphy, NPRA: Biostratigraphics, v. 1 and 2, 133 p. [Available from National Oceanographic and Atmospheric Administration (E.D.S.), Mail Code D621, Boulder, Colorado 80303]

Jamieson, H.C., Brockett, L.D., and McIntosh, R.A., 1980, Prudhoe Bay; a ten-year perspective, *in* Halbouty, M.T., ed., Giant oil and gas fields of the decade 1968-1978: American Association of Petroleum Geologists Memoir 30, p. 289-314.

Jones, H.P., and Speers, R.G., 1976, Permo-Triassic reservoirs of Prudhoe Bay Field, North Slope, Alaska, *in* Brownstein, Jules, ed., North American oil and gas fields: American Association of Petroleum Geologists Memoir 24, p. 23-50.

Kirschner, C.E., 1983, The Arctic platform in the National Petroleum Reserve in Alaska; deposition, deformation, and petroleum potential [abs.]: U.S. Geological Survey Circular 911, p. 24-27.

Lamb, C.F., 1980, Painter Reservoir Field; giant in Wyoming thrust belt: American Association of Petroleum Geologists Bulletin, v. 64, no. 5, p. 638-644.

Lathram, E.H., 1965, Preliminary geologic map of northern Alaska: U.S. Geological Survey open-file report, 2 sheets, scale 1:1,000,000.

Lerand, Monti, 1973, Beaufort Sea, *in* McCrossan, R.G., ed., The future petroleum provinces of Canada; their geology and potential: Canadian Society of Petroleum Geologists Memoir 1, p. 315-386.

Magoon, L.B., and Claypool, G.E., 1981, Petroleum geochemistry of the North Slope of Alaska—time and degree of thermal maturity, *in* Bjoroy, Malvin, and others, eds., Advances in organic geochemistry 1981; proceedings of the 10th international meeting on organic geochemistry, Bergen, Norway, September 1981: New York, Wiley, p. 28-38.

Mayfield, C.F., Tailleur, I.L., Mull, C.G., and Sable, E.G., 1978, Bedrock U.S. Geological Survey Open-File Report 78-70-B, 2 sheets, scale 1:500,000.

McIver, R.D., 1982, Role of naturally occurring gas hydrates in sediment transport: American Association of Petroleum Geologists Bulletin, v. 66, no. 6, p. 789-792.

Mickey, M.B., and Haga, Hideyo, 1987, Jurassic-Neocomian biostratigraphy, North Slope, Alaska, *in* Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Calif., Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 397-404.

Mitchum, R.M., Jr., Vail, P.R., and Sangree, J.B., 1977, Seismic stratigraphy and global changes of sea level, part 6. Stratigraphic interpretation of seismic reflection patterns in depositional sequences, *in* Payton, C.E., Seismic stratigraphy; applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26., p. 117-133.

Morgridge, D.L., and Smith, W.B., 1972, Geology and discovery of Prudhoe Bay field, eastern Arctic slope, Alaska, *in* King, R.E., ed., Stratigraphic oil and gas fields; classification, exploration methods, and case histories: American Association of Petroleum Geologists Memoir 16, p. 489-501.

Molenaar, C.M., 1981, Depositional history and seismic stratigraphy of Lower Cretaceous rocks, National Petroleum Reserve in Alaska and adjacent areas: U.S. Geological Survey Open-File Report 81-1084, 42 p.

Molenaar, C.M., Egbert, R.M., and Krystinik, L.F., 1981, Depositional facies, petrography, and reservoir potential of the Fortress Mountain Formation (Lower Cretaceous), central North Slope, Alaska: U.S. Geological Survey Open-File Report 81-967, 35 p.

Mull, C.G., Roeder, D.H., Pessel, G.H., Grantz, Arthur, and May, Steven, 1982, Geologic sections and maps across Brooks Range and Arctic Slope to Beaufort Sea, Alaska: Geological Society of America Map and Chart Series MC-28, 2 sheets.

Mutti, Emiliano, 1974, Examples of ancient deep-sea fan deposits from circum-Mediterranean geosynclines, *in* Dott, R.H., and Shaver, R.H., eds., Modern and ancient geosynclinal sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 19, p. 92-105.

Mutti, Emiliano, and Ricci-Lucchi, Franco, 1972, Turbidites of the northern Apennines; introduction to facies analysis: International Geology Review, v. 20, no. 2, p. 127-160.

Nilsen, T.H., 1980a, Modern and ancient submarine fans; discussion of papers by R.G. Walker and W.R. Normark: American Association of Petroleum Geologists Bulletin, v. 64, no. 7, p. 1094-1101.

—— 1980b, Geometry and dispersal patterns of deep-sea fans from various tectonic settings [abs.]: American Association of Petroleum Geologists Bulletin, v. 64, no. 5, p. 758.

Normark, W.R., 1978, Fan valleys, channels and depositional lobes of modern submarine fans; characters for recognition of sandy turbidite environments: American Association of Petroleum Geologists Bulletin, v. 62, no. 6, p. 912-931.

Paris, C.E., 1981, Petrography, lithofacies and depositional setting of the Kuparuk River Formation, North Slope, Alaska: Fairbanks, University of Alaska, M.S. thesis, 95 p.

Payne, T.G. and others, 1951, Geology of the Arctic slope of Alaska: U.S. Geological Survey Oil and Gas Investigations Map OM-126, 3 sheets, scale 1:1,000,000.

Petroleum Information Corp., 1981, The overthrust belt-1981, a complete review of oil and gas exploration on the Cordilleran thrust belt from Canada to Mexico: Denver, Colorado, Petroleum Information Corporation, 251 p.

Reed, J.C., 1958, Exploration of Naval Petroleum Reserve No. 4 and adjacent areas, northern Alaska, 1944-53, pt. 1, History of the exploration: U.S. Geological Survey Professional Paper 301, 192 p.

Rickwood, F.K., 1970, The Prudhoe Bay field, *in* Adkison, W.L., and Brosge, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska: Los Angeles, American Association of Petroleum Geologists, Pacific Section, p. L1-L11.

Robinson, F.M., 1956, Core tests and test wells, Oumalik area, Alaska: U.S. Geological Survey Professional Paper 305-A, p. 1-70.

—— 1959a, Test wells, Simpson area, Alaska: U.S. Geological Survey Professional Paper 305-J, p. 523-568.

—— 1959b, Test wells, Titaluk and Knifeblade areas, Alaska: U.S. Geological Survey Professional Paper 305-G, p. 377-422.

—— 1964, Core tests, Simpson area, Alaska: U.S. Geological Survey Professional Paper 305-L, p. 645-730.

Robinson, F.M., and Collins, F.R., 1959, Core test, Sentinel Hill area and test well, Fish Creek area, Alaska: U.S. Geological Survey Professional Paper 305-I, p. 485-521.

Robinson, F.M., and Roberts, T.G., 1949, Suggested correlation in Simpson Seeps region: U.S. Geological Survey Investigations, Naval Petroleum Reserve No. 4 and adjacent areas, Alaska, Special Report 13, 3 p. [Available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey.]

Rockwell, D.W., 1981a, Report on reinterpretation of seismic data pertaining to Mesozoic strata in the Cape Simpson region, National Petroleum Reserve in Alaska: Stewart Folk and Co., Inc., 28 p. [Available from National Geophysical Data Center, 325 Broadway, E/GC1, Dept. CNP, Boulder, Colorado 80303.]

—— 1981b, Report on an integrated interpretation of seismic and well data pertaining to the Barrow gas fields and the Avak disturbed zone, part of the National Petroleum Reserve in Alaska: Stewart Folk and Co., Inc., 24 p. [Available from National Geophysical Data Center, 325 Broadway, E/GC1, Dept. CNP, Boulder, Colorado 80303.]

Rockwell, D.W., and Folk, S.H., 1982, Analysis and reinterpretation of seismic and well data pertaining to Jurassic sandstone prospects in the northern part of the National Petroleum Reserve in Alaska: Stewart Folk and Company, Inc., 31 p. [Available from National Geophysical Data Center, 325 Broadway, E/GC1, Dept. CNP, Boulder, Colorado 80303.]

Sable, E.G., Dutro, J.T., Jr., and Morris, R.H., 1951, Preliminary report on the stratigraphy and structure of the Driftwood-Noluk area, Alaska: U.S. Geological Survey Investigations, Naval Petroleum Reserve No. 4 and adjacent areas, Alaska, Preliminary Report 39, 28 p. [Available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey.]

Sable, E.G., and Mangus, M.D., 1950a, Preliminary report on the stratigraphy and structure of the Driftwood anticline: U.S. Geological Survey Investigations, Naval Petroleum Reserve No. 4 and adjacent areas, Alaska, Preliminary Report 28, 9 p., 2 pls. [Available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey.]

—— 1950b, Preliminary report on the stratigraphy and structure of the upper Utukok and Kokolik Rivers area: U.S. Geological Survey Investigations, Naval Petroleum Reserve No. 4 and adjacent areas, Alaska, Preliminary Report 29, 17 p., 2 pls. [Available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey.]

—— 1951a, Stratigraphy and structure of Driftwood anticline: U.S. Geological Survey Investigations, Naval Petroleum Reserve No. 4 and adjacent areas, Alaska, Regular Report 44, 9 p., 2 pls. [Available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey.]

—— 1951b, Stratigraphy and structure of the upper Utukok-Kokolik Rivers area, Alaska: U.S. Geological Survey Investigations, Naval Petroleum Reserve No. 4 and adjacent areas, Alaska, Regular Report 45, 19 p., 2 pls. [Available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey.]

Sangree, J.B., and Widmier, J.M., 1977, Seismic stratigraphy and global changes of sea level, part 9: Seismic interpretation of clastic depositional facies, *in* Payton, C.E., Seismic stratigraphy; applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 165-184.

Scott, R.M., and Tillman, R.W., 1981, Models for deep-water sedimentation in tectonic basin; Stevens Sandstone, San Joaquin basin, California [abs.]: American Association of Petroleum Geologists Bulletin, v. 65, no. 5, p. 990.

Stille, Hans, 1917, Injektivfaltung und damit zusammenhängende Erscheinungen: Geologische Rundschau, v. 8, p. 89-142.

Tailleur, I.L., 1969, Rifting speculation on the geology of Alaska's North Slope: Oil and Gas Journal, v. 67, no. 39, p. 128-130.

—— 1973, Probable rift origin of Canada basin, Arctic Ocean, *in* Pitcher, M.G., ed., Arctic geology: American Association of Petroleum Geologists Memoir 19,

p. 526-535.

Tailleur, I.L., and Brosgé, W.P., 1970, Tectonic history of northern Alaska, *in* Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska: Los Angeles, American Association of Petroleum Geologists, Pacific Section, p. E1-E19.

Tailleur, I.L., and Kent, B.H., Jr., 1950, Preliminary report on the stratigraphy and structure of the southern foothills section between the Etivluk and Kiligwa Rivers: U.S. Geological Survey Investigations, Naval Petroleum Reserve No. 4 and adjacent areas, Alaska, Preliminary Report 34, 32 p. [Available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey.]

Tailleur, I.L., Kent, B.H., Jr., and Reiser, H.N., 1966, Outcrop/geologic maps of the Nuka-Etivluk region, northern Alaska: U.S. Geological Survey open-file report, 7 sheets, scale 1:63,360.

Tetra Tech, Inc., 1982a, Petroleum exploration of NPRA, 1974-1981, Final report: Houston, Tex., Tetra Tech, Inc., Report 8200, v. I, II, and III, 183 p., 132 fig., 71 seismic maps [Available from National Oceanic and Atmospheric Administration (E.D.S.), Mail Code D621, Boulder, Colorado 80303]

——— 1982b, Technical services contract; 1981 exploration program, drilling interpretations, geological and geophysical reports: Houston, Tex., Tetra Tech, Inc., Report 8202, v. I and III [Available from National Oceanic and Atmospheric Administration (E.D.S.), Mail Code D621, Boulder, Colorado 80303]

——— 1982c, Gravity and magnetic investigations of the National Petroleum Reserve in Alaska: Houston, Tex., Tetra Tech, Inc., Report 8201, 88 p. [Available from National Oceanic and Atmospheric Administration (E.D.S.), Mail Code D621, Boulder, Colorado 80303]

Wahrhaftig, Clyde, 1965, Physiographic divisions of Alaska: U.S. Geological Survey Professional Paper 482, 52 p.

Walker, R.G., 1967, Turbidite sedimentary structures and their relationship to proximal and distal depositional environments: Journal of Sedimentary Petrology, v. 37, p. 25-43.

——— 1970, Review of the geometry and facies organization of turbidites and turbidite-bearing basins, *in* Lajoie, K.R., ed., Flysch sedimentology in North America: Geological Association of Canada Special Paper 7, p. 219-251.

——— 1978, Deep-water sandstone facies and ancient submarine fans; models for exploration for stratigraphic traps: American Association of Petroleum Geologists Bulletin, v. 62, no. 6, p. 932-966.

Walker, R.G., and Mutti, Emiliano, 1973, Turbidite facies and facies associations, *in* Middleton, G.V., and Bouma, A.H., eds., Turbidites and deep-water sedimentation: Los Angeles, Society of Economic Paleontologists and Mineralogists, Pacific Section, Lecture Notes for a Short Course, Anaheim, p. 119-157.

Weimer, R.J., 1978, Preliminary report on environments of deposition of Jurassic sandstones, South Barrow gas field, NPR-4, Alaska: 8 p. [No. 7801 in ONPRA technical files, U.S. Geological Survey, Menlo Park, Calif.]

Wilde, Pat, Normark, W.R., and Chase, T.E., 1978, Channel sands and petroleum potential of Monterey deep-sea fan, California: American Association of Petroleum Geologists Bulletin, v. 62, no. 6, p. 967-983.

Williamson, C.R., and Hill, D.R., 1981, Submarine fan deposition of the Upper Cretaceous Winters Sandstone, Union Island field, Sacramento Valley, California, *in* Siemers, C.T., Tillman, R.W., and Williamson, C.R., Deep-water clastic sediments, a core workshop: Society of Economic Paleontologists and Mineralogists Core Workshop 2, San Francisco, p. 78-115.

Woolson, J.R., and others, 1962, Seismic and gravity surveys of Naval Petroleum Reserve No. 4 and adjoining areas, Alaska: U.S. Geological Survey Professional Paper 304-A, 25 p.

10. REGIONAL GEOLOGY AND PETROLEUM POTENTIAL OF THE UNITED STATES CHUKCHI SHELF NORTH OF POINT HOPE

By ARTHUR GRANTZ and STEVEN D. MAY

INTRODUCTION

An extensive frontier terrain that is prospective for petroleum but is as yet incompletely explored and entirely untested underlies the United States Chukchi shelf north of Point Hope (fig. 10.1). The area is in most places underlain by a thick section of sedimentary rocks prospective for oil and gas, and it contains diverse geologic structures and stratigraphic features that may have trapped hydrocarbon fluids. The prospective sedimentary section includes every geologic system from the Carboniferous to the Tertiary and includes several formations that contain petroleum deposits or strong shows of oil or gas on parts of the North Slope of Alaska. These formations have proved disappointing, however, where tested in a few exploratory wells in the western part of the National Petroleum Reserve in Alaska (NPRA), an area that lies adjacent to the Chukchi shelf.

Exploration and development of petroleum in the Chukchi Sea are hindered by the Arctic climate, polar ice pack, winter darkness, absence of harbors in Alaska north of the Aleutian Islands, and remoteness from exploration support facilities and supplies. Pack ice covers the entire area from October or November to June, and part of it is only ice free in favorable years for a short time in late summer. The bathymetry, however, is favorable for exploration because most of the area is less than 60 m (200 ft) below sea level. The National Petroleum Council (1981, p. 5) estimates that ''Proven technology and sufficient information and technical expertise for advanced design work is available for the industry to proceed confidently with operations in water as deep as 650 ft in the southern Bering Sea and to about 200 ft in the more severely ice-covered areas of the northern Bering, Chukchi, and Beaufort Seas.'' Thus, essentially all of the United States Chukchi shelf is thought by the National Petroleum Council to be technologically accessible to petroleum exploration and development at the present time.

Our data base consists mainly of the U.S. Geological Survey (USGS) multichannel seismic-reflection profiles and accompanying high-resolution seismic-reflection profiles shown in figure 10.1 and some additional USGS single-channel seismic-reflection profiles, sonobuoy refraction measurements, and seabed samples. The multichannel seismic profiles, on which the interpretations presented here are mainly based, are mostly 30 to 90 km apart, with typical line spacings of 40 to 50 km. Ice conditions during data acquisition were such, however, that profile coverage in the northern and northwestern parts of the Chukchi Sea is sparse (fig. 10.1). Because of the wide spacing and irregular distribution of the profiles, our interpretations are reconnaissance in character. Some of the profiles, particularly in the southwestern part of the study area, are affected by strong artifacts that further limit their usefulness for geologic interpretation and resource assessment.

GEOLOGIC FRAMEWORK

The northern United States Chukchi shelf encompasses seven major structural provinces (figs. 10.2, 10.12), each with more or less distinct geologic character and petroleum potential. The general stratigraphy and lithology of the region are summarized in Grantz and others (chapter 11, fig. 11.4). A cross section based on correlated test wells in the adjacent onshore areas is presented in figure 10.3. The offshore geologic data are mostly new, but some material was taken from Grantz and others (1981). Onshore data are mainly from Lathram (1965), Miller and others (1979), Guldenzopf and others (1980), Alaska Geological Society (1981), and Tetra Tech, Inc. (1982).

The depth to seismic horizons and the thickness of seismic-stratigraphic units are given in seconds of two-way seismic-reflection traveltime. An approximate conversion of time to depth can be made through the graph in figure 10.4, which represents the average regional velocity structure. The curve for the North Chukchi basin also approximates conditions in the northern Hope basin and the young sedimentary sequence in the Tertiary canyon fill (fig. 10.2). The

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curve for the Chukchi shelf is biased by the Tertiary canyon fill and gives depths that are somewhat shallower than the actual depths where the canyon fill is not present. Thickness of sediment in Nuwuk basin is based on a time-depth function derived for the Beaufort Sea (Grantz and others, chapter 11, fig. 11.6).

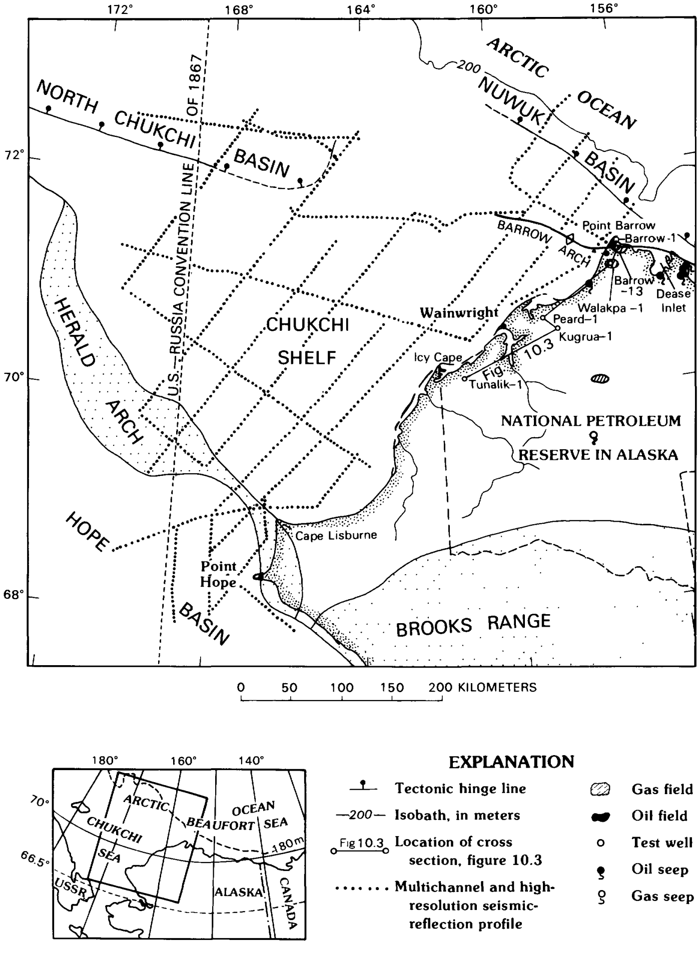


Figure 10.1—Northern United States Chukchi Sea and vicinity, showing major geologic features, petroleum development, oil and gas seeps, and locations of seismic-reflection profiles.

STRATIGRAPHY

The sedimentary strata of northern Alaska and the United States Chukchi shelf are conveniently grouped into three regionally extensive sequences, the Franklinian, Ellesmerian, and Brookian, each having contrasting lithology, tectonic character, and hydrocarbon potential (Grantz and others, chapter 11, fig. 11.4). The Cambrian to Devonian Franklinian sequence, which regionally consists of slightly to strongly metamorphosed sedimentary and some volcanic rocks, is inferred to constitute the economic basement for the Chukchi shelf. Following mild metamorphism and regional deformation, an extensive platform was cut across the Franklinian rocks in Late Devonian and Early Mississippian time. This, the Arctic platform, is a low-gradient surface that has remained remarkably stable beneath northern Alaska and the Chukchi shelf and is the foundation for the potentially petroliferous strata of the region. A diverse suite of clastic and carbonate sedimentary rocks—the Ellesmerian sequence—was deposited on the Arctic platform. That sequence contains both marine and nonmarine beds, including stratigraphically condensed organic-rich shale, texturally mature sandstone and conglomerate, and some dolomitized limestone. Clastic components were derived from a northern sourceland that lay at and north of the present position of the outer part of the continental shelf. In a following section on the Hanna trough, we suggest that the Chukchi platform of the west-central Chukchi Sea (fig. 10.6) may have been an additional, western sourceland for the Ellesmerian clastic strata of the United States Chukchi shelf. In the Chukchi shelf, the main Ellesmerian sequence appears to be underlain, beneath a mild angular unconformity, by a thick sedimentary unit that filled in structurally low areas of the Arctic platform. This unit is called the Eo-Ellesmerian sequence in this chapter.

EO-ELLESMERIAN SEQUENCE

Structural sags and faulted depressions in the angular unconformity (the Arctic platform) at the top of the Franklinian sequence beneath the Chukchi shelf are filled with sedimentary prisms that coalesce at their edges to form a regional stratigraphic sequence of irregular outline, having marked local variations in thickness (fig. 10.5). The deepest of these depressions, located about 50 km west of Icy Cape, contains a section as much as 5 km thick on one seismic profile. These sedimentary prisms are closely related to the Ellesmerian sequence because they produce coherent seismic reflections over a large area and are only slightly more deformed than that sequence. However, there is commonly a low-angle but pronounced angular unconformity between these rocks and the Ellesmerian beds, and in places fault-bounded prisms of these rocks are overstepped by Ellesmerian strata. This sequence is here referred to as the Eo-Ellesmerian sequence because of its structurally close, but unconformable, relation with the overlying Ellesmerian sequence.

The character of the Eo-Ellesmerian beds can only be inferred, because they cannot be definitively correlated with rocks observed in outcrops or test wells. Comparison with onshore seismic-stratigraphic and subsurface units recognized in the NPRA (Guldenzopf and others, 1980; Alaska Geological Society, 1981; Tetra Tech, Inc., 1982) indicates, however, that the Eo-Ellesmerian beds probably belong to the Endicott Group, which has a somewhat sporadic distribution in the NPRA. Where encountered in the subsurface or interpreted from seismic-reflection profiles in the NPRA, the Endicott consists of a thick sequence of pre-Lisburne Group, predominantly Mississippian and perhaps Upper Devonian clastic, rocks, mainly nonmarine and in part coal bearing. Its principal development is in the northwest-elongated, compound Ikpikpuk-Umiat basin of the eastern NPRA, but seismic-reflection profiles (Kirschner and Rycerski, chapter 9) indicate that a wedge of Endicott clastic rocks may also occur in the Meade basin, which underlies the western NPRA between about 158° and 159° W. longitude and 69°30′ and 70°30′ N. latitude. The extent of the inferred Endicott beds in the Meade basin is much smaller than in the Ikpikpuk-Umiat basin to the east.

Several characteristics imply probable correlation of the Eo-Ellesmerian seismic-stratigraphic

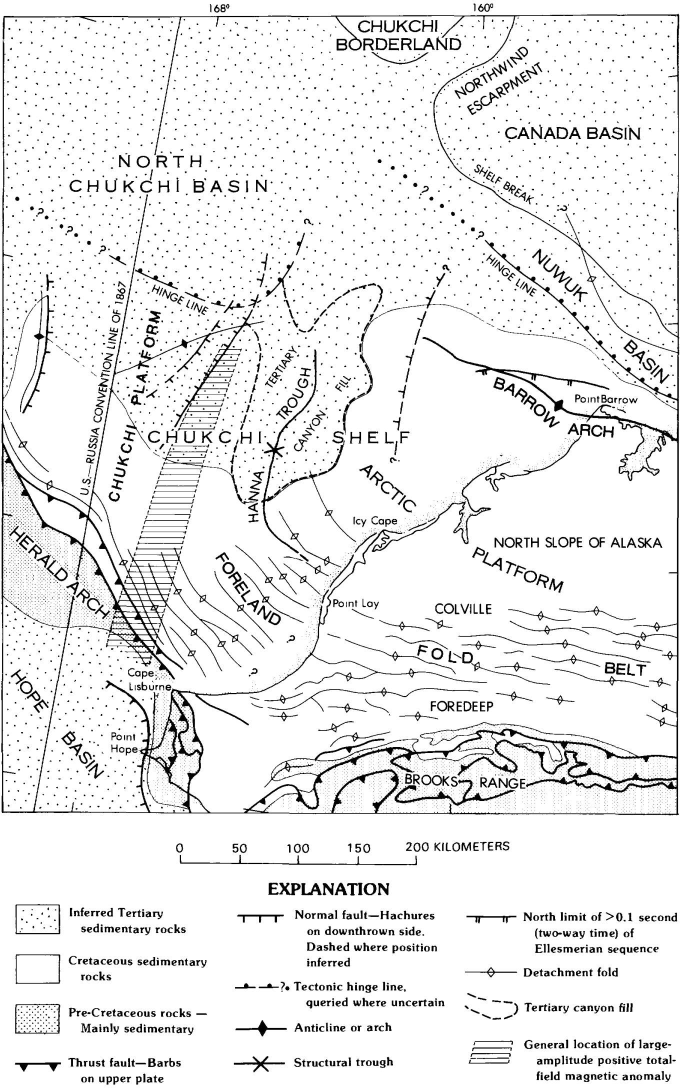


FIGURE 10.2—Preliminary tectonic map of the United States Chukchi Sea and vicinity.

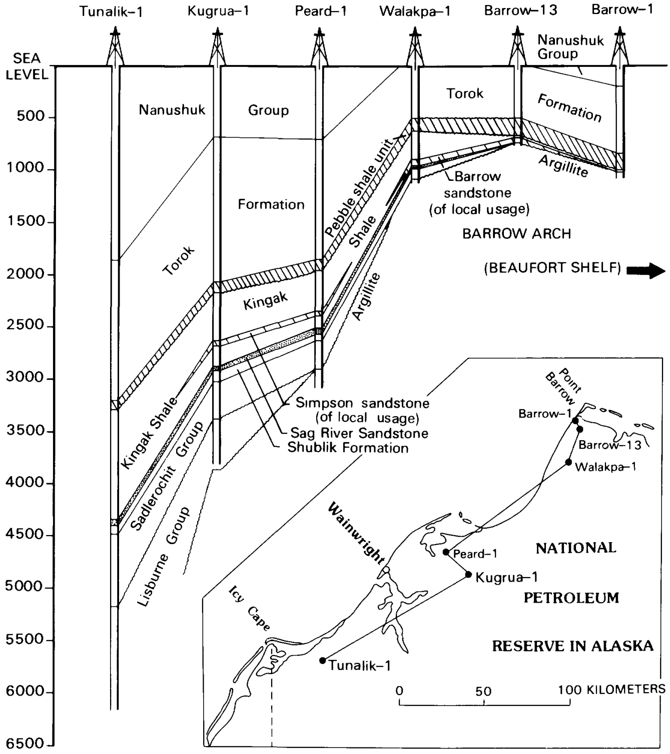


FIGURE 10.3—Geologic cross section approximately along margin of northern Chukchi Sea based on correlated test wells in the National Petroleum Reserve in Alaska. Inset map shows location of wells; see also figure 10.1.

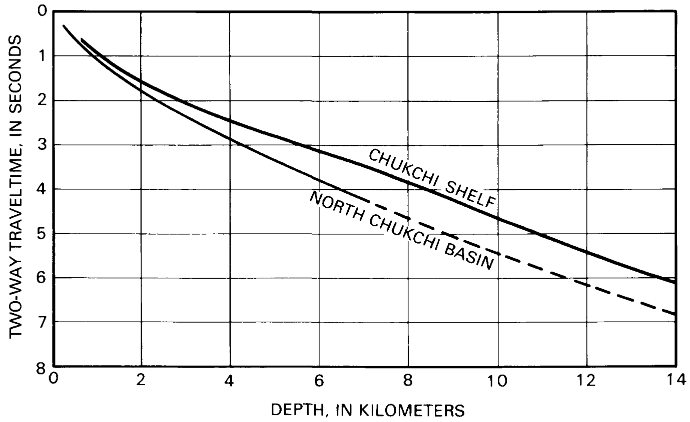


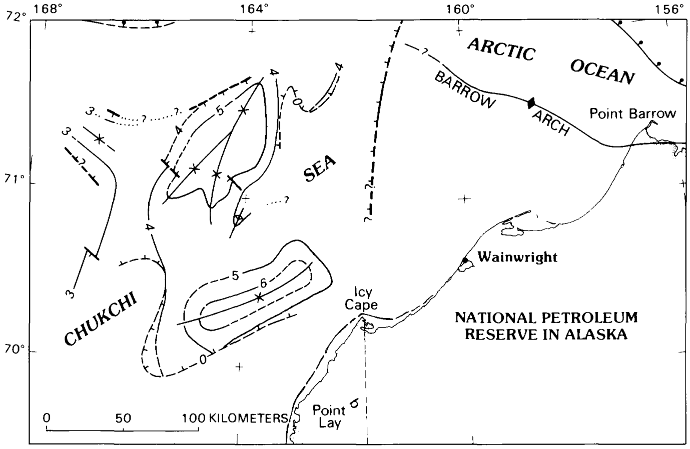
FIGURE 10.4.—Generalized average seismic-reflection time as a function of depth for the Chukchi shelf and North Chukchi basin, derived from measurements of seismic stacking velocity.

sequence with the subsurface Endicott Group of the NPRA. Chief of these is the stratigraphic position of the Eo-Ellesmerian beds, underlying with mild angular unconformity a seismic-stratigraphic unit that correlates with the Lisburne Group of the Ellesmerian sequence in the western NPRA. In addition, the shape of the Eo-Ellesmerian prism (fig. 10.5) closely resembles that of the Endicott Group. Both consist of coalesced, locally thick subbasins that in aggregate are less extensive and less uniform in thickness than the overlying Ellesmerian sequence (figs. 10.6, 10.7). Both also have significant structural relief at the base and considerable thickness locally. Maximum observed thickness of the Eo-Ellesmerian prism is 5 km, and that of the Endicott prism in the subsurface of the NPRA more than 3 km (Kirschner and Rycerski, chapter 9). Although the seismic-stratigraphic correlation of the Eo-Ellesmerian sequence with the Endicott Group of the NPRA appears well supported, it should be noted that these prisms are not contiguous. The principal development of the Endicott Group is in the Ikpikpuk-Umiat basin, more than 200 km east of the Eo-Ellesmerian prism of the Chukchi shelf. The smaller prism of the Endicott Group in the Meade basin is at least 100 km east of the Eo-Ellesmerian prism, and no pre-Lisburne Endicott rocks have been reported from the westernmost North Slope.

ELLESMERIAN SEQUENCE

The dominantly clastic Ellesmerian sequence of the western North Slope (fig. 10.3), which was derived from a northern sourceland, underlies most, but not all, of the United States Chukchi shelf north of Point Hope (figs. 10.6, 10.7). Beneath the eastern part of the shelf the sequence rests unconformably on the south-sloping Arctic platform and has the same general west strike, south dip, and southward increase in thickness that characterize it on the North Slope. In this area the sequence, as measured by seismic traveltime, thickens from 0.1 s (about 100-150 m) at a depth of about 1 s (1 km) on the Barrow arch to about 2 s (5 km) at a depth of 3 s to a little more than 5 s (6-11 km) in a southeast-striking structural low off Point Lay. This structural low merges with the Hanna trough—a north-striking structural low and sedimentary thick near long 164° W. The base of the Ellesmerian sequence is more than 4.85 s (10 km) deep, and the sequence is more than 3.0 s (7.7 km) thick near lat 71°15″ N. A northward-deepening, probably genetically related structural low north of lat 71°30″ N. near long 162° W. contains a similar or greater thickness of Ellesmerian strata. West of Hanna trough the Ellesmerian sequence becomes progressively shallower and thinner. Beyond long 167° W. it is generally less than 0.5 s (1.3 km) thick, and in places beyond about long 168° W. it appears to be entirely absent. The decrease in thickness is caused both by stratal thinning and by erosional truncation and overlap, indicating the possibility that a platform or sourceland lay to the west. On the other hand, sections of tentatively identified Ellesmerian rocks as thick as 2 s (5.5 km) are preserved in fault blocks near Cape Lisburne, and these sections appear to extend west of the 0.5-s isopach of Ellesmerian rocks from the region north of the fault blocks. A strong seismic reflector of regional extent is interpreted to mark the top of the Ellesmerian sequence.

In the eastern part of the Chukchi shelf the reflectors correlated with the Ellesmerian sequence consist of an upper unit of relatively weak, less continuous reflectors and a lower unit that contains a number of stronger reflectors of considerable lateral extent. One strong reflector, which typically lies stratigraphically 30 to 50 percent below the top of the Ellesmerian reflector packet on the seismic profiles, marks the top of the lower unit. The relative thickness of the units changes markedly to the west, however, and in places one or both are absent. Comparison of our seismic-stratigraphic units with those of the western NPRA, as shown by Tetra Tech, Inc. (1982), in the area between Icy Cape and Barrow arch, indicates that the upper unit consists of the Lower Cretaceous (Neocomian) pebble shale unit and the Jurassic and Lower Cretaceous Kingak Shale. North of Icy Cape, however, the interval interpreted to be the Kingak contains



EXPLANATION

(Applies to figures 10.5–10.10, 10.12. Not all symbols appear on each figure)

☐ Tertiary and Cretaceous sedimentary rocks—Slightly to moderately deformed

Ks Cretaceous sedimentary rocks

Ksd Cretaceous sedimentary rocks—Strongly deformed

El Ellesmerian sequence

Fr Franklinian sequence

AB Perched acoustic basement of Herald arch allochthon

Structural features

Note: All geologic line symbols, including isochrons and isopachs, on figures 10.5 to 10.10 are shown solid where interpolated between adequately distributed control points, dashed where extropolated beyond adequate control, dotted where speculative, queried where doubtful.

Thrust fault—Sawteeth on upper plate

Normal fault—Hachures on downthrown side

Syncline

Anticline

Arch

Tectonic hinge line

Boundary of Hope basin

Boundary between areas of Herald arch allochthon containing shallow rocks with $Vp=<4$ km/s (to north) and >4 km/s (to south)

0 Zero isopach of Eo-Ellesmerian sequence

5 Isochron, in seconds of two-way seismic-reflection traveltime, to base of Eo-Ellesmerian sequence

FIGURE 10.5.—Isochrons on base of the Eo-Ellesmerian sequence (top of the Franklinian sequence) beneath the northern part of the United States Chukchi shelf. Northeast limit of the Eo-Ellesmerian sedimentary prism was not recognized on the seismic-reflection profiles.

a few stronger reflectors in its lower part that may represent sandstone beds. The lower Ellesmerian unit is thought to represent the Lisburne Group (Pennsylvanian and Permian in age in the western NPRA; see Bird, chapter 15), the Permian and Triassic Sadlerochit Group, and the Triassic Shublik Formation and Sag River Sandstone. The upper unit (Kingak Shale and pebble shale unit) appears to be relatively thinner and the lower unit relatively thicker offshore than beneath the western North Slope. The northern limits of key stratigraphic components of the Ellesmerian sequence in the western NPRA (taken from Guldenzopf and others, 1980, and Tetra Tech, Inc., 1982), where there is a progressive south-to-north overlap of older by younger stratigraphic units, are shown in figures 10.6 and 10.7. The seismic data indicate that the same progressive overlap occurs beneath the eastern Chukchi Sea.

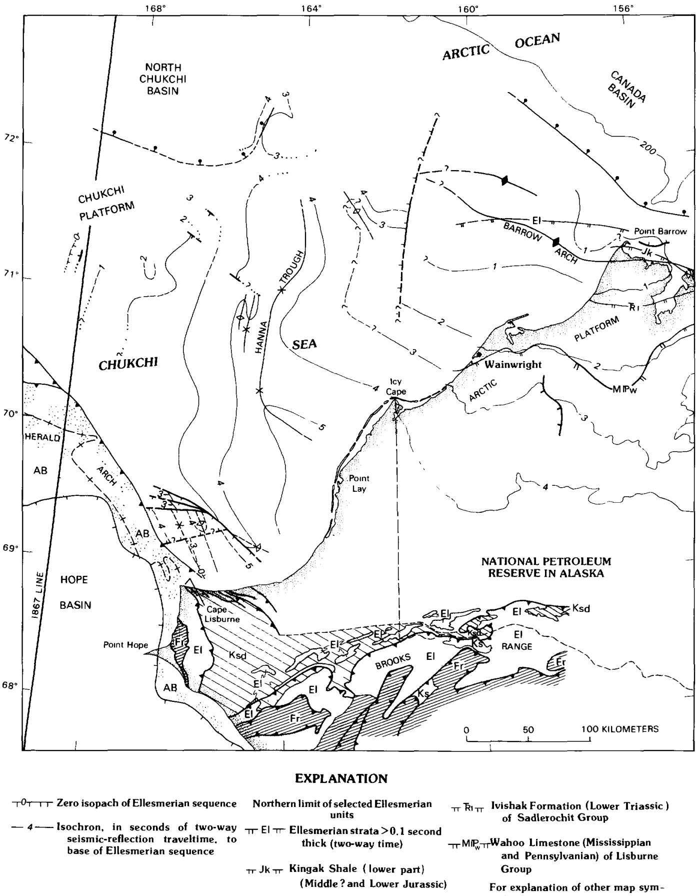


FIGURE 10.6.—Isochrons on base of the Ellesmerian sequence beneath United States Chukchi shelf. Onshore isochrons from Miller and others (1979), onshore limits of selected Ellesmerian stratigraphic units from Guldenzopf and others (1980) and Tetra Tech, Inc. (1982).

LOWER PART OF BROOKIAN SEQUENCE

The lower part of the Brookian sequence in the United States Chukchi shelf consists of a thick succession of seismic reflectors of low to moderate strength that are interpreted to represent Cretaceous marine and nonmarine clastic sedimentary rocks of the Colville foredeep. Structural contours drawn at the base of the Brookian sequence on the eastern Chukchi shelf are shown in figures 10.8 and 10.9. The sequence rests, typically by downlap, on a strong regional seismic reflector that is thought to mark the top of the pebble shale unit (Neocomian) at the top of the Ellesmerian sequence. The character of the seismic reflectors and comparison with onshore data (Molenaar, 1981; Tetra Tech, Inc., 1982) indicate that the lower Brookian sequence of the Chukchi shelf probably consists of marine prodelta clastic deposits of the intertonguing Fortress Mountain and Torok Formations and nonmarine and shallow-marine intradelta deposits of the Nanushuk Group (fig. 10.3; see also Grantz and others, chapter 11, fig. 11.4). The overall age of these units is Aptian(?), Albian, and possibly earliest Late Cretaceous (Cenomanian). Foreset bedding, as interpreted from our seismic records, and paleocurrent data (Molenaar, 1981) imply that these beds were derived from a sourceland that lay to the southwest. Near lat 70° N. on the North Slope and, possibly, in places in the western and northern parts of the Chukchi shelf, the Albian beds are overlain by nonmarine and shallow-marine intradelta deposits of the Colville Group (Upper Cretaceous). The Colville Group is interpreted to intertongue northward and northeastward into marine prodelta deposits beneath the northern Chukchi and Beaufort Shelves.

The lower Brookian sequence thickens northward and southward from a minimum of 0.25-0.67 s (0.25-0.7 km) on the Barrow arch. North of the arch, the base of the sequence deepens gradually to about 1.5-2 s (2-3 km) at the faulted tectonic hinge line (figs. 10.1, 10.2, 10.8) that is thought to have formed during the opening of the Canada Basin by sea-floor spreading in late Neocomian time (Grantz and others, chapter 11; Grantz and May, 1983). At the hinge line the slope increases markedly, and the base of the Brookian sequence lies more than 12 km below sea level beneath the outer continental shelf. The overlying sedimentary prism, called the Nuwuk basin (figs. 10.1, 10.2, 10.8), is progradational, and it is probable that near the shelf break it extends from the continental basement of the Arctic platform onto transitional or oceanic crust of the Arctic Basin. The Nuwuk basin contains both foreset and topset beds and large erosional channels and channel fills. Structurally it is dominated by large, multistrand, down-to-the-north growth faults that preliminary studies indicate were active since Late Cretaceous or early Tertiary time. The faults appear to be restricted to the Brookian sequence and to curve into, but not displace, the upper surface of pre-Brookian bedrock.

Southward from the Barrow arch, beneath the eastern Chukchi shelf, the lower Brookian sequence thickens rather uniformly to a maximum of 3.7 s (about 7.5 km) beneath the axis of the Colville foredeep between Icy Cape and Point Lay. From this structural low and sedimentary thick the axis of the foredeep plunges southeastward beneath the foothills of the Brooks Range. Up the plunge, the axis merges with the north-trending Hanna trough, in which the base of the Brookian sequence lies 2.4-3.0 s (about 4-5.5 km) below sea level. The thickness of the lower part of the Brookian sequence in the trough is reduced, however, by a paleocanyon filled with a thick sedimentary prism of presumed Tertiary age belonging to the upper part of the Brookian sequence (figs. 10.2, 10.10). West of Hanna trough and south of lat 71°30′ N., the lower Brookian sedimentary sequence thins to less than 1.0 s (about 1 km), but noise artifacts in the data caused by rocks of high seismic velocity near the surface in the area northwest of Cape Lisburne preclude determining whether or not it wedges out entirely. Northwest of Hanna trough the lower Brookian sequence thickens sharply as it drops into the eastern

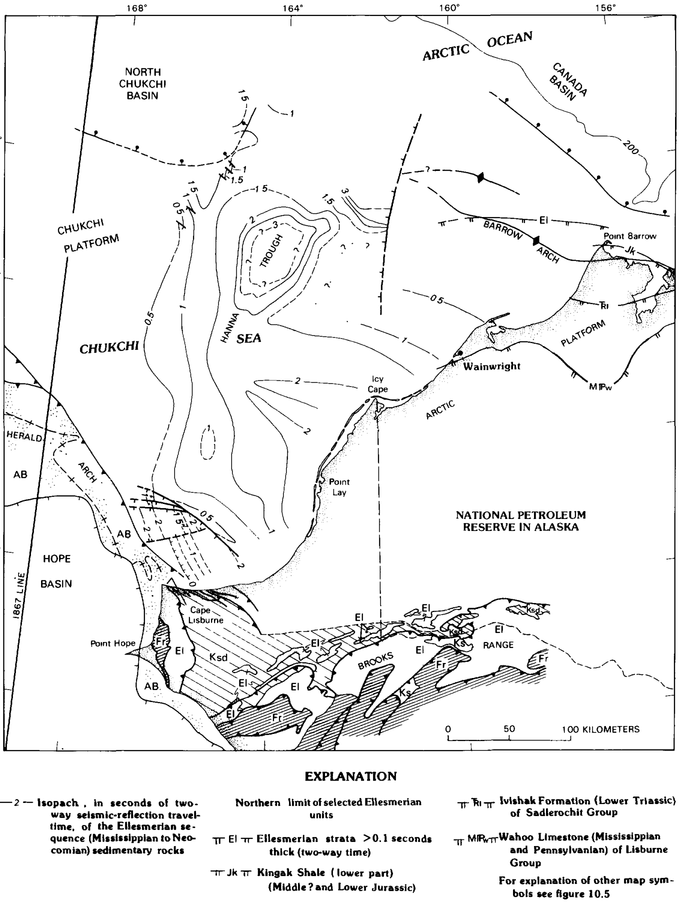
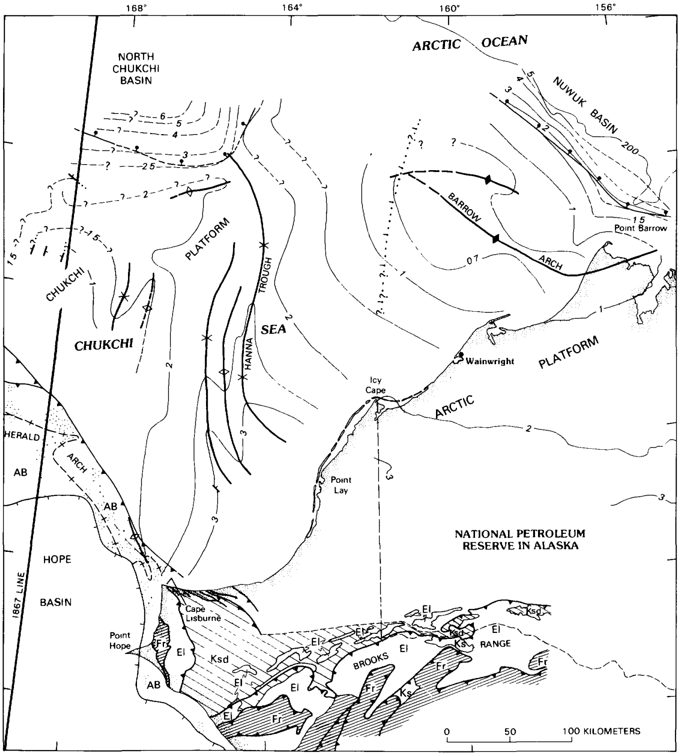


FIGURE 10.7.—Isopachs, in seconds of two-way seismic-reflection time of the Ellesmerian sequence beneath the United States Chukchi shelf. Onshore limits of selected Ellesmerian stratigraphic units from Guldenzopf and others (1980) and Tetra Tech, Inc. (1982).

part of the North Chukchi basin, where the sequence is extensively deformed by listric normal faults of large displacement. The base of the unit lies more than 6 s (about 12 km) below sea level in this basin, and the unit is 4.5 km to perhaps 8.5 km or more thick.

The lower Brookian sequence of the North Slope and eastern Chukchi Sea was derived from a southwestern sourceland, sediment from which filled the Colville foredeep by progressive downlap on the top of the Ellesmerian sequence and by onlap against an early phase of the Barrow arch to the northeast. The lower Brookian rocks also thicken into Hanna trough, which has somewhat less structural relief at the base of the Brookian than at the base of the underlying Ellesmerian rocks. The suggested, though incompletely documented, westward reduction in the thickness of the lower Brookian sequence west of Hanna trough by stratal thinning and erosional truncation implies that a sourceland, or at least a structurally positive area, lay to the west of the trough in early Brookian time.



EXPLANATION

—3— Isochron, in seconds of two-way seismic reflection traveltime,to base of Brookian sequence (base of Torok or Fortress Mountain Formation).

For explanation of other map symbols see figure 10.5

FIGURE 10.8.—Isochrons on base of the lower part of the Brookian sequence (Torok and Fortress Mountain Formations) beneath the United States Chukchi shelf. Onshore data from Miller and others (1979).

UPPER PART OF BROOKIAN SEQUENCE

The Beaufort and northeastern Chukchi shelves north of the Barrow arch, the area of Hanna trough, the shelf west of Hanna trough north of the latitude of Icy Cape, and the North Chukchi basin are underlain by an irregular body of young sedimentary rocks. Structural contours at the base of these rocks, which are called the upper Brookian sequence in this report, are shown in figure 10.10. Because these rocks overlie the lower Brookian rocks with angular unconformity, have fairly low seismic-reflection velocities, and constitute the youngest bedrock stratigraphic unit on the Chukchi shelf, we infer that they are largely or entirely of Tertiary age. While much of the section can be traced into Tertiary beds of the Beaufort shelf and North Slope east of Harrison Bay, the basal contact or unconformity has not been tied to the Cretaceous-Tertiary boundary. The sequence may therefore lack the lowest part of the Tertiary or, alternatively, the lowest beds may be latest Cretaceous in age. Because the upper Brookian rocks are the highest stratigraphic sequence in the area and their upper beds lie at or close to the floor of the shallow Chukchi Sea, the structural contours at their base (fig. 10.10) are essentially isopachs.

The upper Brookian rocks are as much as 2.0 s (2.2 km) thick in the subbasin that overlies Hanna trough, 1.5-1.9 s (1.6-2.1 km) thick in a filled channel that connects the subbasin with the North Chukchi basin, more than 1.5 s (1.6 km) thick in Nuwuk basin, and more than 3.6 s (5.6 km) thick in the North Chukchi basin itself. The morphology of the subbasin that overlies Hanna trough and the fact that the subbasin is linked to the deep North Chukchi basin by a buried channel (fig. 10.10) imply that it is a submarine canyon that was tributary to the North Chukchi basin before both were filled by Tertiary sedimentary rocks. In morphology and size the postulated submarine canyon resembles the modern Navarinsky and Zhemchug Canyons of the outer Bering shelf (Carlson and Karl, 1984).

The upper Brookian sequence of the Chukchi shelf is inferred to consist of clastic sedimentary rocks, as indicated by its low seismic velocities, the geometry of the seismic reflectors, and the character of Tertiary strata on the North Slope. On the east side of the subbasin overlying Hanna trough the seismic reflectors are conformable with the basal unconformity. On the more steeply sloping west side of the basin, however, reflectors within the subbasin buttress against the basal unconformity and underlying basin wall. Because the height of the west wall of the subbasin (and therefore the thickness of the buttressing beds) is at least 1.25 s (about 1.75 km), it is likely that much of the section in the subbasin is marine. Presumably, the even thicker section in the North Chukchi basin is also dominantly marine. The Tertiary beds of the North Slope and Beaufort shelf grade southward into nonmarine beds, and those of the Chukchi shelf probably do the same.

STRUCTURAL PROVINCES

Most of the United States Chukchi shelf north of Point Hope is underlain by the Arctic platform (see fig. 10.11 and preceding section on "Stratigraphy"), which has been remarkably stable since its development in Devonian and Early Mississippian time. The platform has been tilted and warped, but high-gradient folds have not been recognized, and faults of significant displacement are common only in the Chukchi platform of the western part of the United States Chukchi shelf. Although structural gradients in the tilted and warped areas of the platform are very low, the affected areas are extensive, and consequently the amplitude of the resultant deformation is large. Most of the major structural provinces of the shelf (fig. 10.12) are recorded in the morphology of the Arctic and Chukchi platforms.

BARROW ARCH AND ARCTIC PLATFORM

Structurally the northern part of the Arctic platform east of Hanna Shoal is dominated by the Barrow arch (figs. 10.2, 10.6-10.10). Franklinian basement lies within 0.25 s (0.3 km) of the sea surface in one locality along the broad crest of the arch, and flank dips are very low. The south-sloping Arctic platform forms the south flank of the arch. The crest and north flank are also underlain by the Arctic platform, but the platform in those areas was modified by uplift and erosion adjacent to the late Neocomian rift

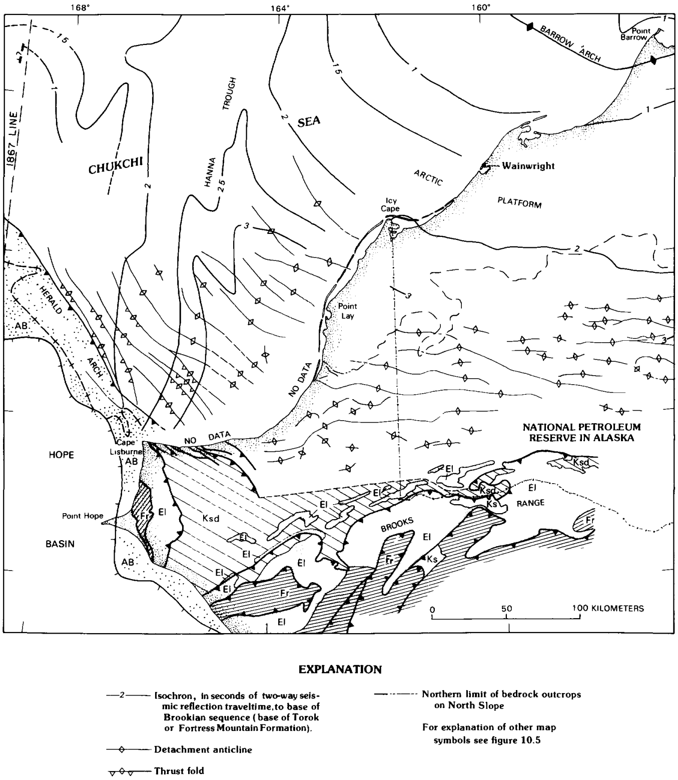
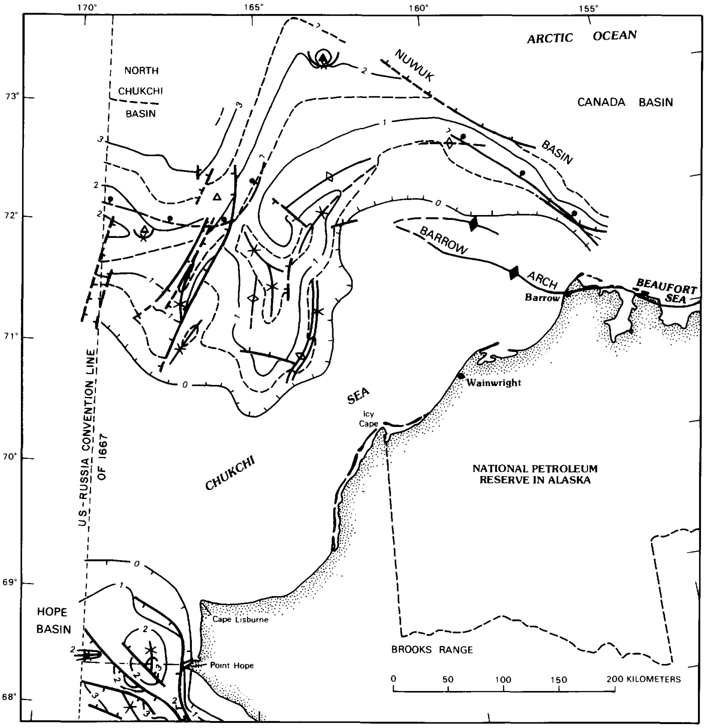


FIGURE 10.9.—Detachment folds and thrust folds in Cretaceous sedimentary rocks of the Colville Foredeep on the United States Chukchi shelf and western North Slope. Beneath the Chukchi shelf the folds are detached at, or close to, the base of the Torok or Fortress Mountain Formation, which is contoured in isochrons. Onshore isochrons from Miller and others (1979); onshore folds from Lathram (1965).

that created the present continental margin and Canada Basin north of Alaska (Grantz and May, 1983) and by subsequent sedimentary loading of the margin north of the tectonic hinge line (figs. 10.5-10.8, 10.10, 10.12). The tectonic hinge line, which lies north of the arch and is thought to have resulted from the rifting process, is the north boundary of the Barrow arch and of the Arctic platform province in offshore northern Alaska.

The Arctic platform slopes uniformly south-southwest, with a gradient of about 2.5°, from the crest of Barrow arch to the present structural axis of the Colville foredeep near Point Lay (figs. 10.6, 10.8). The sedimentary section on the platform near Point Lay consists of about 5.5 km of Ellesmerian clastic and carbonate strata and about 7.5 km of lower Brookian marine and nonmarine strata. Off Icy Cape an elongate local basin of northeast trend contains a section about 1.7 s (5 km) thick of Eo-Ellesmerian strata (fig. 10.5). The northeastern limit of these beds is uncertain. The Ellesmerian sequence thins northward by stratal thinning and progressive northward overlap of older by younger formations (figs. 10.3, 10.5, 10.6), and it is less than 200 m thick where present on the crest of Barrow arch. The lower Brookian sequence thins northward by the progressive northward downlap of foreset beds on its substrate and by erosion at the present land surface following Tertiary uplift along Barrow arch (fig. 10.3). The foresets were formed in a prograding prodelta that filled the Colville foredeep from the southwest. The lower Brookian sequence on the Chukchi shelf consists mainly of the marine Torok Formation and the marine and nonmarine Nanushuk Group. In places less than 0.25 s (about 0.3 km) of these elsewhere very thick units remain on Barrow arch.



EXPLANATION

2 Isochron, in seconds of two-way seismic-reflection traveltime, to base of presumed Tertiary strata. Supplementary contours dashed

▲ Diapir

△ Deformation probably peripheral to a nearby diapir

For explanation of other map symbols see figure 10.5

FIGURE 10.10.—Isochrons on base of the upper part of the Brookian (presumed Tertiary) sequence beneath the northern United States Chukchi Sea. Isochrons north of the multichannel profiles (fig. 10.1) are based only on shallow-penetration single-channel seismic-reflection profiles and are speculative.

Barrow arch, as expressed by the configuration of the base of the Brookian sequence (fig. 10.8), dies out at Hanna trough near long 163° W. A large fault near long 162° W. is an important component of the boundary between the thin Ellesmerian section on Barrow arch and the inferred thick Ellesmerian section in Hanna trough and its northern extension. The fault was observed on only one multichannel profile, and we are therefore uncertain of its exact strike, but it appears to die out to the south near lat 71° N. Other than Barrow arch and the south tilt of strata south of the arch, the only significant deformational structures on the Arctic platform are the detachment folds of the foreland fold belt structural province (fig. 10.9).

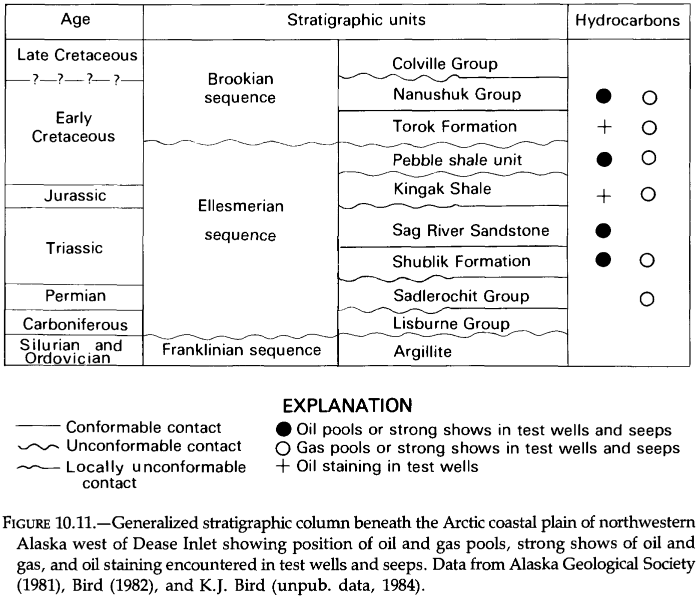
HANNA TROUGH

Downwarping and downfaulting of the Arctic platform from depths as shallow as 0.25 s (0.3 km) on Barrow arch to depths as great as 4.85 s (about 10 km) in the vicinity of long 164° W. created the east flank of Hanna trough (fig. 10.6). The change in structural level is largely accomplished by downwarping, but the major north-striking fault near long 162° W. forms the boundary of a northeast structural extension or subbasin of the trough near lat 71°40′ N. Except for the large north-striking fault and a broad arch that separates the trough from its northeast extension, the Arctic platform beneath the east flank of Hanna trough has almost no deformational structures. In contrast to the basement of the east flank, the Franklinian basement beneath the axial region of the trough and the Chukchi platform to the west of it are in many places warped or folded and broken by faults. On the south, the trough loses its identity where its trend changes from north-south to northwest-southeast off Point Lay, and it merges with the Ellesmerian basin of the North Slope. The north end lies beyond our multichannel profiles, but gravity data indicate that the trough or a related subbasin extends to the north-north-east.

A section including at least 0.4 s (1 km) of Eo-Ellesmerian strata and more than 3 s (7-8 km) of Ellesmerian strata was deposited in the deepest parts of Hanna trough and its northeast extension or subbasin (fig. 10.7). The Eo-Ellesmerian beds were deposited in structural downwarps, locally faulted, in the Arctic platform. The overlying Ellesmerian strata of the trough are areally more extensive and less variable in thickness. As noted above, Ellesmerian strata in the west flank of Hanna trough thin westward by stratal thinning and by erosional thinning and overlap, implying that the Chukchi platform was a structural high and perhaps a sourceland for Ellesmerian clastic materials. The Ellesmerian strata on the Arctic platform also thin toward a sourceland, which lay to the north, and therefore the Hanna trough is a depositional basin as well as a structural trough (fig. 10.7).

Hanna trough is also expressed in the thickness of the Brookian sequence and the structure of its basal contact (fig. 10.8), but on the flanks of the trough these rocks have very low gradients and the structural relief at their basal contact is less than in the underlying Ellesmerian rocks. The maximum thickness of Brookian strata in the trough on our profiles is about 2.5 s (4 km). It is not known from our present data whether or not an extension or subbasin of Hanna trough, as expressed in Brookian rocks, also continues to the north-northeast, as is inferred for the Ellesmerian rocks. The lower Brookian thick in Hanna trough formed in part by infilling an existing broad sag and in part by postdepositional faulting and downwarping. Crustal loading by the underlying Ellesmerian sedimentary rocks, Cretaceous uplift of Barrow arch and the Chukchi platform, and perhaps some differential compaction in Ellesmerian rocks may have all contributed to the structural relief of lower Brookian rocks in Hanna trough.

Upper Brookian strata filling a postulated submarine canyon form the highest sedimentary sequence in Hanna trough. The axis of the canyon fill and the channel connecting it to North Chukchi basin coincide generally with the axis of the trough as defined by the base of the lower Brookian sequence (fig. 10.8), even though these prisms are thought to have quite different origins. The canyon fill laps against the steep west wall of the canyon, which is clearly an erosional feature. To the east, however, the base of the presently preserved canyon fill is nearly conformable with the underlying lower Brookian strata; a steep canyon wall has not been



Age	Stratigraphic units		Hydrocarbons
Late Cretaceous —?—?—?—?— Early Cretaceous	Brookian sequence	Colville Group	
		Nanushuk Group	● ○
		Torok Formation	+ ○
	Ellesmerian sequence	Pebble shale unit	● ○
Jurassic		Kingak Shale	+ ○
Triassic		Sag River Sandstone	●
		Shublik Formation	● ○
Permian		Sadlerochit Group	○
Carboniferous		Lisburne Group	
Silurian and Ordovician	Franklinian sequence	Argillite	

EXPLANATION

——— Conformable contact

⁓⁓ Unconformable contact

–⁓– Locally unconformable contact

● Oil pools or strong shows in test wells and seeps

○ Gas pools or strong shows in test wells and seeps

+ Oil staining in test wells

FIGURE 10.11.—Generalized stratigraphic column beneath the Arctic coastal plain of northwestern Alaska west of Dease Inlet showing position of oil and gas pools, strong shows of oil and gas, and oil staining encountered in test wells and seeps. Data from Alaska Geological Society (1981), Bird (1982), and K.J. Bird (unpub. data, 1984).

identified in that area. Thus the canyon was broad and the east side had a gentle slope, or a formerly existing steep east wall was removed by subsequent uplift and erosion.

The maximum height of the west wall of the filled canyon is at least 1.25 s (about 1.75 km), and the total thickness of the upper Brookian section is 2 s (about 2.5 km). Thus most of the relief at the base of these rocks is due to erosion and canyon filling, but some downwarping of strata into the basin added a small structural component to the present depth of the infilled paleocanyon. Structural deformation may also have created the sill in the buried channel that appears to connect the filled paleocanyon with North Chukchi basin. The sill is 0.5 s (about 0.75 km) higher than the deepest part of the filled paleocanyon on our profiles and creates an obvious difficulty for the canyon-fill hypothesis. The sill may be partly explained, however, by the large north-northeast-trending graben that obliquely crosses the channel near its junction with the North Chukchi basin. Isochrons (seismic traveltime contours) on the base of the upper Brookian sequence (fig. 10.10) indicate that the basal surface has been tilted east in the footwall of the fault bounding the east side of the graben. The tilt is interpreted to represent actual, as well as relative, uplift of the footwall, and this uplift is thought to have contributed to the elevation of the adjacent sill. Additional relief on the sill was created by downwarping of the paleocanyon fill in late Brookian and later time that is recorded in the strata above the canyon fill.

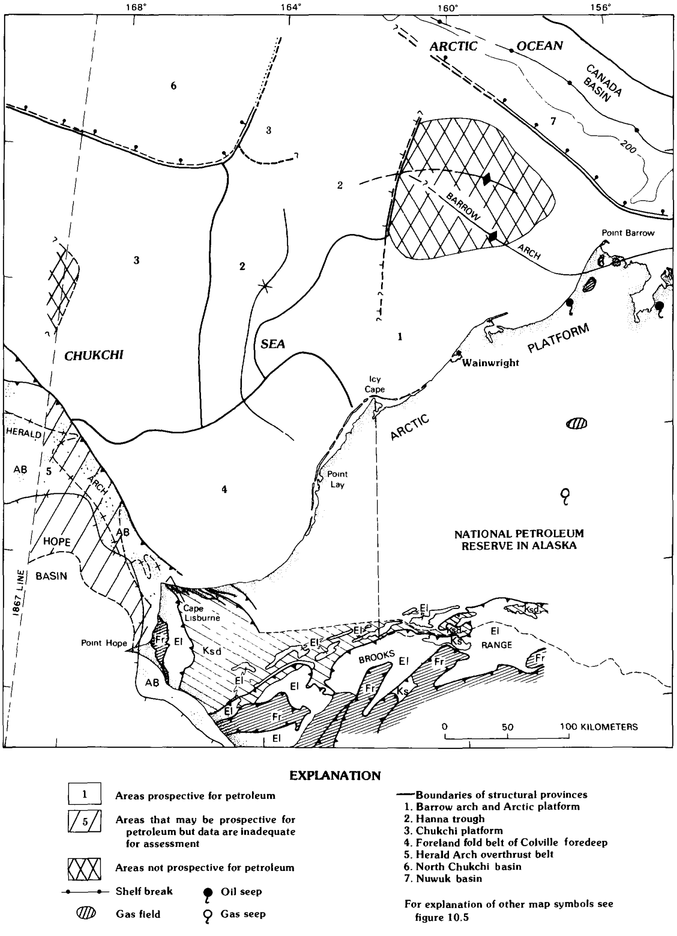


FIGURE 10.12.—Structural provinces and areas prospective for petroleum on the United States Chukchi shelf north of Point Hope.

CHUKCHI PLATFORM

Westward shallowing of the acoustic basement, westward overlap of older by younger Ellesmerian beds, westward stratal thinning within the Ellesmerian and lower Brookian sequences, and extensive high-angle normal faulting characterize the Chukchi platform, which underlies the United States Chukchi shelf west of Hanna trough (figs. 10.6-10.8). The platform (top of Franklinian basement) shallows from depths of 4.5-5.5 s (9-12 km) at the axis of Hanna trough and Colville foredeep to less than 1 s (1.0-1.25 km) in places near the U.S.-Russia Convention line of 1867. As noted in a previous section, the westward overlap of older by younger Ellesmerian units against the westward-shallowing Chukchi platform indicates that an Ellesmerian structural high and perhaps a sourceland lay to the west. In places, the Ellesmerian rocks wedge out entirely in the western part of the United States Chukchi shelf (fig. 10.7), and the lower Brookian rocks thin to less than 1 km. The numerous normal faults west of Hanna trough are young features because they offset Brookian rocks.

Upper Brookian rocks on the Chukchi platform constitute a gently northward-dipping and -thickening sedimentary wedge that is broken by some large high-angle normal faults (fig. 10.10). Southward, these rocks wedge out near lat 71°30′ N. Northward, they thicken to about 2 s (2.3 km) at the hinge line that separates the platform from the North Chukchi basin. The Brookian rocks are sufficiently shallow in many places to be mapped from single-channel profiles. Accordingly many structural features, such as a north-northeast-striking graben near long 166° W., are shown in these rocks (fig. 10.10) that could not be delineated in older sequences. The graben has as much as 1.2 s (about 1.4 km) of structural relief and a total sedimentary section that is 2 s (about 2.3 km) thick. It is aligned with the east end of North Chukchi basin and is possibly related to its formation.

FORELAND FOLD BELT OF COLVILLE FOREDEEP

Large, high-amplitude detachment folds and thrust folds characterize the Chukchi shelf between Icy Cape on the northeast and Cape Lisburne and Herald arch on the southwest (fig. 10.9). The folds have flank dips of 1° to 15°, amplitudes as large as 1.2 km, wavelengths generally in the range of 10 to 30 km, and strike lengths of 10 to more than 120 km. They are the continuation of the folds in the foreland fold province of the north side of the Brooks Range, where they involve mainly lower Brookian but apparently also Ellesmerian beds. The folds swing in strike from east-west on the western North Slope to west-northwest and northwest offshore. They die out about 70 km off Icy Cape and about 140 km off Cape Lisburne. Offshore, the folds appear to be restricted to the lower Brookian sequence and to die out abruptly at the top of the Ellesmerian sequence, probably in the pebble shale unit of Neocomian age. Their geometry indicates that they are detachment folds in an allochthonous plate of a regional low-angle detachment fault system. Immediately above the detachment zone the cores of the folds contain thickened wedges of poorly reflective sediment—presumably tectonically mobilized shale. The folds become progressively more complex toward Herald arch, and near the arch they are thrust folds with cores that are appressed and contain upward-steepening listric thrust faults that rise northeast from the detachment fault to the seabed. Northeast vergence and the southwest increase in structural complexity indicate that the folds and the upper plate of the detachment fault moved relatively northeast. As observed on incompletely processed multichannel profiles, the folds appear to die out to the northwest by a decrease of displacement and shortening in the upper plate, rather than by extension of the basal detachment fault to the surface or its transformation into tear faults.

The faulted, folded, and therefore structurally thickened lower Brookian prism is 2 s to more than 3.6 s (about 2.8 to 7.3 km) thick in the fold belt. Beneath this prism and its basal detachment fault lies a thickness of 0.5 to more than 2 s (about 1 to more than 5 km) of Ellesmerian section (figs. 10.6 and 10.7). Near Cape Lisburne, tentatively identified Ellesmerian and older rocks are broken by a system of large normal faults whose trends and structural effects are presented conjecturally in figures 10.6 and 10.7. These faults, and the faulted blocks of Ellesmerian(?) and older rocks, terminate upward at the low-dipping detachment surface at the base of the folded Brookian sequence. The Ellesmerian(?) rocks in the fault blocks appear to range in thickness from a feather edge between Franklinian and Brookian rocks near Cape Lisburne to a little more than 2 s (about 5.5 km) in the next fault block to the north.

HERALD ARCH OVERTHRUST

A belt of perched acoustic basement that trends northwest across the Chukchi shelf from Cape Lisburne has been named Herald arch (Grantz and others, 1975). This belt lies between the folded lower Brookian rocks of the Colville foredeep to the northeast, which it overlies structurally, and the young sedimentary rocks of Hope basin, which overlie it depositionally. The fault plane at the base of the perched acoustic basement was not recognized on the seismic profiles. However, a reflector inferred to represent the detachment fault at the base of the folded lower Brookian rocks can be traced at least 60 km southwest of Cape Lisburne, generally down the inferred dip of the fault plane.

The perched acoustic basement is tentatively interpreted to be the upper allochthonous plate of a large overthrust fault system that dips southwest at a low angle from the north side of Herald arch. The folded lower Brookian rocks below the overthrust fault are thought to form a lower allochthonous plate that in turn rests on the detachment fault discussed in the preceding section. The lower Brookian rocks extend at least 15 km southwest beneath the acoustic basement of the upper allochthonous plate, and a significant area and thickness of Ellesmerian rocks appears to underlie the lower allochthonous plate and its basal detachment fault. The sole faults underlying the upper and lower allochthons appear to merge west of the Lisburne Peninsula. The Tertiary Hope basin, which overlies the upper allochthonous plate west and south of Cape Lisburne, is thought to postdate the thrust faulting because it unconformably overlies an interpreted extension of the Herald arch and fault zone south of Point Hope.

Shallow seismic-refraction measurements obtained with a multichannel streamer divide the perched acoustic basement of Herald arch into two domains of shallow bedrock (0-0.5 km deep) that have contrasting ranges of compressional-wave seismic velocity V_p (figs. 10.8, 10.9). In the northern domain, V_p ranges from 3.1 to 4.0 km/s; in the southern domain, from 3.7 to 7.3 km/s. These velocities, a few dredge and dart-core samples, and projection of onshore geologic boundaries from the Lisburne Peninsula (Martin, 1970) indicate that the domain of shallow bedrock with lower V_p consists mainly of strongly deformed lower Brookian and perhaps upper Ellesmerian (post-Lisburne) sedimentary rocks. They also indicate that the domain of shallow bedrock with higher V_p consists, in places, of the Lisburne Group, Endicott Group, and Franklinian sequence and that these rocks are more common in this domain than Brookian rocks.

NORTH CHUKCHI BASIN

A tectonic hinge line at which the dip of Ellesmerian and Brookian beds and the thickness of the lower Brookian sequence increase to the north and west marks the south and east boundaries of the eastern part of the North Chukchi basin (figs. 10.2, 10.6, 10.8, 10.10). The position of the hinge line is imperfectly defined by three multichannel profiles (fig. 10.1), which do not adequately relate the hinge line to the lower Brookian isochrons.

The base of the Brookian sequence deepens, and the sequence thickens, from 2-3.5 s (about 2.5-5.5 km) on the Chukchi platform near the hinge line to more than 6 s (12 km) on our northernmost multichannel lines in the basin. Most of the increase in thickness is in the lower Brookian sequence, but some of it, especially in the east end of the basin, is in upper Brookian rocks. The former attains a thickness of at least 7 km, and the latter at least 5 km, in the basin. On one profile near the eastern margin of the basin, about 4 km of Ellesmerian rocks appear to underlie the lower Brookian beds.

Contrasting structural deformation in the tentatively identified lower and upper Brookian sequences of North Chukchi basin indicates that the basin probably formed in two stages of rifting. The first stage is recorded in the tectonic hinge line and the basinward thickening of the lower Brookian beds. It presumably correlates with the late Neocomian rifting event (Grantz and others, chapter 11; Grantz and May, 1983) that produced Canada Basin and the continental margin of the Alaskan Beaufort Sea. The second stage is recorded by numerous listric normal faults in the lower Brookian rocks of the eastern part of the North Chukchi basin. These faults are commonly antithetic, bound rotated fault blocks, and appear to extend into pre-Brookian rocks at moderate angles of dip. The faulting and rotation produced a structurally and paleomorphologically complex seabed surface that was smoothed soon after deformation by sedimentary infilling of the structurally produced low spots. The smoothed seabed was then covered by the only slightly faulted basin-fill sequence contoured in figure 10.10. Both the infilling sedimentary rocks and the subsequent basin fill are thought to belong to the upper Brookian sequence. If our correlation of the youngest sedimentary sequences of North Chukchi basin as the lower and upper Brookian is correct, the second stage of rifting originated in latest Cretaceous or earliest Tertiary time.

Crustal stretching related to the initial stages of a sea-floor spreading event according to the model of Montadert and others (1979), as observed in the Bay of Biscay, is thought to have induced the second stage of rifting observed in the eastern part of the North Chukchi basin. Stretching, expressed in the upper crust as listric normal faulting and rotated fault blocks, resulted in crustal thinning, subsidence of the sea floor over the thinned crust, and deepening of the basin. Initiation of the second stage of basin subsidence coincided with development of the listric faults in middle Brookian time. Faulting was in part older than, and in part coeval with, deposition of the basal upper Brookian lenticular sedimentary sequence that smoothed the block-faulted sea floor.

Diapirs are observed on single-channel seismic-reflection profiles to intrude the sedimentary rocks within or adjacent to North Chukchi basin. Two diapirs were actually traversed, and two others are inferred from isolated upwarps in otherwise flat-lying upper Brookian beds (Grantz and others, 1975). The upwarps resemble drag structure peripheral to the diapirs. The diapirs are piercement structures that rise to within 100 m of the seabed. The best studied diapir, located near lat 73° N., long 163° W. (fig. 10.10), is about 2 km in diameter and extends at least 3 km beneath the seabed. Low sonobuoy velocities, apparent lack of strong gravity or magnetic anomalies, and regional stratigraphy indicate that the diapirs are probably composed of shale rather than salt, gypsum, or igneous rock. On the basis of single-channel data, the diapirs are tentatively interpreted to originate in the lower Brookian or possibly the upper Ellesmerian sequence.

NUWUK BASIN

A thick clastic sedimentary prism, Nuwuk basin, was prograded northward across the faulted tectonic hinge line and continent-ocean boundary on the outermost northeastern Chukchi shelf (figs. 10.1, 10.2, 10.8). The basin contains a thickness of least 12 km of clastic sedimentary rocks of the lower and upper Brookian sequences derived from sourcelands to the south and southwest. Lower Brookian rocks appear to make up two-thirds or more of the section north of Barrow arch. Numerous large listric growth faults and related rotational megaslumps, or rollover anticlines, dominate the structure of Nuwuk basin. Additional information on the basin is given in Grantz and others (chapter 11). The extent of the basin to the northwest and its relation to the North Chukchi basin are not shown on our seismic lines.

PETROLEUM POTENTIAL

An assessment of the petroleum potential of the northern United States Chukchi shelf on the basis only of reconnaissance seismic-reflection data and a few dredge samples, but no subsurface information, is necessarily speculative. Nevertheless, the seismic data, augmented by the extrapolation of the results of petroleum exploration in the NPRA, permit a preliminary evaluation of the petroleum potential and relative prospectivity of various parts of the Chukchi shelf. The assessment is more objective in the eastern part of the shelf, adjacent to the NPRA, than elsewhere. A synopsis of general lithologic conditions relevant to the petroleum potential of the western North Slope, taken mainly from Bird (chapter 4) and Kirschner and Rycerski (chapter 9), Carter and others (1977), Bird and Andrews (1979), Guldenzopf and others (1980), Bird (1981), and Tetra Tech, Inc. (1982), is given below as background for evaluating the potential of the Chukchi shelf.

A preliminary map of petroleum prospectiveness of the Chukchi shelf is presented in figure 10.12. Most of the shelf is considered prospective because seismic data show that most of it is underlain by more than 1 km of Ellesmerian and Brookian sedimentary rocks. Small areas near the U.S.-Russia Convention line and on the crest of Barrow arch, incompletely outlined by our reconnaissance data, are considered not prospective because the sedimentary section in those areas appears to be less than 1 km thick. One kilometer is probably less than the minimum thickness of sedimentary rock that is prospective for petroleum because, barring truly exceptional discoveries, offshore oil and gas pools at shallower depths would require too many costly production platforms for development to be economically feasible. Prospectiveness in figure 10.12 is based solely on sedimentary thickness because subsurface data are lacking on the Chukchi shelf.

WESTERN NORTH SLOPE

STRATA

The general subsurface stratigraphy and structure, and the location and stratigraphic position of oil and gas pools and shows in the western NPRA, are shown in figures 10.1, 10.3, and 10.11. The Permian Echooka Formation (basal unit of the Sadlerochit Group) and all formations from the Shublik (Middle and Upper Triassic) to the Nanushuk Group (Albian and Cenomanian?) have yielded shows of oil or gas in test wells. However, neither the Lisburne Group (Pennsylvanian and Permian in the western NPRA) nor the Lower Triassic Ivishak Formation (uppermost unit of the Sadlerochit Group) has as yet yielded oil or gas in test wells west of Dease Inlet. These stratigraphic units do, however, produce oil or gas shows in test wells east of Dease Inlet, and they contain the major oil and gas accumulations at Prudhoe Bay. The hydrocarbon occurrences west of Dease Inlet include structurally trapped, subeconomic gas pools in Lower Jurassic sandstones in the South Barrow and East Barrow fields, which lie 15-20 km south of Point Barrow, and it is believed that additional small accumulations of similar type are likely to occur in the vicinity (Lantz, 1981). Sandstones of Early Cretaceous (pebble shale unit) age may also contain pools in combination stratigraphic-structural traps at the Iko Bay No. 1 and Walakpa Nos. 1 and 2 wells, 30-40 km southeast and southwest of Point Barrow, but these occurrences have not been adequately evaluated (Kirschner and Rycerski, chapter 9; Bird, 1981). Pre-Lisburne (Endicott Group) and post-Nanushuk (Colville Group and Sagavanirktok Formation) sedimentary strata have not been encountered in test wells west of Dease Inlet, even though many of the wells reached Ordovician and Silurian argillite.

In general, reservoir quality is better in the Ellesmerian shelf and shelf-basin deposits than in the Brookian sequence. The Ellesmerian sandstone beds are thicker, coarser, and cleaner to the north, toward their sourceland, and most of them shale out southward in an east-trending zone across the central NPRA. Reservoir quality in the Brookian rocks is harder to characterize. The Brookian sequence consists of thick deltaic and prodeltaic deposits that filled a foredeep and were deposited much more rapidly than the Ellesmerian rocks. The best reservoirs may be expected in the paralic and shallow marine facies of the intradelta and in submarine-fan turbidites at the foot of the prodelta slope.

Geochemical studies at the Prudhoe Bay field (Seifert and others, 1979) indicate that the oil there was derived from the Shublik Formation, Kingak Shale, and pebble shale unit, which agrees well with the occurrence of oil and gas shows in the western NPRA (fig. 10.11). The absence of shows in the Lisburne in the test wells of the western NPRA may be because permeability pathways have not connected them with petroleum source beds, or because they consist of the nondolomitic, light-colored Wahoo Limestone rather than the locally dolomitic and vuggy, dark-colored and shaly Alapah Limestone that contains the major Lisburne reservoirs at Prudhoe Bay. It is not certain, however, that the prospects drilled in the western NPRA are traps at the Lisburne level. Thermal alteration studies on the Inigok No. 1 well, in the eastern NPRA, indicate that the Endicott and Lisburne Groups are apt to be postmature and gas prone at depths below 3,600 m on the Arctic platform (Magoon and Claypool, 1982). These rocks lie at similar or greater depths in the western NPRA, where the thermal maturity of the surface formations, as estimated from vitrinite reflectance studies (Magoon and Bird, chapter 17), tends to be even higher than at Inigok No. 1.

The Lower Triassic Ivishak Formation of the Sadlerochit Group, the main reservoir at Prudhoe Bay, is represented by lutite in the western NPRA (Guldenzopf and others, 1980). The only significant sandstone in the Sadlerochit of the western NPRA occurs in a 30-km-wide band in the Upper Permian Ikiakpaurak Member of the Echooka Formation (Guldenzopf and others, 1980). This sandstone yielded minor gas shows in the Peard No. 1 well. It is about 50-60 m thick in the Peard No. 1 and Kugrua No. 1 wells and extends from a seismically mapped pinch-out about 10 km north of Wainwright to a shale-out several kilometers north of the Tunalik No. 1 well. It is separated from the source rocks of the Shublik Formation by the Kavik Member (of the Ivishak Formation) and the lutite facies that constitutes the Ivishak in the western NPRA. The gas shows may therefore have originated in the adjacent shales of the Sadlerochit Group.

The Middle and Upper Triassic Shublik Formation and Upper Triassic Sag River Sandstone, which are reservoirs for oil and gas at Prudhoe Bay, are possibly more prospective than the Sadlerochit in the western NPRA and the eastern Chukchi shelf. These units yield oil and gas shows in test wells west of Dease Inlet, and they contain sandstones that are in depositional contact with the Shublik Formation and Kingak Shale, which contain petroleum source rocks. Sandstone in the Shublik occurs in a west-southwest-striking belt 40 km or more wide that onlaps Barrow arch on the north and shales out a few kilometers north of the Kugrua No. 1 and Tunalik No. 1 wells. Sand/shale ratios in the Shublik are highest in the western NPRA, reaching values of 5.0 and 5.1, respectively, in the Walakpa No. 1 and Peard No. 1 wells, where the formation is about 90 m thick. The overlying Sag River Sandstone, mainly a lutite in the western NPRA, is 30-40 m thick and contains sandy barlike complexes of unknown extent at the Peard No. 1 and Kugrua No. 1 wells (Guldenzopf and others, 1980). Good prospects may also be found in the Kingak Shale, a westerly thickening Jurassic and Neocomian lutite that ranges in thickness from 500 m to more than 1,000 m in the western NPRA. The Kingak, a source rock at Prudhoe Bay, contains several sandstone units west of Dease Inlet, and some of these contain subeconomic or incompletely evaluated gas pools at the South Barrow and East Barrow fields and the Tunalik No. 1 test well. The sandstones, which may include transgressive nearshore and offshore barlike deposits and deep-water turbidites (Guldenzopf and others, 1980), appear to have been derived from northerly and northwesterly sources, and in general become more abundant toward the Chukchi shelf. In the western NPRA, the Kingak is truncated by the unconformity at the base of the upper Neocomian pebble shale unit, which could serve as both a source rock and reservoir seal for hydrocarbon deposits in Kingak sandstone in contact with the unconformity. Several thin sandstone bodies in the pebble shale unit may also have reservoir potential. One such body in the Peard No. 1 well, where the pebble shale unit is 116 m thick, is inferred to extend into the Chukchi shelf north of Icy Cape (Guldenzopf and others, 1980).

The Brookian rocks of the western NPRA were derived from sourcelands that lay to the south and southwest, and they consist of the interfingering Fortress Mountain and Torok Formations and the partly interfingering, partly overlying Nanushuk Group of Albian and Cenomanian(?) age. The mainly intradeltaic Nanushuk and the prodeltaic Torok both yield shows of oil and gas in the western NPRA. The shows in the Torok west of Dease Inlet are from foreset and bottomset turbidite and submarine-fan deposits (Kirschner and Rycerski, chapter 9). The Nanushuk Group contains several small oil and gas fields in the eastern NPRA and contains a small gas field (Meade) west of Dease Inlet. It is dominantly nonmarine and contains thick coal beds south of Point Lay, and it thins and becomes paralic and then shallow marine to the northeast (Chapman and Sable, 1960; Ahlbrandt, 1979). These conditions should result in improved reservoir quality in that direction. Accordingly, the Nanushuk is expected to be gas-prone and contain less capable reservoirs to the southwest, and to be more likely to contain oil and have more capable reservoirs to the north or northeast. An oil seep from the Nanushuk at Skull Cliff, 50 km southwest of Barrow (McKinnery and others, 1959), may support this contention.

THERMAL MATURATION

Vitrinite reflectance data and the rank of coal in test wells and outcrops provide some insight into the thermal history and possible stage of hydrocarbon generation and preservation in the sedimentary rocks of the western NPRA, but they do not reveal whether the rocks actually generated oil or gas. The vitrinite reflectance data are reported by Magoon and Claypool (1979, 1982), and we are grateful to them for access to their additional unpublished data. Data on coal rank were taken from Barnes (1967) and Conwell and Triplehorn (1976). Relation of coal rank to stages of hydrocarbon generation is from Héroux and others (1979), but we follow Magoon and Claypool (1982) in using vitrinite reflectance values of 0.6 and 2.0 for the top and base of the liquid window—the zone of oil and gas-condensate generation.

Vitrinite reflectance data indicate that equivalent stages of thermal maturation become shallower from the eastern and central to the western NPRA, indicating more uplift on the west (Magoon and Claypool, 1979). The data also imply that the top of the liquid window (the highest rocks that have experienced a thermal history capable of generating oil) lies about 0.3-1.0 km below the surface in the western NPRA between the latitude of Point Lay and the Peard No. 1 well (fig. 10.1). The rank of outcropping Albian coal in this area is subbituminous, which corresponds to the zone of wet-gas generation above the liquid window. North of Peard No. 1, the deepest prospective strata on basement are at the top of or above the liquid window, in the overlying zone of wet-gas generation. The base of the liquid window between the latitudes of Point Lay and Peard No. 1 in the western NPRA, as interpreted from vitrinite reflectance measurements, lies 2.3-3.4 km below the surface in the three wells that reached the underlying zone of overmature rocks. One test well and the rank of outcropping Albian coal indicate that surface rocks in the foothills of the Brooks Range south of the latitude of Point Lay are in the liquid window and that the base of the liquid window lies about 2.0 km below the surface. The rank of Endicott Group coal on the Lisburne Peninsula indicates that the Paleozoic rocks of the western Brooks Range and the upper allochthon of Herald arch are overmature for oil and for gas condensate and that former hydrocarbon liquids in these beds would now be dry gas. The vitrinite reflectance values also indicate that, in the eastern half of the United States Chukchi shelf, upper Paleozoic and Triassic strata are overmature from Icy Cape or Wainwright south, and that the lower part of the lower Brookian sequence and older strata are overmature from the general latitude of Point Lay south.

UNITED STATES CHUKCHI SHELF NORTH OF POINT HOPE

BARROW ARCH AND ARCTIC PLATFORM

The petroleum potential of the Arctic platform (area 1 in fig. 10.12) is much like that of the western NPRA, which it adjoins. Offshore seismic data and projection of onshore stratigraphy and thermal maturation data indicate that in area 1 sandstones from the Permian and Triassic Sadlerochit Group to the lower part of the Albian and Cenomanian(?) Nanushuk Group may be in contact with adequate source rocks and could contain significant pools of oil and, especially, gas. To date, only some subeconomic or inadequately evaluated gas deposits have been found in the adjacent onshore area. Subsurface data (Kirschner and Rycerski, chapter 9; Guldenzopf and others, 1980) indicate, however, that sandstone beds in the Middle Triassic to Lower Cretaceous section (the Shublik Formation, Sag River Sandstone, Kingak Shale, and pebble shale unit), which locally attain significant thickness in the western NPRA, may be even thicker, more numerous, and perhaps better reservoirs in area 1. If structural traps exist in this area, they have very low amplitude and have not been recognized on our reconnaissance seismic network. Stratigraphic traps caused by permeability gradients or shale oversteps at one of several unconformities in the section may occur. If present, such traps could be very large because of the uniform but low regional dip. Eo-Ellesmerian and Lisburne strata in area 1 are probably overmature and at best would contain dry gas. A large but incompletely defined area on the crest of Barrow arch is underlain by less than 1 km of post-Franklinian sedimentary rocks and is therefore considered nonprospective.

The petroleum potential of the pre-Ellesmerian strata that underlie Barrow arch in the northeastern Chukchi Sea is equivocal. These beds, interpreted by Grantz and May (1983) to be of early Paleozoic and perhaps Precambrian age, are well bedded, slightly deformed, and more than 10 km thick. Seismic velocities (V_p) measured in the upper part of this section with sonobuoys range from 4.15 to at least 5.35 km/s, and in the lower part from 5.70 to 7.30 km/s (Houtz and others, 1981). These velocities equal or exceed those found in the strongly deformed Ordovician and Silurian argillite and graywacke that underlie the Ellesmerian rocks of the North Slope. The reflections that define these strata beneath the northern Chukchi Sea lose their coherence near the Alaskan coast; they may represent an undeformed equivalent of the Ordovician, Silurian, and underlying older rocks of the North Slope. In any case, the pre-Ellesmerian age of these strata (which are therefore older than the Ellesmerian orogeny) and their high seismic velocities indicate that their petroleum potential is slight.

HANNA TROUGH

Economically significant oil and gas deposits could be present in Hanna trough (area 2 in fig. 10.12) because the trough contains a very thick section of sedimentary rocks. Some large folds involving basement, locally numerous faults, and rotated fault blocks provide possible oil traps. In addition to the area shown in figure 10.12, the trough may extend north of lat 72° N., but we have no multichannel seismic reflection data there.

If the thermal history of the sedimentary rocks in Hanna trough is similar to that found in the Tunalik No. 1 well, the Eo-Ellesmerian and most of the Ellesmerian section are overmature and could only contain dry gas. Ellesmerian and Brookian strata thicken into Hanna trough (figs. 10.5-10.8), but the nature of any accompanying facies changes is conjectural. The marked thickening of the Ellesmerian beds into the trough (fig. 10.7) indicates that it may there be in a basinal facies, perhaps dominated by lutite, and possibly containing turbidite beds. Although these thickened deposits are probably themselves now overmature, they could have generated oil or gas at an earlier time—oil and gas that migrated out of the trough into possible reservoirs on the flanks, where subsequent thermal alteration was less intense.

The presence of westward-increasing amounts of sandstone of northern and northwestern provenance in the Shublik-pebble shale unit interval in the western NPRA indicates that the broad crestal region of the present Barrow arch east of Hanna trough was part of a more extensive sourceland for detrital sediment through late Ellesmerian time. This sourceland might also have furnished reservoir sands to the upper Ellesmerian section of Hanna trough. Most of the upper Ellesmerian rocks are probably in the liquid window in most parts of Hanna trough.

The thickening of the lower and upper Brookian sequences into Hanna trough (figs. 10.8, 10.10) may have also created conditions favorable for the generation and entrapment of oil and gas. Extrapolation of thermal conditions and facies patterns from the western NPRA indicates that at least part of the lower Brookian sequence in Hanna trough is in the liquid window and that in places the section probably contains paralic and shallow marine beds that could include winnowed sands. In addition, the deeper parts of the fill in the late Brookian canyon (fig. 10.10) might also be in the upper part of the liquid window, but we have no thermal data from which to judge whether this is indeed the case. The upper Brookian canyon fill and the adjacent wallrocks could contain hydrocarbon traps where reservoir sands or sealing shale beds of the fill are in contact with lower Brookian source beds or sands in the canyon walls. Faults and rotated fault blocks, which are locally numerous in the canyon fill and adjacent wallrocks, may have created structural traps in both the lower and upper Brookian beds.

CHUKCHI PLATFORM

The westward thinning and shallowing of Ellesmerian and Brookian strata in area 3 on the Chukchi platform (fig. 10.12) indicate that a structural high or former sediment sourceland probably lay to the west. If it did, these rocks could contain good reservoir beds analogous to the north-derived sandstone and conglomerate beds that are productive at Prudhoe Bay and elsewhere on the North Slope. Hydrocarbon fluids could have entered these beds from interlayered source beds or migrated into them from shales that lay downdip in Hanna trough. Much of the Ellesmerian and lower Brookian section in the eastern part of area 3 may be in the liquid window, but extrapolating thermal conditions this far offshore from the western NPRA is speculative at best. If source and reservoir beds are present in area 3, the presence of numerous normal faults, overlaps at unconformities, some folds, and possibly updip pinchouts may provide traps, but our reconnaissance seismic grid does not demonstrate whether closed structures are present. The eastern and central parts of area 3 are more prospective than the western part, where the total post-Franklinian sedimentary section thins to less than 1 km.

FORELAND FOLD BELT

Extrapolation of thermal maturation conditions from the western NPRA indicates that the top of the liquid window in the foreland fold belt (area 4 in fig. 10.12) is at the surface, or has been removed by erosion, from near Point Lay south. North of Point Lay, the top of the window deepens to about 1 km opposite the northern part of area 4. The vertical height of the liquid window in the Tunalik No. 1 and Awuna No. 1 wells of the western NPRA (Magoon and Bird, chapter 17) is about 2.0-2.5 km, which implies that most of the Ellesmerian sequence, and in places the lower part of the lower Brookian sequence in the broad structural low off Point Lay, are overmature and now contain only dry gas. All or most of the lower Brookian sequence, on the other hand, appears to lie within the liquid window and could have generated and preserved oil and gas condensate.

Broad folds and fault blocks in the Ellesmerian strata below the detachment fault that underlies area 4 offer possible structural traps for gas, but the extrapolation of stratigraphic trends from the western NPRA suggests that adequate reservoirs may be lacking. The numerous large folds and thrust folds in the lower Brookian rocks above the detachment fault are probably the most prospective structures in area 4. Thrust faults, however, disrupt the cores of many of the folds in the central and southern parts of area 4 and may reduce their capacity to hold hydrocarbon fluids. The folds may also be largely within the Nanushuk intradelta deposits, which are less likely to contain winnowed sandstones of paralic and neritic facies and therefore have poorer prospects for oil than their equivalents in the eastern and north-central NPRA, where the Nanushuk contains several small oil and gas fields.

HERALD ARCH OVERTHRUST BELT

Brookian rocks in the Herald arch overthrust belt (area 5 in fig. 10.12) are probably too strongly deformed by listric thrusts and thrust folds, related to the underlying detachment fault zone, to have significant petroleum potential. Extrapolation of onshore data indicates that both the perched Ellesmerian rocks in the overthrust and those that underlie the detachment fault are overmature for hydrocarbon liquids in the southeastern part of area 5, and the overlying Ellesmerian rocks are, in addition, probably too strongly faulted to be prospective. If Ellesmerian rocks are present beneath the detachment fault zone in the northwestern part of area 5, where the Brookian sequence is thinner, they may have escaped deep burial and overmaturation and might be comparable in potential to the Ellesmerian rocks on the Chukchi platform (area 3).

NORTH CHUKCHI BASIN

It is inferred that the Brookian sequence of the eastern North Chukchi basin (area 6 in fig. 10.12) contains a substantial or dominant component of marine sedimentary rocks, and therefore source beds for oil and gas are likely to be present. Strong reflectors in both sequences also indicate that many sandstone and perhaps conglomerate beds that could serve as reservoirs may be present. This interpretation is supported by the observed westward thinning of Brookian sedimentary units on the Chukchi platform. A sourceland in that direction would have been much closer to the North Chukchi basin than the Brooks Range sourceland was to the Brookian clastic deposits of the North Slope, and this could have resulted in the delivery of coarser detritus to the basin. The numerous listric normal faults and rotated fault blocks that characterize the lower Brookian sequence in the eastern North Chukchi basin may provide large structural traps. The prospectiveness of these traps may be enhanced by the locally thick, early postfaulting infilling sedimentary unit that unconformably overlies the fault blocks. The infilling unit has weaker seismic reflectors than the sequences above and below, and it probably contains more shale. It could have served as a seal for hydrocarbon fluids in the underlying faulted rocks, and also as a hydrocarbon source. Where the infilling unit is absent, the base of the upper Brookian sequence unconformably overlies the faulted beds and may have placed sealing or reservoir beds across truncated sandstones and shales of the lower sequence. The upper Brookian rocks offer possible traps against small normal faults, in a few very low amplitude folds (closure not demonstrated), against possible updip permeability barriers or pinchouts, and around shale(?) diapirs.

Assessment of the petroleum potential of the North Chukchi basin is particularly sensitive to its thermal history. In the absence of data, we have applied the position of the liquid window in the partially analogous Norton basin to the North Chukchi basin. Fisher (1982) estimates that in the extensional, epicontinental Norton basin, having an assumed moderately high heat flow, the liquid window may lie about 2.8-5.0 km below the sea bottom. In the North Chukchi basin, a liquid window in this range would intersect the structurally important boundary between the extensively faulted lower Brookian and the little-faulted upper Brookian sequences. If the Norton basin model or one that assumes a less intense thermal history is realistic, then a substantial part of the faulted lower Brookian section and perhaps the deeper part of the little-faulted upper Brookian section are in the liquid window. However, if the basin had two episodes of crustal thinning and subsidence, as proposed in an earlier section, then most of the lower Brookian sequence and the deeper part of the upper Brookian section may be overmature, and the liquid window might encompass the lower part of the upper sequence and only the structurally highest parts of the lower sequence. The Norton basin model or models involving a cooler thermal history would thus place substantially more of the very prospective block-faulted lower Brookian sequence in the liquid window than the two-stage model. However, even the latter model places a large volume of lower Brookian rocks at the margins of the basin in the liquid window, and the overmature rocks could contain substantial deposits of dry gas. In addition, some faults cut both the lower and upper Brookian sequences, and these faults might have provided pathways for the migration of hydrocarbon fluids out of the lower sequence into higher reservoirs before the lower sequence became overmature. Updip migration of hydrocarbon fluids in the little-faulted upper sequence might have achieved a similar result.

NUWUK BASIN

A thick clastic sedimentary section, numerous growth faults and rollover anticlines, and some strong seismic reflectors that may represent sandstone beds indicate that Nuwuk basin (area 7 in fig. 10.12) may have good prospects for petroleum. A more complete discussion of the petroleum potential of the basin, which is better known on the Beaufort shelf, is given in Grantz and others (chapter 11).

RELATIVE PROSPECTIVENESS OF THE STRUCTURAL PROVINCES

Ranking the relative petroleum potential of the seven structural provinces of the northern United States Chukchi shelf from available data is highly speculative. Subsurface information in areas 2, 3, and 6 is especially needed. Nevertheless, despite the logistic and engineering problems posed by the Arctic climate and polar ice pack, the Arctic platform east of Hanna trough (area 1), Hanna trough (area 2), the Chukchi platform (area 3), eastern North Chukchi basin (area 6), and Nuwuk basin (area 7) appear to have potential for significant deposits of oil or gas. However, in large parts of these areas, stratigraphic traps that are difficult to define will have to be sought. Exploration in the western NPRA indicates that in at least the eastern part of area 1 the potential may be greater for gas than for oil. The foreland fold belt (area 4) is estimated to have modest potential for significant deposits of oil and gas, and it may be gas prone. Structural complexity and estimated thermal conditions indicate that most of the Herald arch overthrust belt (area 5) has a low potential for significant deposits of oil or gas. The northwest part of area 5 may have some potential in Ellesmerian rocks beneath the overthrust faults, but our data there are inadequate for assessment.

REFERENCES CITED

Ahlbrandt, T.S., ed., 1979, Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, 163 p.

Alaska Geological Society, 1981, West to east stratigraphic correlation section, N.P.R.A.-Prudhoe Bay, Arctic Slope, Alaska: Anchorage, Alaska Geological Society, 1 sheet.

Barnes, F.F., 1967, Coal resources of the Cape Lisburne-Colville River region, Alaska: U.S. Geological Survey Bulletin 1242-E, 37 p.

Bird, K.J., 1981, Petroleum exploration of the North Slope in Alaska, U.S.A.: U.S. Geological Survey Open-File Report 81-227, 43 p.

——— 1982, Rock-unit reports of 228 wells drilled on the North Slope, Alaska: U.S. Geological Survey Open-File Report 82-278, 105 p.

Bird, K.J., and Andrews, Jack, 1979, Subsurface studies of the Nanushuk Group, North Slope, Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 32-41.

Carlson, P.R., and Karl, H.A., 1984, Discovery of two new large submarine canyons in the Bering Sea: Marine Geology, v. 56, p. 159-179.

Carter, R.D., Mull, C.G., Bird, K.J., and Powers, R.B., 1977, The petroleum geology and hydrocarbon potential of Naval Petroleum Reserve No. 4, North Slope, Alaska: U.S. Geological Survey Open-File Report 77-475, 61 p.

Chapman, R.M., and Sable, E.C., 1960, Geology of the Utukok-Corwin region, northwestern Alaska: U.S. Geological Survey Professional Paper 303-C, p. 47-167.

Conwell, C.N., and Triplehorn, D.M., 1976, High-quality coal near Point Hope, northwestern Alaska, *in* Short notes on Alaskan geology—1976: Alaska Division of Geological and Geophysical Surveys Geologic Report 51, p. 31-35.

Fisher, M.A., 1982, Petroleum geology of Norton basin, Alaska: American Association of Petroleum Geologists Bulletin, v. 66, p. 286-301.

Grantz, Arthur, Eittreim, Stephen, and Whitney, O.T., 1981, Geology and physiography of the continental margin north of Alaska and implications for origin of the Canada Basin, *in* Nairn, A.E.M., Churkin, Michael, Jr., and Stehli, F.G., eds., The Arctic Ocean: The ocean basins and margins, v. 5, p. 439-492.

Grantz, Arthur, Holmes, M.L., and Kososki, B.A., 1975, Geologic framework of the Alaskan continental terrace in the Chukchi and Beaufort Seas, *in* Yorath, C.J., Parker, E.R., and Glass, D.J., eds., Canada's continental margins and offshore petroleum exploration: Canadian Society of Petroleum Geologists Memoir 4, p. 669-700. [Also *as* U.S. Geological Survey Open-File Report 75-124]

Grantz, Arthur, and May, S.D., 1983, Rifting history and structural development of the continental margin north of

Alaska, *in* Watkins, J.S., and Drake, C.L., eds., Studies in continental margin geology: American Association of Petroleum Geologists Memoir 34, p. 77-100.

Guldenzopf, E.C., Orlovsky, M.B., Higgs, D.A., Freytag, C.G., and Ovalle, E.R., 1980, National Petroleum Reserve, Alaska, Summary geological report fiscal year 1980: Tetra Tech, Inc., *for* Husky Oil NPR Operations, Inc., under contract to U.S. Geological Survey, 41 p.

Héroux, Yvon, Chagnon, André, and Bertrand, Rudolf, 1979, Compilation and correlation of major thermal maturation indicators: American Association of Petroleum Geologists Bulletin, v. 63, no. 12, p. 2128-2144.

Houtz, R. E., Eittreim, Stephen, and Grantz, Arthur, 1981, Acoustic properties of northern Alaskan shelves in relation to the regional geology: Journal of Geophysical Research, v. 86, no. B5, p. 3932-3943.

Lantz, R.J., 1981, Barrow gas fields—North Slope, Alaska: Oil and Gas Journal, v. 79, no. 13, p. 197-200.

Lathram, E.H., 1965, Preliminary geologic map of northern Alaska: U.S. Geological Survey open-file report, scale 1:1,000,000, 2 sheets.

Magoon, L.B., and Claypool, G.E., 1979, Hydrocarbon source potential of the Nanushuk Group and the Torok Formation, a preliminary report, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 54-60.

—— 1982, NPRA Inigok No. 1—use of Lopatin's method to reconstruct thermal maturity: Pacific Petroleum Geologist Newsletter, American Association of Petroleum Geologists, Pacific Section, p. 4-6.

Martin, A.J., 1970, Structure and tectonic history of the Western Brooks Range, De Long Mountains and Lisburne Hills, northern Alaska: Geological Society of America Bulletin, v. 81, p. 3605-3622.

McKinnery, C.M., Garton, E.L., and Schwartz, F.G., 1959, Analyses of some crude oils from Alaska: U.S. Bureau of Mines, Department of Investigation Report 5447, 29 p.

Miller, C.C., Pickard, J.E., Taber, E.C., and Rogers, R.B., 1979, National Petroleum Reserve, Alaska; Summary geophysical report fiscal year 1979: Tetra Tech., Inc., *for* Husky Oil NPR Operations, Inc., under contract to U.S. Geological Survey, 18 p.

Molenaar, C.M., 1981, Depositional history and seismic stratigraphy of Lower Cretaceous rocks, National Petroleum Reserve in Alaska and adjacent areas: U.S. Geological Survey Open-File Report 81-1084, 42 p.

Montadert, L., Roberts, D.G., De Charpal, O., and Guennoc, P., 1979, Rifting and subsidence of the northern continental margin of the Bay of Biscay, *in* Initial Reports of the Deep Sea Drilling Project: Washington, U.S. Government Printing Office, v. 48, p. 1025-1060.

National Petroleum Council, 1981, U.S. Arctic oil and gas: Washington, National Petroleum Council, 286 p.

Seifert, W.K., Moldowan, J.M., and Jones, R.W., 1979, Application of biological marker chemistry to petroleum exploration, *in* World Petroleum Congress, 10th, Bucharest, 1979, Proceedings: London, Heyden and Sons, v. 2, p. 425-440.

Tetra Tech, Inc., 1982, Petroleum exploration of NPRA, 1974-1981: Houston, Tex., Energy Management Division Report 8200, *for* Husky Oil NPRA Operations, Inc., Anchorage, Alaska, under contract to U.S. Geological Survey, 183 p.

11. GEOLOGIC FRAMEWORK, PETROLEUM POTENTIAL, AND ENVIRONMENTAL GEOLOGY OF THE UNITED STATES BEAUFORT AND NORTHEASTERNMOST CHUKCHI SEAS

By Arthur Grantz, Steven D. May, and David A. Dinter

INTRODUCTION

The Beaufort and northeasternmost Chukchi Seas (fig. 11.1) offer petroleum explorationists a promising terrane for medium to giant oil and gas accumulations, but the area is the most environmentally difficult region for petroleum exploration and development in the Nation. Despite the difficulties, however, the National Petroleum Council (1981, p. 5) estimates that "proven technology and sufficient information and technical expertise for advanced design work is available for the industry to proceed confidently with operations in water as deep as 650 feet in the southern Bering Sea and to about 200 feet in the more severely ice-covered areas of the northern Bering, Chukchi, and Beaufort Seas." The region lies adjacent to the North Slope of Alaska, which is served by the Trans-Alaska Pipeline System (TAPS), a common carrier that would provide an outlet for oil brought to its northern terminus near Prudhoe Bay. If the proposed Alaska Natural Gas Transportation System is also built, its pipeline and terminus near Prudhoe Bay would provide the means for carrying offshore natural gas to market. The feasibility of economically transporting large volumes of oil or gas by tanker year-round from the Beaufort Sea to markets in the conterminous United States has yet to be demonstrated.

This chapter gives an overview of the geologic framework, petroleum potential, and environmental geology of the Alaskan Beaufort and northeasternmost Chukchi Seas. The principal data base consists of the multichannel seismic-reflection profiles and accompanying high-resolution profiles shown in figure 11.1 and some additional single-channel seismic-reflection profiles, sonobuoy refraction measurements, seabed samples, and bathymetric data. The study area includes the entire Outer Continental Shelf (OCS) in the Alaskan Beaufort Sea and most of the OCS in the northeastern Chukchi Sea (fig. 11.1). Most of the continental shelf north of Alaska consists of areas shallower than 60 m (200 ft), where the National Petroleum Council considers that the petroleum industry can now confidently proceed with operations. Sea-ice conditions in this area during late September, the usual period of maximum retreat, are shown in figure 11.2. The base maps in this report use the conformal polar stereographic projection. East of long 158°00′ W., the planimetry and bathymetry are from Greenberg and others (1981). West of long 158°00′ W., they are from U.S. Naval Oceanographic Chart N.O. 16002, published by the Defense Mapping Agency's Hydrographic Center, Washington, DC 20390.

GEOLOGIC FRAMEWORK

The continental shelf in the study area is conveniently divided into two sectors of contrasting geologic structure. The western (Barrow) sector is dominated by the Barrow arch and extends from the northeast Chukchi Sea eastward to near long 147° W. The eastern (Barter Island) sector extends from there to the Canadian border. For convenience in describing its petroleum potential, the region has been further divided into six petroleum provinces and five subprovinces. The areal extent of these provinces and their relations to the major geologic and physiographic features of the region are shown in figure 11.3. The stratigraphy and structure of northern Alaska and of the Beaufort and northeastern Chukchi shelves are shown in figures 11.4 and 11.5, respectively. Figure 11.6 gives the approximate relation between depth and seismic-reflection times in this region. The thickness of sedimentary rocks above the Franklinian sequence, which is considered to be basement for oil and gas deposits on the Beaufort shelf, is given in figure 11.7, and typical cross-sections and seismic profiles are presented in figures 11.8-11.16. Data for this report are mainly from Eittreim and Grantz (1979), Grantz and others (1979, 1981), and Grantz and May (1983). Data for the onshore areas are from Alaska Geological Society (1971, 1972, 1977, 1981), Brosgé and Tailleur (1971), Jones and Speers

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(1976), Grantz and Mull (1978), Tailleur and others (1978), Miller and others (1979), and Guldenzopf and others (1980).

SEDIMENTARY SEQUENCES

The sedimentary strata of northern Alaska and the Beaufort shelf are conveniently grouped into three regionally extensive sequences of contrasting lithology, tectonic character, and hydrocarbon potential (figs. 11.4, 11.8). The Cambrian to Devonian Franklinian sequence, consisting of mildly to strongly metamorphosed sedimentary and some volcanic rocks that are in places intruded by granitic plutons, is inferred to constitute economic basement. Following mild metamorphism and regional deformation, an extensive platform was cut across the Franklinian rocks in Late Devonian and Early Mississippian time. This, the Arctic platform, was a surface of low relief that remained fairly stable from Early Mississippian to Neocomian (Early Cretaceous) time, an interval of more than 200 m.y. During this time a lithologically diverse suite of clastic and carbonate sedimentary rocks, the Ellesmerian sequence, was deposited on the platform. This sequence contains both marine and nonmarine beds, including stratigraphically condensed organic-rich shale, texturally mature sandstone and conglomerate, and some dolomitized limestone. Clastic components were derived from a source terrane in the area of the present outer Beaufort shelf and farther north.

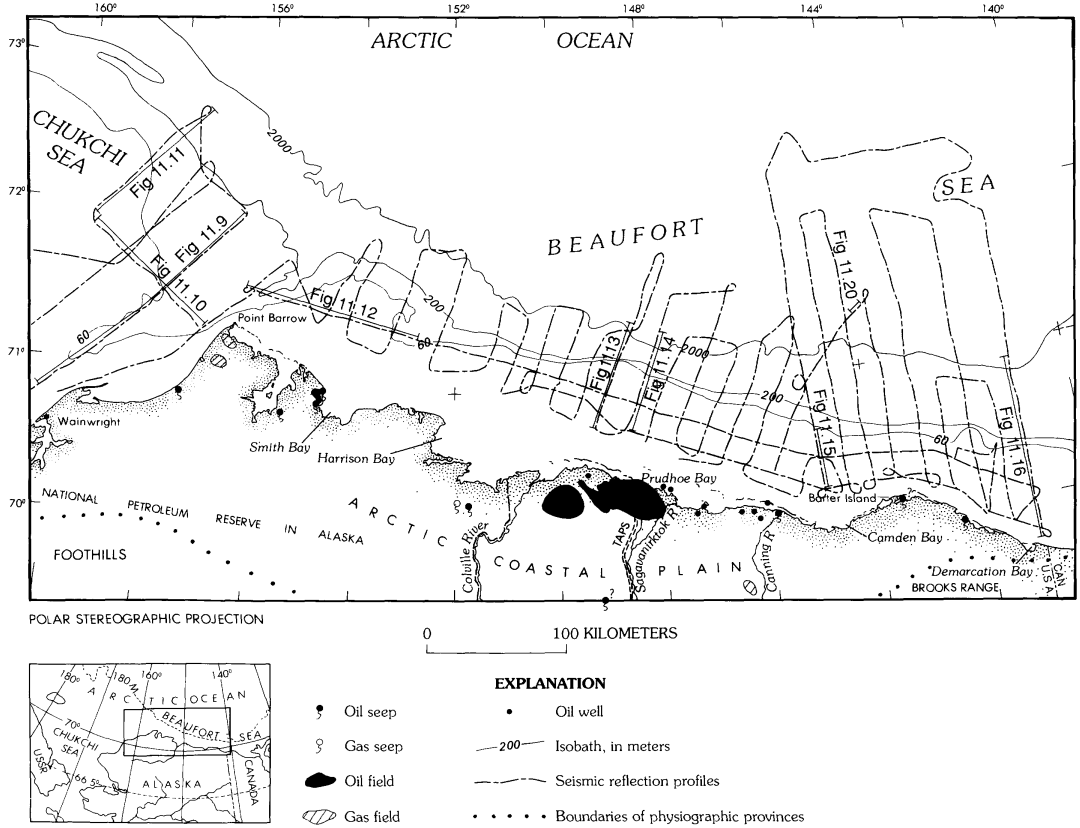


FIGURE 11.1.—Alaskan Beaufort and northeasternmost Chukchi Seas, showing oil and gas fields and seeps in northern Alaska, the Trans-Alaska Pipeline System (TAPS), USGS multichannel seismic-reflection profile lines, and locations of geologic cross sections shown in figures 11.9-11.16 and 11.20.

In Early Jurassic time the northern part of the Arctic platform, the source terrane for the Ellesmerian shelf sediments, was separated from northern Alaska by an incipient rifting event that disrupted earlier sedimentation patterns in the eastern Beaufort Sea (Grantz and May, 1983). This event was followed in Late Neocomian (mid-Early Cretaceous) time by the main rifting event that created the present continental margin of northern Alaska. Beginning in latest Jurassic or earliest Cretaceous time, and continuing to mid-Cretaceous time, the Arctic platform was tilted down to the south and overridden by nappes from newly formed tectonic highlands in the area of the present Brooks Range. An asymmetric foreland basin, the Colville foredeep, formed on the southward-tilted platform and received large volumes of sediment from the nascent Brooks Range to the south. Because of their provenance, these deposits have been named the Brookian sequence by Lerand (1973). The section in the Colville foredeep consists of Upper Jurassic(?) to Cretaceous and, on the eastern North Slope, Tertiary clastic sedimentary rocks. In the southern part of the asymmetric foredeep, where it consists mainly of Upper Jurassic(?) and Lower Cretaceous flysch and mid- and Upper Cretaceous molasse, the Brookian section is more than 9,000 m thick. The sequence thins northward to between 500 m and 2,000 m, and its basal beds are Albian in age where it onlaps the Barrow arch beneath the northern North Slope, northeastern Chukchi Sea, and Beaufort shelf. The younger beds of the Brookian sequence overtop the Barrow arch and thicken northward beneath the outer continental shelf.

BARROW SECTOR

The Barrow arch, a broad basement high that trends parallel to the coast, is the dominant structure of the Barrow sector of the Beaufort shelf. The south flank of the arch is defined by the south-sloping Arctic platform; the north flank is defined by the Arctic platform where it dips north beneath the Beaufort shelf. Faulting, erosion, and tilting on the arch during and soon after the rifting created the oil-bearing structure at Prudhoe Bay.

The position of the tectonic hinge line produced by postrift subsidence with respect to the structural shelf break off northern Alaska largely determines the distribution of geologic provinces—the Arctic platform, Dinkum graben, and Nuwuk basin—beneath the continental shelf and slope in the Barrow sector (fig. 11.3). Some of the geologic features of the Barrow sector are encountered in test wells on the North Slope of Alaska. Others, however, are absent from the North Slope and are known only from seismic-reflection and sonobuoy refraction data.

ARCTIC PLATFORM

The Arctic platform (figs. 11.7, 11.9-11.13) extends offshore from northern Alaska with typically gentle dips to the tectonic hinge line (figs. 11.5, 11.7, 11.11-11.14) beneath the shelf, where it is bent down to the north and is faulted in some places. The crest of the broad Barrow arch (figs. 11.5, 11.7, 11.9), which formed initially during mid-Early Cretaceous rifting, underlies the continental shelf west of Point Barrow and between Smith Bay and the Colville River delta. The northern edge of the Ellesmerian sequence of clastic and carbonate rocks, which contains the giant oil

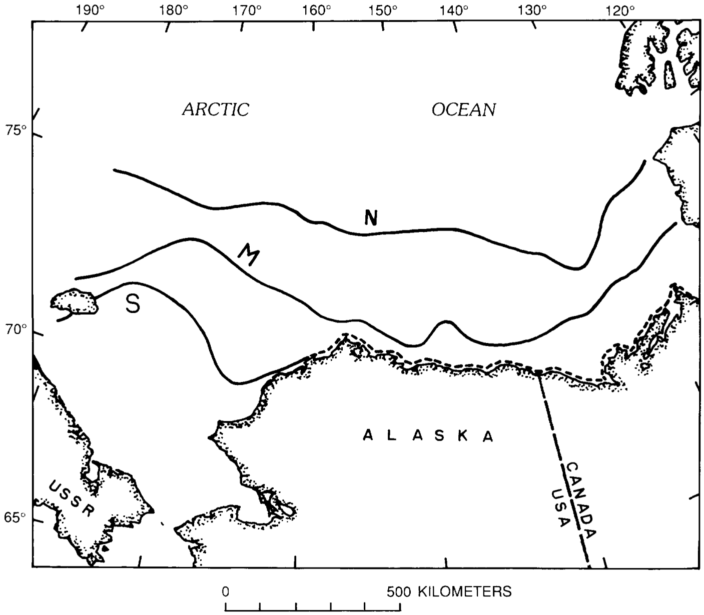
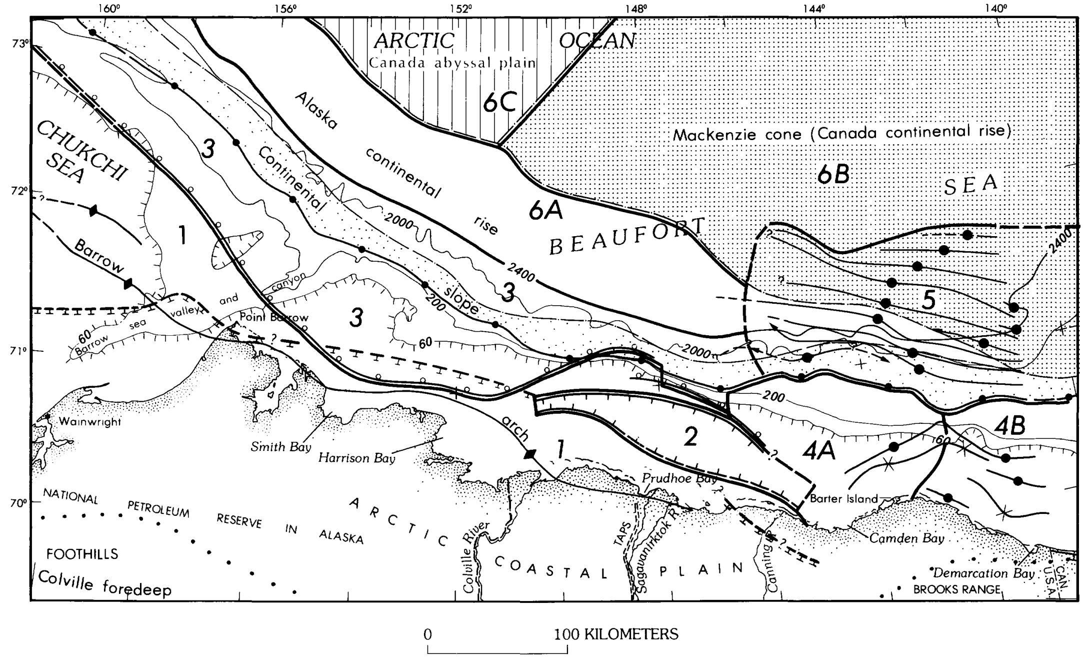


FIGURE 11.2.—Most northerly (N), most southerly (S), and median (M) positions of southern edge of Arctic ice pack north of Alaska during usual period of maximum retreat, September 16 to 30, based on data from 1954 through 1970 (after Brower and others, 1977).

and gas deposits near Prudhoe Bay and small gas deposits near Barrow, also extends offshore. A rough estimate of the offshore position of this edge, based mainly on projection of onshore trends, is shown in figures 11.3 and 11.5. Seaward of the wedge edge of the Ellesmerian beds, the Arctic platform and the



EXPLANATION

Boundary of petroleum provinces. Dashed where approximately located. Provinces are—

1	Arctic platform
2	Dinkum graben west of Kaktovik basin
3	Nuwuk basin
	Kaktovik basin
4A	West Kaktovik basin (area west of diapiric shale ridges)
4B	East Kaktovik basin (area of diapiric shale ridges and related Tertiary subbasins)
5	Diapiric fold province (minimum extent shown)
	Canada Basin
6A	Alaska continental rise seaward of 2,400-m isobath
6B	Mackenzie cone of Canada continental rise exclusive of diapiric fold province
6C	Abyssal plain

Boundary of physiographic provinces seaward of shelf break. Selected provinces highlighted by patterns

Structural shelf break

200 Isobath, in meters

60 60-m isobath. Current limit of petroleum operations (National Petroleum Council, 1981)

Approximate north limit of pre-pebble shale unit Ellesmerian rocks

Hinge line. Circles on downwarped side, dashed where projected

Normal fault. Hachures on downthrown side, dashed where projected

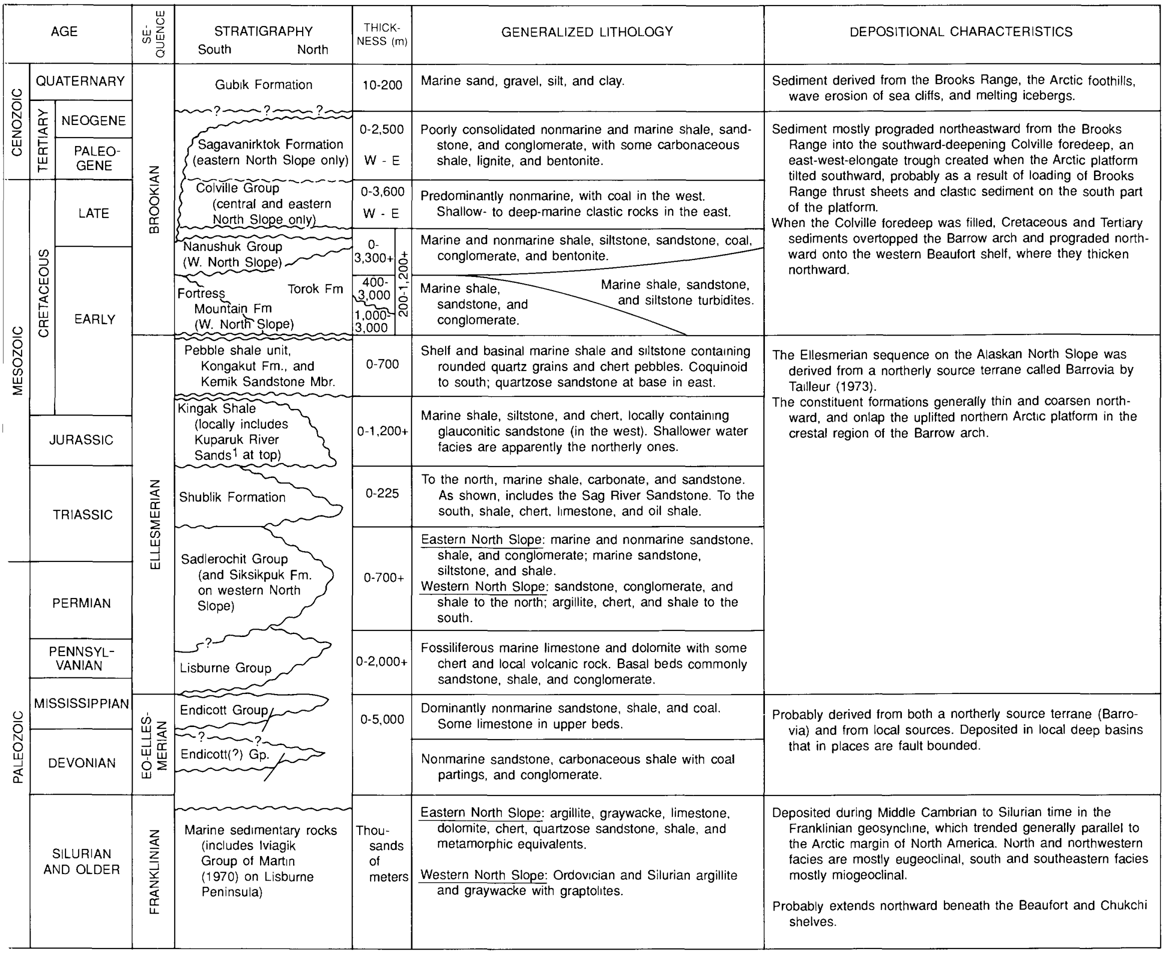
Arch

Syncline

Detachment anticline above thrust fault—Dashed where projected or inferred. Arrows indicate plunge direction

FIGURE 11.3.—Petroleum provinces of the Alaskan Beaufort and northeasternmost Chukchi Seas. TAPS, Trans-Alaska Pipeline System. Dotted lines separate onshore physiographic provinces.

Franklinian sequence (economic basement) into which it was cut are directly overlain by upper Lower Cretaceous to Tertiary rocks of the Brookian sequence. The Ellesmerian strata on the Arctic platform range upward in thickness from the wedge edge to 1,000 m or more near the coast (Alaska Geological Society, 1977). The overlying Brookian rocks range in thickness from 300 m or less in the crestal



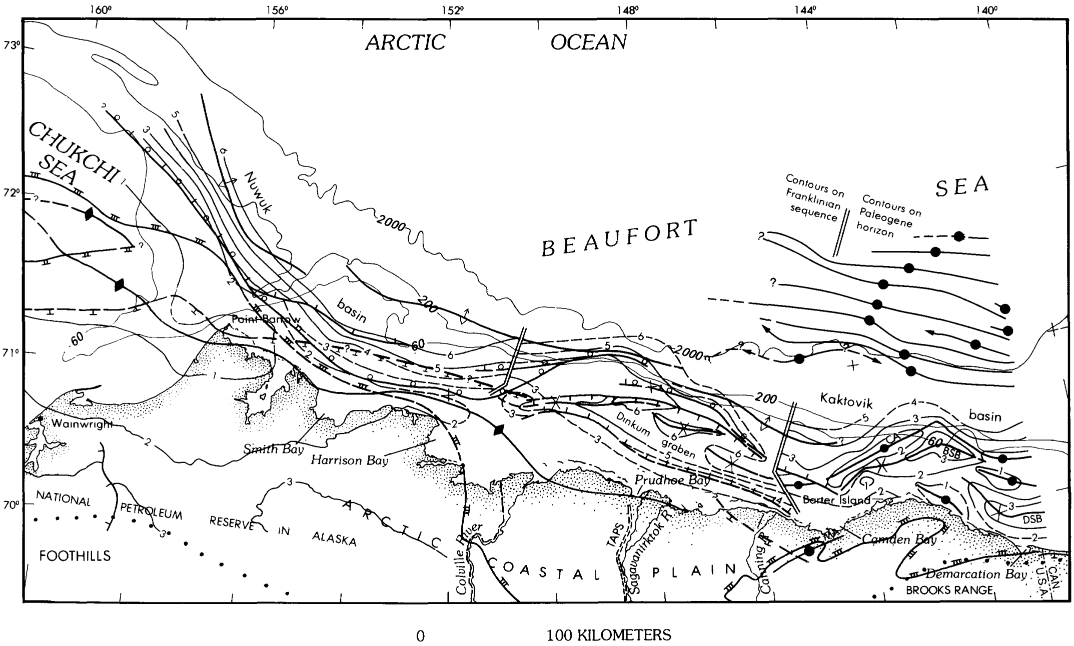
AGE			SE-QUENCE	STRATIGRAPHY South North	THICK-NESS (m)	GENERALIZED LITHOLOGY	DEPOSITIONAL CHARACTERISTICS
CENOZOIC	QUATERNARY		BROOKIAN	Gubik Formation	10-200	Marine sand, gravel, silt, and clay.	Sediment derived from the Brooks Range, the Arctic foothills, wave erosion of sea cliffs, and melting icebergs.
	TERTIARY	NEOGENE PALEOGENE		? ? ? Sagavanirktok Formation (eastern North Slope only)	0-2,500 W - E	Poorly consolidated nonmarine and marine shale, sandstone, and conglomerate, with some carbonaceous shale, lignite, and bentonite.	Sediment mostly prograded northeastward from the Brooks Range into the southward-deepening Colville foredeep, an east-west-elongate trough created when the Arctic platform tilted southward, probably as a result of loading of Brooks Range thrust sheets and clastic sediment on the south part of the platform. When the Colville foredeep was filled, Cretaceous and Tertiary sediments overtopped the Barrow arch and prograded northward onto the western Beaufort shelf, where they thicken northward.
MESOZOIC	CRETACEOUS	LATE		Colville Group (central and eastern North Slope only)	0-3,600 W - E	Predominantly nonmarine, with coal in the west. Shallow- to deep-marine clastic rocks in the east.	
		EARLY		Nanushuk Group (W. North Slope)	0-3,300+ 200-1,200+	Marine and nonmarine shale, siltstone, sandstone, coal, conglomerate, and bentonite.	
				Fortress Mountain Fm (W. North Slope) Torok Fm	400-3,000 1,000-3,000	Marine shale, sandstone, and conglomerate. Marine shale, sandstone, and siltstone turbidites.	
			ELLESMERIAN	Pebble shale unit, Kongakut Fm., and Kemik Sandstone Mbr.	0-700	Shelf and basinal marine shale and siltstone containing rounded quartz grains and chert pebbles. Coquinoid to south; quartzose sandstone at base in east.	The Ellesmerian sequence on the Alaskan North Slope was derived from a northerly source terrane called Barrovia by Tailleur (1973). The constituent formations generally thin and coarsen northward, and onlap the uplifted northern Arctic platform in the crestal region of the Barrow arch.
	JURASSIC			Kingak Shale (locally includes Kuparuk River Sands[1] at top)	0-1,200+	Marine shale, siltstone, and chert, locally containing glauconitic sandstone (in the west). Shallower water facies are apparently the northerly ones.	
	TRIASSIC			Shublik Formation	0-225	To the north, marine shale, carbonate, and sandstone. As shown, includes the Sag River Sandstone. To the south, shale, chert, limestone, and oil shale.	
PALEOZOIC	PERMIAN			Sadlerochit Group (and Siksikpuk Fm. on western North Slope)	0-700+	Eastern North Slope: marine and nonmarine sandstone, shale, and conglomerate; marine sandstone, siltstone, and shale. Western North Slope: sandstone, conglomerate, and shale to the north; argillite, chert, and shale to the south.	
	PENNSYLVANIAN			? Lisburne Group	0-2,000+	Fossiliferous marine limestone and dolomite with some chert and local volcanic rock. Basal beds commonly sandstone, shale, and conglomerate.	
	MISSISSIPPIAN		EO-ELLESMERIAN	Endicott Group	0-5,000	Dominantly nonmarine sandstone, shale, and coal. Some limestone in upper beds.	Probably derived from both a northerly source terrane (Barrovia) and from local sources. Deposited in local deep basins that in places are fault bounded.
	DEVONIAN			? ? Endicott(?) Gp.		Nonmarine sandstone, carbonaceous shale with coal partings, and conglomerate.	
	SILURIAN AND OLDER		FRANKLINIAN	Marine sedimentary rocks (includes Iviagik Group of Martin (1970) on Lisburne Peninsula)	Thousands of meters	Eastern North Slope: argillite, graywacke, limestone, dolomite, chert, quartzose sandstone, shale, and metamorphic equivalents. Western North Slope: Ordovician and Silurian argillite and graywacke with graptolites.	Deposited during Middle Cambrian to Silurian time in the Franklinian geosyncline, which trended generally parallel to the Arctic margin of North America. North and northwestern facies are mostly eugeoclinal, south and southeastern facies mostly miogeoclinal. Probably extends northward beneath the Beaufort and Chukchi shelves.

[1] Unit of local usage

FIGURE 11.4.—Generalized subsurface stratigraphy of Alaskan North Slope and adjacent Beaufort shelf.

region of the Barrow arch northwest of Point Barrow to as much as 6,000 m on the outer continental shelf east of Prudhoe Bay.

Structurally, the Arctic platform province is dominated by the broad Barrow arch (figs. 11.5, 11.7, 11.9), and dips in the province are generally low (figs. 11.10-11.12). Belts of normal faults, however, offset the platform and the underlying Franklinian basement at and near the tectonic hinge line (figs. 11.11, 11.12, 11.14), at the margins of Dinkum graben (figs. 11.13, 11.14), and on the north side of the faulted anticline that contains the Prudhoe Bay oil field (Jamison and others, 1980). The faults north of the Prudhoe Bay field extend beneath the inner Beaufort shelf, probably as far as Dinkum graben. The seismic profiles (fig. 11.1), however, lie too far offshore to corroborate this. In addition to the normal faults that cut basement and offset the Arctic platform, an extensive system of large suprabasement growth faults offsets the Brookian (Cretaceous and Tertiary) sedimentary rocks



EXPLANATION

— 2 —	Structural contour, two-way seismic-reflection time, in seconds
—♦—	Barrow arch
	Rootless rotational-slump anticline
	Anticline
—●→	Detachment anticline above thrust fault—Arrows indicate plunge direction
	Syncline
	Hinge line. Circles on downwarped side, hachures on downthrown side where faulted
	Normal fault. Hachures on downthrown side
	Datum change
	Approximate north limit of pre-pebble shale unit Ellesmerian rocks
	Local north limit of pebble shale unit
	Approximate south limit of Tertiary rocks
—200—	Isobath, in meters
CA	Camden anticline
MA	Marsh anticline
DSB	Demarcation subbasin
BSB	Barter Island subbasin

FIGURE 11.5.—Structural geology of areas of the Alaskan Beaufort and northeastern Chukchi Seas covered by USGS multichannel seismic-reflection data (see fig. 11.1). All lines dashed where inferred or projected. Dotted lines separate onshore physiographic provinces. Onshore data west of Colville River from Miller and others (1979). TAPS, Trans-Alaska Pipeline System.

over and seaward of the hinge line. Some of these faults extend updip into the Brookian prism over the outer (seaward) part of the Arctic platform province (figs. 11.3, 11.5, 11.12-11.14).

The normal faults associated with the tectonic hinge line displace basement, the Arctic platform, and only the lowest part of the overlying Cretaceous section above the breakup unconformity (figs. 11.11, 11.12). Thus the time of major subsidence along these faults was before or contemporaneous with rifting. A large normal fault with many splays that begins about 10 km northeast of Point Barrow and trends east-southeastward along the coast to within 35 km of Harrison Bay (Miller and others, 1979) may also be related to the hinge line. This fault, like some of the hinge-line faults, appears to cut basement and only the lower part of the overlying Lower Cretaceous section.

Jamison and others (1980) indicate that the system of basement-cutting, northwest-and west-striking down-to-the-north normal faults on the north side of the Prudhoe Bay faults are truncated by the pre-pebble shale (mid-Neocomian) unconformity, which is interpreted to be the breakup unconformity. Small normal faults having similar stratigraphic relations also occur

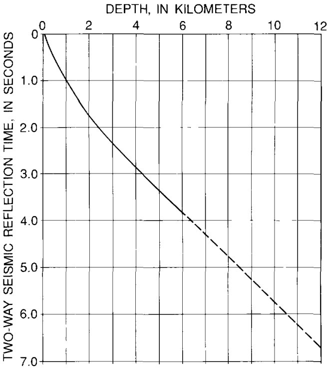
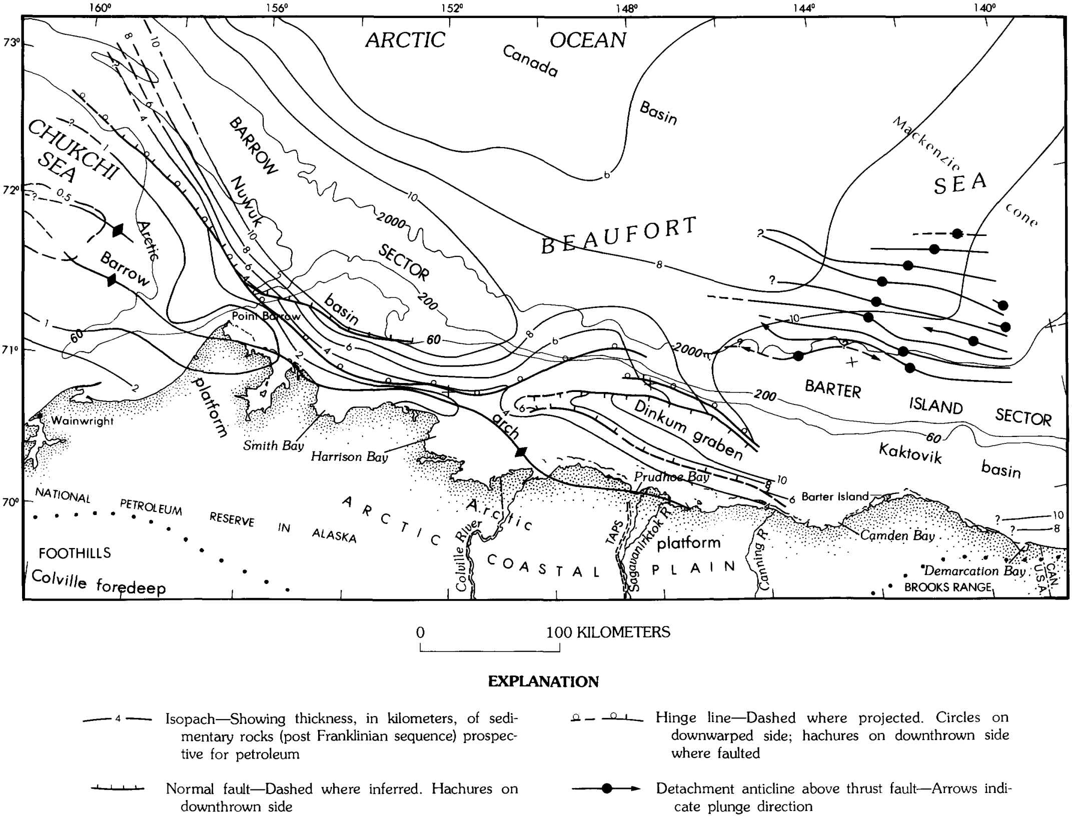


FIGURE 11.6.—Generalized average seismic-reflection time as a function of depth for the Beaufort shelf, derived from seismic-stacking-velocity measurements.



EXPLANATION

—4— Isopach—Showing thickness, in kilometers, of sedimentary rocks (post Franklinian sequence) prospective for petroleum

Normal fault—Dashed where inferred. Hachures on downthrown side

Hinge line—Dashed where projected. Circles on downwarped side; hachures on downthrown side where faulted

Detachment anticline above thrust fault—Arrows indicate plunge direction

FIGURE 11.7.—Interpretive map showing approximate thickness of sedimentary rocks favorable for petroleum prospects beneath the Alaskan Beaufort and northeasternmost Chukchi Seas. TAPS, Trans-Alaska Pipeline System. Dotted lines separate onshore physiographic provinces.

nearby on the south side of the Dinkum graben (fig. 11.13). The similarities between the Prudhoe Bay and Dinkum graben faults indicate that they may belong to the same structural set and that similar faults may underlie the region between the north side of the Prudhoe Bay structure and the graben.

DINKUM GRABEN

The eastern part of the Arctic platform province is disrupted by the deep, strongly assymetric east-southeast-trending Dinkum half-graben (figs. 11.5, 11.13, 11.14). Franklinian basement beneath the deepest parts of the graben is more than 6 s (10.5 km) below sea level. The oldest seismic-stratigraphic

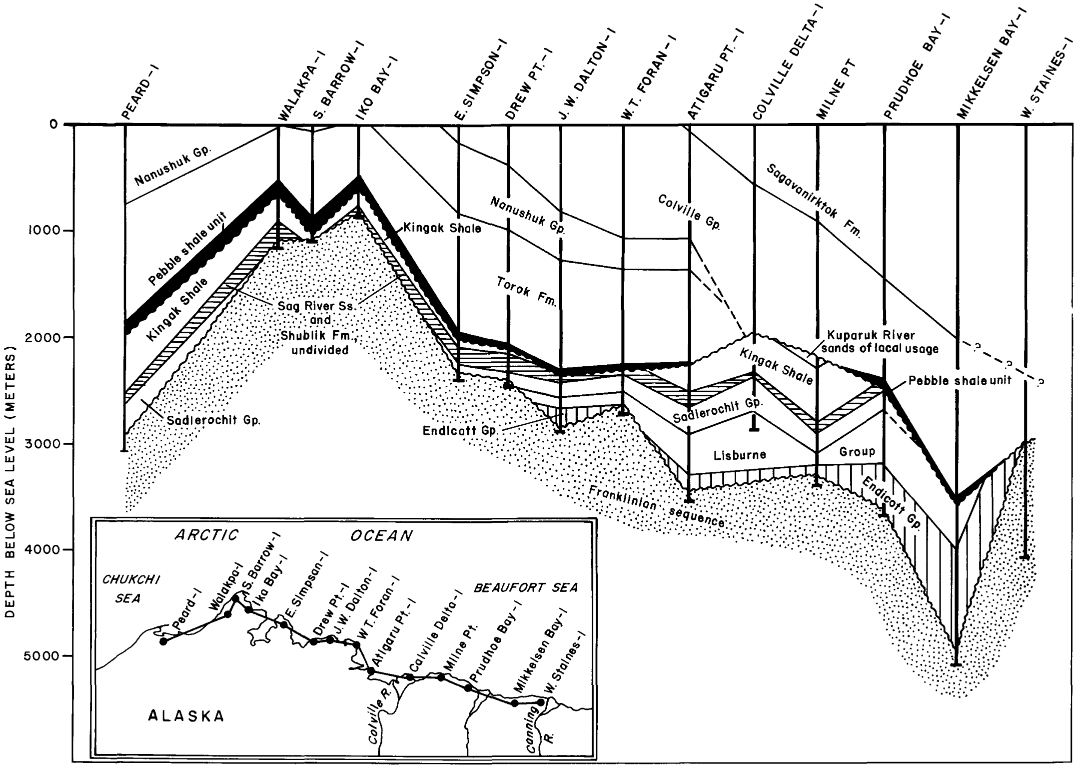


FIGURE 11.8—Correlated well sections in northern Alaska adjacent to the Beaufort and northeasternmost Chukchi Seas.

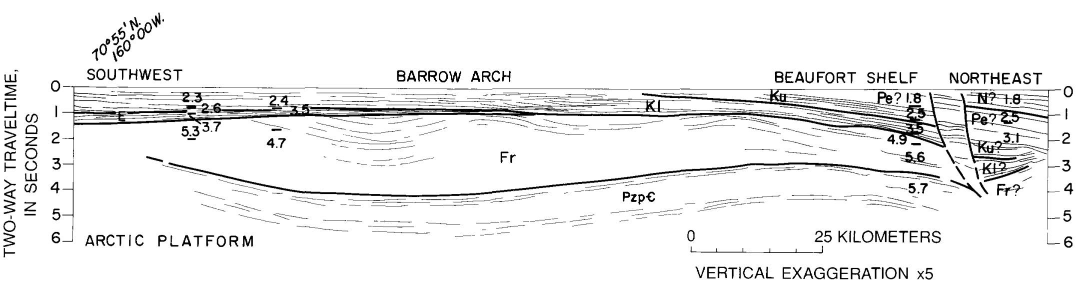


FIGURE 11.9.—Northeast-southwest cross section, based on seismic-reflection profiles across Barrow arch in northeastern Chukchi Sea. PzpЄ, lower Paleozoic or Precambrian bedded rocks; Fr, Franklinian sequence; E, Ellesmerian sequence; Kl, Ku, Pe, and N are Lower Cretaceous, Upper Cretaceous, Paleogene(?), and Neogene(?) sedimentary rocks, respectively. Numbers are sonobuoy velocities in km/s. See figure 11.1 for location.

unit within the graben consists of fairly strong, well-developed reflectors postulated to be Jurassic or older Ellesmerian sandstone and (or) carbonate rock (unit Je in figs. 11.13, 11.14). This unit is overlain by a thick section of weaker reflectors that may be the Jurassic and early Neocomian (Early Cretaceous) Kingak Shale (unit KJk in figs. 11.13, 11.14) These units are tilted to the north and dropped down against a large fault system (fig. 11.13, 11.14) that appears to be largely pre-pebble shale (unit Kps in figs. 11.10-11.14) in age. Post-pebble shale displacement has augmented the structural relief on this fault system, which is the main graben-forming structure. This fault movement, in combination with

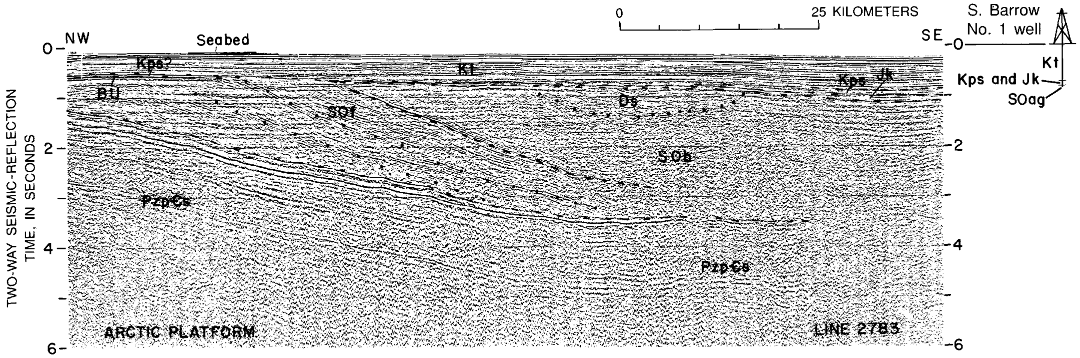


FIGURE 11.10.—Seismic-reflection profile of CDP line 2783, showing pre-Jurassic clastic wedge (SOf) beneath Arctic platform west of Point Barrow. BU, breakup unconformity. Inferred acoustic units: Kt, Cretaceous Torok Formation (Albian foreset beds); Kps, probably the Lower Cretaceous pebble shale unit (Hauterivian to Barremian bottomset beds), possibly including bottomset beds of basal part of Torok Formation (Albian); Jk, Jurassic shale, siltstone, and sandstone of lower part of Kingak Shale of Jurassic and early Neocomian age; SOf, inferred submarine-fan deposits, and SOb, marine basinal deposits correlated with Ordovician and Silurian marine argillite and graywacke (SOag) of subsurface northern Alaska; Ds, Devonian(?) bedded, presumably sedimentary rocks; Pzp-Єs, lower Paleozoic and upper Precambrian(?) bedded, presumably sedimentary rocks. See figure 11.1 for location of profile.

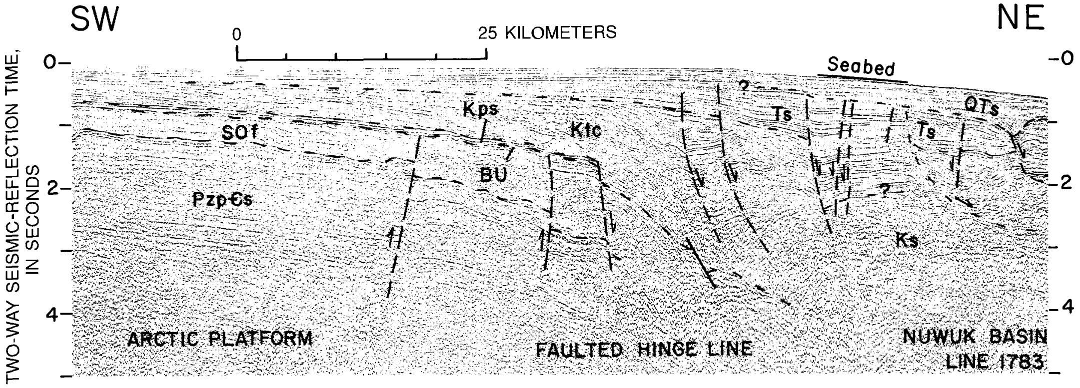


FIGURE 11.11.—Seismic-reflection profile of CDP line 1783 across rifted continental margin northwest of Point Barrow. Note rifted edge of Arctic platform, breakup unconformity (BU), faulted subsidence hinge line, deep Nuwuk basin seaward of hinge line, and growth faults beneath outer shelf. Inferred acoustic units: QTs, Quaternary and upper Tertiary(?) clastic sedimentary rocks; Ts, Tertiary and possibly Upper Cretaceous clastic sedimentary rocks; Ktc, Cretaceous Torok Formation (Albian foreset beds), and Colville Group (Upper Cretaceous) and possibly Tertiary clastic sedimentary rocks; Kps, probably the Lower Cretaceous pebble shale unit (Hauterivian to Barremian bottomset beds), possibly including bottomset beds of basal part of Torok Formation (Albian); Ks, Upper and Lower Cretaceous clastic sedimentary rocks of Nuwuk basin; SOf, inferred submarine-fan deposits tentatively correlated with Ordovician and Silurian marine argillite and graywacke of subsurface northern Alaska; Pzp-Єs, lower Paleozoic and upper Precambrian bedded, presumably sedimentary rocks. See figure 11.1 for location of profile.

residual structural relief and perhaps local renewed displacement on older (pre-pebble shale) strands of the fault system, produced a late-stage basin in the graben. Post-pebble shale Cretaceous and Paleogene fill, locally as much as 1.5 km thick, was deposited in this basin. A shallow syncline in this fill near the northern graben-bounding fault system implies renewed displacement of the fault system, and perhaps some differential compaction, in Paleogene time. The graben appears to be dying out, and its sedimentary fill is thinning, where it strikes west-southwest out of our area of seismic coverage. The east end is structurally well developed where we lose it, near Camden Bay, beneath the thick sedimentary section of the Kaktovik basin.

NUWUK BASIN

From the Prudhoe Bay area west, the outer continental shelf and slope are underlain by a deep sedimentary basin that contains a thickness of more than 12 km of post-pebble shale (mid-Neocomian) Cretaceous and Tertiary (Brookian) clastic sediment. The sediment was prograded across the subsided Arctic platform and underlying basement seaward of the tectonic hinge line (figs. 11.5, 11.9, 11.11, 11.12), and it constitutes a progradational continental-terrace sedimentary prism rather than a true sedimentary basin. It is probable that beneath the continental slope these sediments step from the continental basement of the Arctic platform onto transitional or oceanic crust of the Arctic Ocean.

The Nuwuk basin contains foreset and topset beds, large slump excavations, and slump fills. Structurally it is dominated by large multistrand growth faults that preliminary studies indicate have been active since Late Cretaceous or early Tertiary time. The youngest faults of this system displace Holocene sediment and, in places, the seabed. The faults appear to be restricted to the Brookian sequence and curve into, but do not displace, the upper surface of pre-Brookian bedrock. The growth faults bound two rootless anticlines (rotational megaslumps) of regional extent that were produced by movement on the growth faults (figs. 11.11-11.14). The profiles, although widely spaced (fig. 11.1), indicate that the rootless anticlines are continuous or semicontinuous features as much

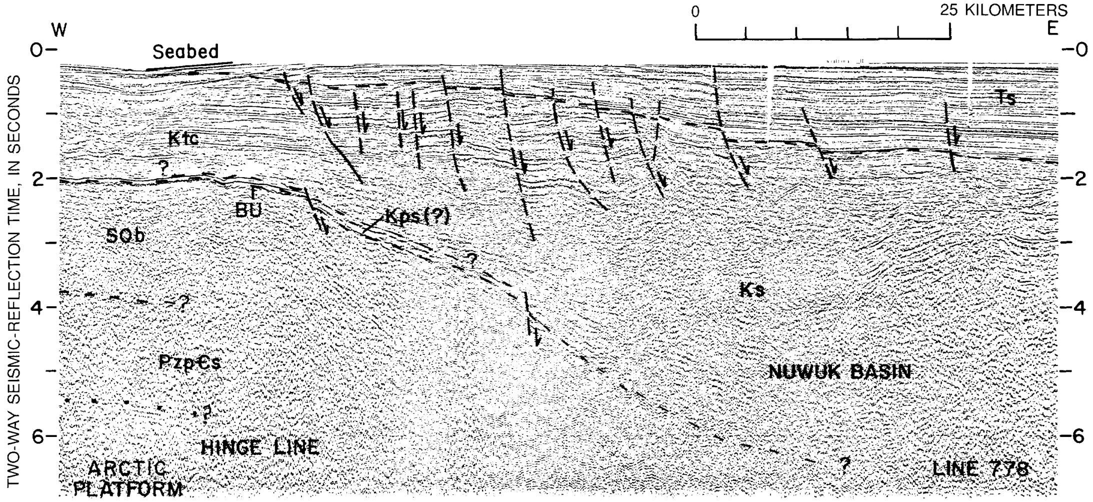


FIGURE 11.12.—Oblique crossing of rifted continental margin along CDP seismic-reflection profile 778 northeast of Point Barrow, showing Arctic platform, breakup unconformity (BU), subsidence hinge line, and Nuwuk basin. Inferred acoustic units: Ts, Tertiary and possibly Upper Cretaceous clastic sedimentary rocks; Ktc, Cretaceous Torok Formation (Albian) and Colville Group (Upper Cretaceous) marine and possibly some paralic sedimentary rocks; Kps, probably the pebble shale unit (Hauterivian to Barremian bottomset beds); Ks, Upper and Lower Cretaceous clastic sedimentary rocks of Nuwuk basin; SOb, inferred basinal deposits, tentatively correlated with Ordovician and Silurian marine argillite and graywacke of subsurface northern Alaska; PzpЄs, lower Paleozoic and upper Precambrian(?) bedded, presumably sedimentary rocks. Note concentration of growth faults over steep slope north of subsidence hinge line, and extensive slumping and channeling in Cretaceous beds of Nuwuk basin. See figure 11.1 for location of profile.

as 200 km long and have variable structural relief that commonly exceeds 0.5 km.

BARTER ISLAND SECTOR

The deep Kaktovik basin (figs. 11.3, 11.5), which contains large detachment thrust faults and folds and diapiric shale ridges, characterizes the Barter Island sector. The field of detachment anticlines of the continental slope and rise of the eastern Alaskan Beaufort Sea (figs. 11.3, 11.5, 11.7) is limited to this sector.

KAKTOVIK BASIN

Between Prudhoe Bay and the Canning River (figs. 11.3, 11.5) the tectonic hinge line swings southeast from a position near the shelf break toward the coast of eastern Camden Bay. In the same area the structural shelf break changes trend from east-southeast to east-northeast; as a consequence, the continental terrace for some distance to the east is wider than it is to the west (fig. 11.3). The widened continental terrace east of the swing in trend of the hinge line and the structural shelf break is underlain by the Kaktovik basin (figs. 11.3, 11.15, 11.16). It is likely that much of the basin rests on transitional and oceanic crust. The thick pre-pebble shale unit sedimentary prism of the Dinkum graben trends beneath the Kaktovik basin, where it is too deep to map on our seismic records. The pebble shale and younger (Brookian) graben fill and the Brookian sedimentary prism of the Arctic platform province are stratigraphically continuous with the sedimentary fill in the Kaktovik basin. The total thickness of suprabasement sedimentary rocks beneath the basin exceeds 12.5 km, and local subbasins (BSB and DSB in fig. 11.5) are filled with Tertiary strata as much as 7.2 km thick. The seismic profiles record Franklinian basement beneath only a small part of the Kaktovik basin, and therefore the horizon that is contoured in the area of the basin in figure 11.5 is inferred to be mid-Paleogene (middle Eocene?) in age for reasons discussed by Grantz and May (1983). Onshore outcrops in Alaska and

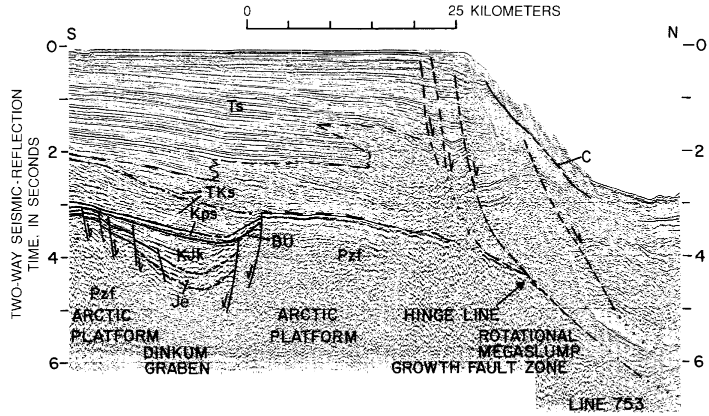


FIGURE 11.13.—Seismic-reflection profile of CDP line 753 across continental margin northwest of Prudhoe Bay, showing rifted Arctic platform, Dinkum graben, subsidence hinge line, breakup unconformity (BU), and growth faults and associated rotational megaslump near shelf break. Interpreted acoustic units: Ts, Tertiary topset beds in regressive sequence in upper part of postbreakup progradational sedimentary prism; TKs, lower Tertiary and Cretaceous foreset and some bottomset beds in mainly transgressive lower part of postbreakup progradational sedimentary prism (dot-dash line within unit TKs is rough estimate for base of Tertiary, projected from onshore); Kps, pebble shale unit and possibly condensed bottomset beds at base of Torok Formation; KJk, weakly reflective beds of Jurassic and Lower Cretaceous Kingak? Shale in Dinkum graben; Je, moderately reflective Jurassic or older beds (sandstone? and possibly carbonate? rocks) of Ellesmerian sequence in Dinkum graben; Pzf, Paleozoic Franklinian sequence (Cambrian to Devonian); C, basal reflector of zone of gas hydrate. See figure 11.1 for location of profile.

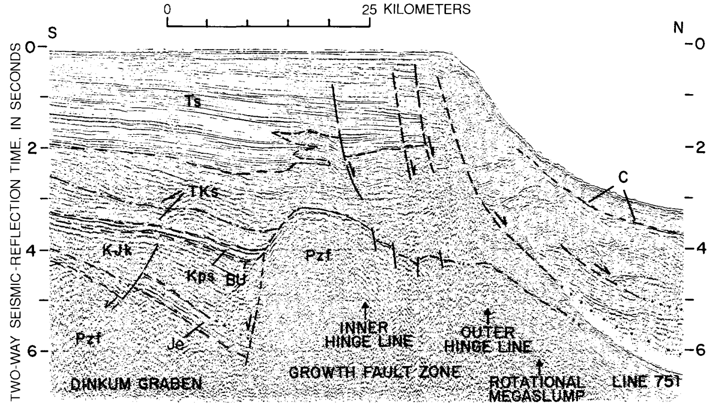


FIGURE 11.14.—Seismic-reflection profile of CDP line 751 across continental margin north of Prudhoe Bay, showing Dinkum graben, compound subsidence hinge line, breakup unconformity (BU), and zone of growth faults and associated rotational megaslump overlying hinge zone. Interpreted acoustic units same as in figure 11.13. See figure 11.1 for location of profile.

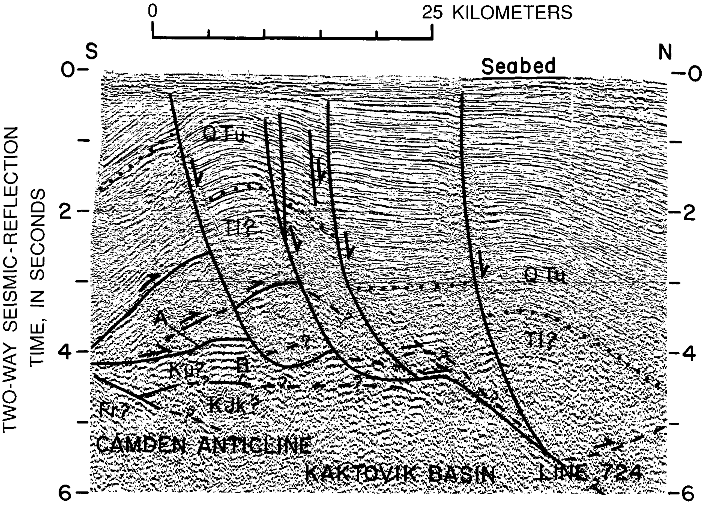


FIGURE 11.15.—Seismic-reflection profile of CDP line 724 across Camden anticline, a large east-northeast-striking detachment fold off Camden Bay. Fold is inferred, from discordance between horizon A and higher beds, to be detached near 4-s isochron. Horizon A is estimated by projection from onshore to be near base of the Tertiary sedimentary section. Horizon B may be at top of thin sequence of Lower Cretaceous Kingak Shale (Kjk). Other unit symbols: QTu, Quaternary and upper Tertiary beds; Tl?, probable lower Tertiary beds; Ku?, possible Upper Cretaceous marine sedimentary rocks; Fr?, possible Franklinian sequence. See figure 11.1 for location of profile.

subsurface data on the Canadian Beaufort shelf (Hea and others, 1980) seem to indicate that if Jurassic to mid-Upper Cretaceous beds underlie the Kaktovik basin, they will be marine sedimentary rocks. Uppermost Cretaceous beds and Paleocene beds are likely to be nonmarine nearshore and paralic to probably marine offshore. Higher Tertiary beds are probably both marine and nonmarine.

Contrasting structural styles distinguish the eastern and western parts of the Kaktovik basin. West of the general vicinity of Barter Island the lower part of the basin, below the horizon contoured in figure 11.5, appears to deepen uniformly northward and eastward, whereas the upper part of the section is broken by the large northeast-striking Camden detachment anticline (CA on fig. 11.5) and its basal thrust fault and by a few smaller parallel folds. The Camden anti-

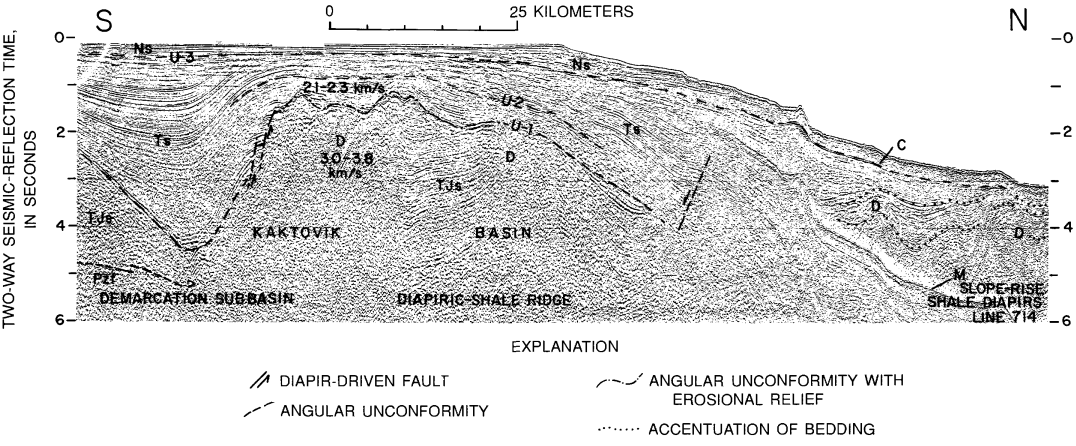


FIGURE 11.16.—Seismic-reflection profile of CDP line 714 across Kaktovik basin north of Alaska-Yukon Territory boundary, showing Demarcation subbasin, diapiric shale ridge that dominates shelf structure, and a few shale-cored diapiric folds on continental slope and rise. Inferred acoustic units and features: Ns, Neogene nonmarine and marine sedimentary rocks; Ts, middle Tertiary (Oligocene? and Eocene) marine and nonmarine(?) sedimentary rocks; TJs, Cretaceous and Jurassic marine and possibly lower Paleogene marine or nonmarine sedimentary rocks; Pzf, Paleozoic Franklinian(?) sequence; D, diapiric structure; C, base of gas hydrate; M, seabed multiple. Sonobuoy seismic velocity (in km/s) given for some units. Note that three angular unconformities (dashed lines U-1, U-2, and U-3) cross top of diapiric ridge. Lowest of these unconformities (U-1) shows rough erosional relief and, on south flank of diapiric ridge, is believed to have been disrupted by normal faults related to diapirism. Unconformities and axial thickening of reflector packets in Demarcation subbasin demonstrate that diapirism and sedimentation were penecontemporaneous. See figure 11.1 for location of profile.

cline appears (fig. 11.15) to be detached at about 4 s (6 km) subsea, probably near the base of the Tertiary. The involvement of beds as young as Holocene in the fold and the distribution of shallow earthquakes in the Camden Bay area (see fig. 11.23) seem to indicate that the thrust fault and folds are active (Grantz and others, 1983). In places a number of large, northward-dipping growth faults, at least in part related to the hinge line, offset the basin sediments. A large fold, inferred to be a rootless rotational-slump anticline related to growth faulting in the Brookian strata north of the hinge line, is present beneath the western part of the Kaktovik basin seaward of the Camden anticline (fig. 11.5). This fold is broad, apparently deep, and obscured on the east by a thick section of undeformed Neogene(?) beds in the upper part of the Kaktovik basin fill.

East of the vicinity of Barter Island the structure of Kaktovik basin is dominated by large diapiric shale ridges or anticlines (figs. 11.5, 11.16) and by Tertiary sedimentary subbasins (BSB and DSB on fig. 11.5) that formed contemporaneously with the diapirs. Multiple unconformities observed over one of the structures (fig. 11.16) record at least three episodes of diapiric movement. At the oldest of these unconformities (U-1 on fig. 11.16) the core sediments of the fold were raised above wave base, and perhaps above sea level. In places, delta-like topset-foreset-bottomset sedimentary packets were built out from structurally high areas in the subunconformity section. Regional geologic relations (Grantz and May, 1983) imply that the cores of the diapiric structures contain Jurassic, Cretaceous, and lower Paleogene clastic sedimentary rocks, and that the overlying, less strongly deformed beds may be mid-Eocene in age and younger.

DETACHMENT FOLD PROVINCE

Numerous detachment folds underlie the continental slope and rise in the Barter Island sector east of long 146° W. (figs. 11.5, 11.16). These structures are much smaller and have more regular cross-sectional shapes than do the large diapiric anticlines of the eastern Kaktovik basin. They are symmetrical folds with diapiric cores, rather than piercement structures or irregular shale ridges. Although reflection profiles are too widely spaced for us to map these structures, the profiles seem to indicate that the structures strike east-west and are moderately elongate.

The detachment folds are typically 2 to 10 km wide on seismic crossings, and the largest folds have at least 1.5 s (1.25 km) of structural relief in two-way reflection time. The most northerly structures, about 100 km north of the structural shelf break (fig. 11.3), die out upward and are overlain by undisturbed beds about 2 s (2 km) below the seabed. The tops of the folds affect progressively younger beds landward, and beginning about 50 or 60 km seaward of the shelf break they buckle the seabed and act as dams for clastic sediment and landslide debris moving down the continental slope.

CANADA BASIN

Water depths exceeding 3,500 m, dispersion patterns of L_g-phase seismic waves (Oliver and others, 1955), and seismic-refraction measurements (Grantz and others, 1981; Mair and Lyons, 1981) indicate that the Canada Basin is underlain by oceanic crust and was therefore formed by sea-floor spreading. The inferred thickness of sediment in the southern part of the basin is shown in figure 11.7, and the three major physiographic provinces into which it can be subdivided are shown in figure 11.3. All three of these provinces—the Alaska continental rise, the Mackenzie cone, and the abyssal plain—are the result of rapid sedimentation from the continental landmasses that surround the basin. Their relative areal extent, and the relative thicknesses of the sedimentary prisms that underlie them, are the result of the positions of the major rivers and glaciers that entered the Canada Basin since it was formed in Cretaceous time.

ALASKA CONTINENTAL RISE

The Alaska continental rise, at water depths of about 2,000 to 3,800 m, is underlain by clastic sedimentary rocks of the Brookian sequence derived from sources to the south, in continental Alaska and probably also Eurasia. The strata are inferred to consist dominantly of foreset and bottomset lutites, but there are probably some turbidite sandstones and submarine slump deposits. When deposited, these sediments were in stratigraphic continuity with the beds of the progradational continental-terrace sedimentary prisms herein called the Nuwuk and Kaktovik basins. A few of the seismic profiles shown in figure 11.1 extend over the rise and show it to be underlain by well-bedded strata dipping uniformly basinward. These strata are internally deformed beneath their upslope margin by submarine slumps and the distal ends of listric growth faults that originate on the continental slope and outer shelf seaward of the tectonic hinge line. The age of the main sedimentary prism is inferred to range from late Neocomian (mid-Early Cretaceous) to Quaternary. The distribution of Brookian rocks and facies in northern Alaska indicates that the sedimentary prism may consist mainly of Albian strata near Point Barrow and mainly of Tertiary strata in the Barter Island sector. In addition, Jurassic and lower Lower Cretaceous beds of the rift-valley stage of rifting on the Alaskan continental margin (Grantz and May, 1983) underlie the Neocomian beds beneath the eastern Beaufort Sea and probably beneath part of the Canada Basin. The thickness of the sedimentary prism beneath the Alaska continental rise is estimated to range from 6 km to more than 10 km (fig. 11.7).

MACKENZIE CONE

The Mackenzie cone is the portion of the Canada continental rise lying off the mouth of the Mackenzie River. Water depths on the cone in the Beaufort Sea (fig. 11.3) range from about 1,800 to 3,700 m. The cone, which occupies about three-fifths of the southern Canada Basin north of the Alaska continental rise, owes its areal extent and the thickness of its underlying sedimentary prism (fig. 11.7) to its proximity to the delta of the large Mackenzie River system and to the heavily glaciated Canadian Arctic Islands and Canadian shield. These sources have supplied great volumes of sediment to the cone, and the cone grew much more rapidly, at least in Tertiary time, than the Alaska continental-rise sedimentary prism, which it overwhelmed. The boundary between the Alaskan rise and Mackenzie cone is marked by a change in trend of the depth contours (fig. 11.3). The oldest sedimentary strata in the cone are certainly late Early Cretaceous in age and may be as old as Early Jurassic in possible local rift basins; the youngest are Quaternary. Seismic-reflection profiles show the sedimentary section beyond the diapiric folds to consist of flat, basinward-dipping strata that produce some well-defined, but mainly weak, seismic reflections. The sequence is interpreted to consist dominantly of lutite with some turbidite beds and to range in thickness from less than 6 km to more than 10 km (fig. 11.7).

ABYSSAL PLAIN

The abyssal plain of the Canada Basin (fig. 11.3) occupies about two-fifths of the southern Canada Basin north of the Alaska continental rise. Water depths over the plain range from about 3,700 m to about 4,000 m. We have no seismic-reflection data for the abyssal plain and can only speculate on the character of the underlying sedimentary prism. Presumably it is composed of fine-grained sediment, the distal portions of turbidity currents and density flows that originated at the Mackenzie delta and were ponded in the deepest part of the Canada Basin between the foot of the Mackenzie cone and the Chukchi Continental Borderland. In addition, there may have been a contribution from the smaller Alaska continental rise. Extrapolation of seismic-refraction data indicates that the sedimentary section beneath the portion of the abyssal plain adjacent to northern Alaska is a little less than 6 km thick.

PETROLEUM POTENTIAL

It is probable that commercial deposits of oil and gas will be found beneath the Alaskan Beaufort and northeasternmost Chukchi Seas. Large economic and potentially economic oil and gas pools of several ages have been developed or discovered along the Beaufort Sea coast in the Prudhoe Bay area (Jamison and others, 1980) and between the Sagavanirktok and Canning Rivers (fig. 11.1). Some of these are known, and others can be surmised, to extend offshore. It is remarkable that every major stratigraphic unit of formation or group rank beneath the Arctic coastal plain of northern Alaska has been found to contain commercial or potentially commercial pools, or strong shows, of oil and gas (fig. 11.17). All of these major stratigraphic units are inferred to extend offshore beneath the Beaufort shelf. The chances for commercial discoveries there are considered good because, in addition to favorable sedimentary rocks, the area contains many structures and stratigraphic configurations that have been found to trap economic petroleum deposits in other regions. The chief concern appears to be whether sufficiently large deposits can be found to support the anticipated substantial cost of offshore exploration and development in the Beaufort and Chukchi Seas and adjacent Arctic Ocean and to support the development of new technologies to make these operations possible.

THERMAL MATURITY OF POST-RIFT SEDIMENTARY STRATA

To determine whether a sedimentary package may have generated petroleum hydrocarbons, two factors must be considered: first, whether there was organic material of suitable type within the sediment to be converted to petroleum hydrocarbons; secondly, whether the thermal history of the sediment has been conducive to the chemical transformation of organic material into petroleum hydrocarbons. As figure 11.17 implies, organic matter is abundant in the strata that underlie the Arctic coastal plain of northern Alaska. The second factor, thermal maturity, will be considered here. In the absence of thermal data for the Beaufort shelf, we used a method developed by Royden and others (1980) to estimate the thermal history of a passive continental margin. The method is based on a relation between the amount of subsidence a passive margin undergoes following breakup of the continent and the heat flow through time in that area. If the depth to the breakup unconformity can be measured, a thermal history of the area can be reconstructed.

The depth range, derived by means of this method, at which petroleum hydrocarbons may have been generated in the postbreakup (post-Neocomian) sedimentary rocks of the Beaufort and northeast Chukchi Seas is shown in figure 11.18. The area has been analyzed as three separate regions based on the thickness of the sedimentary section and the heat-flow curves.

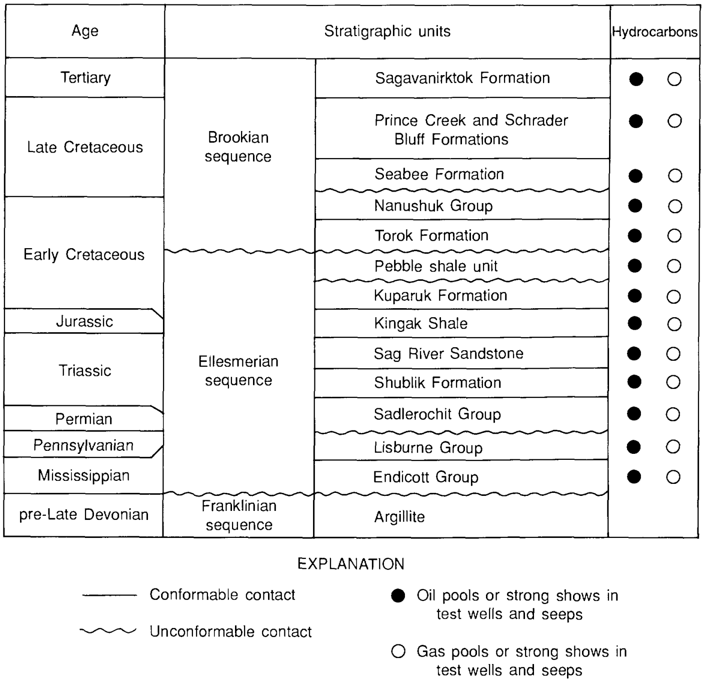
ARCTIC PLATFORM

Most of the Arctic platform province (area 1 in figure 11.3) is prospective for petroleum. Thermal-history calculations indicate that the Cretaceous rocks are within the oil-generating zone or so-called oil window (fig. 11.18), and the Ellesmerian rocks are known to be productive onshore. The areas of greatest potential lie along the broad crest of the Barrow arch off Prudhoe and Harrison Bays, where significant sections of Ellesmerian rocks can be extrapolated offshore. Lesser prospects of this type are projected for the crestal region of the arch near Smith Bay and west of Point Barrow because onshore and some offshore data (figs. 11.5, 11.8) indicate that the lower part of the Ellesmerian section is much attenuated or missing in those areas. The possibility that the pre-pebble shale faults on the north side of the Prudhoe Bay structure extend to the south side of the Dinkum graben further enhances the prospects of finding petroleum in the area between Prudhoe Bay and the graben.

Additional prospects in the Arctic platform province are fault-block plays in Cretaceous rocks, and possibly Ellesmerian rocks, on the north side of hinge-line-related faults that lie off the coast between Point Barrow and Harrison Bay. Hinge-line-associated growth faults and rollovers in Brookian rocks in the northern part of the province may also have potential. Interdigitated topset and foreset seismic-stratigraphic units of inferred Cretaceous and Paleogene age in appropriate structural configurations may offer prospects in parts of the Arctic platform province, but it is difficult to infer from our data how large such stratigraphically controlled accumulations might be.

DINKUM GRABEN

We can estimate from the curves in figure 11.18 that the Cretaceous and lowest Tertiary strata in the thick sedimentary section of the Dinkum graben (area 2 in figure 11.3) are now within the oil window. The underlying pre-Jurassic(?) or Jurassic(?) Ellesmerian beds within the deep central parts of the graben range from just below the oil window downward into the overmature zone, and they would be of interest only as a possible source of oil or gas that migrated out of these beds during Cretaceous or Paleogene time. Good prospects may exist where the Cretaceous and lower Tertiary beds of the graben fill are upturned against pregraben rocks at buttress unconformities or fault contacts, provided these beds are no deeper than about 5 km. However, our data do not permit speculation on the size of any such accumulations.



Age	Stratigraphic units		Hydrocarbons
Tertiary	Brookian sequence	Sagavanirktok Formation	● ○
Late Cretaceous		Prince Creek and Schrader Bluff Formations	● ○
		Seabee Formation	● ○
Early Cretaceous		Nanushuk Group	● ○
		Torok Formation	● ○
	Ellesmerian sequence	Pebble shale unit	● ○
		Kuparuk Formation	● ○
Jurassic		Kingak Shale	● ○
Triassic		Sag River Sandstone	● ○
		Shublik Formation	● ○
Permian		Sadlerochit Group	● ○
Pennsylvanian		Lisburne Group	● ○
Mississippian		Endicott Group	● ○
pre-Late Devonian	Franklinian sequence	Argillite	

EXPLANATION

——— Conformable contact

﹏ Unconformable contact

● Oil pools or strong shows in test wells and seeps

○ Gas pools or strong shows in test wells and seeps

FIGURE 11.17.—Generalized stratigraphic column showing position of oil and gas pools and of strong shows of oil and gas encountered in test wells beneath the Arctic coastal plain of northern Alaska. Data from Alaska Geological Society (1971, 1972), Brosgé and Tailleur (1971), Jones and Speers (1976), Jamison and others (1980), and petroleum industry announcements.

NUWUK BASIN

The section between about 3 and 6 km below the seabed in the thick (more than 12 km) Brookian sedimentary prism in the Nuwuk basin (area 3 in figure 11.3) is within the oil window. Thus, the many early growth faults and associated large rootless anticlines (rotational megaslumps) and smaller rollover anticlines were potentially available to trap migrating hydrocarbons. The presence of topset as well as foreset and bottomset seismic-stratigraphic units in the Cretaceous and lower Tertiary beds of the basin holds out the possibility that reservoir sands may be present in these structures. The seismic lines are too widely spaced to demonstrate closure on the possible structures and stratigraphic traps recognized on seismic profiles, but they indicate that large closed structures could be present in most parts of the Nuwuk basin.

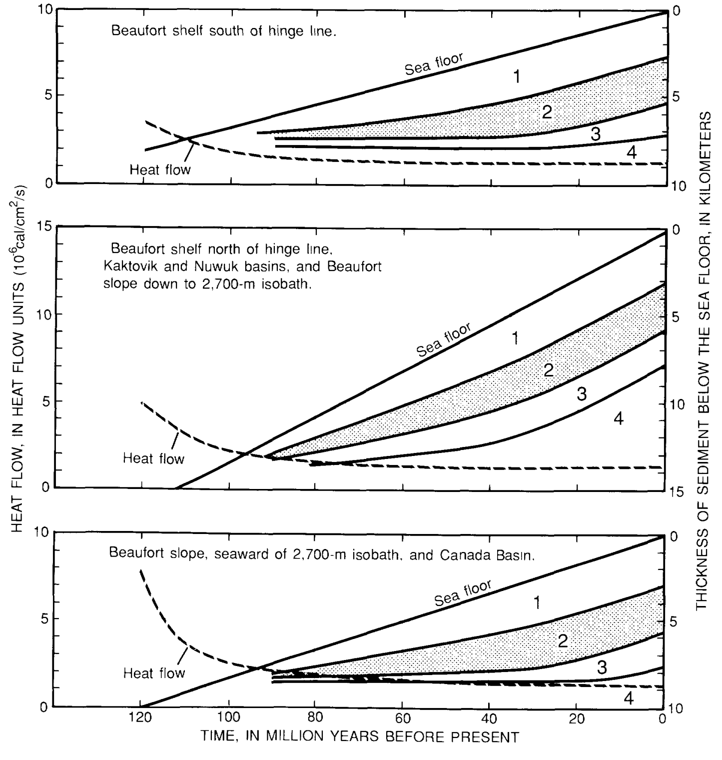


FIGURE 11.18.—Thermal maturity of postrift sediments as a function of time and present depth of burial for three parts of the study area. Numbered zones are: 1, Immature zone—generation of biogenic gas only; 2, oil zone or oil window—generation of oil and associated gas; 3, thermal gas zone— generation of thermal gas and breakdown of liquid hydrocarbons into gas; 4, overly mature zone—temperature above that at which hydrocarbons are stable. Heat-flow curves, used to determine the temperature history of the sediment, calculated from heat-flow measurements in the Canada Basin by Lachenbruch and Marshall (1966) and from Geothermal Gradient Map of North America (American Association of Petroleum Geologists, 1976). Heat-flow curves extrapolated back in time using method of Royden and others (1980).

KAKTOVIK BASIN

Heat-flow curves (fig. 11.18) indicate that the section between about 3 and 6 km below the seabed in the Kaktovik basin is within the oil window. This section includes the upper (but not the highest) parts of the diapiric anticlines and the deeper parts of the Tertiary subbasins in the eastern part of the province (area 4B in figure 11.3). The subbasins formed contemporaneously with diapirism, and the buttress unconformities at their upturned and locally faulted margins may offer good prospects for large accumulations of oil or gas. In addition, updip migration of hydrocarbon fluids may have created local accumulations in the tops of the diapiric anticlines.

The discovery of Cretaceous and lower Tertiary oil deposits at or near the coast between the Sagavanirktok and Canning Rivers, and the presence of the large Camden anticline offshore, indicate that the western Kaktovik basin (area 4A in figure 11.3) also has good prospects. The Camden anticline (figs. 11.5, 11.15) may not be as attractive, however, as its substantial size and structural relief might suggest. The anticline is apparently still growing; probably it is entirely a Neogene or perhaps even a Quaternary structure. If the fold is indeed this young, it may substantially postdate the migration of oil from the lower Tertiary and older beds of the basin, and there may not yet have been sufficient time to accumulate large quantities of hydrocarbons generated in the Tertiary strata. Because of its youth, the Camden anticline may be more prospective for gas than for oil.

DETACHMENT FOLD PROVINCE

Most of the anticlinal structures in the detachment fold province (area 5 in figure 11.3) lie beneath 1,500 to 3,000 m of water in areas of the Arctic basin that are seldom free of ice (fig. 11.2). They offer, for possible future exploration, many structural traps within the oil window, and updip migration may have carried hydrocarbon fluids into higher structural positions on the folds. A large unknown factor in the detachment fold province is whether suitable hydrocarbon source beds and reservoir rocks are present.

CANADA BASIN

Water depths exceeding 2,400 m, perennial ice cover (fig. 11.2), and uncertainties concerning the presence of source and reservoir rocks appear to assure that petroleum exploration in the Canada Basin (areas 6A, 6B, and 6C in figure 11.3) will not be undertaken in this century. However, the sedimentary rocks of the basin, which are believed to be of Brookian age, are potentially prospective: They are 5 km to more than 10 km thick, and a substantial part of the section is estimated to be within the oil window (fig. 11.18). The adequacy of hydrocarbon source beds and reservoir rocks is not known, but suitable source beds and porous turbidite sands could be present. Seismic-reflection profiles across part of the Alaskan continental rise subprovince (area 6A in figure 11.3) demonstrate the presence of low-angle faults and buckled beds and fault planes at the toes of growth faults and deep slumps. These low-angle faults originated in Nuwuk basin and beneath the continental slope. Such complex structures might have formed suitable traps for the accumulation of hydrocarbons, but the seismic lines are too widely spaced to show whether or not structural closures are present.

GAS HYDRATE

Where water depths exceed about 400 m, the top 300 to 700 m of sediment below the sea floor in the Beaufort and northeast Chukchi Seas is in the temperature-pressure range for stability of natural gas hydrate (fig. 11.19). Evidence for the presence of gas hydrate was found on about 75 percent of our seismic-reflection coverage in the area between the 400-m isobath and the north end of our seismic lines or the 2,800-m isobath. The zone of gas hydrate may also extend beyond the 2,800-m isobath, but the evidence is difficult to recognize in the nearly flat sedimentary strata that underlie the Canada Basin at those depths.

It is not known from our seismic data what portion of the sediment in the zone of potential occurrence is actually cemented with gas hydrate. Hydrate formation requires either the in-place generation of gas in the appropriate temperature-pressure zone or the introduction of gas by migration from outside the zone. The completeness of hydrate cementation within the zone depends on the availability of gas or of suitable organic matter for the generation of gas, the permeability of the sediment, and the existence of appropriate pathways for gas migration. We assume that the hydrate contains mostly methane because this gas is the most abundant in naturally occurring gas hydrates, but this has yet to be demonstrated.

Until the hydrate zone is sampled, its resource potential can only be conjectured, but theoretical calculations imply that the potential resource could be very large. To date, however, attempts onshore in the Soviet Union and Canada to decompose subpermafrost hydrate in place have apparently not led to a method for producing methane gas commercially. Subsurface gas hydrate is of greater current interest as a potential geological hazard than as a resource. Under the environmental conditions of the Arctic Ocean, development of the gas hydrate resource will probably be undertaken first, if at all, in conjunction with the development of deeper conventional deposits of oil and gas in the region of hydrate occurrence.

A more likely resource in the region of gas hydrate is the free gas that, in many places, may immediately underlie the base of the hydrate zone. Many of the strongest concentrations occur under pseudoanticlines formed where the base of the gas hydrate, which tends to parallel the seabed, underlies bathymetric highs (fig. 11.20). Large volumes of gas at low to moderate pressure could be present in such structures and other subhydrate accumulations. However, estimating the extent of this resource will require additional seismic-reflection profiles and sampling to determine the properties of the potential reservoirs, the composition of the gas, the thickness of the gas zone, and the gas content of the associated connate water.

RELATIVE PETROLEUM PROSPECTS OF THE PROVINCES

Prospects for the occurrence of large petroleum deposits, without regard to economic realities, appear to be highest in the Arctic platform province east from Smith Bay and in the Kaktovik and Nuwuk basins. Also included as prospective, although somewhat less favorable for large deposits, are the Dinkum graben, the Arctic platform near the hinge line (including the area with hinge-line-related faults between Point Barrow and Harrison Bay), the Arctic platform south of the wedgeout of Ellesmerian strata west of Point Barrow, and probably the diapiric fold province. The structurally shallow area of the Arctic platform in the broad crestal region of the Barrow arch northwest of the Ellesmerian wedgeout in the Chukchi Sea has poor prospects. Insufficient data and a lack of suitable analogs make it difficult to rank the subprovinces of the Canada Basin or the gas hydrate zone. The best prospects in the Canada Basin, exclusive of the diapiric folds, may lie in the structurally disturbed and stratigraphically complex zone that lies at the foot of the listric growth faults within the upslope (landward) part of the sedimentary prism on the Alaska continental rise.

ENVIRONMENTAL GEOLOGY

GENERAL DESCRIPTION

Holocene tectonism, active slumping and sliding, shallow free-gas concentrations, unconsolidated sediment, natural gas hydrates, subsea permafrost, and other factors will complicate petroleum development in the Beaufort and northeasternmost Chukchi Seas. During favorable years, the continental shelf here is mostly free of ice and accessible to drill ships for as much as two months; other troublesome subsea conditions will hamper drilling even when sea ice does not.

Natural gas hydrate with a zone of free gas at its base 300 to 700 m beneath the sea floor is widespread where water is deeper than 400 m. In addition, shallow bedding-plane slides as wide as 38 km underlie much of the outer shelf. East of long 146° W., drilling platforms and

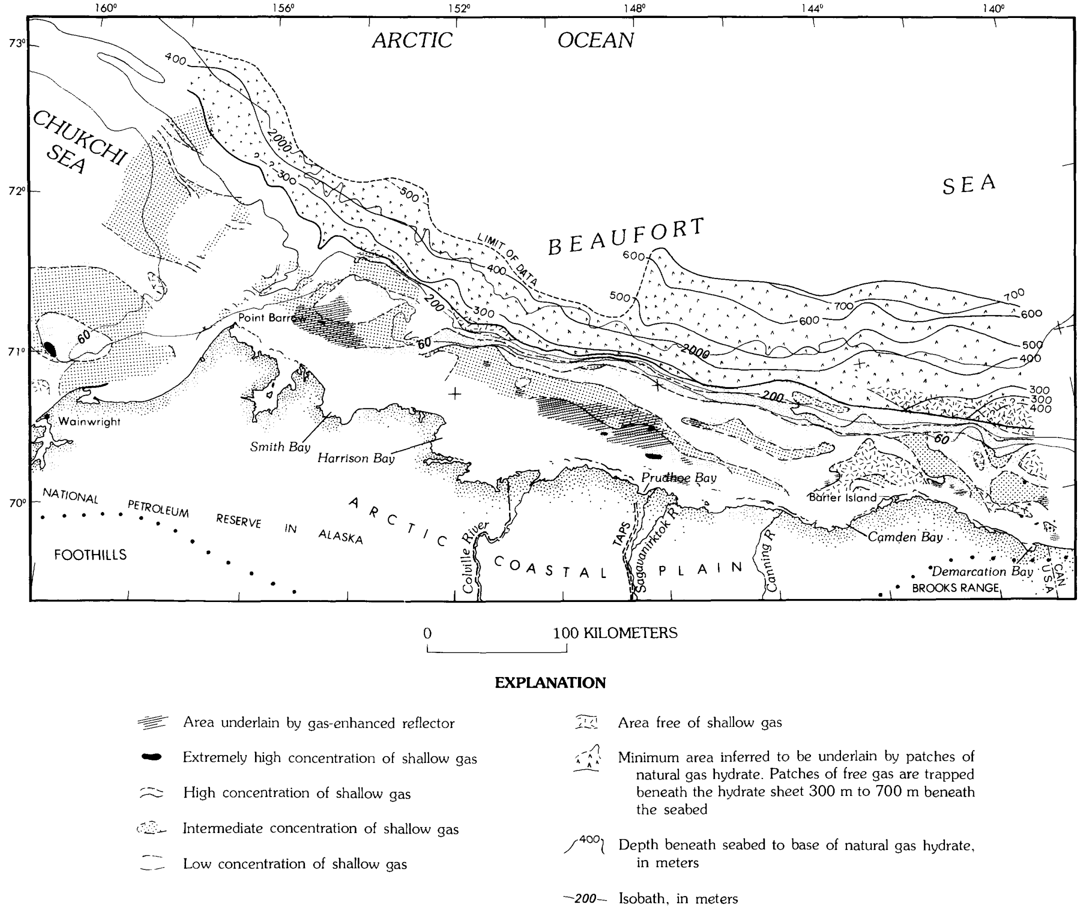


FIGURE 11.19.—Distribution of shallow free-gas concentrations and depth to base of natural gas hydrate offshore northern Alaska. Selected bathymetric contours in meters. Dotted lines separate onshore physiographic provinces. TAPS, Trans-Alaska Pipeline System.

other production facilities may be subject to earthquakes as large as magnitude 6 and, in places, to active faulting, uplift, and subsidence. Subsea permafrost, probably containing gas pockets, extends from near the sea bottom to depths of several hundred meters in sediments near the coast and may present thawing and compaction hazards to production facilities on the inner shelf. Shallow free gas is concentrated in isolated patches on the inner shelf and in a long and continuous, but narrow, zone near the shelf break.

The westward-drifting polar ice pack, which lies seaward of a zone of shorefast and bottomfast ice extending out to the 10- or 20-m isobath, will be a major obstacle to exploration and production. In addition, the seabed between the coastline and at least the 60-m isobath is gouged by keels of drifting ice ridges and tabular icebergs. Subbottom completions in this zone, and pipelines crossing it, will have to be buried below the base of the gouges, which locally exceed 5 m in depth. Coastal bluffs are deformed by slumping and mass wasting, due primarily to the erosion of ground ice and frozen soil by surface water during the summer months. As a result, the coastal bluffs retreat at average rates of 1 to 3 m/yr along the entire coast. Rates of as much as 30 to 50 m/yr have been recorded at coastal promontories in years having major storms (Hopkins and Hartz, 1978).

UNCONSOLIDATED DEPOSITS

The thickness of a poorly consolidated, late Wisconsin to early Holocene transgressive marine stratum composed of mud, silt, sand, and gravel has been contoured on figure 11.21. Its age and geologic significance have been interpreted from high-resolution (Uniboom) seismic profiles on the basis of acoustic properties and geometric considerations. On the inner Beaufort shelf, drilling, sampling, and diving information corroborate interpretations based on the acoustic data. These deposits form a wedge that thickens offshore to a maximum of about 40 to 50 m near the shelf break, where the wedge overlaps the upper part of a chaotic slump terrane. The wedge appears to be thinner on the western half of the shelf than farther east, but records in the west are much less definitive. Correlative deposits are notably thin or absent along the coast.

The shear strength of the contoured stratum may be quite low, because bedding-plane slides at angles as low as 0.5° to 2.0° have developed in its offshore extension. Locally, concentrations of sand and silt may be susceptible to liquefaction as well. The instability of these deposits poses a great potential hazard to pipelines, platforms, and artificial islands on the outer shelf, where the deposits are thickest and have the steepest topographic gradient, and near the active seismic zone near Camden Bay.

The absence of this poorly consolidated transgressive stratum off Camden Bay (fig. 11.21) is inferred to be the result of 10 to 25 m of late Quaternary uplift in a northeast-trending zone about 30 km wide and at least 60 km long. Many historical earthquakes have epicenters in this zone (see fig. 11.23). Structures placed on the thick section of Holocene sediment flanking this uplifted, seismically active area will be subject to especially strong shaking during earthquakes.

Holocene sediment in the shallow offshore parts of the eastern Chukchi Sea apparently is less than 5 m thick in most places, but locally it can be as much as 12 m thick (Moore, 1964). In nearshore regions of the northeastern Chukchi shelf, Holocene sediment forms a thin veneer over Cretaceous bedrock. The maximum known Holocene sediment thickness, 16 m, occurs directly off Point Franklin. The sur-

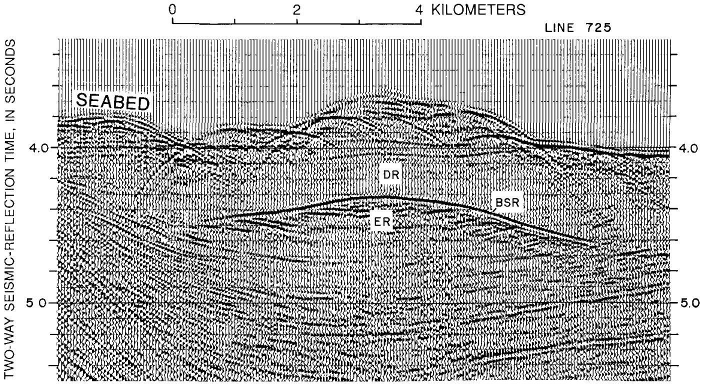


FIGURE 11.20.—Seismic-reflection profile of CDP line 725 on the continental slope at water depths of 2,670 to 2,935 m off Camden Bay, showing zone of diminished reflections (DR) thought to be caused by cementation with gas hydrate and the underlying zone of enhanced reflections (ER) interpreted as representing gas-charged sediment beneath the gas hydrate. The strong bottom-simulating reflector (BSR) is believed to represent interface between hydrated zone and underlying hydrate-free gas-charged sediment. Note that hydrate-related reflections are best developed under bathymetric high, where they form pseudoanticline superimposed on synclinal structure of bedded country rock.

ficial deposits are mixtures of mud, sand, and gravel (R.L. Phillips, oral commun., 1982).

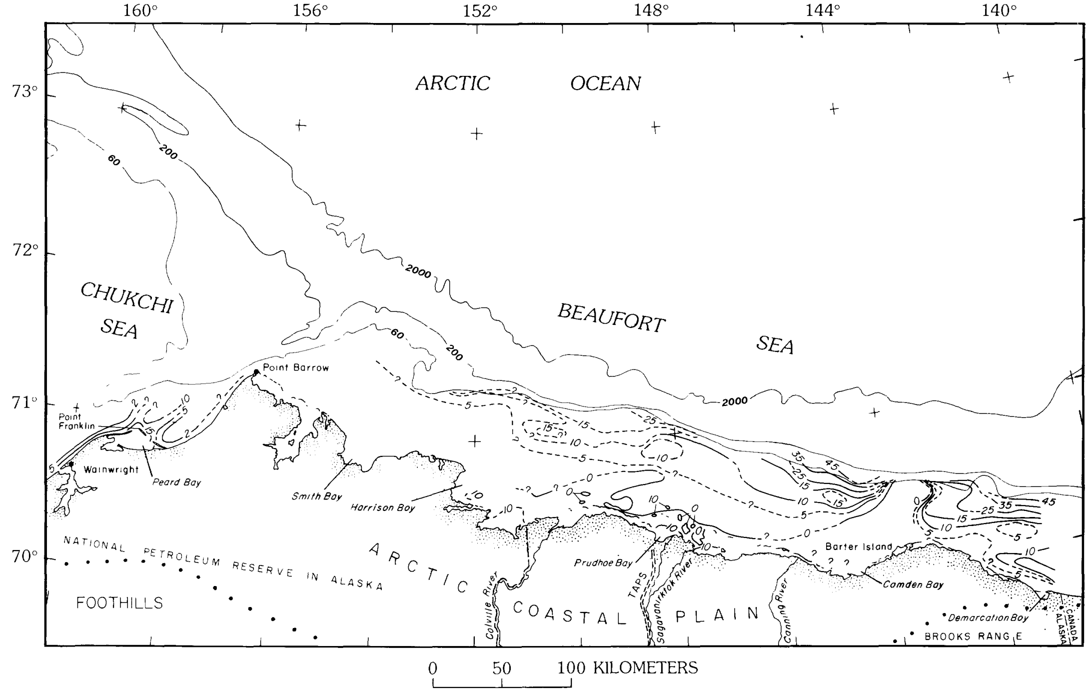
LANDSLIDES

Much of the Beaufort outer shelf and upper slope seaward of the 50- to 65-m isobaths is disrupted by bedding-plane slides and massive slumps developed in unconsolidated or poorly consolidated Pleistocene and Holocene sediment (fig. 11.22). High-resolution seismic records (principally Uniboom) collected across the entire western shelf and slope at 15- to 50-km intervals have allowed the delineation of several distinct unstable terranes. These include sags at the heads of extensional zones, bedding-plane slide zones, rotational slumps in which large masses have broken along listric surfaces and slid downslope at high angles, and hummocky rubble piles at the base of the slides where slump masses accumulated.

The bedding-plane masses are tabular sheets as much as several kilometers wide (perpendicular to the shelf break) and typically 20 to 70 m thick, which move seaward along slip planes that commonly dip only 0.5° to 1.5° and therefore must have low shear strength. The sediments involved in sliding have not been dated paleontologically; however, the thinner slides and the uppermost parts of the thicker ones formed in deposits that, judging from their acoustic stratigraphy, are believed to be lower Holocene.

YOUNG FAULTS

High-angle normal faults, some of which affect Holocene deposits and the seabed, and monoclines overlying such faults are abundant off Camden Bay (fig. 11.23). The youthfulness and local abundance of these features, and their areal coincidence with a zone of Holocene uplift and modern earthquakes, imply that at least some of them are active. These faults lie within the



EXPLANATION

5 ?	Isopachs of Holocene sediment in meters; dashed where approximately located, queried where doubtful
200	Isobath, in meters

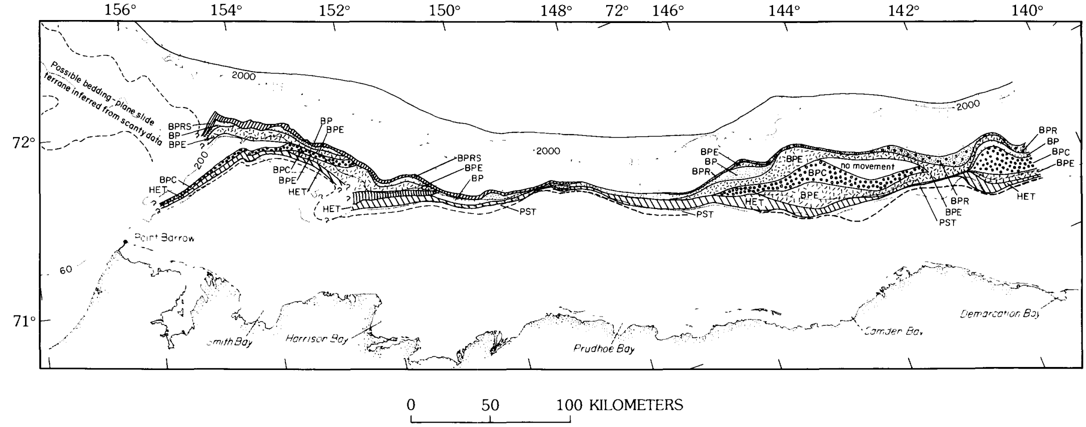
FIGURE 11.21.—Thickness of Holocene marine sediment on the Alaskan Beaufort and northeasternmost Chukchi shelves. Selected bathymetric contours in meters. Dotted lines separate onshore physiographic provinces. TAPS, Trans-Alaska Pipeline System.

western part of an area of large-amplitude late Cenozoic detachment folds that characterize the western part of the Barter Island sector of the Beaufort shelf; they appear to represent part of the active front of the northeastern Brooks Range orogene.

In addition to such tectonic, apparently seismogenic faults, two types of north-dipping, down-to-the-basin gravity faults underlie the western Beaufort shelf (fig. 11.23). These gravity faults are listric surfaces along which the sedimentary prism of the shelf has failed and moved toward the free face of the continental slope. One type, which is restricted to the outermost shelf and upper slope, has total displacements as great as 1,055 m and bounds shallow structural blocks that are akin to large rotational slumps. Most of the offset along these faults may have occurred in one or more large displacement events. Additional features of this type are likely to disrupt the adjacent outermost shelf in the future.

The second type of gravity fault, which occurs beneath the middle and outer shelf, is characterized by much smaller offsets of Quaternary deposits and the seabed than the first type and includes many growth faults having long histories of activity. The outer-shelf faults of this set displace Holocene deposits and the seabed as much as 15 to 20 m, and in one area possibly as much as 70 m. Those on the mid-shelf displace sediment no younger than late Pleistocene.

The gravity faults are considered active because they formed in the present tectonic environment and displace Pleistocene or Holocene sediments. However, they have not generated earthquakes of sufficient magnitude to be detected by the regional and local seismograph networks in place since 1968. The lack of seismicity may be due to the low stress drops that are characteristic of movement along gravity faults. In the absence of earthquakes or detailed physical stratigraphy, the recurrence interval of displacement events along the gravity faults is impossible to calculate. We estimate,



EXPLANATION

PST	Terrane with "pull-apart sags", shallow depressions inferred to mark incipient pull-apart zones
HET	Headwall extension and subsidence terrane characterized by rough and blocky seabed
BP	Terrane of tabular bedding-plane slides in which the slide mass is coherent
BPE	Terrane of extensional bedding-plane slides with open pull-apart crevasses commonly as deep as 8-17 m
BPC	Compressional terrane of bedding-plane slide masses shortened in the direction of sliding
BPRS	Terrane of bedding-plane slides with superimposed rotational slips
BPR	Rubble at foot of bedding-plane slides
▥	Areas vacated by slide masses; may be thinly mantled by slide debris
☐	Terrane of large slump masses partially buried by smaller landslides, and by turbidity-current, debris-flow, and hemipelagic sediment

FIGURE 11.22.—Preliminary map of youthful landslide areas on the Beaufort shelf and slope north of Alaska. Selected bathymetric contours in meters.

however, that the faults beneath the outer shelf, which show large Holocene offsets, may have recurrence intervals in the range of a few hundred to several thousand years. Those on the midshelf, which show only Pleistocene or early Holocene offsets, may be quiescent or have very long recurrence intervals.

SEISMICITY

The Beaufort and northeast Chukchi continental margin has been historically aseismic with the exception of a zone of concentrated seismic activity in the vicinity of Barter Island and an anomalous earthquake located by the worldwide seismograph network about 200 km north of the Colville River delta. Epicenters of representative earthquakes of magnitude 3.0 or greater on the Beaufort continental margin are shown on figure 11.23. These were recorded by the worldwide seismograph network through 1980 (Meyers, 1976; U.S. Geological Survey, unpub. data) and by the Canadian network and a local seismographic network in northeastern Alaska from 1968 to 1977 (Biswas and Gedney, 1978). These workers concluded that the seismogenic zone in the vicinity of Barter Island is a northeastern extension of the central Alaska seismic zone. Seismic-reflection data on the eastern Alaskan Beaufort shelf indicate that the earthquakes are associated with Quaternary movement on the Camden and Marsh detachment anticlines and related structures in northeastern Alaska and adjacent areas offshore.

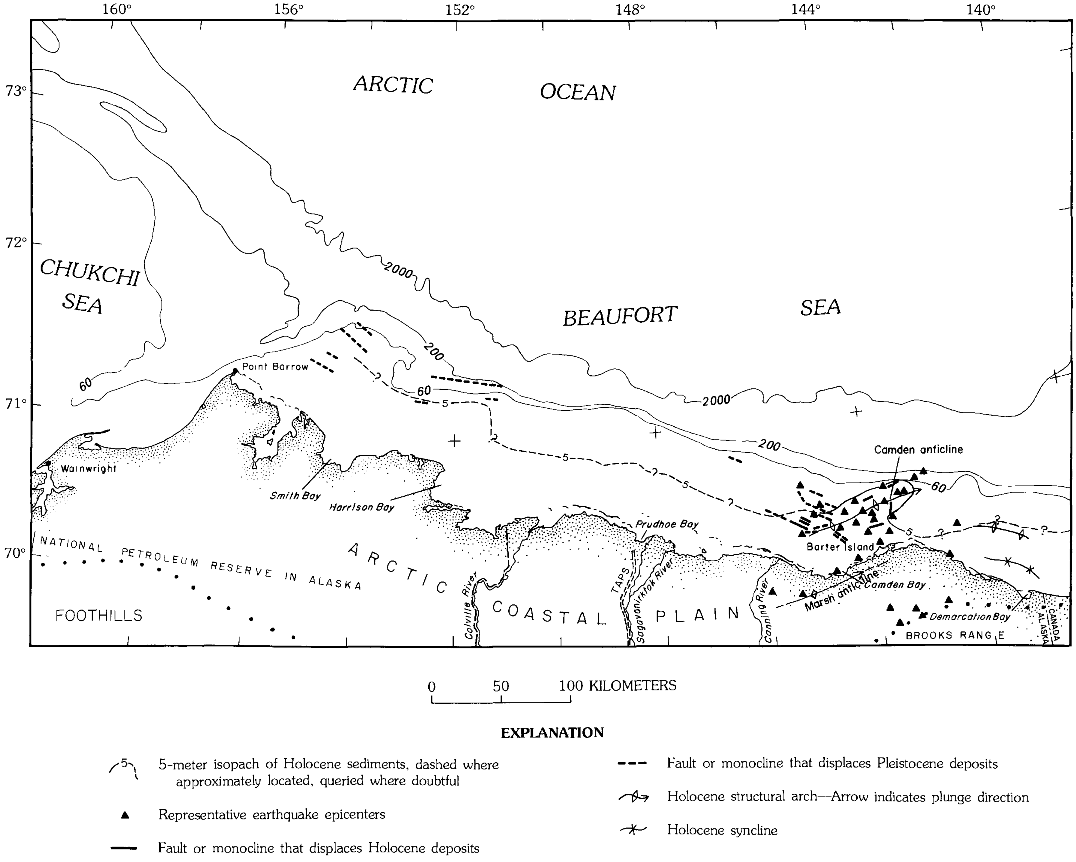


FIGURE 11.23.—Holocene faults, earthquake epicenters, and structural axes on the continental margin north of Alaska. Selected bathymetric contours in meters. Dotted lines separate onshore physiographic provinces. TAPS, Trans-Alaska Pipeline System.

The magnitudes of measured earthquakes near Barter Island range from less than 1.0 to a maximum of 5.3. Consequently, structures placed in this area should be designed to withstand ground vibrations corresponding to those from a shallow earthquake (less than 20 km) of at least magnitude 6.0 (Biswas and Gedney, 1978). Studies by Thenhaus and others (1982) on seismic horizontal ground motion in Alaska and adjacent offshore areas indicate that there is a 90 percent probability that ground accelerations with maximum values of 4.0-5.0 percent of gravity will not be exceeded (and a 10 percent probability that they will be exceeded) in 50 years in the Barter Island seismic terrane.

SHALLOW GAS

Shallow free gas has accumulated in several geologic environments beneath the shelf and slope of the western Beaufort and northeastern Chukchi Seas. In some cases this gas may indicate the presence of natural gas deposits in underlying sedimentary strata (thermogenic origin). In other cases the gas may originate in surficial sediment as a product of bacterial metabolism of organic constituents (biogenic origin). Wherever it occurs, shallow free gas must be considered a potential engineering hazard to petroleum exploration or development structures founded on the seabed. Such gas can inhibit the normal consolidation of accumulating sediment, leading to abnormally low shear strength. In addition, overpressured gas concentrated in pockets might cause blowouts during drilling.

High concentrations of shallow gas have been mapped in scattered, isolated areas of the inner shelf and in a fairly continuous band at or near the head of the landslide area near the shelf break from high-resolution (Uniboom) seismic-reflection profiles (fig. 11.19). Varying gas concentrations are distinguishable on these records as acoustically "turbid" intervals, in which normally strong reflectors are hazy or completely wiped out. Delineation of the zones shown on figure 11.19 depends on the assumption that the degree to which a reflection record is degraded or turbid is a function of how much free gas is present in the bubble phase. Ambiguity arises where records have been degraded because of strong ship motion during storms. In a few areas high gas concentrations are marked not by turbid intervals but by prominent reflectors that commonly exhibit reversed polarity (Boucher and others, 1981). Such reflectors form where gas accumulates beneath a relatively impermeable stratum, thus enhancing the acoustic impedence contrast at the base of the stratum.

On the middle and inner shelf, high concentrations of shallow gas are most commonly associated with buried Pleistocene delta and channel systems and with active faults overlying sources of natural gas. Additional pockets probably are present within and beneath permafrost very near the shore, but data on this type of occurrence are sparse. Beneath the outer shelf and continental slope, shallow gas is concentrated in two, probably related, environments. It is thought to underlie a large body of gas hydrate (see following section) and also occurs almost ubiquitously at the head of the landslide area on the outermost shelf and upper slope. As this area lies just inshore and updip from the gas hydrate sheet, it seems likely that the gas here has migrated from beneath the hydrate.

GAS HYDRATE

Gas hydrates (solids composed of light gases caged in the interstices of an expanded ice crystal lattice) are stable and widespread under the conditions of low temperature and fairly high pressure that prevail within the uppermost 300 m to more than 700 m of sediment beneath the continental slope and outermost shelf of the Beaufort Sea, where water depths exceed about 400 m. The hydrate, the gas component of which consists mostly of methane in submarine strata, tends to cement the sediment, somewhat increasing its seismic velocity and reducing its permeability. As a result, large amounts of free gas, detected on seismic reflection profiles, have accumulated beneath the hydrate zone (fig. 11.20). The presence of this free gas and the danger that the hydrate may decompose and release large quantities of methane and perhaps other hydrocarbon gases during drilling pose a substantial potential hazard to drilling on the outer shelf and continental slope and rise of the Beaufort Sea. However, the petroleum industry, particularly in the Canadian Arctic, has acquired considerable experience in coping with gas hydrate in bore holes. The resource potential of the gas hydrate and underlying free gas were discussed earlier in this chapter, in the section titled "Petroleum Potential."

PERMAFROST

Before about 10,000 years ago, during the last glacial sea-level lowstand, the present Beaufort and Chukchi shelves were subaerially exposed to frigid temperatures, and ice-bonded permafrost probably formed in the sediment to depths exceeding 300 m. Reflooding of the shelf covered these sediments with saline water at temperatures above the freezing point, and much of the permafrost has probably warmed and remelted.

Studies are underway to assess seismically the depth to, and thickness of, relict permafrost over the entire Beaufort shelf. However, only certain areas on the inner shelf have been characterized thus far. Sellman and Chamberlain (1979) report that three obvious groups of seismic velocities are apparently related to the degree of ice-bonding in the sediment. Fully ice-bonded permafrost having ice-saturated pores and velocities greater than 4.0 km/s crops out onshore, on some barrier islands, and in adjacent wide zones landward of the 2-m isobath that are overlain by bottom-fast ice in winter. Between the shore and the barrier islands, fully ice-bonded permafrost occurs at highly variable depths as deep as several hundred meters beneath the sea floor. The ice-bonded permafrost is overlain in this area mostly by material with velocities around 2.7 km/s, inferred to be partially ice-bonded sediment containing a varying proportion of unfrozen pore water. Material with velocity less than 2.2 km/s is sparse and assumed to be unbonded.

Although the distribution of relict permafrost on the coastal and outer shelf is unknown, the base of Holocene marine sediment on the Beaufort shelf, contoured in figure 11.21, provides a probable minimum depth to its upper surface. This is so because it is unlikely that permafrost grew upward by freezing of saline pore water in the Holocene marine mud deposited on the shelf after the rise in sea level. By analogy with the conditions described in nearshore areas, any permafrost in the uppermost sediment beneath the Holocene sediment wedge was probably melted, or partially melted, down to unknown depths. Depending on such parameters as pore-water salinity, original thickness, temperature of the subaerial permafrost, and the insulating effect of the Holocene mud, fully ice-bonded permafrost may or may not be encountered at depth offshore. Where it exists, care must be taken to avoid melting it beneath pipelines and drilling platforms and within frozen intervals encountered in drilling.

Permafrost might occur locally in the Chukchi Sea. Ice-bonded permafrost is known to occur in Elson Lagoon, which connects with the Beaufort Sea just east of Point Barrow, but none was found in the Chukchi Sea 705 m from shore near Barrow (Osterkamp and Harrison, 1977). Nearshore permafrost is most likely to occur in areas where coastal erosion is rapid. Because the rates of coastal erosion are typically lower in the Chukchi Sea than in the Beaufort Sea, permafrost may not be as common in the Chukchi Sea (Harper, 1978).

REFERENCES CITED

Alaska Geological Society, 1971, West to east stratigraphic correlation section, Point Barrow to Ignek Valley, Arctic North Slope, Alaska: Anchorage, Alaska Geological Society.

——— 1972, Northwest to southeast stratigraphic correlation section, Prudhoe Bay to Ignek Valley, Arctic North Slope, Alaska: Anchorage, Alaska Geological Society.

——— 1977, North to south stratigraphic correlation section, Beaufort Sea-Prudhoe Bay-Nora No. 1, Arctic Slope, Alaska: Anchorage, Alaska Geological Society.

——— 1981, West to east stratigraphic correlation section, N.P.R.A.-Prudhoe Bay, Arctic Slope, Alaska: Anchorage, Alaska Geological Society.

American Association of Petroleum Geologists, Geothermal Survey of North America Subcommittee, 1976, Geothermal gradient map of North America: U.S. Geological Survey Special Map, 2 sheets, scale 1:5,000,000.

Biswas, N.N., and Gedney, L., 1978, Seismotectonic studies of northeast and western Alaska: Fairbanks, University of Alaska, Geophysical Institute, 45 p.

Boucher, Gary, Reimnitz, Erk, and Kempema, Edward, 1981, Seismic evidence for an extensive gas-bearing layer at shallow depth, offshore from Prudhoe Bay, Alaska: Cold Regions Science and Technology, v. 4, p. 63-71.

Brosgé, W.P., and Tailleur, I.L., 1971, Northern Alaska petroleum province, *in* Cram, I.H., ed., Future petroleum provinces of the United States—their geology and potential: American Association of Petroleum Geologists Memoir 15, p. 68-99.

Brower, W.A., Jr., Searby, H.W., Dias, H.F., Prechtel, A.S., and Wise, J.L., 1977, Climatic atlas of the outer continental shelf waters and coastal regions of Alaska, v. 3, Chukchi-Beaufort Sea: Arctic Environmental Information and Data Center Publication B-77, 409 p.

Eittreim, Stephen, and Grantz, Arthur, 1979, CDP seismic sections of the western Beaufort continental margin: Tectonophysics, v. 59, p. 251-262.

Grantz, Arthur, Dinter, D.A., and Biswas, N.N., 1983, Map, cross sections, and chart showing late Quaternary faults, folds, and earthquake epicenters on the Alaskan Beaufort shelf: U.S. Geological Survey Miscellaneous Investigations Series Map I-1182-C, 3 sheets, scale 1:500,000.

Grantz, Arthur, Eittreim, Stephen, and Dinter, D.A., 1979, Geology and tectonic development of the continental margin north of Alaska: Tectonophysics, v. 59, p. 263-291.

Grantz, Arthur, Eittreim, Stephen, and Whitney, O.T., 1981, Geology and physiography of the continental margin north of Alaska and implications for the origin of the Canada Basin, *in* Nairn, A.E.M., Churkin, Michael, Jr., and Stehli, F.G., eds., The ocean basins and margins, v. 5, The Arctic Ocean: New York, Plenum Press, p. 439-492.

Grantz, Arthur, and May, S.D., 1983. Rifting history and structural development of the continental margin north of Alaska, *in* Watkins, J.S., and Drake, C.L., eds., Studies in continental margin geology: American Association of Petroleum Geologists Memoir 34, p. 77-100.

Grantz, Arthur, and Mull, C.G., 1978, Preliminary analysis of the petroleum potential of the Arctic National Wildlife Range, Alaska: U.S. Geological Survey Open-File Report 78-489, 20 p., 3 sheets.

Greenberg, Jonathan, Hart, P.E., and Grantz, Arthur, 1981, Bathymetric map of the continental shelf, slope, and rise of the Beaufort Sea north of Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1182-A, 6 p., scale 1:500,000.

Guldenzopf, E.C., and others, 1980, National Petroleum Reserve, Alaska, Summary geologic report, FY-1980 (81-TGB-22): Tetra Tech., Inc., prepared for Husky Oil NPRA Operations, Inc., under contract to U.S. Geological Survey, 168 p. [Available from National Geophysical Data Center, 325 Broadway, E/GC, Dept. CNP, Boulder, Colorado

80303].

Harper, J.R., 1978, Coastal erosion rates along the Chukchi Sea coast near Barrow, Alaska: Arctic, v. 31, no. 4, p. 428-433.

Hea, J.P., Arcuris, J., Campbell, G.R., Fraser, I., Fuglem, M.O., O'Bertos, J.J., Smith, D.R., and Zayat, M., 1980, Post-Ellesmerian basins of Arctic Canada; their depocentres, rates of sedimentation and petroleum potential, *in* Miall, A.D., ed., Facts and principles of world petroleum occurrence: Canadian Society of Petroleum Geologists Memoir 6, p. 447-488.

Hopkins, D.M., and Hartz, R.W., 1978, Coastal morphology, coastal erosion, and barrier islands of the Beaufort Sea, Alaska: U.S. Geological Survey Open-File Report 78-1063, 54 p.

Jamison, H.C., Brockett, L.D., and McIntosh, R.A., 1980, Prudhoe Bay—a 10-year perspective, *in* Halbouty, M.T., ed., Giant oil and gas fields of the decade 1968-1978: American Association of Petroleum Geologists Memoir 30, p. 289-314.

Jones, H.P., and Speers, R.G., 1976, Permo-Triassic reservoirs of Prudhoe Bay field, North Slope, Alaska, *in* Braunstein, Jules, ed., North American oil and gas fields: American Association of Petroleum Geologists Memoir 24, p. 23-50.

Lachenbruch, A.H., and Marshall, B.V., 1966, Heat flow through the Arctic Ocean floor; the Canada basin-Alpha rise boundary: Journal of Geophysical Research, v. 71, p. 1223-1248.

Lerand, Monti, 1973, Beaufort Sea, *in* McCrossan, R.G., ed., The future petroleum provinces of Canada; their geology and potential: Canadian Society of Petroleum Geologists Memoir 1, p. 315-386.

Mair, J.A., and Lyons, J.A., 1981, Crustal structure and velocity anisotropy beneath the Beaufort Sea: Canadian Journal of Earth Sciences, v. 18, p. 724-741.

Martin, A.J., 1970, Structure and tectonic history of the western Brooks Range, De Long Mountains and Lisburne Hills, northern Alaska: Geological Society of America Bulletin, v. 81, p. 3605-3621.

Meyers, H., 1976, A historical summary of earthquake epicenters in and near Alaska: NOAA Technical Memo EDS NGSDG-1, 57 p.

Miller, C.C., and others, 1979, National Petroleum Reserve, Alaska, Summary geophysical report FY-1979 (1980 SE-LL): Tetra Tech., Inc., prepared for Husky Oil NPR Operations, Inc., under contract to U.S. Geological Survey, 47 p. [Available from National Geophysical Data Center, 325 Broadway, E/GC, Dept. CNP, Boulder, Colorado 80303].

Moore, D.G., 1964, Acoustic reflection reconnaissance of continental shelves; the Bering and Chukchi Seas, *in* Miller, R.I., ed., Papers in marine geology (Shepard volume): New York, MacMillan, p. 319-362.

National Petroleum Council, 1981, U.S. Arctic oil and gas: Washington, D.C., National Petroleum Council, 286 p.

Oliver, Jack, Ewing, Maurice, and Press, Frank, 1955, Crustal structure of the Arctic regions from the L_g phase: Geological Society of America Bulletin, v. 66, p. 1063-1074.

Osterkamp, T.E., and Harrison, W.D., 1977, Sub-sea permafrost regime at Prudhoe Bay, Alaska, U.S.A.: Journal of Glaciology, v. 19, no. 81, p. 627-637.

Royden, Leigh, Sclater, J.G., and von Herzen, R.P., 1980, Continental margin subsidence and heat flow; important parameters in formation of petroleum hydrocarbons: American Association of Petroleum Geologists Bulletin, v. 64, no. 2, p. 173-187.

Sellman, P.V., and Chamberlain, E., 1979, Delineation and engineering characteristics of permafrost beneath the Beaufort Sea: Fairbanks, Alaska, National Oceanic and Atmospheric Administration, Arctic Projects Office, quarterly report to U.S. Department of Commerce.

Tailleur, I.L., 1973, Probable rift origin of the Canada Basin, *in* Pitcher, M.G., ed., Arctic geology: American Association of Petroleum Geologists Memoir 19, p. 526-535.

Tailleur, I.L., Pessel, G.H., Levorsen, J.A., and Engwicht, S.E., 1978, Maps showing land status and well locations and tables of well data, eastern North Slope petroleum province, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-928-A, 5 sheets, scale 1:500,000.

Thenhaus, P.C., Ziony, J.I., Diment, W.H., Hopper, M.G., Perkins, D.M., Hanson, S.L., and Algermissen, S.T., 1982, Probabilistic estimates of maximum seismic horizontal ground motion on rock in Alaska and the adjacent outer continental shelf, *in* Coonrad, W.L., ed., The United States Geological Survey in Alaska; accomplishments during 1980: U.S. Geological Survey Circular 844, p. 5-9.

12. DEPOSITIONAL FACIES, PETROGRAPHY, AND RESERVOIR POTENTIAL OF THE FORTRESS MOUNTAIN FORMATION (LOWER CRETACEOUS), CENTRAL NORTH SLOPE, ALASKA

By Cornelius M. Molenaar, Robert M. Egbert[1], and Lee F. Krystinik[2]

INTRODUCTION

The Fortress Mountain Formation of early Albian (Early Cretaceous) age is a thick clastic wedge of largely deep-water origin that was deposited in a foredeep immediately north of the Brooks Range orogen. The formation crops out discontinuously in a wide, structurally complex belt along the southern part of the southern foothills of the Brooks Range. Outcrops are restricted to the area between Elusive Lake east of the Sagavanirktok River on the east and the Kukpowruk River area on the far west, a distance of about 600 km (fig. 12.1). Areal geologic mapping projects in the late 1940's and early 1950's covered much of the outcrop area of the Fortress Mountain. The general lithologic and stratigraphic aspects of the formation were discussed in subsequent reports, which include, from east to west, Keller and others (1961), Detterman and others (1963), Patton and Tailleur (1964), Chapman and others (1964), Tailleur and others (1966), Tailleur and Kent (1951), Tailleur and others (1951), Sable and others (1951), and Chapman and Sable (1960).

This report covers primarily the central part of the outcrop belt of the Fortress Mountain Formation (fig. 12.2). In addition to reviewing the general stratigraphy of the Fortress Mountain, this report discusses (1) depositional environments and facies patterns, (2) petrography, and (3) the subsurface projection in relation to hydrocarbon-reservoir potential. The section on petrography is the work of one of us (Egbert), whereas the other sections are joint efforts. Many of the conclusions in this report are necessarily highly interpretive, and therefore supporting evidence is discussed in more detail.

Field work for this report consisted of one month of helicopter-supported investigations by the authors between July 23 and August 21, 1980. Adverse weather conditions, including early snowfalls, limited the field work. Consequently, areal coverage of the outcrop belt of the Fortress Mountain Formation was curtailed. Most of the time was spent in the area between the Chandler River on the east and the lower Nuka River on the west, a distance of 280 km (figs. 12.1, 12.2). In addition, a reconnaissance was made of outcrops of the Fortress Mountain Formation in the Kukpowruk River area west of the National Petroleum Reserve in Alaska (NPRA). Because of limited time, the field work concentrated on those outcrops throughout the area that would yield the most stratigraphic information.

Structural complexities and rapid facies changes account for the discontinuous nature of the outcrops of the Fortress Mountain Formation and make lateral tracing of beds for any distance difficult or impossible. In order to project facies trends with greater confidence, emphasis was placed on interpretation of depositional environments and measurement of paleocurrent directions. Most of the sedimentologic observations are generalized in order to relate depositional facies in general to the paleogeography. With local variations, the conclusions reached in this study would probably be applicable to much of the remaining parts of the outcrop belt of the Fortress Mountain Formation.

Our interpretations of the general facies relations of the Fortress Mountain Formation and the lower part of the Torok Formation are shown diagrammatically in figure 12.3.

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of Umiat Enterprises, Inc., helped overcome several communication and food-shortage problems.

TYPE SECTION AND DEFINITION

The Fortress Mountain Formation was named by Patton (1956, p. 219) for exposures on Fortress Mountain (lat 68°34′30″ N., long 152°58′ W.). The type section is a composite of several partial sections exposed along the Kiruktagiak River and on Castle Mountain for which an aggregate thickness of approximately 3,000 m was computed (fig. 12.4).

The name Fortress Mountain Formation was applied to a coarse southern facies that formerly had been included in the Torok Formation. The Torok is now geographically restricted to the predominantly shaly facies to the north. The two facies are separated by either a zone of intense thrust faulting or a band in which there are few exposures (Patton, 1956, p. 219; see fig. 12.2); however, the Fortress Mountain Formation is probably the lateral equivalent of the lower part of the Torok Formation to the north in the southern foothills and the southern part of the northern foothills.

The Fortress Mountain Formation as defined by Patton (1956) includes all strata above the Okpikruak Formation (Lower Cretaceous, Neocomian, and locally Upper Jurassic) or older formations in the southern part of the outcrop belt where the top of the unit is not exposed. To the north it intertongues with, and is overlain by, the Torok Formation (fig. 12.3).

CHARACTER AND THICKNESS

The Fortress Mountain Formation consists of a thick sequence of sand-

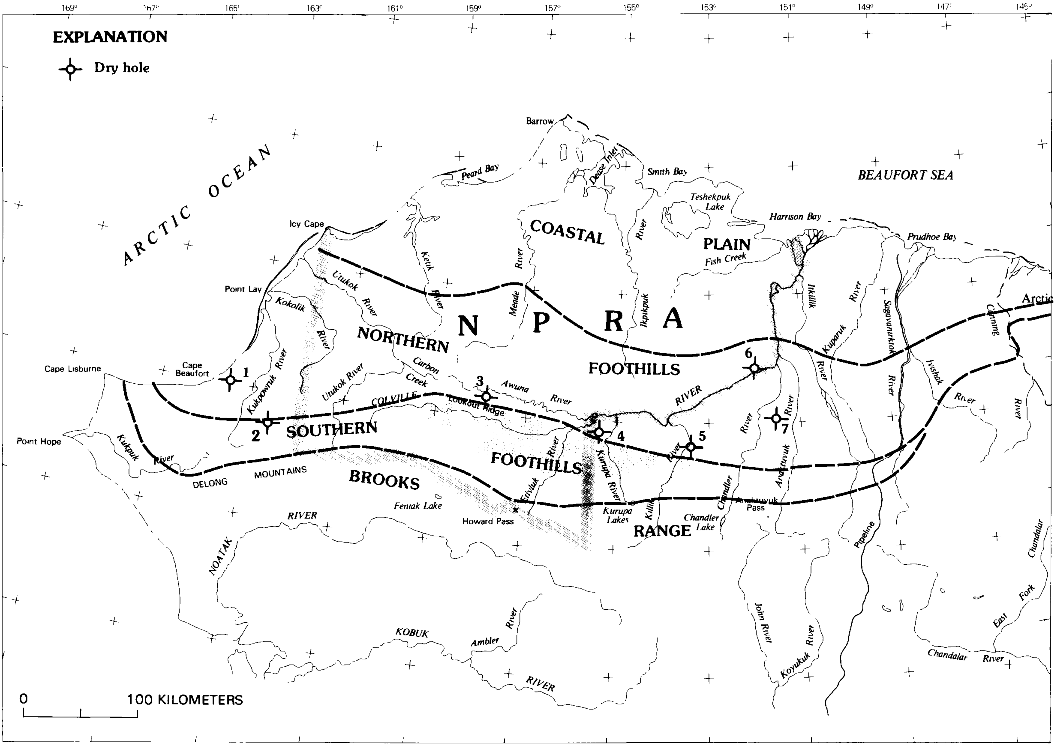


FIGURE 12.1.—Index map showing physiographic subdivisions of North Slope and area of investigation (shaded). Except for a small area near the Kukpowruk River on the far west, outcrops of the Fortress Mountain Formation occur only in the southern foothills. Wells shown are those that may have penetrated strata laterally equivalent to the Fortress Mountain Formation. From west to east, these wells are (1) Chevron Akulik No. 1, (2) Chevron Eagle Creek No. 1, (3) Awuna No. 1, (4) Texaco West Kurupa No. 1, (5) Texaco East Kurupa No. 1, (6) Seabee No. 1, and (7) Texaco Tulugak No. 1.

stone, conglomerate, and shale. Outcrops are limited to discontinuous cutbank exposures and to isolated hilltops or mountain tops (fig. 12.5). The rocks in most outcrops are moderately to tightly folded. Large areas of flat or gently sloping colluvium covered by tundra-type vegetation separate the outcrops, making it difficult or impossible to trace stratigraphic units laterally. In addition, the units are lenticular because of the way they were deposited. The isolated hills and mountains along the outcrop belt are held up by thick units of sandstone or conglomerate, giving the misleading impression that coarse clastics rocks are predominant. Shale or siltstone is actually the dominant lithology, as indicated at the type section (fig. 12.4). The shale is generally dark gray, silty, and non-fissile, although fissile shale has been reported as well (Chapman and others, 1964, p. 353). Concretion zones commonly delineate the bedding within the shale. Bentonitic shale and bentonite were observed at one outcrop in the lower part of the Torok Formation, on the east bank of the Chandler River in sec. 1, T. 9 S., R. 2 W. These rocks are probably correlative with the Fortress Mountain Formation to the south.

Thick-bedded, massive conglomerate and sandstone units make up the prominant exposures in the southern part of the outcrop belt, and thinly interbedded flyschoid sequences predominate along river cutbanks to the north. Thin-bedded sequences also occur within the dominantly massive southern facies. The massive conglomerate and sandstone units are generally lenticular and grade laterally into thinner bedded sequences or shale along the depositional strike (fig. 12.4). Bedding characteristics are discussed later in more detail in the section on "Depositional Environments."

The sandstone is generally a greenish-gray, poorly sorted, very fine grained to coarse-grained graywacke in the southern part of the outcrop area and becomes finer grained to the north. The grains consist mostly of lithic fragments in a clayey chloritic matrix. In the Kukpowruk River area far to the

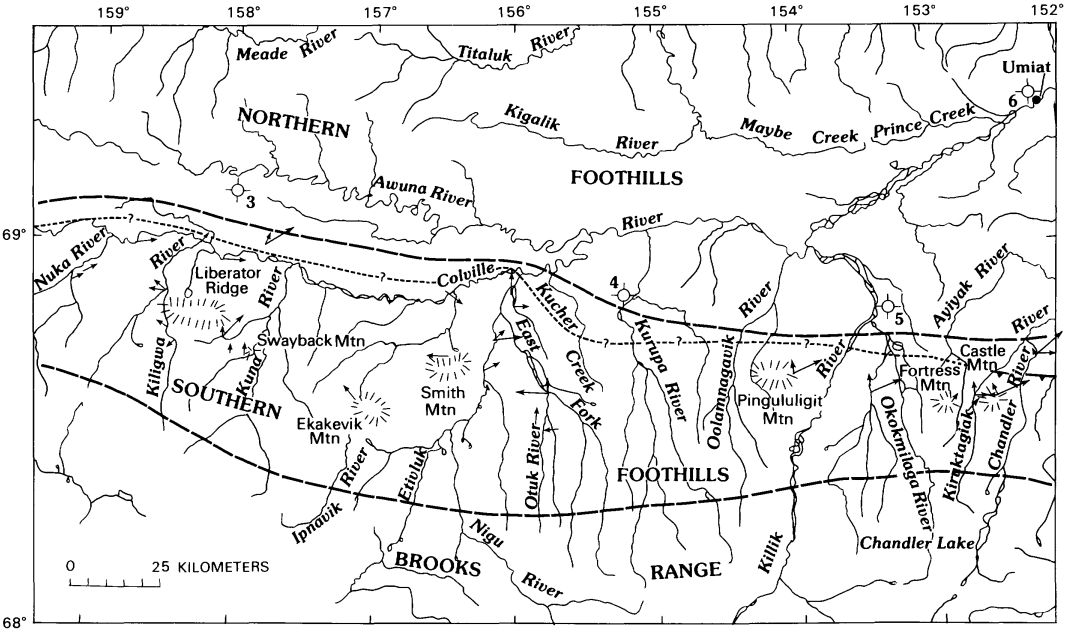


FIGURE 12.2.—Index map of primary area of investigation. Arrows indicate paleocurrent directions determined from outcrops of the Fortress Mountain Formation and lower part of the Torok Formation; longest arrow of each group (if distinguished) indicates predominant direction or most reliable data. Dotted line and thrust fault delineate concealed boundary or contact between the Fortress Mountain Formation to south and Torok Formation to north. Boundary is based on, from west to east, Tailleur and others (1966), Chapman and others (1964), in part, and Patton and Tailleur (1964). Wells shown are (3) Awuna No. 1, (4) Texaco West Kurupa No. 1, (5) Texaco East Kurupa No. 1, and (6) Seabee No. 1.

west, the sandstone contains more quartz and is characteristically very calcareous and micaceous. Because of these mineralogical differences, Mull (1985) assigned the name Mount Kelly Graywacke Tongue of the Fortress Mountain Formation to the rocks in that area. Porosity appears to be very low in all the sandstone. Details of the petrography are discussed later.

Most of the conglomerate is poorly sorted and disorganized (that is, lacking stratification, grading, or clast orientation), and it consists of pebbles, cobbles, and a few boulders. The clasts consist of chert, mafic igneous rocks, and sandstone or quartzite in various proportions, with lesser amounts of limestone and shale. Most of the chert clasts appear to be of sedimentary origin, but some are silicified volcanic rocks. The dominant type of clast is not the same in all areas, thus indicating differences in the rocks exposed in the adjacent source terranes, either laterally or vertically, during Fortress Mountain time. Preliminary observations indicate that chert is the dominant rock type in the conglomerates in the Fortress Mountain-Castle Mountain area; sandstone and mafic igneous clasts are dominant in the Ekekavik Mountain area; mafic igneous clasts are dominant in the Swayback Mountain area; and chert, mafic igneous rock, and sandstone clasts occur in approximately equal proportions in the Kiligwa River area.

The 3,000-m thickness calculated for the type section is the greatest reported for any section of the Fortress Mountain Formation. Other generalized sections measured by previous workers range in thickness from about 450 to 1,800 m (Keller and others, 1961, p. 200; Patton and Tailleur, 1964, p. 452; Chapman and others, 1964, p. 355; Chapman and Sable, 1960, p. 72). None of these sections, including the type section, is complete; the top of all sections in the southern part of the outcrop belt is a Holocene erosion surface, and the base is covered, although the base of the type section is near exposures of older rocks. In the northern part of the outcrop belt, the Fortress Mountain Formation grades into the lower part of the Torok Formation (fig. 12.3).

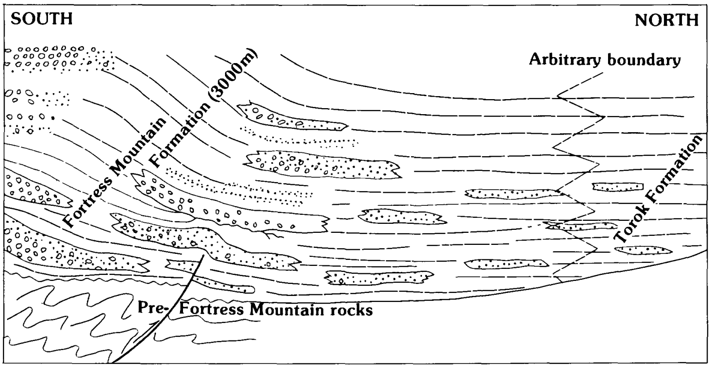


FIGURE 12.3.—Diagrammatic cross section across southern foothills region of North Slope showing inferred relations of facies of the Fortress Mountain and Torok Formations before intense folding. Horizontal beds in upper left are alluvial and shallow-marine deposits, tilted beds are slope shale and submarine canyon fill, and lower horizontal beds are basinal shale and turbidites. Arbitrary boundary showing terminology change is indicated by zig-zag line, unconformity by wavy line. Stipple pattern, sandstone; small circles, conglomerate.

CONTACT RELATIONS

Although its basal contact with older rocks is everywhere covered, the Fortress Mountain Formation is believed to rest unconformably on older rocks, usually the Okpikruak Formation of Neocomian (Early Cretaceous) and locally Late Jurassic age. In some areas the contact is considered to be an angular unconformity (Patton and Tailleur, 1964, p. 452). Such a relation is apparently present in the southern outcrop belt in the areas of Castle Mountain, Fortress Mountain, Ekakevik Mountain, and Swayback Mountain. Faulting and structural complexities, however, are common in these areas, and some of the relations are subject to interpretation. In the Castle Mountain-Fortress Mountain area, the Fortress Mountain Formation overlies a chaotic assemblage of separate blocks of either chert, limestone, mafic igneous rocks, or sandstone ranging in age from Mississippian to Early Cretaceous (Neocomian). These blocks, some of which are more than 100 m across, have been interpreted to be slivers in a pre-Fortress Mountain thrust zone (Patton and Tailleur, 1964, p. 452) or part of a widespread olistostrome of Neocomian age (Mull and others, 1976, p. 25). Either interpretation suggests intense tectonism, at least to the south, before deposition of the Fortress Mountain Formation. Relations are apparently similar at Ekakevik Mountain and Swayback Mountain, although the underlying chert and mafic igneous rocks in those areas are not as chaotic and have more continuity.

The nature of the unconformity should be considered in relation to the depositional setting. Wherever the basal part of the Fortress Mountain Formation is exposed, those rocks are interpreted as having been deposited in deep water (here considered as below the effect of storm-wave base or surface currents and in some cases probably of at least bathyal depth). Unconformities may be the result of submarine scouring along submarine canyons cutting into a deformed basin slope. Along Anuk Creek (sec. 7, T. 8 S., R. 26 W.) about 10 km northwest of Swayback Mountain, the faulted core of an anticline developed in the Fortress Mountain Formation contains an outcrop of fossiliferous cherty shale of the Shublik Formation (Triassic) and lapilli tuff of Jurassic(?) age. A short distance downstream, an outcrop of conglomerate in the Fortress Mountain Formation contains angular clasts of chert and organic-rich shale, presumably derived from the Shublik Formation. This conglomerate is believed to have been deposited in a submarine channel, and some of the clasts probably were scoured from the channel walls up the basin slope to the south. Tailleur and Kent (1951, p. 24) suggested that these relations indicate that the middle or upper part of the Fortress Mountain Formation was deposited on an actively growing structure within the depositional basin.

Farther north in the basin, the Fortress Mountain Formation may be conformable with older rocks, although this has not been proven. In an anticlinal fold along the lower Kiligiwa River near Brady, about 9 km from the mouth of the river, the Fortress Mountain Formation lies about 100 m or less above shale and siltstone containing Valanginian fossils that are common to the Okpikruak Formation (Tailleur and Kent, 1953; Imlay, 1961, p. 22). The character of the contact, however, is indeterminate (Tailleur and Kent, 1953, p. 7).

Seismic data in the northern foothills indicate that Albian or older strata progressively onlap the south-dipping Neocomian pebble shale unit (Molenaar, chapter 25). Therefore, older post-Neocomian rocks may be present in the axial part of the Colville basin in the northern part of the southern foothills.

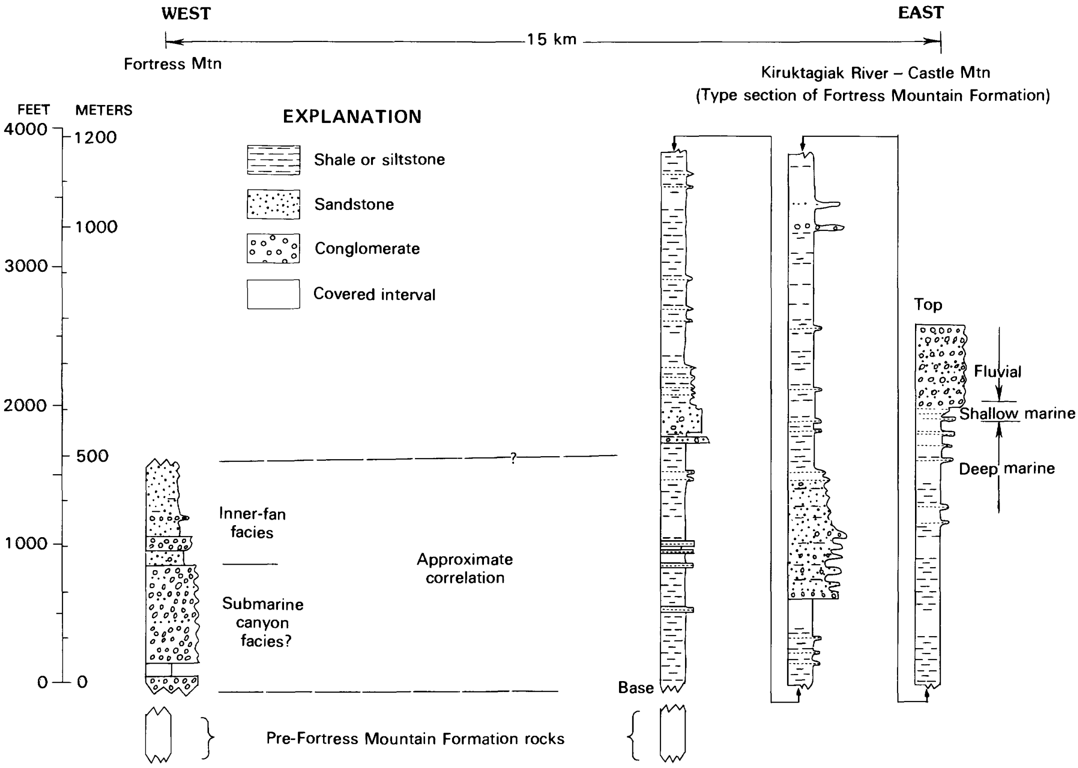
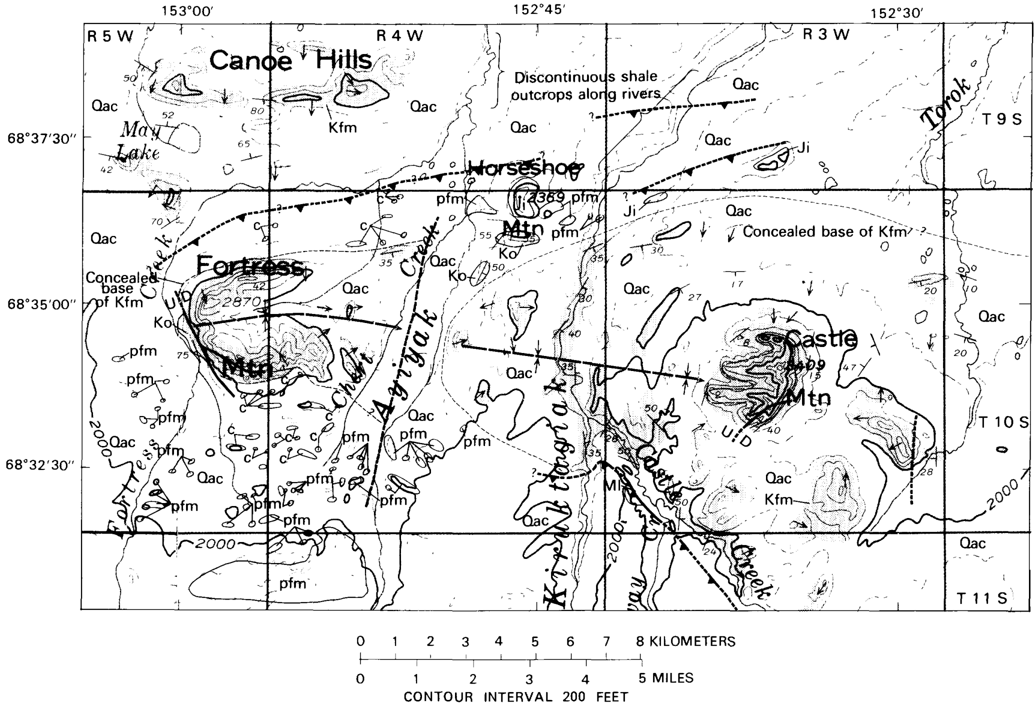


FIGURE 12.4.—Inferred correlation of the Fortress Mountain Formation between Fortress Mountain and Castle Mountain. Castle Mountain section (type section) modified from Patton and Tailleur (1964).



EXPLANATION

Qac	Alluvium and colluvium (Quaternary)
Kfm	Fortress Mountain Formation (Early Cretaceous, Albian)
Ko	Okpikruak Formation (Early Cretaceous, Neocomian)
Ji	Mafic intrusive rocks (Jurassic)
Ml	Lisburne Group (Mississippian)
pfm	Pre-Fortress Mountain Formation rocks (consist of the undivided Okpikruak Formation through Lisburne Group) (Mesozoic and Paleozoic)
c	Chaotic assemblage rocks (blocks of the Okpikruak Formation, mafic intrusive rocks, Otuk and Nuka Formations, and Lisburne Group) (Mesozoic and Paleozoic)

○	Outcrop (from aerial photograph). Outcrops of Fortress Mountain Formation shaded
↗	Dip estimated from aerial photograph
- - - -	Contact of formation or bed
┼	Syncline axis
	Faults
---▼---	Thrust fault—Dotted where concealed; sawteeth on upper plate
U D	Normal fault—Dotted where concealed; U, upthrown side; D, downthrown side
——----	Fault of unknown displacement-Dotted where concealed
— — —	Inferred fault
┬ 17	Strike and dip of beds

FIGURE 12.5.—Geologic map of the area around Fortress Mountain and Castle Mountain (type section of the Fortress Mountain Formation) showing outcrops and relation of the Fortress Mountain Formation. Geology modified from Patton and Tailleur (1964).

Thin-bedded turbidites of the Fortress Mountain Formation intertongue northward with shale of the Torok Formation in the northern part of the southern foothills. Locally, thick-bedded, coarser grained turbidites occur in rocks mapped as Torok Formation, such as near the junction of Torok Creek and the Chandler River (Patton and Tailleur, 1964) and near the mouth of the Etivluk River (Chapman and others, 1964). These beds are interpreted as being northerly extending midfan deposits. The rocks exposed near the mouth of Etivluk River are here included in the Fortress Mountain Formation (fig. 12.2). The contact between the Fortress Mountain and Torok Formations has been placed arbitrarily, because of poor exposures and structural complications (fig. 12.2). If the contact were traceable, it undoubtedly would be found to range in stratigraphic position.

PENECONTEMPORANEOUS DEFORMATION

Folding during Fortress Mountain time has been suggested to account for numerous local unconformities within the Fortress Mountain Formation and for the overall decrease in deformation upward in the formation (Patton and Tailleur, 1964, p. 456). Some of this apparent decrease may result from differences in competence between the more shaly basal parts and the massive conglomeratic parts in the upper part of the formation (Tailleur and Kent, 1951, p. 23). There are indications, however, of penecontemporaneous deformation. One indication is along the East Fork of the Etivluk River in sec. 25, T. 9 S., R. 17 W., where Chapman and others (1964, p. 355) reported a local unconformity. This unconformity is interpreted here as being at the base of a deep-water, conglomerate-filled channel that truncates a thin-bedded turbidite facies with an angular difference of about 20° over the outcrop width of about 150 m (see fig. 12.9).

An angular unconformity has also been reported by Tailleur and Kent (1951, p. 23; the rocks were referred to as units of the Torok Formation at that time) and Tailleur and others (1966) between units of the Fortress Mountain Formation on the south side of Ekakevik Mountain. We believe the strata above the unconformity to be nonmarine, thus indicating that subaerial erosion was involved. Facies relationships are discussed in more detail in the following section.

As was noted earlier, active tectonism was apparently taking place along the southern margin of the basin during the time that the Fortress Mountain Formation was being deposited. This explanation would help to account for the apparent variations in thickness and some of the complex structural relations.

DEPOSITIONAL ENVIRONMENTS

The interpretation of depositional environments is especially important when analyzing the depositional history and facies patterns of the Fortress Mountain Formation, because structural complications and discontinuous outcrops severely limit direct tracing of units within the sequence. Correct interpretation of the depositional environments and associations enables us to position a rock unit paleogeographically within the basin and hence be able to project facies trends or patterns more accurately.

For purposes of discussion and analysis, we are herein subdividing depositional environments into three major categories: nonmarine, shallow-water marine, and deep-water marine. The division between shallow water and deep water is based on the depth to which wave and surface currents are active, that is, usually about 50 or 100 m. Except for submarine-canyon deposits, most deep-water sandstone and conglomerate were probably deposited at depths much greater than 50-100 m. Deep-water deposits are further subdivided in terms of the turbidite-fan facies model of Mutti and Ricci Lucchi (1972), with a fair degree of confidence, although there are probably significant differences between that model, derived from the northern Apennines of Italy, and the Fortress Mountain Formation.

It should be emphasized that determinations of depositional environments using the analog approach are highly inferential and may be subject to other interpretations. For this reason, some of the evidence will be discussed in more detail, especially that from the better known or previously studied sections or areas. Also, nonmarine and shallow-water marine deposits are discussed together because they are closely related and constitute a smaller part of the Fortress Mountain Formation than the deep-water facies.

Outcrops representative of different inferred depositional environments or facies typical of the Fortress Mountain Formation are shown in figures 12.6 through 12.19.

NONMARINE AND SHALLOW-MARINE DEPOSITS

Deposits believed to be nonmarine and shallow marine were noted in two areas along the outcrop belt between the Chandler and Nuka Rivers. These deposits are in the upper 150 m of Castle Mountain (fig. 12.6) and constitute at least 180 m of the section on the southwest side of Ekakevik Mountain. In addition, part of the thick conglomerate at Fortress Mountain may be partly nonmarine to shallow marine, a fan delta. The upper part of the Castle Mountain section is interpreted as representing a rapid upward gradation from marine shale through a poorly developed shoreface facies (a fan delta) to a braided-stream or alluvial-fan sequence of conglomerate and sandstone. This interpretation is based on the following evidence. (1) A 30- to 50-m-thick upward-coarsening transition zone, from silty marine shale below to thick-bedded conglomerate above, occurs at the base of the massive resistant conglomerate. This zone consists of interbedded and intermixed shale, sandstone, and pebbly sandstone, some of which contains medium-scale crossbeds. (2) Low-angle northerly dipping accretion planes occur in the lower part of the conglomerate and sandstone on the north side of the mountain (fig. 12.6). These planes may represent foreshore accretion surfaces. Symmetrical ripple marks trending north-northeast occur on one bed that was correlated across the ridge a distance of about 600 m. (3) On the southwest side of the mountain, foreset beds more than 8 m thick and having depositional dips of 18° NNW. occur near the base of the massive conglomerate. These beds are interpreted to be Gilbert-type deltaic deposits that may have been deposited in a protected embayment or abandoned channel. (4) The absence of channels and the even and regular bedding of the thick-bedded conglomerate units above the transition zone are indicative of a rapidly aggrading fluvial sequence.

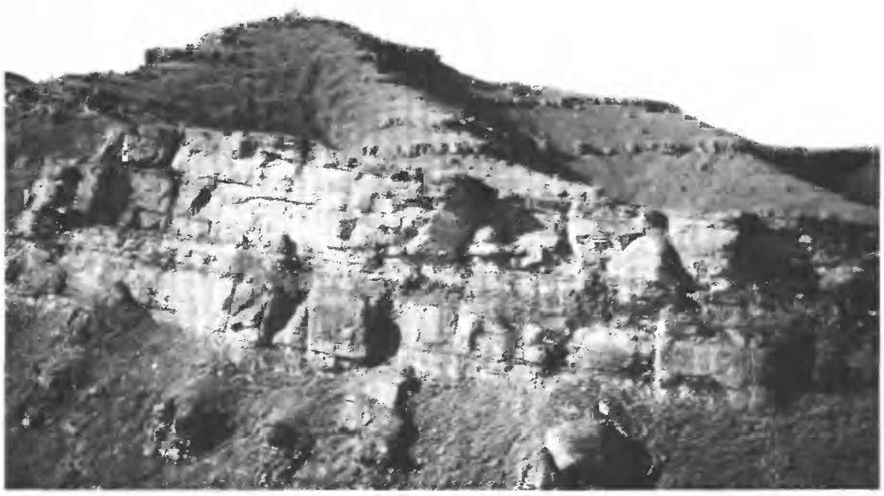


FIGURE 12.6.—Resistant conglomeratic sandstone beds in upper part of the Fortress Mountain Formation, north side of Castle Mountain (SW¼ sec. 15, T. 10 S., R. 3 W.). The beds are interpreted as being a shallow-marine transitional facies between marine beds below and nonmarine conglomerates above (background). Low-angle accretion bedding dipping from left to right is faintly visible in lower resistant bed, about 7 m thick.

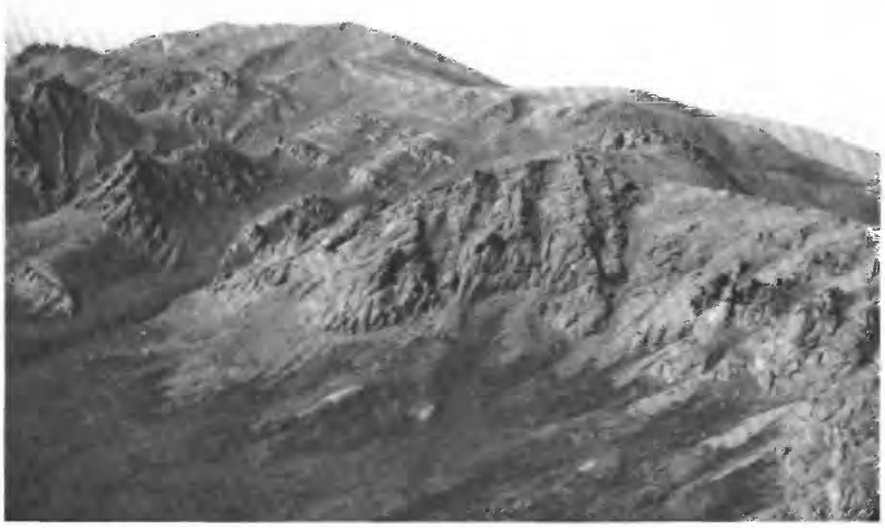


FIGURE 12.7.—Lower part of the Fortress Mountain Formation, southeast side of Fortress Mountain (secs. 18, 19, T. 10 S., R. 4 W.). Lower massive resistant unit in center of photo is 200-m-thick conglomerate believed to be a submarine-canyon facies. Above it are sandstone and conglomerate units of either submarine-canyon or inner-fan-channel facies.

Inasmuch as the vertical transition from marine to nonmarine deposits is abrupt, it is probable that the lateral gradation is also abrupt and that the shelf, if present, was narrow. Two conglomerate beds 6 to 12 m thick occur interbedded in the shale about 60 m below the transitional base of the massive conglomerate on the northwest side of the mountain. These two conglomerate beds are interpreted as having been deposited in submarine channels cutting into the upper slope or shelf.

Nonmarine deposits are also present on the southwest side of Ekakevik Mountain, as reported by Hunter and Fox (1976, p. 30). In addition to their evidence, we found coal beds a few centimeters thick, delicate fern-leaf impressions, root casts, and possible paleosols in one soft, weathered shaly and sandy interval within the conglomerate. This interval, which is at least 50 m thick, can be traced for at least 5 km along the southwest side of the mountain. About 50 to 100 m above the nonmarine zone are beds of sandstone with low-angle crossbedding, and of conglomerate, some of which contain strata of well-sorted, well-rounded chert pebbles and granules. These deposits are believed to represent a shallow-marine or beach environment. The sandstone unit capping Ekakevik Mountain was not examined in great detail, but pelecypods were collected from that unit and are listed in the section below entitled "Age." Hunter and Fox (1976, p. 30), who also found pelecypods in this unit, believed these rocks to be of shallow-marine origin. Thus, the middle and upper parts of Ekakevik Mountain form a transgressive or deepening-upward sequence.

DEEP-WATER DEPOSITS

Most of the Fortress Mountain Formation is believed to be of deep-water origin. These deposits range from some of the thick massive conglomerate units on the south, which are thought to be submarine-canyon facies (figs. 12.7, 12.8) to thinly interbedded very fine grained sandstone and shale exposed along cutbanks as far north as the Colville River that are thought to be outer-fan or basin-plain deposits (fig. 12.14). Chapman and others (1964) included rocks of this character along the lower part of the Etivluk River in the Torok Formation, but following Tailleur and others (1966), we include them in the Fortress Mountain Formation (fig. 12.2).

The thick conglomerate units at Swayback Mountain, and possibly those at Fortress Mountain and in the lower part of the Ekakevik Mountain section are believed to have been deposited in or at the heads of submarine canyons at or near local entry points for coarse clastic sediment entering the basin. At Fortress Mountain the conglomerate unit is about 300 m thick and occurs near the base of the formation, if the contact with older rocks is a depositional rather than a fault contact. The conglomerate is largely unstratified and consists of ungraded pebbles and cobbles with a few boulders. The unit can be traced northward across a syncline for about 2.5 km, where it grades into sandstone of probable inner- or mid-fan facies. To the east across an inferred large fault that parallels the Ayiyak River, the unit is believed to correlate with the lower part of the type section in the Kiruktagiak River-Castle Mountain areas, as shown in figure 12.4.

FIGURE 12.8.—Exposures of the Fortress Mountain Formation, south side of Swayback Mountain (sec. 30, T. 8 S., R. 25 W.). Thick conglomerate is interpreted as being a submarine-canyon facies. Height of exposure is about 25 m.

FIGURE 12.9.—Local unconformity within the Fortress Mountain Formation on East Fork of Etivluk River (NE¼ sec. 25, T. 9 S., R. 17 W.). Inner-fan-channel or submarine-canyon facies cutting into thin-bedded turbidite facies. Angular discordance is believed to be due to penecontemporaneous folding. Scale indicated by parked helicopter at right.

The 50-m-thick conglomerate unit exposed on the northwest and northeast sides of Ekakevik Mountain is interpreted as being either a submarine-canyon or inner-fan-channel facies. The clasts range in size from pebbles to small boulders and are unstratified and ungraded, but many of the clasts are imbricated, indicating a northward current. This unit underlies the previously mentioned nonmarine section that is exposed on the southwest side of the mountain—an anomalous relation. An angular unconformity, however, is indicated between these two units at one exposure on the south side of the mountain. This unconformity is shown by Tailleur and Kent (1951—mapped as within Torok Formation at that time) and Tailleur and others (1966) and is apparent in a small area (NW¼ sec. 23, T. 10 S., R. 22 W.) on aerial photographs. We believe that a fault cuts out the lower unit along Taffy Creek on the southwest side of the mountain. In other areas around the mountain, the lower unit is assumed to underlie the nonmarine unit unconformably with no apparent angular discordance.

FIGURE 12.10.—Inner-fan-channel rock association in the Fortress Mountain Formation along East Fork of Etivluk River (NE¼ sec. 25, T. 9 S., R. 17 W.). Thinly bedded interchannel overbank deposits overlie massive channel deposits. Scale indicated by men at lower left.

Other conglomerate units within the outcrop belt are interpreted as submarine-channel deposits of an inner- or mid-fan facies. These conglomerate units are commonly associated with thinly interbedded sandstone and shale intervals of interchannel deposits (fig. 12.10). The sequences are well exposed along the upper part of the Kiligwa River. Another notable exposure is along the East Fork of the Etivluk River (sec. 25, T. 9 S., R. 17 W.) where a channel sequence unconformably overlies a thin-bedded outer-fan turbidite facies (fig. 12.9).

Thick sandstone units make up many of the isolated hills and mountains such as Pingaluligit Mountain, Smith Mountain, and much of Liberator Ridge (fig. 12.11). Outcrops are commonly rubbly or fractured, and few diagnostic features are apparent. The sandstone is generally fine to coarse grained, poorly sorted, and poorly bedded. Curved fracture planes that could be mistaken for crossbedding may follow water-escapement paths (fig. 12.12). These sandstone units are believed to be inner- or possibly mid-fan

FIGURE 12.11.—Steeply dipping, thick-bedded or massive sandstone of inner- to mid-fan facies of the Fortress Mountain Formation exposed on Liberator Ridge (sec. 15, T. 7 S., R. 27 W.). Relief between peak and saddle at lower right is about 150 m.

grain-flow deposits (facies B of Mutti and Ricci Lucchi, 1972).

More classical thin-bedded turbidites are common in cutbanks in the more topographically subdued areas of the northern part of the southern foothills (fig. 12.14). The sandstone is usually fine to very fine grained and occurs as graded beds as much as 2 m thick, though most are less than 20 cm thick. Partial Bouma bedding sequences (Bouma, 1962, p. 49) are easily recognized; most are Tb-e, with the a interval missing and the c interval (the small-scale crossbedded or ripple-bedded division) the most prevalent. Climbing ripples and contorted bedding are common features. Flute casts and other sole markings are abundant. Tracks and trails are also common on the base of sandstone beds (figs. 12.16-12.19). The sand-to-shale ratio of the more resistant outcrops in this part of the area ranges from 1:2 to 3:1. Thickening-upward (lobe) sequences are thin where recognized; commonly, a cycle is only 1-2 m thick (fig. 12.15).

Most of the turbidites in the northern part of the southern foothills are considered to be outer-fan deposits, and the more subdued outcrops are outer-fan or basin-plain deposits.

PALEOCURRENT DIRECTIONS

Paleocurrent features are numerous in the Fortress Mountain Formation in the study area, especially in the thin-bedded, more distal facies in the northern part of the outcrop belt. Observations were made wherever possible, and although the number of data points is limited, a pattern does emerge (fig. 12.2). In the outcrops of nonmarine or shallow-marine facies, current-direction data are based on a limited number of medium-scale crossbeds, which show a wide scatter of directions, and parallel ripple marks. Clast imbrication is common in some of the submarine-channel conglomerates. In most of these, the preferred direction of the long axes of the clasts is parallel to the current direction as indicated by the imbrication. Interbedded sandstone and shale, believed in part to be interchannel deposits, contain minor groove or flute casts on the bases of

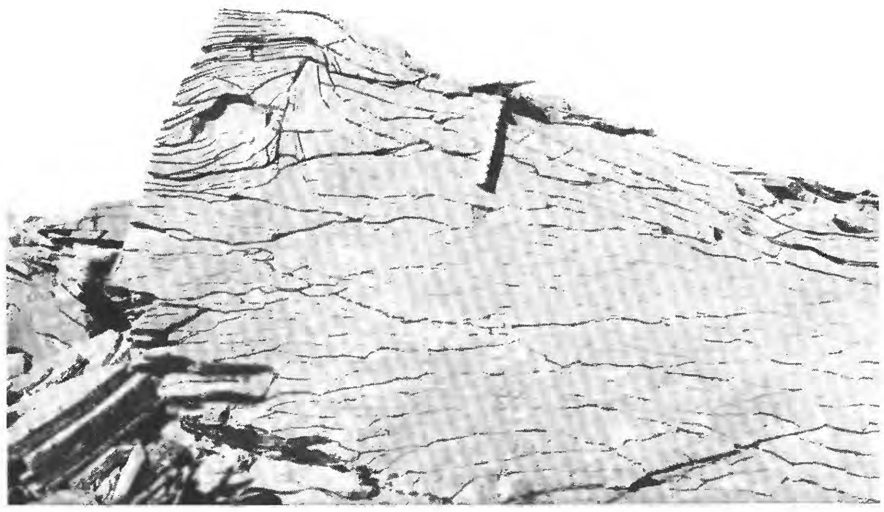


FIGURE 12.12.—Fractured outcrop of thick-bedded or massive sandstone (facies B) of inner- or mid-fan facies association of the Mount Kelly Graywacke Tongue of the Fortress Mountain Formation in westernmost part of area (NW¼ sec. 1, T. 9 S., R. 46 W.). Fracture pattern, which is probably influenced by dish structure and larger water-escape features, gives outcrop a false crossbedded appearance. Geologic hammer is 33 cm long.

FIGURE 12.13.—Mid- or inner-fan association in the Fortress Mountain Formation northeast of Liberator Ridge (NW¼ sec. 7, T. 7 S., R. 25 W.). Turbidites on left are overlain by channel deposits of conglomeratic sandstone in center, showing channel-bank accretion bedding, overlain in turn by 10 m of pebbly mudstone and then another channel on right.

the sandstone beds. Some of these current directions are divergent, which would be expected in interchannel deposits. By far the most numerous and consistent directional features occur in the more distal facies to the north. These features consist of groove and flute casts and also small-scale ripple bedding and climbing ripples (figs. 12.17, 12.18). Paleocurrent directions in that part of the area are predominantly to the east-northeast after correcting for structural deformation.

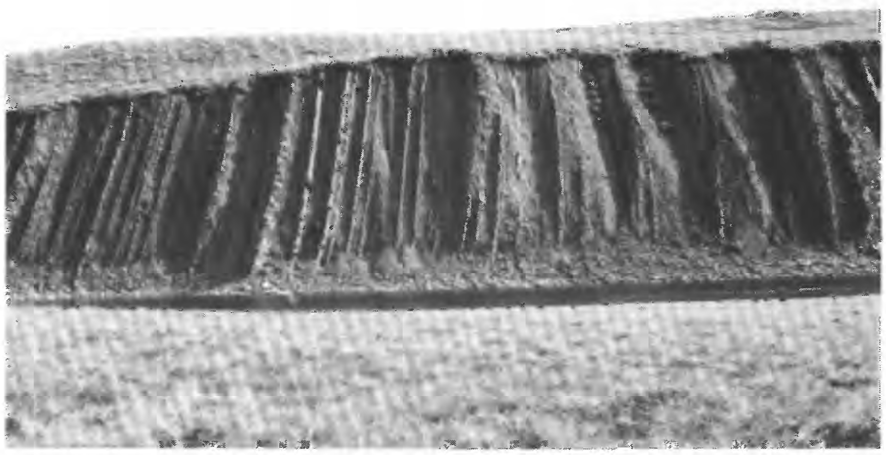


FIGURE 12.14.—Riverbank exposure of outer-fan facies of the Fortress Mountain Formation along upper Colville River (E½ sec. 20, T. 5 S., R. 29 W.). Stratigraphic top is to left. Cliff is about 25 m high.

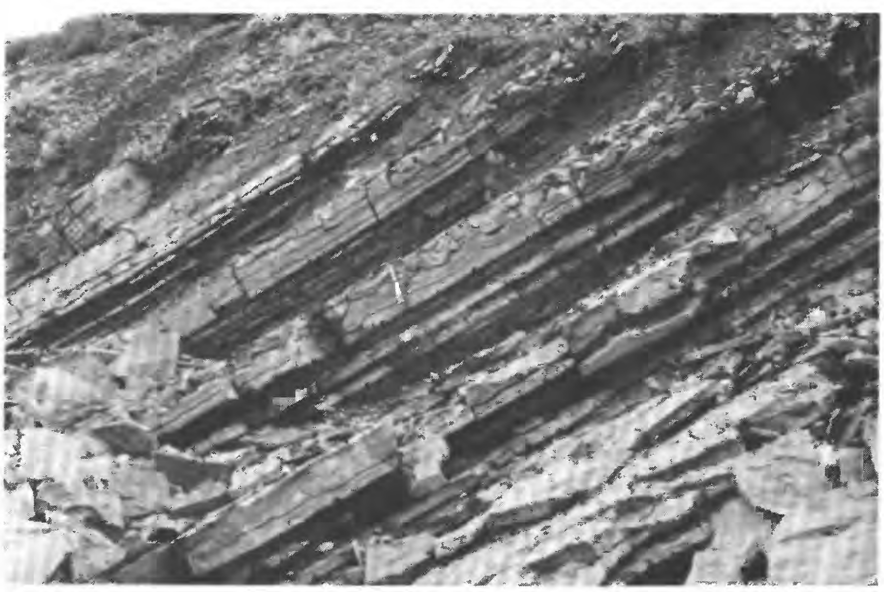


FIGURE 12.15.—Thin lobe sequences of outer-fan facies of the Fortress Mountain Formation along lower Kiligwa River (NW¼ sec. 29, T. 5 S., R. 27 W.). Interbedded sandstone (light beds, some showing convolute bedding) and mudstone (dark beds). Geologic hammer indicates scale.

DEPOSITIONAL PATTERNS

The Fortress Mountain Formation appears to have been deposited rapidly into an asymmetric steep-sided basin from many point sources along the ancestral Brooks Range (fig. 12.3). The many point sources are indicated by changes in the composition of the conglomerate clasts of the Fortress Mountain in different areas and by abrupt lateral facies changes along the depositional strike. Such changes are exemplified by the inferred relation between the sections at Fortress Mountain (T. 10 S., R. 5 W.) and at Castle Mountain, two conglomerate-capped mountains about 16 km apart along an east-west line (fig. 12.4). The 300-m-thick conglomerate unit at Fortress Mountain grades into a predominantly sandstone unit 2.5 km north across a syncline. To the east, this unit thins and apparently grades into a predominantly shale section in the lower part of the 3,000-m-thick type section of the Fortress Mountain Formation near Castle Mountain (fig. 12.5). These relations and the many thick but apparently discontinuous lenses of coarse clastic materials support the interpretation that the Fortress Mountain Formation is composed of a number of deep-sea-fan complexes, overlapping in part and each one of limited lateral extent.

Rapid facies changes downdip into the basin are also apparent, even though direct correlations are usually not possible because of the presence of complex folds and faults. However, turbidites of the Fortress Mountain Formation are finer grained and more thinly bedded to the north, and the thick conglomerate sections are always on the south side of the outcrop belt. The rapid change from conglomerate to sandstone noted at Fortress Mountain is also exemplified in the almost continuous exposures along the Kiligwa River, which transects about 27 km of the outcrop belt (Tps. 5-8 S., R. 2 W.). Although the strata are tightly folded and faulted, and stratigraphic correlation across the belt cannot be established, there is a marked gradation of proximal to distal facies from south to north. In the southern part of the outcrop belt, many conglomerate units are interpreted as representing inner-fan channel deposits. About 16-20 km to the north, the Fortress Mountain Formation consists of thin-bedded fine-grained turbidites of an outer-fan or basin-plain facies. This section must include the basal part of the Fortress Mountain Formation inasmuch as pre-Fortress Mountain Valanginian (Early Cretaceous) fossils were found nearby in shales in the exposed core of the anticline in sec. 36, T. 5 S., R. 28 W., near Brady, about 9 km from the mouth of the river (Tailleur and Kent, 1953, p. 12).

Deformation occurring during deposition of the Fortress Mountain is indicated by unconformities within the formation and apparent variations in thickness of the unit along the southern part of the basin.

Paleocurrent directions from the outer-fan or basin-plain facies associations indicate a current flow to the east-northeast (fig. 12.2). The sediments were probably derived from the south, but the turbid flow directions were influenced also by an easterly slope of the depositional basin. In the northern foothills, seismic data indicate a gentle south-dipping basin slope during the time of deposition of the lower part of the Torok Formation and (or) Fortress Mountain Formation (Molenaar, chapter 25). Thus it appears that the northern part of the southern foothills area may coincide with the depositional axis of the Colville basin during at least a part of Fortress Mountain time (fig. 12.3).

AGE

Megafossils are rare in the Fortress Mountain Formation, and only two collections of pelecypods were made during this study. Patton and Tailleur (1964, p. 456) and Chapman and others (1964, p. 357) list and discuss previously collected megafossils and microfossils, many of which are long ranging or nondiagnostic. The diagnostic species include the ammonites *Colvillia crassicostata* Imlay, *C. Kenti* Imlay,

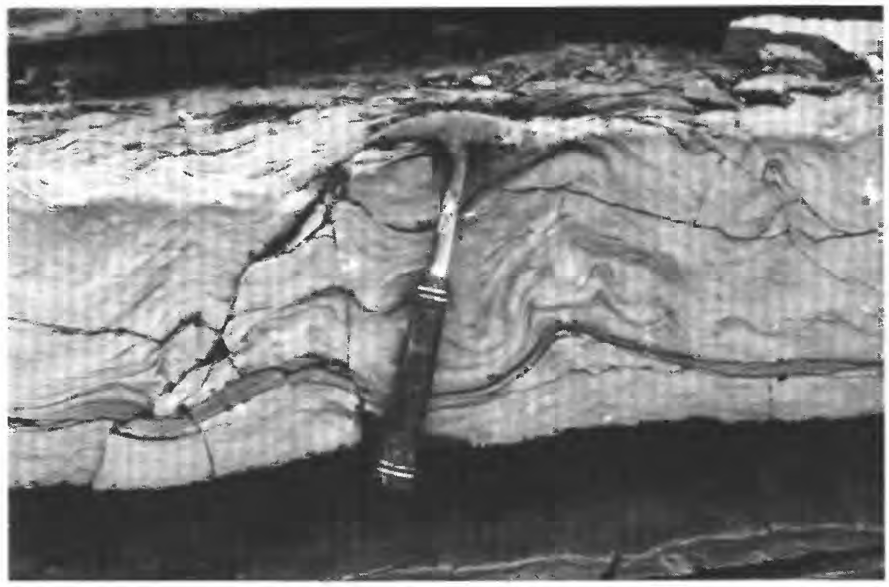


FIGURE 12.16.—Convolute bedding in a turbidite bed of the Fortress Mountain Formation along upper Colville River (NW¼ sec. 29, T. 5 S., R. 27 W.).

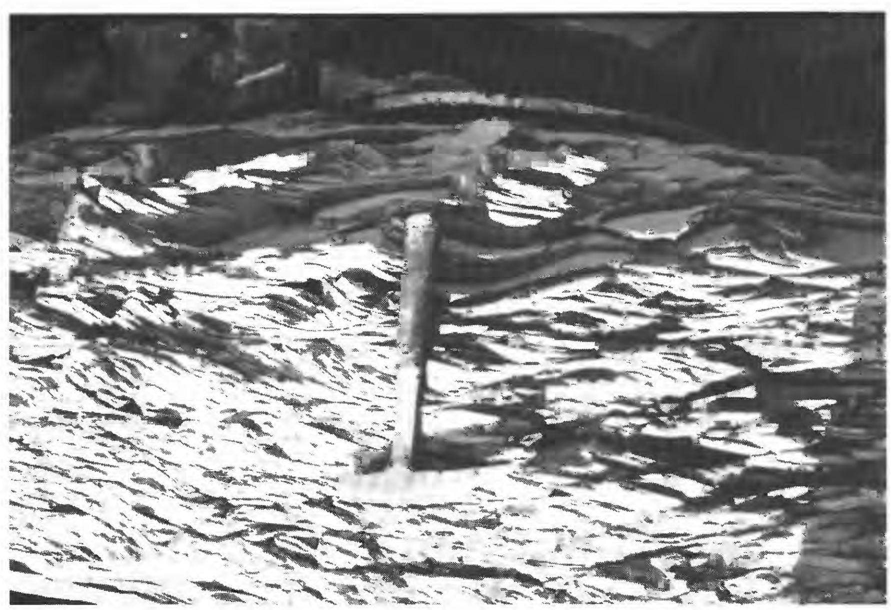


FIGURE 12.17.—Climbing ripples in small-scale crossbedded interval (Bouma interval Tc) in sandstone bed of outer-fan facies of the Fortress Mountain Formation along upper Colville River (E½ sec. 20, T. 5 S., R. 29 W.). Stratigraphic top is toward top of photograph.

and *Beudanticeras* (*Grantziceras*) aff. (Whiteaves), and the pelecypods *Aucellina dowlingi* McLearn, *Thracia kissoumi* McLearn, *Pleuromya kelleri* Imlay, *Placunopsis nuka* Imlay, and *Inoceramus* cf. *I. altifluminus* McLearn. On the basis of the occurrence of *Colvillia crassicostata* and *Aucellina dowlingi*, Imlay (1961, p. 8) assigned a probable early Albian (late Early Cretaceous) age to the Fortress Mountain Formation. These fossil collections, mostly from along the Kiruktagiak River, were considered to be from the lower 1,000 m of the formation (Patton and Tailleur, 1964, p. 457). *Colvillia crassicostata* was also collected from a turbidite zone about 1,250 m below the top of the Torok Formation at its type section along the Chandler River (Patton and Tailleur, 1964, p. 461). This turbidite zone is the stratigraphically highest significant turbidite deposit in the type section of the Torok, although the lithology is obscured in large parts of the section. On the basis of this occurrence of *C. crassicostata* and of *Beudanticeras* collected elsewhere in this part of the Torok Formation, Imlay (1961, p. 4) correlates the lower part of the Torok with the lower part of the Fortress Mountain Formation. We suggest that the lower part of the Torok at its type section is fairly high in the total Torok-Fortress Mountain interval. Seismic data indicate that this interval may be as much as 6,000 m thick in the southern part of the northern foothills; however, the interval probably has been tectonically thickened (Molenaar, chapter 25).

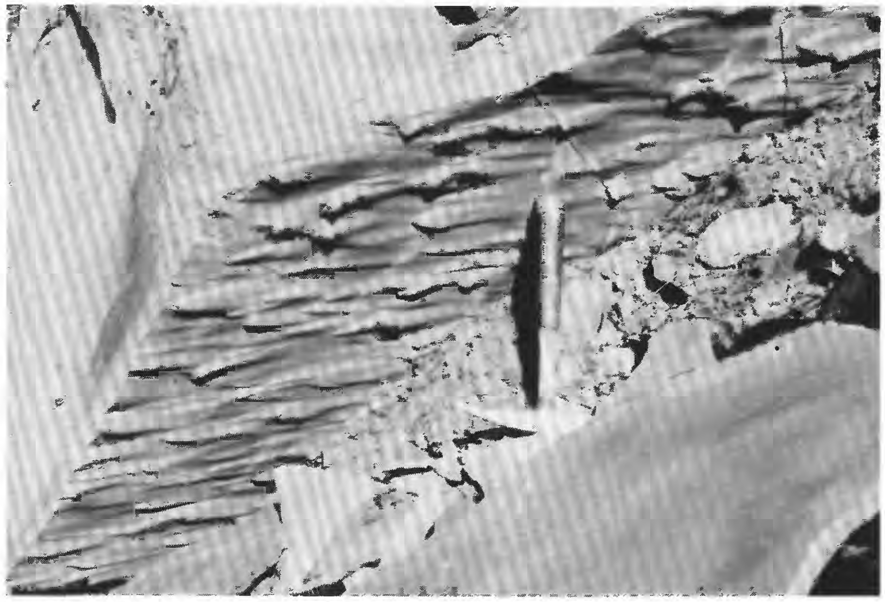


FIGURE 12.18.—Flute casts on base of turbidite sandstone bed in outer-fan facies of the Fortress Mountain Formation along upper Colville River (E½ sec. 20, T. 5 S., R. 29 W.). Current moved from left to right (N. 80° E.).

FIGURE 12.19.—Trace fossil (possible worm burrows) along base of turbidite sandstone bed in outer-fan facies of the Fortress Mountain Formation along upper Colville River (W½ sec. 33, T. 5 S., R. 26 W.). Note small, uniformly oriented groove casts or other sole marks.

From the faunal evidence, it seems that the time span represented by the Fortress Mountain Formation was relatively short despite the great thickness of the unit. However, it is possible that the lower part of the Fortress Mountain, for which there is no faunal evidence, could extend down into the Aptian in the axial part of the deep Colville basin.

The two fossil collections from the Fortress Mountain Formation made during this study were identified by D.L. Jones and J.W. Miller of the U.S. Geological Survey and are listed as follows:

80AMK-176, USGS locality M7413, from north bank of Colville River, NW¼ sec. 31, T. 6 S., R. 19 W., lat 68°53′03″ N., long 156°31′03″ W.

Inoceramus cf. *I. altifluminis* McLearn. Early Cretaceous (early middle Albian).

80AMK-189, USGS locality M7414, from high on southwest side of

Ekakevik Mountain, SE¼ sec. 8, T. 10 S., R. 22 E., lat 68°35′11″ N., long 157°04′57″ W.

Astarte sp.
Panope elongatissima McLearn
Tancredia stelcki McLearn
Thracia stelcki McLearn
Yoldia kissoumi McLearn

This assemblage is considered Early Cretaceous (Albian) in age.

HYDROCARBON OCCURRENCES AND ORGANIC GEOCHEMISTRY

Solid hydrocarbon dikes or fracture fillings as much as 25 cm wide were observed at several localities in the Fortress Mountain Formation and in one place in the underlying Okpikruak Formation. Patton and Tailleur (1964, p. 496) reported similar occurrences of asphaltic matter in the Okpikruak, Fortress Mountain, and Torok Formations. The solid hydrocarbon material is black, brittle, and shiny, similar to coal except that it is more brittle and breaks into smaller fragments (granule to small pebble size) than coal.

Most occurrences of the solid hydrocarbons are within shale sections, but some cut across sandstone beds. In no case was oil staining observed in the adjacent sandstone beds. At one locality, the hydrocarbon material was found along a fracture in a sandstone bed in which the fracture was lined with quartz crystals. This occurrence clearly indicates that the hydrocarbons came in after lithification and induration. The source of the hydrocarbons may have been the laterally adjacent or underlying shale or, alternatively, shale rich in organic matter in the underlying Triassic or Jurassic(?) formations.

In addition to these occurrences of solid hydrocarbon, a fetid odor of natural gas was noted on freshly broken surfaces of the sandstone beds of the Fortress Mountain in the lower Nuka River area of T. 6 S., R. 31 W. These sandstone beds are very fine grained and represent an outer-fan environment of deposition.

Organic geochemical data from 22 outcrop samples indicate that the shale of the Fortress Mountain Formation is a fair source rock for petroleum. Total organic carbon ranges from 0.45 to 1.40 percent and averages about 0.80 percent. The visual kerogen is dominantly herbaceous and amorphous. Average vitrinite reflectance values of samples range from 0.45 to 1.10; the highest value is from a single sample from the Kukpowruk River area on the far west. The average of all samples tested is 0.65, which is within the mature range of hydrocarbon generation. The organic geochemical data are listed in table 12.1.

RESERVOIR DATA

Sandstone of the Fortress Mountain Formation contains a high percentage of lithic grains and appears to have very poor reservoir potential, as indicated by both visual and petrographic examination of outcrop samples. The pore space is largely filled with clay resulting either from alteration of unstable lithic fragments or from the formation of authigenic cements. Because of surface weathering and alterations, the porosity and permeability values of surface samples may not apply to similar sandstones in the subsurface. However, 15 surface samples were measured for porosity and permeability by Core Laboratories, Inc., of Denver, Colo.; the results are listed in table 12.2.

SUBSURFACE EXTRAPOLATION

It seems that much of the Fortress Mountain Formation intertongues with the lower part of the Torok Formation. It has also been shown that the bottomset or basinal beds of the Torok Formation in the coastal plain area of the NPRA, which contain thin turbidites, are coeval with the deltaic, shallow marine to nonmarine Nanushuk Group (see Molenaar, chapter 25; Molenaar, 1985). In the northern foothills, where the structure is complex and the quality of seismic data is not good enough to show the stratigraphic details, it is difficult or impossible to distinguish between turbidites that may be age equivalent to the Nanushuk Group and those that may be age equivalent to the Fortress Mountain Formation. Indeed, at some stratigraphic interval, turbidites equivalent to the two units may merge or intertongue. For this reason, the Fortress Mountain Formation is here recognized as limited in geographic extent to the southern foothills area, while the laterally equivalent sandstone beds in the subsurface of the northern foothills are here included within the lower part of the Torok Formation.

Inasmuch as the sandstone of the Fortress Mountain Formation becomes finer grained and thinner bedded to the north in the outcrop belt of the southern foothills, very little sandstone or a more distal facies would be expected in the subsurface farther north. However, coarser clastic materials were contributed from many point sources, and some individual fans could extend into the northern foothills area. We need to consider how far north these sandstone units or the entire assemblage of Fortress Mountain lateral equivalents might be expected. Seismic data in the northern foothills indicate that laterally equivalent Fortress Mountain strata or strata in the lower part of the Torok Formation onlap south-dipping Neocomian strata (Molenaar, chapter 25). Strata coeval with the Fortress Mountain Formation probably are not present or form a condensed section north of the northern foothills. Thus, the southern part of the northern foothills would be the most likely area for the subsurface occurrence of thicker or

TABLE 12.1.—*Organic geochemical data for outcrop samples of the Fortress Mountain Formation*

[TAI, thermal alteration index; min Ro, minimum reflectance; max Ro, maximum reflectance; mean Ro, mean reflectance; TOC, total organic carbon; A, amorphous; H, herbaceous; Hu, humic; I, inert. Analytical work by Geochem Research, Inc., Houston, Texas]

Sample	Location			TAI	Vitrinite reflectance (percent)			TOC	Visual kerogen (percent)			
	Sec.	T. (S)	R. (W)		Min. Ro	Max. Ro	Mean Ro		A	H	Hu	I
80 AMK-101A	1	9	2	2.1	0.47	0.73	0.58	1.39	31	3B	23	8
80 AMK-111	15	10	3	2.1	.50	.76	.65	.58	25	42	17	17
80 AMK-116	34	9	5	2.5	.49	.77	.63	.49	0	40	40	20
80 AMK-122A	14	10	5	2.5	.57	.84	.71	.68	23	38	23	15
80 AMK-122B	14	10	5	2.5	.60	.88	.74	.70	15	38	23	24
80 AMK-122C	14	10	5	2.7	.62	.89	.75	.75	23	38	23	15
80 AMK-122D	14	10	5	2.7	.54	.87	.73	.64	9	45	27	18
80 AMK-138A	25	10	22	2.5	.36	.56	.45	.62	8	46	23	23
80 AMK-138B	25	10	22	2.3	.35	.55	.45	.45	20	50	20	10
80 AMK-138C	25	10	22	2.1	.37	.61	.49	.58	18	45	27	9
80 AMK-147A	7	10	22	2.1	.41	.64	.53	.74	23	38	23	15
80 AMK-147B	7	10	22	2.3	.43	.63	.56	.75	15	38	23	23
80 AMK-152	1	9	19	2.4	.42	.65	.54	.76	0	50	20	30
80 AMK-157B	18	6	17	2.3	.46	.69	.57	1.26	0	42	33	25
80 AMK-159C	25	9	17	2.1	.60	.84	.73	.74	0	40	30	30
80 AMK-159D	25	9	17	2.1	.46	.71	.58	.75	0	36	36	27
80 AMK-167B	13	8	28	2.1	.54	.76	.64	.94	8	42	33	17
80 AMK-167C	13	8	28	2.1	.51	.70	.61	.84	0	50	30	20
80 AMK-167D	13	8	28	2.1	.51	.70	.61	.84	0	50	30	20
80 AMK-167E	13	8	28	2.3	.52	.67	.60	.83	31	38	15	15
80 AMK-182B	13	6	31	2.4	.87	1.08	.99	1.40	0	38	31	31
80 AMK-192B	35	10	50	2.7	.93	1.25	1.10	.74	0	40	30	30

TABLE 12.2.—*Porosity and permeability values from selected outcrop samples of the Fortress Mountain Formation*

[Permeabilities determined with procedure from American Petroleum Institute (1960); calculated permeabilities are air permeabilities and have not been corrected for the Klinkenberg effect. Facies interpretations by authors based on Mutti and Ricci Lucchi (1972)]

Sample	Location			Porosity (percent)	Permeability (millidarcys)	Facies
	Sec.	T. (S.)	R. (W.)			
80 AMK-101B	C 1	9	2	10.0	0.11	Facies C, mid to outer fan.
80 AMK-104A	SW 1/4 15	10	3	6.5	<.01	Shallow marine or nonmarine?
80 AMK-118A	NE 1/4 35	9	7	5.8	.07	Facies C, mid fan.
80 AMK-124	E 1/2 12	10	5	8.8	<.01	Facies B, inner fan.
80 AMK-156	NW 1/4 19	6	17	6.4	.03	Facies D, outer fan.
80 AMK-160A	NW 1/4 3	9	14	8.5	<.01	Facies D, outer fan.
80 AMK-166A	CW 1/2 2	8	28	6.3	.02	Facies E, inner or mid fan.
80 AMK-172	NW 1/4 29	5	27	11.9	.04	Facies C or D, outer fan.
80 AMK-176	NW 1/4 31	6	19	9.7	.02	Facies D, outer fan.
80 AMK-180	N 1/2 22	5	25	14.1	.46	Turbidites, probably Nanushuk Group equivalent.
80 AMK-184	E 1/2 20	5	29	3.0	<.01	Facies D, outer fan.
80 AMK-189	SE 1/4 8	10	22	7.4	.05	Shallow marine?
80 AMK-190	NW 1/4 1	9	46	4.1	.11	Facies B, mid fan.
80 AMK-192	E 1/2 35	10	50	2.2	.10	Facies B, mid fan.
80 AMK-196	SW 1/4 34	8	9	8.1	<.01	Facies B, mid fan.

coarser grained sandstone facies. On the basis of observed directional features in the outcrop belt, strata laterally equivalent to the Fortress Mountain in the subsurface would probably have been deposited by turbidity currents flowing east-northeast.

Seven wells in the northern foothills may have penetrated at least part of the strata equivalent in age to the Fortress Mountain Formation (fig. 12.1). Gas shows have been reported from some of these tests, but for the most part, available data indicate that the sandstone units are thin and have limited reservoir potential. This conclusion is corroborated by the outcrop and petrographic studies. However, thicker sandstone beds in combination with favorable fracture porosity and permeability could conceivably provide a commercial hydrocarbon reservoir.

PETROGRAPHY

Thirty-nine sandstone samples collected from randomly chosen outcrops of the Fortress Mountain Formation were examined to determine general petrographic characteristics, provenance, and factors that might affect the reservoir potential of the sandstone. A total of 36 samples was obtained between Castle Mountain and the Nuka River (fig. 12.2) and will be referred to herein as the eastern samples. Three samples of the Mount Kelly Graywacke Tongue of the Fortress Mountain Formation (Mull, 1985) from the Kukpowruk River area (fig. 12.1) were also examined petrographically and will be referred to herein as the western samples. From the petrographic analyses, these sandstone samples from the Fortress Mountain Formation are all subquartzose (<75 percent quartz) lithic sandstones following the classification of Dickinson (1970) modified from Crook (1960). The lithology of lithic fragments and conglomerate clasts indicates that the upper allochthonous thrust sequences of the central and western Brooks Range were the predominant sediment source for the Fortess Mountain Formation. The western samples, however, show significant differences from other samples of the Fortress Mountain Formation and may indicate a different source terrane.

The initial porosity in the samples studied has been largely occluded by compaction causing deformation of unstable lithic fragments and by the formation of authigenic calcite, chlorite, and quartz cements. If these characteristics occur also in the subsurface, they greatly reduce the reservoir potential of the sandstones of the Fortress Mountain Formation.

METHODS

Thin sections cut from the sandstone samples were impregnated with blue epoxy, to enhance the definition of pores, and stained with Alizarin Red S and sodium cobaltinitrate to facilitate the identification of calcite and potassium feldspar (K-feldspar), respectively. The petrographic analysis followed the methods of Dickinson (1970), and the results are summarized in tables 12.3 and 12.4 and figure 12.20, following the methods of Dickinson and Suczek (1979). A minimum of 300 points per thin section were counted to determine framework modes (quartz, Q; feldspar, F; and lithic fragments, L), cements, and visible porosity.

Volumetric percentages of 24 constituents were determined and combined into the 16 categories shown on table 12.3. Normalized volumetric percentages of the following groups of framework grains are listed in table 12.4 and plotted in figure 12.20 to characterize the sandstones of the Fortress Mountain Formation. The Q_tFL data used to construct the triangular plot in figure 12.20*A* are normalized percentages of total quartzose grains (Q_t), total feldspar (F), and unstable lithic fragments (L). The Q_mFL_t data used for figure 12.20*B* are normalized percentages of monocrystalline quartz (Q_m), total feldspar (F), and total lithic fragments (L_t), the last category including unstable lithic fragments, chert, quartzite, and polycrystalline quartz fragments. The $Q_pL_vL_s$ data used for figure 12.20*C* are normalized percentages of polycrystalline quartz (Q_p), including chert and quartzite fragments, volcanic lithic fragments (L_v), and unstable sedimentary lithic fragments (L_s). The Q_mPK data used for figure 12.20*D* are normalized percentages of monocrystalline quartz (Q_m), plagioclase (P), and K-feldspar (K).

Both the Q_tFL and the Q_mFL_t data include total framework grain populations; the Q_tFL data, in which all quartzose grains are grouped together, emphasize grain stability, whereas the Q_mFL_t data, in which all lithic fragments, including quartzose ones, are grouped together, emphasize the grain size of the source rocks. The $Q_pL_vL_s$ and Q_mPK data include only partial grain populations, but they reveal the character of the polycrystalline and monocrystalline components of the framework, respectively.

QUARTZ

All of the sandstone samples studied are subquartzose (<75 percent quartzose fragments), although the finer grained samples are relatively richer in quartz, apparently due to mechanical disaggregation of lithic fragments during transport and deposition (table 12.3; figs. 12.20*A*, *B*). The eastern samples of the Fortress Mountain Formation average 32 percent quartzose fragments, whereas the three western samples average 51 percent quartzose fragments (table 12.4). Ratios of polycrystalline quartz to total quartz

TABLE 12.3.—*Composition and grain size of sandstone samples of the Fortress Mountain Formation*

[Data from thin-section point counts; compositional figures in percent of total rock volume. Grain sizes: c, coarse, m, medium; f, fine]

	Location			Grains												Cement			Por	Grain size
Sample	Sec.	T.(S)	R.(W)	Q_m	Q_p	C_q	Q_{zt}	P	K	Slt	Ac	Lms	V	M	Accm	Cal	Q	Cl		
									Eastern samples											
80 AMK-101B	1	9	2	5	5	13	2	5	0	3	46	2	2	0	0	7	0	7	3	C
80 AMK-101C	1	9	2	5	1	32	2	5	0	1	25	2	4	1	1	17	0	2	1	C
80 AMK-104A	15	10	3	0	0	32	1	2	1	2	29	1	18	1	1	1	8	2	1	C
80 AMK-113	20	10	3	2	Tr	26	1	3	0	1	16	0	39	0	0	0	1	11	0	C
80 AMK-118A	35	9	7	10	1	19	0	11	0	0	17	5	15	0	Tr	15	0	7	0	M
80 AMK-124	12	10	5	8	2	21	2	7	3	1	30	0	20	Tr	1	0	4	0	1	M
80 AMK-125	9	10	4	3	1	14	1	8	0	1	22	2	38	0	0	2	1	6	1	C
80 AMK-136	5	10	22	3	2	14	4	3	0	2	41	Tr	21	2	Tr	3	1	3	0	C
80 AMK-137D	16	10	22	12	4	10	17	2	0	10	32	1	7	1	1	1	Tr	2	0	C
80 AMK-152	1	9	19	5	1	8	3	8	0	2	32	2	27	Tr	2	3	0	6	0	M
80 AMK-153B	1	9	20	7	2	12	6	4	0	2	31	3	20	1	1	2	1	8	0	M
80 AMK-154	30	8	19	6	1	16	3	9	0	6	30	2	10	1	0	10	Tr	6	0	C
80 AMK-156	19	6	17	26	2	9	Tr	11	3	1	16	3	3	2	1	15	1	5	1	F
80 AMK-157A	18	6	17	10	2	14	2	6	0	2	21	2	13	2	1	4	Tr	19	1	C
80 AMK-158	24	7	18	19	4	7	1	7	Tr	1	11	3	9	3	3	7	0	23	1	F
80 AMK-159A	25	9	17	8	3	4	3	6	1	3	29	Tr	22	1	2	8	Tr	10	0	M
80 AMK-159B	25	9	17	4	1	10	2	4	4	1	27	5	21	0	0	12	0	8	1	C
80 AMK-160A	3	9	14	3	Tr	15	1	9	Tr	1	21	1	34	0	4	1	0	10	0	C
80 AMK-161	35	9	14	3	1	17	4	4	2	1	23	0	36	0	0	5	0	4	0	C
80 AMK-166A	2	8	28	10	5	5	2	9	4	1	19	1	19	2	5	2	0	14	2	M
80 AMK-167A	13	8	28	3	4	12	7	7	Tr	4	22	2	29	Tr	2	2	0	6	Tr	C
80 AMK-169	35	6	28	4	1	7	2	9	0	1	15	1	27	1	Tr	28	0	3	1	M
80 AMK-172	29	5	27	20	2	1	0	6	0	0	7	39	5	2	2	0	0	9	7	F
80 AMK-173	25	7	29	3	6	9	2	8	3	2	30	0	28	1	2	0	0	6	Tr	C
80 AMK-175	30	10	16	8	1	4	2	9	Tr	2	26	3	21	Tr	3	0	0	20	Tr	M
80 AMK-176	31	6	19	25	4	11	0	7	0	1	20	1	3	2	1	1	0	18	6	F
80 AMK-177	7	7	25	4	2	19	2	4	0	2	29	1	23	1	Tr	8	0	4	1	C
80 AMK-181	3	7	20	12	3	9	1	9	1	Tr	15	7	9	2	1	28	0	3	0	M
80 AMK-182	13	6	31	27	3	10	0	8	0	1	12	14	3	0	2	9	0	8	3	F
80 AMK-184	20	5	29	29	1	4	0	6	0	1	9	16	2	3	4	20	0	4	1	F
80 AMK-186	8	10	22	4	1	6	0	3	2	3	41	1	10	1	Tr	22	2	4	0	M
80 AMK-187B	8	10	22	9	4	12	0	7	2	3	24	0	15	1	1	0	4	15	3	M
80 AMK-189	8	10	22	12	2	8	0	9	0	3	23	0	11	2	7	1	2	19	1	F
80 AMK-193	14	9	10	4	1	22	0	3	0	3	23	0	32	Tr	2	8	0	0	2	C
80 AMK-196	34	8	9	4	2	12	1	5	0	2	14	1	43	0	1	7	0	8	Tr	C
80 AMK-197	23	9	7	8	2	13	Tr	8	1	1	21	0	28	1	2	0	2	6	6	C
Average				9	2	13	2	6	1	2	23	3	19	1	2	7	1	8	1	
									Western samples											
80 AMK-190	1	9	46	24	4	4	0	1	0	Tr	6	33	3	2	6	12	0	5	0	F
80 AMK-191B	18	10	45	18	7	11	0	8	0	0	8	11	5	6	3	16	0	7	0	M
80 AMK-192A	35	10	50	20	11	7	0	3	2	1	4	11	5	6	2	28	0	0	0	M
Average				21	7	7	0	4	1	Tr	6	18	4	5	4	19	0	4	0	

(C/Q, table 12.4) indicate that polycrystalline quartz (mostly chert) dominates the quartzose grain population in the eastern samples but monocrystalline quartz dominates the quartzose grain population in the western samples. Polycrystalline quartz of a stretched metamorphic variety is present in minor amounts in samples from both areas, but it is slightly more abundant in the western samples (table 12.3). Quartzite fragments are present in minor amounts in the eastern samples but were not noted in any of the three western samples.

FELDSPAR

Feldspar constitutes a small but consistent percentage of the sandstone, averaging 9 percent of the framework grains in the eastern samples and 6 percent in the western samples. High ratios of plagioclase to total feldspar (P/F) in both areas indicate that nearly all of the feldspar present is plagioclase (tables 12.3, 12.4; fig. 12.20*D*).

LITHIC FRAGMENTS

Lithic fragments are the most abundant framework grains in samples of the Fortress Mountain Formation. The stable lithic grains (chert, polycrystalline quartz, and quartzite) have already been discussed. Unstable lithic fragments, in order of decreasing abundance, include argillaceous and carbonaceous, mafic volcanic, limestone, metamorphic, and siltstone fragments. Argillaceous and carbonaceous lithic fragments (treated together because of their close association in many grains and because of the difficulty of differentiation) are the most abundant unstable lithic-grain type in most samples studied. In the western samples, however, limestone (calcite) clasts are most abundant, followed by argillaceous-carbonaceous, metamorphic, and volcanic fragments (table 12.3). In the eastern samples, argillaceous-carbonaceous fragments and volcanic fragments predominate, with only small quantities of limestone, metamorphic, and siltstone fragments.

Ratios of volcanic lithic fragments to total unstable lithic fragments (table 12.4) are low for the western samples (avg 0.18) but reach moderate values in the eastern samples (avg 0.35). In the eastern samples,

TABLE 12.3.—*Composition and grain size of sandstone samples of the Fortress Mountain Formation*—Continued

Grains

Ac --Argillaceous-carbonaceous fragments; includes all gradations from claystone through shale to fragments of organic debris.

Accm --Accessory minerals; includes, in order of decreasing abundance, magnetite, pyrite, muscovite, pyroxene, olivine, biotite, and garnet.

C_q --Chert; includes dense, nearly isotropic varieties to well crystallized aggregates; some contain euhedral calcite rhombs and are probably from silicified limestones; others contain no inclusions.

K --K-feldspar; probably orthoclase.

Lms --Limestone fragments; includes many varieties ranging from rounded calcite clasts (probably from recrystallized limestone) to bioclastic, microgranular, and micritic types.

M --Metamorphic rock fragments; mostly quartz-mica tectonite.

P --Plagioclase; highly altered, usually showing albite twinning.

Q_m --Monocrystalline quartz.

Q_p --Polycrystalline quartz; mostly displaying stretched and sutured internal grain contacts, probably of metamorphic origin.

Q_{zt} --Quartzite; composed mostly of monocrystalline quartz, chert, and mica; the quartzite fragments are probably derived from the Kanayut Conglomerate.

Slt --Siltstone fragments.

V --Volcanic rock fragments; mostly mafic varieties with laths of feldspar in parallel or subparallel alignment set in a chlorite or isotropic to nearly isotropic groundmass; also includes minor amounts of mafic hypabyssal grains.

Cement

Cal --Calcite cement; usually sparry, often replacing framework grains.

Q --Quartz cement; occurring as overgrowths on quartz grains and as microgranular pore fillings.

Cl --Phyllosilicate cement; mostly chlorite, occurring as linings on framework grains and also as radial pore fillings.

Miscellaneous

Por --Pore space.

Tr --Trace amounts.

TABLE 12.4.—*Framework grain composition of sandstone samples of the Fortress Mountain Formation*

[Data calculated from thin-section point counts; compositional figures are normalized percents totaling 100 within each group]

	Location			Grains												Ratios		
Sample	Sec.	T.(S)	R.(W)	Q_t	F	L	Q_m	F	L_t	Q_p	L_v	L_s	Q_m	P	K	C/Q	P/F	V/L
Eastern samples																		
80 AMK-101B	1	9	2	29	6	65	6	6	88	26	4	70	53	47	0	0.78	1.0	0.03
80 AMK-101C	1	9	2	52	7	41	7	7	86	53	7	40	50	50	0	.87	1.0	.13
80 AMK-104A	15	10	3	39	3	58	0	3	97	40	23	37	13	63	24	.99	.71	.32
80 AMK-113	20	10	3	32	3	65	2	3	95	32	47	21	36	64	0	.95	1.0	.69
80 AMK-118A	35	9	7	38	15	47	12	15	73	35	26	39	46	50	4	.68	.92	.36
80 AMK-124	12	10	5	35	11	54	9	11	80	33	26	41	45	37	18	.75	.68	.36
80 AMK-125	9	10	4	21	9	70	4	9	87	20	48	32	28	72	0	.83	1.0	.58
80 AMK-136	5	10	22	24	3	73	3	3	94	23	27	50	53	47	0	.87	1.0	.32
80 AMK-137D	16	10	22	45	2	53	13	2	85	38	9	53	84	16	0	.71	1.0	.13
80 AMK-152	1	9	19	19	9	72	5	9	86	16	36	48	36	64	0	.73	1.0	.43
80 AMK-153B	1	9	20	30	4	66	8	4	88	26	26	48	66	34	0	.75	1.0	.35
80 AMK-154	30	8	19	31	11	58	7	11	82	29	16	55	39	59	2	.78	.96	.20
80 AMK-156	19	6	17	49	18	33	34	18	48	31	15	54	66	27	7	.31	.80	.13
80 AMK-157A	18	6	17	38	8	54	13	8	79	32	25	43	63	37	0	.66	1.0	.30
80 AMK-158	24	7	18	47	11	42	28	11	60	31	31	38	72	27	1	.39	.96	.34
80 AMK-159A	25	9	17	23	9	68	10	9	81	16	35	50	53	43	4	.56	.91	.40
80 AMK-159B	25	9	17	23	9	68	6	9	85	21	31	48	37	33	30	.76	.52	.40
80 AMK-160A	3	9	14	22	11	67	4	11	85	21	47	32	26	72	2	.83	.97	.57
80 AMK-161	35	9	14	28	7	65	4	7	90	27	44	29	34	41	25	.87	.62	.59
80 AMK-166A	2	8	28	28	18	54	13	18	69	21	40	39	43	39	18	.51	.69	.47
80 AMK-167A	13	8	28	28	8	64	4	8	88	28	37	35	32	66	2	.87	.96	.51
80 AMK-169	35	6	28	20	14	66	5	14	81	19	49	32	28	72	0	.74	1.0	.60
80 AMK-172	29	5	27	28	8	64	24	8	68	6	10	84	76	24	0	.14	1.0	.07
80 AMK-173	25	7	29	22	13	65	3	13	84	22	35	43	21	56	23	.85	.71	.43
80 AMK-175	30	10	16	18	12	70	11	12	77	10	34	56	48	51	1	.43	.97	.36
80 AMK-176	31	6	19	54	9	37	34	9	57	35	12	53	79	21	0	.37	1.0	.11
80 AMK-177	7	7	25	31	4	65	4	4	92	29	31	40	50	50	0	.87	1.0	.41
80 AMK-181	3	7	20	37	14	49	17	14	69	28	25	47	56	41	3	.52	.92	.28
80 AMK-182	13	6	31	52	10	38	35	10	55	31	7	62	78	22	0	.32	1.0	.11
80 AMK-184	20	5	29	48	9	43	41	9	50	13	14	73	82	18	0	.14	1.0	.08
80 AMK-186	8	10	22	15	7	78	6	7	87	10	18	72	48	34	18	.59	.67	.18
80 AMK-187B	8	10	22	32	12	56	12	12	76	27	28	45	50	37	13	.64	.74	.35
80 AMK-189	8	10	22	31	13	56	17	13	70	20	25	55	56	44	0	.46	1.0	.28
80 AMK-193	14	9	10	31	3	66	4	3	93	29	40	31	59	41	0	.86	1.0	.54
80 AMK-196	34	8	9	22	6	72	4	6	90	20	57	23	42	58	0	.80	1.0	.70
80 AMK-197	23	9	7	27	12	61	10	12	78	22	44	34	45	47	8	.65	.86	.55
Average				32	9	59	12	9	79	26	28	46	50	44	6	.66	.90	.35
Western samples																		
80 AMK-190	1	9	46	41	1	58	31	1	68	14	10	76	97	3	0	.23	1.0	.07
80 AMK-191B	18	10	45	49	10	41	25	10	65	37	23	40	71	29	0	.49	.0	.16
80 AMK-192A	35	10	50	54	7	39	29	7	64	40	26	34	80	12	8	.47	.61	.32
Average				51	6	43	30	6	64	34	22	44	83	14	3	.40	.87	.18

argillaceous-carbonaceous, volcanic, and chert fragments together average 68 percent of the framework grains, whereas in the western samples these three types together average only 23 percent of the framework.

ACCESSORY MINERALS

Accessory minerals are present in small amounts in the samples studied, averaging 2 percent in the eastern samples and 4 percent in the western samples from the Kukpowruk River area. Muscovite is almost the only accessory mineral population in these western samples, whereas in the eastern samples accessory minerals in varying proportions include magnetite, pyrite, muscovite, pyroxene, olivine, biotite, epidote, and trace amounts of garnet. A more exhaustive discussion of heavy minerals in the Fortress Mountain Formation is found in Patton and Tailleur (1964).

MATRIX

All the sandstone samples of the Fortress Mountain Formation are matrix rich. Most of the matrix, however, is a pseudomatrix formed from the compaction and plastic deformation of many unstable lithic fragments. The initial porosity of the sandstone is almost totally occluded by this pseudomatrix, and most of the remaining pore space is filled by authigenic cements. These cements include phyllosilicates, mostly chlorite, occurring as rims on detrital grains and as radial pore fillings; calcite, occurring mainly as sparry aggregates and also replacing some framework grains; and quartz, occurring as overgrowths on detrital quartz grains and as microgranular aggregates in pores.

Chlorite and calcite cements are present in most samples studied. In the eastern samples, chlorite and calcite cements dominate and occur in various proportions, Quartz cement is present in minor amounts, but it is most prevalent in samples from the coarser facies of the formation, especially at Castle Mountain, Fortress Mountain, and Ekakevik Mountain. In the western samples, calcite is the dominant cement.

PROVENANCE

The petrographic analyses of samples of the Fortress Mountain Formation indicate different source terranes for sediment deposited in the Kukpowruk River area on the west and sediment deposited in the area between the Nuka River and Castle Mountain. Conclusions based on the western samples from the Kukpowruk River area are considered tentative because only three samples were studied. However, these three western samples are all similar in composition and dissimilar to the eastern samples. In the

TABLE 12.4.—*Framework grain composition of sandstone samples of the Fortress Mountain Formation*—Continued

C/Q -- Ratio of polycrystalline quartzose fragments (mostly chert) to total quartzose fragments.

F -- Total Feldspar.

K -- K-feldspar.

L -- Unstable lithic fragments; includes argillaceous-carbonaceous, siltstone, metamorphic, and volcanic fragments.

L_s -- Unstable sedimentary rock fragments.

L_t -- Total lithic fragments; includes unstable lithic fragments and polycrystalline quartz, quartzite, and chert.

L_v -- Volcanic and metavolcanic rock fragments.

P -- Plagioclase.

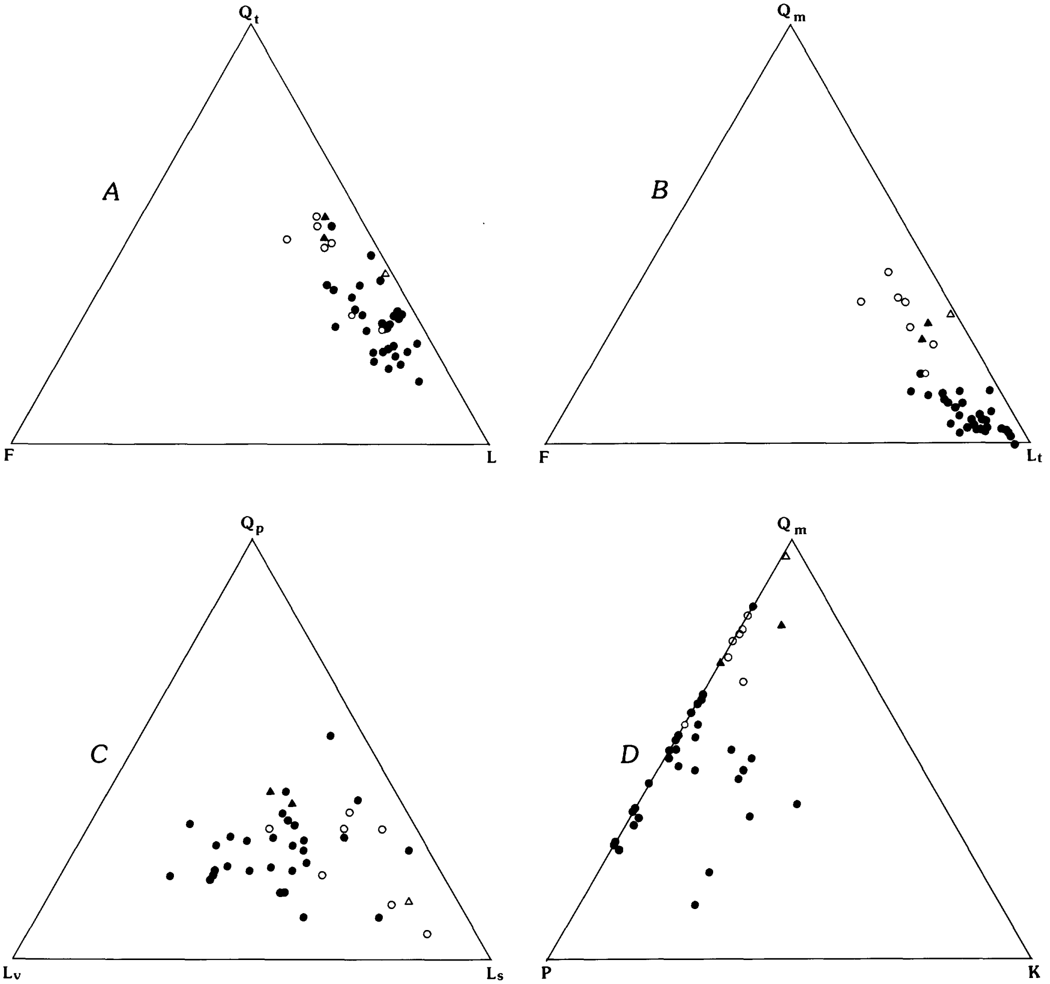
P/F -- Ratio of plagioclase to total feldspar.

Q_m -- Monocrystalline quartz.

Q_p -- Polycrystalline quartz, quartzite, and chert.

Q_t -- Total quartzose grains; monocrystalline and polycrystalline quartz, chert, and quartzite.

V/L -- Ratio of volcanic fragments to total unstable lithic fragments.



EXPLANATION

Samples from eastern (Nuka River — Castle Mountain) area

- ● Medium and coarse-grained
- ○ Fine and very fine grained

Samples from western (Kukpowruk River) area

- ▲ Medium and coarse-grained
- △ Fine and very fine grained

FIGURE 12.20.—Triangular compositional plots of sandstone samples from the Fortress Mountain Formation. Data from thin-section point counts. *A*, Framework modes, with emphasis on grain stability. Q_t, total quartzose grains, including monocrystalline and polycrystalline quartz, chert, and quartzite; F, total feldspar; L, total unstable lithic fragments. *B*, Framework modes, with all lithic fragments grouped. Q_m, monocrystalline quartz; F, total feldspar; L_t, total of all lithic fragments. *C*, Proportions of polycrystalline lithic fragments. Q_p, polycrystalline quartzose grains, mostly chert; L_v, volcanic-metavolcanic fragments; L_s, unstable sedimentary rock fragments. D, Proportions of monocrystalline framework mineral grains. Q_m, quartz; P, plagioclase; K, potassium feldspar.

western samples, monocrystalline quartz is the most abundant constituent, followed by limestone, chert, polycrystalline quartz, and argillaceous-carbonaceous fragments; only minor amounts of volcanic and metamorphic fragments and palgioclase are present (table 12.4). These framework grain lithologies are similar to the compositional data given by Bartsch-Winkler (1979) for the overlying Nanushuk Group in the same area. Both sets of data indicate a similar source terrane—the Tigara uplift in the area of the Lisburne Hills and offshore, possibly including the Herald arch, where a western extension of the Brooks Range schist belt may have been exposed during the Albian (Mull, 1985).

Most of the samples studied are from the area between the Nuka River and Castle Mountain. The samples are all compositionally similar except that fine-grained samples tend to have a higher percentage of monocrystalline quartz (tables 12.3, 12.4; figs. 12.20*A*, *B*). Argillaceous-carbonaceous fragments are most abundant, followed closely by volcanic rock fragments and chert. These three components make up approximately 68 percent by volume of the framework grains and indicate a sedimentary and volcanic source terrane. This petrographic analysis of sandstone of the Fortress Mountain Formation supports the contention of Mull (1979) and Roeder and Mull (1978) that the mafic igneous and gabbroic pebbles in the associated conglomerates indicate a source terrane composed of the Misheguk sequence (uppermost Brooks Range allochthon). However, the many fine-grained sedimentary rock fragments indicate that the allochthonous thrust sequences underlying the Misheguk also were dissected and supplied sediment to the basin during deposition of the Fortress Mountain Formation.

SUMMARY

The Fortress Mountain Formation of early Albian (Early Cretaceous) age is a clastic wedge as much as 3,000 m thick of largely deep-water origin that was deposited in a foredeep immediately north of the Brooks Range orogen. The formation consists of shale, sandstone, and conglomerate, and appears to be made up of many overlapping submarine fan complexes, each one of limited lateral extent. Structural complications preclude lateral tracing of units across the outcrop belt. However, thick units of sandstone and conglomerate on the south, which range from fan-delta to submarine-canyon and inner-fan facies, apparently grade into thin-bedded, fine-grained, outer-fan and basin-plain turbidites to the north. Paleocurrent directions in the northern facies are to the east-northeast, indicating an easterly slope of the basin.

The sandstones of the Fortress Mountain Formation are subquartzose and lithic rich, containing much matrix or pseudomatrix and authigenic calcite, chlorite, and quartz cements. Hydrocarbon reservoir potential appears to be poor. Moreover, most of the age-equivalent rocks would probably be thin-bedded outer-fan or basin-plain facies in the subsurface north of the outcrop belt, where they are included in the lower part of the Torok Formation.

REFERENCES CITED

American Petroleum Institute, 1960, Recommended practice for core-analysis procedure: American Petroleum Institute Recommended Practices 40, 55 p.

Bartsch-Winkler, Susan, 1979, Textural and mineralogical study of some surface and subsurface sandstones from the Nanushuk Group, western North Slope, Alaska, *in* Ahlbrandt, T. S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 61-76.

Bouma, A.H., 1962, Sedimentology of some flysch deposits: Amsterdam, Elsevier Publishing Company, 168 p.

Chapman, R.M., Detterman, R.L., and Mangus, M.D., 1964, Geology of the Killik-Etivluk Rivers region, Alaska: U.S. Geological Survey Professional Paper 303-F, p. 325-407.

Chapman, R.M., and Sable, E.G., 1960, Geology of the Utukok-Corwin region, northwestern Alaska: U.S. Geological Survey Professional Paper 303-C, p. 47-167.

Crook, K.A.W., 1960, Classification of arenites: American Journal of Science, v. 258, p. 419-428.

Detterman, R.L., Bickel, R.S., and Gryc, George, 1963, Geology of the Chandler River region, Alaska: U.S. Geological Survey Professional Paper 303-E, p. 223-324.

Dickinson, W.R., 1970, Interpreting detrital modes of graywacke and arkose: Journal of Sedimentary Petrology, v. 40, p. 695-707.

Dickinson, W.R., and Suczek, C.A., 1979, Plate tectonics and sandstone compositions: American Association of Petroleum Geologists Bulletin, v. 63, no. 12, p. 2164-2182.

Hunter, R.E., and Fox, J.E., 1976, Interpretation of depositional environments in the Fortress Mountain Formation, central Arctic Slope, *in* Cobb, E.H., ed., The United States Geological Survey in Alaska—Accomplishments during 1975: U.S. Geological Survey Circular 733, p. 30-31.

Imlay, R.W., 1961, Characteristic Lower Cretaceous megafossils of northern Alaska: U.S. Geological Survey Professional Paper 335, 74 p.

Keller, A.S., Morris, R.H., and Detterman, R.L., 1961, Geology of the Shaviovik and Sagavanirktok Rivers region, Alaska: U.S. Geological Survey Professional Paper 303-D, p. 169-222.

Molenaar, C.M., 1985, Subsurface correlations and depositional history of the Nanushuk Group and related strata, North Slope, Alaska, *in* Huffman, A.C., Jr., ed., Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 37-59.

Mull, C.G., 1979, Nanushuk Group deposition and the late Mesozoic structural evolution of the central and western Brooks Range and Arctic Slope, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 5-13.

——— 1985, Cretaceous tectonics, depositional cycles, and the Nanushuk Group, Brooks Range and Arctic Slope, Alaska, *in* Huffman, A.C., Jr., ed., Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 7-36.

Mull, C.G., Tailleur, I.L., Mayfield, C.F., and Pessel, G.H., 1976, New structural and stratigraphic interpretations, central and western Brooks Range and Arctic Slope, *in* Cobb, E.H., ed., The United States Geological Survey in Alaska—Accomplishments during 1975: U.S. Geological Survey Circular 733, p. 24-26.

Mutti, Emilliano, and Ricci Lucchi, Franco, 1972, Le torbiditi dell'Appennino settentrionale: introduzione all'analisi di facies: Societá Geologica Italiana Memoire., v. 11, p. 161-199 (Translated by T.H. Nilsen, 1978, Turbidites of the northern Apennines: Introduction to facies analysis, American Geological Institute Reprint Series 3, reprinted from International Geology Review, v. 20, no. 2, p. 125-166.)

Patton, W.W., Jr., 1956, New and redefined formations of Early Cretaceous age, *in* Gryc, George, and others, Mesozoic sequence in Colville River region, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 40, no. 2, p. 219-223.

Patton, W.W., Jr., and Tailleur, I.L., 1964, Geology of the Killik-Itkillik region, Alaska: U.S. Geological Survey Professional Paper 303–G, p. 409-500.

Roeder, Dietrich, and Mull, C.G., 1978, Tectonics of Brooks Range ophiolites, Alaska: American Association of Petroleum Geologists Bulletin, v. 62, no. 9, p. 1696-1713.

Sable, E.G., Dutro, T.J., Jr., and Morris, R.H., 1951, Preliminary report on the stratigraphy and structure of the Driftwood-Noluck area, Alaska: U.S. Geological Survey Preliminary Report 39, 28 p. [Available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey].

Tailleur, I.L., and Kent, B.H., 1951, Stratigraphy and structure of the southern foothills section between the Etivluk and Kiligwa Rivers, Alaska: U.S. Geological Survey Geological Investigations, Naval Petroleum Reserve No. 4 and Adjacent Areas, Alaska, Regular Report 43, 28 p. [Available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey].

——— 1953, Progress report on the Kiligwa anticlinorium: U.S. Geological Survey Geological Investigations, Naval Petroleum Reserve No. 4 and Adjacent Areas, Alaska, Special Report 40, 17 p. [Available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey].

Tailleur, I.L., Kent, B.H., and Reiser, H.N., 1951, Preliminary report on the stratigraphy and structure of the Kiligwa River area, Alaska: U.S. Geological Survey Geological Investigations, Naval Petroleum Reserve No. 4 and Adjacent Areas, Alaska, Preliminary Report 37, 18 p. [Available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey].

Tailleur, I.L., Kent, B.H., Jr., and Reiser, H.N., 1966, Outcrop/geologic maps of the Nuka-Etivluk region, northern Alaska: U.S. Geological Survey Open-File Report 66-128, 7 sheets, scale 1:63,360.

13. SEDIMENTOLOGY OF THE NANUSHUK GROUP, NORTH SLOPE

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INTRODUCTION

The Nanushuk Group of Albian and Cenomanian age is a regressive sequence of marine, transitional, and nonmarine deposits exposed in an outcrop belt 30 to 50 km wide and approximately 650 km long in the Arctic foothills province, North Slope, Alaska (fig. 13.1). Sedimentary rocks of the Nanushuk Group constitute a potentially major hydrocarbon source within the National Petroleum Reserve in Alaska (NPRA). The most significant known oil field within the NPRA is in the Nanushuk Group at Umiat anticline (fig. 13.1) and has been estimated to contain as much as 122 million barrels of oil (Espach, 1951).

Previous outcrop and subsurface studies established the regional nature and extent of the Nanushuk Group. Most of these studies can be grouped by geographic areas into those dealing primarily with the (1) southwestern North Slope (Chapman and Sable, 1960; Smiley, 1966, 1969b); (2) south-central North Slope (Gryc and others, 1951, 1956; Detterman and others, 1963; Chapman and others, 1964; Brosgé and Whittington, 1966; Smiley, 1969a); (3) eastern North Slope (Detterman and others, 1975); and (4) subsurface of northwestern and north-central North Slope (Robinson, 1956, 1958, 1959a, b, c, 1964; Collins, 1958a, b, c, 1959; Robinson and Collins, 1959). More recent work, undertaken as a part of the NPRA exploration program, concentrated on a regional synthesis of various aspects of the geology of the Nanushuk Group. Preliminary results of this work were reported by Ahlbrandt (1979) and Huffman (1985).

Recent sedimentologic studies of the Nanushuk Group have employed a genetic-stratigraphy approach in order to avoid the confusion surrounding the nomenclature and arrive at a better understanding of the systems responsible for the deposition of the Nanushuk. Results of these studies have been reported by Ahlbrandt and Huffman (1978), Ahlbrandt and others (1979), Bartsch-Winkler (1979), Fox (1979), Fox and others (1979), Huffman (1979), Huffman and Ahlbrandt (1979), Roehler and Stricker (1979), Bartsch-Winkler and Huffman (1980), Huffman and others (1981a, b), Bartsch-Winkler (1985), Huffman and others (1985), and Molenaar (1985).

The currently accepted stratigraphic nomenclature for the Nanushuk Group and related rocks is shown in figure 13.2; however, very few stratigraphic names below group rank will be used in the following discussion. Terminology employed in any discussion of depositional environments is determined to a large extent by the depositional model being used. Depositional models currently applied to the Nanushuk Group together with their terminology are described below.

DEPOSITIONAL MODELS

Before the present investigation, the Nanushuk Group was recognized as a regressive marine and nonmarine sequence of sedimentary rocks (Gryc and others, 1951; Chapman and Sable, 1960). Fisher and others (1969) first used a deltaic model in discussing the Nanushuk of the central North Slope. The present study began by applying a regressive marine model to the exposures in the western North Slope. During the preliminary analyses of field data, it became apparent that the Nanushuk in this area was also deltaic—a conclusion based on the recognition criteria summarized by Weimer (1970). A detailed discussion of this reasoning is presented by Ahlbrandt and others (1979), who named the Nanushuk deltaic deposits in the western North Slope the Corwin delta and those in the central North Slope the Umiat delta. Subsequent work has confirmed these findings and described the Corwin delta as an elongate river-dominated delta and the Umiat delta as an elongate to lobate river-dominated delta (Huffman and others, 1985). The terminology employed in describing these river-dominated deltaic systems is modified after Coleman (1976) and illustrated in figure 13.3. The characteristics of each of these environments, as recognized in the Nanushuk deltaic deposits, are discussed by Huffman and others (1985).

Contours of sandstone percent (fig. 13.4) and of modal grain size (fig. 13.5) roughly delimit the general form of the delta systems. The belt of high sandstone percentage trending northwest from the vicinity of Umiat to the Ikpikpuk well is interpreted here as a coastal-barrier type of regressive shoreline

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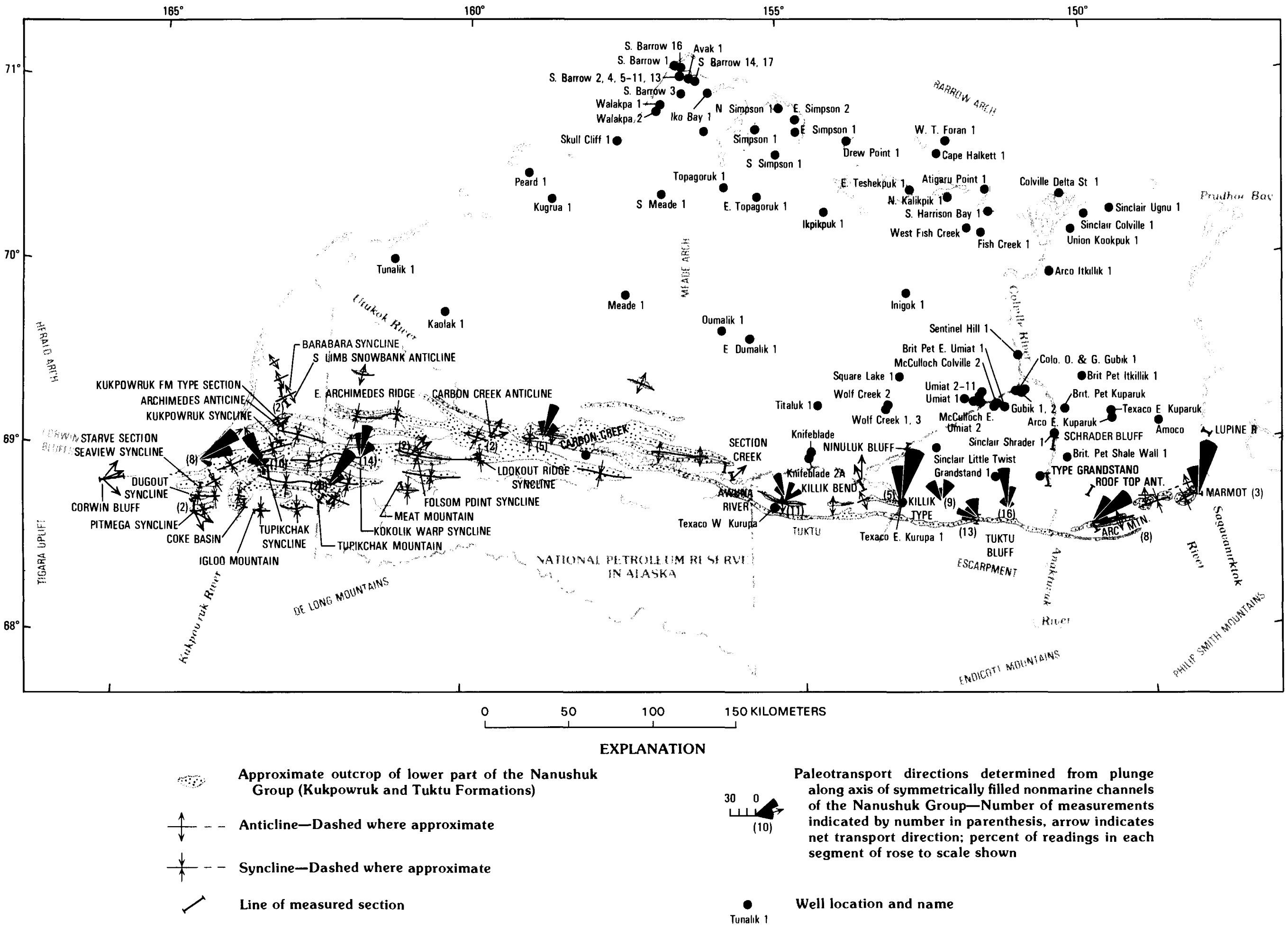

FIGURE 13.1.—Western and central North Slope, Alaska, showing locations of stratigraphic sections in the Nanushuk Group measured in 1977 and 1978 and well sites in relation to the outcrop area of the Nanushuk Group. Paleotransport directions from trough-axis measurements in the nonmarine channels of the Nanushuk Group shown by rose diagrams and arrows.

constructed with material supplied by longshore drift from the Umiat delta and by sediment from streams flowing to the northeast from the Corwin delta. The terminology employed in this region is that commonly used for coastal-barrier shorelines (Reineck and Singh, 1975).

The sedimentology of the Nanushuk Group will be discussed first for the western, then for the south-central, and finally for the north-central North Slope.

DEPOSITION OF THE NANUSHUK GROUP

WESTERN NORTH SLOPE

The Nanushuk Group of the western North Slope (west of long 157° W.) was deposited in the elongate river-dominated Corwin delta, which prograded to the east and northeast over shelf and prodelta muds and sands of the Aptian and Albian Torok Formation (Anderson, Warren, and Associates, 1980). Bird and Andrews (1979) and Molenaar (1985) have interpreted seismic data from the NPRA as indicating that the Torok represents large foreset beds prograding generally eastward and grading upward into topset beds of the Nanushuk Group. Individual reflectors can be traced up the foreset slope and into the nearly horizontal topset beds, indicating a genetic and time relation between the sediments of the Corwin delta and those of the Torok Formation. This relation is also supported by petrographic data (fig. 13.6) that strongly indicate a similar source for these two units—a source quite different from that of the Umiat delta.

In the western North Slope, the Nanushuk is generally considered to be middle and late Albian in age; it becomes younger to the east and north. Scott and Smiley (1979), however, suggested that in the vicinity of Corwin Bluff the Nanushuk ranges in age from late Aptian(?) to late Albian, and along the Kuk River, 250 km to the northeast, it ranges from middle Albian to

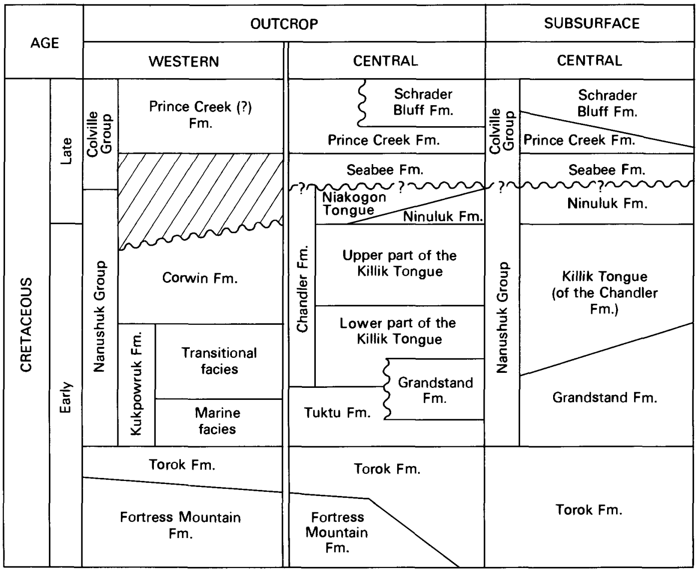

FIGURE 13.2.—Stratigraphic nomenclature for the Nanushuk Group and related rocks, western and central North Slope, Alaska (modified after Ahlbrandt and others, 1979).

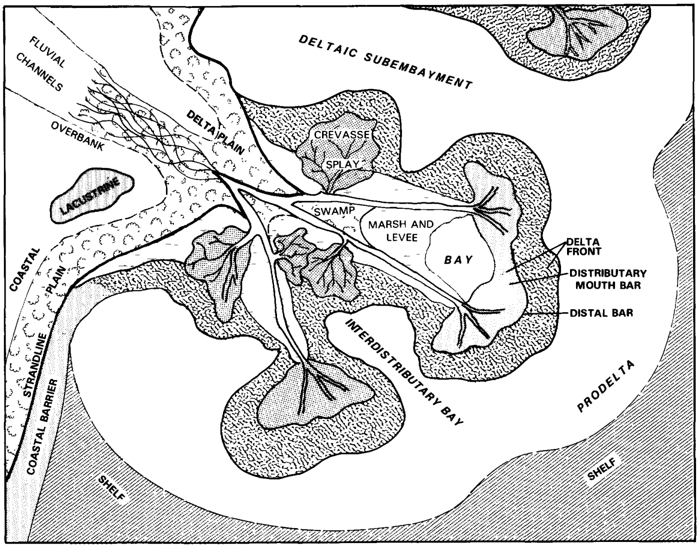

FIGURE 13.3.—Terminology used in describing deltaic environments (modified after Coleman, 1976).

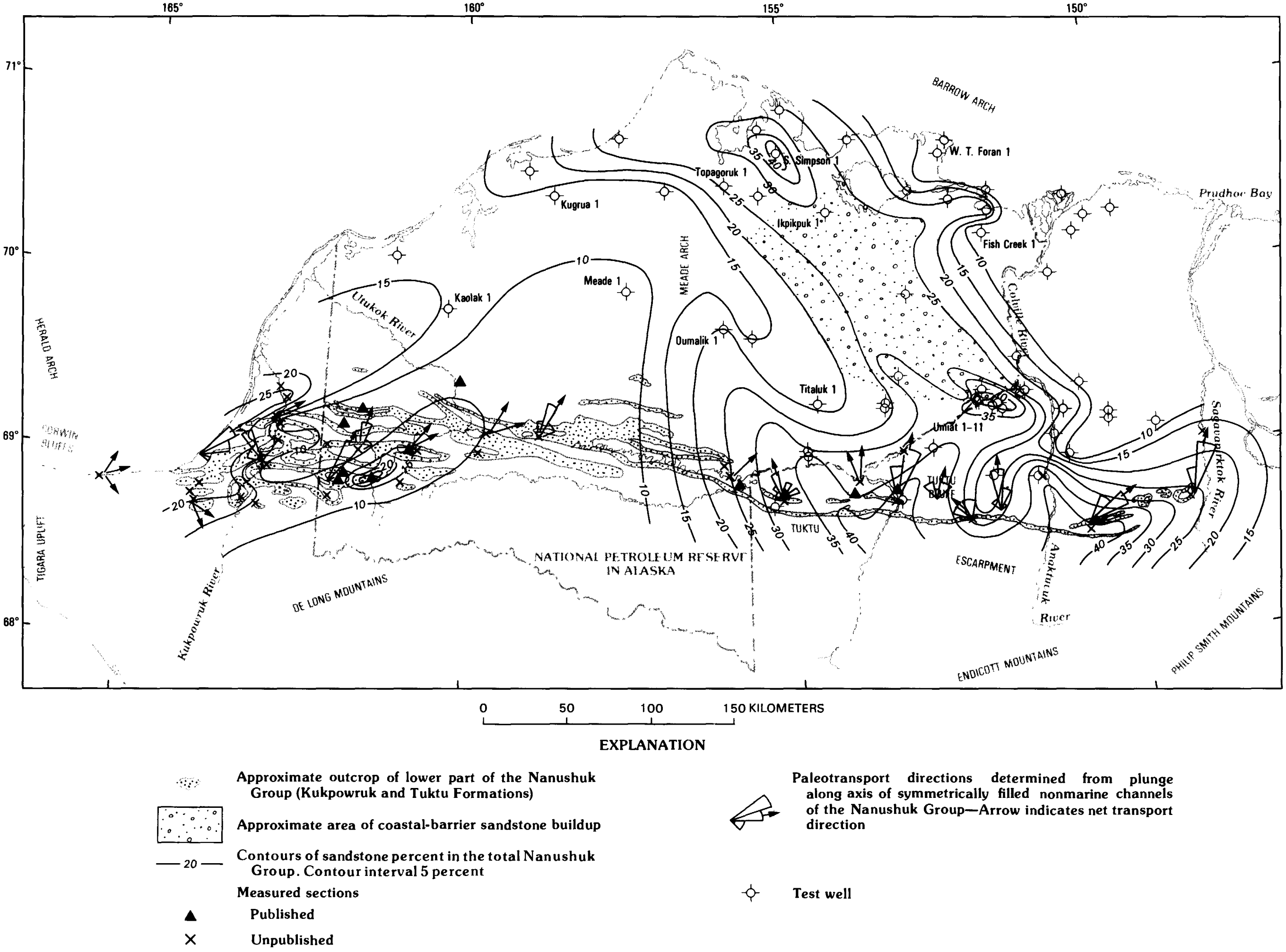

FIGURE 13.4.—Sandstone percent contours for the total Nanushuk Group. Data from sections measured in 1977 and 1978, previously published measured sections, and well-log interpretations (K.J. Bird, unpub. data). Selected wells, locations, and other data from figure 13.1 given for reference.

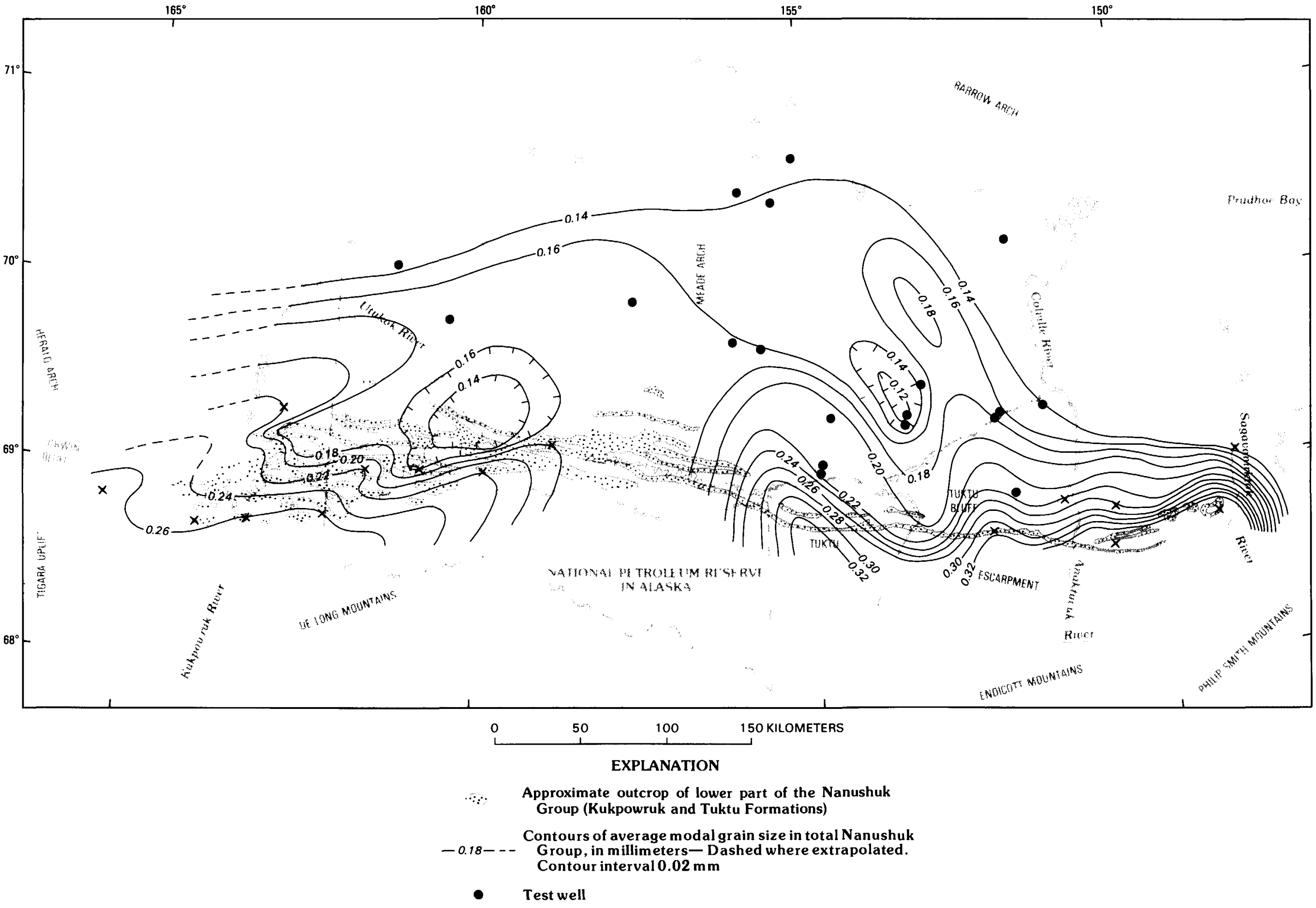

FIGURE 13.5.—Average modal grain-size contours for the total Nanushuk Group. Data from petrographic analyses, field descriptions of measured sections, and core descriptions. ×, measured sections.

early Cenomanian. The decrease in age of the Nanushuk to the north and east from the area of Corwin Bluff is also shown by decreases in both sandstone content (fig. 13.4) and average grain size (fig. 13.5). The general shape of the Corwin delta is indicated by the contours of these two parameters and, combined with the paleotransport directions (fig. 13.4), indicates an elongate river-dominated system prograding to the north and east in two major lobes with a large deltaic subembayment between them. Several characteristics, including (1) the type and character of the sandstone bodies, (2) the type and abundance of fossils and trace fossils, and (3) the distribution and relation of sedimentary environments, indicate that the Corwin delta was a fairly muddy system that prograded rapidly over a shallow shelf and was deposited in a slowly subsiding basin with restricted wave energies and circulation.

TYPE AND CHARACTER OF SANDSTONE BODIES

The sandstone beds of the Corwin delta are of fine-grained sedarenite (fig. 13.6), which is subject to diagenetic alteration detrimental to reservoir quality (Huffman, 1979; Bartsch-Winkler, 1979). With very few exceptions, the interstices are choked with primary and secondary clays, and much of the sandstone in the nonmarine part of the section is tightly cemented with sparry calcite that is related both to the source rock and to postdepositional processes (Bartsch-Winkler and Huffman, chapter 35; Huffman, 1979). Lithic fragments of chert, limestone, and argillaceous rocks are characteristic of the sandstone throughout the section. Many of the softer lithic fragments have been deformed during compaction to further reduce pore space (Bartsch-Winkler, 1979). The relative abundances of these constituents are correlatable with the stratigraphic sequence that was progressively exposed by erosion in the DeLong Mountains and Tigara uplift, which probably constitute, together with the Herald arch, the source terrain for most of the Corwin delta (Huffman, 1979). Molenaar (1985) has pointed out the need for a larger source area for the total Nanushuk Group-Torok Formation system and has suggested that such an area may have existed in the present-day Chukchi Sea between Alaska and Siberia.

Where seen in outcrop and on subsurface well logs, the Corwin delta generally contains less than 20 percent sandstone (fig. 13.4), most of which is concentrated in distributary channel deposits and elongate distributary mouth bars. The distributary mouth-bar deposits may be laterally continuous over a distance of only a few kilometers parallel to the paleoshoreline and rarely are more than 10-15 m thick. Their continuity perpendicular to the paleoshoreline is unknown but possibly is several tens of kilometers. Distributary mouth bars are rarely stacked on top of one another but are commonly overlain by either mudstone and sandstone of interdistributary bay fill or by prodelta shale and mudstone.

Distal mouth-bar deposits of the Corwin delta may be laterally extensive, are commonly thin (<3 m), and are composed of fine-grained sandstone with a high percentage of matrix. The sandstone of the distal mouth bars grades upward, both in grain size and thickness, into the coarser grained and thicker distributary mouth-bar sequences but is not stacked into thick delta-front deposits as in the Umiat delta.

Distributary channel deposits of the lower delta plain, adjacent to the distributary mouth bars, are composed of fine-grained sandstone and are generally less than 200 m wide and 10 m thick, lenticular in shape, and encased in silt-

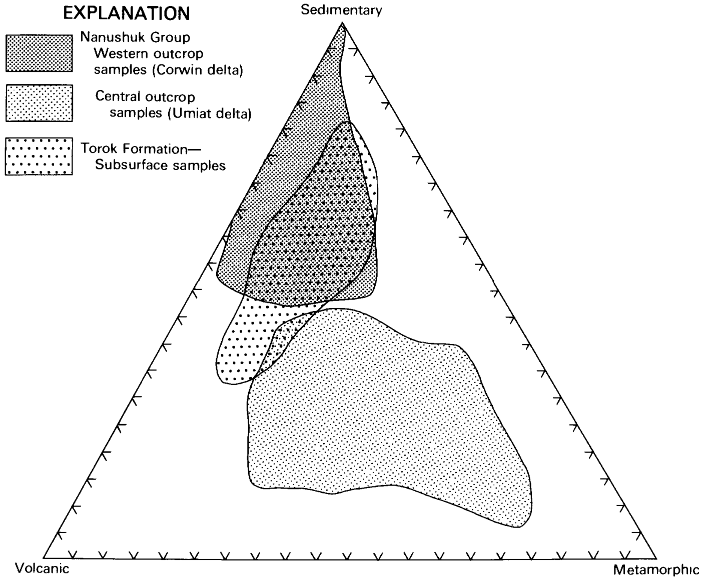

FIGURE 13.6.—Proportions of different types of lithic fragments in outcrop samples of the Nanushuk Group and subsurface samples of the Torok Formation following classification of Folk (1968). Outlined areas include all petrographic analyses from the suites indicated.

stone and mudstone. The only observed exception to this is where distributary channels merge with the sandstone of the distributary mouth bars or crevasse splays. Higher on the delta plain, the deposits of the fluvial channels are coarser grained and less well sorted and commonly contain conglomeratic lags at the base of trough sets. The major distributary deposits are as thick as 30 m (38 m at Corwin Bluff) and as wide as several hundred meters; they are the composite deposits of low-sinuosity streams. Middle and upper delta-plain deposits are also characterized by coal beds as much as 4 m thick. Coal is more abundant in the interdistributary regions than in the vicinity of the higher energy sandy distributary channels.

Very fine to fine-grained crevasse-splay sandstone deposits are also concentrated in the interdistributary areas. Although these deposits may be extensive laterally, they are rarely more than a few meters thick and are commonly interbedded with mudstone and siltstone of the interdistributary bay fill.

TYPE AND ABUNDANCE OF ORGANIC REMAINS

The Corwin delta is characterized by a low diversity and abundance of both macrofaunas and microfaunas. Poorly preserved, low-diversity foraminiferal assemblages from outcrop samples studied by Sliter (1979) indicate shallow water and a preponderance of nearshore and foreshore environments in the marine part of the section. Palynologic studies are also hampered by poor preservation of pollen and spores in outcrop samples due both to deep burial and subsequent near-surface weathering effects. Plant megafossils are abundant and, combined with the observed pollen and spores from the nonmarine parts of the Corwin delta, indicate a "warm, frost-free environment in the Albian, followed by cooler, warm-temperate conditions from latest Albian to Turonian time" (Scott and Smiley, 1979, p. 97).

Trace-fossil assemblages found in outcrops of the Nanushuk Group provide useful indicators of depositional environment for the unit but are of limited diversity and abundance, indicating probable high sedimentation rates in a turbid, perhaps low-oxygen environment. Distal bar sands commonly contain *Gyrochorte*, *Helicodromites*, *Arthrophycus*, and occasionally *Asterosoma*. Distributary mouth bars commonly contain *Diplocraterion* and *Skolithos*. Bioturbation is rare in distributary mouth bars and only slightly more common in the distal bars and prodelta. Trace fossils and bioturbation are somewhat more common in interdistributary bay fill and include *Arenicultes*, *Rosselia*, *Rhizocorallium*, *Diplocraterion*, and *Asteriacites*, indicating slower sedimentation rates and a greater abundance of nutrients.

DISTRIBUTION AND RELATION OF SEDIMENTARY ENVIRONMENTS

The Nanushuk Group can be divided into three facies: marine, transitional, and nonmarine (fig. 13.7). These facies are differentiated primarily on the basis of depositional environments as reflected by differences in lithology and paleontology. They roughly correspond to the marine and transitional facies of the Kukpowruk Formation and the Corwin Formation (fig. 13.2).

The marine facies consists of nothing but marine deposits from the lowest recognizable distal bar to the first distributary-channel or interdistributary-bay fill deposit. The uppermost sandstone in the marine facies is commonly the lowest distributary mouth bar. The marine facies of the Corwin delta ranges in thickness from 85 to 850 m, the thickest sections being in the deltaic subembayment and interdistributary bays. Deposits of the marine facies are predominantly mudstone and shale of the prodelta, interbedded with sandstone and siltstone of the distal bars. Sand content and grain size increase upward, and eventually the deposit grades into a distributary-mouth bar or interdistributary-bay fill. On the two major lobes of the Corwin delta both the sand content and the average grain size are greater than in the subembayment. The absence of thick delta-front sandstone deposits, the immature composition of both the distal-bar and distributary-mouth-bar sandstones, and the paucity of filter-feeding and horizontally burrowing animals indicate a delta with high sedimentation rates prograding rapidly into a low-energy, turbid environment.

The transitional facies contains estuarine as well as marine and nonmarine deposits. In the simplest case, the transitional facies represents deposits of the lower delta plain. However, because of periodic lateral shifting of the distributary streams and hence of the depocenter, this facies commonly contains several cycles or partial cycles of marine to nonmarine sedimentation. The facies is best developed on the delta lobes, reaching thicknesses as great as 600 m, commonly representing two or more delta cycles. Because the transitional facies on the lobes contains several sequences from distal bar through distributary-mouth bar to distributary channel, as well as crevasse-splay deposits, it represents by far the best sandstone development of the three facies. Away from the lobes there are fewer cycles, commonly just one, and much less sandstone. Prodelta and distal-bar deposits may also be directly overlain by fine-grained estuarine sediments with no intervening distributary-mouth bar or distributary-channel deposits, as in the Tupikchak syncline measured section.

The nonmarine facies is composed of sandstone, mudstone, and coal of the middle and upper delta plain. On the delta lobes the base is commonly marked by a thick, laterally extensive, conglomeratic sandstone deposited by high-energy, braided streams. Above this basal sandstone, the fluvial channel deposits are thinner and finer grained, most having been deposited by meandering streams. The middle delta-plain facies of the Corwin delta contains large thicknesses of fine-grained sediments and many thin beds of bituminous and subbituminous coal and carbonaceous shale deposited in poorly drained swamps (Callahan and Sloan, 1978). The general absence of coal in the transitional facies probably indicates a high sedimentation rate along the rapidly prograding delta front.

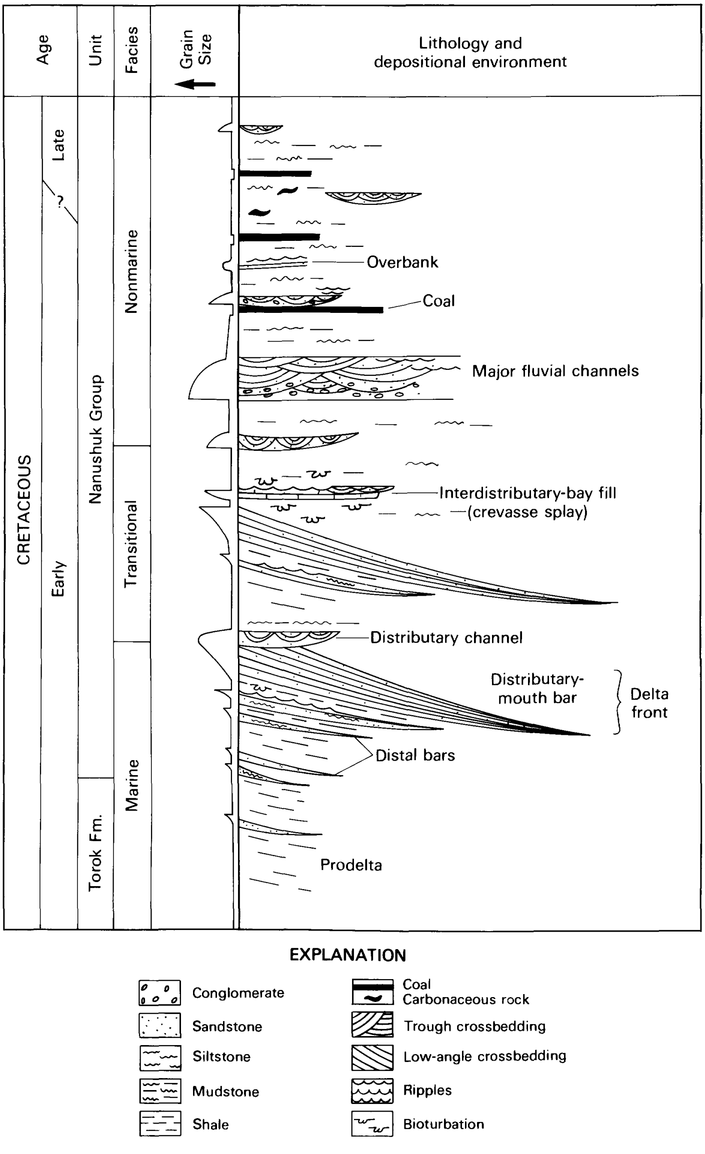

FIGURE 13.7.—Generalized stratigraphic sequence with sedimentologic interpretation for the Nanushuk Group, western North Slope, Alaska (modified after Ahlbrandt and others, 1979).

SOUTH-CENTRAL NORTH SLOPE

The Nanushuk Group of the south-central North Slope (long 157°-149° W.) was deposited in the elongate to lobate river-dominated Umiat delta (Huffman and others, 1985). Transport directions from the nonmarine facies of the Umiat delta, as well as variations in sandstone percentage and modal grain size (figs. 13.4, 13.5), indicate that the Umiat delta prograded generally northward from the vicinity of the Endicott Mountains.

The Umiat delta prograded across an already existing shelf and bears no genetic relation to the continental rise and shelf sediments of the underlying Torok Formation. Both seismic (Bird and Andrews, 1979; Molenaar, 1985) and petrographic studies (Bartsch-Winkler, 1985) indicate that most of the shelf and slope sediments of the Torok were supplied from the west (figs. 13.4, 13.6). The actual timing of the growth and many of the characteristics of the Umiat delta were probably determined by its relation to this narrow, deep-water shelf.

At the far eastern end of the Umiat delta, large volumes of material from the vicinity of the Marmot syncline (fig. 13.1) were apparently dumped onto a narrow shelf and later transported downslope to the northeast, resulting in thick turbidite and submarine-fan deposits in the vicinity of the Ivishak River 50 km to the northeast. A similar mechanism may be responsible for the apparent lobe of sandstone just north of the Fish Creek No.1 test well (fig. 13.4), but the only core descriptions available from that area (Robinson and Collins, 1959) do not identify or infer environments of deposition in this part of the section.

The nonmarine facies of the Umiat delta is overlain by intertonguing marine and nonmarine deposits signaling a major transgression that culminated in deposition of the overlying marine Seabee Formation of the Upper Cretaceous Colville Group (fig. 13.2).

The age of the Nanushuk Group in the central North Slope is generally considered to range from middle Albian to Cenomanian (Imlay, 1961; Bergquist, 1966; Sliter, 1979; Scott and Smiley, 1979). Dinoflagellate and palynological data from well material (May and Shane, 1985) indicate progressively younger deposits from west to east. This interpretation is consistent with the hypothesis that the timing of Umiat delta growth was controlled to a large extent by the presence of a shelf which itself was building from the west.

The shape of the Umiat delta, as indicated by the percentage of sandstone (fig. 13.4) and by modal grain-size contours (fig. 13.5), indicates a multilobed delta system prograding generally northward from the vicinity of the Endicott Mountains, beginning as an elongate system and gradually assuming a more lobate form. Possible reasons for this change in character are (1) an increase in wave energy, (2) a change in the balance of sediment supply and subsidence, or (3) eustatic sea-level changes. Data bearing on these possibilities and some of their implications are presented in the following discussion of the Umiat delta.

TYPE AND CHARACTER OF SANDSTONE BODIES

Sandstone of the Umiat delta differs significantly from that of the Corwin delta as well as from the shelf sandstone of the Torok Formation. Whereas sandstone from the western source area is characterized by a high percentage of sedimentary lithic fragments and is classified as sedarenite, that from the central source is high in quartzite and metamorphic lithic fragments and is classified as phyllarenite (fig. 13.6).

This marked difference between the two major source areas makes it possible to identify the provenance of a sandstone bed and thus infer the interaction between the deltas at any given location and time. For example, using only the data presented by Bartsch-Winkler and Huffman (chapter 35), it is possible to argue that at the Titaluk No. 1 well the lowermost sandstone sampled, at 1,046 m (3,431 ft), bears a strong similarity to sandstone of the Torok, whereas higher units show progressively more similarity to the sandstone of the Umiat delta (fig. 13.8). At the Oumalik No. 1 well, where only two samples of the Nanushuk Group were studied, from 298 m and 490 m (979 ft and 1,600 ft), there is an indication of an initial influx of sand from the Umiat delta followed by deposition of sediment from the Corwin delta (fig. 13.8). The limited number of samples from each well precludes

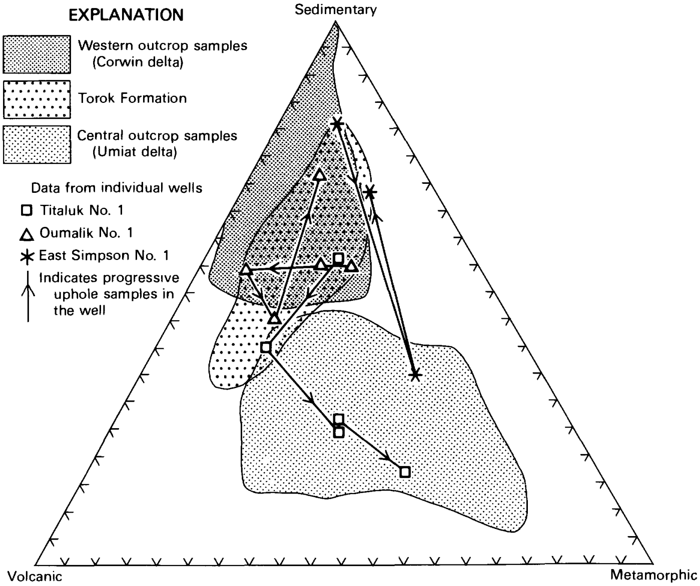

FIGURE 13.8.—Proportions of different types of lithic fragments in progressive uphole samples from Titaluk, Oumalik, and East Simpson test wells; also shown are fields for units from figure 13.6.

any firm conclusions, but these findings may warrant further investigation.

Where examined at the surface in the southern part of the central North Slope, the Nanushuk Group is coarser grained (medium grained) and sandier (more than 25 percent sand) than in the western area (figs. 13.4, 13.5). Huffman and Ahlbrandt (1979) attributed some of these and other differences between the two areas to the presence of the thick quartzitic and quartz-rich Kanayut Conglomerate in the probable source area of the Umiat delta and the absence of any comparable unit southwest of the Corwin delta. Other major factors causing the differences between these two delta systems are the higher energy level of the marine environment into which the Umiat delta prograded and the generally greater distances from the probable source areas for most of the Corwin delta exposures than for the Umiat delta outcrops.

Along the outcrop belt of the Umiat delta, distal-bar deposits are composed of very fine grained, poorly sorted sandstone and siltstone beds as much as 25 m thick interbedded with mudstone and shale intervals as thick as 90 m. Although the distal-bar deposits could not be traced their full length in outcrop, they extend several kilometers parallel to depositional strike where exposed on the Tuktu escarpment (fig. 13.4). In the Tuktu Bluff measured section (fig. 13.1) these sandstone bodies are stacked on top of one another to make a 200-m-thick section of nearly 100 percent sandstone (Huffman and others, 1981b).

The primary sites of clastic sedimentation in the southern portion of the Umiat delta were distributary mouth bars. These fine- to medium-grained sandstone bodies are 10 to 25 m thick and are generally lenticular in cross section, although they may coalesce laterally to form sheets of sandstone several tens of kilometers wide. Grain size and porosity increase upward in individual bars. In a normal regressive or prograding succession, the bar deposits are overlain by fluvial deposits of the distributary channels above a scour surface or by fine-grained interdistributary bay sediments. Stacked regressive beach sequences, possibly indicating eustatic sea-level changes, are also present within the Umiat delta complex, for instance in the Kurupa anticline measured section (Huffman and others, 1981b).

Fluvial channel deposits of the Umiat delta are typically fine- to medium-grained, trough-cross-bedded sandstone or conglomeratic sandstone. They range in thickness from 1 to 25 m and are several hundred meters in width. The contact between the transitional and nonmarine facies is commonly marked by laterally extensive high-energy braided stream deposits as much as 14 m thick. These channel deposits are conglomeratic, containing white quartz and dark chert clasts as well as large plant fragments. The channels flowed generally northward from the vicinity of the Endicott Mountains.

Adjacent to the major distributaries and overlying the delta-front deposits, the interdistributary fill is composed primarily of mudstone and siltstone sequences ranging in thickness from 10 to 100 m. Overlying and interbedded with these fine-grained sediments are cross-bedded and ripple-laminated fine-grained sandstone bodies deposited in crevasse splays and small distributary channels. These sandstones are typically 5 to 6 m thick but may be stacked to as much as 30 m. Marsh deposits of claystone, siltstone, and coal, commonly rooted in crevasse-splay sandstone, are typically less than a meter and rarely more than 3 m thick.

TYPE AND ABUNDANCE OF ORGANIC REMAINS

Diversity, abundance, and preservation of all types of fossils in both surface and subsurface material are greater in the Nanushuk of the central North Slope than in the western area. This indicates both better living conditions (slower sedimentation rates, better circulation, more oxygen) and a shallower, cooler burial history. Foraminiferal studies (Bergquist, 1966; Sliter, 1979) indicate a generally deeper water, offshore environment for much of the marine facies of the Nanushuk Group of the central North Slope compared to the shallow nearshore and foreshore environments characteristic of the western area. Because of the good preservation and the high diversity and abundance of dinoflagellates, pollen, and spores from subsurface material, May and Shane (1985) were able to map facies changes and infer delta-lobe positions through time. The results of the micropaleontologic and palynologic studies agree well with the seismic and sedimentologic investigations.

Megafossils and trace fossils are also more abundant and show a higher diversity in the Umiat delta than in the Corwin delta. Distal-bar deposits are commonly bioturbated or contain both vertical and horizontal burrows of *Cruziana* and *Planolites*. Molds and casts of pelecypods (*Pleuromya*, *Corbicula*, and tellinimerids) are scarce but widespread. Higher energy deposits of the distributary mouth bars are characterized by *Skolithos*, *Diplocraterion*, *Rhizocorallium*, *Gyrochorte*, and *Helicodromites*. Both pelecypods (*Inoceramus*, *Corbicula*, *Nucla*, *Pecten*, and tellinimerids) and scaphopods (*Ditrupa*) are common. Fine-grained deposits of the interdistributary fill are commonly bioturbated, and crevasse-splay sandstone bodies contain *Corbicula* and rarely *Unio*.

DISTRIBUTION AND RELATIONS OF SEDIMENTARY ENVIRONMENTS

The Nanushuk Group of the central North Slope can also be divided into marine, transitional, and nonmarine facies (fig. 13.9). In the southern outcrop belt, these roughly correspond to the Tuktu Formation and lower and upper parts of the Killik Tongue of the Chandler Formation, respectively. In the subsurface to the north, the Grandstand Formation commonly includes both the marine facies and parts of the transitional facies. The Ninuluk Formation represents a marine incursion followed by deposition of the transitional to nonmarine Niakogon Tongue of the Chandler Formation.

One of the major differences between the Umiat and Corwin deltas is the nature of the marine facies. The marine facies of the Umiat delta is both much sandier and coarser grained than that of the Corwin delta. Moreover, the delta-front sandstone bodies of the Umiat delta have greater lateral extent, are better sorted, and contain higher energy sedimentary structures than those of the Corwin delta. On the major lobes of the Umiat delta the marine facies is generally sandier, coarser, and thinner than in the major deltaic subembayment. At Tuktu Bluff, in the subembayment (fig. 13.4), the marine facies is 747 m thick and contains 34 percent sandstone in the measured section, whereas on a lobe, such as at the nearby type Grandstand section, the marine facies is 209 m thick and contains 60 percent sandstone.

The transitional facies of the southern Umiat delta commonly contains as many as three or four deltaic cycles. On the major lobes, as at Kurupa anticline (fig. 13.1), this part of the section is thick (1,044 m) and contains more than 50 percent of the sandstone in the entire Nanushuk Group (Huffman and others, 1985). The sandstone of

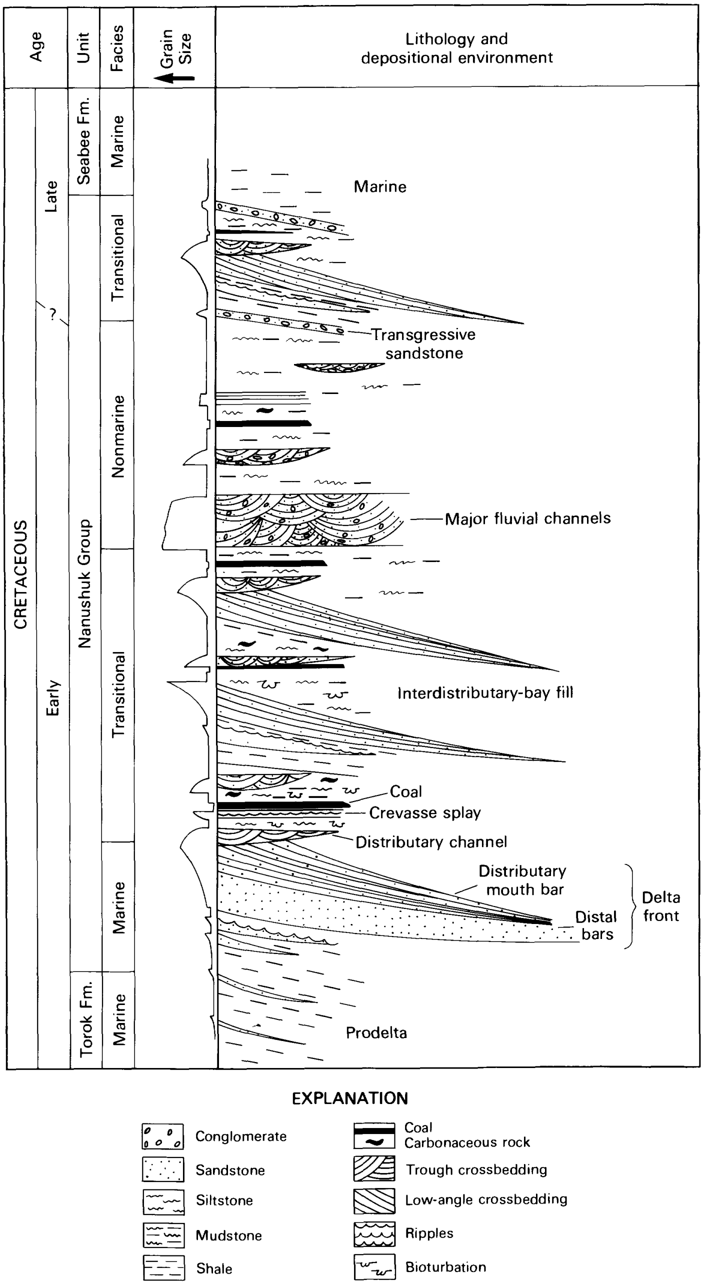

FIGURE 13.9.—Generalized stratigraphic sequence with sedimentologic interpretation for the Nanushuk Group, south-central North Slope.

the transitional facies along the outcrop belt is typically medium grained and moderately to well sorted and was deposited in moderate- to high-energy environments. Sandstone bodies 15 to 30 m thick, composed of delta-front and distributary-channel deposits, are commonly associated with each identifiable deltaic cycle. The lateral extent of these bodies could not be determined because the outcrops were limited.

Coal beds are common in the transitional facies of the Umiat delta. Although the coal beds are thin (<1.5 m), they are commonly rooted in crevasse-splay deposits and are significant as indicators of more stable environments and slower sedimentation rates than were present in the transitional facies of the Corwin delta.

Where exposed, the base of the nonmarine facies of the Umiat delta is commonly marked by a conglomerate, of white quartzite and dark chert pebbles, deposited by high-energy braided streams. This basal conglomerate may be as thick as 14 m and contain clasts as much as 30 cm across. All of the higher energy channel deposits above the basal conglomerate are conglomeratic and also contain the white quartzite and dark chert pebbles. The widespread, coarse-grained nature of the conglomerate indicates renewed uplift of the source area, which may be a synchronous event throughout the south-central North Slope.

The nonmarine facies is sandier, coarser grained, and contains more coal on the lobes than in the subembayment. On the lobes, it typically contains 20 percent of the total sandstone in the Nanushuk Group as compared with 12 percent in the subembayment (Huffman and others, 1985). Sandstone is concentrated in fluvial-channel and finer grained overbank deposits. The channel sandstones may be as thick as 12 m but more typically are 4-6 m thick and were deposited by both braided and meandering streams. The lateral extent of the sandstone bodies is unknown. Coal is sparse and occurs as thin (<2 m) beds whose lateral continuity is also unknown.

Throughout much of the central North Slope, nonmarine deposition on the Umiat delta plain was halted by a marine transgression during early Cenomanian time (Detterman and others, 1963; Scott and Smiley, 1979; Sliter, 1979). In the outcrop area, this transgression is characterized by intertonguing marine and nonmarine deposits similar to the transitional facies already described. Several thin (30-60 cm) beds of crossbedded, conglomeratic sandstone containing both pelecypod and bone fragments are present in these transitional beds and were interpreted by Huffman and others (1985) to be transgressive sandstones recording several pulses of the regional transgression. At Ninuluk Bluff, this upper transitional facies is 320 m thick and contains 25 percent sandstone. Coal beds (<1 m thick) containing 6-cm-thick tonsteins are common in the nonmarine deposits of the transitional facies at Ninuluk Bluff.

NORTH-CENTRAL NORTH SLOPE

The Umiat delta does not extend north of Umiat as a recognizable feature (fig. 13.4). Instead, a belt with a high concentration of sandstone extends northward from the vicinity of Umiat to the Ikpikpuk well and the apparent sandstone buildup in the vicinity of the South Simpson well (fig. 13.4). Huffman and others (1985) concluded that this belt of sandstone represents a coastal barrier shoreline supplied with sediment transported northward by longshore drift from the Umiat delta as well as by sediment transported to the coast by Corwin streams. Very little sedimentologic information bearing on this question is currently available; however, petrographic studies reported by Bartsch-Winkler and Huffman (chapter 35) show that the rocks in the East Simpson No. 1 well at a depth of 1,854 m (6,083 ft) fall within the Torok field on figure 13.8, those at a depth of 734.6 m (2,410 ft) are within the Umiat delta field, and those at a depth of 733.5 m (2,406 ft) are closely related to the Corwin delta. These limited observations, although by no means conclusive, tend to support the suggested interaction of the two sediment sources even as far north as the East Simpson No. 1 well.

Bird and Andrews (1979) traced the northeastern limit of recognizable nonmarine and coal deposits (their facies A) from Umiat to the vicinity of the East Simpson No. 1 well. This limit of alluvial and delta-plain deposition lies within the eastern third of the belt of sandstone (fig. 13.4), precisely where lagoonal and lower alluvial-plain deposition would be expected in a coastal-barrier shoreline. To the southwest of this line, marine sandstone bodies should intertongue with nonmarine deposits in the transitional facies, as suggested by Bird and Andrews (1979) and predicted by the model presented here (fig. 13.10) and more fully discussed by Ahlbrandt and others (1979) and Huffman and others (1985).

The sandstone concentration in the vicinity of the South Simpson well also was probably caused by an interaction between Corwin deltaic sedimentation and sand redistribution from the Umiat delta. The location, nature, and age of this buildup are of interest because it may have significance in the interpretation of sedimentation patterns for the Nanushuk Group of the central North Slope. Huffman and others (1985) interpreted the high sandstone percentages immediately north of the Kugrua well (fig. 13.4) as marking a continuation of the northern lobe of the Corwin delta. If this interpretation is correct, the location of the sandstone buildup at the northeastern end of this long, roughly linear lobe indicates that in the vicinity of the South Simpson well the Corwin distributaries encountered higher energy conditions.

The higher energy deposits in this sandstone buildup were dated by Bergquist (1966) as middle and late Albian in the Topagoruk and Simpson wells. May and Stein (1979) arrived at the same age for the Nanushuk in the Simpson 25 core test and interpreted the dinoflagellate data as indicating nearshore marine environments of deposition. These ages agree well with the late Albian age of the upper marine and transitional facies in such wells as Oumalik, Square Lake, and Umiat (May and Shane, 1985). In these and other wells located along the northern margin of the Umiat delta, thick sandstone accumulations in this part of the section and a little above this deposit signal a general change in conditions perhaps caused by increased rates of basin subsidence with concurrent increases in wave energy and current activity.

DISCUSSION

The Nanushuk Group depositional system and the resulting deposits were controlled to a great extent by two major factors: (1) the type and source of the sediment, and (2) the shape and stability of the receiving basin at the time of deposition of the Nanushuk. Nearly all characteristics of the Nanushuk can be attributed to a combination of these two variables. The following discussion will analyze these factors through the period of deposition of the Nanushuk.

The basin into which the Cretaceous and Tertiary sediments of the North Slope were deposited was the elongate Colville trough, bounded on the south by the ancestral Brooks Range, on the west by the Tigara uplift and Herald arch, and on the north by the Barrow arch, and open to the sea on the east. During the deposition of the Torok Formation and the lower part of the Nanushuk Group, the Barrow arch was not exposed to erosion, but rather acted as a sill, described by Molenaar (1985) as a slowly subsiding passive high. From late Aptian through early Albian time (fig. 13.11A) the rate of subsidence in the western Colville trough was apparently rather slow, and the ratio of sediment supply to rate of subsidence was weighted heavily on the supply side. These conditions are indicated by several lines of evidence, such as the low angle of foreset beds of the Torok (Molenaar, 1985) and the rapid progradation and elongate form of the Corwin delta.

The large volume of fine-grained sediment in the Torok Formation and the muddy nature of the Corwin delta indicate a source terrain containing widespread thick deposits of clay-rich sediment. Huffman (1979) correlated the vertical lithologic variations within the sandstone of the Corwin delta with

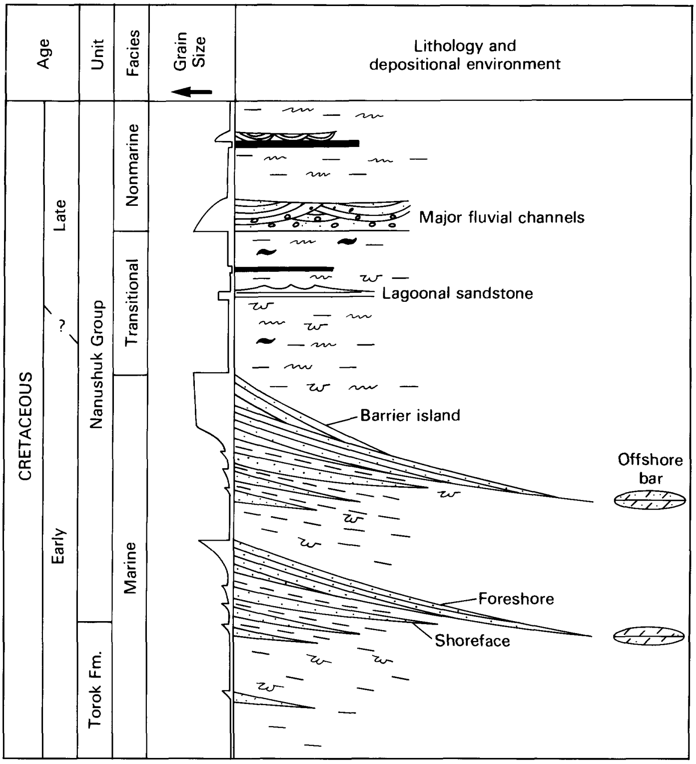

FIGURE 13.10.—Generalized stratigraphic sequence with sedimentologic interpretation for the Nanushuk Group, north-central North Slope. For explanation, see figure 13.9.

successive lithologic changes exposed by progressive erosion of the sequence in the Lisburne Hills and DeLong Mountains. The thick sections of limestone and dolomitic limestone of the Lisburne Group (Mississippian to Permian) and the calcareous and shaly Siksikpuk Formation (Pennsylvanian to Early Triassic) and Shublik Formation (Triassic) provided easily accessible source rocks for the western part of the Nanushuk Group. The relative abundance of chert and scarcity of quartz sand in the source terrain are reflected by both the amounts and types of sandstone in the Corwin delta.

Porosity and permeability are generally low in the sandstone of the marine and transitional facies in the Corwin delta (fig. 13.12*A*). The primary causes of this are the large amount of matrix material (clay, mud, and silt), the deformation of soft clastic grains during compaction, and pervasive diagenetic effects (Bartsch-Winkler, 1979). Because the Corwin delta prograded into a low-energy environment, the sands in the distributary mouth bars and distal bars were not subjected to the winnowing effects of strong wave and current activity. Only in some of the high-energy fluvial deposits were fine-grained materials consistently removed, thus producing good porosity and permeability (fig. 13.12*A*).

During middle Albian time (fig. 13.11*B*) the shelf of mudstone and shale (Torok Formation) continued to prograde eastward, fed by sediment from the Corwin delta as well as by contributions from the ancestral Brooks Range to the south. The foreset beds of the Torok Formation steepen rapidly from 1° or 2° dips

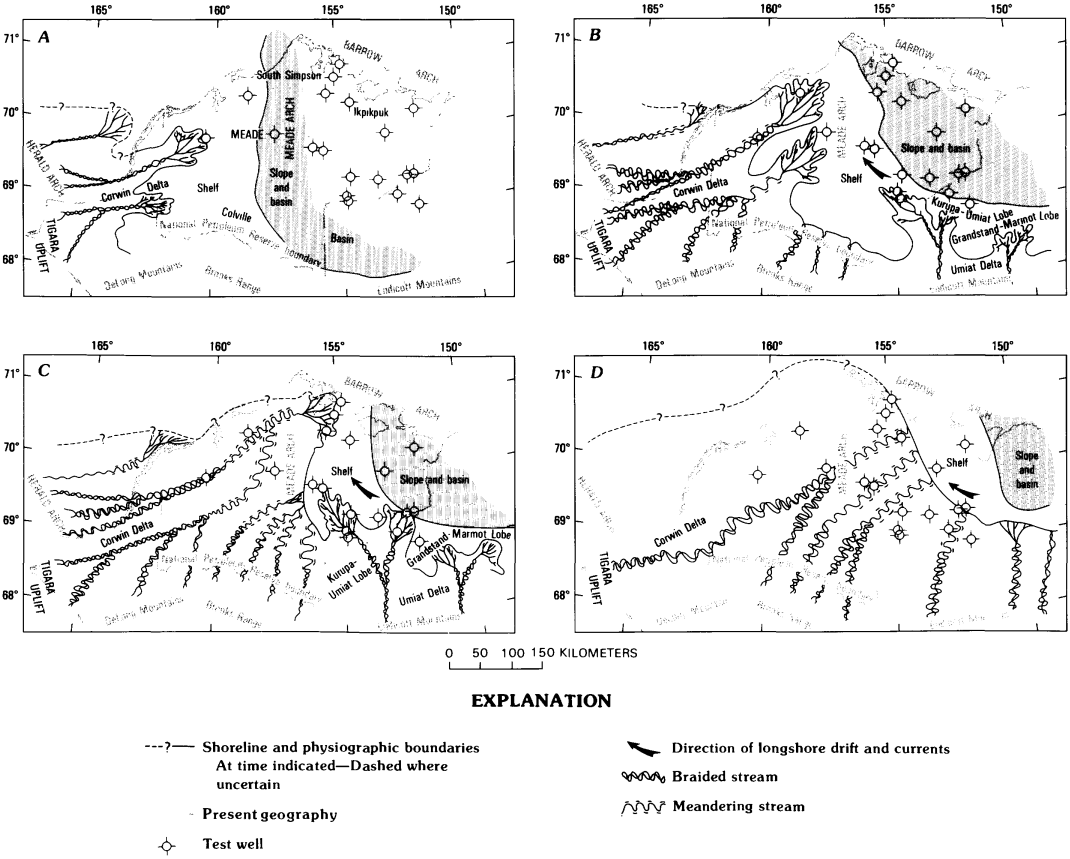

FIGURE 13.11— Paleogeographic maps depicting depositional history of the Nanushuk Group. *A*, Early and middle Albian. *B*, Middle and late Albian. *C*, Late Albian and Cenomanian(?). *D*, Cenomanian (at time of maximum regression).

west of the ancestral Meade arch to more than 6° to the east (Molenaar, 1985). The significance of this steepening is not fully understood. Possibilities include the following: (1) The Meade arch was also a passive high acting as a sill. (2) The Meade arch marks the location of a hinge line, to the east of which subsidence was more rapid. (3) The entire basin began an episode of more rapid subsidence at about the time the Torok reached this point. None of these possibilities can be completely ruled out by present data; perhaps a combination of all three is the most likely. At this point, the role of the Meade arch is problematical; however, both the sand percentage and the modal grain-size contours (figs. 13.4, 13.5) can be taken to indicate that it exerted some control on deposition of the Nanushuk before late Albian time. In the absence of definitive paleontologic data, seismic studies offer the best approach to resolving this question.

The Umiat delta began to prograde northward during middle Albian time. Deposition was initiated in the west (the Kurupa-Umiat lobe of Huffman and others, 1985) and proceeded to the east (Grandstand-Marmot lobe). The Umiat delta began as an elongate, river-dominated delta with numerous deltaic cycles but gradually assumed a lobate form and the characteristics of a wave-dominated delta. This change in character through time can be explained by increasing wave and current activity resulting from the continued subsidence of the Barrow arch, which reduced its effect as a sill.

The sandy nature of the Umiat delta can be partially attributed to the presence of the thick quartzitic Kanayut Conglomerate (Devonian and Mississippian?) in the source area, partially to the high-energy marine environment, which winnowed out much of the fine-grained material, and perhaps partially to proximity to its source area. The many metamorphic lithic fragments in the sandstone of the Umiat delta (fig. 13.6) were contributed by both the Kanayut and the underlying phyllitic Hunt Fork Shale (Devonian). The phyllite fragments act in much the same way as the shale fragments of the Corwin delta, deforming and filling pore space during compaction (Bartsch-Winkler, 1985). The matrix material in many of the distributary-mouth bar and foreshore deposits was reduced by the higher energy marine environment, thereby improving their reservoir characteristics. This condition is reflected in figure 13.12*B*, which shows good porosity and permeability values concentrated in the fluvial and distributary-mouth-bar deposits of the transitional facies.

Northward progradation of the Umiat delta was halted during the late Albian (fig. 13.11C), probably by more rapid subsidence of the trough bringing the subsidence/supply ratio into equilibrium. The widespread, high-energy fluvial conglomerate at the base of the nonmarine facies could be associated with this event but is more apt to have been the result of renewed uplift in the source area. The cessation of Umiat delta growth was accompanied by redistribution of sediment to the north by longshore drift and probably by the formation of a small delta in the vicinity of the South Simpson well.

The concentration of sandstone around South Simpson may have resulted from several factors. The inferred accelerated subsidence would have caused an increase in the amount of sediment supplied to the coast by the Corwin distributaries, and this, combined with the effect of the higher wave energies encountered once deposition progressed east of the Meade arch, resulted in a small wave-dominated delta. Sediment supplied from the Umiat delta, when merged with

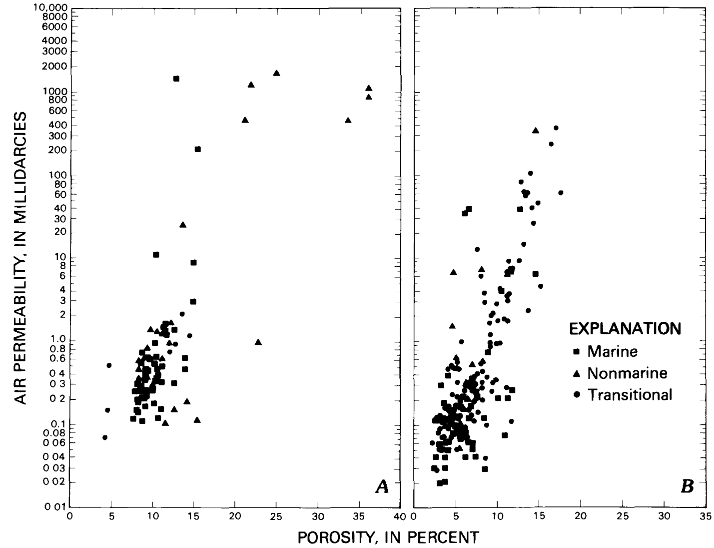

FIGURE 13.12.—Plots of porosity against permeability for outcrop samples from deltaic sequences in the Nanushuk Group. *A*, Corwin (western) delta; permeability measurements were generally not made on samples with porosities of less than 8 percent. *B*, Umiat (eastern) delta.

this small Simpson delta, could have caused the southerly elongation of the area of high sand percentage.

Eustatic sea-level changes in Cenomanian time (fig. 13.11*D*) resulted in several transgressions, finally halting deposition of the Nanushuk Group completely. The last and major transgression was preceded by several smaller pulses producing the transitional facies in the upper part of the Nanushuk. The effects of these initial pulses are reflected in Nanushuk sediments as far south as the Tuktu escarpment and an unknown distance to the west. Cenomanian time also marks the first appearance of significant thicknesses of bentonite deposits in the Nanushuk. The Cenomanian and Turonian (Anderson, Warren and Associates, 1980) bentonitic marine deposits of the Seabee Formation overlie the Nanushuk in an apparently normal transgressive sequence.

CONCLUSIONS

The preceding discussion of Nanushuk Group sedimentology is a summary of data and interpretations presented by Ahlbrandt (1979) and Huffman (1985) plus the results of more recent work. The following conclusions relate the findings of these studies to the location and possible development of hydrocarbon reservoirs within the Nanushuk.

1. Potential for the presence of significant reservoirs in the Nanushuk Group is generally poor from the Meade arch to the west, primarily because of the low sand content of the Corwin delta, the high matrix and cement contents, the generally low energy environment, and the limited lateral and vertical extent of the sandstone bodies. The most favorable locations for possible reservoir development are in the nonmarine channel sandstones and the distributary-mouth bars of the transitional facies on the major lobes of the delta.

2. Reservoir potential in the sandstone of the Nanushuk east of the Meade arch is much better than to the west. Good reservoir sandstone bodies have been identified in almost every well and measured section in the Nanushuk of the central North Slope. The distributary-mouth-bar sandstones of the Umiat delta and the coastal barrier sandstones to the north of the delta are high-energy, quartzose, vertically stacked sandstone bodies that are laterally continuous over several kilometers or perhaps tens of kilometers. Multistage secondary porosity has been recognized in the subsurface deposits north of the delta (Bartsch-Winkler and Huffman, chapter 35).

3. It is likely that stratigraphic traps exist in the coastal barrier sandstones north of the delta. There is a reasonable probability of barrier-island sandstone bodies northeast of the prograding coastline and pinchouts of the coastal barrier foreshore sandstones into back-beach and nonmarine sediment to the southwest. If hydrocarbons were generated in the organic-rich Cretaceous black shales (pebble shale unit, Torok Formation) in the eastern part of the area, it could easily have migrated updip and up the foreset beds of the Torok to the west, ultimately to accumulate in the topset beds of the Nanushuk in stratigraphic traps or to be concentrated in a structure in the zone of stratigraphic traps. Bird and Andrews (1979) suggested such a mechanism for the Umiat field.

4. Several lines of evidence, such as contours of sandstone percentage and grain size, seismic studies, and facies models indicate that the ancestral Meade arch was of fundamental importance in the development of sedimentary patterns in the Torok Formation and Nanushuk Group. One of the implications of this interpretation is that the area of the Meade arch, especially the eastern flank, would be a likely location for a concentration of depositional pinchouts, both in the Nanushuk and in stratigraphically lower units. If such pinchouts do occur on the flank of this structure, they could make suitable sites for hydrocarbon accumulations.

5. The sandstone buildup in the vicinity of the South Simpson well could also provide suitable sites for stratigraphic traps. The most likely locations for significant depositional pinchouts would be to the south and west of the well site.

6. An unknown and potentially important factor in this analysis of reservoirs is the role of secondary porosity development. Such development has been documented in samples of the Nanushuk from the subsurface of the central North Slope (Bartsch-Winkler and Huffman, chapter 35), but the lack of data from the subsurface of the western North Slope precludes any speculation as to its possible importance in that area.

REFERENCES CITED

Ahlbrandt, T.S., ed., 1979, Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, 163 p.

Ahlbrandt, T.S., and Huffman, A.C., Jr., 1978, Cretaceous Nanushuk Group, North Slope of Alaska, *in* Johnson, K.M., ed., The United States Geological Survey in Alaska—accomplishments during 1977: U.S. Geological Survey Circular 772-B, p. 13-15.

Ahlbrandt, T.S., Huffman, A.C., Jr., Fox, J.E., and Pasternack, Ira, 1979, Depositional framework and reservoir-quality studies of selected Nanushuk Group outcrops, North Slope, Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 14-31.

Anderson, Warren, and Associates, 1980,

Alaskan North Slope generalized subsurface biostratigraphic correlating chart: San Diego, California, Anderson, Warren, and Associates, Inc.

Bartsch-Winkler, Susan, 1979, Textural and mineralogical study of some surface and subsurface sandstones from the Nanushuk Group, western North Slope, Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 61-76.

—— 1985, Petrography of sandstones of the Nanushuk Group from four measured sections, central North Slope, Alaska, *in* Huffman, A.C., Jr., ed., Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 75-95.

Bartsch-Winkler, Susan, and Huffman, A.C., Jr., 1980, Compositional variation in Nanushuk Group sandstones, Arctic North Slope, *in* Albert, N.R.D., and Hudson, T., eds., The United States Geological Survey in Alaska—accomplishments during 1979: U.S. Geological Survey Circular 823-B, p. 6-8.

Bergquist, H.R., 1966, Micropaleontology of the Mesozoic rocks of northern Alaska: U.S. Geological Survey Professional Paper 302-D, p. 93-227.

Bird, K.J., and Andrews, Jack, 1979, Subsurface studies of the Nanushuk Group, North Slope, Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 32-41.

Brosgé, W.P., and Whittington, C.L., 1966, Geology of the Umiat-Maybe Creek region, Alaska: U.S. Geological Survey Professional Paper 303-H, p. 501-638.

Callahan, J.E., and Sloan, E.G., 1978, Preliminary report on analyses of Cretaceous coals from northwestern Alaska: U.S. Geological Survey Open-File Report 78-319, 29 p.

Chapman, R.M., Detterman, R.L., and Mangus, M.D., 1964, Geology of the Killik-Etivluk Rivers region, Alaska: U.S. Geological Survey Professional Paper 303-F, p. 325-407.

Chapman, R.M., and Sable, E.G., 1960, Geology of the Utukok-Corwin region, northwestern Alaska: U.S. Geological Survey Professional Paper 303-C, p. 47-174.

Coleman, J.M., 1976, Deltas; processes of deposition and models for exploration: Champaign, Ill., Continuing Education Publication Co., Inc., 102 p.

Collins, F.R., 1958a, Test wells, Umiat area, Alaska, *with* Micropaleontologic study of the Umiat field, northern Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-B, p. 71-206.

—— 1958b, Test wells, Topagoruk area, Alaska, *with* Micropaleontologic study of the Topagoruk test wells, northern Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-D, p. 265-316.

—— 1958c, Test wells, Meade and Kaolak areas, Alaska, *with* Micropaleontology of Meade test well 1 and Kaolak test well 1, northern Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-F, p. 341-376 (1959).

—— 1959, Test wells, Square Lake and Wolf Creek areas, Alaska, *with* Micropaleontology of Square Lake test well 1 and the Wolf Creek test wells, northern Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-H, p. 423-484.

Detterman, R.L., Bickel, R.A., and Gryc, George, 1963, Geology of the Chandler River region, Alaska: U.S. Geological Survey Professional Paper 303-E, p. 223-324.

Detterman, R.L., Reiser, H.N., Brosgé, W.P., and Dutro, J.T., Jr., 1975, Post-Carboniferous stratigraphy, northeastern Alaska: U.S. Geological Survey Professional Paper 886, 46 p.

Espach, R.H., 1951, Recoverable petroleum reserves in the Umiat structure, Naval Petroleum Reserve No. 4, Alaska: U.S. Bureau of Mines Petroleum and Natural Gas Branch Open-File Report, 9 p.

Fisher, W.I., Brown, L.F., Jr., Scott, A.J., and McGowen, J.H., 1969, Delta systems in the exploration for oil and gas, a research colloquium: Austin, Texas, Bureau of Economic Geology, University of Texas, 78 p.

Folk, R.L., 1968, Petrology of sedimentary rocks: Austin, Texas, Hemphill's Book Store, 170 p.

Fox, J.E., 1979, A summary of reservoir characteristics of the Nanushuk Group, Umiat Test Well 11, National Petroleum Reserve in Alaska, *in* Ahlbrandt, T.S., ed. Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 42-53.

Fox, J.E., Lambert, P.W., Pitman, J.K., and Wu, C.H., 1979, A study of reservoir characteristics of the Nanushuk and Coville Groups, Umiat Test Well 11, National Petroleum Reserve in Alaska: U.S. Geological Survey Circular 820, 47 p.

Gryc, George, Bergquist, H.R., Detterman, R.L., Patton, W.W., Jr., Robinson, F.M., Rucker, F.P., and Whittington, C.L., 1956, Mesozoic sequence in Colville River region, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 40, p. 209-254.

Gryc, George, Patton, W.W., Jr., and Payne, T.G., 1951, Present Cretaceous stratigraphic nomenclature of northern Alaska: Washington Academy of Sciences Journal, v. 41, no. 5, p. 159-167.

Huffman, A.C., Jr., 1979, Stratigraphy and petrography of a measured section on the south limb of Barabara syncline, North Slope, Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 77-88.

Huffman, A.C., Jr., ed., 1985, Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, 129 p.

Huffman, A.C., Jr., and Ahlbrandt, T.S., 1979, The Cretaceous Nanushuk Group of the western and central North Slope, Alaska, *in* Johnson, K.M., ed., The U.S. Geological Survey in Alaska—accomplishments during 1978: U.S. Geological Survey Circular 804-B, p. 46-50.

Huffman, A.C., Jr., Ahlbrandt, T.S., Pasternack, Ira, Fox, J.E., Bartsch-Winkler, Susan, May, F.E., Scott, R.A., and Materna, W.L., 1981a, Measured sections of the Cretaceous Nanushuk Group undivided, western North Slope, Alaska: U.S. Geological Survey Open-File Report 81-176.

Huffman, A.C., Jr., Ahlbrandt, T.S., Pasternack, Ira, Stricker, G.D., Bartsch-Winkler, Susan, Fox, J.E., May, F.E., Scott, R.A., and Materna, W.L., 1981b, Measured sections in the Cretaceous Nanushuk and Colville Groups undivided, central North Slope, Alaska: U.S. Geological Survey Open-File Report 81-177.

Huffman, A.C., Jr., Ahlbrandt, T.S., Pasternack, Ira, Stricker, G.D., and Fox, J.E., 1985, Depositional and sedimentologic factors affecting the reservoir potential of the Cretaceous Nanushuk Group, central North Slope, Alaska, *in* Huffman, A.C., Jr., ed., Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 61-74.

Imlay, R.W., 1961, Characteristic Lower Cretaceous megafossils of northern Alaska: U.S. Geological Survey Professional Paper 335, 74 p.

May, F.E., and Shane, J.D., 1985, An analysis of the Umiat delta using palynologic and other data, North Slope, Alaska, *in* Huffman, A.C., Jr., ed., Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 97-120.

May, F.E., and Stein, J.A., 1979, Dinoflagellate and Acritarch assemblages from the Grandstand Formation (Middle to Upper Albian) of the Nanushuk Group, Simpson core test 25, National Petroleum Reserve in Alaska, northern Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 128-145.

Molenaar, C.M., 1985, Subsurface correlations and depositional history of the Nanushuk Group and related strata, North Slope, Alaska, *in* Huffman, A.C., Jr., ed., Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 37-59.

Reineck, H.E., and Singh, I.B., 1975, Depositional sedimentary environments: New York, Springer-Verlag, 439 p.

Robinson, F.M., 1956, Core tests and test wells, Oumalik area, Alaska, *with* Paleontology of test wells and core tests in the Oumalik area, Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-A, p. 1-70.

——— 1958, Test wells, Gubik area, Alaska, *with* Micropaleontologic study of the Gubik test wells, northern Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-C, p. 207-264.

——— 1959a, Test well, Grandstand area, Alaska, *with* Micropaleontologic study of Grandstand test well 1, northern Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-E, p. 317-339.

——— 1959b, Test wells, Titaluk and Knifeblade areas, Alaska, *with* Micropaleontologic study of test wells in the Titaluk and Knifeblade areas, northern Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-G, p. 377-422.

——— 1959c, Test wells, Simpson area, Alaska, *with a section on* Core analyses, by S.T. Yuster: U.S. Geological Survey Professional Paper 305-J, p. 523-568.

——— 1964, Core tests, Simpson area, Alaska, *with a section on* Temperature measurement studies, by M.C. Brewer: U.S. Geological Survey Professional Paper 305-L, p. 654-730.

Robinson, F.M., and Collins, F.R., 1959, Core test, Sentinel Hill area, and test well, Fish Creek area, Alaska: U.S. Geological Survey Professional Paper 305-I, p. 485-521.

Roehler, H.W., and Stricker, G.D., 1979, Stratigraphy and sedimentation of the Torok, Kukpowruk, and Corwin Formations of Cretaceous age in the Kokolik-Utukok River region, National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 79-995, 80 p.

Scott, R.A., and Smiley, C.J., 1979, Some Cretaceous plant megafossils and microfossils from the Nanushuk Group, northern Alaska; a preliminary report, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 89-111.

Sliter, W.V., 1979, Cretaceous foraminifers from the North Slope of Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 147-157.

Smiley, C.J., 1966, Cretaceous floras from Kuk River area, Alaska—stratigraphic and climatic interpretations: Geological Society of America Bulletin, v. 77, no. 1, p. 1-14.

——— 1969a, Cretaceous floras of Chandler-Colville region, Alaska—stratigraphy and preliminary floristics: American Association of Petroleum Geologists Bulletin, v. 53, p. 482-502.

——— 1969b, Floral zones and correlations of Cretaceous Kukpowruk and Corwin Formations, northwestern Alaska: American Association of Petroleum Geologists Bulletin, v. 53, p. 2079-2093.

Weimer, R.J., 1970, Rates of deltaic sedimentation and intrabasin deformation, Upper Cretaceous of Rocky Mountain region, *in* Morgan, J.P., and Shaver, R.H., eds., Deltaic sedimentation—modern and ancient: Society of Economic Paleontologists and Mineralogists Special Publication 15, p. 270-292.

14. GEOLOGY OF THE UPPER DEVONIAN AND LOWER MISSISSIPPIAN(?) KANAYUT CONGLOMERATE IN THE CENTRAL AND EASTERN BROOKS RANGE

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INTRODUCTION

The nonmarine Upper Devonian and Lower Mississippian(?) Kanayut Conglomerate and related clastic rocks of the Endicott Group crop out continuously in a belt approximately 640 km long by 65 km wide in the north-central and southeastern Brooks Range, from about long 144° to 158° W., between the Sheenjek and Kuna Rivers. The Endicott Group also crops out discontinuously for another 250 km westward, in the DeLong and Baird Mountains, between the Kuna River and the Chukchi Sea. Although only 270 km of their outcrop belt lies within the National Petroleum Reserve in Alaska (NPRA), the Kanayut and related units may extend northward beneath the North Slope and could be correlative with clastic middle Paleozoic strata present in the subsurface within the NPRA.

The Kanayut and related clastic rocks were studied in the area of continuous exposures in the central and eastern Brooks Range in order to understand better the pre-Carboniferous clastic rocks known or inferred to be present in the subsurface beneath the North Slope. Clastic Devonian strata are reported from two wells in the northern part of the NPRA. A Middle Devonian conglomerate, sandstone, and shale unit older than the Kanayut was reported from the Topagoruk well by Collins (1958), and similar clastic rocks recently encountered in the bottom of the South Meade well may be correlative with those in the Topagoruk (Witmer and others, 1981). Interpretations of recently acquired seismic data show the presence of a thick sequence of clastic rocks that thickens southeastward from the Topagoruk and Ikpikpuk wells into the Umiat Basin and beyond (Tetra Tech, Inc., 1979). The upper part of this sequence is Early Mississippian in age where penetrated by the Inigok well (Witmer and others, 1981). The lower part, not penetrated by the well, is probably also Mississippian, but it may include older rocks correlative with the Kanayut. In either case, these clastic rocks can be assigned to the Endicott Group.

We have mapped the Kanayut Conglomerate in the central and eastern Brooks Range at a scale of 1:250,000 and have made stratigraphic, sedimentologic, petrographic, and paleontologic analyses to determine the depositional history and tectonic framework for these nonmarine clastic rocks in the eastern 640 km of their outcrop belt. In this chapter we present general results from our study of the Kanayut Conglomerate and suggest models for its depositional and structural history. We also show the distribution of mappable units within the Kanayut at a scale of 1:500,000 (pl. 14.1). Previous results were published as a series of open-file reports (Nilsen and others, 1980a, b, 1981b, 1982; Nilsen and Moore, 1982), circular articles (Nilsen and others, 1981a) and maps (Brosgé and others, 1979a, b). Nomenclature of the Kanayut Conglomerate and associated units has been revised by Nilsen and Moore (1984) after the mapping for plate 14.1 was completed.

REGIONAL GEOLOGY

The central and eastern Brooks Range is underlain chiefly by upper Paleozoic rocks that are progressively younger toward the north edge of the mountains. The Paleozoic rocks have been divided by Tailleur and others (1967) into three main sequences: the Middle and Upper Devonian Baird Group, the Upper Devonian and Lower Mississippian Endicott Group, and the Mississippian and Pennsylvanian Lisburne Group. The Baird Group and the Lisburne Group in the central Brooks Range are marine platform sequences that consist mainly of carbonate rocks and were thought to conformably underlie and overlie the Endicott Group, respectively. The Endicott Group was defined by Tailleur and others (1967) as a succession of shale, sandstone, and conglomerate. They suggested that the clastic rocks of the Endicott Group in the central Brooks Range formed a major Late Devonian and Early Mississippian offlap-onlap cycle defined by the outbuilding to the south of a large clastic wedge.

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In the Endicott Mountains in the central Brooks Range (fig. 14.1), the Endicott Group consists, in ascending order, of the Hunt Fork Shale, Noatak Sandstone, Kanayut Conglomerate, and Kayak Shale (figs. 14.2, 14.3). The Kanayut Conglomerate forms the middle nonmarine and coarse-grained component of the offlap-onlap cycle, and the underlying Hunt Fork Shale and Noatak Sandstone and overlying Kayak Shale are the fine-grained marine components. In the western Brooks Range, the Noatak Sandstone is the main coarse clastic unit of the Endicott Group, and Dutro (1953) correlated it with the Kanayut Conglomerate; in the central Brooks Range the Noatak is a thin unit lying beneath the Kanayut.

In much of the central Brooks Range, the Endicott Group rests on the Upper Devonian marine Beaucoup Formation (Dutro and others, 1979). The Beaucoup consists of a basal conglomerate overlain by calcareous siltstone and black shale, capped in many places by carbonate coral reefs. The Beaucoup is characterized by rapid lateral facies changes and pinchouts in its lower parts. These rocks are depositionally overlain by the Hunt Fork Shale and rest unconformably on the Skajit Limestone of the Baird Group. The Beaucoup Formation may represent an older depositional system around local highs in the pre-Endicott sedimentary basin.

In the northeastern Brooks Range and in the subsurface beneath the North Slope, the Endicott Group (Tailleur and others, 1967) consists of the Kekiktuk Conglomerate, Kayak Shale, and Itkilyariak Formation (Mull and Mangus, 1972). This sequence rests unconformably on pre-Upper Devonian rocks and is entirely Early and Late Mississippian in age. These rocks to the

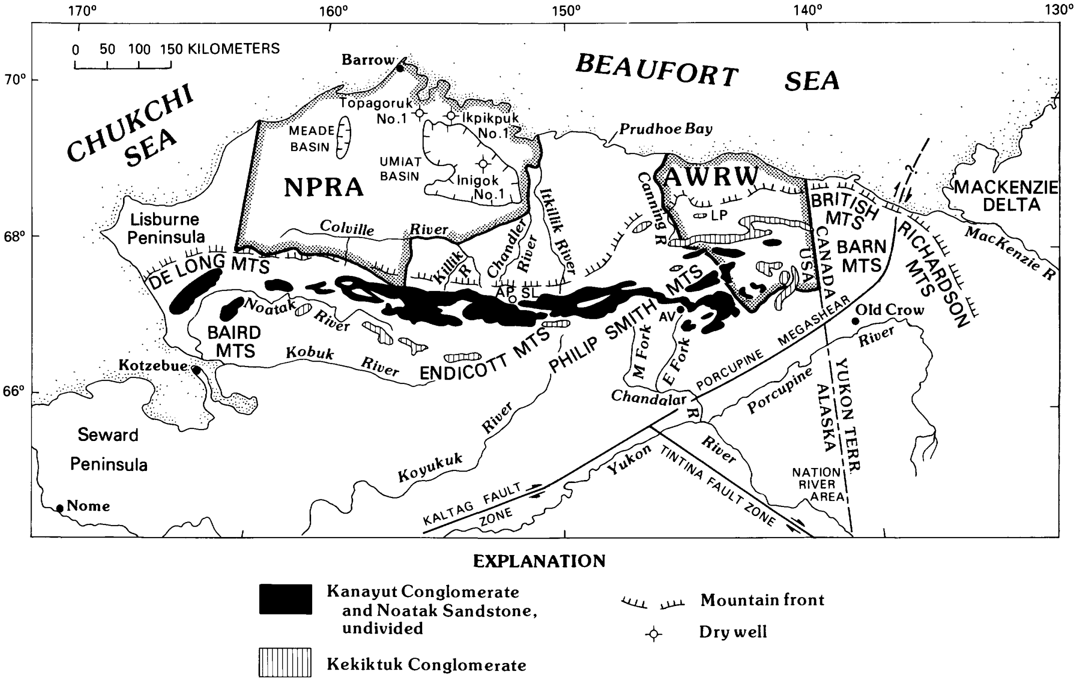

FIGURE 14.1.—Outcrops of the undivided Kanayut Conglomerate and Noatak Sandstone and of the Kekiktuk Conglomerate in northern Alaska. Also shown are major subsurface basins that may contain thick Devonian or Mississippian sections. AP, Anaktuvuk Pass; AV, Arctic Village; AWRW, Arctic Wildlife Refuge Wilderness; LP, Lake Peters; NPRA, National Petroleum Reserve in Alaska; SL, Shainin Lake. Outlines of outcrops are from: Brosgé and Reiser (1962, 1964, 1965, 1969, 1971); Reiser and others (1971, 1980); Brosgé and others (1976, 1979a, b); Mayfield and Tailleur (1978); Mayfield and others (1978); Nelson and Grybeck (1980); and unpublished mapping by I.L. Tailleur, C.F. Mayfield, and I.F. Ellersieck in the Howard Pass, Misheguk Mountain, Baird Mountains, and Noatak quadrangles, and by the authors and H.N. Reiser in the Arctic and Killik River quadrangles.

north were thought to represent deposition along the northern margin of the basin into which the Kanayut detritus was shed, and the Kekiktuk Conglomerate was thought to represent the updip correlative of the Kanayut Conglomerate (Tailleur and others, 1967). However, a similar sequence of Mississippian rocks above an unconformity is also present near Mount Doonerak and in the Schwatka Mountains in the southern Brooks Range (Mull and Tailleur, 1977; Mayfield and Tailleur, 1978), so the relations between the Devonian and Mississippian parts of the Endicott Group cannot be as simple as originally proposed.

Fossils are locally abundant in both the Beaucoup Formation and the Endicott Group. Marine megafossils from the Beaucoup Formation and the lower shale member of the Hunt Fork Shale indicate a Frasnian (early Late Devonian) age, whereas marine megafossils from the upper wacke member of the Hunt Fork Shale and from the Noatak Sandstone indicate a Famennian age. Plant fossils from the upper beds of the Kanayut Conglomerate indicate a Late Devonian to Early Mississippian(?) age, and marine megafossils in interbedded marine tongues indicate a Famennian age for the basal beds. The Kekiktuk Conglomerate contains plant fossils that are Early Mississippian in age, and the Kayak Shale contains marine megafossils and microfossils that indicate an Early Mississippian (late Kinderhookian) to early Late Mississippian (Meramecian) age. In the central Brooks Range, however, the Kayak is entirely of Early Mississippian age.

The Brooks Range is characterized by west-trending thrust faults and overturned folds that disrupt the Paleozoic strata. Imbrication of the strata along these faults has resulted in a stacked series of folded thrust plates. Several thrusts within this series represent fundamental structural boundaries of regional importance. Tailleur and others (1967) recognized lithologic disparities between the Baird Group and the Endicott Group and suggested that the Baird Group had been thrust northward over the western end of the Endicott Group outcrop belt. Brosgé and Tailleur (1971) reported that the Endicott Group, together with the overlying Lisburne Group, had been thrust northward over the Mesozoic sedi-

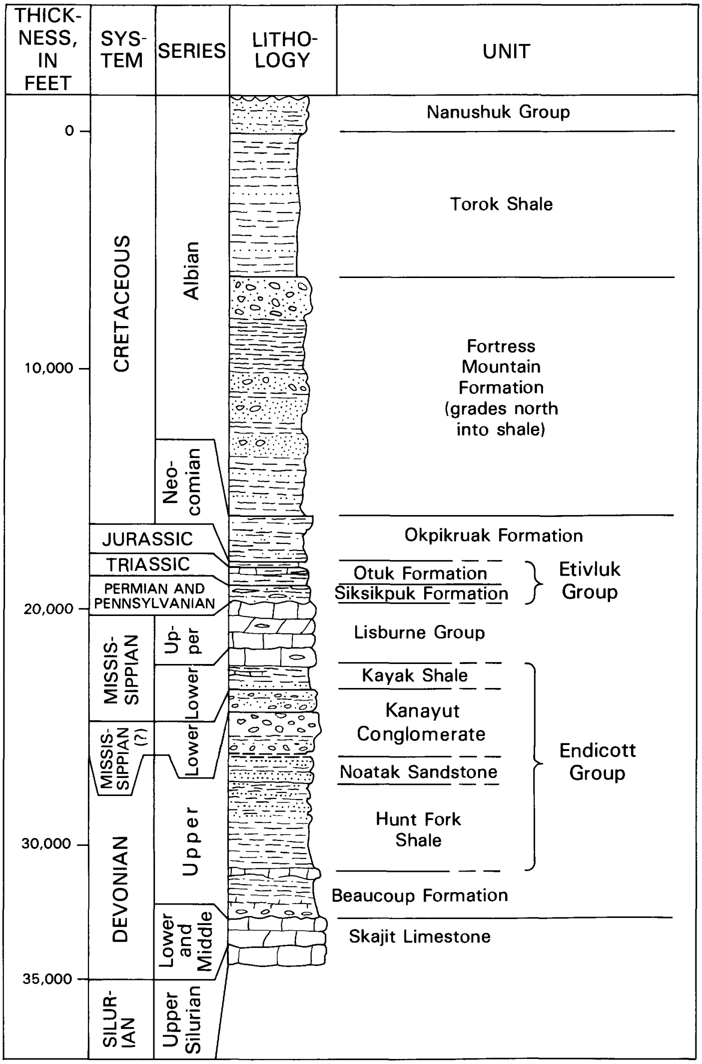

FIGURE 14.2.—Stratigraphic column for the central Brooks Range. Names for Permian, Triassic, and Jurassic rocks are from Mull and others (1982).

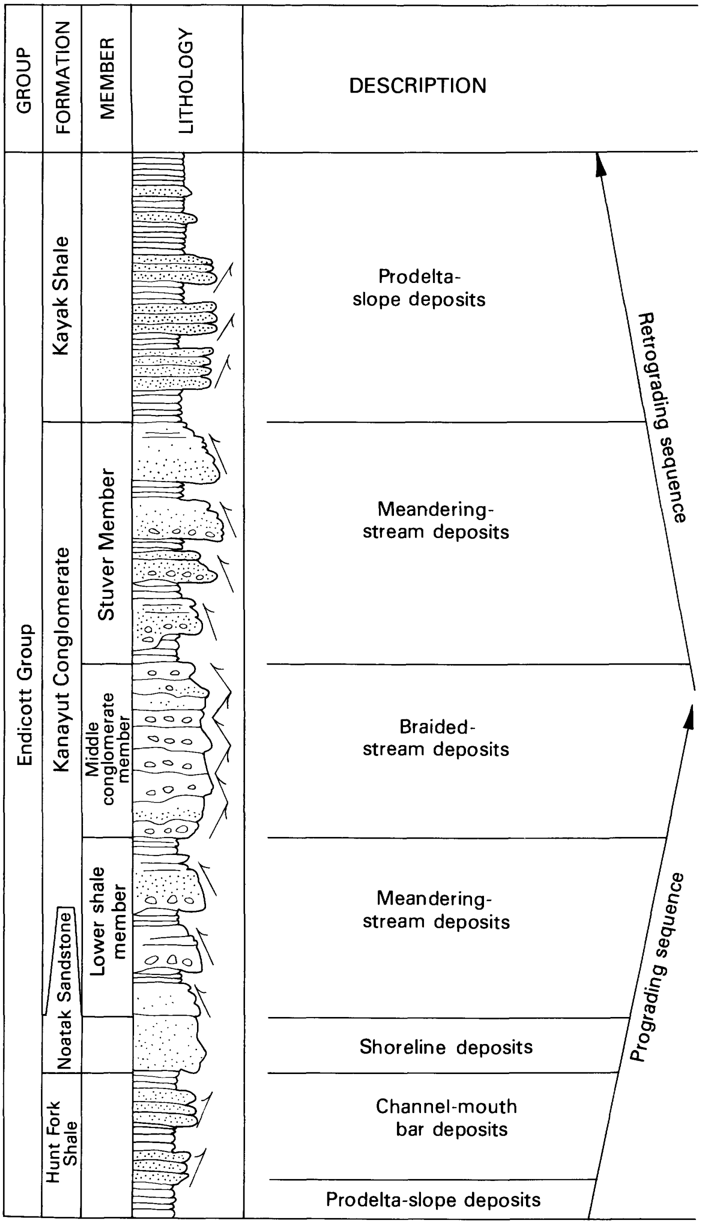

FIGURE 14.3.—Generalized stratigraphy, depositional environments, and progradational and retrogradational cycles of allochthonous sequence of the Endicott Group in the central Brooks Range. Small arrows inclined upward to right indicate coarsening-upward cycles; small arrows inclined upward to left indicate fining-upward cycles.

mentary rocks of the North Slope, and Mull and others (1976) gave evidence that these rocks had also been thrust northward across the older Paleozoic rocks of the southern Brooks Range. Roeder and Mull (1978) describe Paleozoic ophiolitic rocks that were thrust northward over the Brooks Range rocks and form the highest structural unit in the Range. The Christian ophiolite, a part of this unit, structurally overlies the Endicott Group at the east end of its belt of exposure (see fig. 14.8).

Mull and Tailleur (1977), Newman and others (1979), and Nilsen (1981) argued that the Endicott Group consists of two distinct sequences, one allochthonous and the other autochthonous. The thickest and best developed sequence of the Endicott Group is allochthonous and forms a thick pile of thrust plates. It consists, in ascending and conformable order, of the Hunt Fork Shale, Noatak Sandstone, Kanayut Conglomerate, and Kayak Shale, capped by limestone of the Lisburne Group. The thinner and less well developed sequence of the Endicott Group is autochthonous or parautochthonous and crops out around the northeastern and southern margins of the inferred allochthon. The autochthonous Endicott Group consists, in ascending order, of the Kekiktuk Conglomerate and Kayak Shale, also capped by the Lisburne Group. The Kekiktuk Conglomerate everywhere rests unconformably on deformed Middle Devonian and older basement rocks. The original paleogeographic relations between the two different sequences of the Endicott Group remain unclear. In the rest of this chapter, we focus on the stratigraphy and sedimentology of the allochthonous Kanayut and associated rocks of the Endicott Group and examine their internal structural relations.

STRATIGRAPHY

The Kanayut Conglomerate was described by Bowsher and Dutro (1957) in the Shainin Lake area, by Porter (1966) in the Anaktuvuk Pass area, and by Nelson and Grybeck (1980) in the upper Killik River area. Bowsher and Dutro described three nonmarine members for the Kanayut and formally named and measured a type section for the uppermost member, the Stuver Member. The lower member was informally called the lower shale member, and the coarse-grained middle member, the middle conglomerate member.

Porter (1966) recognized a fourth and lowest member, chiefly marine sandstone, which is not present near Shainin Lake. Nelson and Grybeck (1980) distinguished the quartzitic part of the Kanayut and an undifferentiated sandy Kanayut that we interpret from our mapping to be equivalent to Porter's (1966) lower member. In preliminary regional maps of the Philip Smith Mountains area (Brosgé and others, 1979a) and the area between the Killik River and the Trans-Alaska Pipeline (Brosgé and others, 1979b), as well as in preliminary reports on the sedimentology and stratigraphy of the Endicott Group (Nilsen and others, 1980a, b; 1981a, b; 1982), the Kanayut was subdivided into the four previously recognized members (fig. 14.3). In this chapter, however, we correlate the marine basal sandstone member with the Noatak Sandstone, the finer grained shallow-marine sandstone in the western Brooks Range. Therefore, the Kanayut Conglomerate, as used herein, consists of the three original nonmarine fluvial members. More recently Nilsen and Moore (1984) have given formal names and new descriptions for all three members.

The Hunt Fork Shale, defined by Chapman and others (1964) from exposures southwest of the Okokmilaga River, underlies the Noatak Sandstone. It consists of as much as 1,000 m of laminated black phyllite with lesser amounts of siltstone and fine- to medium-grained sandstone and thin beds of fossiliferous ferruginous limestone or calcareous sandstone probably deposited by debris flows. Many thin graded beds of sandstone and siltstone contain incomplete Bouma sequences; they are thin-bedded turbidites, probably deposited in slope or prodelta settings. The true thickness of the Hunt Fork is not known because of tectonically produced thickening and thinning, abundant small-scale faults and folds, low-grade metamorphism, and the absence of undisturbed complete sections. Outcrops of the Hunt Fork are most common in southern outcrops of the allochthonous sequence, where they extend across many mountain crests and structurally form one of the higher thrust plates.

The Noatak Sandstone in the central Brooks Range consists primarily of cross-stratified, fine- to medium-grained quartzose sandstone that is rarely conglomeratic and is interstratified with red, brownish-gray, and black shale (fig. 14.3). The Noatak is discontinuous (see pl. 14.1), interfingering laterally with the fluvial lower shale member of the Kanayut Conglomerate, and has a gradational lower contact with the Hunt Fork Shale. Where recognized, it ranges in thickness from 90 to 560 m and generally contains middle Famennian (late Late Devonian) shelly megafossils. The coarser grained deposits form bundles or cycles, generally as thick as 15 m, that represent various kinds of shallow-shelf and shoreline sand accumulations. Variable paleocurrent directions from the Noatak indicate mean sediment transport toward the southwest (Nilsen and others, 1980b).

The lower shale member of the Kanayut consists of fining-upward fluvial cycles of conglomerate, sandstone, and shale (figs. 14.3, 14.4); it probably was deposited chiefly by meandering streams carrying a coarse-grained bedload. The lower shale member generally thins and fines southward and westward across the outcrop area. Its maximum measured thickness is about 1,150 m in the longitude of the Trans-Alaska Pipeline (149°30′ W.), where the entire formation attains its maximum thickness of about 3,000 m.

The middle conglomerate member, consisting of repetitive fining-upward lens-shaped couplets of conglomerate and sandstone, probably was deposited by braided streams. It is the coarsest and most massive part of the Kanayut, forming near-vertical cliffs. It extends along most of the outcrop belt, thinning out west of the Killik River. The member is coarsest and thickest in the eastern Brooks Range and in the Anaktuvuk Pass-Shainin Lake area, where it is as thick as 550 m, but it generally fines southward and westward.

The Stuver Member consists of fining-upward fluvial cycles of conglomerate, sandstone, and shale (figs. 14.3, 14.4). It is generally similar to the lower shale member and probably was also deposited chiefly by meandering streams carrying a coarse-grained bedload. The Stuver Member is about 270 m thick in its type area near Shainin Lake and thins westward to the Killik River. Eastward, it thickens to 1,300 m near the Trans-Alaska Pipeline.

The Kayak Shale overlies the Kanayut and was named by Bowsher and Dutro (1957) for exposures of black marine shale between the Kanayut Conglomerate and Lisburne Group at Shainin Lake, within the central part of the allochthonous sequence of the En-

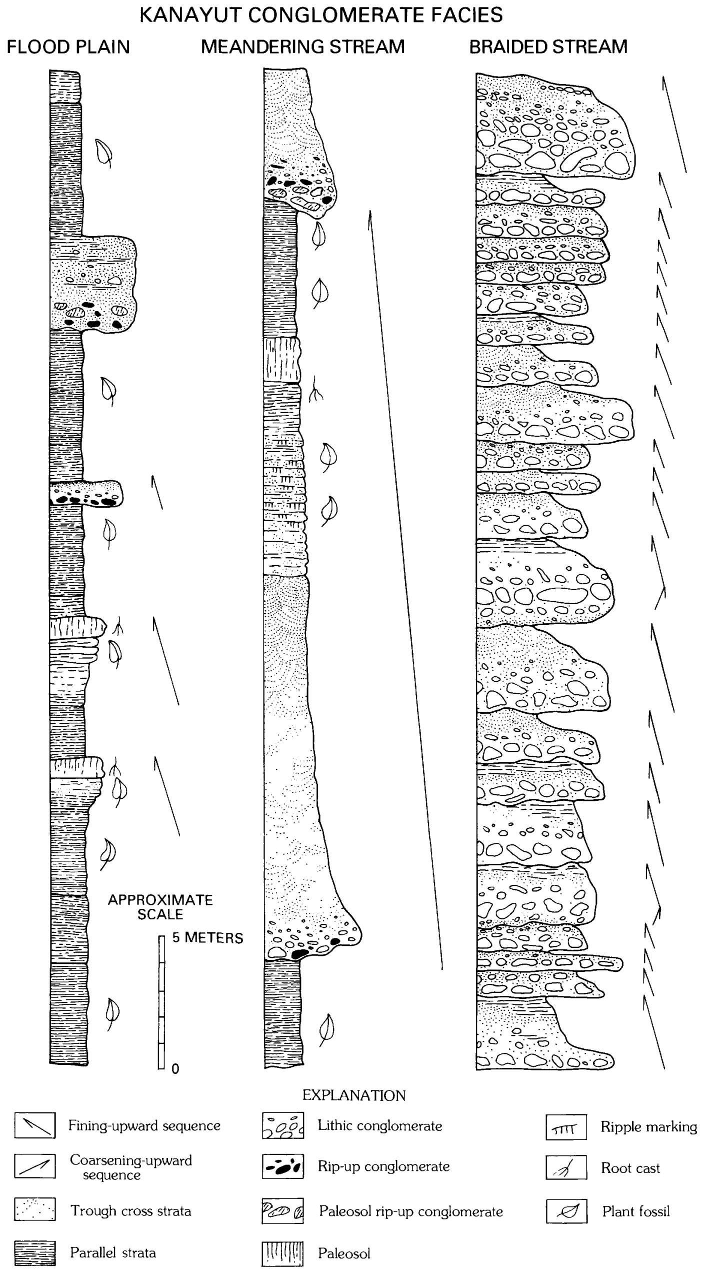

FIGURE 14.4.—Schematic measured sections showing typical facies cycles in braided-stream, meandering-stream, and flood-plain sequences of the Kanayut Conglomerate. Arrows indicate vertical extent of fining-upward and coarsening-upward cycles.

dicott Group. In its type area, the Kayak is about 300 m thick and is subdivided into five members: (1) basal fine-grained sandstone, 40 m thick; (2) lower black shale, 180 m thick; (3) argillaceous limestone, 24 m thick; (4) upper black shale, 40 m thick; and (5) red limestone, 5 m thick. Although the base of the Kayak was originally described as disconformable (Bowsher and Dutro, 1957), it rests conformably on the nonmarine facies of the Stuver Member.

The basal sandstone of the Kayak typically is fine grained, contains abundant marine burrows (*Scolithos*), and is characterized by current ripple marks. In many places the basal sandstone contains herringbone cross-strata, shale drapes, reactivation surfaces, and flaser bedding characteristic of tide-influenced sedimentation. The middle part of the Kayak consists chiefly of black marine shale with some thin-bedded sandstone and siltstone turbidites, probably indicative of prodelta deposition. The three lower members can be traced along the entire north-central Brooks Range, despite marked thickening and thinning of the Kayak as a whole from the effects of thrust faulting. However, in the southern and eastern Brooks Range, the Kayak Shale in the allochthonous sequence of the Endicott Group is generally less than 300 m thick and consists mostly of black shale.

SEDIMENTOLOGY

The Kanayut Conglomerate consists of a variety of fluvial deposits, from thick conglomerate beds containing clasts as large as 23 cm in diameter to thick sequences of red or black shale. In most outcrop areas, particularly of the lower shale member and Stuver Member, the coarse- and fine-grained deposits are organized into fining- and thinning-upward cycles typical of fluvial deposits. Cycle thicknesses range from a few meters to as much as 75 m. Most of the middle conglomerate member consists of coarse conglomerate beds alternating with sandstone beds to form fining-upward couplets as thick as 5 m.

SEDIMENTARY STRUCTURES

Primary sedimentary structures of various types characterize the vertical cycles of fluvial deposits within the Kanayut Conglomerate. These structures can be grouped into those characteristic of braided stream, meandering stream, and floodplain sequences (fig. 14.4). Many sequences are transitional between these end members and are not easily classified by this scheme.

The braided stream sequences most typically contain massive to irregular parallel-stratified conglomerate overlain by parallel-stratified sandstone and conglomeratic sandstone (fig. 14.4). The conglomerate beds have a basal scoured surface that cuts into underlying sandstone generally less than a meter; larger channels are found rarely. The conglomerate most commonly fines upward, although the lowermost 30 cm or more may coarsen upward. The conglomerate is most commonly massive and has well-developed closed framework, upstream-dipping imbrication, and preferred orientation of long axes of clasts parallel to current flow directions. Locally, conglomerate beds contain large-scale tabular cross-strata with amplitudes of more than a meter. The upward transition to sandstone is generally gradual, forming fining-upward couplets ranging from 0.5 to 5 m in thickness. The sandstone typically contains parallel-stratified layers and lenses of conglomerate; more rarely, the sandstone contains trough or tabular cross-strata. Siltstone, shale, and paleosol layers are typically rare or absent within the braided stream deposits.

Most meandering stream sequences are 5-15 m thick and consist of the following strata, in ascending order: a basal channelized massive or crudely parallel-stratified conglomerate with locally abundant shale, mudstone, or paleosol rip-up clasts; medium- to very coarse-grained sandstone characterized by abundant large- to medium-scale trough cross-strata; fine- to medium-grained sandstone characterized by abundant medium- to small-scale trough cross-strata; thin-bedded siltstone to fine-grained sandstone characterized by abundant current-ripple marks; paleosols marked by reddish, orange, yellow, and brown colors; shale and siltstone (fig. 14.4). The sequences are characterized by the erosional truncation of underlying shale and paleosols by thick beds of conglomerate and sandstone and by the upward fining of grain size, thinning of bedding thickness, and decrease in amplitude of cross-strata.

The flood-plain sequences, from less than 1 to as much as 55 m thick, consist of thick accumulations of shale and siltstone with some sandstone interbeds and paleosol horizons (fig. 14.4). The fine-grained units most commonly are black and contain abundant organic matter, chiefly plant fragments. In some sequences, brown, maroon, and yellow colors predominate, recording various stages of oxidation of iron minerals and original exposure to the atmosphere. In some floodplain sequences, black, unoxidized fine-grained units alternate with multicolored, oxidized units. Brightly colored oxidized shale is most abundant in the lower shale member west of the Killik River and least abundant in the Stuver Member east of the Anaktuvuk. Thin, coarsening-upward cycles 1-2 m thick are common locally; the upper parts of these cycles consist of ripple-marked siltstone or fine-grained sandstone capped by a paleosol. We infer that these cycles were distal parts of levees that prograded over the floodplain. More irregular cycles containing coarser clastic detritus may represent crevasse-splay deposits.

Abundant sedimentary features include: trough and tabular cross-strata, current ripple marks, clast imbrication, clast long-axis orientation, pebble trains, aligned plant fragments, flute marks, channels, primary current lineation, slump folds, and faults; in addition, oscillation ripple markings are found in the upward transition to the marine Kayak Shale. Massive to parallel-stratified units are most characteristic of the braided stream deposits; trough-cross-stratified units are most characteristic of the meandering stream deposits; and plant-bearing shale and siltstone with thin ripple-marked fine-grained sandstone are most characteristic of floodplain sequences.

PALEOCURRENTS

During the 1978-80 field seasons, 605 paleocurrent measurements were collected from 88 separate locations in the fluvial lower shale member, middle conglomerate member, and Stuver Member of the Kanayut Conglomerate (fig. 14.5). Results from the 1978 field season were previously plotted by Nilsen and others (1980b) and later compiled and presented in map form with data from the 1979 season (Nilsen and others, 1980a).

Sedimentary features measured include: trough cross-strata (249 measurements), clast imbrication and long-axis orientations (170 measurements), tabular cross-strata (88 measurements), primary current lineations (60 measurements), current ripple markings (16 measurements), flute marks (8 measurements), pebble trains and erosional scours (4 measurements each), aligned plant fragments and oscillation ripple markings (2 measurements each), and channel margin orientation and fluid escape folds (1 measurement each). Because unidirectional features show a dominantly southwestward direction of sediment transport, bidirectional indicators such as primary current lineation are preferentially assigned a similar transport direction. This results in an azimuthal vector mean and associated standard deviation of 243±45° for all measurements from the Kanayut. Although vector means and standard deviations range from 172±38° to 303±28° for individual locations having more than four measurements, the overall southwesterly transport direction is consistent among members: 243±47° for the lower shale member (209 measurements), 245±40° for the middle conglomerate member (247 measurements), and 234±61° for the Stuver Member (128 measurements); 31 paleocurrent determinations were not assigned to a particular member. These data indicate that the fluvial sediment transport direction was predominantly toward the southwest throughout the entire time of deposition of the Kanayut Conglomerate. Donovan and Tailleur (1975) previously determined southward directions of transport for the Kanayut.

MAXIMUM CLAST SIZE

The maximum clast size of conglomerate in the Kanayut Conglomerate was determined in the field by measuring the longest exposed dimensions of clasts (fig. 14.6). With the exception of ripup clasts,

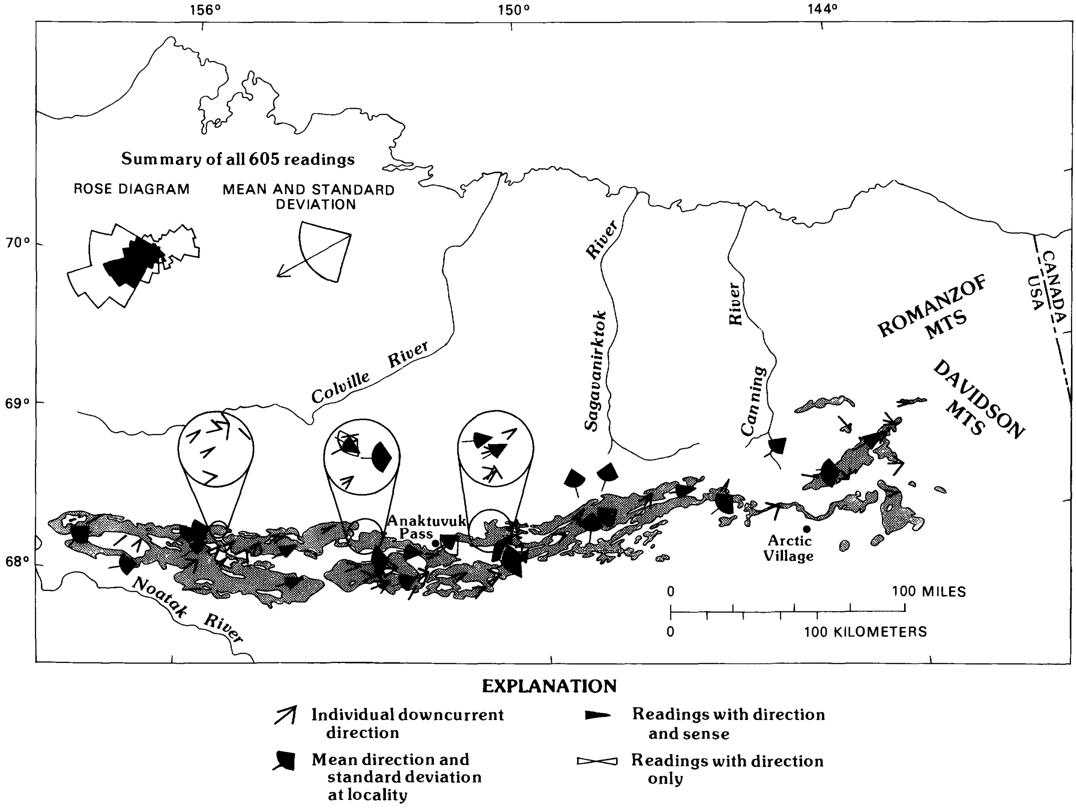

FIGURE 14.5.—Paleocurrent map of the Kanayut Conglomerate based on measurements in 1978, 1979, and 1980 field seasons.

the largest clast was measured regardless of lithology. These measurements, taken routinely at all field stops within the Kanayut, were systematically recorded for each conglomerate bed in the measured sections. The results of the measurements for all observed outcrops are shown in figure 14.6. Donovan and Tailleur (1975) previously demonstrated that the maximum size of quartz clasts within the Endicott Group systematically decreases southward.

The largest clasts in the Kanayut Conglomerate are about 23 cm in diameter and are concentrated in the Shainin Lake-Anaktuvuk Pass area of the north-central Brooks Range. Clast size decreases regularly west and south of this area to a maximum of 2 cm at the west end of the study area in the region north of the Noatak River; conglomeratic

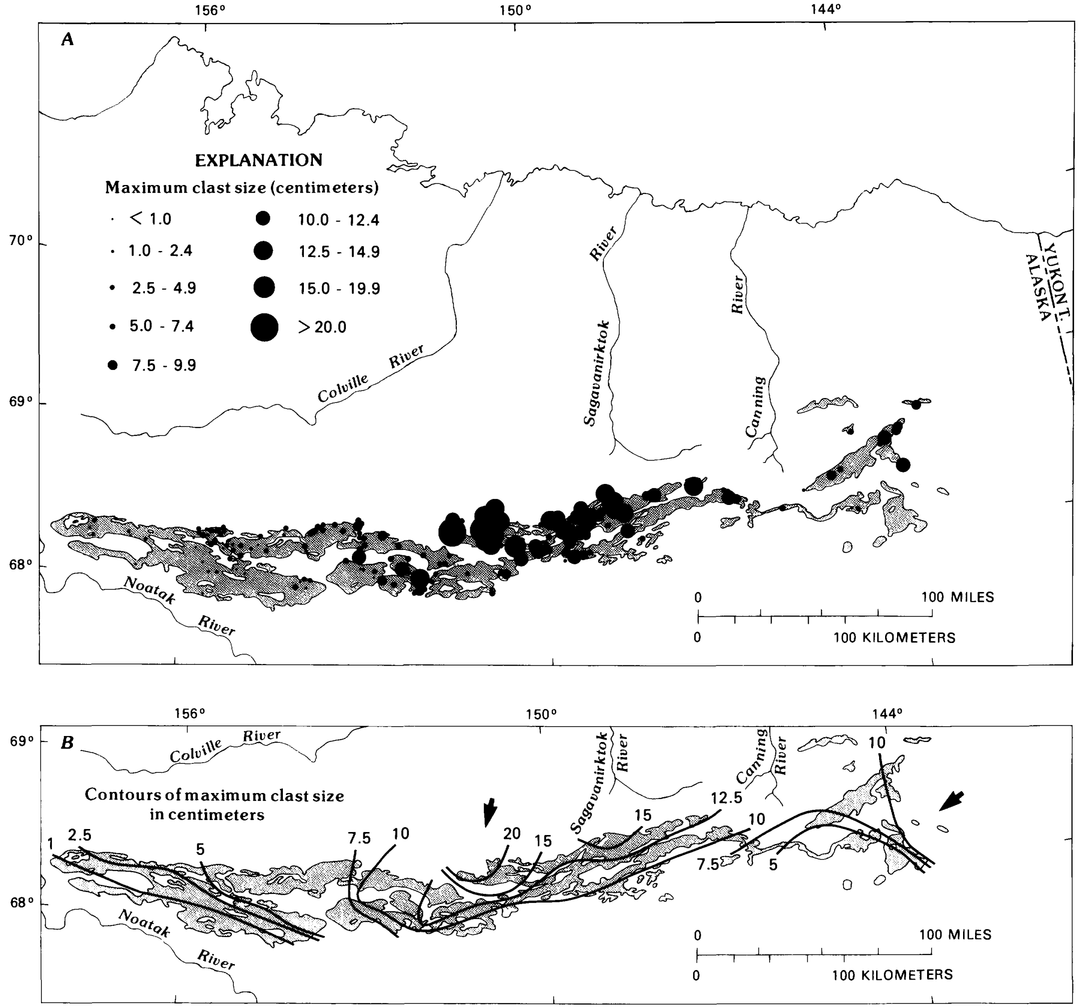

FIGURE 14.6.—Maximum clast size in the Kanayut Conglomerate (outcrop area shaded). *A*, Distribution of measurements. *B*, Contour map. Arrows indicate chief sites of sediment input.

strata are rare farther west. Clast size also decreases southward and southeastward from the Shainin Lake-Anaktuvuk Pass area as far east as the longitude of the Canning River in the eastern Brooks Range, where the largest clasts are 5 cm in diameter. The distribution of declining clast sizes around the Shainin Lake-Anaktuvuk Pass region suggests that it may mark the entry site of a major trunk system into the Kanayut depositional basin.

A second major trunk system may be indicated by the clast size data in the northeastern outcrops of the Kanayut. Maximum clast size here decreases from about 10 cm in the northeasternmost outcrops to less than 5 cm in the Arctic Village area. This distribution of clast sizes indicates that sediment dispersal in the eastern part of the Kanayut was from northeast to southwest.

We previously suggested, on the basis of preliminary compilations of such data, that maximum clast size gradually decreased toward the southwest from the eastern Brooks Range (Nilsen and others, 1980b, 1981a, b). This earlier suggestion permitted definition of what appeared to be a simple depositional system fed by a single major fluvial system draining a source area to the northeast (Nilsen and others, 1980b). However, the completed map of maximum clast size (fig. 14.6) indicates that the dispersal of sediment was more complex, the coarsest clasts being in the central part of the east-trending outcrop belt. On the basis of presently available data, we now conclude that the bulk of the Kanayut detritus was transported to the depositional basin by two major drainage systems separated by at least 250 km (see fig. 14.10). Although additional data may delineate more dispersal systems, any such were probably smaller and superimposed on the two dominant regional systems described above.

CLAST SHAPE

Roundness and sphericity of 50 randomly selected clasts each of black chert, gray chert, vein quartz, quartzite, and quartzite conglomerate were determined at one field locality within the middle conglomerate member of the Kanayut Conglomerate about 50 km east of Anaktuvuk Pass. Values were estimated using the visual comparative charts of Krumbein and Sloss (1963); because clasts could not be removed from the matrix, circularity was actually determined rather than sphericity. In general, the Kanayut clasts are moderately to well rounded and have a moderate to high circularity when viewed on bedding surfaces.

Chert clasts are the least well rounded, vein quartz clasts are intermediate, and quartzite and quartzite conglomerate clasts are most highly rounded. These characteristics probably reflect the greater tendency of chert to chip and splinter during transport, whereas the more durable quartzite and quarzite conglomerate clasts gradually round without major breakage. This relation is also indicated by the relative clast sizes; quartzite and quartzite conglomerate clasts are generally both the largest and best rounded, whereas chert clasts are the smallest and least rounded. All clast types have similar values of circularity; quartzite and quartzite conglomerate clasts show the highest values and vein quartz the lowest values.

COMPOSITION AND PETROGRAPHY

The Kanayut Conglomerate was recognized by a number of workers to consist predominantly of chert and vein quartz clasts (Dutro, 1953; Bowsher and Dutro, 1957; Tailleur and others, 1967; Donovan and Tailleur, 1975), but no systematic compositional study of the Kanayut was done previously. In order to determine the conglomerate distribution and provenance for the Kanayut, we made 56 pebble counts on fluvial conglomerate at 40 locations scattered throughout the eastern and central Brooks Range. In addition, about 30 thin sections of sandstone samples from the Anaktuvuk Pass area were studied.

Pebble counts of 100 randomly selected clasts larger than 1 cm in diameter show that the Kanayut is compositionally very mature (fig. 14.7). Quartzose clasts (chert + vein quartz + quartzite) range from 83 to 100 percent and average greater than 99 percent in all the Kanayut pebble counts. Other clasts, including argillite and carbonate, are only locally present. A ternary diagram of clast types with chert, vein quartz, and quartzite as poles shows that the pebble counts from the Kanayut Conglomerate are displaced toward the chert pole and away from the quartzite pole (fig. 14.7). Chert clasts range from 34 to 100 percent and average 82 percent. Vein quartz averages 15 percent but ranges up to 61 percent. Quartzite clasts are a minor but persistent constituent (average 3 percent) that locally comprises as much as 21 percent of the clasts.

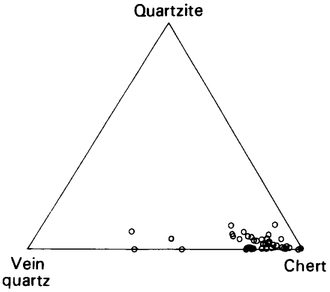

FIGURE 14.7.—Proportions of major resistant clast types in fluvial conglomerate of the Kanayut Conglomerate; data from pebble counts.

Sandstone is composed mainly of chert (10-50 percent) and quartz (30-75 percent), with subordinate amounts of argillite (0-20 percent) and of granite, gneiss, and quartzite rock fragments (3-20 percent). Feldspar is generally absent or is present in only small quantities. Minor constituents include metamorphic rock fragments of quartz-mica tectonite, biotite, muscovite, tourmaline, and rare volcanic rock fragments. Opaque iron minerals are also present in minor amounts.

The sandstone framework is tightly compacted, and many samples have a fabric defined by parallel orientation of elongate grains. Most quartz grains are fractured and polygonized, indicating extensive postdepositional deformation.

The cement is dominated by overgrowths of silica on quartz grains and by generally less abundant, but relatively coarse, phyllosilicates that have grown interstitially. Other cements include: local authigenic hematite as poikilotopic grains and lenticular concretions as much as 1 cm in length; calcite that has partly replaced detrital grains; and silica in several samples. The combination of good sorting and little primary matrix shows that the sandstone is texturally mature.

Our petrologic data suggest that there is little variation in conglomerate or sandstone composition by either stratigraphic or geographic position. This generally constant detrital composition indicates that the very extensive Kanayut depositional system was probably derived from a single major source terrane.

The high compositional maturity of the Kanayut Conglomerate could be the result of a provenance rich in chert and quartz or of a history of intense weathering and (or) abrasion. The predominance of chert, quartz, quartzite, and argillite clasts and grains indicates that the provenance of these Devonian and Mississippian(?) strata was largely a sedimentary terrane; the good sorting and moderate rounding of sand grains and the near-absence of feldspar in all units support this interpretation. The presence of rock fragments of phyllite, gneiss, and quartz-mica tectonite in the sandstones indicates that the sedimentary provenance may have been locally metamorphosed. Scarce volcanic rock fragments and locally abundant carbonate clasts imply that these rock types were also exposed in the source area, at least in small quantities. However, if the compositional maturity of the detritus results from chemical or physical abrasion, the present composition of the Kanayut may not be fully indicative of its provenance.

DEPOSITIONAL MODEL

Stratigraphically underlying the fluvial part of the Kanayut Conglomerate are, in ascending order, marine shale and siltstone probably deposited in deep-marine conditions; marine thin-bedded sandstone and siltstone turbidites probably deposited in a prodelta setting; marine sandstone characterized by abundant parallel stratification and low-angle cross-stratification probably deposited in a shelf setting; and bodies of cross-stratified marine sandstone and conglomerate that were probably deposited as offshore bars, deltaic channel-mouth bars, and shoreline accumulations. These underlying deposits include most of the Hunt Fork Shale and Noatak Sandstone; they gradually increase upward in coarseness and bed thickness, indicating a genetic relation to the fluvial sequence. The contact between the Noatak Sandstone and the fluvial lower shale member of the Kanayut Conglomerate is generally gradational, reflecting interfingering of marine and nonmarine deposits. In the central Brooks Range, a prominent marine incursion eastward over the westward-progressing fluvial part of the delta is recorded in a number of measured stratigraphic sections of the lower shale member (Nilsen and others, 1982).

The lower shale member consists predominantly of fining-upward cycles characteristic of meandering stream deposits. The coarse basal facies of each cycle probably consists of channel and lower point-bar deposits incised into underlying floodplain deposits. These deposits represent fill of the channel by transverse and longitudinal bars that migrate downchannel as the stream channel gradually shifts and migrates laterally by the meander process. Inasmuch as the coarse basal facies of each cycle is a preserved record of filling of an individual river channel, cycle thicknesses indicate that stream depths were on the order of 5-10 m in the central and eastern Brooks Range. The overlying fine-grained sediments were probably deposited on the upper surfaces of point bars, as prograding levees, in lakes, and as crevasse splays. These floodplain sequences are generally thick and laterally continuous, especially in the lower part of the lower shale member, indicating that the floodplain area was extensive. In the upper part of the lower shale member, in the transition to the braided stream deposits of the middle conglomerate member, conglomerate generally becomes more abundant, coarser, and thicker and the fining-upward cycles more complex.

The middle conglomerate member consists of fining-upward, lens-shaped couplets of conglomerate and sandstone that are thought to represent deposition of various kinds of bars within the braided stream complex. Sandstone and conglomerate were deposited on the flanks, tops, and downstream edges of gravel bars as thin but wide lens-shaped bodies characterized by parallel stratification, low-angle trough cross-stratification, or very low angle tabular cross-stratification. The sediment probably accumulated during the waning stages of floods and on the protected downstream margins of bars. The thickest parts of the middle conglomerate member, located in the northeastern Brooks Range and in the Shainin Lake-Anaktuvuk Pass areas, contain the coarsest clasts (as large as 23 cm), indicating that these are the most proximal deposits of the Kanayut.

The Stuver Member of the Kanayut Conglomerate is similar to the lower shale member in most respects and has a gradational contact with the middle conglomerate member. It is as thick as 1,300 m and consists of repetitive fining-upward meandering-stream cycles and locally extensive floodplain deposits. In the southern and western Brooks Range, however, the Stuver Member thins to as little as 50 m and consists of smaller and laterally less continuous cycles, probably reflecting deposition by smaller streams. The member typically grades abruptly upward into the thin-bedded basal sandstone of the Kayak Shale in the central and eastern Brooks Range.

The typically fine-grained basal sandstone of the Kayak is characterized by current ripple markings, herringbone cross-strata, shale drapes, reactivation surfaces, and flaser bedding characteristic of tide-influenced sedimentation. The middle part of the Kayak consists chiefly of black marine shale with some thin-bedded sandstone and siltstone turbidites probably indicative of prodelta deposition. The Endicott Group is capped by extensive platform carbonate deposits of the Mississippian and Pennsylvanian Lisburne Group.

The Kanayut Conglomerate thus records a major Late Devonian and Early Mississippian(?), fluvial-dominated, coarse-grained delta that prograded over marine deposits and later was covered by a transgressing sea. Maximum clast sizes, paleocurrents, and stratigraphic analyses indicate that the delta was fed by at least two major river systems, the first feeding sediment southwestward into the present area of the eastern Brooks Range, the second into the central Brooks Range near Anaktuvuk Pass (fig. 14.10). At its greatest extent, fluvial deposition occurred over an east-west distance of at least 950 km stretching from near the present course of the Sheenjek River to near the Chukchi Sea. The original extent of fluvial deposition in the present north-south direction is not known because of extensive crustal shortening, but it probably exceeded 100 km (see below). The extent of associated marine deposition is not now ascertainable, but it must have been considerably larger. The deltaic complex therefore must record a major mountain-building event, with a large and nearby uplifted source terrane required to supply the large volume and coarse debris characteristic of the Kanayut delta. The pre-Devonian sequences exposed in the cores of several anticlinoria in the northeastern Brooks Range (Reiser and others, 1971, 1980) are possible source areas for some of the Kanayut clasts, but the allochthonous nature and mature composition of the Kanayut prevents a thorough understanding of its provenance.

STRUCTURE

The north-central Brooks Range consists of a series of folded thrust plates with relative displacements of at least 10-30 km. The thrust faults can be divided into two groups: those that separate the allochthonous sequence of the Endicott Group from the autochthonous Endicott sequence and those that are contained wholly within the allochthonous part of the Endicott (fig. 14.8).

THRUST FAULTS SEPARATING THE ALLOCHTHONOUS AND AUTOCHTHONOUS SEQUENCES OF THE ENDICOTT GROUP

The Endicott Group was divided by Mull and Tailleur (1977) and Nilsen (1981) into an autochthonous sequence consisting of the Kekiktuk Conglomerate and Kayak Shale and an allochthonous sequence consisting of the Hunt Fork Shale, Noatak Sandstone, Kanayut Conglomerate, and Kayak Shale. The two sequences have not been found in depositional contact, nor have they been traced laterally into one another; where the sequences are juxtaposed, they are everywhere in fault contact.

The autochthonous sequence of the Endicott Group crops out to the north, east, and south of the allochthonous sequence. It forms a belt of outcrops in the northeastern Brooks Range that extends eastward across the Canadian border and wraps around the east end of the allochthonous sequence. It also forms a narrow discontinuous belt of outcrops along the southwest edge of the allochthonous sequence (Mayfield and Tailleur, 1978; Nelson and Grybeck, 1980). In the western part of the south-central Brooks Range, the two sequences are separated by north-dipping thrust faults for almost 400 km (fig. 14.8). In the northeastern Brooks Range, the autochthonous sequence is separated from part of the allochthonous sequence by south-dipping thrust faults. However, the contact relation between the two sequences is unclear in the southeastern Brooks Range, because the two sequences cannot be discriminated with any certainty in critical areas. The contact relation is also unclear along the northern margin of the central Brooks Range because the allochthonous sequence has been thrust over Mesozoic rocks, and the location of the autochthonous sequence can only be inferred in the subsurface.

Two different structural interpretations of the physical relations of the allochthonous and autochthonous sequences in the central Brooks Range are illustrated in cross sections in figure 14.9. The faults that dip north from the southern Brooks Range are shown in figure 14.9, upper diagram, to extend beneath the north-central Brooks Range as a sole fault. All of the allochthonous Endicott Group is above this fault, and the autochthonous Endicott both to the north and the south is beneath it. Therefore, Mull and others (1976) inferred that the autochthonous Endicott Group and the polydeformed lower Paleozoic basement upon which it rests depositionally are continuous at depth from the Arctic coast to the southern Brooks Range and that the allochthonous Endicott Group at the surface is part of a great klippe, thrust at least 80 km northward in Early Cretaceous time from an original position somewhere south of the Brooks Range. Uplift of the southern Brooks Range in Late Cretaceous time caused internal foreshortening of the klippe and produced the northward dips along its present

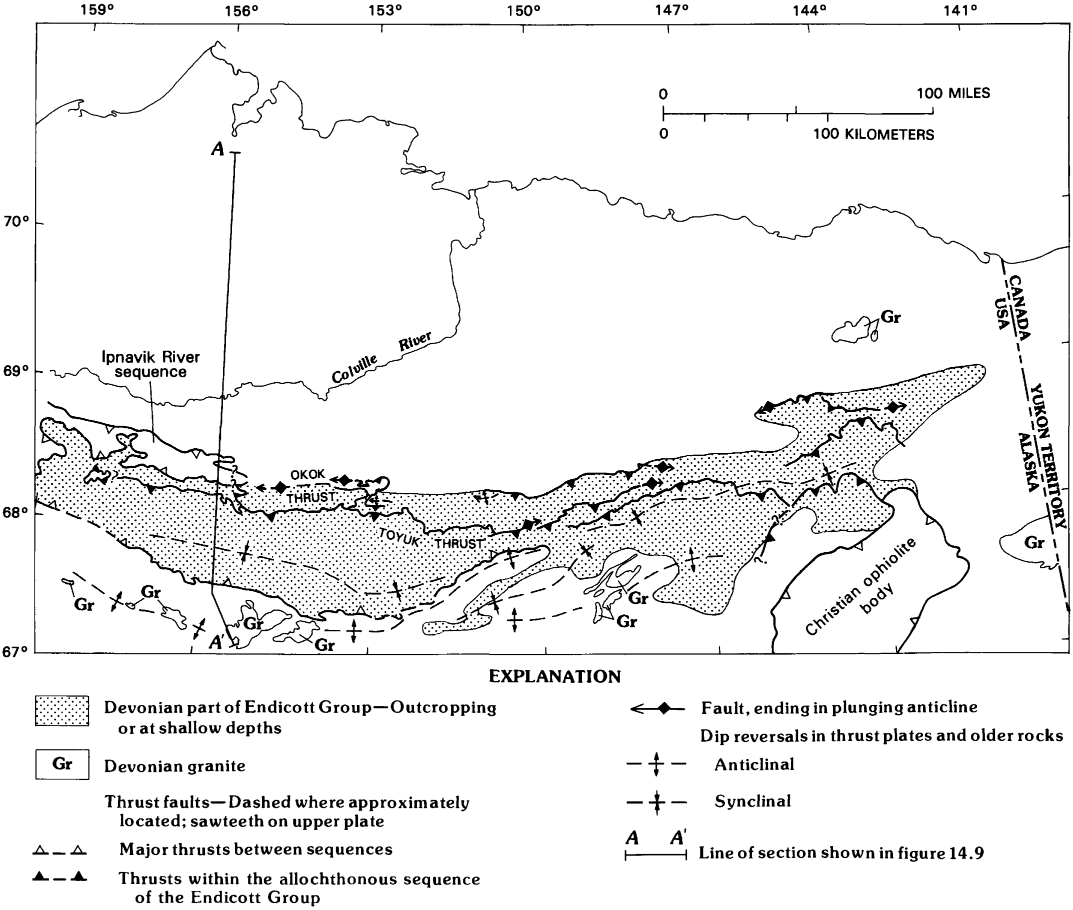

FIGURE 14.8.—Major structures affecting the Endicott Group. The Christian ophiolite body and Ipnavik River sequence are allochthons of Mississippian and younger rocks. Area labeled "Ipnavik River sequence" includes small areas of other equivalent allochthonous sequences of Ellersieck and others (1979). Similar smaller bodies in western part of map area are not shown.

south edge. According to this interpretation, both the Early and the Late Cretaceous structures in the Endicott Group verged northward.

An alternative interpretation, shown in figure 14.9, lower diagram, is based on the assumption that the allochthonous Endicott was deposited in approximately its present location in a basin that was bounded on the north by highlands along the present Arctic Coast and on the south by an orogenic belt of Middle Devonian granites in the southern Brooks Range, as described by Dillon and others (1980). According to this interpretation, the allochthonous Endicott and the

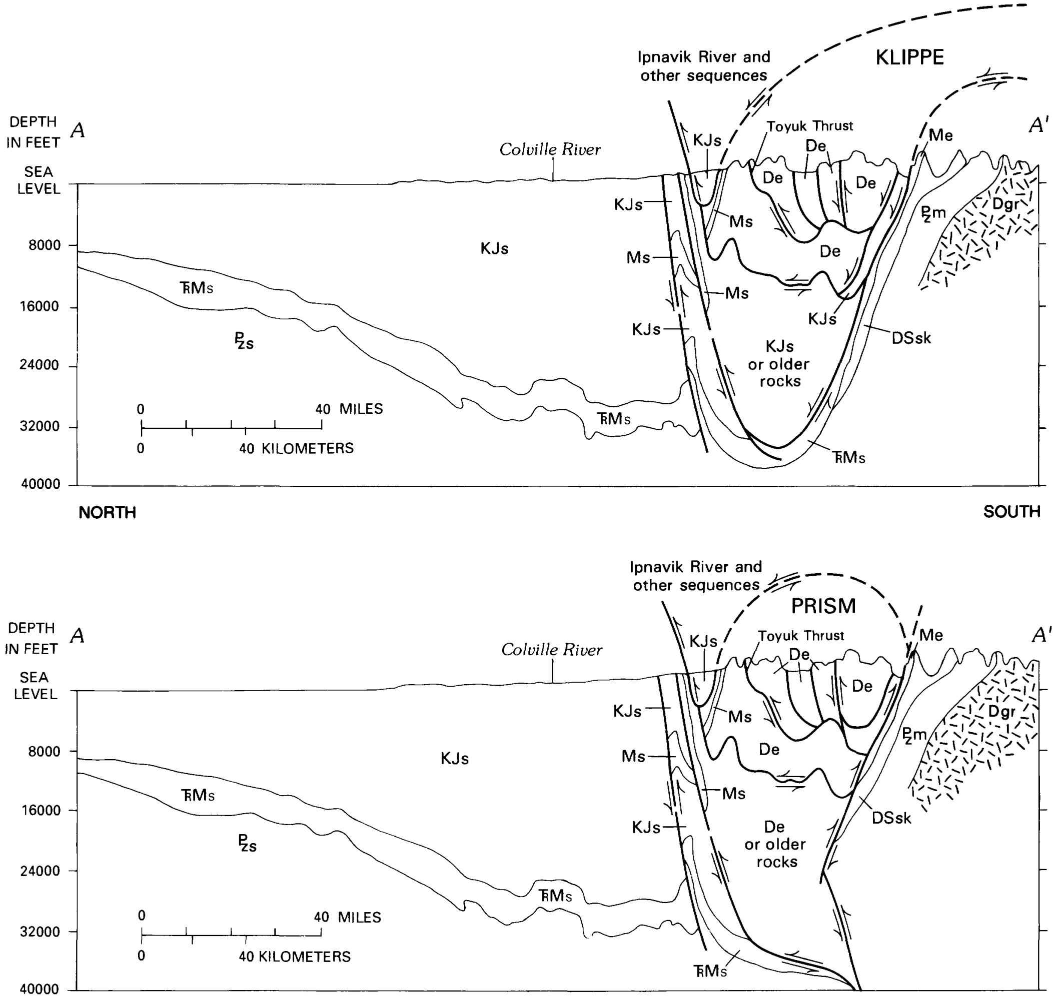

FIGURE 14.9.—Cross sections of the north-central Brooks Range showing interpretations of the structure of the Devonian part of the Endicott Group as a klippe (upper diagram) and as a prism underthrust from both sides (lower diagram). KJs, Cretaceous and Jurassic sedimentary rocks; TR Ms, Triassic, Permian, Pennsylvanian, and Mississippian sedimentary rocks, including the Mississippian part of the Endicott Group; Ms, Mississippian sedimentary rocks; Me, Mississippian part of the Endicott Group; De, Devonian part of the Endicott Group and Beaucoup Formation, undivided; DSsk, Devonian and Silurian Skajit Limestone; Pzs, lower Paleozoic sedimentary rocks; Pzm, Paleozoic metamorphic rocks; Dgr, Devonian granite (Dillon and others, 1980). Location of line of section is shown on figure 14.8.

younger rocks in associated thrust plates were compressed in Early Cretaceous time by underthrusting of the basement and its autochthonous cover, both from the north and from the south, at the same time that the basement itself was foreshortened by about 200 km (at the longitude of figure 14.9) by a deeper thrust fault. If this is the case, structures in the northern part of the allochthonous Endicott initially verged northward while those in the southern part verged southward. Additional internal foreshortening along structures that verge northward throughout the allochthonous Endicott would have resulted from the same Late Cretaceous event described in the first interpretation. In both interpretations, the driving force for Early Cretaceous thrusting is assumed to be the convergence of a northern continental plate with a southern oceanic plate along the south edge of the Brooks Range.

THRUST FAULTS WITHIN THE ALLOCHTHONOUS SEQUENCE

The northward-dipping thrust plates along the south edge of the allochthonous sequence mostly involve the Hunt Fork Shale and the underlying Beaucoup Formation and Skajit Limestone. The Kanayut occurs farther north in a series of south-dipping thrust plates. Two major south-dipping faults, the Toyuk thrust and the Okok thrust, extend in a westerly direction for more than 300 km, have measurable displacements of as much as 30 km, and generally displace the Hunt Fork Shale and Kanayut over the Kanayut and the Lisburne Group. Smaller thrusts north of the Toyuk thrust are only 100-150 km long, have measurable displacements of 10-20 km, and die out laterally as overturned anticlines. These thrusts generally place the Kanayut over the Lisburne Group or younger rocks.

The Toyuk and Okok thrusts juxtapose different facies of the Kanayut. The area north of the Toyuk thrust is divided by the Okok thrust into eastern and western segments. The eastern segment contains the type section of the Kanayut, and all of the members are well developed there. In the western segment, the middle conglomerate member is thin and the lower shale member is especially prominent. The Kanayut in both segments typically contains much red shale, particularly in the lower shale member, and the Stuver Member is laterally persistent for more than 300 km. The Noatak Sandstone is usually present where the base of the Kanayut is exposed, but such exposures are rare.

South of the Toyuk thrust, the Stuver Member is generally absent or very thin, and the lower shale member contains only a small amount of red shale and is not distinctive except in the central part of the area. In this thrust plate, the Kanayut consists mainly of the middle conglomerate member. In the western part of the thrust plate this member contains little or no conglomerate. The Kanayut generally rests on the Noatak Sandstone, which is widespread in this thrust plate.

The Kanayut outcrop belt is about 50 km wide through most of the central Brooks Range. Restoration of the foreshortening of the belt caused by the northward verging folds and faults suggests that originally it was at least 30 km wider near the west end of the study area at longitude 156° W. and about 20 km wider in the eastern part of the central Brooks Range at longitude 148° W. Most of the difference in the calculated foreshortening from east to west over a distance of 350 km is due to the displacement on the Toyuk thrust, which increases from about 3 km in the east to more than 20 km in the west. The Toyuk thrust plate migrates northward across the other thrust plates of Kanayut so that it includes most of the Kanayut at the west end of the outcrop belt. As the Kanayut in the Toyuk thrust plate is generally finer grained and more distal than that to the north, the increased displacement on the Toyuk thrust from east to west may exaggerate the westward component of facies changes in the Kanayut at the expense of the southern component. This may account for the strong northwestward trend of the clast size contours in the western part of the study area (fig. 14.6) as compared with the southwestward trend in the eastern part.

SUMMARY AND CONCLUSIONS

The Upper Devonian and Lower Mississippian(?) Kanayut Conglomerate crops out in the northern Brooks Range for almost 1,000 km in a belt that was probably 80-100 km wide before folding and faulting. It was deposited mainly by southwest-flowing meandering and braided streams as a large, river-dominated delta (fig. 14.10). The fluvial part of the deltaic complex is as thick as 3,000 m in the central Brooks Range. The coarseness and thickness of the fluvial deposits diminish gradually westward and southward from the central Brooks Range to the western Brooks Range.

The original site of deposition of the Kanayut is uncertain because the Kanayut and associated Upper Devonian clastic rocks are thought to be allochthonous with respect to a surrounding terrane in which Mississippian rocks rest directly on deformed pre-Upper Devonian basement rocks. Thus, the Kanayut may be part of a large klippe transported from a depositional site south of the Brooks Range, rather than part of a sedimentary prism that was deformed in place.

The Kanayut delta was deposited at approximately the same time as similar, but generally finer grained fluvial strata were deposited in the Innuitian foldbelt of the Canadian Arctic Islands, the Caledonian orogen (Old Red Sandstone), and the northern Appalachian orogen (Catskill Formation). However, the presumably allochthonous nature of the outcrops and difficulties in matching the Kanayut with Devonian deposits elsewhere in Alaska and surrounding areas leave the original paleogeography unclear (Nilsen, 1981). The position of the Brooks Range terrane relative to the pre-Mississippian subsurface basement of most of the NPRA and to the Cordilleran, Franklinian, Caledonian, and other circum-Arctic orogens remains speculative, preventing full understanding of the tectonic framework of deposition of the Kanayut Conglomerate.

REFERENCES CITED

Bowsher, A.L., and Dutro, J.T., Jr., 1957, The Paleozoic section in the Shainin Lake area, central Brooks Range, Alaska: U.S. Geological Survey Professional Paper 303-A, p. 1-39.

Brosgé, W.P., and Reiser, H.N., 1962, Preliminary geologic map of the Christian quadrangle, Alaska: U.S. Geological Survey open-file report, scale 1:250,000.

—— 1964, Geologic map and section of the Chandalar quadrangle, Alaska: U.S. Geological Survey Miscellaneous Geological Investigations Map I-375, scale 1:250,000.

—— 1965, Preliminary geologic map of the Arctic quadrangle, Alaska: U.S. Geological Survey open-file report, scale 1:250,000.

—— 1969, Preliminary geologic map of Coleen quadrangle, Alaska: U.S. Geological Survey open-file report, scale 1:250,000.

—— 1971, Preliminary bedrock geologic map, Wiseman and eastern Survey Pass quadrangles, Alaska: U.S. Geological Survey open-file report, 2 sheets, scale 1:250,000.

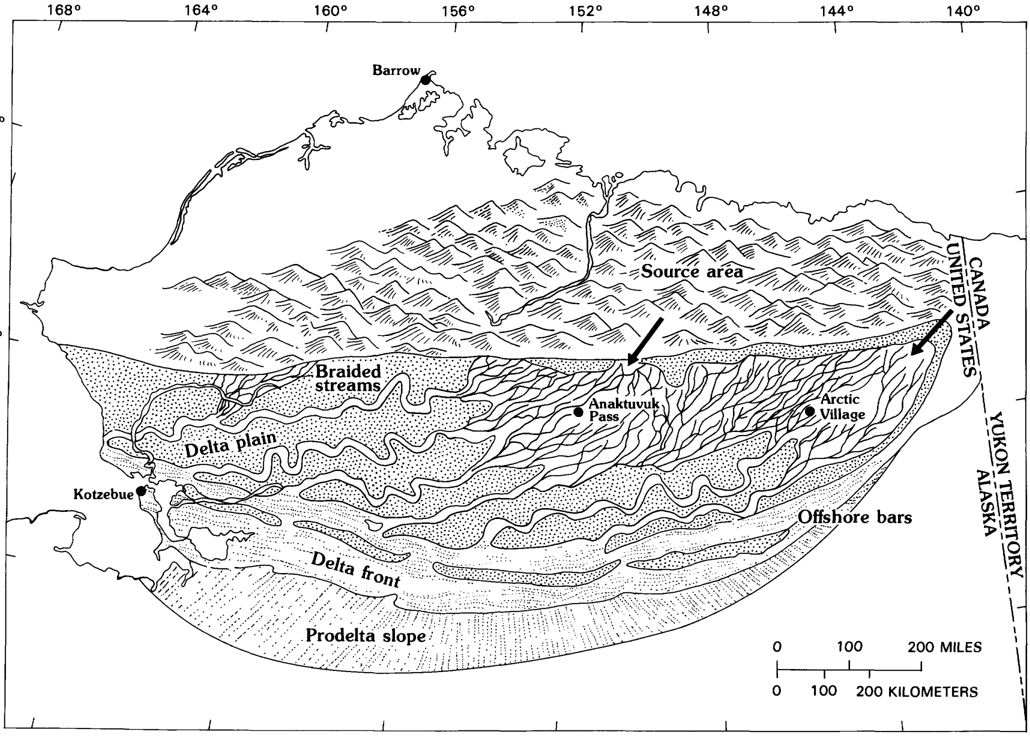

FIGURE 14.10.—Paleogeographic diagram showing approximate extent of the Kanayut delta during deposition of the middle conglomerate member of the Kanayut Conglomerate. Delta is shown without palinspastic restoration of presently allochthonous outcrops; line marking northern edge of sedimentary basin is present northern edge of allochthons. Arrows indicate chief sites of sediment input to the delta.

Brosgé, W.P., Reiser, H.N., Dutro, J.T., Jr., and Detterman, R.L., 1976, Reconnaissance geologic map of the Table Mountain quadrangle, Alaska: U.S. Geological Survey Open-File Report 76-546, 2 sheets, scale 1:200,000.

——— 1979a, Bedrock geologic map of the Philip Smith Mountains quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-879-B, scale 1:250,000.

Brosgé, W.P., Reiser, H.N., Dutro, J.T., Jr., and Nilsen, T.H., 1979b, Geologic map of Devonian rocks in parts of the Chandler Lake and Killik River quadrangles, Alaska: U.S. Geological Survey Open-File Report 79-1224, scale 1:200,000.

Brosgé, W.P., and Tailleur, I.L., 1971, Northern Alaska petroleum province, *in* Future petroleum provinces of the United States—their geology and potential: American Association of Petroleum Geologists Memoir 15, v. 1, p. 68-99.

Chapman, R.M., Detterman, R.L., and Mangus, M.D., 1964, Geology of the Killik-Etivluk Rivers region, Alaska: U.S. Geological Survey Professional Paper 303-F, p. 325-407.

Collins, F.R., 1958, Test wells, Topagoruk area, Alaska: U.S. Geological Survey Professional Paper 305-D, p. 265-316.

Dillon, J.T., Pessel, G.H., Chen, J.H., and Veach, N.C., 1980, Middle Paleozoic magmatism and orogenesis in the Brooks Range, Alaska: Geology, v. 8, p. 338-343.

Donovan, T.J., and Tailleur, I.L., 1975, Map showing paleocurrent and clast-size data from the Devonian-Mississippian Endicott Group, northern Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-692, scale 1:7,500,000.

Dutro, J.T., Jr., 1953, Stratigraphy and paleontology of the Noatak and associated formations, Brooks Range, Alaska: New Haven, Conn., Yale University, Ph.D. dissertation.

——— 1981, Geology of Alaska bordering the Arctic Ocean, *in* Stehli, F.G., Nairn, A.E.M., and Churkin, Michael, Jr., eds., Ocean basins and margins, v. 5, The Arctic Ocean: New York, Plenum, p. 21-26.

Dutro, J.T., Jr., Brosgé, W.P., Detterman, R.L., and Reiser, H.N., 1979, Beaucoup Formation, a new Upper Devonian stratigraphic unit in the central Brooks Range, northern Alaska, *in* Sohl, N.F., and Wright, W.B., eds., Changes in stratigraphic nomenclature by the U.S. Geological Survey, 1978: U.S. Geological Survey Bulletin 1482-A, p. A63-A69.

Ellersieck, Inyo, Mayfield, C.F., Tailleur, I.L., and Curtis, S.M., 1979, Thrust sequences in the Misheguk Mountain quadrangle, Brooks Range, Alaska, *in* Johnson, K.M., and Williams, J.R., ed., The United States Geological Survey in Alaska; accomplishments during 1978: U.S. Geological Survey Circular 804-B, p. B8-B9.

Krumbein, W.C., and Sloss, L.L., 1963, Stratigraphy and sedimentation: San Francisco, Freeman and Co., 660 p.

Mayfield, C.F., and Tailleur, I.L., 1978, Bedrock geologic map of the Ambler River quandrangle, Alaska: U.S. Geological Survey Open-File Report 78-120-A, scale 1:250,000.

Mayfield, C.F., Tailleur, I.L., Mull, C.G., and Sable, E.G., 1978, Bedrock geologic map of the south half of National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 78-70-B, 2 sheets, scale 1:500,000.

Mull, C.G., and Mangus, M.D., 1972, Itkilyariak Formation: New Mississippian formation of Endicott Group, Arctic slope of Alaska: American Association of Petroleum Geologists Bulletin, v. 56, no. 8, p. 1364-1369.

Mull, C.G. and Tailleur, I.L., 1977, Sadlerochit(?) Group in the Schwatka Mountains, South Central Brooks Range, *in* Blean, K.M., ed., The United States Geological Survey in Alaska; accomplishments during 1976: U.S. Geological Survey Circular 751-B, p. B27-B29.

Mull, C.G., Tailleur, I.L., Mayfield, C.F., Ellersieck, Inyo, and Curtis, S.M., 1982, New upper Paleozoic and lower Mesozoic stratigraphic units, central and western Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 66, no. 3, p. 348-362.

Mull, C.G., Tailleur, I.L., Mayfield, C.F., and Pessel, G.H., 1976, New structural and stratigraphic interpretations, central and western Brooks Range and Arctic Slope, *in* Cobb, E.H., ed., The United States Geological Survey in Alaska; accomplishments during 1975: U.S. Geological Survey Circular 733, p. 24-26.

Nelson, S.W., and Grybeck, Donald, 1980, Geologic map of the Survey Pass quadrangle, Brooks Range, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1176-A, 2 sheets, scale 1:250,000.

Newman, G.W., Mull, C.G., and Watkins, N.D., 1979, Northern Alaska paleomagnetism, plate rotation and tectonics: Alaska Geological Society Symposium, 1977, Proceedings, p. C1-C7.

Nilsen, T.H., 1981, Upper Devonian and Lower Mississippian redbeds, Brooks Range, Alaska, *in* Miall, A.D. ed., Sedimentation and tectonics in alluvial basins: Geological Association of Canada Paper 23, p. 187-219.

Nilsen, T.H., Brosgé, W.P., Dutro, J.T., Jr., and Moore, T.E., 1981a, Depositional model for the fluvial Upper Devonian Kanayut Conglomerate, Brooks Range, Alaska, *in* Albert, N.R., and Hudson, Travis, eds., The United States Geological Survey in Alaska; accomplishments during 1979: U.S. Geological Survey Circular, 823-B, p. 20-21.

Nilsen, T.H., and Moore, T.E., 1982, Sedimentology and stratigraphy of the Kanayut Conglomerate, central and western Brooks Range, Alaska—report of 1981 field season: U.S. Geological Survey Open-File Report 82-674, 68 p.

——— 1984, Stratigraphic nomenclature for the Upper Devonian and Lower Mississippian(?) Kanayut Conglomerate, Brooks Range, Alaska, *in* Contributions to stratigraphy: U.S. Geological Survey Bulletin 1529-A, p. A1-A64.

Nilsen, T.H., Moore, T.E., and Brosgé, W.P., 1980a, Paleocurrent maps for the Upper Devonian and Lower Mississippian Endicott Group, Brooks Range, Alaska: U.S. Geological Survey Open-File Report 80-1066, 2 sheets, scale 1:1,000,000.

Nilsen, T.H., Moore, T.E., Balin, D.F., and Johnson, S.Y., 1982, Sedimentology and stratigraphy of the Kanayut Conglomerate, central Brooks Range, Alaska; report of 1980 field season: U.S. Geological Survey Open-File Report 82-199, 85 p.

Nilsen, T.H., Moore, T.E., Brosgé, W.P., and Dutro, J.T., Jr., 1981b, Sedimentology and stratigraphy of the Kanayut Conglomerate and associated units, Brooks Range, Alaska—report of 1979 field season: U.S. Geological Survey Open-File Report 81-506, 44 p.

Nilsen, T.H., Moore, T.E., Dutro, J.T., Jr., Brosgé, W.P., and Orchard, D.M., 1980b, Sedimentology and stratigraphy of the Kanayut Conglomerate and associated units, central and eastern Brooks Range, Alaska—report of 1978 field season: U.S. Geological Survey Open-File Report 80-888, 80 p.

Porter, S.C., 1966, Stratigraphy and deformation of Paleozoic section at Anaktuvuk Pass, Central Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 50, no. 5, p. 952-980.

Reiser, H.N., Brosgé, W.P., Dutro, J.T., Jr., and Detterman, R.L., 1971, Preliminary geologic map, Mt. Michelson quadrangle, Alaska: U.S. Geological Survey open-file report, 2 sheets, scale 1:200,000.

——— 1980, Geologic map of the Demarcation Point quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1133, scale 1:250,000.

Roeder, Dietrich, and Mull, C.G., 1978, Tectonics of Brooks Range ophiolites, Alaska: American Association of Petroleum Geologists Bulletin, v. 62, no. 9, p. 1696-1702.

Tailleur, I.L., Brosgé, W.P., and Reiser, H.N., 1967, Palinspastic analysis of Devonian rocks in northwestern Alaska, *in* Oswald, D.H., ed., International symposium on the Devonian system: Alberta Society of Petroleum Geologists, v. 2, p. 1345-1361.

Tailleur, I.L., Kent, B.H., Jr., and Reiser, H.N., 1966, Outcrop/geologic maps of the Nuka-Etivluk region, northern Alaska: U.S. Geological Survey open-file report, 7 sheets, scale 1:63,360.

Tetra Tech, Inc., 1979, Summary report; interpretation of the FY '77 seismic survey data, National Petroleum Reserve in Alaska, revised May 1978: U.S. National Oceanographic and Atmospheric Administration, Environmental Data and Information Service, 18 p., 21 sheets, scale 1:250,000, 10 sheets, scale 1:500,000.

Witmer, R.J., Haga, Hideyo, and Mickey, M.B., 1981, Biostratigraphic report of thirty-three wells drilled from 1975 to 1981 in National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 81-1166, 50 p.

15. ALASKAN NORTH SLOPE STRATIGRAPHIC NOMENCLATURE AND DATA SUMMARY FOR GOVERNMENT-DRILLED WELLS

By KENNETH J. BIRD

INTRODUCTION

In the years since the discovery of the Prudhoe Bay oil field in 1968, a great amount of new information on the geology of the North Slope has become available, largely as a result of continued oil exploration and development. In an attempt to organize and summarize some of this information, I have compiled in this chapter an annotated list of North Slope stratigraphic names and a tabulation of selected well data for Government-drilled North Slope wells. This work was facilitated by the National Petroleum Reserve in Alaska (NPRA) computerized data base (Wilcox and others, chapter 39).

The list of stratigraphic names (table 15.1) includes names for most of the rock units that might be encountered in wells or surface exposures anywhere on the North Slope. Because these names are accompanied by explanatory notes or references, this chapter provides the first update of North Slope stratigraphic nomenclature since the earlier summary by Kopf (1970).

The tabulation of well data (tables 15.2-15.5) is patterned after the summary made by Collins and Robinson (1967, fig. 2) of wells drilled during the Pet-4 Program (U.S. Navy program in Naval Petroleum Reserve No. 4, 1944 to 1953). My summary includes updated information on each of the 81 Pet-4 wells and information on all of the 45 wells drilled by the Government since then. For each well, the information provided consists of identification, location, hydrocarbon occurrences, and drilling period (table 15.2); total depth and depths of penetration of stratigraphic units (table 15.3); cores attempted and core recovery (table 15.4); and drill-stem or production test results (table 15.5).

STRATIGRAPHIC NOMENCLATURE

North Slope stratigraphic nomenclature has evolved considerably since Kopf's (1970) tabulation. Table 15.1 includes stratigraphic names, ages, and numbers keyed to the following explanatory notes. These notes describe changes in usage or provide references for names proposed since the summary by Kopf (1970).

1. The age of the Gubik Formation has been extended, at least locally within the NPRA, into the Pliocene (Nelson and Carter, 1985).
2. The Flaxman Formation of Leffingwell (1919) is now included as a member of the Gubik Formation (Dinter, 1985).
3. Quaternary and, locally, latest Tertiary deposits on the North Slope have been assigned to either the Gubik Formation or surficial deposits. In most North Slope wells, rocks of this age are unconsolidated, less than a few hundred feet thick, and neither sampled nor logged. To reflect this general absence of information from wells, the term "surficial deposits and (or) Gubik Formation, undivided" is employed in this summary (table 15.3). For information on these rocks east of the NPRA, see Detterman and others (1975); for the NPRA, see Williams and others (1977); for the Brooks Range, see Hamilton (1986); and for offshore areas on the Beaufort shelf, see Dinter (1985).
4. The Sagavanirktok Formation, a name originally proposed by Gryc and others (1951) for Tertiary rocks exposed east of the NPRA, was later subdivided by Detterman and others (1975) into members. Molenaar and others (1987), on the basis of new paleontologic and well data east of the NPRA, recognized that the Tertiary deltaic and shallow marine deposits of the Sagavanirktok Formation extend downward without significant change into similar deposits of Late Cretaceous age. To reflect this situation, they proposed revising the definition of the Sagavanirktok Formation to include all Late Cretaceous and Tertiary deltaic and shallow marine deposits east of the NPRA. This unit name and other new unit names for underlying and laterally equivalent rocks are applied to that area east of the shale-out of the Nanushuk Group (fig. 15.1).
5. The age of the type section of the Franklin Bluffs Member of the Sagavanirktok Formation is early to middle Eocene on the basis of palynomorphs and dinoflagellates (Ager and others, 1985).
6. The Staines Tongue (new name) of the Sagavanirktok Formation was proposed by Molenaar and others (1987) for an interval of shallow-marine sandstone and shale of Paleocene age overlain and under-

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TABLE 15.1.—*Stratigraphic nomenclature for the North Slope of Alaska, listed by increasing age of unit*

Age	Unit	Comment in text
Quaternary	Surficial deposits	
Pleistocene and Pliocene	Gubik Formation	1
Pleistocene	Flaxman Member	2
Quaternary to Pliocene	Surficial deposits and Gubik Formation, undivided	3
Tertiary and Late Cretaceous	Sagavanirktok Formation	4
Pliocene and Miocene(?)	Nuwok Member	
Miocene(?) to Eocene	Franklin Bluffs Member	5
Eocene and Paleocene	Sagwon Member	
Paleocene	Staines Tongue	6
Tertiary and Late Cretaceous	Sagavanirktok Formation and Colville Group, undivided	7
Tertiary and Late Cretaceous	Sandstone of Colville Group and Sagavanirktok Formation, undivided.	7
Tertiary and Late Cretaceous	Ugnu sands	8
Tertiary and Late Cretaceous	Jago River Formation	9
Tertiary and Cretaceous	Canning Formation	10
Eocene	Mikkelsen Tongue	10
Cretaceous	Arctic Creek unit	11
Late Cretaceous	Colville Group	
Late Cretaceous	Sandstone of Colville Group	7
Late Cretaceous	Shale of Colville Group	7
Late Cretaceous	West Sak sands	12
Late Cretaceous	Prince Creek Formation	
Late Cretaceous	Kogosukruk Tongue	
Late Cretaceous	Tuluvak Tongue	
Late Cretaceous	Schrader Bluff Formation	
Late Cretaceous	Sentinel Hill Member	
Late Cretaceous	Barrow Trail Member	
Late Cretaceous	Rogers Creek Member	
Late Cretaceous	Seabee Formation	
Late Cretaceous	Ayiyak Member	
Late Cretaceous	Shale Wall Member	
Late and Early Cretaceous	Ignek Formation (now abandoned)	13
Tertiary(?) and Late and Early Cretaceous	Hue Shale	14
Late and Early Cretaceous	Gamma-ray zone	14
Late Cretaceous	Red-weathering zone	14
Late Cretaceous	Inoceramus zone	14
Late and Early Cretaceous	Nanushuk Group	15
Late and Early Cretaceous	Corwin Formation	
Late and Early Cretaceous	Chandler Formation	
Late Cretaceous	Niakogon Tongue	
Late(?) and Early Cretaceous	Killik Tongue	
Late Cretaceous	Ninuluk Formation	
Early Cretaceous	Tuktu Formation	
Early Cretaceous	Grandstand Formation	
Early Cretaceous	Torok Formation	16
Early Cretaceous	Oumalik Formation (now abandoned)	16
Early Cretaceous	Topagoruk Formation (now abandoned)	16
Early Cretaceous	Fortress Mountain Formation	17
Early Cretaceous	Bathtub Graywacke	18
Early Cretaceous and Late Jurassic	Okpikruak Formation	19
Early Cretaceous	Kisimilok Formation	19
Early Cretaceous	Kemik Sandstone	20
Early Cretaceous	Kongakut Formation	21
Early Cretaceous	Siltstone member	21
Early Cretaceous	Pebble shale member	21
Early Cretaceous	Kemik Sandstone Member	21
Early Cretaceous	Clay shale member	21
Early Cretaceous	Pebble shale unit	22
Early Cretaceous	Gamma-ray zone	22
Early Cretaceous	Basal sandstone member	22
Early Cretaceous	Thomson sand	23
Early Cretaceous	Put River sand	23

TABLE 15.1.—*Stratigraphic nomenclature for the North Slope of Alaska, listed by increasing age of unit*—Continued

Age	Unit	Comment in text
Early Cretaceous	Walakpa sandstone	23
Early Cretaceous	Ugnuravik Group	24
Early Cretaceous	HRZ	24
Early Cretaceous	Kalubik Formation	24
Early Cretaceous	Kuparuk Formation	25
Early Cretaceous	Miluveach Formation	24
Late Jurassic	Ogotoruk Formation	19
Late Jurassic	Telavirak Formation	19
Early Cretaceous and Jurassic	Ipewik unit	26
Early Cretaceous	Tingmerkpuk subunit	26
Early Cretaceous and Jurassic	Kingak Shale	27
Jurassic	Simpson sandstone	28
Jurassic	Barrow sandstone	29
Late Jurassic	Tiglukpuk Formation (now abandoned)	30
Triassic	Sag River Sandstone	31
Triassic	Karen Creek Sandstone	32
Triassic	Shublik Formation	
Jurassic to Pennsylvanian	Etivluk Group	33
Jurassic and Triassic	Otuk Formation	33
Jurassic	Blankenship Member	33
Triassic to Pennsylvanian	Siksikpuk Formation	33
Pennsylvanian(?) and Mississippian	Nuka Formation	34
Triassic and Permian	Sadlerochit Group	35
Triassic	Ivishak Formation	35
Triassic	Fire Creek Member	35
Triassic	Ledge Sandstone Member	35
Triassic	Kavik Member	35
Permian	Echooka Formation	35
Permian	Ikiakpaurak Member	35
Permian	Joe Creek Member	35
Permian to Mississippian	Lisburne Group	36
Pennsylvanian and Mississippian	Wahoo Limestone	
Pennsylvanian	Upper limestone unit	37
Mississippian	Alapah Limestone	
Mississippian	Dolomite unit	37
Mississippian	Lower limestone unit	37
Pennsylvanian and Mississippian	Kuna Formation	33
Mississippian	Tupik Formation	
Pennsylvanian and Mississippian	Kogruk Formation	38
Mississippian	Nasorak Formation	
Mississippian	Wachsmuth Formation	
Mississippian	Utukok Formation	
Permian(?) to Devonian	Endicott Group	39
Mississippian	Itkilyariak Formation	40
Mississippian	Kayak Shale	
Mississippian	Kekiktuk Conglomerate	
Mississippian and Devonian	Noatak Sandstone	
Mississippian(?) and Devonian	Kanayut Conglomerate	41
Mississippian	Stuver member	
Devonian	Shainin Lake Member	
Devonian	Ear Peak Member	
Devonian	Hunt Fork Shale	
Devonian	Beaucoup Formation	42
Devonian to Cambrian	Baird Group	43
Devonian and Silurian	Skajit Limestone	
Devonian	Eli Limestone	
Devonian	Kugururok Formation	
Devonian and (or) older	Basement complex	44
Silurian and Ordovician	Argillite	45
Devonian to Cambrian or Proterozoic	Nanook Limestone	46
Proterozoic	Katakturuk Dolomite	46
Proterozoic	Neruokpuk Quartzite	47

TABLE 15.2.—*Location, class, and operating period of Government-drilled wells on the North Slope of Alaska*

[Operating agencies: USAF, U.S. Air Force; USGS, U.S. Geological Survey; USN, U.S. Navy. Well classes: abandoned producing wells: AP-1, oil; AP-2, gas; AP-4, oil with gas shows; AP-5, gas with oil shows; dry abandoned wells: DA-0, no shows; DA-1, oil shows; DA-2, gas shows; DA-3, oil and gas shows; producing wells: P-2, gas; P-3, oil and gas; P-4, oil with gas shows; P-5, gas with oil shows; suspended producing wells: SP-1, oil. Quadrangles are U.S. Geological Survey 1:250,000-scale quadrangles. API, American Petroleum Institute. Section, township, and range measured from Umiat base and meridian. Surface elevation: Gr., ground; K.B., kelly bushing or derrick floor]

Agency	Well	Class	Quadrangle	API well No.	Location					Elevation (ft)		Operation period	
					Lat N.	Long W.	Sec.	T.	R.	Gr.	K.B.	Spudded	Completed
Naval Petroleum Reserve No. 4 Program (1944-53)													
USN	Simpson Core Test 21	DA-0	Barrow	50-023-10001	71°00'29"	154°36'54"	13	19 N.	11 W.	22	26	10/13/49	10/27/49
USN	Simpson Core Test 23	DA-0	do	50-023-10002	71°02'04"	154°38'02"	1	19 N.	11 W.	15	18	11/08/49	11/16/49
USN	Simpson Core Test 24	DA-0	do	50-023-10003	71°01'46"	154°37'01"	6	19 N.	10 W.	8	11	11/22/49	11/28/49
USN	North Simpson 1	DA-0	do	50-023-10004	71°03'23"	154°58'06"	26	20 N.	12 W.	16	31	05/06/50	06/03/50
USN	Barrow Core Rig 1	DA-0	do	50-023-10005	71°19'25"	156°39'02"	22	23 N.	18 W.	10	13	09/17/44	10/07/44
USN	Barrow Core Rig 2	DA-0	do	50-023-10006	71°19'00"	156°38'59"	27	23 N.	18 W.	13	16	10/09/44	10/17/44
USN	Barrow Big Rig 1	DA-0	do	50-023-10007	71°19'44"	156°40'06"	22	23 N.	18 W.	9	16	10/13/44	10/22/44
USN	Arcon Barrow 1	DA-0	do	50-023-10008	71°19'40"	156°40'01"	22	23 N.	18 W.	11	19	03/29/47	05/03/47
USN	South Barrow 1	DA-1	do	50-023-10009	71°19'12"	156°42'16"	28	23 N.	18 W.	5	18	08/15/48	11/11/48
USN	South Barrow 2	AP-5	do	50-023-10010	71°15'49"	156°38'03"	14	22 N.	18 W.	24	35	12/18/48	04/05/50
USN	South Barrow 3	DA-2	do	50-023-10011	71°09'46"	156°34'44"	24	21 N.	18 W.	30	44	06/23/49	08/26/49
USN	South Barrow 4	AP-5	do	50-023-10012	71°15'51"	156°37'50"	14	22 N.	18 W.	24	43	03/09/50	05/09/50
USN	Avak 1	DA-0	do	50-023-10013	71°15'02"	156°28'06"	17	22 N.	17 W.	1	17	10/21/51	01/14/52
USN	Grandstand 1	DA-2	Chandler Lake	50-057-10001	68°57'58"	151°55'02"	32	5 S.	1 E.	645	660	05/01/52	08/08/52
USN	Fish Creek 1	AP-4	Harrison Bay	50-103-10001	70°18'43"	151°52'20"	15	11 N.	1 E.	17	32	05/17/49	09/04/49
USN	Ikpikpuk Core Test 1	DA-0	Ikpikpuk River	50-119-10001	69°49'36"	155°41'57"	5	5 N.	15 W.	170	180	07/09/47	07/17/47
USN	Oumalik Core Test 1	DA-0	do	50-119-10002	69°49'45"	155°41'30"	32	6 N.	15 W.	245	255	07/21/47	07/29/47
USN	Oumalik Core Test 2	DA-0	do		69°50'18"	155°59'24"	30	6 N.	16 W.	178	---	09/08/47	09/10/47
USN	Oumalik Core Test 11	DA-0	do	50-119-10003	69°50'18"	155°59'24"	30	6 N.	16 W.	172	177	03/09/49	03/22/49
USN	Oumalik Core Test 12	DA-0	do	50-119-10004	69°50'18"	155°59'24"	30	6 N.	16 W.	172	182	04/--/49	04/--/49
USN	Oumalik 1	DA-2	do	50-119-10005	69°50'18"	155°59'24"	30	6 N.	16 W.	176	194	06/11/49	04/23/50
USN	East Oumalik 1	DA-3	do	50-119-10006	69°47'29"	155°32'39"	13	5 N.	15 W.	277	293	10/23/50	01/07/51
USN	Square Lake 1	DA-2	do	50-119-10007	69°34'00"	153°18'00"	2	2 N.	6 W.	324	340	01/26/52	04/18/52
USN	Wolf Creek 1	DA-2	do	50-119-10008	69°23'11"	153°31'15"	2	1 S.	7 W.	712	714	04/29/51	06/04/51
USN	Wolf Creek 2	DA-2	do	50-119-10009	69°24'17"	153°31'15"	36	1 N.	7 W.	437	443	06/06/51	07/01/51
USN	Wolf Creek 3	DA-3	do	50-119-10010	69°23'11"	153°31'25"	2	1 S.	7 W.	732	750	08/20/52	11/03/52
USN	Titaluk 1	DA-2	do	50-119-10011	69°25'21"	154°34'04"	23	1 N.	11 W.	822	840	04/22/51	07/06/51
USN	Knifeblade 1	DA-1	do	50-119-10012	69°09'04"	154°43'21"	36	3 S.	12 W.	993	999	10/13/51	12/22/51
USN	Knifeblade 2	DA-0	do	50-119-10013	69°08'19"	154°44'12"	2	4 S.	12 W.	871	876	07/26/51	08/05/51
USN	Knifeblade 2A	DA-3	do	50-119-10014	69°08'19"	154°44'12"	2	4 S.	12 W.	869	874	08/06/51	10/07/51
USN	Skull Cliff Core Test 1	DA-0	Meade River	50-163-10001	70°54'00"	157°36'00"	23	18 N.	22 W.	41	50	02/02/47	03/17/47
USN	Meade 1	DA-2	do	50-163-10002	70°02'30"	157°29'23"	19	8 N.	22 W.	197	211	05/02/50	08/21/50
USN	Simpson Core Test 1	DA-0	Teshekpuk	50-279-10001	70°55'42"	155°17'22"	10	18 N.	13 W.	21	27	06/25/45	06/29/45
USN	Simpson Core Test 2	DA-0	do	50-279-10002	70°55'39"	155°17'30"	10	18 N.	13 W.	21	29	06/30/45	07/02/45
USN	Simpson Core Test 3	DA-0	do	50-279-10003	70°55'39"	155°17'30"	10	18 N.	13 W.	27	29	07/03/45	07/07/45
USN	Simpson Core Test 4	DA-0	do	50-279-10004	70°55'46"	155°15'52"	10	18 N.	13 W.	12	14	07/08/45	07/10/45
USN	Simpson Core Test 5	DA-0	do	50-279-10005	70°56'17"	155°16'45"	3	18 N.	13 W.	11	17	07/11/45	07/12/45
USN	Simpson Core Test 6	DA-3	do	50-279-10006	70°55'58"	155°18'33"	9	18 N.	13 W.	20	26	07/12/45	07/13/45
USN	Simpson Core Test 7	DA-0	do	50-279-10007	70°55'49"	155°18'09"	9	18 N.	13 W.	14	26	07/15/45	07/25/45
USN	Simpson Core Test 8	DA-1	do	50-279-10008	70°56'43"	155°17'38"	4	18 N.	13 W.	14	16	07/27/45	08/03/45
USN	Simpson Core Test 9	DA-1	do	50-279-10009	70°57'27"	155°17'31"	34	19 N.	13 W.	8	11	08/05/45	08/07/45
USN	Simpson Core Test 10	DA-1	do	50-279-10010	70°57'43"	155°17'32"	34	19 N.	13 W.	7	11	08/08/45	08/15/45
USN	Simpson Core Test 11	DA-0	do	50-279-10011	70°58'49"	155°17'32"	21	19 N.	13 W.	1	3	08/17/45	08/26/45
USN	Simpson Core Test 12	DA-0	do	50-279-10012	70°58'19"	155°17'30"	27	19 N.	13 W.	1	6	08/27/45	08/29/45
USN	Simpson Core Test 13	DA-3	do	50-279-10013	70°58'58"	154°38'43"	24	19 N.	11 W.	27	33	06/09/45	07/20/45
USN	Simpson Core Test 14	DA-3	do	50-279-10014	70°59'12"	154°37'36"	24	19 N.	11 W.	29	34	07/21/49	08/12/49
USN	Simpson Core Test 14A	DA-0	do	50-279-10015	70°59'12"	154°37'38"	24	19 N.	11 W.	27	30	08/13/49	08/15/49
USN	Simpson Core Test 15	DA-3	do	50-279-10016	70°59'06"	154°38'09"	24	19 N.	11 W.	25	30	08/16/49	08/23/49
USN	Simpson Core Test 16	DA-3	do	50-279-10017	70°59'00"	154°37'52"	24	19 N.	11 W.	24	28	08/24/49	08/31/49
USN	Simpson Core Test 17	DA-3	do	50-279-10018	70°59'12"	154°38'33"	24	19 N.	11 W.	23	27	08/31/49	09/08/49
USN	Simpson Core Test 18	DA-0	do	50-279-10019	70°59'38"	154°40'13"	23	19 N.	11 W.	14	18	09/10/49	09/21/49
USN	Simpson Core Test 19	DA-0	do	50-279-10020	70°59'16"	154°42'57"	22	19 N.	11 W.	15	19	09/23/49	09/29/49
USN	Simpson Core Test 20	DA-0	do	50-279-10021	70°59'49"	154°35'19"	18	19 N.	10 W.	20	24	10/05/49	10/11/49
USN	Simpson Core Test 22	DA-0	do	50-279-10022	70°59'32"	154°36'15"	19	19 N.	10 W.	20	27	10/29/49	11/05/49
USN	Simpson Core Test 25	DA-3	do	50-279-10023	70°56'10"	154°42'12"	3	18 N.	11 W.	17	20	07/03/50	08/12/50
USN	Simpson Core Test 26	AP-4	do	50-279-10024	70°56'08"	154°41'04"	11	18 N.	11 W.	20	23	08/13/50	10/23/50
USN	Simpson Core Test 27	DA-1	do	50-279-10025	70°56'07"	154°40'04"	11	18 N.	11 W.	24	29	02/08/51	03/14/51
USN	Simpson Core Test 28	DA-0	do	50-279-10026	70°59'33"	154°40'16"	19	19 N.	10 W.	20	37	09/05/50	09/24/50
USN	Simpson Core Test 29	DA-0	do	50-279-10027	70°55'47"	154°41'31"	11	18 N.	11 W.	20	25	10/31/50	11/26/50
USN	Simpson Core Test 30	DA-3	do	50-279-10028	70°55'51"	154°40'35"	11	18 N.	11 W.	20	25	11/30/50	01/23/51
USN	Simpson Core Test 30A	DA-3	do	50-279-10029	70°55'49"	154°40'51"	11	18 N.	11 W.	20	25	01/23/51	02/06/51
USN	Simpson Core Test 31	AP-1	do	50-279-10030	70°57'20"	154°37'44"	36	19 N.	11 W.	14	19	03/20/51	04/02/51
USN	Minga Velocity Test 1	DA-0	do	50-279-10031	70°59'00"	154°44'36"	21	19 N.	11 W.	0	5	04/29/50	05/09/50
USN	Simpson 1	DA-3	do	50-279-10032	70°57'12"	155°21'52"	32	19 N.	13 W.	15	29	06/14/47	06/09/48
USN	Topagoruk 1	DA-0	do	50-279-10033	70°37'30"	155°53'36"	25	15 N.	16 W.	28	42	06/15/50	09/28/51
USN	East Topagoruk 1	DA-2	do	50-279-10034	70°34'38"	155°22'39"	12	14 N.	14 W.	50	67	02/18/51	04/16/51
USN	Umiat 1	DA-1	Umiat	50-287-10001	69°23'48"	152°19'39"	35	1 N.	2 W.	729	738	06/22/45	10/05/46
USN	Umiat 2	DA-3	do	50-287-10002	69°23'00"	152°04'52"	2	1 S.	1 W.	261	270	06/25/47	12/12/47

TABLE 15.2.—*Location, class, and operating period of Government-drilled wells on the North Slope of Alaska*—Continued

Agency	Well	Class	Quadrangle	API well No.	Location					Elevation (ft)		Operation period	
					Lat N.	Long W.	Sec.	T.	R.	Gr.	K.B.	Spudded	Completed
					Naval Petroleum Reserve No. 4 Program (1944-53)--Continued								
USN	Umiat (Core Test 1) 3	AP-1	do	50-287-10003	69°23'12"	152°05'05"	3	1 S.	1 W.	279	288	11/15/46	12/26/46
USN	Umiat (Ruby 1) 4	SP-1	do	50-287-10004	69°23'16"	152°04'44"	2	1 S.	1 W.	410	411	05/26/50	07/29/50
USN	Umiat (Ruby 2) 5	SP-1	do	50-287-10005	69°23'01"	152°04'47"	2	1 S.	1 W.	262	263	07/05/50	10/04/51
USN	Umiat (Ruby 3) 6	AP-4	do	50-287-10006	69°22'40"	152°05'30"	3	1 S.	1 W.	262	265	08/14/50	12/12/50
USN	Umiat (Ruby 4) 7	DA-3	do	50-287-10007	69°22'29"	152°06'05"	10	1 S.	1 W.	254	258	12/14/50	04/12/51
USN	Umiat 8	P-3	do	50-287-10008	69°23'55"	152°06'46"	34	1 N.	1 W.	663	668	05/02/51	08/28/51
USN	Umiat 9	AP-1	do	50-287-10009	69°23'11"	152°10'01"	5	1 S.	1 W.	346	352	06/25/51	01/15/52
USN	Umiat 10	AP-1	do	50-287-10010	69°24'01"	152°07'44"	33	1 N.	1 W.	669	674	09/09/51	01/10/52
USN	Umiat 11	DA-3	do	50-287-10011	69°24'26"	152°05'50"	27	1 N.	1 W.	392	409	06/03/52	08/29/52
USN	Sentinel Hill Core Test 1	DA-0	do	50-287-10012	69°36'57"	151°27'11"	20	3 N.	3 E.	200	209	01/26/47	03/23/47
USN	Gubik 1	AP-2	do	50-287-10013	69°26'02"	151°28'33"	19	1 N.	3 E.	144	156	05/20/51	08/11/51
USN	Gubik 2	DA-3	do	50-287-10014	69°25'27"	151°26'30"	20	1 N.	3 E.	151	163	09/10/51	12/14/51
USN	Kaolak 1	DA-3	Utukok River	50-297-10001	69°56'00"	160°14'51"	25	7 N.	34 W.	164	178	07/21/51	11/12/51
					Barrow Program (1955-81)								
USAF	South Barrow	P-2	Barrow	50-023-10014	71°15'51"	156°37'59"	14	22 N.	18 W.	25	38	05/17/55	06/17/55
USN	South Barrow 6	P-5	do	50-023-10015	71°15'44"	156°36'53"	14	22 N.	18 W.	22	40	02/28/64	03/24/64
USN	South Barrow 7	P-2	do	50-023-20001	71°15'38"	156°35'43"	14	22 N.	18 W.	24	36	03/04/68	04/02/68
USAF	South Barrow 8	P-5	do	50-023-20002	71°15'54"	156°35'32"	14	22 N.	18 W.	19	31	04/04/69	05/01/69
USN	South Barrow 9	P-5	do	50-023-20003	71°16'04"	156°36'53"	11	22 N.	18 W.	16	29	03/19/70	04/15/70
USN	South Barrow 10	P-2	do	50-023-20004	71°15'32"	156°37'34"	14	22 N.	18 W.	26	38	03/07/73	03/24/73
USN	South Barrow 11	P-2	do	50-023-20005	71°15'22"	156°36'24"	14	22 N.	18 W.	22	36	02/10/74	03/06/74
USN	South Barrow 12	P-5	do	50-023-20006	71°14'14"	156°20'16"	23	22 N.	17 W.	26	38	03/10/74	05/04/74
USN	Iko Bay 1	P-5	do	50-023-20007	71°10'16"	156°10'05"	16	21 N.	16 W.	28	40	02/01/75	03/11/75
USN	South Barrow 13	P-5	do	50-023-20008	71°15'14"	156°37'40"	14	22 N.	18 W.	22	40	12/17/76	01/17/77
USN	South Barrow 14	P-5	do	50-023-20009	71°13'59"	156°18'11"	25	22 N.	17 W.	12	31	01/28/77	03/01/77
USGS	South Barrow 16	DA-0	do	50-023-20010	71°16'57"	156°32'47"	1	22 N.	18 W.	8	30	01/28/78	02/16/78
USGS	South Barrow 17	P-5	do	50-023-20011	71°14'01"	156°15'34"	30	22 N.	16 W.	7	33	03/02/78	04/13/79
USGS	South Barrow 19	P-5	do	50-023-20012	71°14'29"	156°20'02"	23	22 N.	17 W.	10	30	04/18/78	05/16/78
USGS	South Barrow 20	P-4	do	50-023-20015	71°13'57"	156°20'12"	26	22 N.	17 W.	7	30	04/07/80	05/10/80
USGS	South Barrow 15	P-5	do	50-023-20016	71°14'59"	156°20'42"	23	22 N.	17 W.	7	30	08/23/80	09/18/80
USGS	South Barrow 18	P-2	do	50-023-20017	71°14'23"	156°18'41"	24	22 N.	17 W.	7	30	09/22/80	10/14/80
					Naval Petroleum Reserve No. 4 Program (1973-77)								
USN	Cape Halkett 1	DA-3	Harrison Bay	50-103-20004	70°46'03"	152°27'59"	5	16 N.	2 W.	17	40	03/24/75	06/01/75
USN	East Teshekpuk 1	DA-3	do	50-103-20006	70°34'12"	152°56'37"	16	14 N.	4 W.	6	28	03/12/76	05/11/76
USN	South Harrison Bay 1	DA-3	do	50-103-20007	70°25'29"	151°43'52"	6	12 N.	2 E.	25	45	11/21/76	02/08/77
USN	Atigaru Point 1	DA-2	do	50-103-20008	70°33'22"	151°43'02"	19	14 N.	2 E.	7	27	01/12/77	03/18/77
USN	West Fish Creek 1	DA-3	do	50-103-20009	70°19'36"	152°03'38"	11	11 N.	1 W.	92	113	02/14/77	04/27/77
USN	W.T. Foran 1	DA-3	do	50-103-20010	70°49'56"	152°18'11"	13	17 N.	2 W.	13	39	03/07/77	04/24/77
USN	South Simpson 1	DA-2	Teshekpuk	50-279-20001	70°48'25"	154°58'55"	22	17 N.	12 W.	5	25	03/09/77	04/30/77
					National Petroleum Reserve in Alaska Program (1977-81)								
USGS	Walakpa 1	DA-3	Barrow	50-023-20013	71°05'58"	156°53'04"	9	20 N.	19 W.	31	50	12/25/79	02/07/80
USGS	West Dease 1	DA-1	do	50-023-20014	71°09'33"	155°37'45"	21	21 N.	14 W.	5	24	02/19/80	03/26/80
USGS	Tulageak 1	DA-1	do	50-023-20018	71°11'22"	155°44'01"	7	21 N.	14 W.	10	27	02/26/81	03/23/81
USGS	Walakpa 2	P-2	do	50-023-20019	71°03'00"	156°57'10"	31	20 N.	19 W.	44	61	01/03/81	02/15/81
USGS	North Kalikpik 1	DA-2	Harrison Bay	50-103-20011	70°30'33"	152°22'04"	3	13 N.	2 W.	15	40	02/27/78	04/14/78
USGS	North Inigok 1	DA-2	do	50-103-20017	70°15'27"	152°45'58"	36	11 N.	4 W.	13	166	02/13/81	04/04/81
USGS	Koluktak 1	DA-2	Ikpikpuk River	50-119-20001	69°45'09"	154°36'40"	27	5 N.	11 W.	183	205	03/24/81	04/19/81
USGS	Lisburne 1	DA-3	Killik River	50-137-20003	68°29'05"	155°41'36"	17	11 S.	16 W.	1,834	1,862	06/11/79	06/02/80
USGS	Awuna 1	DA-2	Lookout Ridge	50-155-20001	69°09'12"	158°01'21"	30	3 S.	25 W.	1,103	1,129	03/01/80	04/20/81
USGS	South Meade 1	DA-2	Meade River	50-163-20001	70°36'54"	156°53'24"	31	15 N.	19 W.	40	60	02/07/78	01/22/79
USGS	Kugrua 1	DA-2	do	50-163-20002	70°35'13"	158°39'43"	8	14 N.	26 W.	65	85	02/12/78	05/29/78
USGS	Kuyanak 1	DA-2	do	50-163-20003	70°55'53"	156°03'53"	10	18 N.	16 W.	1	28	02/13/81	03/31/81
USGS	Drew Point 1	DA-3	Teshekpuk	50-279-20002	70°52'47"	153°54'00"	26	18 N.	8 W.	16	39	01/13/78	03/13/78
USGS	Inigok 1	DA-3	do	50-279-20003	70°00'17"	153°05'57"	34	8 N.	5 W.	135	163	06/07/78	05/22/79
USGS	Ikpikpuk 1	DA-2	do	50-279-20004	70°27'20"	154°19'53"	25	13 N.	10 W.	32	52	11/28/78	02/28/80
USGS	East Simpson 1	DA-3	do	50-279-20005	70°55'04"	154°37'05"	18	18 N.	10 W.	14	30	02/19/79	04/10/79
USGS	J.W. Dalton 1	DA-1	do	50-279-20006	70°55'14"	153°08'15"	14	18 N.	5 W.	19	37	05/01/79	08/01/79
USGS	East Simpson 2	DA-3	do	50-279-20007	70°58'43"	154°40'26"	23	19 N.	11 W.	23	40	01/29/80	03/15/80
USGS	Seabee 1	DA-3	Umiat	50-287-20007	69°22'49"	152°10'31"	5	1 S.	1 W.	292	322	07/01/79	04/15/80
USGS	Tunalik 1	DA-2	Wainwright	50-301-20001	70°12'21"	161°04'09"	20	10 N.	36 W.	8	110	11/10/78	01/07/80
USGS	Peard 1	DA-2	do	50-301-20002	70°42'56"	159°00'03"	25	16 N.	28 W.	75	103	01/26/79	04/13/79

TABLE 15.3.—*Total depth and depths to selected stratigraphic horizons for Government-drilled wells on the North Slope of Alaska*

[See figure 15.3 and table 15.2 for locations of wells. Total depth and depth to top of each rock unit measured from kelly bushing; all depths to top of each rock unit rounded to nearest 5 ft except for unit 1. e, estimated depth based on regional trends; dashes, unit not penetrated, absent, or not recognized. Units: 1, surficial deposits and (or) Gubik Formation; 2, sandstone of the Colville Group and Sagavanirktok Formation, undivided; 3, shale of the Colville Group; 4, Nanushuk Group; 5, Torok Formation; 6, pebble shale unit; 7, Kingak Shale; 8, Sag River Sandstone; 9, Shublik Formation; 10, Fire Creek Siltstone Member of the Ivishak Formation, Sadlerochit Group; 11, Ledge Sandstone Member of the Ivishak Formation, Sadlerochit Group; 12, Kavik Member of the Ivishak Formation, Sadlerochit Group; 13, Echooka Formation, Sadlerochit Group; 14, Lisburne Group; 15, Endicott Group; 16, basement complex]

Well	Total depth (ft)	Depth to top of rock unit (ft)															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Naval Petroleum Reserve No. 4 Program (1944-53)																	
Simpson Core Test 21	1,502	4	---	85	1,270	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 23	1,035	3	---	110	575	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 24	901	3	---	85	570	---	---	---	---	---	---	---	---	---	---	---	---
North Simpson 1	3,774	15	---	90	---	2,770	---	---	---	---	---	---	---	---	---	---	---
Barrow Core Rig 1	344	3	---	---	95	---	---	---	---	---	---	---	---	---	---	---	---
Barrow Core Rig 2	236	2	---	---	100	---	---	---	---	---	---	---	---	---	---	---	---
Barrow Big Rig 1	685	8	---	---	90	---	---	---	---	---	---	---	---	---	---	---	---
Arcon Barrow 1	1,442	8	---	---	100	795	---	---	---	---	---	---	---	---	---	---	---
South Barrow 1	3,553	13	---	---	70	690	2,800	---	---	---	---	---	---	---	---	---	3,355
South Barrow 2	2,505	11	---	---	---	80	1,910	2,330	---	---	---	---	---	---	---	---	2,445
South Barrow 3	2,900	14	---	---	---	65	1,260	1,660	2,585	2,610	---	---	---	---	---	---	2,795
South Barrow 4	2,538	19	---	---	---	115	1,930	2,355	---	---	---	---	---	---	---	---	2,470
Avak 1	4,020	16	---	---	---	---	100	1,350	---	---	---	---	---	---	---	---	2,305
Grandstand 1	3,939	15	---	---	110	1,070	---	---	---	---	---	---	---	---	---	---	---
Fish Creek 1	7,020	15	65	1,900	2,890	4,110	---	---	---	---	---	---	---	---	---	---	---
Ikpikpuk Core Test 1	178	10	---	---	39e	---	---	---	---	---	---	---	---	---	---	---	---
Oumalik Core Test 1	392	10	---	---	30e	---	---	---	---	---	---	---	---	---	---	---	---
Oumalik Core Test 2	190	10	---	---	40	---	---	---	---	---	---	---	---	---	---	---	---
Oumalik Core Test 11	303	5	---	---	14	---	---	---	---	---	---	---	---	---	---	---	---
Oumalik Core Test 12	300	10	---	---	17	---	---	---	---	---	---	---	---	---	---	---	---
Oumalik 1	11,872	18	---	---	30e	2,770	10,880	11,160	---	---	---	---	---	---	---	---	---
East Oumalik 1	6,035	16	---	---	50	2,950	---	---	---	---	---	---	---	---	---	---	---
Square Lake 1	3,987	16	35	700	1,630	3,940	---	---	---	---	---	---	---	---	---	---	---
Wolf Creek 1	1,500	2	---	---	10	---	---	---	---	---	---	---	---	---	---	---	---
Wolf Creek 2	1,618	6	---	45	130	---	---	---	---	---	---	---	---	---	---	---	---
Wolf Creek 3	3,760	18	---	---	30e	3,575	---	---	---	---	---	---	---	---	---	---	---
Titaluk 1	4,020	---	---	18	40	3,500	---	---	---	---	---	---	---	---	---	---	---
Knifeblade 1	1,805	---	---	---	6	---	---	---	---	---	---	---	---	---	---	---	---
Knifeblade 2	373	---	---	---	5	---	---	---	---	---	---	---	---	---	---	---	---
Knifeblade 2A	1,805	---	---	---	5	---	---	---	---	---	---	---	---	---	---	---	---
Skull Cliff Core Test 1	779	9	---	---	50	450	---	---	---	---	---	---	---	---	---	---	---
Meade 1	5,305	14	---	---	25	3,450	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 1	116	6	---	---	85	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 2	226	8	---	---	75	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 3	368	2	---	---	80	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 4	151	2	---	---	80	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 5	130	6	---	---	50	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 6	149	6	---	---	80	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 7	532	12	---	---	70	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 8	580	2	---	---	65	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 9	320	3	---	---	85	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 10	500	4	---	---	65	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 11	580	2	---	80	---	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 12	460	5	---	65	---	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 13	1,438	6	---	85	660	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 14	1,270	5	---	85	335	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 14A	290	3	---	85	---	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 15	900	5	---	75	325	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 16	800	4	---	80	320	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 17	1,100	4	---	80	570	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 18	1,460	4	---	90	---	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 19	1,061	4	---	80	---	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 20	1,001	4	---	85	980	---	---	---	---	---	---	---	---	---	---	---	---

Simpson Core Test 22--------	903	7	---	85	---	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 25--------	1,510	3	---	110	830	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 26--------	1,171	3	---	85	200	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 27--------	1,500	5	---	100	225	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 28--------	2,505	17	---	120	1,020	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 29--------	700	5	---	85	490	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 30--------	693	5	---	85	210	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 30A-------	701	5	---	85	210	---	---	---	---	---	---	---	---	---	---	---	---
Simpson Core Test 31--------	355	5	---	110	230	---	---	---	---	---	---	---	---	---	---	---	---
Minga Velocity Test 1-------	1,233	5	---	85	625	---	---	---	---	---	---	---	---	---	---	---	---
Simpson 1-------------------	7,002	17	---	---	25e	980	5,290	5,500	6,030	6,270	---	---	---	---	---	---	6,535
Topagoruk 1-----------------	10,503	14	---	---	50	2,150	6,685	6,885	8,665	8,830	9,220	9,380	9,585	---	---	9,775	10,045
East Topagoruk 1------------	3,589	17	---	---	90	2,280	---	---	---	---	---	---	---	---	---	---	---
Umiat 1---------------------	6,005	---	---	9	915	2,840	---	---	---	---	---	---	---	---	---	---	---
Umiat 2---------------------	6,212	9	---	---	80	1,060	---	---	---	---	---	---	---	---	---	---	---
Umiat (Core Test 1) 3-------	572	9	---	---	60	---	---	---	---	---	---	---	---	---	---	---	---
Umiat (Ruby 1) 4------------	840	1	---	---	90	---	---	---	---	---	---	---	---	---	---	---	---
Umiat (Ruby 2) 5------------	1,077	1	---	---	65	---	---	---	---	---	---	---	---	---	---	---	---
Umiat (Ruby 3) 6------------	825	3	---	30	220	---	---	---	---	---	---	---	---	---	---	---	---
Umiat (Ruby 4) 7------------	1,384	4	---	50	380	---	---	---	---	---	---	---	---	---	---	---	---
Umiat 8---------------------	1,327	5	---	20	60	---	---	---	---	---	---	---	---	---	---	---	---
Umiat 9---------------------	1,257	---	---	---	6	---	---	---	---	---	---	---	---	---	---	---	---
Umiat 10--------------------	1,573	---	---	---	15	---	---	---	---	---	---	---	---	---	---	---	---
Umiat 11--------------------	3,303	17	22	775	2,040	3,080	---	---	---	---	---	---	---	---	---	---	---
Sentinel Hill Core Test 1---	1,180	---	9	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Gubik 1---------------------	6,000	12	65	1,950	3,070	3,975	---	---	---	---	---	---	---	---	---	---	---
Gubik 2---------------------	4,620	12	110	2,220	3,330	4,385	---	---	---	---	---	---	---	---	---	---	---
Kaolak 1--------------------	6,952	14	---	---	110e	5,205	---	---	---	---	---	---	---	---	---	---	---
Barrow Program (1955-81)																	
South Barrow 5--------------	2,456	13	---	---	---	100e	1,920	2,340	---	---	---	---	---	---	---	---	2,450
South Barrow 6--------------	2,363	18	---	---	---	120	1,845	2,285	---	---	---	---	---	---	---	---	---
South Barrow 7--------------	2,351	12	---	---	---	110	1,820	2,245	---	---	---	---	---	---	---	---	---
South Barrow 8--------------	2,359	13	---	---	---	100e	1,850	2,270	---	---	---	---	---	---	---	---	---
South Barrow 9--------------	2,450	13	---	---	---	100e	1,935	2,350	---	---	---	---	---	---	---	---	---
South Barrow 10-------------	2,349	12	---	---	---	100e	1,825	2,265	---	---	---	---	---	---	---	---	---
South Barrow 11-------------	2,350	14	---	---	---	100e	1,765	2,195	---	---	---	---	---	---	---	---	---
South Barrow 12-------------	2,285	14	---	---	---	100e	1,320	1,735	2,200	---	---	---	---	---	---	---	2,265
Iko Bay 1-------------------	2,731	28	---	---	---	100e	1,510	1,890	2,535	2,585	---	---	---	---	---	---	2,705
South Barrow 13-------------	2,535	18	---	---	---	100e	1,705	2,240	---	---	---	---	---	---	---	---	2,475
South Barrow 14-------------	2,257	19	---	---	---	80e	1,365	1,725	2,235	---	---	---	---	---	---	---	---
South Barrow 16-------------	2,400	22	---	---	---	80e	1,930	---	---	---	---	---	---	---	---	---	2,340
South Barrow 17-------------	2,382	26	---	---	---	80e	1,410	1,770	2,275	---	---	---	---	---	---	---	2,345
South Barrow 19-------------	2,300	20	---	---	---	80e	1,350	1,745	2,195	---	---	---	---	---	---	---	2,265
South Barrow 20-------------	2,356	18	---	---	---	75e	1,310	1,735	2,230	---	---	---	---	---	---	---	2,315
South Barrow 15-------------	2,278	23	---	---	---	75e	1,480	1,910	---	---	---	---	---	---	---	---	---
South Barrow 18-------------	2,125	18	---	---	---	75e	1,375	1,760	---	---	---	---	---	---	---	---	---
Naval Petroleum Reserve No. 4 Program (1973-77)																	
Cape Halkett 1--------------	9,900	23	100e	2,220	3,115	4,235	7,280	7,555	7,730	7,855	8,130	8,160	8,705	---	8,770	---	9,305
East Teshekpuk 1------------	10,664	22	100e	1,000	1,585	3,100	6,850	7,125	8,505	8,640	8,855	9,000	9,445	9,615	9,650	---	10,625
South Harrison Bay 1--------	11,290	20	100e	2,060	3,220	4,220	---	7,290	8,845	8,955	9,240	9,360	9,935	10,140	10,235	---	---
Atigaru Point 1-------------	11,535	20	100e	2,420	3,470	4,400	7,280	7,320	8,190	8,345	8,600	8,705	9,245	9,410	9,510	10,820	11,210
West Fish Creek 1-----------	11,427	21	100e	1,500	2,550	3,915	7,280	7,320	9,175	9,285	9,515	9,620	10,175	10,445	10,500	11,315	---
W.T. Foran 1----------------	8,864	26	100e	2,600	3,480	4,380	7,340	---	---	7,545	7,640	7,740	8,135	---	8,195	---	8,565
South Simpson 1-------------	8,795	20	---	---	80e	1,910	6,315	6,525	7,400	7,685	---	8,270	8,470	---	---	8,590	8,745
National Petroleum Reserve in Alaska Program (1977-81)																	
Walakpa 1-------------------	3,666	19	---	---	---	50e	1,700	2,090	3,220	3,260	---	---	---	---	---	---	3,630
West Dease 1----------------	4,173	19	---	---	---	80e	2,910	3,370	3,800	3,830	---	---	---	---	---	---	4,005
Tulageak 1------------------	4,015	17	---	---	---	100e	2,505	2,955	3,760	3,800	---	---	---	---	---	---	3,960
Walakpa 2-------------------	4,360	17	---	---	---	50e	2,205	2,640	3,845	3,885	---	---	---	---	---	---	4,300
North Kalikpik 1------------	7,395	21	100e	1,700	2,395	3,470	6,895	7,150	---	---	---	---	---	---	---	---	---

TABLE 15.3.—*Total depth and depths to selected stratigraphic horizons for Government-drilled wells on the North Slope of Alaska*—Continued

Well	Total depth (ft)	Depth to top of rock unit (ft)															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
National Petroleum Reserve in Alaska Program (1977-81)--Continued																	
North Inigok 1	10,170	30	100e	885	1,920	3,265	7,385	7,650	10,050	10,090	---	---	---	---	---	---	---
Koluktak 1	5,882	27	---	---	75e	4,210	---	---	---	---	---	---	---	---	---	---	---
Lisburne 1	17,000	[2]28	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Awuna 1	11,200	26	---	---	---	50e	---	---	---	---	---	---	---	---	---	---	---
South Meade 1	9,945	20	---	---	80e	2,490	6,475	6,735	8,770	8,860	9,185	9,335	---	---	---	---	9,535
Kugrua 1	12,588	25	---	---	80e	2,330	6,890	7,200	9,515	9,650	10,010	10,345	10,820	11,005	11,180	---	---
Kuyanak 1	6 690	17	---	---	75e	1,250	4,640	5,160	6,245	6,335	---	---	---	---	---	---	6,560
Drew Point 1	7,946	23	80e	740	1,230	3,200	6,700	6,900	6,955	7,060	---	7,570	---	---	---	---	7,850
Inigok 1	20,102	43	100	1,380	2,250	3,935	9,040	9,260	12,160	12,190	12,430	12,840	13,285	13,660	13,985	17,870	---
Ikpikpuk 1	15,481	20	---	---	100e	2,950	7,230	7,480	9,845	9,905	10,395	10,600	11,100	11,295	11,445	14,550	15,320
East Simpson 1	7,739	16	---	80	295	2,690	6,365	6,580	6,760	7,025	---	7,455	---	---	---	---	7,590
J.W. Dalton 1	9,367	18	210	2,060	2,660	4,140	7,480	---	---	7,640	7,900	7,955	8,230	---	8,305	8,615	9,265
East Simpson 2	7,504	17	---	80	1,045	2,700	6,325	---	6,525	6,770	---	---	---	---	---	7,150	7,355
Seabee 1	15,611	30	---	100e	280	1,295	13,000	13,200	---	---	---	---	---	---	---	---	---
Tunalik 1	20,335	30	---	---	100e	6,250	10,635	10,900	14,350	14,510	14,825	---	15,560	16,885	17,100	---	---
Peard 1	10,225	28	---	---	80e	2,470	6,195	6,525	8,340	8,465	8,740	8,855	9,360	9,475	---	---	9,640

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[1] Well penetrates thrust-faulted section; faults at 250 and 500 ft. Top of the Nanushuk Group is at 5, 400, and 630 ft; top of shale of the Colville Group is at 250 and 500 ft.

[2] Well penetrates thrust-faulted section; faults at 8,600, 10,900, 13,375, and 15,315 ft. Top of the Okpikruak(?) Formation is at 930 ft; top of the Etivluk Group is at 28, 6,130, 8,600, 10,900, 13,375, and 15,315 ft; top of the Lisburne Group is at 7,410, 9,670, 11,550, 13,730, and 15,395 ft.

lain by marine shale of the Canning Formation (new name) in the subsurface of the Point Thomson area, east of Prudhoe Bay (fig. 15.1).

7. Pending further study, Tertiary rocks in the northeastern NPRA are assigned to the Sagavanirktok Formation, following the original definition of this formation, whereas Upper Cretaceous rocks are assigned to the Colville Group. The relation of these rocks to the recently proposed nomenclature east of the NPRA (Molenaar and others, 1987) is illustrated in figure 15.1.

8. The (informal) Ugnu sands is a local name used for a partially oil-bearing interval, in the subsurface between Prudhoe Bay and the NPRA, exemplified in the British Petroleum East Ugnu No. 1 well between 827 and 994 m (2,716-3,260 ft) measured depth (Werner, 1987). These rocks reportedly span the Cretaceous-Tertiary boundary and, as described herein, are included in the Sagavanirktok Formation (fig. 15.1).

9. The Jago River Formation (new name), named by Buckingham (1987), is a thick (3,000 m, 10,000 ft) section of predominantly nonmarine sandstone, conglomerate, shale, and coal of Late Cretaceous and Early Tertiary age exposed in the foothills of the Brooks Range in the Arctic National Wildlife Refuge.

10. The Canning Formation (new name), named by Molenaar and others (1987), is a thick, predominantly marine shale of Cretaceous and Tertiary age that is present in the coastal plain subsurface east of the NPRA and in outcrops in the foothills of the eastern Brooks Range. The Mikkelsen Tongue (new name) of the Canning Formation, also named by Molenaar and others (1987), is an interval of marine shale and siltstone of Eocene age overlain and underlain by Sagavanirktok Formation in the subsurface of the Point Thomson area, east of Prudhoe Bay (fig. 15.1).

11. The (informal) Arctic Creek unit, a name introduced by Molenaar and others (1987), is a thick section of complexly deformed shale, bentonitic shale, and turbidite sandstone of Cretaceous age exposed in the foothills of the Brooks Range southeast and east of the Sadlerochit Mountains.

12. The (informal) West Sak sands is a local name used for the sandstone and shale interval in the ARCO West Sak No. 1 well between 1,141 and 1,171 m (3,742-3,842) ft measured depth (Jamison and others, 1980). These rocks are Late Cretaceous in age and, as described herein, are included in the Sagavanirktok Formation (fig. 15.1).

13. The Ignek Formation has been abandoned by Detterman and others (1975, p. 20).

14. The Hue Shale and its distinctive divisions (gamma ray, red-weathering, and *Inoceramus* zones) were named by Molenaar and others (1987) and consist of Cretaceous and lower Tertiary(?) shale, bentonite, and tuff in the coastal plain subsurface east of the NPRA and in outcrops in the foothills of the eastern Brooks Range.

15. Important summaries of terminology and stratigraphic relations for the Nanushuk Group are provided by Ahlbrandt (1979), Huffman (1985), and Molenaar (chapter 25).

16. The Oumalik and Topagoruk Formations of Robinson and others (1956) are now abandoned, and their rocks reassigned to the Torok Formation as proposed by Molenaar (chapter 25).

17. Following the recommendation of Molenaar and others (chapter 12), the Fortress Mountain Formation has been geographically restricted solely to those areas where it occurs in outcrop.

18. The Bathtub Graywacke, named by Detterman and others (1975), is a thick sequence of Lower Cretaceous graywacke sandstone, conglomerate, and shale exposed along Bathtub Ridge in the eastern Brooks Range. A reference section was proposed by Detterman and others north of the Brooks Range on Sabbath Creek; Buckingham (1987) included this section as part of his Jago River Formation (see note 9).

19. The Okpikruak Formation was geographically restricted by Detterman and others (1975) to the Neocomian flyschlike sequences of rhythmically bedded graywacke, shale, and siltstone in the central and western parts of northern Alaska that are lithologically similar to the unit's type locality on the Okpikruak River (Gryc and others, 1951). The age of this formation has been revised to Late Jurassic and Early Cretaceous (Mayfield and others, chapter 7). Similar flyschlike units that occur in the lowlands between the Lisburne Hills and the western Brooks Range are known as the Kisimilok, Ogotoruk, and Telavirak Formations (Campbell, 1965a, b, c). The currently accepted ages of the latter two units are Late Jurassic (Imlay and Detterman, 1973).

20. Molenaar and others (1987) proposed raising the rank of the Kemik Sandstone Member (of the Kongakut Formation) to the Kemik Sandstone, but only for the Lower Cretaceous quartzose sandstone that crops out around the Sadlerochit Mountains and as far as 65 km (40 mi) to the southwest and that occurs in wells as far as 110 km (70 mi) to the west (see note 21). Both the Kemik Sandstone and the (thus geographically restricted) Kemik Sandstone Member are Hauterivian in age. Mull (1987) also recommended raising the rank of the Kemik Sandstone Member in the same area.

21. The Kongakut Formation and its members, the siltstone member, pebble shale member, Kemik Sandstone Member, and clay shale member, were named by Detterman and others (1975) and consist of Lower Cretaceous marine siltstone, shale, and sandstone exposed along Bathtub Ridge in the eastern Brooks Range and in the foothills to the northwest. Because only the Kemik Sandstone Member, pebble shale member, and part of the clay shale member (which is now assigned to the upper part of the Kingak Shale) of this thick formation are present along the mountain front and coastal plain, Molenaar and others (1987) recommended that the name Kongakut Formation not be used along the mountain front and coastal plain, thus geographically restricting its use to the Bathtub Ridge area.

22. The (informal) pebble shale unit is the interval of Lower Cretaceous (Hauterivian and Barremian) marine shale in the NPRA that lies below the Torok Formation and above a regional unconformity. It is characterized by the scattered occurrence of rounded pebbles and sand grains. The uppermost part of the unit is shale characterized by unusually high gamma radiation and is called the gamma-ray zone (GRZ), whereas the base of the unit is locally composed of a thin sandstone, the basal sandstone member (fig. 15.2). East of the NPRA, Molenaar and others (1987) assigned the (informal) GRZ to the Hue Shale (fig. 15.1).

23. The Thomson sand, Put River sand, and Walakpa sandstone are informal names of local usage applied to the basal sandstone member of the pebble shale unit (figs. 15.1, 15.2) in the Point Thomson area (Molenaar and others, 1987), the Prudhoe Bay area (Jamison and others, 1980), and the northern NPRA (Schindler, chapter 2), respectively. These sandstones are discontinuous, of local (northern) derivation, and considered stratigraphic equivalents of the Kemik Sandstone.

TABLE 15.5.—*Summary of tests for subsurface fluids in Government-drilled wells on the North Slope of Alaska*

[Wells listed in same sequence as in tables 15.2 and 15.3; see figure 15.3 for locations. DST, drill-stem test; IP, initial potential. All intervals measured in feet below kelly bushing or derrick floor. BPD, barrels per day (1 bbl = 42 gal); MCFGPD, thousand cubic feet of gas per day]

Test No.	Interval tested (ft)	Results
Naval Petroleum Reserve No. 4 Program		
South Barrow 1		
DST 01	3,030-3,226	Packer failed.
DST 02	3,042-3,226	Do.
DST 03	3,013-3,553	Misrun.
South Barrow 2		
DST 01	1,992-2,030	Weak blow. Recovered 250 ft of mud.
DST 02	2,314-2,391	Strong blow. Flowed gas to surface in 12 minutes.
DST 03	2,381-2,443	Recovered 95 ft of gas-cut mud.
DST 04	2,260-2,265	Flowed gas to surface in 29 minutes. Recovered 168 ft of highly gas cut mud.
IP 01	2,282-2,402	Initial production potential, 4,100 MCFGPD.
South Barrow 3		
DST 01	2,591-2,675	Packer failed. Recovered 140 ft of mud.
DST 02	2,801-2,899	Fair blow. Recovered 1,060 ft of mud.
DST 03	2,801-2,900	Recovered 300 ft of highly gas cut mud and 150 ft of mud.
South Barrow 4		
DST 01	2,317-2,390	Flowed gas at 511 MCFPD. Recovered 75 ft of gas-cut mud.
DST 02	2,389-2,420	Flowed gas to surface in 6 minutes. Recovered 52 ft of mud.
DST 03	2,472-2,538	Recovered 640 ft of gas-cut saltwater.
DST 04	2,520-2,538	Flowed gas at more than 200 MCFPD. Recovered 520 ft of highly gas cut saltwater.
IP 01	2,343-2,502	Initial production potential, 1,805 MCFGPD.
Avak 1		
DST 01	1,025-1,056	Packer failed.
DST 02	1,030-1,077	Slight blow. Recovered 80 ft of gas-cut mud.
DST 03	1,641-1,676	Weak blow. Recovered 80 bbl of mud.
Grandstand 1		
DST 01	833-862	Recovered 20 ft of mud.
DST 02	865-899	Recovered 352 ft of gas-cut water.
DST 03	1,938-1,951	Recovered 15 ft of mud.
DST 04	3,908-3,939	Recovered 50 ft of mud.
DST 05	3,864-3,939	Misrun.
DST 06	3,834-3,939	Do.
Fish Creek 1		
DST 01	2,925-3,060	Flowed gas to surface in 15 minutes. Recovered 180 ft of slightly gas cut oil and 380 ft of gas, oil, and mud.
DST 02	5,481-5,585	Tester plugged.
DST 03	5,480-5,585	Packer failed.
DST 04	5,480-5,585	Do.
DST 05	6,000-6,050	Misrun.
IP 01	2,918-3,017	36-day pump test. Pumped oil at avg 12 BPD.
Oumalik 1		
DST 01	968-1,011	Weak blow. Recovered 3 ft of mud.
DST 02	1,607-1,637	Weak blow. Recovered 15 ft of mud.
DST 03	2,762-2,767	Flowed gas to surface in 35 minutes. Recovered 20 ft of gas-cut mud.
DST 04	2,762-2,851	Flowed gas to surface in 55 minutes. Recovered 107 ft of gas-cut mud.
DST 05	2,762-3,498	Misrun; tool plugged.
DST 06	2,762-3,498	Weak blow. Recovered 243 ft of mud. Packer failed.
DST 07	2,762-3,498	Fair blow. Dead in 4 hours.
Naval Petroleum Reserve No. 4 Program--Continued		
Square Lake 1		
DST 01	1,642-1,675	Misrun.
DST 02	1,642-1,675	Packer failed.
DST 03	1,646-1,675	Do.
DST 04	1,646-1,675	Flowed gas at 112 MCFPD. Produced water by heads.
DST 05	1,847-1,879	Flowed gas to surface in 30 minutes with strong blow, then water and mud.
DST 06	1,878-1,897	Misrun.
DST 07	1,878-1,897	Recovered 90 ft of water-cut mud.
DST 08	3,033-3,067	Recovered 780 ft of water.
DST 09	3,466-3,482	Recovered 50 ft of mud.
DST 10	3,714-3,742	Recovered 10 ft of mud.
DST 11	3,834-3,845	Do.
DST 12	3,850-3,882	Recovered 100 ft of mud.
Wolf Creek 1		
DST 01	48-865	Flowed gas at 116 MCFPD.
DST 02	48-1,500	Flowed gas at 881 MCFPD.
Wolf Creek 3		
DST 01	1,529-1,545	Flowed gas at 170 MCFPD.
DST 02	1,549-1,565	Flowed gas at 445 MCFPD.
DST 03	1,647-1,670	Flowed gas at 87 MCFPD.
DST 04	1,878-1,915	Recovered 230 ft of gas-cut mud.
DST 05	1,978-2,017	Recovered 50 ft of mud.
DST 06	2,038-2,076	Flowed gas at 285 MCFPD.
DST 07	2,243-2,282	Recovered 14 ft of mud.
DST 08	2,512-2,547	Recovered 6 ft of mud.
DST 09	2,588-2,605	Recovered 10 ft of mud.
DST 10	2,644-2,661	Recovered 900 ft of mud.
DST 11	2,647-2,681	Recovered 70 ft of mud and 2 qt of oil.
DST 12	2,644-2,681	Recovered 90 ft of oil-cut mud.
Titaluk 1		
DST 01	2,984-3,027	Flowed gas to surface in 86 minutes. Recovered 90 ft of gas-cut mud.
DST 02	3,415-3,762	Packer failed.
DST 03	3,658-3,762	Light blow.
DST 04	3,400-3,471	Packer failed.
DST 05	3,408-3,471	Do.
DST 06	3,423-3,471	Do.
Knifeblade 1		
DST 01	52-650	Found hole dry.
DST 02	52-882	Bailed water at 72 BPD.
DST 03	52-910	Bailed water at 180 BPD.
DST 04	52-1,250	Recovered 26 bbl of water.
DST 05	52-1,250	Recovered 33 bbl of water.
DST 06	52-1,250	Recovered water at avg 432 BPD.
DST 07	1,211-1,250	Hole dry after 1-hour test.
DST 08	1,211-1,373	Flowed water at 24 BPD.
DST 09	1,211-1,640	Recovered 15 bbl of water.
DST 10	1,211-1,805	Flowed water at 6 BPD.
Knifeblade 2A		
DST 01	38-750	Bailed hole dry in 30 minutes.
DST 02	38-758	Water level at 170 ft; could not be lowered by bailing.
DST 03	38-1,000	Water level at 250 ft; could not be lowered by bailing.
DST 04	38-1,805	Water level at 235 ft; could not be lowered by bailing.
Meade 1		
DST 01	4,116-4,184	Recovered 50 ft of gas-cut mud.
DST 02	2,949-3,038	Packer failed.

TABLE 15.5.—*Summary of tests for subsurface fluids in Government-drilled wells on the North Slope of Alaska*—Continued

Test No.	Interval tested (ft)	Results
Naval Petroleum Reserve No. 4 Program--Continued		
Meade 1--Continued		
DST 03	2,955-3,038	Do.
DST 04	1,101-3,038	Flowed gas at 301 MCFPD.
DST 05	1,101-3,038	Flowed gas at 1,132 MCFPD.
DST 06	2,560-2,560	Water-shutoff test. Drilling fluid rose 450 ft.
DST 07	2,690-2,696	Water-shutoff test. Packer failed.
DST 08	2,690-2,696	Do.
DST 09	2,690-2,696	Strong blow decreased to faint blow. Swabbing caused gas to flow intermittently.
Simpson Core Test 16		
DST 01	4-800	Bailing recovered a few gallons of oil. Small volume of gas flowed from hole for more than a year.
Simpson Core Test 26		
DST 01	3-306	Flowed oil at 60 BPD.
DST 02	350-895	Bailed water with a trace of oil at 3 BPD.
IP 01	289-325	Flowed oil at 120 BPD and gas at 3 MCFPD.
Simpson Core Test 27		
DST 01	102-380	Bailed oil at 3 BPD.
Simpson Core Test 30		
DST 01	5-350	Bailed oil at 6 BPD.
Simpson Core Test 30A		
DST 01	100-350	Bailed oil at 5 BPD.
DST 02	100-701	Bailed to 701 ft. Recovered a slight volume of gas.
Simpson Core Test 31		
DST 01	101-355	Flowed oil at 125 BPD and gas at 4 MCFPD.
Simpson 1		
DST 01	115-308	Bailed hole dry. Recovered 1-2 qt of oil and a small volume of gas.
DST 02	115-413	Bailed hole dry. Recovered about 1 gal of oil.
DST 03	5,954-7,002	Light blow. Recovered 4,030 ft of gas-cut mud.
DST 04	5,954-7,002	Recovered 5,471 ft of fluid. Lower 2,000 ft was gas-cut water.
DST 05	5,954-7,002	Swabbing recovered gas at 1,000 MCFPD and saltwater at 480 BPD.
Topagoruk 1		
DST 01	5,960-6,052	Very slight blow, then packer failed.
DST 02	6,050-6,162	Moderate blow, decreasing. Recovered 796 ft of mud.
East Topagoruk 1		
DST 01	2,216-2,254	Weak blow. Recovered 1,880 ft of gas-cut mud and water.
Umiat 1		
DST 01	530-584	Recovered 37 ft of oil-cut mud.
DST 02	679-692	Recovered 15 ft of mud.
DST 03	918-1,027	Packer failed.
DST 04	1,213-1,350	Recovered 30 ft of oil-cut mud.
Naval Petroleum Reserve No. 4 Program--Continued		
Umiat 1--Continued		
DST 05	1,325-1,383	Recovered 75 ft of oil-cut mud.
DST 06	1,325-1,414	Recovered mud and oil-cut water.
DST 07	1,693-1,816	Recovered water and oil-cut mud. Misrun.
DST 08	2,252-2,370	Recovered 150 ft of oil-cut mud.
Umiat 2		
DST 01	103-345	Bailed hole dry. Recovered water with a trace of oil and gas.
DST 02	389-444	Recovered mud and oil-cut water.
DST 03	103-444	Bailed dry. Slight show of oil and gas.
DST 04	103-544	Bailed 25 gal of water and 1 pint of oil per trip.
DST 05	755-822	Swabbed brackish water and small volumes of oil and gas.
Umiat 3		
DST 01	62-286	Bailed oil at 5 BPD.
DST 02	62-572	Bailed oil at 44-50 BPD.
IP 01	62-572	Initial oil-production potential, 13-28 BPD.
Umiat 4		
DST 01	33-354	Bailing for 15 minutes produced oil at 200 BPD.
DST 02	33-427	Bailed oil at 7 BPD. Freezing formation water may limit production.
IP 01	33-427	Pumping test. Pumped oil at 14 BPD.
Umiat 5		
DST 01	32-510	Bailed oil at 7 BPD.
DST 02	32-615	Bailed oil at 103-156 BPD.
DST 03	32-615	Pumped oil at 70 BPD.
DST 04	32-837	Bailed water at 48 BPD.
DST 05	771-1,077	Recovered drilling fluid and water. Packer failed.
DST 06	32-1,077	Bailed oil at 121 BPD.
DST 07	32-1,077	Swabbed oil at 347-478 BPD.
IP 01	335-1,060	Pumping test. Pumped oil at 115-448 BPD.
Umiat 6		
DST 01	35-528	Bailed oil at 7 BPD.
DST 02	35-800	Water-shutoff test. Pumped oil at 33 BPD, water at 14 BPD, and a small volume of gas.
DST 03	35-783	Water-shutoff test. Bailed water at 5-120 BPD.
Umiat 7		
DST 01	52-650	Water-shutoff test. Bailed water at 2 BPD.
DST 02	52-780	Bailed 3 hours and recovered no water.
DST 03	52-827	Bailed water at 11-40 BPD.
DST 04	52-833	Bailed oil and water at 23 BPD.
DST 05	52-838	Bailed water at 23-28 BPD.
DST 06	52-850	Bailed water at 19 BPD.
DST 07	52-867	Water-shutoff test. Bailed water at 54 BPD.
DST 08	1,196-1,235	Water-shutoff test. Bailed water at 3 BPD.
DST 09	1,196-1,278	Water-shutoff test. Bailed water at 82 BPD.
Umiat 8		
DST 01	50-640	Bailed oil at 3 BPD.
DST 02	50-820	Bailed oil at 120-144 BPD.
DST 03	50-838	Bailed oil at 132 BPD.
DST 04	50-875	Bailed oil at 120 BPD.
DST 05	50-895	Bailed oil at 104 BPD.
DST 06	50-905	Bailed oil at 72 BPD.
DST 07	50-915	Bailed oil at 72 BPD.
DST 08	50-967	Bailed oil at 84 BPD.
DST 09	50-1,080	Swabbed and pumped oil at 72 BPD.

TABLE 15.5.—*Summary of tests for subsurface fluids in Government-drilled wells on the North Slope of Alaska*—Continued

Test No.	Interval tested (ft)	Results
Naval Petroleum Reserve No. 4 Program--Continued		
Umiat 8--Continued		
DST 10	50-1,327	Bailed oil at 360 BPD.
DST 11	50-1,327	Flowed oil at 60 BPD and gas at 442 MCFPD.
IP 01	1,231-1,327	Initial production potential, 5,859 MCFPD.
Umiat 9		
DST 01	47-533	Swabbing recovered 2 bbl of mud.
DST 02	866-901	Swabbing recovered 3 bbl of mud.
DST 03	959-1,017	Swabbing recovered 5 bbl of mud.
DST 04	61-1,257	Pumped gas-cut oil at 240 BPD.
DST 05	61-1,100	Swabbed oil at 300 BPD.
DST 06	61-948	Swabbed oil at 160 BPD.
DST 07	61-850	Swabbed oil at 130 BPD.
DST 08	61-748	Swabbed oil at 280 BPD.
DST 09	61-555	Swabbed oil at 62 BPD.
DST 10	1,245-1,255	Swabbed dry and remained dry for 19 hours.
DST 11	1,218-1,255	Swabbed dry and remained dry.
DST 12	1,135-1,255	Swabbing showed no fluid entering hole.
DST 13	1,017-1,255	Swabbing produced no fluid.
DST 14	960-1,255	Do.
DST 15	900-1,255	Do.
DST 16	866-1,255	Do.
Umiat 10		
DST 01	70-532	Bailed dry and remained dry after 10.5 hours.
DST 02	70-753	Bailed oil at 96 BPD.
DST 03	70-980	Bailed oil at 130 BPD.
DST 04	70-1,095	Bailed oil at 215 BPD.
DST 05	70-1,124	Bailed oil at 290 BPD.
DST 06	1,339-1,573	Swabbed oil at 12 BPD.
Umiat 11		
DST 01	512-549	Misrun.
DST 02	512-549	Recovered 70 ft of mud.
DST 03	735-782	Recovered 50 ft of mud.
DST 04	792-805	Recovered 25 ft of mud.
DST 05	1,325-1,356	Recovered 127 ft of mud.
DST 06	2,053-2,097	Recovered 90 ft of water-cut mud.
DST 07	2,095-2,145	Recovered 950 ft of water.
DST 08	2,375-2,411	Recovered 102 ft of water.
DST 09	2,447-2,461	Recovered 1,304 ft of water.
DST 10	2,814-2,830	Recovered 1,944 ft of water.
DST 11	2,832-2,850	Recovered 2,285 ft of water.
Gubik 1		
DST 01	1,438-1,495	Misrun.
DST 02	1,438-1,495	Flowed gas to surface in 13 minutes. Recovered 120 ft of fluid.
DST 03	1,681-1,738	Flowed gas to surface in seconds at 2,060 MCFPD.
DST 04	3,435-3,519	Packer failed.
DST 05	3,440-3,519	Do.
DST 06	3,488-3,519	Flowed gas at 2,561 MCFPD.
DST 07	3,491-3,608	Packer failed.
DST 08	3,521-3,608	Flowed gas at 823 MCFPD.
Gubik 2		
DST 01	1,145-1,201	Recovered 200 ft of mud.
DST 02	1,308-1,351	Recovered 175 ft of gas and water-cut mud.
DST 03	1,355-1,402	Recovered 497 ft of gas-cut water.
DST 04	1,431-1,502	Recovered 500 ft of water.
DST 05	1,504-1,554	Recovered 115 ft of mud.
DST 06	1,674-1,737	Recovered 113 ft of mud.
DST 07	1,792-1,841	Flowed gas at 8,000 MCFPD.
DST 08	1,844-1,885	Flowed gas at undetermined rate because of frozen lines.
DST 09	1,876-1,885	Recovered 7 gal of oily, gassy water and too small a volume of gas to measure.
DST 10	1,928-1,984	Recovered 400 ft of oily, gassy, water-cut mud.
DST 11	2,096-2,146	Packer failed.
DST 12	2,103-2,146	Do.
DST 13	3,450-3,496	Recovered 195 ft of water-cut mud.
DST 14	3,781-3,809	Recovered 1,910 ft of water.
DST 15	3,872-3,892	Recovered 10 ft of water-cut mud.
Naval Petroleum Reserve No. 4 Program--Continued		
Gubik 2--Continued		
DST 16	4,034-4,060	Packer failed.
DST 17	4,038-4,060	Do.
DST 18	4,033-4,060	Do.
DST 19	4,039-4,060	Recovered 12 ft of water-cut mud.
DST 20	4,233-4,261	Packer failed.
DST 21	4,233-4,261	Do.
DST 22	4,232-4,261	Recovered 60 ft of oil-cut mud.
Kaolak 1		
DST 01	4,799-4,874	Misrun.
DST 02	4,804-4,874	Do.
Barrow Program		
South Barrow 5		
DST 01	2,320-2,325	Flowed gas to surface at 485 MCFPD.
South Barrow 6		
DST 01	2,276-2,343	Flowed gas at 3,000 MCFPD. Recovered 20 ft of mud.
South Barrow 7		
DST 01	2,178-2,317	Water-shutoff test. Flowed gas to surface in 5 minutes. Recovered 190 ft of mud.
IP 01	2,238-2,351	Initial production potential, 880 MCPFD (calculated absolute open flow measured with questionably calibrated gage).
South Barrow 8		
IP 01	2,261-2,359	Initial production potential, 938 MCFPD (calculated absolute open flow).
South Barrow 9		
DST 01	1,995-2,130	Packer failed.
DST 1A	2,040-2,130	Flowed gas to surface in 25 minutes at 125 MCFPD.
DST 02	2,338-2,449	Flowed gas to surface in 2 minutes at 2,000 MCFPD.
IP 01	2,384-2,450	Initial production potential, 4,900 MCFPD (calculated absolute open flow).
South Barrow 10		
DST 01	2,250-2,290	Very weak blow. Recovered 6 ft of mud.
DST 02	2,250-2,349	Flowed gas to surface in 1 minute. Recovered 2 ft of mud.
South Barrow 11		
DST 01	2,185-2,350	Flowed gas to surface in 2 minutes at unreported rate.
South Barrow 12		
DST 01	1,885-1,985	Weak blow decreasing to very weak. Flowed gas to surface in 22 minutes. Recovery too small to measure.
DST 02	1,985-2,101	Packer failed.
DST 03	1,946-2,101	Do.
DST 04	2,100-2,250	Flowed gas to surface in 20 minutes. Recovered 950 ft of oil and gas-cut muddy saltwater.
DST 05	2,192-2,285	No data.
DST 06	2,008-2,088	Flowed gas at rate too small to measure.

TABLE 15.5.—*Summary of tests for subsurface fluids in Government-drilled wells on the North Slope of Alaska*—Continued

Test No.	Interval tested (ft)	Results
		Barrow Program--Continued
		Iko Bay 1
DST 01	2,541-2,731	Recovered 90 ft of mud and 1 ft of oil.
		South Barrow 14
DST 01	1,947-2,100	Flowed gas at 2,400 MCFPD.
IP 01	1,947-2,130	Initial production potential, 3,700 MCFPD (calculated absolute open flow).
		South Barrow 17
DST 01	1,512-1,715	Flowed gas to surface in 1.5 hours at rate too small to measure.
DST 02	2,105-2,147	Flowed gas at 1,090 MCFPD.
DST 03	2,212-2,322	Flowed gas to surface in 25 minutes. Recovered 24 bbl of gas and oil-cut mud.
DST 04	2,212-2,345	Flowed gas to surface in 2 hours. Recovered 24 bbl of gas and oil-cut mud.
IP 01	2,101-2,127	Initial production potential, 6,500 MCFPD (calculated absolute open flow).
		South Barrow 19
DST 01	2,161-2,243	Flowed gas to surface in 23 minutes at 800 MCFPD.
IP 01	2,018-2,044	Initial production potential, 7,220 MCFPD (calculated absolute open flow). Recovered 2.6 bbl of gas- and water-cut oil.
		South Barrow 20
DST 01	2,127-2,314	Flowed gas to surface in 1 hour at 12 MCFPD. Recovered 2.6 bbl of gas- and water-cut oil.
IP 01	1,994-2,082	Initial production potential, 1,300 MCFPD. Recovered 1 bbl of water.
		South Barrow 15
DST 01	2,080-2,136	Packer failed.
DST 02	2,095-2,136	Moderate blow increasing to strong. Packer failed after 20 minutes.
DST 03	2,105-2,136	Flowed gas to surface in 4 minutes at 500 MCFPD.
DST 04	2,188-2,278	Recovered 2,090 ft of water.
IP 01	2,054-2,051	Initial production potential, 1,000 MCFPD.
		South Barrow 18
IP 01	2,056-2,076	Initial production potential, 1,370 MCFPD.
		National Petroleum Reserve in Alaska Program
		South Harrison Bay 1
DST 01	7,119-7,207	Recovered volume of water too small to measure.
DST 02	7,120-7,290	Recovered water and mud. Sample chamber recovered mud.
DST 03	5,680-5,790	Recovered volume of gas too small to measure. Sample chamber recovered slightly gas cut mud, gas, and a trace of dead oil.
		W.T. Foran 1
DST 01	7,587-7,676	Flowed water to surface in 78 minutes. Recovered 364 ft of water and 1,107 ft of mud. Sample chamber recovered gas and water.
DST 02	8,205-8,253	Misrun.
DST 03	8,206-8,283	Recovered 3,313 ft of water, 2,044 ft of mud, and 628 ft of formation water. Sample chamber recovered gas, oil, and water.
DST 04	7,512-7,520	Flowed saltwater to surface in 117 minutes at 96 BPD. Sample chamber recovered gas and a trace of oil and water.
		National Petroleum Reserve in Alaska Program--Continued
		South Simpson 1
DST 01	6,522-6,568	Flowed gas to surface in 10 minutes at 75 MCFPD.
DST 02	6,183-6,241	Recovered 500 ft of water cushion and 750 ft of water-cut mud. Sample chamber recovered gas-cut mud with an oil sheen.
DST 03	5,807-5,946	Recovered 4 bbl of mud and 500 ft of water cushion. Sample chamber recovered mud.
		Walakpa 1
DST 01	2,063-2,120	Flowed gas to surface in 14 minutes at 200-854 MCFPD. Reported pressure and rates unreliable because of freezing and thawing of flowline.
DST 02	2,073-2,088	Flowed gas to surface in 14 minutes at 335 MCFPD.
		West Dease 1
DST 01	3,699-3,730	Recovered 0.69 bbl of mud and oil.
		Tulageak 1
DST 01	3,770-3,825	Recovered 530 ft of water cushion and 620 ft of saltwater-cut mud. Possible partial plugging during flow and possible leakage during shut-in.
		Walakpa 2
DST 01	2,564-2,720	Misrun.
DST 02	2,606-2,634	Flowed gas to surface in 8 minutes at 369-2,293 MCFPD and varying pressure caused by formation of hydrates and leak in production tubing.
IP 01	2,606-2,634	Initial production potential, 2,200 MCFPD.
		North Inigok 1
DST 01	8,257-8,360	Flowed gas to surface in 52 minutes at 80 MCFPD. Surface pressure declined.
		Lisburne 1
DST 01	11,618-11,941	Weak blow. Recovered 300 ft of water cushion and 2,100 ft of mud filtrate. Sample chamber recovered gas and mud filtrate.
DST 02	7,645-7,662	Recovered 110 ft of mud. Tool plugged.
DST 03	7,645-7,662	Recovered 10 bbl of mud and 61 bbl of water. Sample chamber recovered sour gas and formation water.
DST 04	7,022-7,104	Flowed gas to surface in 28 minutes at 213 MCFPD and declining pressure.
		Awuna 1
DST 01	8,297-8,412	Flowed saltwater to surface in 65 minutes at 2,057 BPD.
		Drew Point 1
DST 01	5,850-5,922	Weak blow. Recovered 63 ft of muddy water.
DST 02	7,472-7,572	Weak blow. Recovered 110 ft of muddy water.
DST 03	7,765-7,821	Sample chamber recovered muddy water. No recovery from test string.
		Ikpikpuk 1
DST 01	7,446-7,472	Weak blow increasing to strong. Recovered 1,338 ft of gas-cut mud.
DST 02	6,877-6,923	Flowed gas to surface in 50 minutes at rate too small to measure.

TABLE 15.5.—*Summary of tests for subsurface fluids in Government-drilled wells on the North Slope of Alaska*—Continued

Test No.	Interval tested (ft)	Results
		National Petroleum Reserve in Alaska Program--Continued
		J.W. Dalton 1
DST 01	7,812-8,140	Flowed muddy water with an oil sheen at 1,218 BPD.
DST 02	8,568-8,665	Medium to strong blow. Recovered small volume of gas, 5 bbl of asphalt, 3.3 bbl of water cushion, 29 bbl of mud filtrate, and 80 bbl of saltwater.
DST 03	8,482-8,538	Moderate to strong blow. Recovered 5 bbl of asphalt, 6.8 bbl of watery mud, and 22 bbl of oily water.
DST 04	8,392-8,436	Recovered 7.5 bbl of water cushion and mud with an oil sheen.
DST 05	7,971-7,976	Flowed gas to surface in 165 minutes and water at 258 BPD.
		East Simpson 2
DST 01	7,165-7,197	Flowed gas at rate too small to measure and saltwater with a trace of oil at 960 BPD declining to 576 BPD.
		Seabee 1
DST 01	5,340-5,388	Misrun.
DST 02	5,310-5,402	Packer failed.
DST 03	5,366-5,394	Flowed gas at 4,000-6,700 MCFPD with various choke sizes at declining rates and pressures.
DST 04	2,652-2,664	Flowed gas to surface in 9 minutes at rate too small to measure.

24. The Ugnuravik Group, (informal) highly radioactive zone (HRZ), Miluveach Formation, and Kalubik Formation are names proposed by Carman and Hardwick (1983) for Cretaceous strata immediately overlying and underlying the Kuparuk Formation (see note 25).

25. The name Kuparuk Formation of Carman and Hardwick (1983) is herein adopted as the formal name of that interval of Lower Cretaceous (Neocomian) sandstone and shale overlying the Kingak Shale and underlying a regional unconformity. The type section is the interval between 1,795 and 1,909 m (5,890-6,262 ft) in the Ugnu State No. 1 well located in the Beechey Point quadrangle in sec. 22, T. 12 N., R. 9 E. The brevity of the name Kuparuk Formation is preferable to the longer names also applied to the same interval, namely the Kuparuk River Formation (Jamison and others, 1980) or (informal) Kuparuk River sands of local usage (North Slope Stratigraphic Committee, 1970). As illustrated by Carman and Hardwick (1983, fig. 7), the Kuparuk Formation in the Ugnu well is more complete than in the North Kuparuk State No. 1 well, the type section originally proposed by the North Slope Stratigraphic Committee (1970).

26. The Ipewik unit and Tingmerkpuk subunit are informal names used by Crane and Wiggins (1976) for Jurassic and Lower Cretaceous rocks that crop out in the western Brooks Range and foothills. See Molenaar (chapter 25) for an interpretation of the regional setting of these units.

27. The Kingak Shale has been revised (Molenaar, chapter 25) to include Lower Cretaceous (Neocomian) strata below the pebble shale unit in the NPRA and elsewhere on the North Slope.

28. The Simpson sandstone is an informal name of local usage for a Middle or Upper Jurassic glauconitic sandstone interval within the Kingak Shale in the north-central NPRA. The sandstone is identified as that interval in the Kugrua, Peard, South Meade, and Topagoruk wells that correlates with the sandstone interval between 1,989 and 2,044 m (6,525-6,705 ft) in South Simpson No. 1 well.

29. The Barrow sandstone is an informal name of local usage for a highly bioturbated silty sandstone interval of Early Jurassic age near the base of the Kingak Shale in the northern NPRA. Gas accumulations in this sandstone near Barrow were described by Lantz (1981).

30. The Tiglukpuk Formation was abandoned by Imlay and Detterman (1973), following the recommendation of Jones and Grantz (1964).

31. The Sag River Sandstone was adopted for the U.S. Geological Survey by Reiser (1970) (following definition of the North Slope Stratigraphic Committee, 1970). The Sag River Formation is a name proposed by Jones and Speers (1976).

32. The Karen Creek Sandstone, an approximate stratigraphic correlate of the Sag River Sandstone, was named by Detterman and others (1975) and consists of a resistant interval of sandstone and siltstone cropping out in northeastern Alaska.

33. The Etivluk Group, Otuk Formation, Blankenship Member (of Otuk Formation), and Kuna Formation are names proposed by Mull and others (1982) for rocks cropping out in the central and western Brooks Range. The Siksikpuk Formation, which was named by Patton (1957), is included in the Etivluk Group.

34. New information on the age and structural interpretation of the Nuka Formation was provided by Tailleur and others (1973).

35. The Sadlerochit Group with its various formations and members (table 15.1) consists of units either revised in rank or newly proposed by Detterman and others (1975) for rocks that crop out in northeastern Alaska. Shortly after their publication, Jones and Speers (1976) proposed a slightly different nomenclature for these same rocks in the subsurface of the Prudhoe Bay area. In the latter scheme, some of the members of Detterman and others' Ivishak Formation are elevated to formation rank (Fire Creek Siltstone and Kavik Shale), and Ivishak Sandstone (formational rank) is used instead of Ledge Sandstone Member.

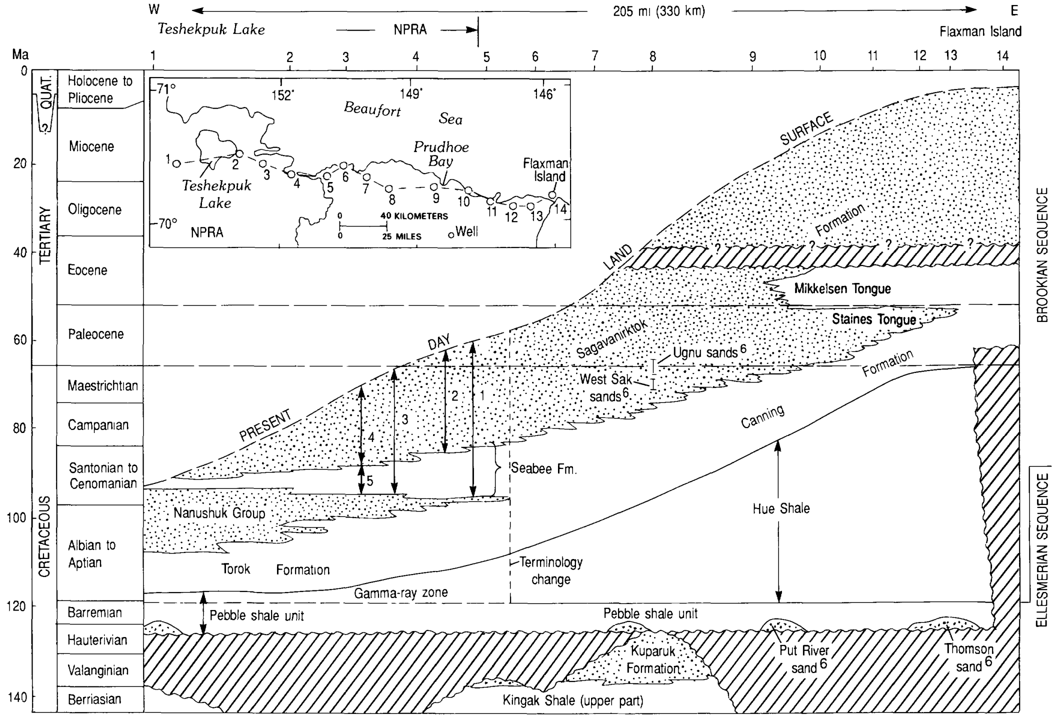
36. Paleontologic study of the Lisburne Group in several NPRA wells (South Harrison Bay No. 1, Inigok No. 1, Ikpikpuk No. 1, Kugrua No. 1, and Tunalik No. 1) indicates that this group apparently is as young as Early Permian (Bird, 1978; Witmer and others, 1981). This age determination is based on occurrence of nodosariid foraminifers whose earliest appearance in the fossil record is Early Permian (B.L. Mamet, written commun., 1982).

37. The upper limestone, lower limestone, and dolomite units are informal names used by Bird and Jordan (1977) for subdivisions of the Lisburne Group in the subsurface of the Prudhoe Bay area.

38. The age of the Kogruk Formation in the Lisburne Hills has been revised to range upward into the Early Pennsylvanian (Dutro, 1987).

39. The upper part (post-Kanayut Conglomerate) of the Endicott Group is mostly a clastic-facies equivalent of the Lisburne Group, a carbonate unit. Because the Lisburne Group is known to range in age to as young as Permian in the northern NPRA, the Endicott Group in this area may likewise be as young as Permian.

40. The Itkilyariak Formation, named by Mull and Mangus (1972), is essentially a red-colored facies



¹ Sagavanirktok Fm. and Colville Gp., undivided ² Sandstone of Colville Gp. and Sagavanirktok Fm., undivided
³ Colville Group ⁴ Sandstone of Colville Group ⁵ Shale of Colville Group ⁶ Unit of local usage

FIGURE 15.1.—Generalized time-stratigraphic cross section of Cretaceous and Tertiary rocks along coastal plain of central North Slope of Alaska, based on data from 14 wells and illustrating stratigraphic nomenclature. Series and stage boundaries are approximate; numerical time scale modified from Palmer (1983). Strata removed by unconformities have not been restored; time span of Eocene unconformity is poorly controlled. Location of wells shown in inset; refer to well-correlation section by Molenaar and others (1986) for identification of wells. Quaternary surficial deposits and Gubik Formation of Pliocene to Holocene age are not shown.

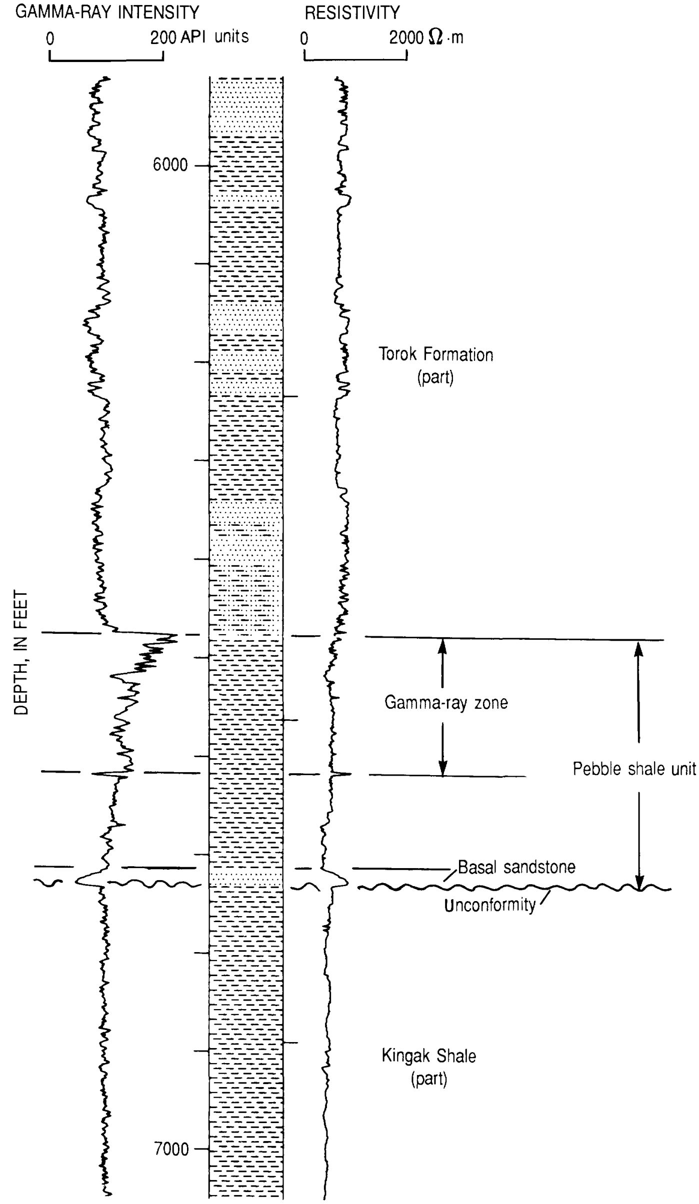


FIGURE 15.2.—Nomenclature, stratigraphic relations, and log response for the pebble shale unit in the subsurface of NPRA, as seen in South Meade No. 1 well (API No. 50-163-20001). As shown in figure 15.1, the gamma-ray zone is included in the Hue Shale east of the NPRA (Molenaar and others, 1987). Location of well shown in figure 15.3.

that is equivalent to the Kayak Shale and that occurs mostly in the subsurface of the Prudhoe Bay area.

41. The Kanayut Conglomerate has been stratigraphically restricted, its Stuver Member has been stratigraphically extended, and two new members have been named by Nilsen and Moore (1984). The new members, which lie beneath the Stuver Member, are the Shainin Lake Member and the Ear Peak Member.

42. The Beaucoup Formation, named by Dutro and others (1978), is composed of carbonate and clastic rocks in the central Brooks Range.

43. The age of the Baird Group around Hub Mountain in the northwestern Baird Mountains is as old as Middle Cambrian as inferred from mollusks, brachiopods, and trilobites (Dumoulin and Harris, 1985). These fossils confirmed the earlier postulate of Tailleur and others (1975) that unfossiliferous Baird strata below Ordovician graptolite-bearing shale extended the age of the group into the Cambrian.

44. Basement complex is an informal term employed in this summary (table 15.3) for all rocks in the subsurface older than the Endicott Group. The basement complex may be as old as Precambrian and as young as Devonian.

45. Argillite is the informal term for the most common rock type encountered within the (subsurface) basement complex. The age of this rock unit is Ordovician and Silurian in wells at Barrow and Prudhoe Bay (Carter and Laufeld, 1975). This rock unit has been referred to as the Neruokpuk Formation by some workers (Alaska Geological Society, 1972, 1977, 1981).

46. The ages of the Nanook Limestone and Katakturuk Dolomite have been revised by recent field-

work in the Shublik Mountains. The Nanook Limestone is Late Proterozoic or Cambrian to Devonian in age, and the underlying Katakturuk Dolomite is Proterozoic in age (Blodgett and others, 1986).

47. The Neruokpuk Formation was renamed the Neruokpuk Quartzite by Reiser and others (1978) and stratigraphically restricted so as to consist of only Precambrian (quartzite) rocks.

WELL DATA

General information on 126 Government-drilled North Slope wells, patterned after the summary of Collins and Robinson (1967), is given in tables 15.2-15.5. Graphical representations of most of these data are given in Magoon and others (chapter 19). Original data sources were used wherever possible; for wells drilled before 1955, the source of most information is the U.S. Geological Survey (USGS) Professional Paper 305 series (Collins, 1958a, b, c, 1959, 1961; Robinson, 1956, 1958a, b, 1959a, b, 1964; Robinson

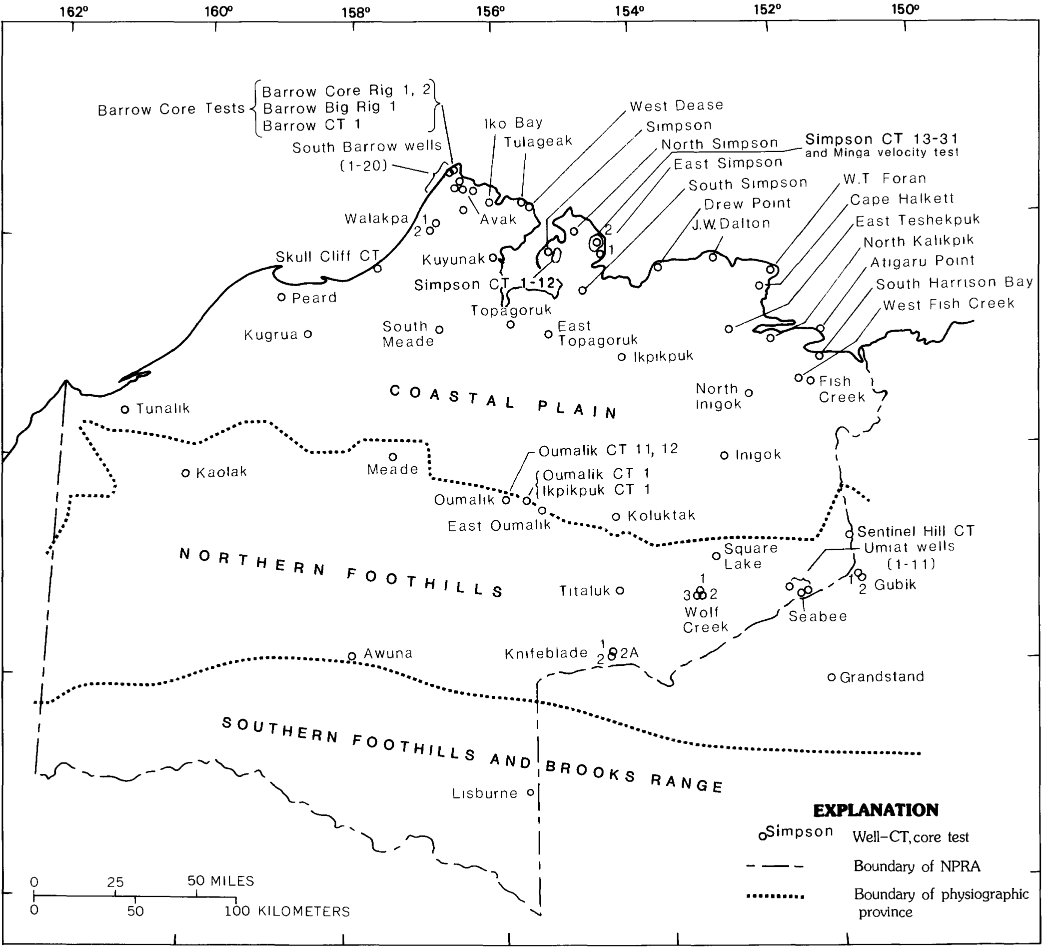


FIGURE 15.3.—Index map of National Petroleum Reserve in Alaska (NPRA) and adjacent area, North Slope, showing names and locations of all 126 government-drilled wells.

and Collins, 1959). For wells drilled after 1955, most information is from unpublished contractor reports currently in the files of the Office of National Petroleum Reserve in Alaska, U.S. Geological Survey, Menlo Park, Calif.

Wells listed in these tables are grouped into four drilling programs, and within each program the wells are listed by API (American Petroleum Institute) number. This well-numbering system is explained below. The four drilling programs are (1) the exploration of Naval Petroleum Reserve No. 4 (NPR-4) by the U.S. Navy (1944-53); (2) the exploration and development of gas reserves in the Barrow area, informally referred to as the Barrow Program (1955-81); (3) the second exploration of NPR-4 by the U.S. Navy (1973-77); and (4) the exploration of the National Petroleum Reserve in Alaska by the U.S. Department of the Interior (1977-81). All the wells included in tables 15.2-15.5 are located in figure 15.3.

The categories of information included in the tables are well identification and hydrocarbon occurrence (table 15.2), stratigraphic data (table 15.3), conventional core data (table 15.4), and test data (table 15.5). Items in each category are explained below.

Well identification and hydrocarbon occurrence data (table 15.2).—Included here is the following information:

a. **Operator**—the Government department or agency responsible for the drilling program.

b. **Well name and number**—unique well identifiers.

c. **Well class**—a well symbol indicating current status of the well and type(s) of hydrocarbon encountered. See Magoon and others (chapter 19, fig. 19.5) for the complete set of well symbols.

d. **Quadrangle name**—the name of the USGS 1:250,000-scale quadrangle in which the well is located.

e. **API well number**—unique 10-digit identifying number applied to wells. The components of this number are diagrammed below. See American Petroleum Institute (1979) for more information.

API well number		
State code	Quadrangle code (Alaska only)	Unique well number[1]
XX	XXX	XXXXX

f. **Well location**—the location coordinates are expressed both in latitude and longitude and by section, township, and range on the basis of currently available maps or surveys. Typographical errors in the reported locations of Skull Cliff Core Test No. 1 (Collins, 1961) and Knifeblade No. 1 (Robinson, 1959a) have been corrected. Also, some well locations have been adjusted to agree with recent topographic maps. These include Umiat numbers 1 through 11 (Molenaar, 1982), Fish Creek No. 1, and Gubik Nos. 1 and 2.

g. **Surface elevation**—elevations of the ground surface and of the kelly bushing (or derrick floor). All measured depths in the well are referenced to the latter elevation.

h. **Date spudded**—the date (month/day/year) on which drilling commenced.

i. **Date completed**—the date (month/day/year) on which the rig was released.

Stratigraphic data (table 15.3).—Included here are both total depth (the greatest depth, measured in feet from the kelly bushing or derrick floor, reached by the drill as reported by the driller) and the well depth (measured in feet from the kelly bushing or derrick floor) to the top of each of the selected rock-stratigraphic units. All well depths are rounded off to the nearest 5 ft to minimize measurement discrepancies caused by cable stretch. Explanations of most of the rock-stratigraphic units are in the section of this paper on stratigraphic nomenclature. Depths reported are updated from the earlier report by Bird (1982).

Conventional core data (table 15.4).—Information given comprises the interval (in feet) over which coring was attempted, the amount of core recovered (in feet), and the stratigraphic unit (formation or group) represented in the core.

Test data (table 15.5).—Information provided includes the type of test, interval of the hole tested, and a brief summary of test results. The drill-stem test (DST) is a type of test conducted during or immediately after the drilling of the well to evaluate the types and flow rates of subsurface fluids. Included are tests conducted through the drill pipe (stem) and bailing tests conducted by lowering a container into the hole on a cable. Relatively long-term tests, usually through a special arrangement of tubing, designed to evaluate the potential production rates of oil or gas are identified in table 15.5 as initial production potential (IP) tests.

REFERENCES CITED

Ager, T.A., Edwards, L.E., Oftedahl, O.G., 1985, Eocene palynomorphs from the Franklin Bluffs, Arctic Slope, northeast Alaska [abs.]: American Association of Stratigraphic Palynologists, Inc., Annual Meeting, 18th, El Paso, Tex., 1985, Program and Abstracts, p. 7.

Ahlbrandt, T.S., ed., 1979, Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, 163 p.

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[1] On January 1, 1967, the State of Alaska began numbering current wells serially within USGS quadrangles, starting with 20001. All wells previously drilled have been assigned API well numbers serially within each quadrangle starting with 10001.

Alaska Geological Society, 1972, Northwest to southeast stratigraphic correlation section, Prudhoe Bay to Ignek Valley, Arctic North Slope, Alaska: Anchorage, Alaska Geological Society.

——— 1977, North to south stratigraphic correlation section Beaufort Sea-Prudhoe Bay-Nora No. 1, Arctic Slope, Alaska: Anchorage, Alaska Geological Society.

——— 1981, West to east stratigraphic correlation section, NPRA-Prudhoe Bay, Arctic Slope, Alaska: Anchorage, Alaska Geological Society.

American Geological Institute, 1956, Handbook of geologic data sheets: Alexandria, Virginia, American Geological Institute.

American Petroleum Institute, 1979, The API well number and standard state and county numeric codes including offshore waters: Washington, D.C., American Petroleum Institute Bulletin D12A, 136 p.

Bird, K.J., 1978, New information on the Lisburne Group (Carboniferous and Permian) in the National Petroleum Reserve in Alaska (NPRA) [abs.]: American Association of Petroleum Geologists Bulletin, v. 62, no. 5, p. 880.

——— 1982, Rock-unit reports of 228 wells drilled on the North Slope, Alaska: U.S. Geological Survey Open-File Report 82-278, 106 p.

Bird, K.J., and Jordan, C.F., 1977, Lisburne Group (Mississippian and Pennsylvanian), potential major hydrocarbon objective of Arctic Slope, Alaska: American Association of Petroleum Geologists Bulletin, v. 61, no. 9, p. 1493-1512.

Blodgett, R.B., Clough, J.G., Dutro, J.T., Jr., Ormiston, A.R., Palmer, A.R., and Taylor, M.E., 1986, Age revisions for the Nanook Limestone and Katakturuk Dolomite, northeastern Brooks Range, *in* Bartsch-Winkler, Susan, and Reed, K.M., eds., Geologic studies in Alaska by the U.S. Geological Survey during 1985: U.S. Geological Survey Circular 978, p. 5-10.

Buckingham, M.L., 1987, Fluvio-deltaic sedimentation patterns of the Upper Cretaceous to Lower Tertiary Jago River Formation, Arctic National Wildlife Refuge (ANWR), northeastern Alaska, *in* Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope Geology: Bakersfield, Calif., Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 529-540.

Campbell, R.H., 1965a, Kisimilok Formation, *in* Cohee, G.V., and West, W.S., eds., Changes in stratigraphic nomenclature by the U.S. Geological Survey, 1963: U.S. Geological Survey Bulletin 1194-A, p. A28-A29.

——— 1965b, Ogotoruk Formation, *in* Cohee, G.V., and West, W.S., eds., Changes in stratigraphic nomenclature by the U.S. Geological Survey, 1963: U.S. Geological Survey Bulletin 1194-A, p. A25-26.

——— 1965c, Telavirak Formation, *in* Cohee, G.V., and West, W.S., eds., Changes in stratigraphic nomenclature by the U.S. Geological Survey, 1963: U.S. Geological Survey Bulletin 1194-A, p. A26-A28.

Carman, G.J., and Hardwick, Peter, 1983, Geology and regional setting of Kuparuk Oil Field, Alaska: American Association of Petroleum Geologists Bulletin, v. 67, no. 6, p. 1014-1031.

Carter, Claire, and Laufeld, Sven, 1975, Ordovician and Silurian fossils in well cores from North Slope of Alaska: American Association of Petroleum Geologists Bulletin, v. 59, no. 3, p. 457-464.

Collins, F.R., 1958a, Test wells, Umiat area, Alaska: U.S. Geological Survey Professional Paper 305-B, p. 71-206.

——— 1958b, Test wells, Topagoruk area, Alaska: U.S. Geological Survey Professional Paper 305-D, p. 265-316.

——— 1958c, Test wells, Meade and Kaolak areas, Alaska: U.S. Geological Survey Professional Paper 305-F, p. 341-376.

——— 1959, Test wells, Square Lake and Wolf Creek areas, Alaska: U.S. Geological Survey Professional Paper 305-H, p. 423-484.

——— 1961, Core test and test wells, Barrow area, Alaska: U.S. Geological Survey Professional Paper 305-K, p. 569-644.

Collins, F.R., and Robinson, F.M., 1967, Subsurface stratigraphic, structural and economic geology, northern Alaska: U.S. Geological Survey open-file report, 259 p.

Crane, R.C., and Wiggins, V.D., 1976, Ipewick (sic) Formation, significant Jurassic-Neocomian map unit in northern Brooks Range foldbelt [abs.]: American Association of Petroleum Geologists Bulletin, v. 60, no. 12, p. 2177.

Detterman, R.L., Reiser, H.N., Brosgé, W.P., and Dutro, J.T., Jr., 1975, Post-Carboniferous stratigraphy, northeastern Alaska: U.S. Geological Survey Professional Paper 886, 46 p.

Dinter, D.A., 1985, Quaternary sedimentation of the Alaskan Beaufort shelf; influence of regional tectonics, fluctuating sea levels, and glacial sediment sources: Tectonophysics, v. 114, p. 133-161.

Dumoulin, J.A., and Harris, A.G., 1985, Lower Paleozoic carbonate rocks of Baird Mountains quadrangle, Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 69, no., 4, p. 662-663.

Dutro, J.T., Jr., 1987, Revised megafossil biostratigraphic zonation for the Carboniferous of northern Alaska, *in* Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope Geology: Bakersfield, Calif., Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 359-364.

Dutro, J.T., Jr., Brosgé, W.P., Reiser, H.N., and Detterman, R.L., 1978, Beaucoup Formation, a new Upper Devonian stratigraphic unit in the central Brooks range, Alaska, *in* Sohl, N.F., and Wright, W.B., eds., Changes in stratigraphic nomenclature by the U.S. Geological Survey, 1978: U.S. Geological Survey Bulletin 1482-A, p. A63-A69.

Gryc, George, Patton, W.W., Jr., and Payne, T.G., 1951, Present Cretaceous stratigraphic nomenclature of northern Alaska: Washington Academy of Science Journal, v. 41, no. 5, p. 159-167.

Hamilton, T.D., 1986, Late Cenozoic glaciation of the central Brooks Range, *in* Hamilton, T.D., Reed, K.M., and Thorson, R.M., eds., Glaciation in Alaska; the geologic record: Anchorage, Alaska Geological Society, p. 9-49.

Huffman, A.C., Jr., ed., 1985, Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, 129 p.

Imlay, R.W., and Detterman, R.L., 1973, Jurassic paleobiogeography of Alaska: U.S. Geological Survey Professional Paper 801, 34 p.

Jamison, H.C., Brockett, L.D., and McIntosh, R.A., 1980, Prudhoe Bay; a 10-year perspective, *in* Halbouty, M.T., ed., Giant oil and gas fields of the decade 1968-1978: American Association of Petroleum Geologists Memoir 30, p. 289-314.

Jones, D.L., and Grantz, Arthur, 1964, Stratigraphic and structural significance of Cretaceous fossils from Tiglukpuk Formation, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 48, no. 9, p. 1462-1474.

Jones, H.P., and Speers, R.G., 1976, Permo-Triassic reservoirs of Prudhoe Bay field, North Slope, Alaska, *in* Braunstein, Jules, ed., North American oil and gas fields: American Association of Petroleum Geologists Memoir 24, p. 23-50.

Kopf, R.W., 1970, Geologic names in use north of the Brooks Range, Alaska, *in* Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geologic seminar on the North Slope of Alaska: Los Angeles, American Association of Petroleum Geologists, Pacific Section, p. Q1-Q5.

Lantz, R.J., 1981, Barrow gas fields; N. Slope, Alaska: Oil and Gas Journal, v. 79, no. 13 [March 30, 1981], p. 197-200.

Leffingwell, E. de K., 1919, The Canning River region, northern Alaska: U.S. Geological Survey Professional Paper 109, 251 p.

Molenaar, C.M., 1982, Umiat field, an oil accumulation in a thrust-faulted anticline, North Slope of Alaska, *in* Powers, R.B., ed., Geologic studies of the Cordilleran thrust belt: Denver, Rocky Mountain Association of Geologists, v. 2, p. 537-548.

Molenaar, C.M., Bird, K.J., and Collett, T.S., 1986, Regional correlation sections across the North Slope of Alaska: U.S. Geological Survey Miscellaneous Field Studies Map 1907.

Molenaar, C.M., Bird, K.J., and Kirk, A.R., 1987, Cretaceous and Tertiary stratigraphy of northeastern Alaska, *in* Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope Geology: Bakersfield, Calif., Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 513-528.

Mull, C.G., 1987, Kemik Sandstone, Arctic National Wildlife Refuge, northeastern Alaska, *in* Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope Geology: Bakersfield, Calif., Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 405-431.

Mull, C.G., and Mangus, M.D., 1972, Itkilyariak Formation; new Mississippian formation of Endicott Group, Arctic Slope of Alaska: American Association of Petroleum Geologists Bulletin, v. 56, no. 8, p. 1364-1369.

Mull, C.G., Tailleur, I.L., Mayfield, C.F., Ellersieck, I.F., and Curtis, S.M., 1982, New upper Paleozoic and lower Mesozoic stratigraphic units, central and western Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 66, no. 3, p. 348-362.

Nelson, R.E., and Carter, L.D., 1985, Pollen analysis of a Late Pliocene and Early Pleistocene section from the Gubik Formation of Arctic Alaska: Quaternary Research, v. 24, no. 3, p. 295-306.

Nilsen, T.H., and Moore, T.E., 1984, Stratigraphic nomenclature for the Upper Devonian and Lower Mississippian(?) Kanayut Conglomerate, Brooks Range, Alaska: U.S. Geological Survey Bulletin 1529-A, p. A1-A64.

North Slope Stratigraphic Committee, Alaska Geological Society, 1970, The Sag River Sandstone and Kuparuk River sands, two important subsurface units in the Prudhoe Bay Field, *in* Adkison, W.W., and Brosgé, M.M., eds., Proceedings of the geologic seminar on the North Slope of Alaska: Los Angeles, American Association of Petroleum Geologists, Pacific Section, p. P1-P3.

Palmer, A.R., 1983, The Decade of North American Geology 1983 geologic time scale: Geology, v. 11, p. 503-504.

Patton, W.W., Jr., 1957, A new upper Paleozoic formation, central Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 40, no. 2, p. 209-254.

Reiser, H.N., 1970, Northeastern Brooks Range; a surface expression of the Prudhoe Bay section, *in* Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geologic seminar on the North Slope of Alaska: Los Angeles, American Association of Petroleum Geologists, Pacific Section, p. K1-K14.

Reiser, H.N., Norris, D.K., Dutro, J.T., Jr., and Brosgé, W.P., 1978, Restriction and renaming of the Neruokpuk Formation, northeastern Alaska, *in* Sohl, N.F., and Wright, W.B., eds., Changes in stratigraphic nomenclature by the U.S. Geological Survey, 1977: U.S. Geological Survey Bulletin 1457-A, p. A106-107.

Robinson, F.M., 1956, Core tests and test wells, Oumalik area, Alaska: U.S. Geological Survey Professional Paper 305-A, p. 1-64.

—— 1958a, Test wells, Gubik area, Alaska: U.S. Geological Survey Professional Paper 305-C, p. 207-260.

—— 1958b, Test well, Grandstand area, Alaska: U.S. Geological Survey Professional Paper 305-E, p. 317-336.

—— 1959a, Test wells, Titaluk and Knifeblade areas, Alaska: U.S. Geological Survey Professional Paper 305-G, p. 377-416.

—— 1959b, Test wells, Simpson area, Alaska: U.S. Geological Survey Professional Paper 305-J, p. 523-568.

—— 1964, Core tests, Simpson area, Alaska: U.S. Geological Survey Professional Paper 305-L, p. 645-730.

Robinson, F.M., and Collins, F.R., 1959, Core test, Sentinel Hill area and test well, Fish Creek area, Alaska: U.S. Geological Survey Professional Paper 305-I, p. 485-521.

Robinson, F.M., Rucker, F.P., and Bergquist, H.R., 1956, Two subsurface formations of Early Cretaceous age, *in* Gryc, George, and others, Mesozoic sequence in Colville River region, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 40, no. 2, p. 223-233.

Tailleur, I.L., Mamet, B.L., and Dutro, J.T., Jr., 1973, Revised age and structural interpretations of Nuka Formation at Nuka Ridge, northwestern Alaska: American Association of Petroleum Geologists, v. 57, no. 7, p. 1348-1352.

Tailleur, I.L., Hamilton, W.B.,Mayfield, C.F., and Pessel, G.H., 1975, New graptolite discovery indicates Lower Ordovician rocks in southwestern Brooks Range, *in* Geological Survey research, 1975: U.S. Geological Survey Professional Paper 975, p. 64.

Werner, M.R., 1987, West Sak and Ugnu sands; low-gravity oil zones of the Kuparuk River area, Alaskan North Slope, *in* Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Calif., Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 109-118.

Williams, J.R., Yeend, W.E., Carter, L.D., and Hamilton, T.D., 1977, Preliminary surficial deposits map, National Petroleum Reserve, Alaska: U.S. Geological Survey Open-File Report 77-868, scale 1:500,000, 2 sheets.

Witmer, R.J., Haga, Hideyo, and Mickey, M.B., 1981, Biostratigraphic report of thirty-three wells drilled from 1975 to 1981 in National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 81-1166, 47 p.

TABLE 15.4

TABLE 15.4.—*Core data for Government-drilled wells on the North Slope of Alaska*

[Wells listed in same order as in tables 15.2 and 15.3. See figure 15.3 for well locations. Do., ditto]

Interval attempted (ft)	Core recovered (ft)	Rock unit
Naval Petroleum Reserve No. 4 Program (1944-53)		
Simpson Core Test 21		
10-20	10	Surficial deposits and Gubik Formation, undivided.
20-30	10	Do.
30-40	10	Do.
100-110	10	Shale of the Colville Group.
110-120	10	Do.
120-130	10	Do.
130-135	3.5	Do.
135-145	9	Do.
145-150	5	Do.
150-158	4	Do.
158-168	10	Do.
168-178	10	Do.
178-188	10	Do.
188-198	10	Do.
198-208	10	Do.
300-307	4	Do.
400-410	10	Do.
500-508	7	Do.
600-610	8.5	Do.
700-710	2.5	Do.
800-810	4	Do.
900-908	8	do.
1,000-1,007	5	Do.
1,100-1,107	7	Do.
1,200-1,209	9	Do.
1,300-1,305	1	Nanushuk Group.
1,305-1,307	1.75	Do.
1,400-1,410	10	Do.
1,420-1,430	10	Do.
Simpson Core Test 23		
100-110	6	Surficial deposits and Gubik Formation, undivided.
110-115	.2	Shale of the Colville Group.
115-120	4	Do.
200-210	2	Do.
210-218	8	Do.
300-310	10	Do.
400-405	4.5	Do.
405-408	3	Do.
408-410	2	Do.
500-510	10	Do.
600-610	10	Nanushuk Group.
700-710	10	Do.
800-810	9.5	Do.
900-910	10	Do.
1,000-1,010	10	Do.
Simpson Core Test 24		
98-108	1	Shale of the Colville Group.
296-306	9	Do.
446-456	10	Do.
600-610	7	Nanushuk Group.
700-710	7.5	Do.
North Simpson 1		
290-300	4	Shale of the Colville Group.
490-498	8	Do.
690-700	10	Do.
890-900	10	Do.
1,190-1,200	10	Do.
1,489-1,499	10	Do.
1,790-1,800	10	Do.
2,090-2,100	4	Do.
2,390-2,400	0	Do.
2,400-2,410	9	Do.
2,690-2,700	0	Do.
2,700-2,710	7	Do.
2,990-2,998	8	Torok Formation.
3,150-3,160	10	Do.
3,160-3,170	10	Do.
3,170-3,180	9	Do.
3,180-3,190	1	Do.
3,190-3,200	.5	Do.
3,200-3,204	3.25	Do.
3,204-3,209	1	Do.
3,209-3,214	5	Do.
3,214-3,224	7	Do.
3,224-3,234	10	Do.
3,234-3,244	8	Do.
3,244-3,254	10	Do.
3,254-3,264	5	Do.
3,264-3,274	10	Do.
3,274-3,280	4	Do.
3,280-3,290	10	Do.
3,290-3,300	10	Do.
3,300-3,310	10	Do.
3,310-3,320	10	Do.
3,320-3,330	10	Do.
3,330-3,340	10	Do.
3,340-3,350	10	Do.
3,760-3,774	14	Do.
Barrow Core Rig 1		
76-81	2	Surficial deposits and Gubik Formation, undivided.
81-83	0	Do.
84-92	1	Do.
92-96	0	Do.
96-106	1.4	Nanushuk Group.
164-166	0	Do.
169-171	.9	Do.
172-174	.8	Do.
197-199	.8	Do.
230-232	0	Do.
254-257	.6	Do.
295-297	.8	Do.
Barrow Core Rig 2		
173-175	.5	Nanushuk Group.
175-177	0	Do.
185-195	0	Do.
Barrow Big Rig 1		
100-120	4	Nanushuk Group.
170-188	13	Do.
188-206	18	Do.
310-317	1	Do.
667-685	12	Do.
Arcon Barrow 1		
144-147	1.5	Nanushuk Group.
165-175	4	Do.
175-185	8.5	Do.
185-195	10	Do.
196-204	1	Do.
218-227	2.5	Do.
227-237	4	Do.
237-246	1.5	Do.
246-256	2	Do.
256-266	7	Do.
266-276	5	Do.
354-364	3	Do.
447-457	7	Do.
548-558	7.5	Do.
558-568	1.5	Do.
568-578	2	Do.
578-588	7	Do.
588-599	4	Do.
599-609	5	Do.
651-661	7	Do.
752-762	1.5	Do.
857-867	7	Torok Formation.
950-960	7	Do.
1,021-1,031	8.5	Do.
1,152-1,162	10	Do.
1,231-1,241	10	Do.
1,342-1,352	3	Do.
1,432-1,442	10	Do.
South Barrow 1		
1,200-1,210	5	Torok Formation.
1,600-1,610	8	Do.
1,906-1,916	8.16	Do.
2,094-2,100	6	Do.
2,352-2,360	6.5	Do.
2,625-2,635	10	Do.
2,847-2,853	.5	Pebble shale unit.
2,853-2,856	1.5	Do.
3,036-3,046	10	Do.
3,046-3,056	.5	Do.
3,056-3,059	.67	Do.
3,059-3,064	2.83	Do.
3,064-3,067	3	Do.
3,067-3,069	2	Do.
3,069-3,071	2	Do.
3,071-3,076	5	Do.
3,076-3,079	.92	Do.
3,079-3,083	3.5	Do.
3,083-3,088	5	Do.
3,088-3,093	0	Do.
3,093-3,098	0	Do.
3,098-3,099	0	Do.
3,099-3,100	0	Do.
3,096-3,115	20.5	Do.
3,115-3,125	.5	Do.
3,125-3,133	8	Do.
3,133-3,144	10.83	Do.
3,144-3,163	19	Do.
3,163-3,181	18	Do.
3,181-3,193	12	Do.
3,193-3,207	4.92	Do.
3,207-3,217	10	Do.
3,217-3,226	9	Do.
3,226-3,237	8.5	Do.
3,237-3,250	4.5	Do.
3,250-3,260	3	Do.
3,330-3,341	11	Do.
3,341-3,346	1	Do.
3,346-3,349	2	Do.
3,349-3,352	3	Do.
3,352-3,355	0	-----
3,355-3,360	1	Argillite.
3,360-3,362	0	Do.
3,368-3,374	1.17	Do.
3,374-3,376	2	Do.
3,382-3,383	.5	Do.
3,402-3,410	1.5	Do.
3,448-3,451	.17	Do.
3,451-3,453	.17	Do.
3,495-3,497	1	Do.
3,537-3,539	.5	Do.
3,551-3,553	.67	Do.
South Barrow 2		
459-469	10	Torok Formation.
660-670	10	Do.
860-870	10	Do.
960-975	13.5	Do.
975-995	19.33	Do.
995-1,004	8.5	Do.
1,004-1,022	19	Do.
1,022-1,042	16	Do.
1,042-1,059	17	Do.
1,059-1,077	17	Do.
1,077-1,096	18	Do.
1,096-1,111	16.75	Do.
1,111-1,130	18.5	Do.
1,130-1,150	18	Do.
1,150-1,169	19	Do.
1,169-1,189	19	Do.
1,189-1,208	17.5	Do.
1,208-1,227	19	Do.
1,227-1,247	20	Do.
1,247-1,267	19	Do.
1,267-1,284	17	Do.
1,284-1,296	11	Do.
1,296-1,316	17	Do.
1,316-1,336	19	Do.
1,336-1,355	18.5	Do.
1,355-1,375	16.25	Do.
1,375-1,395	12	Do.
1,395-1,415	18	Do.
1,415-1,435	18	Do.
1,435-1,453	15	Do.

TABLE 15.4.—*Core data for Government-drilled wells on the North Slope of Alaska*—Continued

Interval attempted (ft)	Core recovered (ft)	Rock unit
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
South Barrow 2--Continued		
1,653-1,663	5.67	Do.
1,752-1,772	13.5	Do.
1,772-1,792	20	Do.
1,950-1,970	20	Pebble shale unit.
1,970-1,972	.5	Do.
1,972-1,990	18.5	Do.
1,990-2,010	15.83	Do.
2,010-2,030	20	Do.
2,030-2,050	20	Do.
2,050-2,070	17.83	Do.
2,070-2,087	17	Do.
2,087-2,106	14.5	Do.
2,106-2,116	10	Do.
2,116-2,136	17	Do.
2,136-2,153	17	Do.
2,153-2,171	20	Do.
2,171-2,178	6.75	Do.
2,178-2,198	19	Do.
2,198-2,218	20	Do.
2,218-2,228	3	Do.
2,228-2,248	20	Do.
2,248-2,265	12.33	Do.
2,265-2,279	14	Do.
2,279-2,287	8	Do.
2,287-2,307	19.5	Do.
2,307-2,322	15	Do.
2,322-2,328	5	Do.
2,328-2,332	3	Pebble shale unit and Kingak Shale, undivided.
2,332-2,341	9	Kingak Shale.
2,341-2,356	10	Do.
2,356-2,375	9	Do.
2,375-2,391	14	Do.
2,391-2,400	9	Do.
2,400-2,420	18.5	Do.
2,420-2,440	7	Do.
2,440-2,443	2.33	Do.
2,443-2,445	0	-----
2,445-2,446	0	-----
2,454-2,457	.33	Argillite.
2,457-2,470	.33	Do.
2,482-2,487	1	Do.
South Barrow 3		
200-220	8	Torok Formation.
220-240	20	Do.
400-414	8	Do.
602-622	15	Do.
774-794	18	Do.
990-1,010	7.5	Do.
1,030-1,050	19.06	Do.
1,210-1,222	12	Do.
1,388-1,406	18	Pebble shale unit.
1,406-1,416	7.5	Do.
1,613-1,625	3	Do.
1,625-1,639	13	Do.
1,739-1,758	19	Kingak Shale.
1,758-1,778	20	Do.
1,778-1,798	20	Do.
1,979-1,999	20	Do.
1,999-2,018	16	Do.
2,018-2,028	10	Do.
2,028-2,048	19	Do.
2,048-2,068	14	Do.
2,068-2,078	9	Do.
2,079-2,099	20	Do.
2,099-2,119	20	Do.
2,120-2,130	0	Do.
2,130-2,151	20	Do.
2,151-2,170	19	Do.
2,170-2,179	9	Do.
2,179-2,199	20	Do.
2,199-2,218	19	Do.
2,218-2,231	0	Do.
2,231-2,251	9	Do.
2,251-2,271	20	Do.
2,271-2,281	10	Do.
2,281-2,300	19	Do.
2,300-2,320	18	Do.
2,320-2,323	3	Do.
2,323-2,343	20	Do.
2,343-2,363	19	Do.
2,363-2,380	17	Do.
2,380-2,400	20	Do.
2,400-2,420	16	Do.
2,420-2,430	6	Do.
2,430-2,450	13	Do.
2,450-2,468	10	Do.
2,468-2,478	9	Do.
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
South Barrow 3--Continued		
2,478-2,496	16	Do.
2,496-2,511	10	Do.
2,511-2,527	16	Do.
2,527-2,547	10	Do.
2,547-2,561	14	Do.
2,561-2,577	0	Do.
2,577-2,589	12	Kingak Shale and Sag River Sandstone, undivided.
2,589-2,595	6	Sag River Sandstone.
2,595-2,610	2	Do.
2,610-2,630	17	Shublik Formation.
2,630-2,639	9	Do.
2,639-2,655	16	Do.
2,655-2,675	7	Do.
2,675-2,681	5	Do.
2,681-2,701	20	Do.
2,701-2,720	19	Do.
2,720-2,732	12	Do.
2,732-2,752	10	Do.
2,752-2,761	1	Do.
2,761-2,779	17	Do.
2,779-2,799	19	Shublik Formation and argillite, undivided.
2,799-2,801	2	Argillite.
2,801-2,820	6	Do.
2,820-2,831	2	Do.
2,831-2,835	6	Do.
2,836-2,849	5	Do.
2,849-2,869	10	Do.
2,869-2,879	4	Do.
2,879-2,898	2	Do.
2,898-2,899	.5	Do.
South Barrow 4		
1,598-1,608	10	Torok Formation.
1,608-1,618	10	Do.
1,618-1,628	9.5	Do.
1,628-1,638	9	Do.
1,638-1,648	10	Do.
2,320-2,329	9	Pebble shale unit.
2,329-2,340	10	Do.
2,340-2,350	7	Do.
2,350-2,354	2	Do.
2,354-2,364	10	Pebble shale unit and Kingak Shale, undivided.
2,364-2,373	9	Kingak Shale.
2,373-2,383	9	Do.
2,383-2,390	3	Do.
2,390-2,400	2.5	Do.
2,400-2,410	3	Do.
2,410-2,420	10	Do.
2,420-2,425	5	Do.
2,425-2,435	10	Do.
2,435-2,445	10	Do.
2,445-2,455	7	Do.
2,455-2,465	10	Do.
2,465-2,475	2.5	Kingak Shale and argillite, undivided.
2,475-2,478	.5	Argillite.
2,536-2,538	1	Do.
Avak 1		
173-182	1	Pebble shale unit.
378-398	20	Do.
572-592	7	Do.
800-804	4	Do.
1,004-1,013	7	Do.
1,019-1,034	15	Do.
1,034-1,057	15	Do.
1,057-1,061	4	Do.
1,061-1,077	5	Do.
1,077-1,092	10	Do.
1,217-1,237	7	Do.
1,237-1,258	20	Do.
1,258-1,278	20	Do.
1,278-1,298	7	Do.
1,314-1,329	7	Do.
1,329-1,348	19	Do.
1,378-1,397	19	Kingak Shale.
1,518-1,536	18	Do.
1,536-1,554	19	Do.
1,554-1,558	3	Do.
1,558-1,569	4	Do.
1,636-1,655	19	Do.
1,655-1,673	18	Do.
1,673-1,676	3	Do.
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Avak 1--Continued		
1,676-1,695	19	Do.
1,695-1,714	19	Do.
1,714-1,733	19	Do.
1,733-1,752	19	Do.
1,752-1,766	2	Do.
1,766-1,784	19	Do.
1,784-1,802	16	Do.
1,802-1,821	19	Do.
1,821-1,836	4	Do.
1,836-1,852	16	Do.
1,852-1,869	17	Do.
1,871-1,890	19	Do.
1,890-1,906	15	Do.
1,906-1,918	10	Do.
1,967-1,986	8	Do.
1,986-2,006	12	Do.
2,006-2,021	10	Do.
2,021-2,036	7	Do.
2,036-2,054	13	Do.
2,054-2,072	12	Do.
2,116-2,134	18	Do.
2,166-2,178	7	Do.
2,278-2,280	1	Do.
2,280-2,283	3	Do.
2,283-2,286	3	Do.
2,286-2,292	5	Do.
2,292-2,299	5	Do.
2,312-2,331	5	Argillite.
2,528-2,529	.08	Do.
2,529-2,536	2	Do.
2,595-2,603	3	Do.
2,698-2,706	4	Do.
2,856-2,871	3	Do.
2,993-3,001	1	Do.
3,147-3,156	3	Do.
3,357-3,364	1	Do.
3,566-3,571	0	Do.
3,571-3,581	3.5	Do.
3,791-3,800	1	Do.
4,000-4,020	10	Do.
Grandstand 1		
227-245	17	Nanushuk Group.
364-369	1	Do.
413-429	16	Do.
429-448	20	Do.
561-575	7	Do.
610-630	19	Do.
733-736	3	Do.
791-809	19	Do.
809-824	15	Do.
824-843	15	Do.
843-862	15	Do.
862-882	4	Do.
882-899	11	Do.
899-919	14	Do.
919-939	19	Do.
939-958	9	Do.
959-979	20	Do.
979-998	20	Do.
1,035-1,055	20	Do.
1,055-1,075	20	Nanushuk Group and Torok Formation, undivided.
1,075-1,095	19	Torok Formation.
1,103-1,123	20	Do.
1,337-1,357	18	Do.
1,357-1,378	20	Do.
1,378-1,398	17	Do.
1,408-1,422	14	Do.
1,469-1,487	17	Do.
1,600-1,620	20	Do.
1,751-1,767	16	Do.
1,835-1,855	10	Do.
1,923-1,941	17	Do.
1,941-1,957	16	Do.
1,957-1,971	7	Do.
2,000-2,017	17	Do.
2,150-2,170	12	Do.
2,203-2,215	10	Do.
2,373-2,386	0	Do.
2,408-2,413	0	Do.
2,413-2,424	10	Do.
2,467-2,480	9	Do.
2,480-2,494	14	Do.
2,494-2,513	10	Do.
2,694-2,712	18	Do.
2,926-2,946	20	Do.
3,170-3,190	19.5	Do.
3,364-3,377	13	Do.

TABLE 15.4.—*Core data for Government-drilled wells on the North Slope of Alaska*—Continued

Interval attempted (ft)	Core recovered (ft)	Rock unit
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Grandstand 1--Continued		
3,502-3,510	7	Do.
3,730-3,742	12	Do.
3,902-3,910	8	Do.
3,910-3,930	3	Do.
3,930-3,939	9	Do.
Fish Creek 1		
225-234	3	Shale of the Colville Group.
425-435	7	Do.
627-635	5.5	Do.
825-835	10	Do.
1,025-1,035	10	Do.
1,225-1,235	10	Do.
1,422-1,432	6	Do.
1,625-1,635	10	Do.
1,635-1,645	10	Do.
1,645-1,655	4	Do.
1,851-1,861	10	Do.
2,051-2,061	0	Do.
2,061-2,071	10	Do.
2,270-2,280	2	Do.
2,280-2,283	0	Do.
2,283-2,293	1	Do.
2,493-2,503	3.67	Do.
2,700-2,710	10	Do.
2,915-2,925	10	Nanushuk Group.
2,925-2,935	1.67	Do.
2,935-2,945	1.42	Do.
2,945-2,950	5	Do.
2,950-2,960	10	Do.
2,960-2,970	10	Do.
2,970-2,980	10	Do.
2,980-2,990	10	Do.
2,990-3,000	4	Do.
3,000-3,010	10	Do.
3,010-3,020	10	Do.
3,020-3,030	10	Do.
3,030-3,040	10	Do.
3,040-3,050	10	Do.
3,050-3,060	10	Do.
3,162-3,171	7.17	Do.
3,171-3,181	10	Do.
3,356-3,366	10	Do.
3,366-3,376	10	Do.
3,376-3,386	10	Do.
3,576-3,586	10	Do.
3,776-3,786	9	Do.
3,976-3,986	8.33	Do.
4,140-4,150	7.5	Torok Formation.
4,340-4,350	8.5	Do.
4,534-4,544	0	Do.
4,544-4,554	8.25	Do.
4,698-4,708	10	Do.
4,900-4,910	9	Do.
5,078-5,088	7.67	Do.
5,280-5,290	7.75	Do.
5,480-5,490	10	Do.
5,490-5,500	9	Do.
5,500-5,510	10	Do.
5,510-5,520	9.5	Do.
5,520-5,530	9	Do.
5,530-5,540	7.83	Do.
5,540-5,550	8	Do.
5,550-5,560	6.25	Do.
5,560-5,565	.83	Do.
5,565-5,575	10	Do.
5,575-5,585	10	Do.
5,588-5,598	7.5	Do.
5,598-5,608	10	Do.
5,800-5,810	7.5	Do.
6,000-6,010	10	Do.
6,010-6,020	3	Do.
6,020-6,030	10	Do.
6,030-6,040	8.5	Do.
6,040-6,050	10	Do.
6,235-6,245	8.67	Do.
6,395-6,408	0	Do.
6,420-6,432	5.5	Do.
6,590-6,605	1.5	Do.
6,740-6,750	8.5	Do.
6,915-6,925	8.83	Do.
7,010-7,020	8	Do.
Ikpikpuk Core Test 1		
98-108	4	Nanushuk Group.
149-159	5	Do.
Oumalik Core Test 1		
102-112	3.5	Nanushuk Group.
152-162	7	Do.
209-219	1.5	Do.
252-262	8	Do.
300-310	8	Do.
383-392	0	Do.
Oumalik Core Test 11		
6-14	8.92	Surficial deposits and Gubik Formation, undivided.
14-24	2.75	Nanushuk Group.
24-33	5.67	Do.
33-40	10	Do.
40-50	5	Do.
50-57	3.5	Do.
57-67	10	Do.
67-77	2.75	Do.
77-87	7.75	Do.
87-97	5	Do.
97-107	10	Do.
107-112	3	Do.
112-117	4	Do.
117-127	7.25	Do.
127-137	7	Do.
137-147	9	Do.
147-157	7	Do.
157-167	10	Do.
167-177	7.75	Do.
177-187	8.17	Do.
187-197	4.75	Do.
197-207	2	Do.
207-217	2	Do.
217-227	2	Do.
227-237	2	Do.
237-247	9	Do.
247-257	10	Do.
257-266	2	Do.
266-276	2.75	Do.
276-280	4	Do.
280-288	1.75	Do.
288-296	4.5	Do.
296-303	7	Do.
Oumalik Core Test 12		
00-10	10	Surficial deposits and Gubik Formation, undivided.
10-17	0	Do.
17-22	4	Nanushuk Group.
22-27	4	Do.
27-32	1.33	Do.
32-43	0	Do.
32-43	0	Do.
32-43	0	Do.
32-43	0	Do.
43-48	5	Do.
48-50	1.33	Do.
50-54	3.17	Do.
54-58	3	Do.
58-60	.67	Do.
60-61	1	Do.
61-65	4.5	Do.
65-71	6	Do.
71-76	0	Do.
76-81	5	Do.
81-85	2.67	Do.
85-92	5	Do.
92-97	3.25	Do.
97-107	10	Do.
107-116	8.5	Do.
116-126	0	Do.
126-135	8.5	Do.
135-144	8	Do.
144-147	2.17	Do.
147-151	3.75	Do.
151-157	5.75	Do.
157-162	5	Do.
162-164	2	Do.
164-174	10	Do.
174-184	4.33	Do.
184-189	5	Do.
189-192	3	Do.
192-195	3	Do.
195-197	0	Do.
197-202	3.33	Do.
202-207	5	Do.
207-212	5	Do.
212-237	0	Do.
237-242	5	Do.
242-252	0	Do.
252-257	5	Do.
257-262	5	Do.
262-265	4.5	Do.
265-267	0.25	Do.
267-272	5	Do.
272-277	5	Do.
277-280	3	Do.
280-287	7	Do.
287-296	0	Do.
296-300	3.5	Do.
Oumalik 1		
160-180	15	Nanushuk Group.
517-528	10	Do.
723-733	10	Do.
911-921	10	Do.
968-979	.5	Do.
979-984	.5	Do.
984-989	2.5	Do.
989-994	4.5	Do.
994-999	1	Do.
991-1,004	1	Do.
1,004-1,010	2.33	Do.
1,033-1,038	4	Do.
1,195-1,205	10	Do.
1,205-1,210	5	Do.
1,210-1,215	5	Do.
1,410-1,422	3.33	Do.
1,604-1,609	1.83	Do.
1,609-1,619	8.5	Do.
1,619-1,626	6.33	Do.
1,626-1,637	11	Do.
1,797-1,803	4	Do.
1,965-1,966	.75	Do.
1,966-1,967	.75	Do.
2,151-2,161	8	Do.
2,161-2,171	10	Do.
2,351-2,356	5	Do.
2,529-2,539	8.5	Do.
2,756-2,757	1	Do.
2,757-2,760	3	Do.
2,767-2,777	10	Nanushuk Group and Torok Formation, undivided.
2,777-2,787	10	Torok Formation.
2,787-2,792	1.25	Do.
2,792-2,799	4	Do.
2,799-2,809	8	Do.
2,809-2,819	10	Do.
2,819-2,829	2.33	Do.
2,829-2,836	6.5	Do.
2,836-2,841	0	Do.
2,841-2,851	8.33	Do.
3,022-3,032	3	Do.
3,022-3,232	8.33	Do.
3,244-3,254	4.5	Do.
3,254-3,262	8	Do.
3,262-3,272	0	Do.
3,072-3,282	10	Do.
3,455-3,465	5	Do.
3,490-3,500	7.25	Do.
3,500-3,510	8	Do.
3,700-3,710	0	Do.
3,710-3,712	.17	Do.
3,712-3,713	.5	Do.
3,752-3,756	3.5	Do.
3,802-3,812	8.75	Do.
3,812-3,817	5	Do.
3,995-4,005	1	Do.
4,005-4,010	5	Do.
4,200-4,210	1	Do.
4,420-4,440	20	Do.
4,670-4,690	16.5	Do.
4,900-4,920	0	Do.
4,920-4,940	1	Do.
5,131-5,150	4	Do.
5,360-5,379	17	Do.
5,605-5,625	16.5	Do.
5,845-5,865	0	Do.
6,041-6,056	6	Do.
6,285-6,293	8	Do.
6,498-6,506	8	Do.
6,669-6,675	4.5	Do.
6,880-6,890	0	Do.
7,078-7,092	0	Do.
7,250-7,258	6	Do.
7,452-7,467	9	Do.
7,650-7,665	0	Do.
8,090-8,094	3	Do.

TABLE 15.4.—*Core data for Government-drilled wells on the North Slope of Alaska*—Continued

Interval attempted (ft)	Core recovered (ft)	Rock unit
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Oumalik 1--Continued		
8,284-8,294	10	Do.
8,488-8,498	10	Do.
8,691-8,701	10	Do.
8,917-8,927	2	Do.
9,138-9,148	0	Do.
9,148-9,158	1	Do.
9,278-9,296	7	Do.
9,537-9,552	15	Do.
9,824-9,841	17	Do.
10,009-10,029	20	Do.
10,233-10,253	15	Do.
10,453-10,473	2.67	Do.
10,669-10,682	8	Do.
10,992-11,007	4.5	Pebble shale unit.
11,852-11,872	3.33	Kingak Shale.
East Oumalik 1		
156-166	1	Nanushuk Group.
310-320	2.42	Do.
517-527	10	Do.
740-750	0	Do.
750-755	5	Do.
950-956	6	Do.
1,150-1,156	6	Do.
1,350-1,360	10	Do.
1,550-1,560	7.5	Do.
1,692-1,702	10	Do.
1,968-1,974	6.67	Do.
2,237-2,246	9	Do.
2,436-2,444	8.25	Do.
2,635-2,643	8.5	Do.
2,835-2,840	5	Do.
3,040-3,045	5	Torok Formation.
3,268-3,275	7.25	Do.
3,470-3,480	10	Do.
3,670-3,675	5	Do.
3,864-3,873	9	Do.
3,873-3,883	10	Do.
4,100-4,110	10	Do.
4,405-4,415	10	Do.
4,710-4,717	5	Do.
5,077-5,085	8	Do.
5,428-5,435	5.42	Do.
5,727-5,736	4	Do.
6,020-6,030	10	Do.
Square Lake 1		
200-212	5	Sandstone of the Colville Group and Sagavanirktok Formation, undivided.
235-255	19	Do.
255-274	18	Do.
449-469	20	Do.
512-532	20	Do.
532-552	18	Do.
570-590	20	Do.
590-608	11	Do.
608-629	20	Do.
629-649	19	Do.
649-669	20	Do.
669-689	20	Do.
689-708	19	Do.
708-728	20	Shale of the Colville Group.
942-960	17	Do.
1,055-1,066	10	Do.
1,066-1,085	19	Do.
1,085-1,087	2	Do.
1,286-1,306	4	Do.
1,451-1,468	7	Do.
1,468-1,478	13	Do.
1,637-1,657	12	Nanushuk Group.
1,657-1,675	20	Do.
1,675-1,695	20	Do.
1,695-1,715	19	Do.
1,715-1,735	20	Do.
1,735-1,755	12.5	Do.
1,755-1,775	0	Do.
1,775-1,776	19	Do.
1,818-1,825	7	Do.
1,841-1,858	17	Do.
1,858-1,878	20	Do.
1,878-1,896	18	Do.
1,915-1,920	5.5	Do.
1,920-1,940	18	Do.
1,940-1,949	7	Do.
2,020-2,035	14	Do.
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Square Lake 1--Continued		
2,056-2,065	9.5	Do.
2,199-2,207	8	Do.
2,340-2,347	7	Do.
2,493-2,505	10	Do.
2,670-2,683	12	Do.
2,840-2,853	12	Do.
3,027-3,047	20	Do.
3,047-3,066	19	Do.
3,087-3,103	10	Do.
3,189-3,205	0	Do.
3,205-3,211	19	Do.
3,239-3,259	20	Do.
3,259-3,279	20	Do.
3,464-3,482	18	Do.
3,482-3,503	8	Do.
3,503-3,510	20	Do.
3,510-3,518	8	Do.
3,541-3,561	20	Do.
3,592-3,602	10	Do.
3,707-3,727	17	Do.
3,727-3,742	15	Do.
3,742-3,757	15	Do.
3,757-3,769	12	Do.
3,825-3,845	20	Do.
3,845-3,862	17	Do.
3,862-3,882	19	Do.
3,882-3,898	15.5	Do.
3,898-3,910	10	Do.
3,910-3,918	7	Do.
3,978-3,987	9	Torok Formation.
Wolf Creek 1		
629-634	.83	Nanushuk Group.
789-794	5	Do.
865-870	3	Do.
935-940	0	Do.
1,073-1,077	0	Do.
1,077-1,080	0	Do.
1,080-1,084	3.25	Do.
1,170-1,174	.5	Do.
1,174-1,175	0	Do.
1,175-1,178	0	Do.
1,273-1,278	2.5	Do.
1,290-1,293	2.5	Do.
Wolf Creek 2		
742-745	.5	Nanushuk Group.
768-770	.42	Do.
943-946	2	Do.
960-963	0	Do.
963-968	5	Do.
1,005-1,010	5	Do.
1,203-1,208	5	Do.
1,208-1,211	3	Do.
1,396-1,400	4	Do.
1,615-1,618	1	Do.
Wolf Creek 3		
1,475-1,495	20	Nanushuk Group.
1,495-1,509	14	Do.
1,509-1,525	16	Do.
1,525-1,528	2.58	Do.
1,528-1,545	17	Do.
1,545-1,565	19.75	Do.
1,565-1,583	18	Do.
1,645-1,665	20	Do.
1,665-1,670	.5	Do.
1,716-1,736	17.5	Do.
1,875-1,895	20	Do.
1,895-1,915	19.5	Do.
1,915-1,935	18	Do.
1,935-1,955	19	Do.
1,977-1,997	19.5	Do.
1,997-2,014	17	Do.
2,014-2,017	3	Do.
2,017-2,033	16	Do.
2,033-2,037	4	Do.
2,037-2,057	20	Do.
2,057-2,076	15	Do.
2,113-2,133	20	Do.
2,133-2,138	5	Do.
2,138-2,156	18	Do.
2,156-2,158	2	Do.
2,182-2,197	15	Do.
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Wolf Creek 3--Continued		
2,241-2,261	20	Do.
2,261-2,282	21	Do.
2,330-2,349	18	Do.
2,349-2,368	11	Do.
2,510-2,530	19	Do.
2,530-2,547	17	Do.
2,547-2,567	20	Do.
2,567-2,573	6	Do.
2,585-2,605	20	Do.
2,641-2,661	20	Do.
2,661-2,681	14	Do.
2,681-2,701	15.5	Do.
2,710-2,730	10	Do.
2,830-2,850	17.5	Do.
3,028-3,048	14	Do.
3,092-3,112	20	Do.
3,293-3,313	20	Do.
3,358-3,378	20	Do.
3,494-3,514	17.5	Do.
3,514-3,532	8	Do.
3,740-3,760	12.5	Torok Formation.
Titaluk 1		
300-320	20	Nanushuk Group.
522-542	20	Do.
850-870	20	Do.
1,136-1,151	10	Do.
1,300-1,307	7	Do.
1,400-1,420	18	Do.
1,500-1,512	12	Do.
1,802-1,812	9	Do.
2,080-2,092	12	Do.
2,378-2,393	12	Do.
2,657-2,670	0	Do.
2,670-2,676	16	Do.
2,983-3,003	20	Do.
3,003-3,014	10	Do.
3,014-3,027	10	Do.
3,102-3,122	20	Do.
3,122-3,137	14	Do.
3,214-3,233	15	Do.
3,289-3,309	20	Do.
3,420-3,435	12	Do.
3,435-3,450	15	Do.
3,550-3,560	7	Torok Formation.
3,650-3,677	10	Do.
3,677-3,689	15	Do.
3,762-3,782	17	Do.
4,001-4,020	19	Do.
Knifeblade 1		
190-194	4	Nanushuk Group.
267-271	4	Do.
311-315	4	Do.
365-368	.5	Do.
567-570	2	Do.
768-773	5	Do.
826-830	4	Do.
845-846	1	Do.
878-882	3.5	Do.
910-915	3	Do.
955-960	3.75	Do.
1,149-1,152	1	Do.
1,160-1,165	3.33	Do.
1,265-1,270	3	Do.
1,295-1,298	1	Do.
1,375-1,379	3	Do.
1,390-1,395	3	Do.
1,485-1,490	2.5	Do.
1,710-1,712	.67	Do.
1,795-1,800	0	Do.
1,801-1,805	1.17	Do.
Knifeblade 2		
300-303	1	Nanushuk Group.
Knifeblade 2A		
171-174	2.75	Nanushuk Group.
365-368	1.5	Do.
464-467	.75	Do.
665-667	.08	Do.

TABLE 15.4.—*Core data for Government-drilled wells on the North Slope of Alaska*—Continued

Interval attempted (ft)	Core recovered (ft)	Rock unit
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Knifeblade 2A--Continued		
755-758	2.83	Do.
771-773	.83	Do.
789-792	1.83	Do.
805-807	0	Do.
807-809	.83	Do.
845-846	1	Do.
893-894	.58	Do.
903-905	1.33	Do.
1,040-1,042	.17	Do.
1,066-1,070	.75	Do.
1,084-1,086	.75	Do.
1,281-1,283	.67	Do.
1,479-1,481	.75	Do.
1,507-1,510	1	Do.
1,517-1,521	2.83	Do.
1,557-1,560	2	Do.
1,580-1,584	3.5	Do.
1,607-1,610	2.83	Do.
1,620-1,622	1.33	Do.
1,661-1,664	1.75	Do.
1,802-1,805	2.75	Do.
Skull Cliff Core Test 1		
100-109	3	Nanushuk Group.
109-120	10	Do.
120-130	10	Do.
130-140	9	Do.
140-149	10	Do.
149-159	5.5	Do.
159-169	9.5	Do.
169-179	9	Do.
179-189	2	Do.
189-199	9	Do.
199-209	8	Do.
211-216	1	Do.
216-226	9	Do.
226-236	10	Do.
236-246	4	Do.
246-256	9.5	Do.
256-266	10	Do.
266-276	9.5	Do.
276-286	2.5	Do.
286-296	10	Do.
296-306	9	Do.
306-316	10	Do.
316-326	10	Do.
326-336	10	Do.
336-346	6	Do.
346-356	10	Do.
356-366	8.06	Do.
366-376	7	Do.
376-386	10	Do.
386-396	10	Do.
396-406	6	Do.
406-416	10	Do.
416-426	3.5	Do.
426-436	0	Do.
436-446	9.5	Do.
446-456	6	Nanushuk Group and Torok Formation, undivided.
456-466	10	Torok Formation.
466-476	10	Do.
476-486	10	Do.
486-496	10	Do.
496-506	10	Do.
506-516	2.5	Do.
516-526	7.5	Do.
526-536	10	Do.
536-546	10	Do.
546-556	7	Do.
556-566	8.5	Do.
566-576	10	Do.
576-586	10	Do.
586-596	10	Do.
596-606	10	Do.
606-616	10	Do.
616-626	7	Do.
626-636	10	Do.
636-646	5.5	Do.
646-656	7.5	Do.
656-666	10	Do.
666-676	10	Do.
676-686	10	Do.
686-696	4	Do.
696-706	10	Do.
706-716	10	Do.
716-726	10	Do.
726-736	10	Do.
736-746	10	Do.
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Skull Cliff Core Test 1--Continued		
746-756	10	Do.
756-766	8	Do.
766-776	10	Do.
Meade 1		
292-300	5	Nanushuk Group.
590-601	4.5	Do.
890-900	6	Do.
1,190-1,197	3.83	Do.
1,490-1,500	10	Do.
1,790-1,800	10	Do.
2,065-2,075	10	Do.
2,365-2,375	10	Do.
2,438-2,445	2.83	Do.
2,689-2,698	.5	Do.
2,698-2,708	1	Do.
2,949-2,969	19	Do.
2,969-2,977	1.25	Do.
3,251-3,256	1.5	Do.
3,256-3,261	5	Do.
3,550-3,555	5	Torok Formation.
3,555-3,560	4	Do.
3,825-3,830	5	Do.
3,830-3,835	.67	Do.
4,114-4,119	4	Do.
4,119-4,124	4	Do.
4,124-4,129	5	Do.
4,129-4,134	5	Do.
4,134-4,140	6	Do.
4,140-4,145	5	Do.
4,145-4,150	5	Do.
4,150-4,160	10	Do.
4,160-4,167	3.67	Do.
4,167-4,174	7	Do.
4,174-4,184	10	Do.
4,457-4,463	2.33	Do.
4,770-4,778	2.5	Do.
5,048-5,058	1.5	Do.
5,300-5,305	3.25	Do.
Simpson Core Test 1		
6-16	0	Surficial deposits and Gubik Formation, undivided.
16-26	0	Do.
26-28	.5	Do.
30-35	.5	Do.
35-40	.5	Do.
40-45	.5	Do.
45-55	1	Do.
55-65	1	Do.
65-72	4	Do.
72-76	1	Do.
76-83	0	Do.
83-86	3	Nanushuk Group.
86-89	0	Do.
89-101	0	Do.
101-116	0	Do.
Simpson Core Test 2		
76-81	5	Nanushuk Group.
81-87	5	Do.
87-93	5	Do.
93-101	5	Do.
101-106	5	Do.
106-111	5	Do.
111-115	4	Do.
115-120	5	Do.
120-130	5	Do.
130-135	5	Do.
135-140	3.75	Do.
140-145	3.5	Do.
145-155	2.99	Do.
155-162	4.25	Do.
162-170	.25	Do.
170-180	7	Do.
180-190	5	Do.
190-200	8	Do.
214-226	6.25	Do.
Simpson Core Test 3		
228-238	5	Nanushuk Group.
238-248	0	Do.
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Simpson Core Test 3--Continued		
248-258	7	Do.
258-268	5.5	Do.
268-278	5	Do.
278-288	2.5	Do.
288-298	2.5	Do.
298-308	4	Do.
308-318	6.5	Do.
318-328	4	Do.
328-338	10	Do.
338-348	10	Do.
348-358	6	Do.
358-368	3.5	Do.
Simpson Core Test 4		
62-71	3	Surficial deposits and Gubik Formation, undivided.
71-81	1	Nanushuk Group.
81-91	3.5	Do.
91-98	2	Do.
98-108	1.5	Do.
108-119	10	Do.
121-131	3	Do.
131-141	6	Do.
141-151	2	Do.
Simpson Core Test 5		
60-70	1.5	Nanushuk Group.
70-80	1.5	Do.
80-90	2	Do.
90-100	0	Do.
100-110	0	Do.
110-120	2.5	Do.
120-130	2.5	Do.
Simpson Core Test 6		
19-29	8	Surficial deposits and Gubik Formation, undivided.
29-39	1	Do.
39-49	2	Do.
49-59	8	Do.
59-69	.5	Do.
69-79	1	Do.
79-89	1	Nanushuk Group.
89-99	3	Do.
99-109	2	Do.
109-111	2	Do.
119-129	2	Do.
129-139	2	Do.
139-149	1	Do.
Simpson Core Test 7		
12-22	0	Surficial deposits and Gubik Formation, undivided.
22-32	1.5	Do.
32-42	1	Do.
42-52	1	Do.
52-62	1	Do.
62-72	1	Nanushuk Group.
72-82	1	Do.
82-92	2	Do.
92-102	1	Do.
102-112	1	Do.
112-122	2.5	Do.
122-132	1	Do.
132-142	1.5	Do.
142-152	1.5	Do.
152-162	3.5	Do.
162-172	0	Do.
172-182	4	Do.
182-192	1.5	Do.
192-202	10	Do.
202-212	1.5	Do.
212-222	8	Do.
222-232	1.5	Do.
232-242	7	Do.
242-252	.25	Do.
252-262	4	Do.
262-272	2	Do.
272-282	2	Do.
282-292	1	Do.
292-302	1.5	Do.

TABLE 15.4.—*Core data for Government-drilled wells on the North Slope of Alaska*—Continued

Interval attempted (ft)	Core recovered (ft)	Rock unit
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Simpson Core Test 7--Continued		
302-312	1	Do.
312-322	.75	Do.
322-332	1.5	Do.
332-342	8	Do.
342-352	10	Do.
352-362	8	Do.
362-372	10	Do.
372-382	8.5	Do.
382-392	7.5	Do.
392-402	9	Do.
402-412	2	Do.
412-422	8	Do.
422-432	0	Do.
432-442	0	Do.
442-452	1.5	Do.
452-462	4	Do.
462-472	2	Do.
472-477	2	Do.
477-482	2	Do.
482-492	3.5	Do.
492-502	3	Do.
502-512	5	Do.
512-522	2.5	Do.
522-532	2.5	Do.
Simpson Core Test 8		
20-30	3	Surficial deposits and Gubik Formation, undivided.
30-40	1	Do.
40-50	5	Do.
50-60	4	Do.
60-70	1	Nanushuk Group.
70-80	1	Do.
80-90	2.5	Do.
90-100	7	Do.
100-110	1.5	Do.
110-120	2.5	Do.
120-130	1.25	Do.
130-140	2	Do.
140-150	1.25	Do.
150-160	10	Do.
160-170	1	Do.
190-200	8	Do.
220-230	0	Do.
230-240	10	Do.
240-250	1.5	Do.
250-260	10	Do.
260-270	2	Do.
270-280	9	Do.
280-290	1.5	Do.
290-300	0	Do.
300-310	0	Do.
310-320	9	Do.
320-330	4.5	Do.
330-340	10	Do.
340-350	5	Do.
350-360	7	Do.
360-370	5.5	Do.
370-380	2.5	Do.
380-390	3	Do.
390-400	8.5	Do.
400-410	0	Do.
410-420	9.5	Do.
420-430	2	Do.
430-440	0	Do.
440-450	2	Do.
450-460	6.5	Do.
460-470	0	Do.
470-480	2	Do.
480-490	6	Do.
490-500	3	Do.
500-510	2.5	Do.
510-520	5.5	Do.
520-530	2.5	Do.
530-540	7	Do.
540-550	1	Do.
550-560	2	Do.
560-570	10	Do.
570-580	0	Do.
Simpson Core Test 9		
20-30	9	Surficial deposits and Gubik Formation, undivided.
30-40	10	Do.
40-50	10	Do.
50-60	10	Do.
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Simpson Core Test 9--Continued		
60-70	10	Do.
70-80	5	Do.
80-90	10	Surficial deposits, Gubik Formation, and Nanushuk Group, undivided.
90-100	7	Nanushuk Group.
100-110	6	Do.
200-210	9	Do.
210-220	9	Do.
220-230	1.5	Do.
230-240	9	Do.
240-250	0	Do.
250-260	1.5	Do.
260-270	6	Do.
310-320	6	Do.
Simpson Core Test 10		
20-30	0	Surficial deposits and Gubik Formation, undivided.
30-40	4	Do.
40-50	6	Do.
50-60	8	Do.
60-70	1.5	Nanushuk Group.
70-80	1.25	Do.
80-90	.75	Do.
90-100	5	Do.
100-110	7	Do.
110-120	1.25	Do.
120-130	.5	Do.
130-140	1.25	Do.
140-150	2.5	Do.
150-160	3.5	Do.
160-170	1.5	Do.
170-180	1.5	Do.
180-190	1.5	Do.
190-200	1.25	Do.
200-210	2	Do.
210-220	8	Do.
220-230	1.25	Do.
230-240	6	Do.
240-250	7	Do.
250-260	8	Do.
260-270	1	Do.
270-280	5	Do.
280-290	1.5	Do.
290-300	10	Do.
300-310	4.5	Do.
310-320	7	Do.
320-330	10	Do.
330-340	10	Do.
340-350	7.5	Do.
350-360	2	Do.
360-370	1	Do.
370-380	1.5	Do.
380-390	7	Do.
390-400	1.5	Do.
400-410	6	Do.
410-420	2.5	Do.
420-430	7	Do.
430-440	3	Do.
440-450	0	Do.
450-460	2	Do.
460-470	10	Do.
470-480	9	Do.
480-490	0	Do.
490-500	0	Do.
Simpson Core Test 11		
100-110	5	Shale of the Colville Group.
110-120	4	Do.
120-130	6.5	Do.
130-140	5	Do.
140-150	6	Do.
150-160	5	Do.
160-170	8	Do.
170-180	4.5	Do.
180-190	10	Do.
190-200	5	Do.
200-210	10	Do.
210-220	10	Do.
220-230	10	Do.
230-240	10	Do.
240-250	10	Do.
250-260	10	Do.
260-270	1.5	Do.
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Simpson Core Test 11--Continued		
310-320	10	Do.
320-330	10	Do.
330-340	10	Do.
340-350	9.5	Do.
350-360	10	Do.
360-370	10	Do.
370-380	10	Do.
380-390	10	Do.
390-400	10	Do.
400-410	10	Do.
410-420	10	Do.
420-430	10	Do.
430-440	10	Do.
440-450	6.5	Do.
450-460	10	Do.
460-470	10	Do.
470-480	10	Do.
480-490	10	Do.
490-500	10	Do.
500-510	10	Do.
510-520	10	Do.
520-530	9	Do.
Simpson Core Test 12		
242-250	8	Shale of the Colville Group.
250-260	9	Do.
260-270	10	Do.
270-280	10	Do.
280-290	10	Do.
290-300	9	Do.
Simpson Core Test 13		
20-26	6	Surficial deposits and Gubik Formation, undivided.
26-32	6	Do.
32-36	6	Do.
36-46	10	Do.
46-50	4	Do.
50-55	3.75	Do.
55-62	6	Do.
62-66	4	Do.
66-72	6	Do.
72-77	5	Do.
77-82	5	Do.
82-85	3.5	Do.
85-91	5.6	Shale of the Colville Group.
91-97	5.6	Do.
97-105	3	Do.
105-111	6	Do.
111-116	5	Do.
116-126	6	Do.
126-133	6.5	Do.
133-138	2.5	Do.
138-143	5	Do.
143-148	5	Do.
148-158	8.67	Do.
158-165	6.25	Do.
165-172	6	Do.
172-175	3	Do.
175-180	5	Do.
180-185	5	Do.
185-190	5	Do.
190-195	5	Do.
195-201	5.33	Do.
201-206	5	Do.
206-215	9	Do.
215-221	6	Do.
221-226	5	Do.
226-227	1	Do.
227-229	1.33	Do.
229-236	6.5	Do.
236-244	8	Do.
244-254	10	Do.
274-284	10	Do.
284-294	10	Do.
294-304	4	Do.
304-314	4	Do.
314-324	8	Do.
324-334	10	Do.
334-344	7.5	Do.
344-354	10	Do.
354-364	8	Do.
364-374	10	Do.
374-384	7.5	Do.
384-394	7.7	Do.

TABLE 15.4.—*Core data for Government-drilled wells on the North Slope of Alaska*—Continued

Interval attempted (ft)	Core recovered (ft)	Rock unit
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Simpson Core Test 13--Continued		
394-402	8.5	Do.
402-412	9.5	Do.
412-422	9	Do.
422-432	10	Do.
432-442	7.5	Do.
442-452	4.5	Do.
452-462	5.5	Do.
462-472	4	Do.
472-482	4.25	Do.
482-492	5	Do.
492-497	4.5	Do.
497-502	3.8	Do.
502-508	4	Do.
508-517	3.5	Do.
517-524	6	Do.
524-528	1	Do.
528-533	5	Do.
533-538	4	Do.
538-548	7.5	Do.
548-558	3	Do.
558-563	4	Do.
563-569	6	Do.
569-577	7	Do.
577-583	4	Do.
583-588	2	Do.
588-592	0	Do.
592-594	2	Do.
594-599	5	Do.
599-604	2	Do.
604-609	4.33	Do.
609-617	5	Do.
617-622	1.39	Do.
622-627	3	Do.
627-633	4	Do.
633-640	8	Do.
640-644	3	Do.
644-649	5	Do.
649-653	3	Do.
653-661	6	Do.
661-663	2	Nanushuk Group.
663-673	10	Do.
673-681	4	Do.
706-711	3	Do.
712-718	4.5	Do.
718-724	3	Do.
724-731	7	Do.
738-744	3.5	Do.
744-754	2.5	Do.
754-760	6	Do.
760-767	3.5	Do.
767-771	3.5	Do.
771-781	3.5	Do.
781-791	10	Do.
791-801	10	Do.
801-810	7	Do.
810-812	1.5	Do.
812-813	1	Do.
813-823	7.5	Do.
823-833	8.75	Do.
833-842	9	Do.
842-852	10	Do.
852-862	8.5	Do.
862-870	8	Do.
870-877	5.5	Do.
870-877	4	Do.
884-895	8.5	Do.
895-904	5.5	Do.
904-910	6.5	Do.
910-920	10	Do.
920-928	8	Do.
928-930	0	Do.
930-950	20	Do.
950-971	17	Do.
971-991	20	Do.
991-999	6.33	Do.
999-1,006	2	Do.
1,006-1,014	5.25	Do.
1,014-1,019	3.5	Do.
1,019-1,026	5.25	Do.
1,026-1,030	1	Do.
1,030-1,036	2.5	Do.
1,036-1,038	1.5	Do.
1,038-1,041	1.75	Do.
1,041-1,050	6	Do.
1,050-1,055	4	Do.
1,055-1,062	2.5	Do.
1,062-1,066	3	Do.
1,066-1,075	7	Do.
1,075-1,079	1	Do.
1,079-1,084	5	Do.
1,084-1,087	2.15	Do.
1,087-1,093	3	Do.
1,093-1,098	5	Do.
1,098-1,102	4	Do.
1,102-1,107	4.5	Do.
1,107-1,113	4.5	Do.
1,113-1,118	5	Do.
1,118-1,125	6	Do.
1,125-1,133	3.5	Do.
1,133-1,135	2	Do.
1,135-1,138	3	Do.
1,138-1,148	10	Do.
1,148-1,152	3	Do.
1,152-1,158	4	Do.
1,158-1,168	10	Do.
1,168-1,188	20	Do.
1,188-1,205	6	Do.
1,205-1,210	5	Do.
1,210-1,212	0	Do.
Simpson Core Test 14		
200-210	8	Shale of the Colville Group.
210-220	4	Do.
285-295	9	Do.
295-305	6.5	Do.
305-315	10	Do.
475-485	10	Nanushuk Group.
485-495	10	Do.
495-505	8	Do.
505-515	4.25	Do.
565-575	8	Do.
575-585	9	Do.
585-595	10	Do.
595-605	10	Do.
605-615	10	Do.
615-625	10	Do.
700-710	10	Do.
845-855	10	Do.
906-916	10	Do.
974-984	10	Do.
1,015-1,023	4	Do.
1,039-1,045	6	Do.
1,072-1,075	3	Do.
1,208-1,218	10	Do.
Simpson Core Test 14A		
200-210	10	Shale of the Colville Group.
210-220	9	Do.
220-230	10	Do.
230-240	10	Do.
240-250	10	Do.
250-258	9	Do.
258-260	1.5	Do.
260-262	1.5	Do.
262-266	4	Do.
266-275	8.5	Do.
275-283	0	Do.
283-290	7	Do.
Simpson Core Test 15		
266-268	2.5	Shale of the Colville Group.
303-310	5	Do.
Simpson Core Test 16		
338-348	5	Nanushuk Group.
492-498	6	Do.
525-535	9.5	Do.
535-544	7	Do.
Simpson Core Test 17		
200-208	7.5	Shale of the Colville Group.
401-407	6	Do.
471-476	5	Do.
581-591	10	Nanushuk Group.
624-628	2.5	Do.
796-803	7	Do.
1,003-1,013	10	Do.
Simpson Core Test 18		
200-210	9	Shale of the Colville Group.
400-410	10	Do.
620-630	10	Do.
816-826	10	Do.
Simpson Core Test 22		
100-105	1.5	Shale of the Colville Group.
200-207	4	Do.
300-304	4	Do.
400-408	7.5	Do.
500-510	9	Do.
600-610	7	Do.
700-710	9.5	Do.
800-810	7	Do.
810-815	4	Do.
900-903	3	Do.
Simpson Core Test 25		
201-206	3	Shale of the Colville Group.
508-518	6	Do.
518-528	7.5	Do.
528-538	10	Do.
538-550	8	Do.
550-560	10	Do.
560-570	9	Do.
570-572	2	Do.
572-580.5	8.5	Do.
580.5-591	10	Do.
591-602	10.5	Do.
602-612	6	Do.
612-623	4	Do.
623-634	6	Do.
634-644	10	Do.
644-655	10	Do.
655-665	10	Do.
675-686	6	Do.
686-696.5	10.5	Do.
696.5-708	7.5	Do.
708-718.5	9	Do.
718.5-729	1	Do.
729-739.5	8.5	Do.
739.5-749	8.5	Do.
749-759.5	8	Do.
759.5-770	7.5	Do.
770-780	8.5	Do.
780-791	8.5	Do.
791-801	8.5	Do.
801-811.5	6	Do.
811.5-822	6	Do.
822-832	1	Do.
832-843	10.33	Nanushuk Group.
843-853.5	10.33	Do.
853.5-864	6.8	Do.
864-874	9.5	Do.
874-885	7.5	Do.
885-896	10	Do.
896-906	10	Do.
906-916	5	Do.
916-927	10.5	Do.
927-938	11	Do.
938-948	5	Do.
948-959	10.5	Do.
959-969	10	Do.
972-982	10	Do.
982-989	5	Do.
989-1,000	8	Do.
1,000-1,011	5	Do.
1,011-1,014	2	Do.
1,014-1,024	5	Do.
1,024-1,034	4	Do.
1,034-1,044	6	Do.
1,044-1,055	10	Do.
1,055-1,065	5	Do.
1,065-1,076	1	Do.
1,076-1,086	10	Do.

TABLE 15.4.—*Core data for Government-drilled wells on the North Slope of Alaska*—Continued

Interval attempted (ft)	Core recovered (ft)	Rock unit
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Simpson Core Test 25--Continued		
1,086-1,097	11	Do.
1,097-1,108	11	Do.
1,108-1,119	1	Do.
1,119-1,129	9	Do.
1,129-1,140	11	Do.
1,140-1,150	10	Do.
1,161-1,171	10	Do.
1,171-1,182	10	Do.
1,192-1,203	9	Do.
1,203-1,213	9	Do.
1,213-1,224	10	Do.
1,224-1,234	7	Do.
1,234-1,245	10	Do.
1,245-1,256	5	Do.
1,256-1,266	10	Do.
1,266-1,277	10	Do.
1,277-1,287	10	Do.
1,287-1,298	11	Do.
1,298-1,308	11	Do.
1,308-1,319	5	Do.
1,319-1,330	11	Do.
1,330-1,340	10	Do.
1,340-1,351	11	Do.
1,351-1,361	10	Do.
1,361-1,372	10	Do.
1,372-1,383	7	Do.
1,393-1,404	11	Do.
1,404-1,414	5	Do.
1,414-1,425	10	Do.
1,425-1,435	10	Do.
1,435-1,446	11	Do.
1,446-1,456	10	Do.
1,456-1,467	10	Do.
1,467-1,478	10	Do.
1,478-1,488	10	Do.
1,488-1,499	10	Do.
1,499-1,510	8	Do.
Simpson Core Test 26		
117-126	8	Shale of the Colville Group.
126-137	10	Do.
137-148	10	Do.
148-159	11	Do.
159-170	11	Do.
170-180	3	Do.
180-190	7	Do.
190-201	11	Shale of the Colville Group and Nanushuk Group, undivided.
263-274	11	Nanushuk Group.
306-317	10	Do.
498-509	10	Do.
569-580	11	Do.
Simpson Core Test 27		
102-107	0	Shale of the Colville Group.
107-112	2	Do.
113-124	3	Do.
124-135	10	Do.
135-146	10	Do.
146-157	10	Do.
157-168	10	Do.
168-179	10	Do.
179-190	9	Do.
190-201	10	Do.
201-211	9	Do.
211-221	9	Do.
221-231	10	Shale of the Colville Group and Nanushuk Group, undivided.
231-242	10	Nanushuk Group.
242-253	10	Do.
253-264	10	Do.
264-267	2.75	Do.
267-278	10	Do.
278-289	10	Do.
289-300	10	Do.
300-311	10	Do.
311-317.5	6.5	Do.
317.5-322.5	4.5	Do.
322.5-325.5	3	Do.
325.5-336	10	Do.
336-347	10	Do.
347-358	10	Do.
358-369	11	Do.
369-380	11	Do.
380-391	10	Do.
291-402	11	Do.
402-413	10	Do.
413-424	10	Do.
424-435	10	Do.
435-446	10	Do.
641-651	6	Do.
651-661	8	Do.
821-831	1	Do.
1,490-1,500	2.25	Do.
Simpson Core Test 28		
1,089-1,095	4	Nanushuk Group.
1,251-1,261	10	Do.
1,261-1,271	10	Do.
1,271-1,281	10	Do.
1,381-1,391	4	Do.
1,491-1,496	5	Do.
1,594-1,604	10	Do.
1,704-1,709	3	Do.
1,809-1,814	5	Do.
1,914-1,919	3	Do.
2,019-2,027	5	Do.
2,127-2,132	5	Do.
2,230-2,239	2	Do.
2,339-2,344	5	Do.
2,446-2,453	5	Do.
2,500-2,505	4	Do.
Simpson Core Test 29		
71-81	10	Surficial deposits and Gubik Formation, undivided.
81-91	10	Surficial deposits, Gubik Formation, and shale of the Colville Group, undivided.
91-102	11	Shale of the Colville Group.
102-112	10	Do.
112-122	10	Do.
122-132	10	Do.
132-142	10	Do.
142-152	8.42	Do.
152-163	11	Do.
163-173	10	Do.
173-183	10	Do.
183-193	10	Do.
193-203	10	Do.
203-213	10	Do.
213-223	7	Do.
223-233	10	Do.
233-243	10	Do.
243-253	10	Do.
253-263	10	Do.
263-273	10	Do.
273-283	10	Do.
283-293	9	Do.
293-303	10	Do.
303-313	10	Do.
313-323	10	Do.
323-333	10	Do.
333-343	10	Do.
343-354	10	Do.
354-365	10	Do.
365-375	10	Do.
375-386	11	Do.
386-396	10	Do.
396-407	11	Do.
407-417	5	Do.
417-427	5	Do.
428-438	6	Do.
438-449	10	Do.
449-459	9	Do.
459-469	10	Do.
679-689	10	Nanushuk Group.
Simpson Core Test 30		
102-112	5	Shale of the Colville Group.
112-122	10	Do.
122-133	10	Do.
133-143	3	Do.
143-153	10	Do.
153-162	9	Do.
162-172	8	Do.
172-182	6	Do.
182-192	9	Do.
192-202	9	Do.
202-212	10	Shale of the Colville Group and Nanushuk Group, undivided.
212-222	10	Nanushuk Group.
222-233	10	Do.
233-243	10	Do.
243-253	10	Do.
253-263	10	Do.
263-273	10	Do.
273-283	10	Do.
283-293	10	Do.
293-303	4.5	Do.
303-313	5	Do.
313-323	5	Do.
323-333	10	Do.
333-343	10	Do.
343-353	10	Do.
353-363	10	Do.
367-377	7	Do.
377-387	10	Do.
387-398	10	Do.
398-408	8	Do.
408-419	10.5	Do.
419-429	7.5	Do.
429-440	6	Do.
453-460	3	Do.
460-471	6	Do.
566-577	1.5	Do.
577-588	10	Do.
588-599	11	Do.
599-609	8	Do.
609-620	9	Do.
620-630	7	Do.
630-640	10	Do.
640-651	11	Do.
651-662	10	Do.
662-673	11	Do.
673-683	10	Do.
Simpson Core Test 30A		
680-691	11	Nanushuk Group.
691-701	10	Do.
Simpson Core Test 31		
115-125	9.5	Shale of the Colville Group.
125-132	4	Do.
132-144	8.33	Do.
144-155	10	Do.
155-166	8	Do.
166-175	8.5	Do.
175-186	9	Do.
186-197	10	Do.
197-208	8	Do.
219-230	9	Do.
230-241	7.66	Nanushuk Group.
241-252	10	Do.
252-263	10	Do.
263-274	10	Do.
274-285	11	Do.
285-296	10.5	Do.
296-307	9.08	Do.
307-318	10	Do.
318-329	7	Do.
329-340	10	Do.
340-351	10	Do.
351-355	3.8	Do.
Simpson 1		
130-133	3	Nanushuk Group.
133-141	2.5	Do.
141-146	5	Do.
146-156	7	Do.
156-166	.83	Do.
166-176	5	Do.
176-181	5	Do.
181-191	5	Do.

TABLE 15.4.—*Core data for Government-drilled wells on the North Slope of Alaska*—Continued

Interval attempted (ft)	Core recovered (ft)	Rock unit
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Simpson 1--Continued		
191-196	5	Do.
196-201	5	Do.
201-206	5	Do.
206-211	5	Do.
211-216	5	Do.
216-221	5	Do.
221-226	0	Do.
226-231	0	Do.
231-236	.5	Do.
236-241	4	Do.
241-246	6	Do.
246-251	5.5	Do.
251-256	5	Do.
256-261	2.5	Do.
261-266	4	Do.
266-271	5	Do.
271-273	5	Do.
273-278	5	Do.
278-283	5	Do.
283-288	5	Do.
288-293	5	Do.
293-298	5	Do.
298-303	5	Do.
303-308	5	Do.
308-313	5	Do.
313-318	5	Do.
318-323	5	Do.
323-328	4	Do.
328-333	5	Do.
333-338	5	Do.
338-343	5	Do.
343-348	5	Do.
348-353	5	Do.
353-358	5	Do.
358-363	5	Do.
363-368	4	Do.
368-373	2.5	Do.
373-378	4	Do.
378-383	5	Do.
383-388	5	Do.
388-393	5	Do.
393-398	5	Do.
398-403	5	Do.
403-408	5	Do.
408-413	5	Do.
413-418	4	Do.
418-423	5	Do.
423-428	5	Do.
428-433	5	Do.
433-438	5	Do.
438-443	5	Do.
443-448	5	Do.
448-453	4	Do.
453-458	5	Do.
458-463	4	Do.
463-468	5	Do.
468-473	5	Do.
473-478	5	Do.
478-483	5	Do.
483-488	5	Do.
488-493	5	Do.
493-498	5	Do.
498-503	5	Do.
503-508	5	Do.
508-513	5	Do.
513-518	5	Do.
518-523	5	Do.
523-528	5	Do.
528-533	5	Do.
533-538	5	Do.
538-543	5	Do.
543-548	5	Do.
548-553	1.5	Do.
553-555	2.75	Do.
555-565	7	Do.
565-573	5	Do.
573-578	5	Do.
578-583	4	Do.
583-588	5	Do.
588-593	2.5	Do.
593-598	3.5	Do.
598-603	5	Do.
603-608	5	Do.
608-613	4.5	Do.
613-623	9	Do.
623-633	7.5	Do.
633-643	8.5	Do.
643-649	2.5	Do.
649-654	4	Do.
654-663	2	Do.
663-668	1.75	Do.
668-673	2.5	Do.
673-683	6	Do.
683-693	3	Do.
693-703	5	Do.
703-713	4	Do.
713-723	9	Do.
723-733	8.5	Do.
733-743	3.75	Do.
743-753	5	Do.
753-763	4	Do.
763-772	6	Do.
772-781	9	Do.
781-791	10	Do.
791-801	9.5	Do.
801-811	10	Do.
811-821	10	Do.
821-831	9	Do.
831-841	3	Do.
841-851	9	Do.
851-858	4.33	Do.
858-867	5.33	Do.
867-877	3	Do.
877-885	4	Do.
885-895	8	Do.
895-900	4.5	Do.
900-910	8.5	Do.
910-920	8	Do.
920-930	8.5	Do.
930-940	6	Do.
940-950	5	Do.
950-960	4.5	Do.
960-970	4.5	Do.
970-980	7.5	Do.
980-990	2.75	Torok Formation.
990-1,000	.33	Do.
1,000-1,010	3	Do.
1,010-1,020	4	Do.
1,020-1,030	6.75	Do.
1,030-1,040	2.5	Do.
1,040-1,045	2.5	Do.
1,045-1,050	5	Do.
1,050-1,060	7.5	Do.
1,060-1,070	3.5	Do.
1,070-1,075	4	Do.
1,075-1,080	2.5	Do.
1,077-1,087	7.75	Do.
1,087-1,097	9	Do.
1,097-1,107	6	Do.
1,107-1,117	2	Do.
1,117-1,127	6.5	Do.
1,127-1,137	10	Do.
1,137-1,147	2.75	Do.
1,147-1,157	2.5	Do.
1,157-1,167	10	Do.
1,167-1,177	3	Do.
1,177-1,187	3	Do.
1,187-1,197	4.5	Do.
1,197-1,207	4	Do.
1,207-1,217	7.5	Do.
1,217-1,227	8	Do.
1,227-1,237	7.5	Do.
1,237-1,247	9.5	Do.
1,247-1,257	8.5	Do.
1,257-1,267	.5	Do.
1,267-1,277	8	Do.
1,277-1,287	10	Do.
1,287-1,297	6	Do.
1,297-1,302	5.5	Do.
1,302-1,312	8	Do.
1,312-1,322	10	Do.
1,322-1,330	8	Do.
1,330-1,340	9	Do.
1,340-1,350	9	Do.
1,350-1,360	9.5	Do.
1,360-1,370	9	Do.
1,570-1,580	10	Do.
1,758-1,768	7.5	Do.
1,967-1,977	9	Do.
2,024-2,026	2	Do.
2,235-2,245	6	Do.
2,275-2,285	7.5	Do.
2,343-2,353	10	Do.
2,353-2,363	3	Do.
2,434-2,440	0	Do.
2,444-2,447	0	Do.
2,530-2,535	3	Do.
2,535-2,540	4	Do.
2,739-2,749	9	Do.
2,939-2,949	10	Do.
3,000-3,003	3	Do.
3,175-3,190	11	Do.
3,365-3,370	3	Do.
3,580-3,585	5	Do.
3,781-3,786	2	Do.
3,786-3,791	0	Do.
3,791-3,796	2	Do.
3,796-3,801	0	Do.
3,801-3,806	1	Do.
3,806-3,811	1.5	Do.
3,811-3,816	3	Do.
3,816-3,819	3	Do.
3,819-3,824	0	Do.
3,824-3,829	1.5	Do.
3,829-3,830	1	Do.
3,981-3,986	0	Do.
3,986-3,991	5	Do.
3,991-3,996	4	Do.
3,996-4,006	5	Do.
4,120-4,130	0	Do.
4,130-4,135	4	Do.
4,201-4,206	.5	Do.
4,206-4,211	2	Do.
4,211-4,221	.75	Do.
4,250-4,255	0	Do.
4,255-4,260	3	Do.
4,330-4,335	2.5	Do.
4,501-4,511	1	Do.
4,698-4,708	7	Do.
4,873-4,878	.25	Do.
4,878-4,883	6	Do.
5,074-5,079	1	Do.
5,079-5,084	1	Do.
5,084-5,087	3.5	Do.
5,277-5,281	0	Do.
5,281-5,287	1	Do.
5,287-5,294	0	-----
5,294-5,297	0	-----
5,297-5,303	1.5	Pebble shale unit.
5,303-5,308	4.5	Do.
5,464-5,484	16	Do.
5,677-5,692	14	Kingak Shale.
5,866-5,874	6	Do.
6,067-6,077	10	Sag River Sandstone.
6,173-6,183	9	Do.
6,183-6,193	8	Do.
6,237-6,247	10	Do.
6,304-6,314	8.5	Shublik Formation.
6,316-6,334	6	Do.
6,334-6,337	1.33	Do.
6,346-6,356	8.5	Do.
6,375-6,385	9.5	Do.
6,455-6,465	8	Do.
6,485-6,495	10	Do.
6,545-6,557	10	Argillite.
6,615-6,619	1.83	Do.
6,653-6,673	7.5	Do.
6,780-6,796	12	Do.
6,896-6,916	18.5	Do.
6,982-7,002	16	Do.
Topagoruk 1		
302-312	10	Nanushuk Group.
596-608	10	Do.
911-919	8	Do.
1,200-1,209	9	Do.
1,490-1,501	11	Do.
1,790-1,800	5	Do.
2,087-2,097	10	Do.
2,390-2,399	9	Torok Formation.
2,637-2,642	3	Do.
2,940-2,950	9	Do.
3,240-3,249	6	Do.
3,540-3,550	0	Do.
3,550-3,560	2.5	Do.
3,804-3,807	2	Do.
4,100-4,110	.67	Do.
4,345-4,348	3	Do.
4,632-4,635	3	Do.
4,785-4,790	5	Do.
4,895-4,899	0	Do.
4,899-4,902	2.5	Do.
5,005-5,010	1.17	Do.
5,010-5,016	.5	Do.
5,091-5,094	0	Do.
5,094-5,098	.33	Do.
5,183-5,193	9	Do.
5,268-5,278	0	Do.
5,278-5,288	0	Do.
5,360-5,365	2.5	Do.
5,365-5,370	.5	Do.
5,370-5,375	2	Do.

TABLE 15.4.—*Core data for Government-drilled wells on the North Slope of Alaska*—Continued

Interval attempted (ft)	Core recovered (ft)	Rock unit
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Topagoruk 1--Continued		
5,475-5,480	5	Do.
5,575-5,582	7	Do.
5,681-5,688	6.5	Do.
5,780-5,790	.5	Do.
5,790-5,795	0	Do.
5,795-5,800	.67	Do.
5,800-5,802	2	Do.
5,860-5,865	2.5	Do.
5,944-5,954	9	Do.
5,954-5,964	10	Do.
5,964-5,967	2.5	Do.
5,967-5,974	4.25	Do.
5,974-5,984	2	Do.
5,984-5,990	0	Do.
5,990-6,000	8	Do.
6,003-6,013	8.5	Do.
6,013-6,023	10	Do.
6,023-6,033	9.5	Do.
6,033-6,043	10	Do.
6,043-6,052	3.83	Do.
6,140-6,150	9.5	Do.
6,150-6,160	9.5	Do.
6,480-6,490	7.25	Do.
6,490-6,500	6	Do.
6,500-6,510	9.5	Do.
6,743-6,753	2.5	Pebble shale unit.
6,849-6,859	5	Do.
6,927-6,932	0	Kingak Shale.
6,932-6,942	0	Do.
6,942-6,950	0	Do.
7,042-7,052	3	Do.
7,052-7,062	5	Do.
7,804-7,814	10	Do.
7,829-7,839	10	Do.
7,839-7,849	8.33	Do.
7,849-7,857	0	Do.
8,104-8,114	7.5	Do.
8,629-8,634	5	Do.
8,917-8,921	2	Shublik Formation.
9,200-9,202	1	Do.
9,416-9,426	5	Ledge Sandstone Member of the Ivishak Formation.
9,426-9,428	1.5	Do.
9,433-9,455	22	Do.
9,455-9,458	3	Do.
9,459-9,462	3	Do.
9,462-9,492	30	Do.
9,492-9,522	30	Do.
9,523-9,538	15	Do.
9,539-9,557	18	Do.
9,557-9,568	11	Do.
9,574-9,597	23	Ledge Sandstone and Kavik Members of the Ivishak Formation, undivided.
9,816-9,821	5	Endicott Group.
10,007-10,017	.25	Do.
10,017-10,022	.25	Do.
10,228-10,229	1.25	Basement complex.
10,384-10,385	0	Do.
10,385-10,390	5	Do.
10,390-10,403	13	Do.
10,403-10,412	9	Do.
10,433-10,450	17	Do.
10,450-10,462	7	Do.
10,460-10,461	0	Do.
10,461-10,468	6	Do.
10,469-10,472	1.67	Do.
10,472-10,476	2	Do.
10,476-10,479	3	Do.
10,479-10,486	6	Do.
10,486-10,487	1	Do.
10,487-10,500	11	Do.
10,500-10,506	5	Do.
10,503-10,503	1	Do.
East Topagoruk 1		
200-210	3	Nanushuk Group.
540-547	7	Do.
800-810	10	Do.
1,100-1,110	10	Do.
1,400-1,410	10	Do.
1,731-1,748	17	Do.
2,000-2,016	4	Do.
2,016-2,032	16	Do.
2,032-2,050	18	Do.
2,050-2,070	19	Do.
2,070-2,083	10	Do.
2,083-2,103	19	Do.
2,103-2,122	19	Do.
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
East Topagoruk 1--Continued		
2,122-2,132	10	Do.
2,132-2,134	2	Do.
2,134-2,144	6	Do.
2,144-2,164	18	Do.
2,164-2,184	19	Do.
2,221-2,231	7	Do.
2,231-2,251	19	Do.
2,485-2,505	5	Torok Formation.
2,505-2,507	0	Do.
2,800-2,820	17	Do.
3,000-3,013	10	Do.
3,013-3,033	20	Do.
3,033-3,053	17	Do.
3,053-3,056	3	Do.
3,056-3,076	20	Do.
3,407-3,426	4	Do.
3,569-3,589	20	Do.
Umiat 1		
31-41	7.67	Shale of the Colville Group.
41-55	7.5	Do.
55-65	8	Do.
65-82	8.5	Do.
82-92	5	Do.
92-96	3.85	Do.
97-102	3.5	Do.
117-132	11.67	Do.
132-142	9.5	Do.
143-163	17.5	Do.
163-183	18	Do.
183-203	12	Do.
203-221	13	Do.
221-232	7.33	Do.
232-252	18	Do.
252-265	11	Do.
265-285	9	Do.
285-292	6.5	Do.
292-302	10	Do.
302-312	9	Do.
312-316	3	Do.
316-326	9.5	Do.
326-336	8.5	Do.
336-346	8.5	Do.
346-356	0	Do.
356-366	0	Do.
366-370	0	Do.
370-374	0	Do.
374-377	3	Do.
377-387	10	Do.
387-397	10	Do.
397-407	10	Do.
407-417	10	Do.
417-427	10	Do.
427-437	10	Do.
437-447	10	Do.
447-457	.85	Do.
457-467	10	Do.
467-477	10	Do.
477-487	10	Do.
487-490	3	Do.
490-499	7	Do.
499-509	10	Do.
509-519	10	Do.
519-529	10	Do.
529-539	10	Do.
539-549	5.5	Do.
549-554	5	Do.
554-559	5	Do.
559-564	5	Do.
564-569	5	Do.
569-574	5	Do.
574-579	4.5	Do.
579-584	5	Do.
584-591	7	Do.
591-601	8	Do.
604-614	9	Do.
614-624	9	Do.
644-654	10	Do.
654-664	10	Do.
682-692	8	Do.
692-693	1	Do.
722-732	9.5	Do.
732-740	7.5	Do.
740-750	9.5	Do.
750-760	9	Do.
760-765	4.5	Do.
765-770	5	Do.
812-817	4.5	Do.
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Umiat 1--Continued		
865-870	4.5	Do.
920-925	4.5	Nanushuk Group.
945-950	4.5	Do.
950-955	4.67	Do.
955-960	1.5	Do.
960-961	.5	Do.
1,020-1,025	2	Do.
1,025-1,027	1.5	Do.
1,080-1,085	5	Do.
1,085-1,090	5	Do.
1,213-1,223	9	Do.
1,223-1,233	10	Do.
1,233-1,243	10	Do.
1,243-1,253	9	Do.
1,253-1,258	5	Do.
1,258-1,268	10	Do.
1,268-1,278	10	Do.
1,278-1,288	.5	Do.
1,288-1,293	0	Do.
1,293-1,295	1.33	Do.
1,295-1,305	9	Do.
1,305-1,315	10	Do.
1,915-1,325	10	Do.
1,325-1,335	10	Do.
1,335-1,345	5	Do.
1,345-1,350	4.5	Do.
1,350-1,355	1.5	Do.
1,355-1,365	10	Do.
1,365-1,375	10	Do.
1,375-1,383	1.5	Do.
1,383-1,393	7.5	Do.
1,393-1,403	8	Do.
1,403-1,409	6	Do.
1,409-1,414	5	Do.
1,414-1,424	9	Do.
1,424-1,434	7	Do.
1,434-1,444	10	Do.
1,444-1,454	10	Do.
1,454-1,464	10	Do.
1,464-1,474	5.33	Do.
1,615-1,625	8.5	Do.
1,625-1,635	10	Do.
1,635-1,645	10	Do.
1,645-1,651	6	Do.
1,693-1,703	10	Do.
1,703-1,713	10	Do.
1,713-1,723	10	Do.
1,723-1,733	10	Do.
1,733-1,743	8	Do.
1,743-1,745	1.5	Do.
1,745-1,755	9	Do.
1,755-1,765	9.5	Do.
1,765-1,772	6	Do.
1,772-1,782	7.5	Do.
1,782-1,792	9.5	Do.
1,792-1,800	2.5	Do.
1,800-1,810	4.5	Do.
1,810-1,816	2.5	Do.
1,910-1,920	4	Do.
2,252-2,257	4	Do.
2,257-2,266	0	Do.
2,266-2,271	0	Do.
2,271-2,277	0	Do.
2,277-2,287	10	Do.
2,287-2,292	5	Do.
2,292-2,297	5	Do.
2,297-2,302	5	Do.
2,302-2,307	2	Do.
2,307-2,309	2	Do.
2,309-2,314	5	Do.
2,314-2,318	3.5	Do.
2,318-2,327	9	Do.
2,327-2,337	6.5	Do.
2,347-2,357	10	Do.
2,357-2,365	8	Do.
2,365-2,370	5	Do.
2,537-2,542	5	Do.
2,542-2,547	5	Do.
2,547-2,557	10	Do.
2,557-2,563	5	Do.
2,563-2,568	5	Do.
2,568-2,573	5	Do.
2,573-2,578	5	Do.
2,660-2,670	8	Do.
2,670-2,680	1.5	Do.
2,680-2,682	0	Do.
2,682-2,688	6	Do.
2,688-2,695	7	Do.
2,695-2,705	10	Do.
2,705-2,715	9	Do.
2,715-2,718	3	Do.
2,718-2,728	0	Do.

TABLE 15.4.—*Core data for Government-drilled wells on the North Slope of Alaska*—Continued

Interval attempted (ft)	Core recovered (ft)	Rock unit
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Umiat 1--Continued		
2,728-2,733	5	Do.
2,733-2,743	10	Do.
2,743-2,748	5	Do.
2,748-2,758	.33	Do.
2,758-2,759	.17	Do.
2,820-2,825	5	Do.
2,825-2,833	8	Do.
2,833-2,843	10	Nanushuk Group and Torok Formation, undivided.
2,843-2,853	10	Torok Formation.
2,853-2,858	1.5	Do.
2,858-2,865	7	Do.
2,865-2,875	10	Do.
2,875-2,885	8	Do.
2,981-2,986	5	Do.
2,986-2,996	10	Do.
2,996-3,001	5	Do.
3,001-3,011	10	Do.
3,011-3,016	0	Do.
3,395-3,405	10	Do.
3,405-3,415	10	Do.
3,415-3,425	10	Do.
3,425-3,430	5	Do.
3,497-3,507	10	Do.
3,507-3,512	5	Do.
3,512-3,522	10	Do.
3,522-3,532	10	Do.
4,085-4,090	3.5	Do.
4,090-4,095	5	Do.
4,095-4,104	8.5	Do.
4,104-4,114	10	Do.
4,176-4,181	3.5	Do.
4,181-4,190	9	Do.
4,190-4,200	9	Do.
4,200-4,204	4	Do.
5,990-6,005	15	Do.
Umiat 2		
297-302	4.33	Nanushuk Group.
302-312	9	Do.
312-322	8.92	Do.
322-332	2.42	Do.
332-342	8.75	Do.
342-345	2.5	Do.
345-355	9	Do.
355-365	3.5	Do.
365-370	1	Do.
370-375	4.58	Do.
375-385	0	Do.
385-387	1.83	Do.
387-392	.17	Do.
392-395	2.5	Do.
395-400	2.75	Do.
400-408	1.67	Do.
408-413	4.75	Do.
413-418	4.08	Do.
418-423	4.67	Do.
423-433	9.5	Do.
433-439	5.5	Do.
439-444	4.17	Do.
444-450	4.5	Do.
450-455	4.92	Do.
455-465	9.75	Do.
465-475	10.17	Do.
482-487	4.33	Do.
487-492	5	Do.
492-499	7	Do.
499-509	7.33	Do.
509-519	9.92	Do.
519-529	9.83	Do.
529-539	0	Do.
539-544	0	Do.
544-554	9.33	Do.
554-560	0	Do.
560-562	0	Do.
562-572	10.17	Do.
572-582	9.08	Do.
602-609	5.58	Do.
630-640	9.33	Do.
640-648	8.08	Do.
680-690	9.17	Do.
750-760	9.67	Do.
760-770	.17	Do.
770-780	10.17	Do.
780-790	10.33	Do.
790-800	9.5	Do.
800-810	6.5	Do.
810-820	1.5	Do.
820-822	1	Do.
824-834	6.33	Do.
834-843	7	Do.
938-948	10.17	Do.
948-956	9.5	Do.
956-966	0.83	Do.
966-969	2.5	Do.
969-979	9	Do.
979-986	6.75	Do.
986-996	9.67	Do.
996-998	2	Do.
998-1,000	2	Do.
1,000-1,005	4.17	Do.
1,005-1,015	9.67	Do.
1,015-1,025	10	Do.
1,025-1,034	9.08	Do.
1,034-1,044	9.58	Do.
1,044-1,045	.58	Do.
1,045-1,055	10	Do.
1,055-1,065	10	Nanushuk Group and Torok Formation, undivided.
1,065-1,066	1	Torok Formation.
1,209-1,211	1.5	Do.
1,429-1,439	10	Do.
1,618-1,623	5	Do.
1,850-1,855	5	Do.
2,145-2,150	5	Do.
2,408-2,413	5	Do.
2,413-2,418	5	Do.
2,631-2,641	9	Do.
2,784-2,794	7.67	Do.
3,000-3,007	6.17	Do.
3,267-3,277	8.92	Do.
3,441-3,450	7	Do.
3,606-3,616	9.5	Do.
3,616-3,621	0	Do.
3,621-3,626	2	Do.
3,737-3,747	1.92	Do.
3,747-3,750	.5	Do.
3,877-3,887	5.5	Do.
4,087-4,097	7.17	Do.
4,220-4,232	6.5	Do.
4,433-4,443	7.75	Do.
4,610-4,620	9.17	Do.
4,787-4,797	9.5	Do.
4,985-4,995	7.75	Do.
5,185-5,195	6.5	Do.
5,385-5,395	.08	Do.
5,585-5,595	8.75	Do.
5,785-5,795	8.75	Do.
5,883-5,903	4.17	Do.
6,052-6,072	17.5	Do.
6,185-6,200	14.5	Do.
Umiat 3		
236-245	1.5	Nanushuk Group.
245-249	4	Do.
249-257	4	Do.
257-262	4	Do.
262-272	1	Do.
272-281	7.5	Do.
281-286	5	Do.
286-294	3.5	Do.
294-303	2.5	Do.
303-312	1	Do.
312-320	4.5	Do.
320-328	2	Do.
328-335	5	Do.
335-344	4	Do.
344-352	8	Do.
352-359	6.5	Do.
359-368	9	Do.
368-377	6	Do.
377-385	3	Do.
385-393	4	Do.
393-402	1.5	Do.
402-411	4.5	Do.
411-419	6	Do.
419-429	4	Do.
429-439	4	Do.
439-445	6	Do.
445-454	9	Do.
454-463	6	Do.
463-472	7	Do.
472-478	4.5	Do.
481-490	2	Do.
490-498	4.5	Do.
498-507	6	Do.
507-514	1.5	Do.
514-520	3	Do.
520-529	9	Do.
529-538	9	Do.
538-547	9	Do.
547-555	0	Do.
555-563	8	Do.
563-572	8	Do.
Umiat 4		
298-299	1	Nanushuk Group.
299-300	1	Do.
343-345	2	Do.
345-350	5	Do.
350-353	3	Do.
357-360	3	Do.
764-767	0	Do.
767-768	1	Do.
821-826	1.5	Do.
826-827	.5	Do.
Umiat 5		
304-306	2	Nanushuk Group.
306-308	2	Do.
308-310	2	Do.
310-312	2	Do.
375-376	.5	Do.
376-377	.5	Do.
377-378	.33	Do.
378-400	1	Do.
400-403	.33	Do.
403-404	.58	Do.
786-789	.75	Do.
835-837	1.5	Do.
Umiat 6		
509-515	6.5	Nanushuk Group.
529-532	2.5	Do.
680-683	1	Do.
683-687	.17	Do.
Umiat 7		
834-838	4	Nanushuk Group.
862-867	4	Do.
879-880	1	Do.
1,057-1,060	1	Do.
1,211-1,215	2	Do.
1,325-1,327	.33	Do.
1,349-1,352	2.5	Do.
1,370-1,372	1.67	Do.
Umiat 8		
195-200	5	Nanushuk Group.
400-405	5	Do.
457-462	5	Do.
482-487	5	Do.
507-512	5	Do.
532-537	3	Do.
640-645	5	Do.
711-716	5	Do.
810-815	5	Do.
1,015-1,018	3	Do.
1,038-1,041	3	Do.
1,061-1,063	1	Do.
1,078-1,080	.83	Do.
1,130-1,133	1.5	Do.
1,183-1,188	3	Do.
1,240-1,243	3	Do.
1,243-1,246	2	Do.
1,296-1,300	4	Do.
Umiat 9		
385-394	9.08	Nanushuk Group.
394-403	10	Do.
403-413	10	Do.
413-423	10	Do.

TABLE 15.4.—*Core data for Government-drilled wells on the North Slope of Alaska*—Continued

Interval attempted (ft)	Core recovered (ft)	Rock unit
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Umiat 9--Continued		
423-433	10	Do.
433-443	10	Do.
443-454	10	Do.
454-464	10	Do.
464-474	10	Do.
474-484	10	Do.
484-494	3	Do.
494-499	.5	Do.
499-500	.66	Do.
500-502	10.5	Do.
502-512	1.6	Do.
512-514	9.5	Do.
514-525	9.5	Do.
525-533	8.55	Do.
533-543	9	Do.
543-553	10	Do.
553-563	9.55	Do.
563-573	10	Do.
573-583	10	Do.
583-593	10	Do.
593-603	8	Do.
603-611	8	Do.
649-659	10	Do.
659-669	10	Do.
669-678	7.5	Do.
678-687	4.17	Do.
687-697	10	Do.
697-707	10	Do.
819-829	8.83	Do.
829-838	6.66	Do.
838-848	8.83	Do.
848-858	10	Do.
858-868	10	Do.
868-878	9.5	Do.
878-888	6	Do.
888-898	10	Do.
898-901	2.5	Do.
901-911	8.5	Do.
911-919	8	Do.
919-929	10	Do.
929-939	8.55	Do.
939-949	10	Do.
949-959	8	Do.
959-969	10	Do.
969-979	10	Do.
979-989	10	Do.
989-1,000	8.5	Do.
1,000-1,010	8	Do.
1,010-1,017	8	Do.
1,017-1,027	9.55	Do.
1,027-1,037	6.55	Do.
1,037-1,047	10	Do.
1,047-1,057	10	Do.
1,057-1,067	3.91	Do.
1,067-1,076	7.91	Do.
1,076-1,086	9.91	Do.
1,086-1,096	10	Do.
1,096-1,106	10	Do.
1,106-1,117	2.5	Do.
1,117-1,127	3.55	Do.
1,127-1,137	3	Do.
1,137-1,147	9	Do.
1,147-1,157	10	Do.
1,157-1,167	5	Do.
1,167-1,177	9.5	Do.
1,167-1,177	8	Do.
1,187-1,197	10	Do.
1,197-1,206	8.5	Do.
1,206-1,208	1.5	Do.
1,208-1,218	5.5	Do.
1,218-1,228	8	Do.
1,228-1,236	9.5	Do.
1,236-1,247	10	Do.
1,247-1,257	10	Do.
Umiat 10		
420-425	4	Nanushuk Group.
468-473	4	Do.
485-490	4	Do.
625-628	2.5	Shale of the Colville Group.
655-659	4.5	Nanushuk Group.
670-675	5	Do.
685-690	5	Do.
700-705	4.75	Do.
715-720	3	Do.
730-735	4	Do.
745-750	3	Do.
830-832	1	Do.
924-930	4.42	Do.
940-944	3.33	Do.
1,010-1,015	5	Do.
1,065-1,070	3.5	Do.
1,070-1,075	3.75	Do.
1,075-1,080	5	Do.
1,090-1,095	2.67	Do.
1,108-1,111	2.5	Do.
1,120-1,124	3	Do.
1,131-1,134	2.5	Do.
1,540-1,542	1	Do.
Umiat 11		
115-136	20.5	Sandstone of the Colville Group and Sagavanirktok Formation, undivided.
136-156	20	Do.
222-242	20	Do.
242-262	20	Do.
278-298	19.33	Do.
328-348	20	Do.
375-395	20	Do.
456-476	20	Do.
476-496	20	Do.
496-516	20	Do.
516-536	19.5	Do.
536-549	13.33	Do.
551-571	15	Do.
709-729	18.5	Do.
742-762	19	Do.
762-782	20	Sandstone of the Colville Group, Sagavanirktok Formation, and shale of the Colville Group, undivided.
805-825	20	Shale of the Colville Group.
1,005-1,025	20	Do.
1,030-1,050	10	Do.
1,230-1,245	15	Do.
1,322-1,330	7.67	Do.
1,330-1,341	6.5	Do.
1,341-1,354	5.33	Do.
1,354-1,356	1.5	Do.
1,357-1,377	18.33	Do.
1,417-1,429	11.33	Do.
1,452-1,469	13.17	Do.
1,670-1,690	20	Do.
1,823-1,843	19.58	Do.
1,843-1,863	2.83	Do.
1,863-1,864	1.25	Do.
1,955-1,983	18.67	Do.
1,955-1,983	0	Do.
1,955-1,983	0	Do.
2,047-2,068	20	Nanushuk Group.
2,068-2,069	1	Do.
2,069-2,078	8.42	Do.
2,078-2,097	19.58	Do.
2,109-2,128	18.42	Do.
2,128-2,145	16.33	Do.
2,153-2,173	19.17	Do.
2,173-2,192	13.5	Do.
2,192-2,203	10	Do.
2,203-2,221	12.5	Do.
2,221-2,239	18	Do.
2,239-2,259	18	Do.
2,295-2,315	19	Do.
2,315-2,335	18.5	Do.
2,374-2,394	19	Do.
2,394-2,405	11.33	Do.
2,405-2,411	.17	Do.
2,444-2,448	2.5	Do.
2,448-2,461	13	Do.
2,529-2,545	16	Do.
2,701-2,721	20	Do.
2,810-2,830	16	Do.
2,830-2,837	7	Do.
2,837-2,850	13	Do.
2,920-2,940	18	Do.
2,989-3,009	15.5	Do.
3,290-3,303	13	Torok Formation.
Sentinel Hill Core Test 1		
109-119	8	Sandstone of the Colville Group and Sagavanirktok Formation, undivided.
119-129	10	Do.
129-139	8	Do.
139-149	6	Do.
149-159	10	Do.
159-169	10	Do.
169-179	8	Do.
179-189	10	Do.
189-199	7	Do.
199-209	8	Do.
209-219	10	Do.
219-229	9	Do.
229-239	10	Do.
239-249	8	Do.
249-259	10	Do.
259-269	10	Do.
269-279	10	Do.
279-289	7.5	Do.
289-299	10	Do.
299-309	10	Do.
309-319	9	Do.
319-329	8.5	Do.
329-339	10	Do.
339-349	10	Do.
349-359	10	Do.
359-369	10	Do.
369-379	9	Do.
379-389	9	Do.
389-399	10	Do.
399-409	10	Do.
409-419	8	Do.
419-429	10	Do.
429-439	10	Do.
439-449	9	Do.
449-459	10	Do.
459-469	7.5	Do.
469-479	8	Do.
479-489	10	Do.
489-499	9	Do.
499-509	10	Do.
509-519	8	Do.
519-529	10	Do.
529-539	9	Do.
539-549	9	Do.
549-559	10	Do.
559-569	10	Do.
569-579	10	Do.
579-589	9	Do.
589-599	8	Do.
599-609	10	Do.
609-619	8	Do.
619-629	10	Do.
629-639	10	Do.
639-649	10	Do.
649-659	10	Do.
659-669	10	Do.
669-679	9	Do.
679-689	10	Do.
689-699	10	Do.
699-709	10	Do.
709-719	10	Do.
719-729	7.5	Do.
729-739	10	Do.
739-749	9.5	Do.
749-759	4.5	Do.
759-769	10	Do.
769-779	8	Do.
779-789	10	Do.
789-799	10	Do.
799-809	10	Do.
809-819	10	Do.
819-829	10	Do.
829-839	10	Do.
839-849	4	Do.
849-859	10	Do.
859-869	7	Do.
869-879	10	Do.
879-889	10	Do.
889-899	8.5	Do.
899-909	4	Do.
909-919	1.5	Do.
919-929	10	Do.
929-939	8	Do.
939-949	8.5	Do.
949-959	.25	Do.
959-969	6	Do.
969-979	7	Do.
979-989	10	Do.
989-999	10	Do.
999-1,005	5	Do.
1,005-1,015	9	Do.
1,015-1,025	10	Do.
1,025-1,035	10	Do.

TABLE 15.4.—*Core data for Government-drilled wells on the North Slope of Alaska*—Continued

Interval attempted (ft)	Core recovered (ft)	Rock unit
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Sentinel Hill Core Test 1--Continued		
1,035-1,045	10	Do.
1,045-1,052	6.5	Do.
1,052-1,060	8	Do.
1,060-1,070	10	Do.
1,070-1,080	8.5	Do.
1,080-1,090	10	Do.
1,090-1,100	9	Do.
1,100-1,110	7	Do.
1,110-1,120	9	Do.
1,120-1,130	4	Do.
1,130-1,140	10	Do.
1,140-1,150	5	Do.
1,150-1,160	10	Do.
1,160-1,170	2	Do.
1,170-1,180	6	Do.
Gubik 1		
365-385	17	Sandstone of the Colville Group and Sagavanirktok Formation, undivided.
731-751	20	Do.
1,086-1,106	20	Do.
1,155-1,163	8	Do.
1,163-1,175	12	Do.
1,218-1,238	20	Do.
1,444-1,457	11	Do.
1,457-1,469	3	Do.
1,469-1,475	3	Do.
1,475-1,495	20	Do.
1,711-1,718	7	Do.
1,723-1,738	11	Do.
1,856-1,877	10	Do.
1,877-1,897	10	Do.
2,185-2,200	10	Shale of the Colville Group.
2,499-2,519	20	Do.
2,620-2,639	10	Do.
2,639-2,659	19	Do.
2,723-2,743	19	Do.
2,840-2,860	7	Do.
2,954-2,974	15	Do.
3,051-3,070	5	Do.
3,169-3,186	0	Nanushuk Group.
3,261-3,281	19	Do.
3,342-3,362	19	Do.
3,435-3,455	20	Do.
3,455-3,466	11	Do.
3,485-3,502	17	Do.
3,502-3,519	17	Do.
3,519-3,535	16	Do.
3,535-3,555	20	Do.
3,555-3,567	12	Do.
3,567-3,586	19	Do.
3,586-3,602	15	Do.
3,602-3,608	4	Do.
3,702-3,707	1	Do.
3,762-3,782	20	Do.
3,782-3,783	1	Do.
3,900-3,920	20	Do.
4,020-4,034	11	Torok Formation.
4,130-4,143	11	Do.
4,261-4,281	17	Do.
4,281-4,290	9	Do.
4,290-4,305	15	Do.
4,352-4,372	10	Do.
4,543-4,563	20	Do.
4,735-4,746	8	Do.
4,746-4,756	0	Do.
5,100-5,115	10	Do.
5,441-5,458	9	Do.
5,458-5,463	4	Do.
5,748-5,768	19	Do.
5,982-6,000	14	Do.
Gubik 2		
320-340	18	Sandstone of the Colville Group and Sagavanirktok Formation, undivided.
800-820	17	Do.
1,142-1,149	1.5	Do.
1,149-1,153	4	Do.
1,153-1,161	6.5	Do.
1,161-1,171	10	Do.
1,171-1,181	10	Do.
1,181-1,191	10	Do.
1,191-1,201	10	Do.
1,201-1,211	10	Do.
1,211-1,218	5	Do.
1,218-1,236	18	Do.
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Gubik 2--Continued		
1,236-1,256	5	Do.
1,305-1,315	6.5	Do.
1,315-1,320	0	Do.
1,320-1,340	20	Do.
1,340-1,351	10	Do.
1,353-1,373	20	Do.
1,373-1,392	1	Do.
1,392-1,402	10	Do.
1,430-1,445	13	Do.
1,445-1,462	11	Do.
1,462-1,482	20	Do.
1,482-1,502	17	Do.
1,502-1,512	9	Do.
1,512-1,522	10	Do.
1,522-1,532	5	Do.
1,532-1,542	1.5	Do.
1,542-1,552	8	Do.
1,552-1,554	2	Do.
1,554-1,558	3	Do.
1,558-1,568	10	Do.
1,568-1,578	10	Do.
1,578-1,580	2	Do.
1,669-1,676	7	Do.
1,676-1,686	4.5	Do.
1,686-1,696	0	Do.
1,696-1,700	0	Do.
1,700-1,706	6	Do.
1,706-1,722	16	Do.
1,722-1,731	8	Do.
1,731-1,737	3.5	Do.
1,806-1,813	0	Do.
1,813-1,820	7	Do.
1,820-1,826	6	Do.
1,826-1,836	6.5	Do.
1,836-1,841	4	Do.
1,841-1,848	7	Do.
1,848-1,868	20	Do.
1,868-1,880	12	Do.
1,880-1,885	5	Do.
1,915-1,935	20	Do.
1,935-1,955	20	Do.
1,955-1,960	5	Do.
1,960-1,980	20	Do.
1,980-1,984	4	Do.
2,069-2,079	10	Do.
2,079-2,089	10	Do.
2,089-2,109	20	Do.
2,109-2,129	17	Do.
2,129-2,145	16	Do.
2,145-2,146	1	Do.
2,170-2,180	7	Do.
2,180-2,190	9	Do.
2,190-2,200	10	Do.
2,200-2,210	8	Shale of the Colville Group.
2,210-2,218	2	Do.
3,100-3,110	10	Do.
3,110-3,120	10	Do.
3,120-3,126	6	Do.
3,324-3,333	3	Shale of the Colville Group and Nanushuk Group, undivided.
3,333-3,343	10	Nanushuk Group.
3,343-3,353	8	Do.
3,353-3,363	10	Do.
3,363-3,368	4	Do.
3,368-3,380	12	Do.
3,380-3,400	20	Do.
3,480-3,490	10	Do.
3,490-3,500	9	Do.
3,500-3,510	3	Do.
3,510-3,518	4	Do.
3,518-3,528	10	Do.
3,528-3,537	9	Do.
3,537-3,540	2.5	Do.
3,620-3,640	19.5	Do.
3,640-3,660	18	Do.
3,660-3,669	7	Do.
3,672-3,682	9	Do.
3,682-3,684	2	Do.
3,684-3,692	8	Do.
3,692-3,702	2	Do.
3,702-3,708	1	Do.
3,708-3,714	2	Do.
3,714-3,734	18	Do.
3,734-3,748	2	Do.
3,748-3,768	20	Do.
3,768-3,777	9	Do.
3,777-3,787	1	Do.
3,787-3,796	0	Do.
3,796-3,809	12.5	Do.
3,809-3,829	20	Do.
3,829-3,848	19	Do.
3,848-3,858	0	Do.
3,858-3,872	14	Do.
Naval Petroleum Reserve No. 4 Program (1944-53)--Continued		
Gubik 2--Continued		
3,872-3,892	20	Do.
3,892-3,912	20	Do.
3,912-3,933	16	Do.
3,933-3,967	0	Do.
3,967-3,987	5	Do.
3,987-3,995	7	Do.
4,031-4,048	16	Do.
4,048-4,058	1	Do.
4,058-4,059	1	Do.
4,059-4,060	1	Do.
4,060-4,075	10	Do.
4,230-4,243	10	Do.
4,243-4,261	15	Do.
4,303-4,323	18	Do.
4,323-4,336	11	Do.
4,336-4,350	15	Do.
4,350-4,370	18	Do.
4,370-4,383	12	Do.
4,399-4,418	19	Torok Formation.
4,502-4,522	20	Do.
4,600-4,620	17	Do.
Kaolak 1		
217-237	15	Nanushuk Group.
420-440	20	Do.
560-580	20	Do.
762-782	18.5	Do.
935-941	4.42	Do.
980-1,000	20	Do.
1,183-1,203	17	Do.
1,338-1,400	16	Do.
1,516-1,536	20	Do.
1,657-1,677	5	Do.
1,677-1,693	13	Do.
1,814-1,842	15	Do.
2,026-2,046	6.5	Do.
2,206-2,225	18	Do.
2,400-2,415	15	Do.
2,453-2,473	13	Do.
2,607-2,618	10	Do.
2,791-2,811	20	Do.
2,945-2,957	11.5	Do.
3,156-3,176	20	Do.
3,176-3,192	16	Do.
3,256-3,271	15	Do.
3,476-3,496	13.5	Do.
3,667-3,679	7.5	Do.
3,873-3,881	0	Do.
3,881-3,892	8	Do.
3,985-4,002	17	Do.
4,002-4,021	14	Do.
4,021-4,033	2.5	Do.
4,077-4,097	18	Do.
4,175-4,193	15.5	Do.
4,429-4,439	10	Do.
4,625-4,643	18	Do.
4,836-4,850	14	Do.
4,850-4,864	14	Do.
4,864-4,874	10	Do.
5,053-5,073	4	Do.
5,073-5,087	15	Do.
5,087-5,100	13	Do.
5,053-5,073	4	Do.
5,073-5,087	15	Do.
5,087-5,100	13	Do.
5,281-5,295	6	Torok Formation.
5,481-5,497	14	Do.
5,646-5,660	13	Do.
5,754-5,772	17	Do.
5,927-5,942	14.5	Do.
6,115-6,127	0	Do.
6,127-6,138	10	Do.
6,367-6,387	12	Do.
6,387-6,404	12	Do.
6,404-6,420	13	Do.
6,591-6,599	7	Do.
6,737-6,757	20	Do.
Barrow Program (1955-81)		
South Barrow 5		
2,300-2,310	8.66	Pebble shale unit.
South Barrow 6		
2,343-2,363	19.5	Kingak Shale.

TABLE 15.4.—*Core data for Government-drilled wells on the North Slope of Alaska*—Continued

Interval attempted (ft)	Core recovered (ft)	Rock unit
Barrow Program (1955–81)--Continued		
South Barrow 9		
1,987-2,016	2	Pebble shale unit.
2,030-2,059	21.5	Do.
2,059-2,080	21.5	Do.
2,080-2,109	28	Do.
2,361-2,389	28	Kingak Shale.
2,389-2,419	30	Do.
2,419-2,450	30	Do.
South Barrow 12		
1,965-1,985	20	Kingak Shale.
1,986-2,016	30	Do.
2,016-2,046	30	Do.
2,046-2,076	30	Do.
2,076-2,101	25	Do.
2,163-2,192	25	Do.
2,192-2,222	28	Kingak Shale and Sag River Sandstone, undivided.
2,220-2,250	30	Sag River Sandstone.
2,255-2,285	30	Argillite.
Iko Bay 1		
2,337-2,396	50	Kingak Shale
2,410-2,470	60	Do.
2,702-2,731	29	Kingak Shale and argillite, undivided.
South Barrow 13		
2,159-2,189	30	Pebble shale unit.
2,189-2,219	27	Do.
2,288-2,318	30	Kingak Shale.
2,318-2,348	30	Do.
2,410-2,425	15	Do.
2,522-2,534	3	Argillite.
South Barrow 17		
2,096-2,126	30	Kingak Shale.
2,126-2,147	22	Do.
2,296-2,322	5.5	Sag River Sandstone.
2,322-2,345	23	Do.
South Barrow 19		
1,330-1,360	30	Torok Formation and pebble shale unit, undivided.
2,039-2,069	30	Kingak Shale.
2,209-2,217	4	Sag River Sandstone.
2,217-2,230	9	Do.
2,230-2,245	15	Do.
South Barrow 20		
2,247-2,269	20.2	Sag River Sandstone.
2,269-2,298	29	Do.
2,299-2,314	15	Do.
South Barrow 15		
800-825	9	Torok Formation.
1,329-1,389	59	Do.
1,838-1,881	42.9	Pebble shale unit.
2,096-2,136	36.2	Kingak Shale.
2,165-2,187	19.9	Do.
South Barrow 18		
1,350-1,371	12	Torok Formation.
1,371-1,400	22.5	Torok Formation and pebble shale unit, undivided.
1,703-1,763	60	Kingak Shale.
1,990-2,020	29	Do.
2,051-2,072	15.5	Do.
2,072-2,087	14.5	Do.
Naval Petroleum Reserve No. 4 Program (1973–77)		
South Harrison Bay 1		
7,022-7,052	13.6	Torok Formation.
10,613-10,628	13.75	Lisburne Group.
Itigaru Point 1		
8,712-8,742	3	Ledge Sandstone Member of the Ivishak Formation.
11,520-11,535	13	Argillite.
W.T. Foran 1		
7,539-7,557	18	Shublik Formation.
8,253-8,283	3	Lisburne Group.
National Petroleum Reserve in Alaska Program (1977–81)		
Walakpa 1		
257-287	23	Torok Formation.
1,590-1,613	0	Do.
1,760-1,800	0	Pebble shale unit.
1,837-1,897	50.5	Do.
1,981-2,042	58	Do.
2,061-2,120	54	Pebble shale unit and Kingak Shale, undivided.
2,808-2,825	3.8	Kingak Shale.
2,930-2,990	60	Do.
2,990-3,020	31.5	Do.
3,051-3,111	60	Do.
3,360-3,420	60	Shublik Formation.
3,656-3,666	60	Argillite.
West Dease 1		
600-630	27	Torok Formation.
1,099-1,129	14	Do.
1,900-1,930	30	Do.
2,945-2,975	30	Pebble shale unit.
3,700-3,732	32	Kingak Shale.
3,730-3,790	58.3	Do.
3,790-3,850	60	Kingak Shale, Sag River Sandstone, and Shublik Formation, undivided.
3,912-3,972	58	Shublik Formation.
3,973-4,033	30	Shublik Formation and argillite, undivided.
4,150-4,160	1.5	Argillite.
Tulageak 1		
2,940-2,980	38	Pebble shale unit and Kingak Shale, undivided.
3,783-3,816	33	Sag River Sandstone and Shublik Formation, undivided.
4,005-4,015	10	Argillite.
Walakpa 2		
2,611-2,640	29	Pebble shale unit.
2,984-3,021	37	Kingak Shale.
3,690-3,749	59	Do.
North Kalikpik 1		
3,810-3,821	11	Torok Formation.
4,994-5,004	10	Do.
5,871-5,881	8	Do.
6,698-6,708	10	Do.
6,992-7,026	34	Pebble shale unit.
7,026-7,047	21	Do.
7,047-7,107	60	Do.
7,107-7,136	29	Do.
7,136-7,140	4	Do.
7,140-7,161	21	Pebble shale unit and Kingak Shale, undivided.
7,161-7,163	2	Kingak Shale.
7,163-7,165	2	Do.
7,165-7,167	2	Do.
Naval Petroleum Reserve in Alaska Program (1977–81)--Continued		
North Kalikpik 1--Continued		
7,167-7,197	30	Do.
7,197-7,225	28	Do.
7,225-7,230	3	Do.
7,385-7,390	5	Do.
North Inigok 1		
4,022-4,037	14.5	Torok Formation.
6,454-6,470	0	Do.
6,852-6,867	15	Do.
7,488-7,506	18	Pebble shale unit.
8,563-8,573	9.5	Kingak Shale.
10,160-10,170	10	Shublik Formation.
Lisburne 1		
1,554-1,570	4	Okpikruak Formation.
2,075-2,091	15.5	Do.
2,990-3,000	9	Do.
3,900-3,910	9	Do.
5,340-5,356	16	Do.
6,215-6,225	10	Etivluk Group.
8,038-8,068	30	Lisburne Group.
8,730-8,740	8.5	Etivluk Group.
9,728-9,738	10	Lisburne Group.
11,162-11,173	11	Etivluk Group.
11,687-11,691	4	Lisburne Group.
13,601-13,609	7.7	Etivluk Group.
13,859-13,870	11.4	Lisburne Group.
15,328-15,342	12	Etivluk Group.
15,596-15,598	0	Lisburne Group.
15,655-15,663	3	Do.
15,902-15,911	4.8	Do.
16,302-16,328	22.5	Do.
16,859-16,876	12.	Do.
16,982-17,000	14.5	Do.
Awuna 1		
2,447-2,477	29.5	Torok Formation.
3,664-3,680	15	Do.
6,010-6,040	30	Do.
South Meade 1		
3,010-3,020	9.6	Torok Formation.
4,010-4,020	1	Do.
4,950-4,961	10	Do.
5,992-6,002	10	Do.
7,500-7,504	3	Kingak Shale.
8,489-8,519	30	Do.
8,807-8,808	0	-----
8,819-8,873	53.3	Sag River Sandstone and Shublik Formation, undivided.
9,040-9,059	16.5	Shublik Formation.
9,305-9,328	21.8	Fire Creek Siltstone Member of the Ivishak Formation.
Kugrua 1		
7,197-7,202	5	Pebble shale unit and Kingak Shale, undivided.
10,480-10,504	24	Ledge Sandstone Member of the Ivishak Formation.
11,030-11,033	3	Echooka Formation.
Kuyunak		
4,965-5,024	58.2	Pebble shale unit.
5,024-5,075	50.9	Do.
5,093-5,153	58.4	Do.
5,153-5,186	33	Pebble shale unit and Kingak Shale, undivided.
6,203-6,236	33	Kingak Shale.
6,254-6,314	60	Sag River Sandstone.
6,682-6,690	7.7	Argillite.

TABLE 15.4.—*Core data for Government-drilled wells on the North Slope of Alaska*—Continued

Interval attempted (ft)	Core recovered (ft)	Rock unit
Naval Petroleum Reserve in Alaska Program (1977-81)-- Continued		
Drew Point 1		
4,130-4,140	10	Torok Formation.
5,530-5,540	2.5	Do.
5,900-5,921	18	Do.
6,905-6,907	1.5	Kingak Shale.
6,917-6,947	26	Do.
6,947-6,957	10	Kingak Shale and Sag River Sandstone, undivided.
6,977-7,009	32	Sag River Sandstone.
7,093-7,103	10	Shublik Formation.
7,350-7,380	30	Do.
7,544-7,572	28	Shublik Formation and Ledge Sandstone Member of the Ivishak Formation, undivided.
7,572-7,602	29	Ledge Sandstone Member of the Ivishak Formation.
7,602-7,629	27	Do.
7,704-7,733	23	Do.
7,793-7,821	22	Do.
7,882-7,901	18.5	Argillite.
Inigok 1		
2,632-2,662	30	Nanushuk Group.
3,072-3,082	10	Do.
4,206-4,216	10	Torok Formation.
5,000-5,010	10	Do.
7,054-7,064	10	Do.
8,210-8,240	30	Do.
8,842-8,852	10	Do.
9,338-9,348	10	Kingak Shale.
9,448-9,458	10	Do.
10,295-10,305	10	Do.
10,998-11,008	10	Do.
11,704-11,714	10	Do.
12,273-12,283	9.5	Shublik Formation.
12,500-12,530	29	Fire Creek Siltstone Member of the Ivishak Formation.
12,705-12,735	30	Do.
13,480-13,510	30	Kavik Member of the Ivishak Formation.
13,831-13,880	49	Echooka Formation.
14,020-14,066	45.5	Lisburne Group.
15,185-15,215	30	Do.
16,185-16,198	12.8	Do.
17,053-17,083	30	Do.
19,360-19,372	10.5	Endicott Group.
20,091-20,102	1.92	Do.
Ikpikpuk 1		
2,930-2,960	30	Nanushuk Group and Torok Formation, undivided.
3,784-3,812	28	Torok Formation.
5,690-5,700	10	Do.
7,132-7,143	11	Do.
Naval Petroleum Reserve in Alaska Program (1977-81)-- Continued		
Ikpikpuk 1--Continued		
7,368-7,378	9	Pebble shale unit.
7,491-7,501	10	Kingak Shale.
10,270-10,300	30	Shublik Formation.
10,619-10,649	30	Ledge Sandstone Member of the Ivishak Formation.
10,815-10,842	27	Do.
11,108-11,135	27	Kavik Member of the Ivishak Formation.
11,718-11,713	15	Lisburne Group.
12,743-12,753	10	Do.
14,971-14,986	15	Endicott Group.
15,421-15,424	1.1	Basement complex.
15,461-15,462	0	Do.
15,463-15,469	4	Do.
East Simpson 1		
2,674-2,685	10.6	Nanushuk Group.
3,739-3,749	0	Torok Formation.
3,749-3,759	0	Do.
5,120-5,130	10	Do.
6,810-6,870	60	Sag River Sandstone.
6,898-6,922	24	Do.
7,426-7,436	10	Shublik Formation.
7,463-7,523	58.2	Ledge Sandstone Member of the Ivishak Formation.
7,564-7,593	28	Ledge Sandstone Member of the Ivishak Formation and basement complex, undivided.
7,729-7,739	8	Basement complex
J.W. Dalton 1		
3,500-3,530	27	Nanushuk Group.
4,667-4,697	30	Torok Formation.
5,603-5,633	27	Do.
6,585-6,615	4.3	Do.
7,524-7,534	8.6	Pebble shale unit.
7,967-8,021	54	Ledge Sandstone Member of the Ivishak Formation.
8,021-8,081	55	Do.
8,081-8,113	13.5	Do.
8,113-8,140	26.5	Do.
8,140-8,200	59	Do.
8,317-8,345	24.9	Lisburne Group.
8,515-8,544	28.1	Do.
9,357-9,367	8.5	Argillite.
East Simpson 2		
2,380-2,410	30	Nanushuk Group.
6,056-6,086	27.5	Torok Formation.
6,340-6,370	30	Pebble shale unit.
6,705-6,735	30	Sag River Sandstone.
7,167-7,197	29	Endicott Group.
Naval Petroleum Reserve in Alaska Program (1977-81)-- Continued		
East Simpson 2--Continued		
7,197-7,227	28	Do.
7,248-7,278	30	Do.
7,293-7,346	53	Do.
7,424-7,458	32.8	Argillite.
Seabee 1		
5,390-5,402	12	Torok Formation.
6,541-6,551	7.3	Do.
10,068-10,098	29.5	Do.
10,870-10,884	14	Do.
12,011-12,041	30	Do.
13,207-13,236	27.6	Kingak Shale.
14,577-14,607	27.6	Do.
Tunalik 1		
3,280-3,308	26	Nanushuk Group.
3,820-3,830	9	Do.
5,552-5,562	9.5	Do.
6,504-6,514	7.25	Torok Formation.
7,870-7,880	10	Do.
8,782-8,810	28	Do.
10,472-10,502	30	Do.
10,671-10,702	31	Pebble shale unit.
10,910-10,940	30	Kingak Shale.
11,672-11,694	22	Do.
12,567-12,597	30	Do.
14,846-14,856	9	Fire Creek Siltstone Member of the Ivishak Formation.
15,408-15,438	30	Do.
16,236-16,261	25	Kavik Member of the Ivishak Formation.
16,929-16,959	21	Echooka Formation.
17,134-17,149	11.5	Lisburne Group.
17,255-17,286	28	Do.
17,858-17,888	30	Do.
Peard 1		
3,035-3,065	30.5	Torok Formation.
4,278-4,294	14.5	Do.
5,409-5,421	12	Do.
5,906-5,916	10.4	Do.
6,119-6,129	10.4	Do.
6,403-6,413	8	Pebble shale unit.
7,837-7,868	31.5	Kingak Shale.
8,275-8,290	9.8	Do.
8,451-8,481	27.5	Sag River Sandstone and Shublik Formation, undivided.
8,977-9,008	31	Ledge Sandstone Member of the Ivishak Formation.
9,490-9,520	30	Echooka Formation.
10,215-10,225	10	Basement complex.

16. STRUCTURE-CONTOUR AND ISOPACH MAPS OF THE NATIONAL PETROLEUM RESERVE IN ALASKA

By KENNETH J. BIRD

INTRODUCTION

This chapter primarily comprises a set of 20 isopach and structure-contour maps of various stratigraphic intervals and horizons in the National Petroleum Reserve in Alaska (NPRA). These maps synthesize all available new information with the old in a format that allows easy integration with geologic studies in nearby areas of the North Slope. They also provide the geologic framework for the evaluation of organic geochemical data in oil and gas source-rock studies (see Magoon and Bird, chapter 17).

The area mapped is limited to the relatively undisturbed (autochthonous) rocks in the NPRA. The tectonically transported (allochthonous) rocks of the Brooks Range and southern foothills provinces (see Mayfield and others, chapter 7) are not included because of differences in stratigraphy, structural complexity, and absence of subsurface information.

These maps differ in several important aspects from isopach and structure maps of many of the same intervals and horizons made by Tetra Tech, Inc. (Bruynzeel and others, 1982). The maps in this chapter integrate the surface geology more completely and are drawn at a more generalized regional scale. The structure contours of the Tetra Tech maps, based on seismic data, have been adjusted to coincide with stratigraphic boundaries established in wells. The isopach intervals used here have stratigraphic boundaries, whereas the Tetra Tech maps used boundaries based on seismic reflections (parastratigraphic units).

STRUCTURE AND ISOPACH MAPS

The stratigraphic intervals and horizons used for the maps in this chapter are indicated on a generalized stratigraphic column in figure 16.1. To avoid clutter and to eliminate redundancies, only 49 of the 126 Government-drilled wells were selected for inclusion on the maps; the identities and locations of these wells are shown on figure 16.2. Each of the 7 structure-contour maps (figs. 16.3-16.9) and 13 isopach maps (figs. 16.10-16.22) is intended to be self-contained and therefore has its own stratigraphic column, list of data sources, and explanatory notes. The maps were originally plotted at a scale of 1:1,000,000 and subsequently reduced for publication.

All available data were included in the construction of these maps. Surface geologic data include measured sections and geologic maps, mostly from USGS publications. Stratigraphic data for the wells are from Bird (chapter 15, table 15.3). Seismic mapping is from Tetra Tech reports (for example, Harris and others, 1977; Bruynzeel and others, 1982) and those of other investigators.

REFERENCES CITED

Brosgé, W.P., and Whittington, C.L., 1966, Geology of the Umiat-Maybe Creek region, Alaska: U.S. Geological Survey Professional Paper 303-H, p. 501-638.

Bruynzeel, J.W., Guldenzopf, E.C., and Pickard, J.E., 1982, Petroleum exploration of NPRA, 1974-1981—Final Report: Houston, Tetra Tech, Inc., report 8200, 3 vols., 5 boxes of geophysical maps. [Available from National Geophysical Data Center, 325 Broadway, E/GC, Dept. CNP, Boulder, CO 80303].

Chapman, R.M., and Sable, E.G., 1960, Geology of the Utukok-Corwin region, northwestern Alaska: U.S. Geological Survey Professional Paper 303-C, p. 47-167.

Haga, Hideyo, and Mickey, M.B., 1983a, South Barrow area Neocomian biostratigraphy: San Diego, Calif., Biostratigraphics, Inc., 2 v. [Available from National Geophysical Data Center, 325 Broadway, E/GC, Dept. CNP, Boulder, CO 80303].

——— 1983b, Jurassic-Neocomian seismic stratigraphy, NPRA: San Diego, Calif., Biostratigraphics, Inc., 2 v. [Available from National Geophysical Data Center, 325 Broadway, E/GC, Dept. CNP, Boulder, CO 80303].

Harris, J.R., Miller, C.C., and Pickard, J.E., 1977, Summary geophysical report; interpretation of the FY '77 seismic survey data, National Petroleum Reserve in Alaska: Houston, Tetra Tech, Inc., report, 18 p. [Available from National Geophysical Data Center, 325 Broadway, E/GC, Dept. CNP, Boulder, CO 80303].

Lathram, E.H., 1965, Preliminary geologic map of northern Alaska: U.S. Geological Survey open-file report, scale 1:1,000,000, 2 sheets.

Mayfield, C.F., Tailleur, I.L., Mull, C.G., and Sable, E.G., 1978, Bedrock geologic map of the south half of National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 78-70-B, scale 1:500,000, 2 sheets.

Mull, C.G., Tailleur, I.L., Mayfield, C.F., Ellersieck, I.F., and Curtis, S.M., 1982, New upper Paleozoic and lower Mesozoic stratigraphic units, central and western Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 66, no. 3, p. 348-362.

Manuscript received for publication on January 3, 1985.

Payne, T.G., 1982, Use of microcomputer in mapping depth of stratigraphic horizons in National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 82-1054, 42 p.

Rockwell, D.W., 1981, Report on reinterpretation of seismic data pertaining to Mesozoic strata in the Cape Simpson region, National Petroleum Reserve in Alaska: Stewart Folk and Co., Inc., 28 p. [Available from National Geophysical Data Center, 325 Broadway, E/GC, Dept. CNP, Boulder, CO 80303].

Smiley, C.J., 1966, Cretaceous floras from Kuk River area, Alaska; stratigraphic and climatic interpretations: Geological Society of America Bulletin, v. 77, no. 1, p. 1-13.

Witmer, R.J., Haga, Hideyo, and Mickey, M.B., 1981, Biostratigraphic report of thirty-three wells drilled from 1975 to 1981 in National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 81-1166, 50 p.

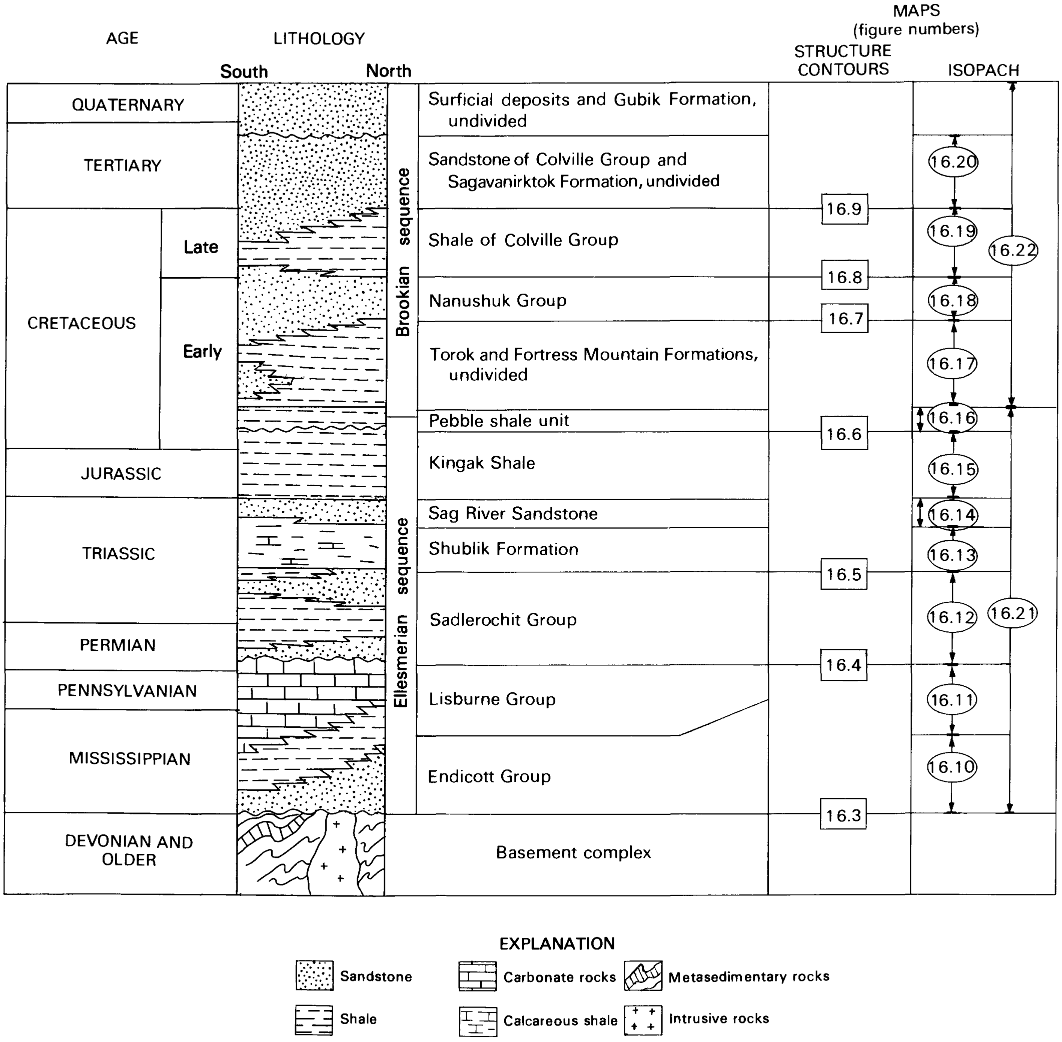


FIGURE 16.1.—Generalized stratigraphic column of northern foothills and coastal plain provinces of NPRA showing age, lithology, unit names, and mapped horizons and isopached intervals; corresponding maps are identified by figure numbers.

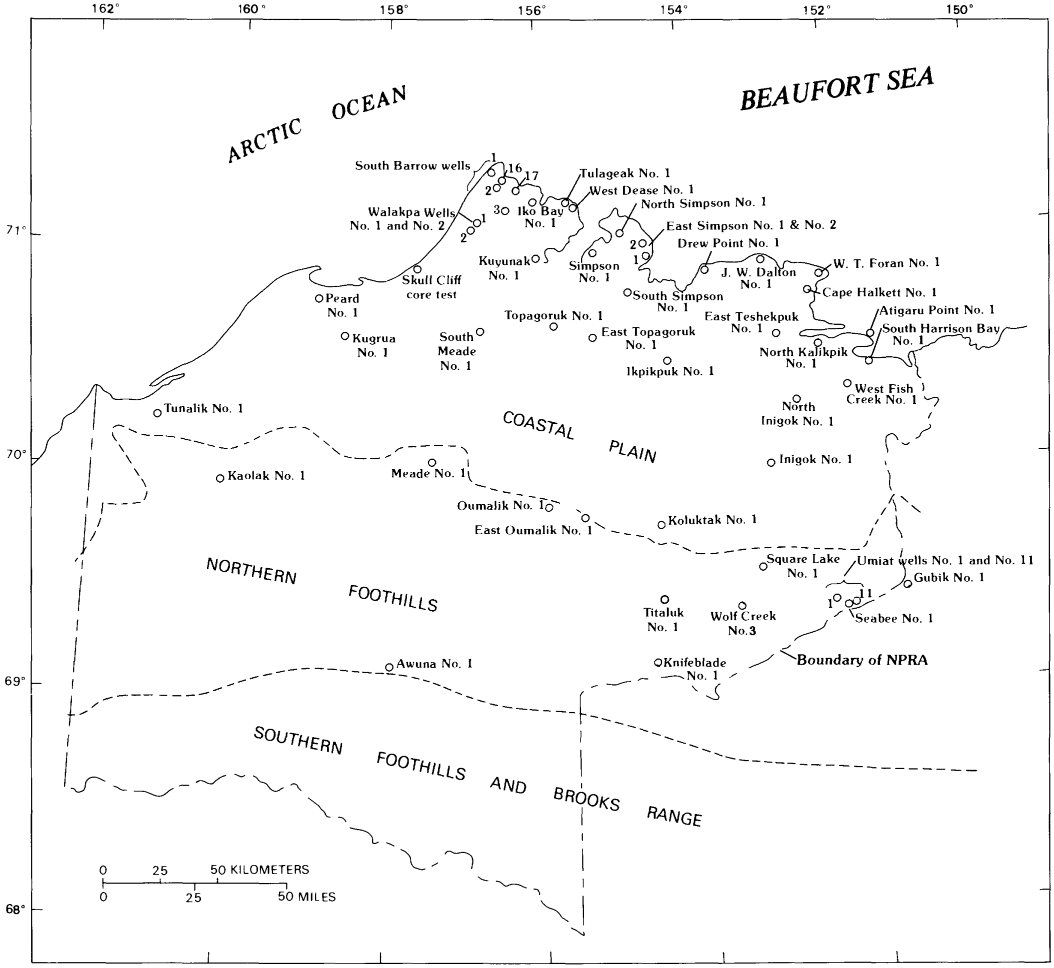


FIGURE 16.2.—Names and locations of the 49 Government-drilled wells in NPRA employed in the isopach and structure-contour maps.

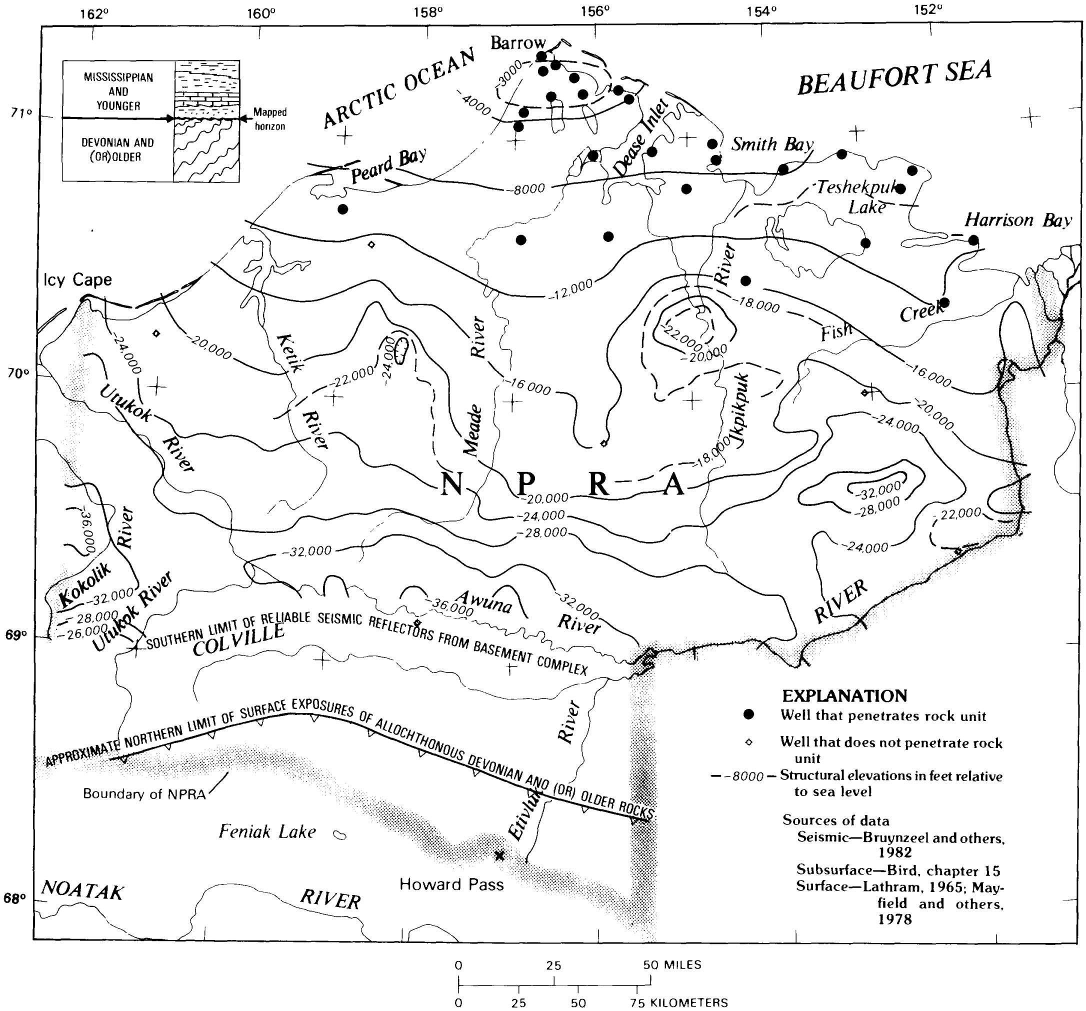


FIGURE 16.3.—Structure-contour map for top of basement complex in NPRA.

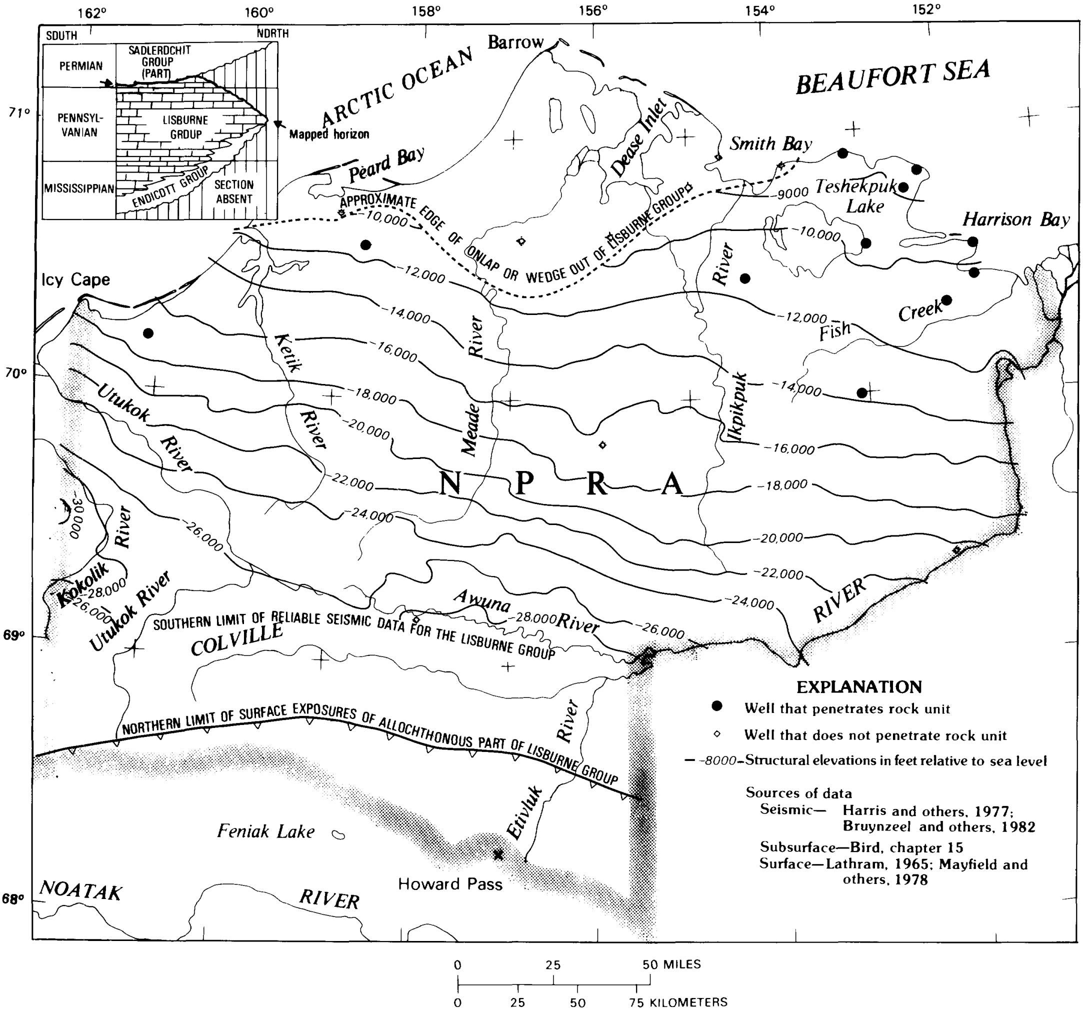


FIGURE 16.4.—Structure-contour map for top of Lisburne Group in NPRA.

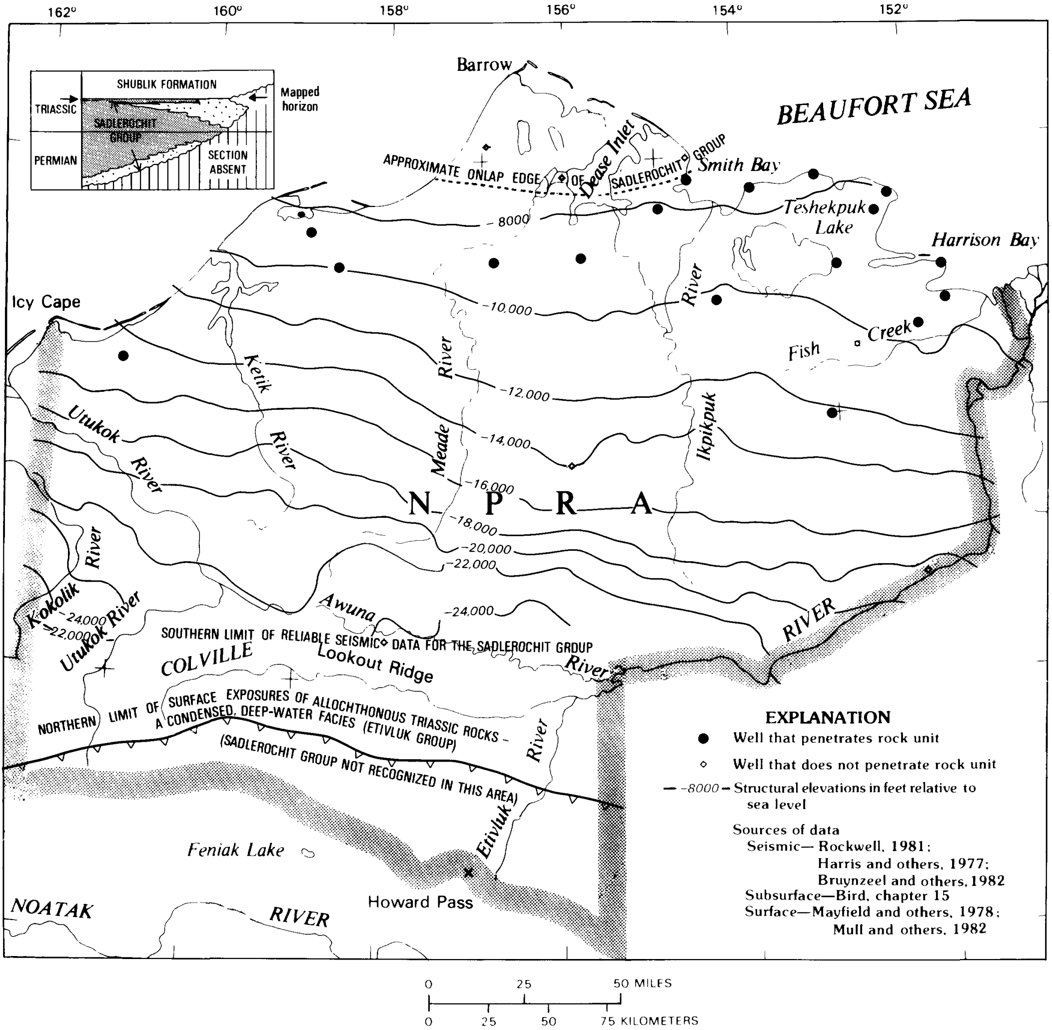


FIGURE 16.5.—Structure-contour map for top of Sadlerochit Group in NPRA.

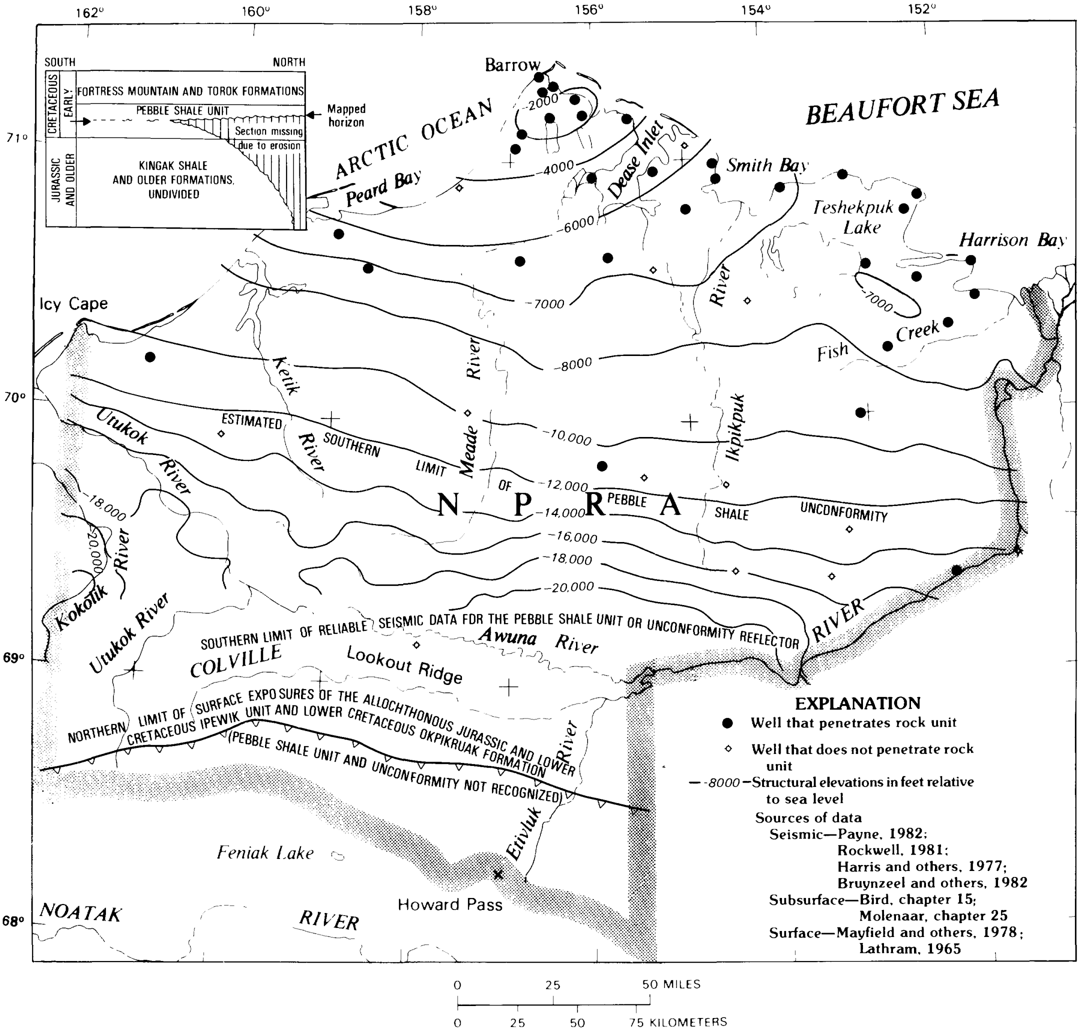


FIGURE 16.6.—Structure-contour map for unconformity at base of pebble shale unit in NPRA. This surface is commonly referred to as the pebble shale unconformity throughout the NPRA.

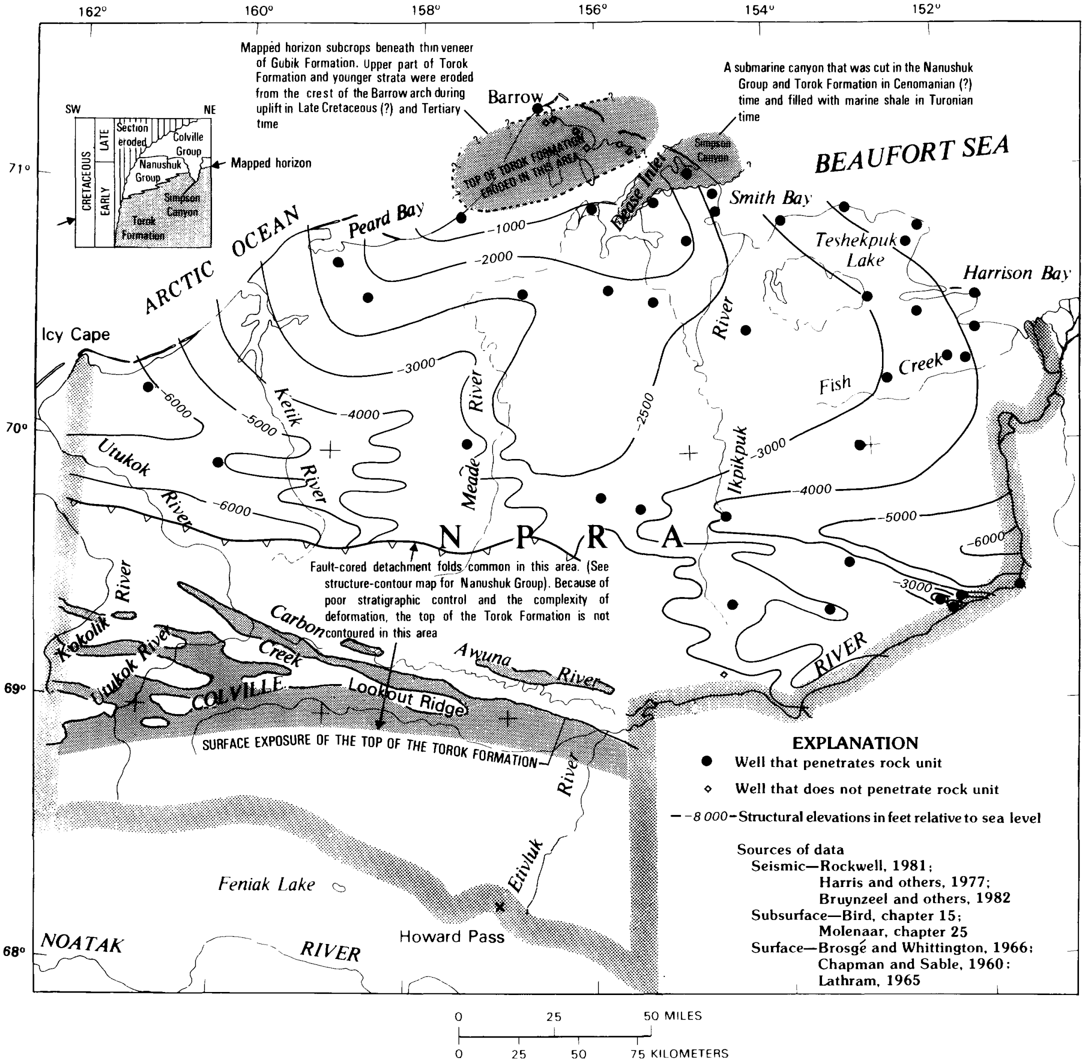


FIGURE 16.7.—Structure-contour map for top of Torok Formation in NPRA.

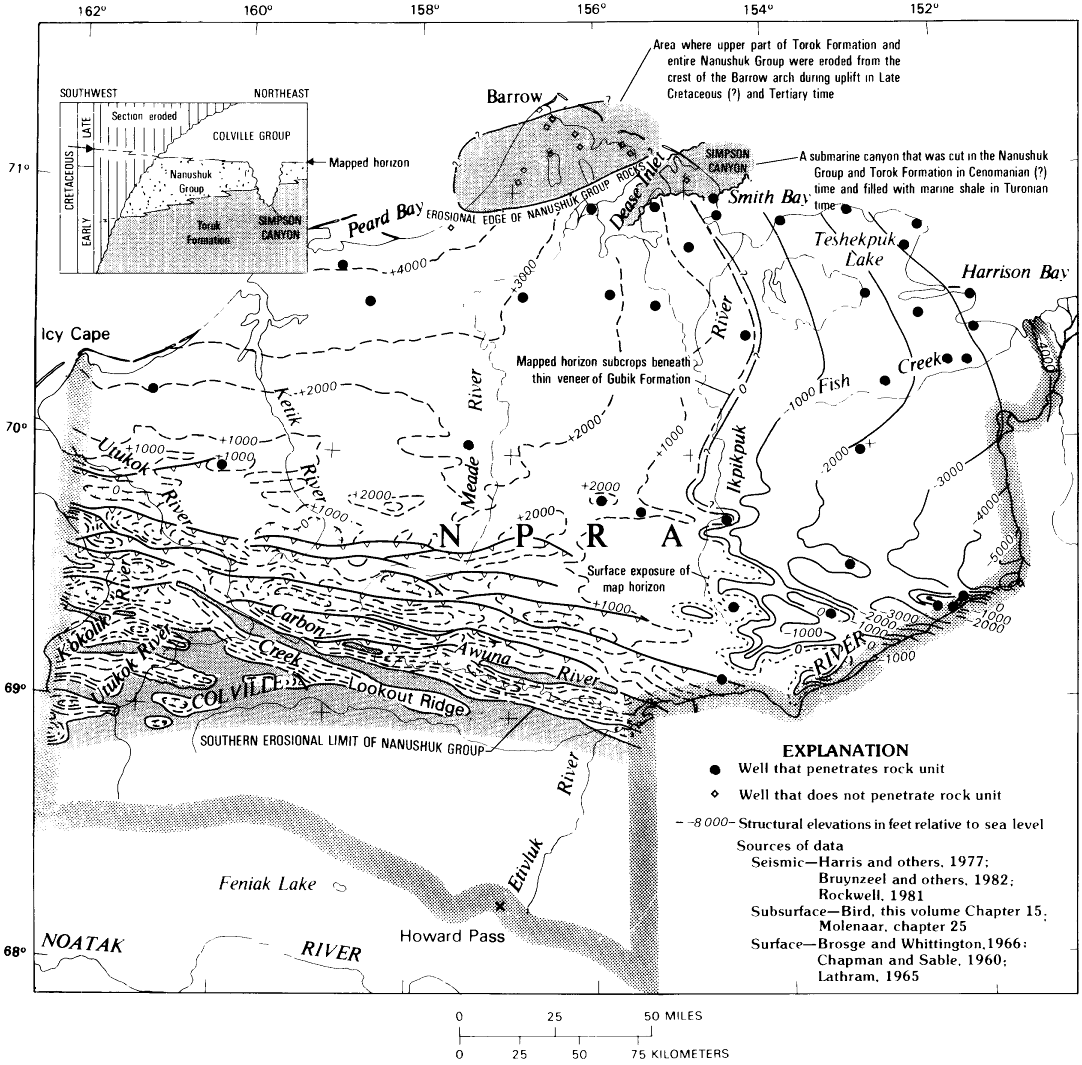


FIGURE 16.8.—Structure-contour map for top of Nanushuk Group in NPRA. Solid contours indicate top of Nanushuk Group present; dashed contours indicate top of Nanushuk Group missing because of erosion, and contour values represent estimated elevation of restored top of Nanushuk Group (restored by projecting constant thickness above mapped intra-Nanushuk seismic horizons. Numerical values not assigned to contours in areas subject to faulting because of uncertainty of seismic correlations across faults. Elevation of restored top of Nanushuk Group in southwest corner of map is greater than 2,950 ft, the greatest elevation of present-day Nanushuk outcrops.

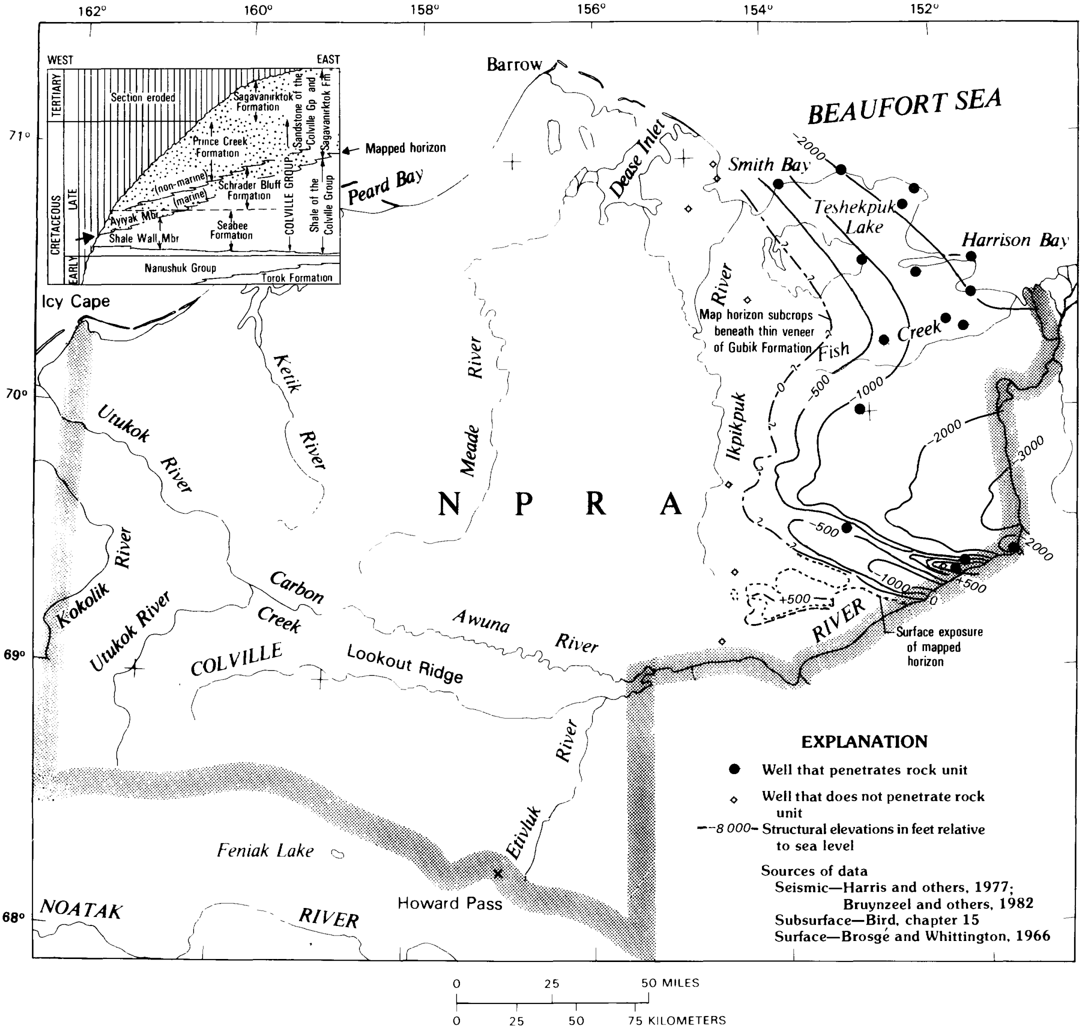


FIGURE 16.9.—Structure-contour map for top of informally designated shale of Colville Group unit in NPRA.

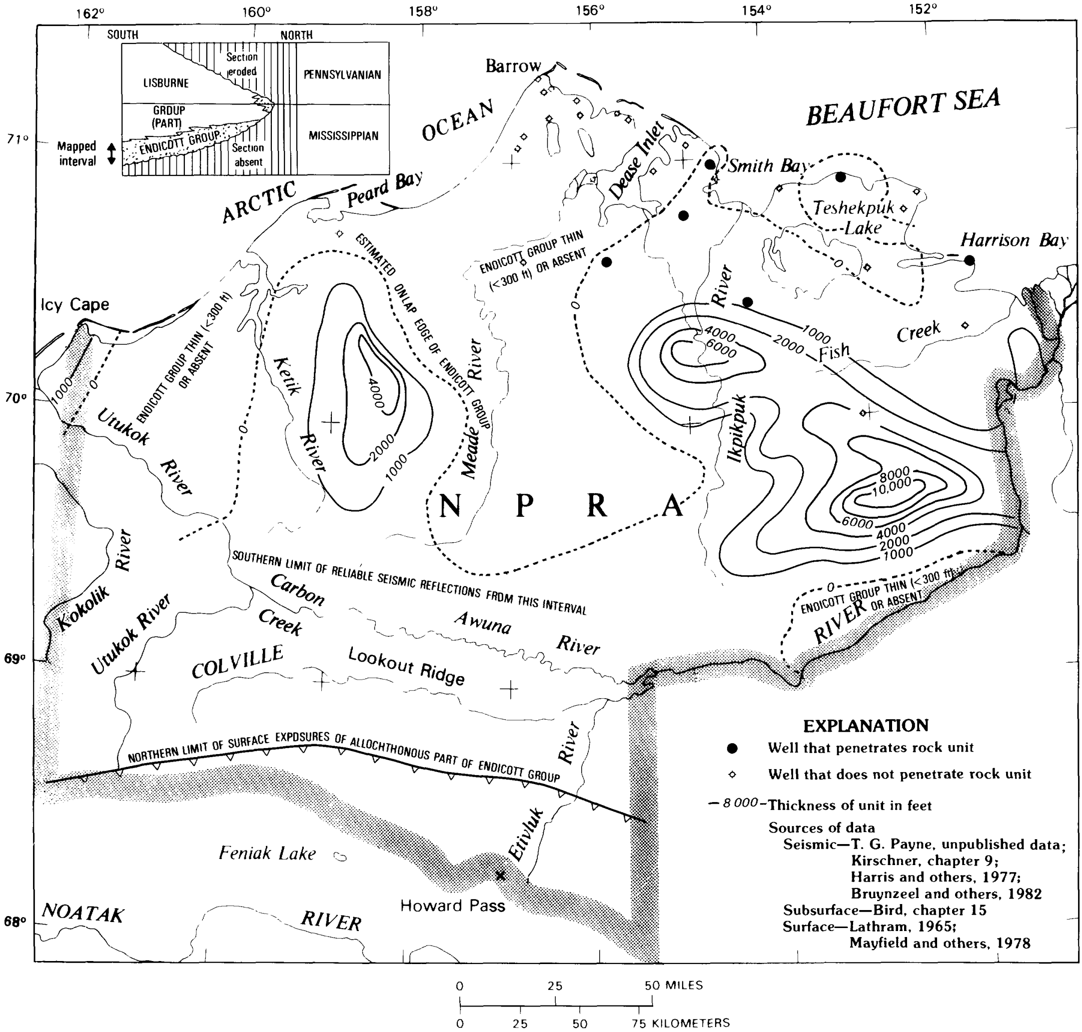


FIGURE 16.10.—Isopach map for Endicott Group (Mississippian and Pennsylvanian) in NPRA.

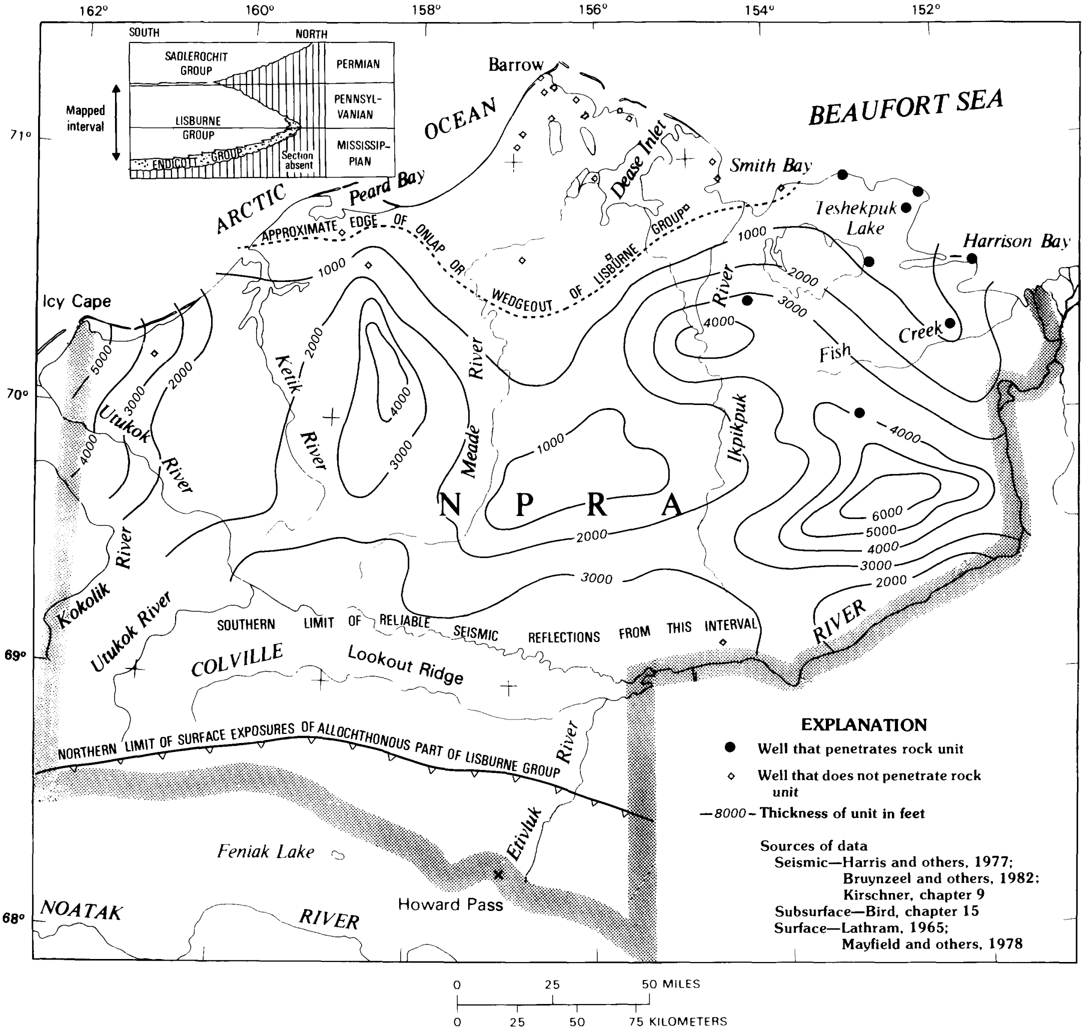


FIGURE 16.11.—Isopach map for Lisburne Group (Mississippian to Permian) in NPRA.

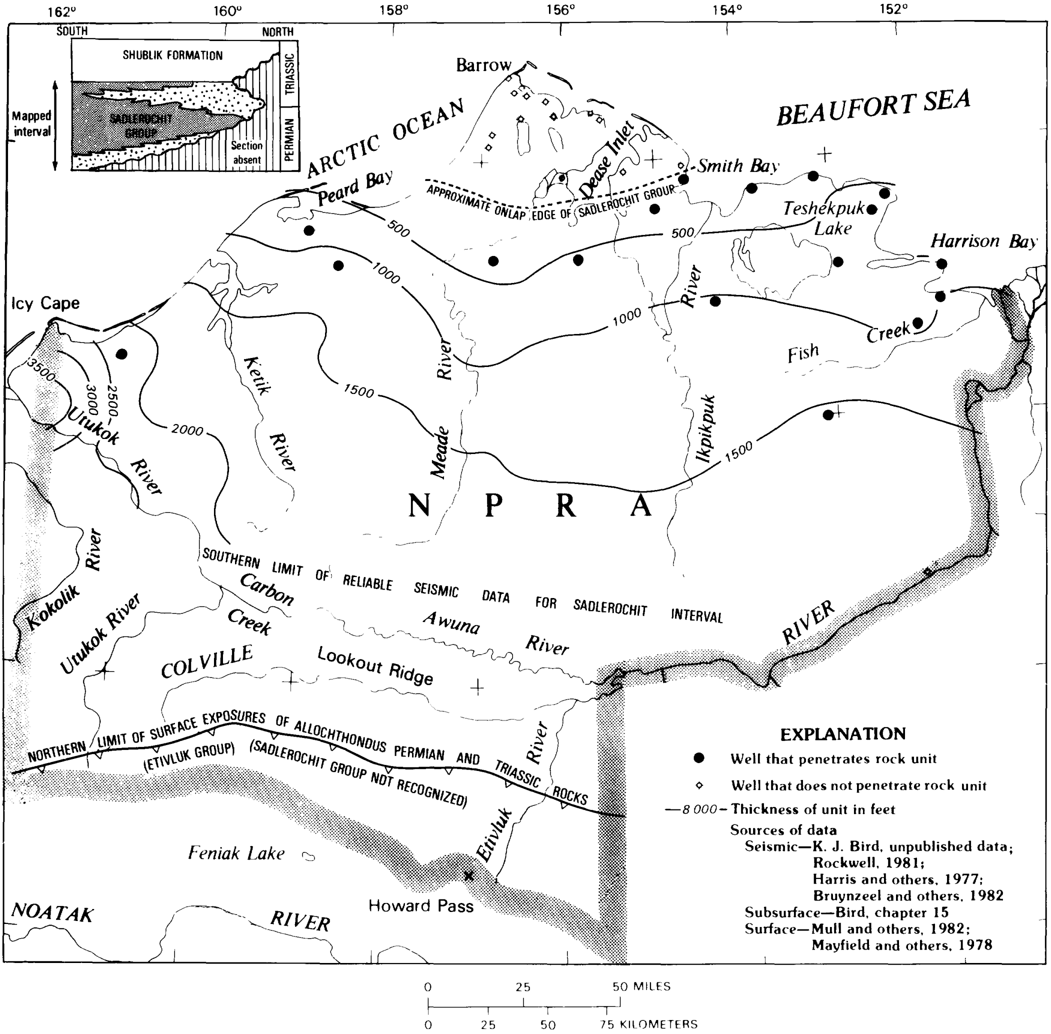


FIGURE 16.12.—Isopach map for Sadlerochit Group (Permian and Triassic) in NPRA.

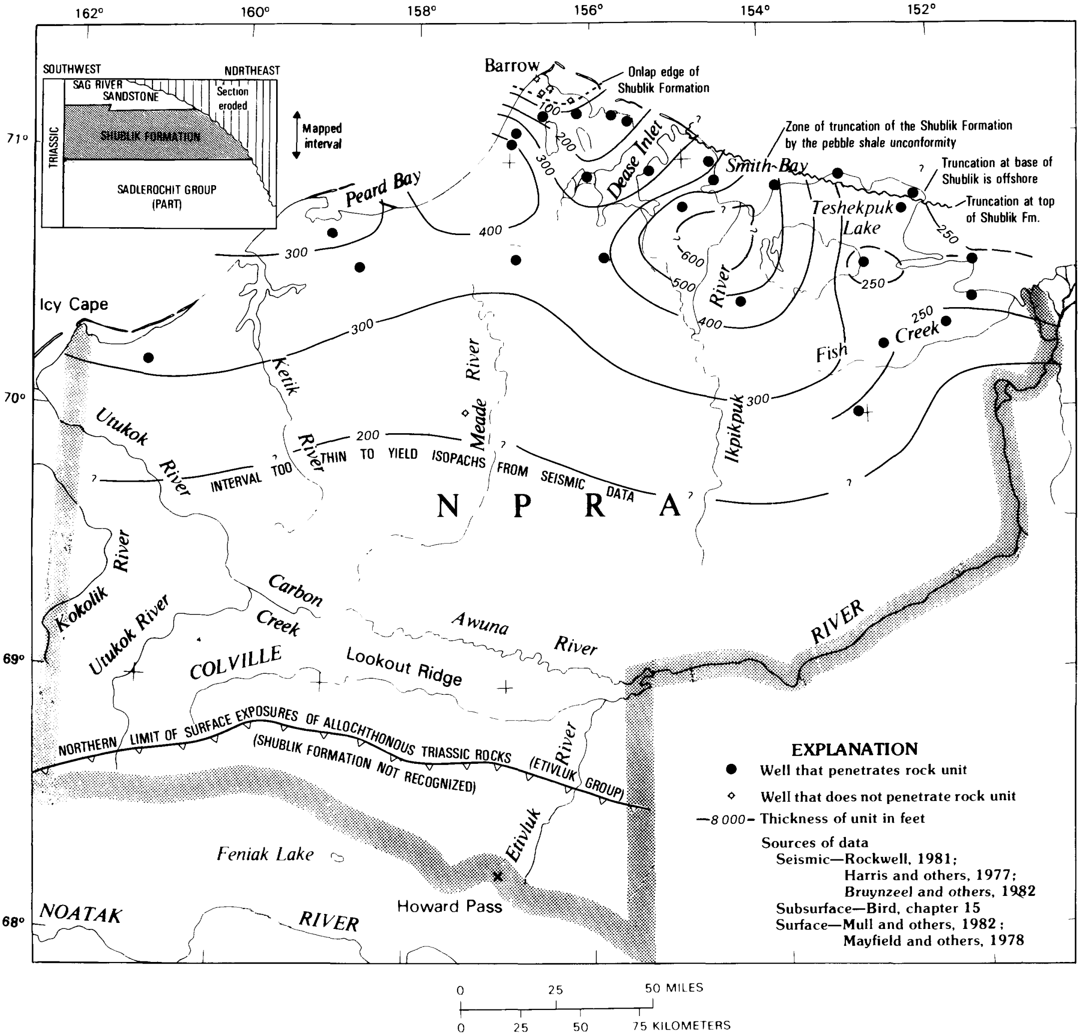


FIGURE 16.13.—Isopach map for Shublik Formation (Triassic) in NPRA.

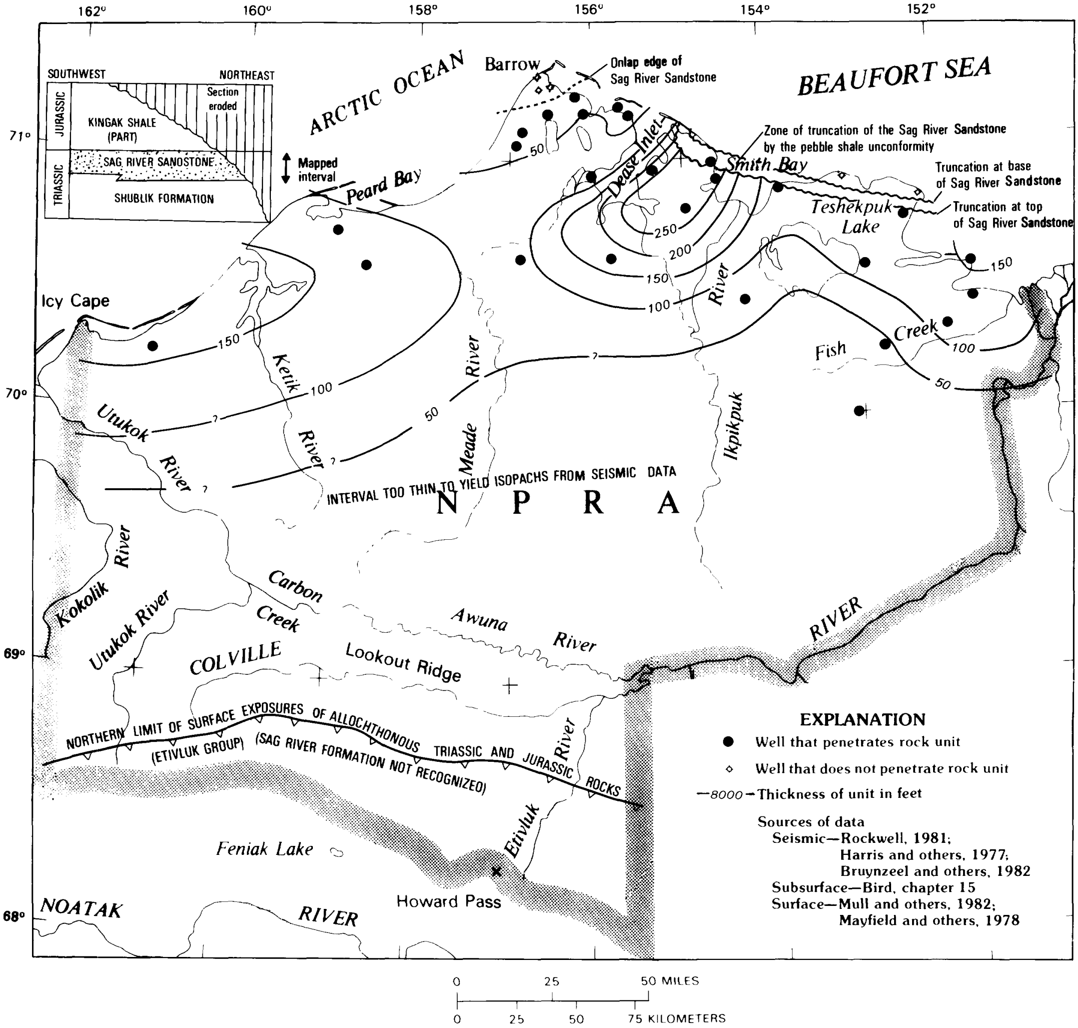


FIGURE 16.14.—Isopach map for Sag River Sandstone (Triassic) in NPRA.

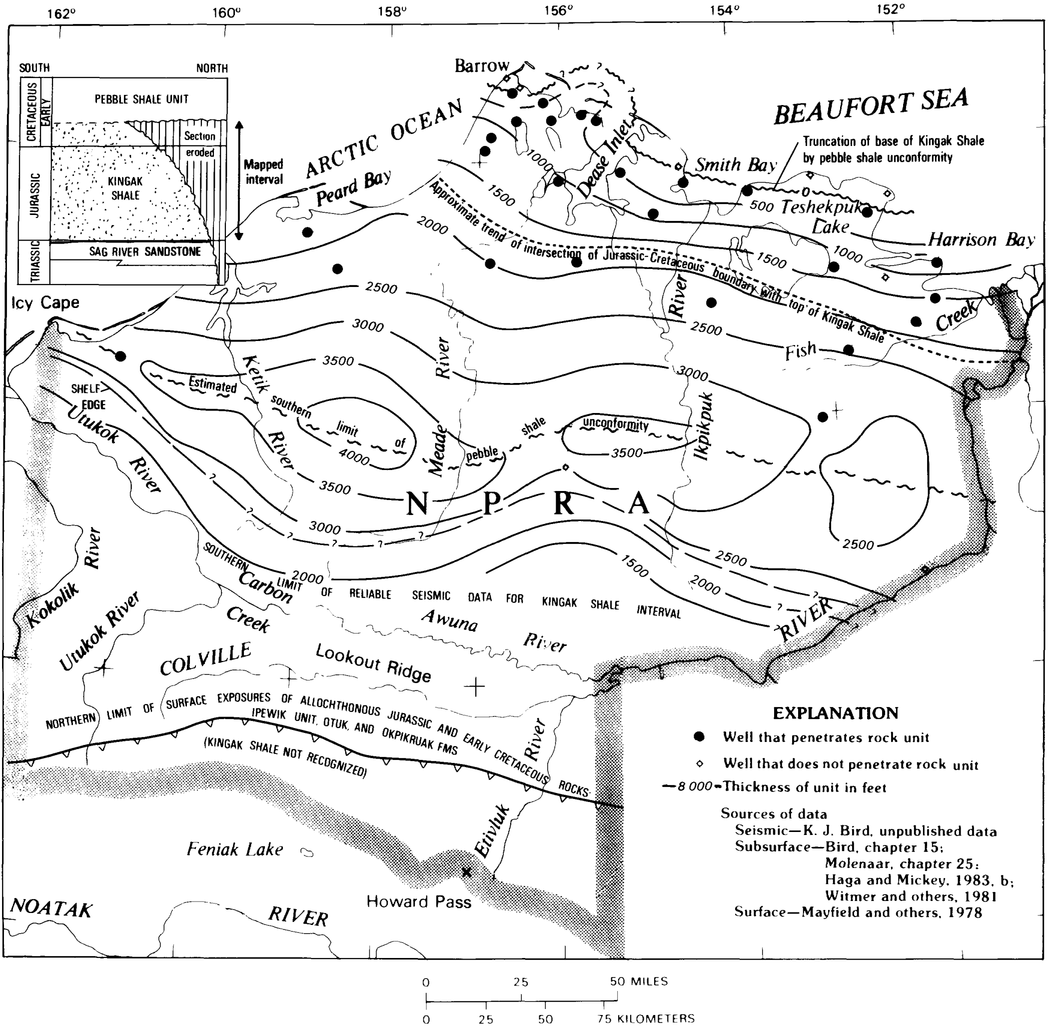


FIGURE 16.15.—Isopach map for Kingak Shale (Jurassic and Lower Cretaceous) in NPRA.

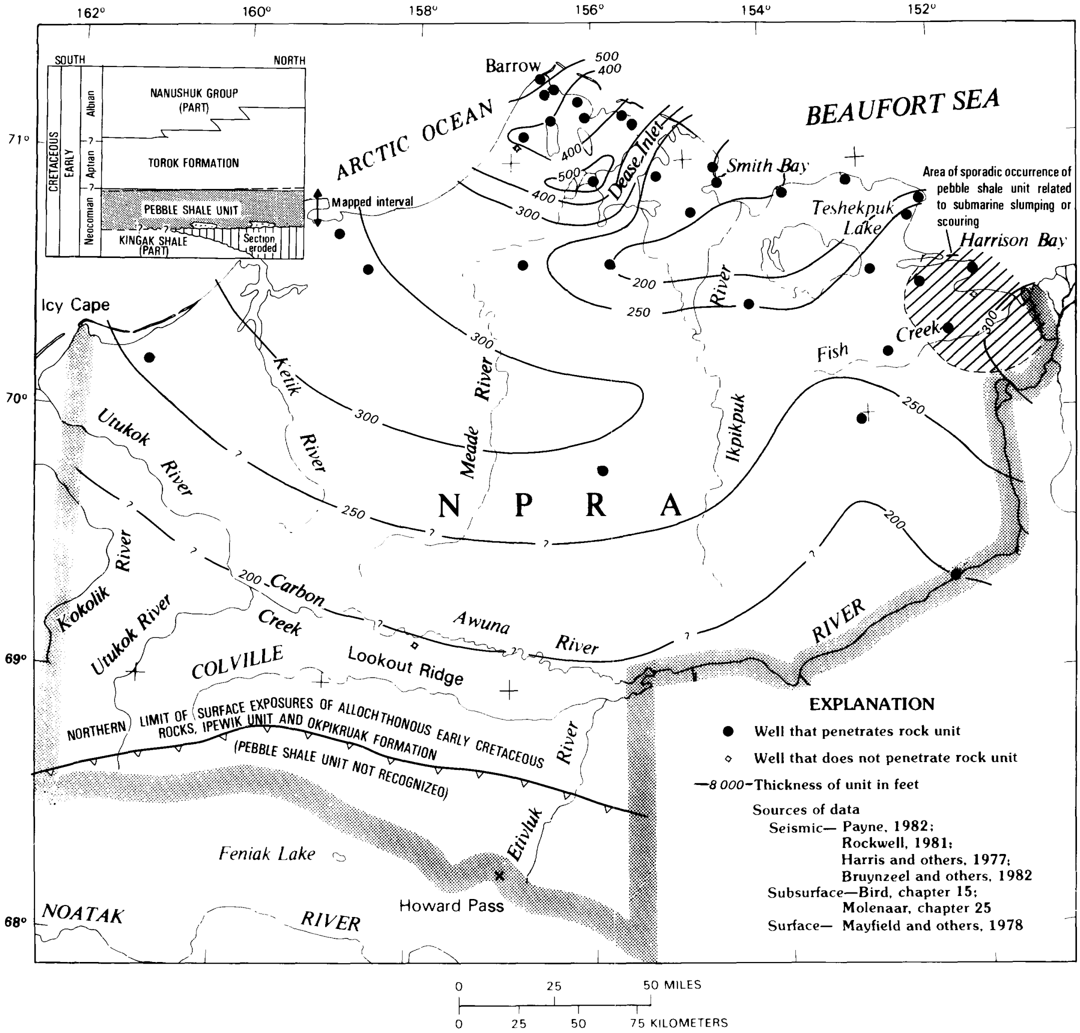


FIGURE 16.16.—Isopach map for informally designated pebble shale unit (Lower Cretaceous) in NPRA.

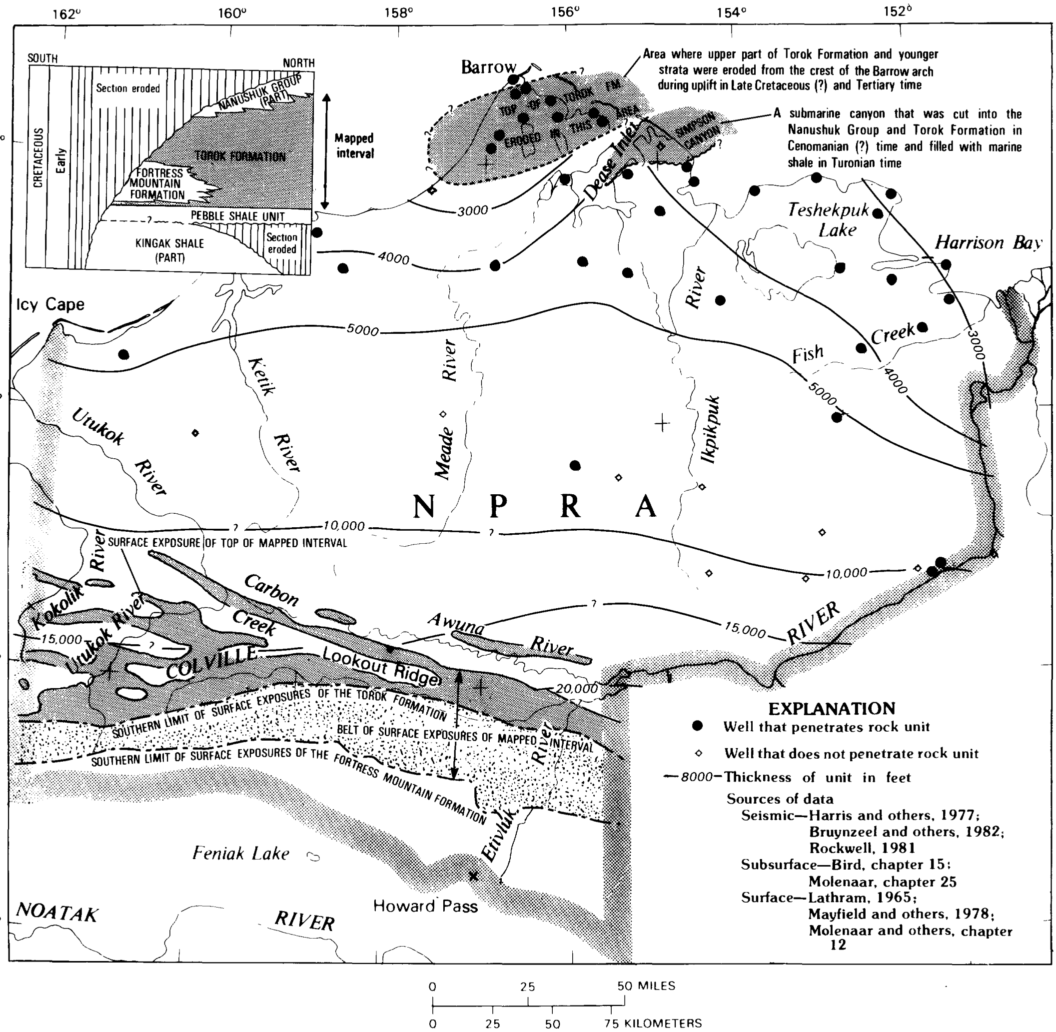
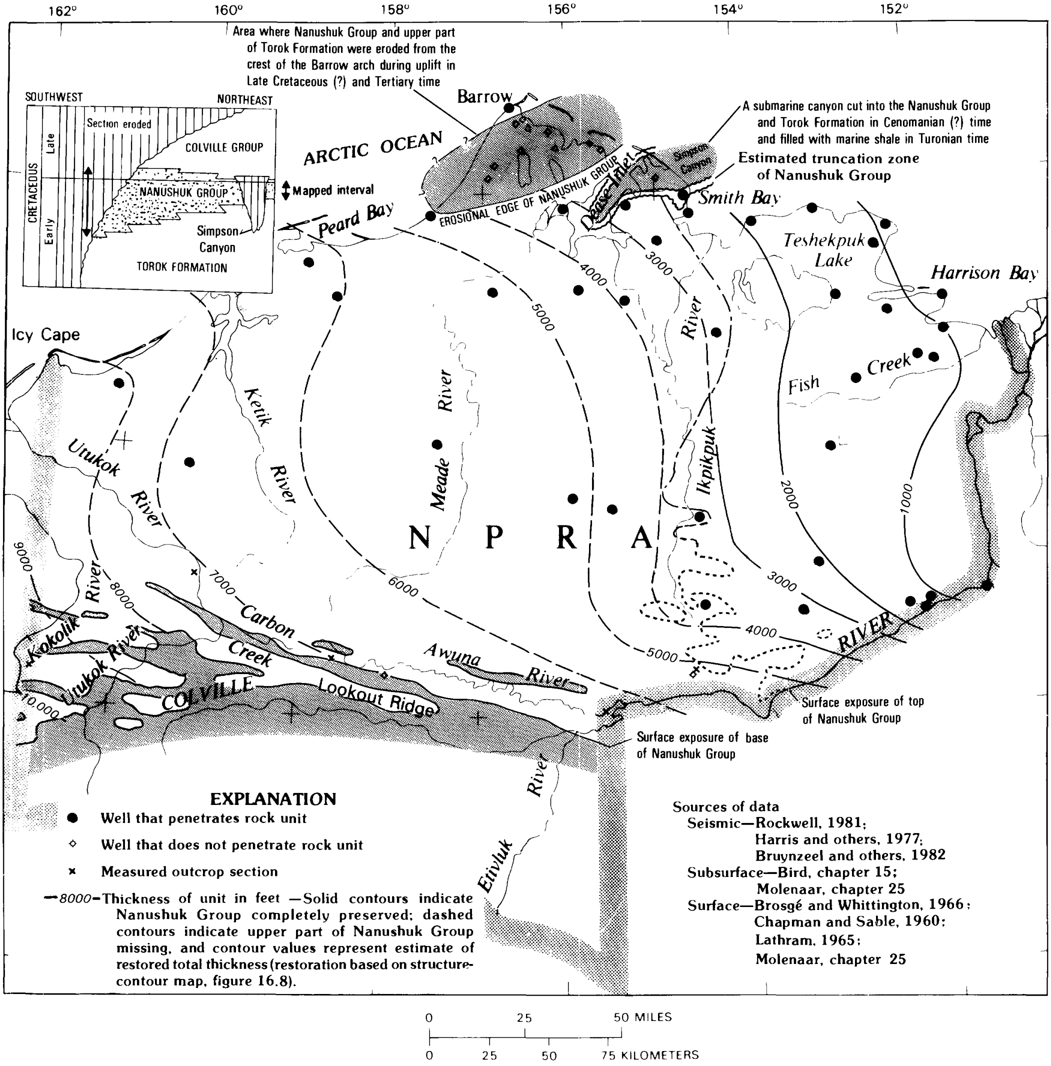


FIGURE 16.17.—Isopach map for Torok Formation (Lower Cretaceous) in NPRA.



EXPLANATION

● Well that penetrates rock unit

◇ Well that does not penetrate rock unit

× Measured outcrop section

—8000—Thickness of unit in feet —Solid contours indicate Nanushuk Group completely preserved; dashed contours indicate upper part of Nanushuk Group missing, and contour values represent estimate of restored total thickness (restoration based on structure-contour map, figure 16.8).

Sources of data
Seismic—Rockwell, 1981;
Harris and others, 1977;
Bruynzeel and others, 1982
Subsurface—Bird, chapter 15;
Molenaar, chapter 25
Surface—Brosgé and Whittington, 1966;
Chapman and Sable, 1960;
Lathram, 1965;
Molenaar, chapter 25

FIGURE 16.18.—Isopach map for Nanushuk Group (Lower and Upper Cretaceous) in NPRA.

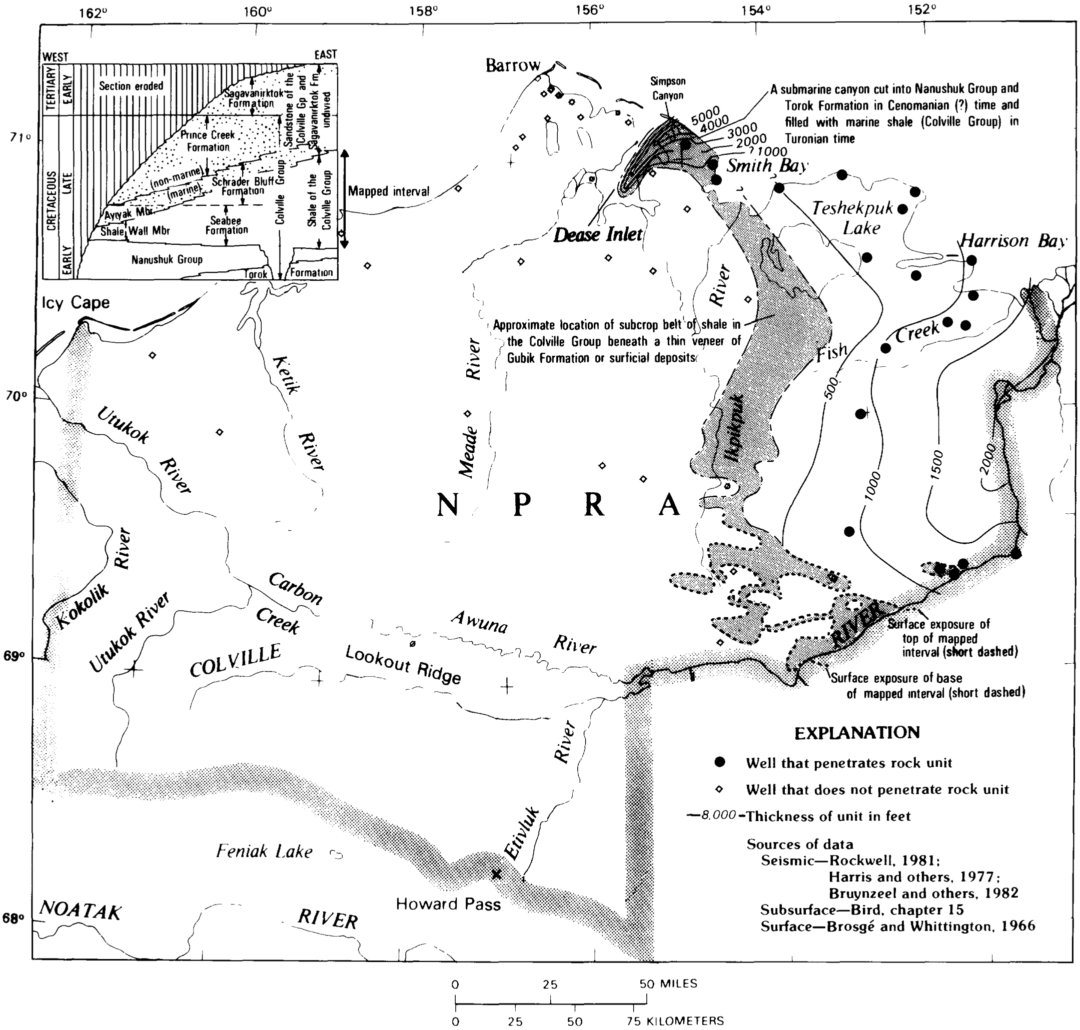
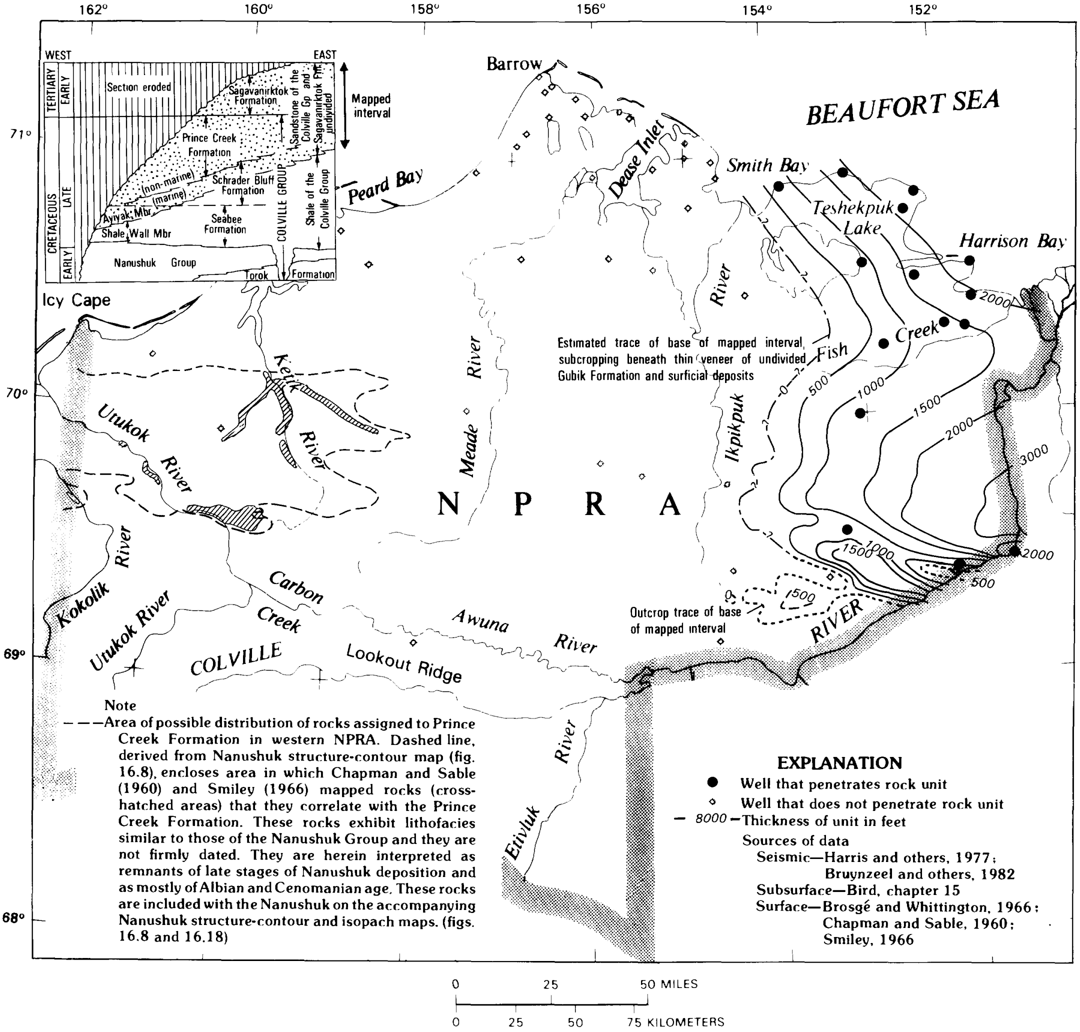


FIGURE 16.19.—Isopach map for informally designated shale of Colville Group unit (Upper Cretaceous) in NPRA.



Note

– – –Area of possible distribution of rocks assigned to Prince Creek Formation in western NPRA. Dashed line, derived from Nanushuk structure-contour map (fig. 16.8), encloses area in which Chapman and Sable (1960) and Smiley (1966) mapped rocks (cross-hatched areas) that they correlate with the Prince Creek Formation. These rocks exhibit lithofacies similar to those of the Nanushuk Group and they are not firmly dated. They are herein interpreted as remnants of late stages of Nanushuk deposition and as mostly of Albian and Cenomanian age. These rocks are included with the Nanushuk on the accompanying Nanushuk structure-contour and isopach maps. (figs. 16.8 and 16.18)

EXPLANATION

● Well that penetrates rock unit

◇ Well that does not penetrate rock unit

— 8000 —Thickness of unit in feet

Sources of data

Seismic—Harris and others, 1977; Bruynzeel and others, 1982

Subsurface—Bird, chapter 15

Surface—Brosgé and Whittington, 1966; Chapman and Sable, 1960; Smiley, 1966

FIGURE 16.20.—Isopach map for informally designated sandstone of Colville Group and Sagavanirktok Formation, undivided, unit (Upper Cretaceous and Tertiary) in NPRA.

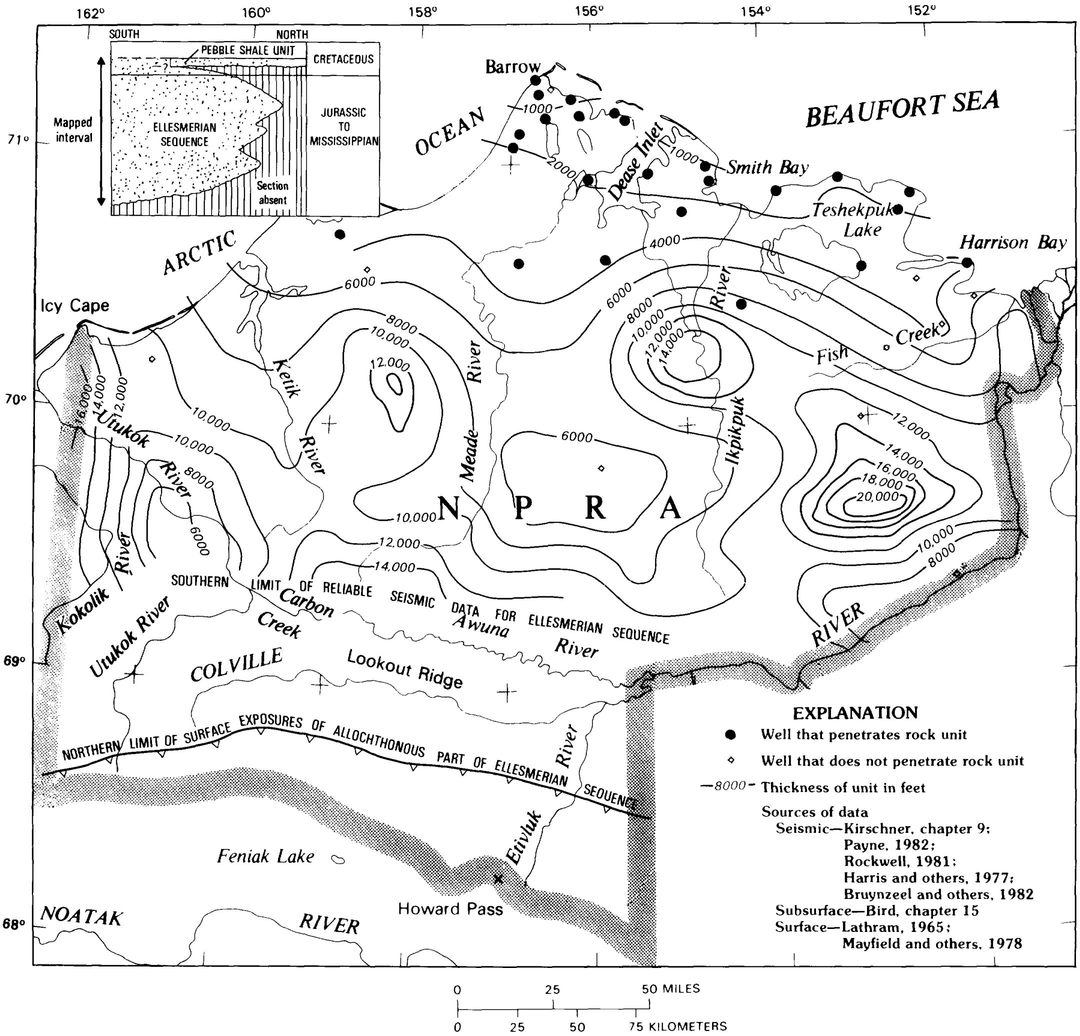


FIGURE 16.21.—Isopach map for Ellesmerian sequence (Mississippian to Cretaceous) in NPRA.

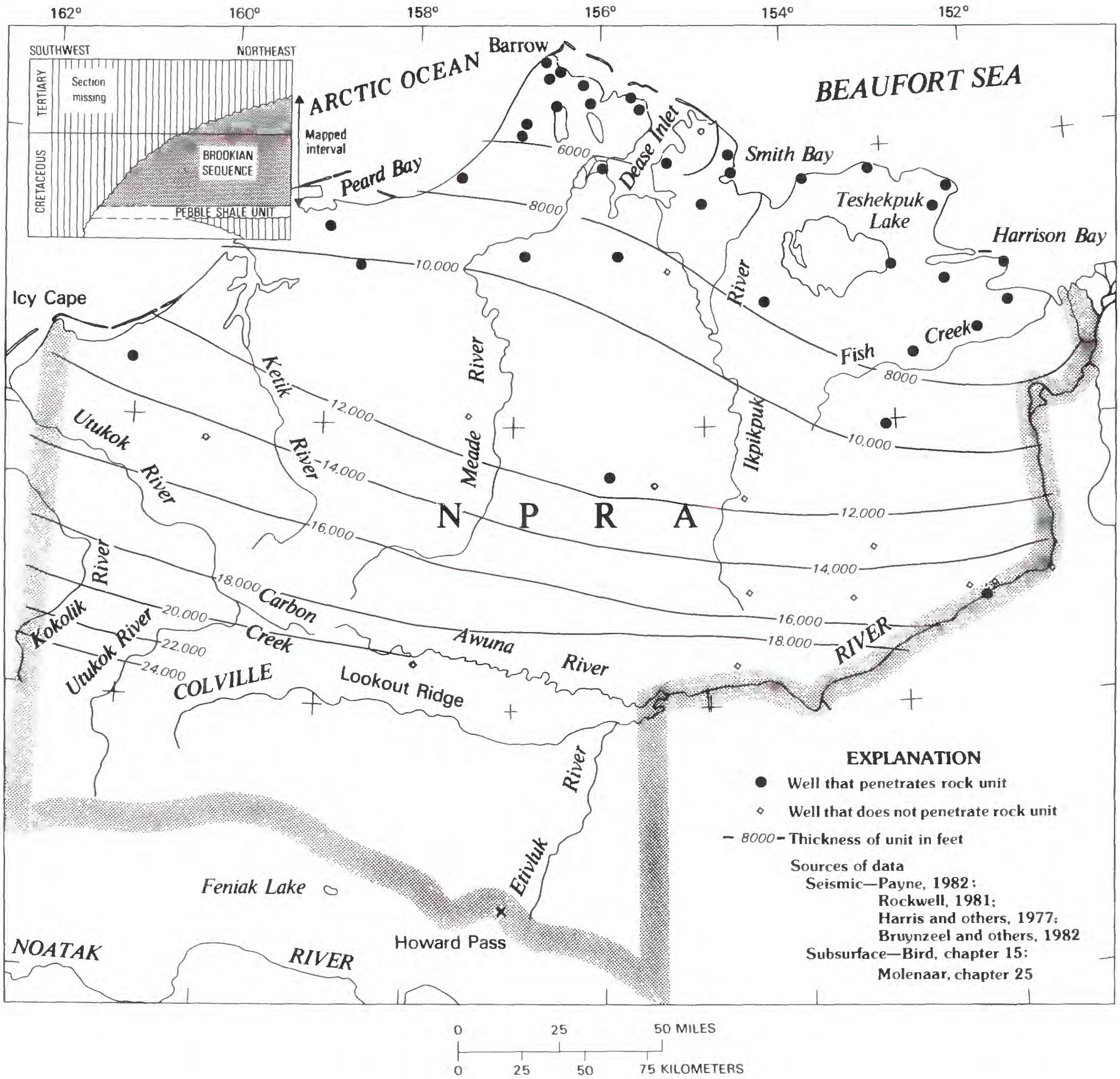


FIGURE 16.22.—Isopach map for Brookian sequence (Cretaceous and Tertiary) in NPRA.

Crude-oil seepages near Cape Simpson. Residual tars were used by the Inupiat (Eskimos) for fuel long before seepages were reported by whalers and early explorers. These seepages were the first indication that northern Alaska might be a future petroleum province. Photograph by George Gryc.

GEOCHEMISTRY

The three principal requirements for the occurrence of petroleum accumulations are a source, a trap, and a reservoir. Many geologists add and emphasize the need for a seal to prevent escape of hydrocarbons as a fourth requirement. The overall geologic history, particularly the history of diagenesis and maturation of the sedimentary rocks, is likewise important. Geochemical analyses of the sedimentary rocks and their contained fluids provide basic information on the petroleum potential of a region. Although earlier studies in the NPRA had recorded much descriptive detail of the rocks, chemical data were limited. Recent developments in analytical methods and in the interpretation of such data has stimulated research in their application to petroleum exploration.

The latest program in the NPRA provided an excellent opportunity to collect and analyze a large set of samples from a single extensive petroleum province in a fairly short time and with uniform standards. These samples have been analyzed, tabulated, and interpreted, and the results are given in the chapters that follow.

A vast amount of geochemical data has been compiled for this volume. The geochemical studies support the general conclusion that the NRPA is underlain by source rocks of sufficient richness to produce large quantities of oil and gas. However, the type and maturation history of these rocks indicate that the Reserve is gas prone with the possible exception of the northeastern quadrant. The exploration drilling to date supports this conclusion.

17. EVALUATION OF PETROLEUM SOURCE ROCKS IN THE NATIONAL PETROLEUM RESERVE IN ALASKA, USING ORGANIC-CARBON CONTENT, HYDROCARBON CONTENT, VISUAL KEROGEN, AND VITRINITE REFLECTANCE

By LESLIE B. MAGOON and KENNETH J. BIRD

INTRODUCTION

PURPOSE

The purpose of this petroleum geochemical study is to assess the oil and gas source potential of the sedimentary rocks in the National Petroleum Reserve in Alaska (NPRA). For this purpose, the organic matter included in the rocks must be evaluated for: (1) organic richness, (2) kerogen type, and (3) thermal history. Four types of analyses were selected for this evaluation: (1) organic-carbon content (weight percent); (2) C_{15+}-hydrocarbon content (ppm); (3) visual kerogen (percent); and (4) vitrinite reflectance (percent R_{o}). Although each type of analysis provides only incomplete information, together they provide a useful approximation of the necessary data and therefore allow a preliminary assessment of the petroleum potential of the source rock. In our assessment, we attempt to characterize each selected stratigraphic interval, from basement to surface, in terms of organic richness, organic type, and thermal history, and we illustrate these characteristics and their variations in a series of maps and charts (see table 17.1).

TABLE 17.1.—*Guide to plots and maps of data concerning organic carbon, visual kerogen, and vitrinite reflectance for rock units considered in this chapter*

[Organic carbon refers to maps of average organic-carbon content; visual kerogen refers to maps of average visual kerogen; vitrinite reflectance refers to maps of vitrinite-reflectance values conformed at base of rock unit. Dashes, not plotted]

Rock unit	Figure number of map or plot		
	Organic carbon	Visual kerogen	Vitrinite reflectance
Sagavanirktok Formation and sandstone of the Colville group, undivided.	17.27	---	17.26
Shale of the Colville Group--	17.25	---	---
Nanushuk Group---------------	17.24	---	17.23
Torok Formation--------------	17.21	17.22A-C	---
Pebble shale unit------------	17.19	17.20A-C	17.18
Kingak Shale-----------------	17.16	17.17A-C	---
Sag River Sandstone----------	17.15	---	---
Shublik Formation------------	17.13	17.14A-C	17.12
Sadlerochit Group------------	17.11	---	---
Lisburne Group---------------	17.10	---	---
Endicott Group---------------	17.8	---	17.9
Pre-Endicott Group rocks-----	17.7	---	---

Data on organic-carbon content, C_{15+}-hydrocarbon content, visual kerogen, and vitrinite reflectance were acquired for rocks penetrated in 63 wells (fig. 17.1; table 18.1) in or adjacent to the NPRA. The analytical scheme for obtaining these data is outlined on figure 17.2 and discussed elsewhere in this volume by Claypool and Magoon (chapter 18); an interpretation of these types of data in four widely spaced wells is also provided elsewhere in this volume by Bayliss and Magoon (chapter 20). The geochemical data are related to the stratigraphic intervals described by Bird (chapter 15). These same intervals are also shown on the regional cross sections (figs. 17.3-17.6) and on the well displays included in this volume by Magoon and others (chapter 19, pls. 19.1-19.39). The analytical results are shown graphically on those well displays. The range and mean values for each stratigraphic interval are tabulated (tables 17.2-17.13) and shown on the maps (figs. 17.7-17.27).

Manuscript received for publication on June 21, 1983.

PREVIOUS WORK AND SCOPE

Previous work in the NPRA on rocks rich in organic matter has been largely concentrated on outcrop material. From the turn of the 20th century, many references have been made to the location and composition of oil shales. Four major occurrences are referred to: (1) the Lisburne Group (Tailleur, 1964); (2) the Shublik Formation (Tailleur, 1964); (3) the Tiglukpuk Formation of former usage and unnamed Jurassic(?) shale (Tailleur, 1964); and (4) cannel coal from the mid-Cretaceous Nanushuk Group (Webber, 1947).

Richness values for the Lisburne Group were determined by a Fisher analysis on one sample that yielded 6.7 gallons of oil per ton of rock (Tailleur, 1964). Bird and Jordan (1977a, b) suggested that oil shows

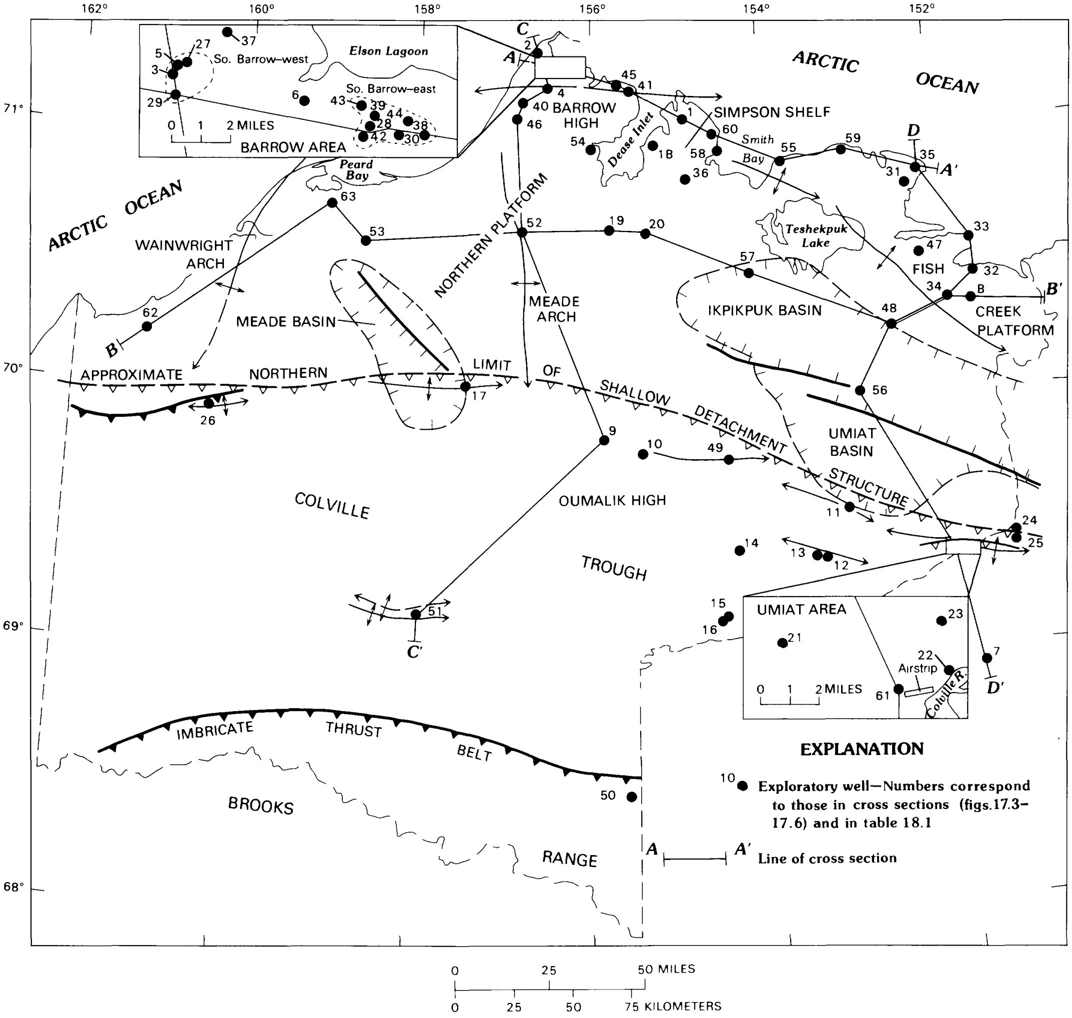


FIGURE 17.1.—Wells drilled in or adjacent to the National Petroleum Reserve in Alaska that were analyzed for petroleum geochemistry. Modified from Kirschner and Rycerski (chapter 9).

in the Lisburne southward from, and structurally lower than, the Prudhoe Bay field may originate from a more basinal facies of the Lisburne that resembles the sample from the Kuna Formation. In outcrops in the foothills of the central Brooks Range, the pore space in the dolomitic rocks of the Lisburne is generally filled with solid bitumen (Kleist and others, 1983), lending further support to the idea that an oil source may be closely related to the Lisburne Group. The Kuna Formation is allochthonous (Mull and others, 1982) and was not penetrated by any wells described in this chapter.

The Triassic part of the Otuk Formation, the second occurrence, is described as a *Pseudomonotis* oil shale (Stadnichenko, 1929), and a Fisher analysis yielded almost 25 gallons of oil per ton of rock (Tailleur, 1964). This allochthonous

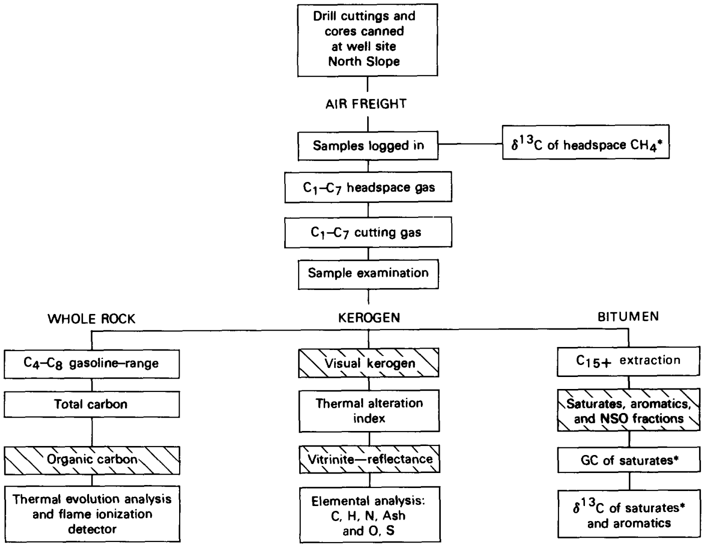


FIGURE 17.2.—Flow chart of geochemical analyses. Crosshatching indicates analyses discussed in this chapter. Analyses marked with asterisk were done by Global Geochemistry Corp.; all others were done by Geochem Research, Inc.

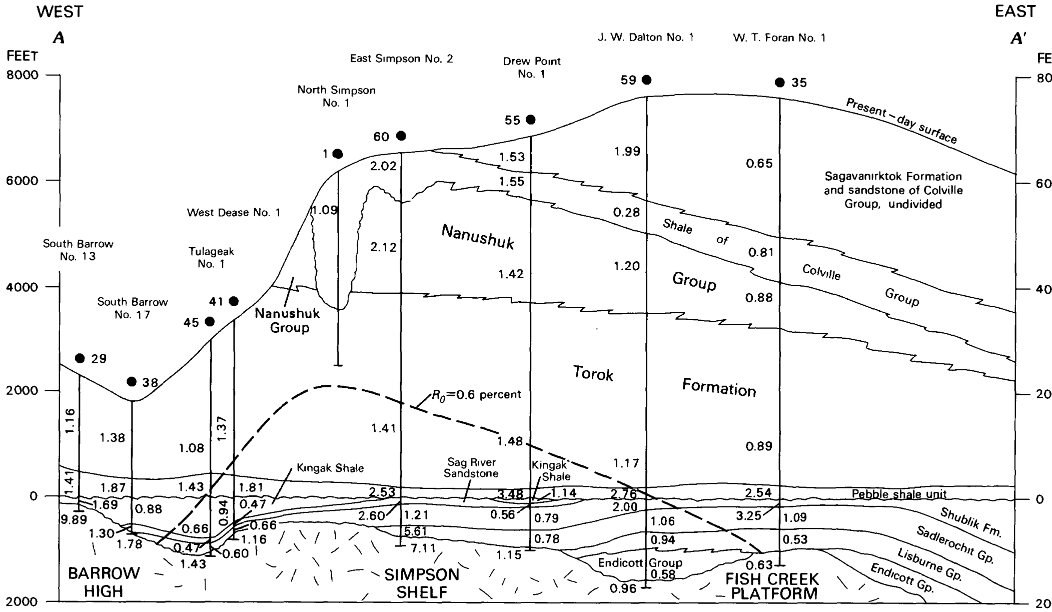


FIGURE 17.3.—Regional east-west cross section *A-A'* along Arctic coastline of Alaska, showing average organic-carbon content for each rock unit and depths (dashed line) at which vitrinite reflectance equals 0.6 percent R_0. Datum is Early Cretaceous unconformity at base of pebble shale unit. Numbering of wells corresponds to that in table 18.1. For location, see figure 17.1.

rock unit in the Brooks Range was distinguished lithologically from the partly time-equivalent autochthonous Shublik Formation to the north (Mull and others, 1982)—a formation penetrated by wells in the NPRA.

The third occurrence is the *Tasmanites* shale interval in the Pennsylvanian to Middle Jurassic Etivluk Group (Mull and others, 1982). Stadnichenko (1929) and White (1929) described this rock as the "Alaskan spore rock," which yielded oil upon heating. Tailleur (1964) reported that a Fisher analysis from six samples (four from the unnamed Jurassic(?) shale and two from the Tiglukpuk Formation) yielded from 26 to 146 gallons of oil per ton of rock. Geochemical analyses of these Alaskan rocks have been reported from at least two laboratories (Leythaeuser and others, 1980; Burlingame and others, 1969), and paleontologic work has been reported by Boneham (Boneham and Tailleur, 1972). Poor exposures, sparse paleontologic control, and severe deformation make the allochthonous Etivluk Group difficult to map (Mull and others, 1982). The Etivluk Group is restricted to the Brooks Range, but its lateral equivalents, the Shublik Formation and part of the Kingak Shale, are penetrated by wells on the Arctic platform to the north and so are discussed in this chapter.

The Lower Cretaceous cannel coal from the Nanushuk Group is the last of these main occurrences. The algal or boghead coal samples reported on by Stadnichenko (1929) and White (1929) were surmised by Webber (1947) to come from thin layers of cannel coal associated with

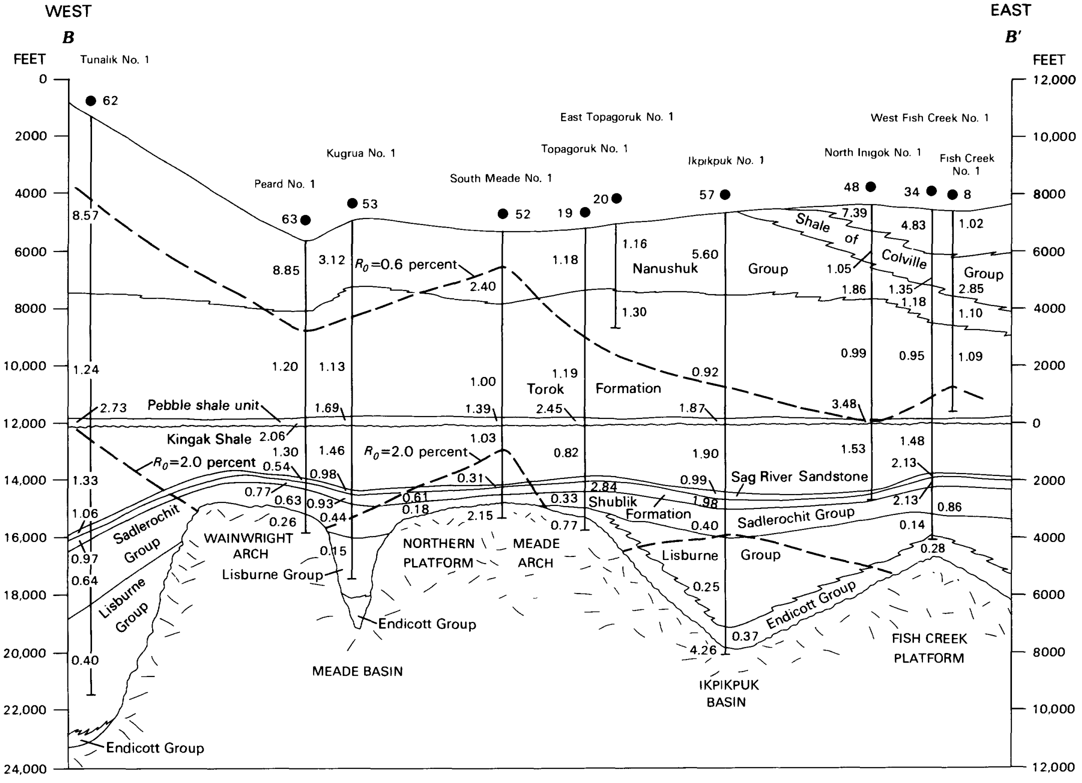


FIGURE 17.4.—Regional east-west cross section *B-B′*, showing average organic-carbon content for each rock unit and depths (dashed line) at which vitrinite reflectance equals 0.6 and 2.0 percent R_0. Uppermost rock unit at *B′* end of section is Sagavanirktok Formation and sandstone of Colville Group, undivided. Datum is Early Cretaceous unconformity at base of pebble shale unit. Numbering of wells corresponds to that in table 18.1. See figure 17.1 for location.

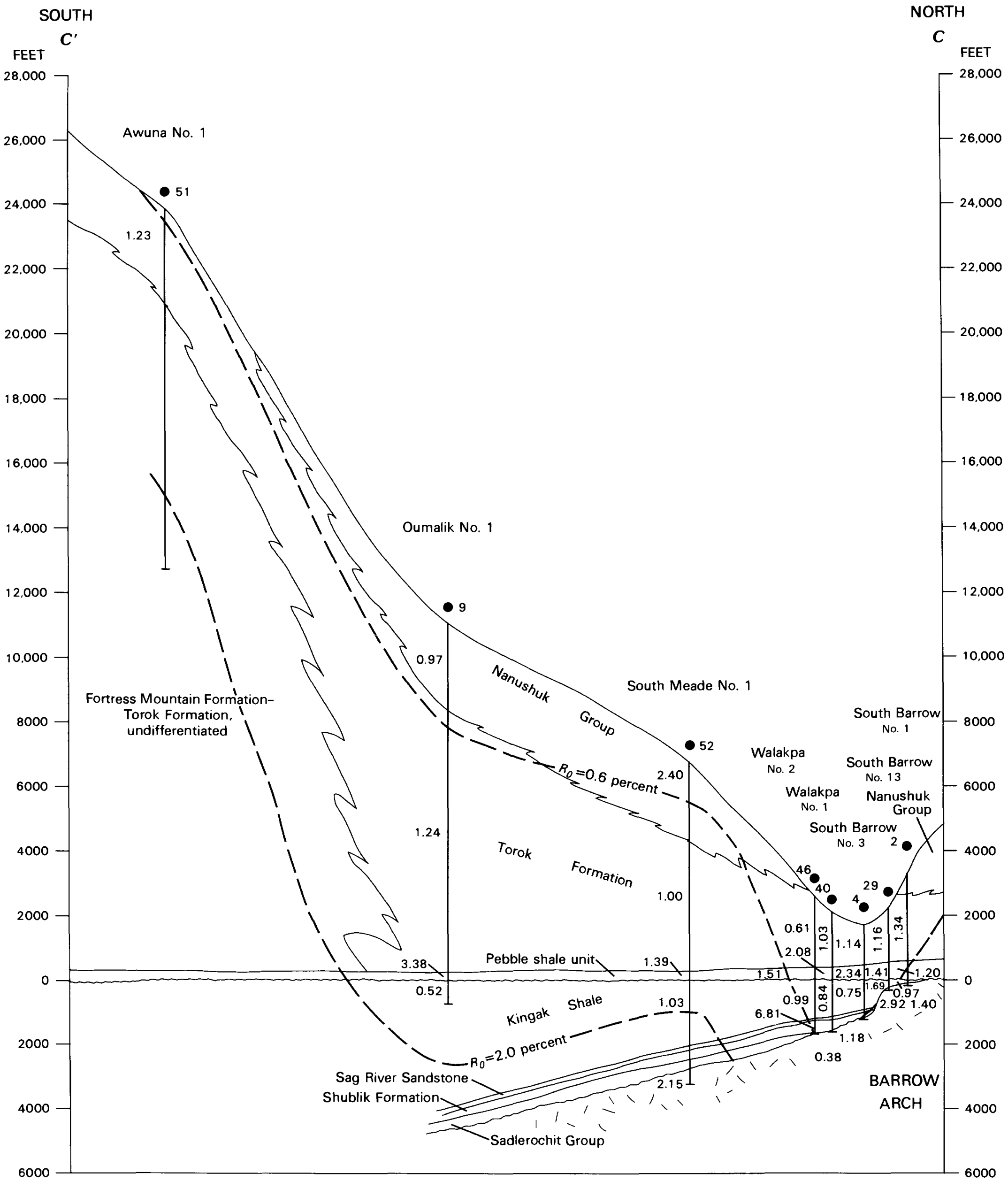


FIGURE 17.5.—Regional north-south cross section C-C′, showing average organic-carboncontent for each rock unit and depths (dashed line) at which vitrinite reflectance equals 0.6 and 2.0 percent R_0. Datum is Early Cretaceous unconformity at base of pebble shale unit. Numbering of wells corresponds to that in table 18.1. See figure 17.1 for location.

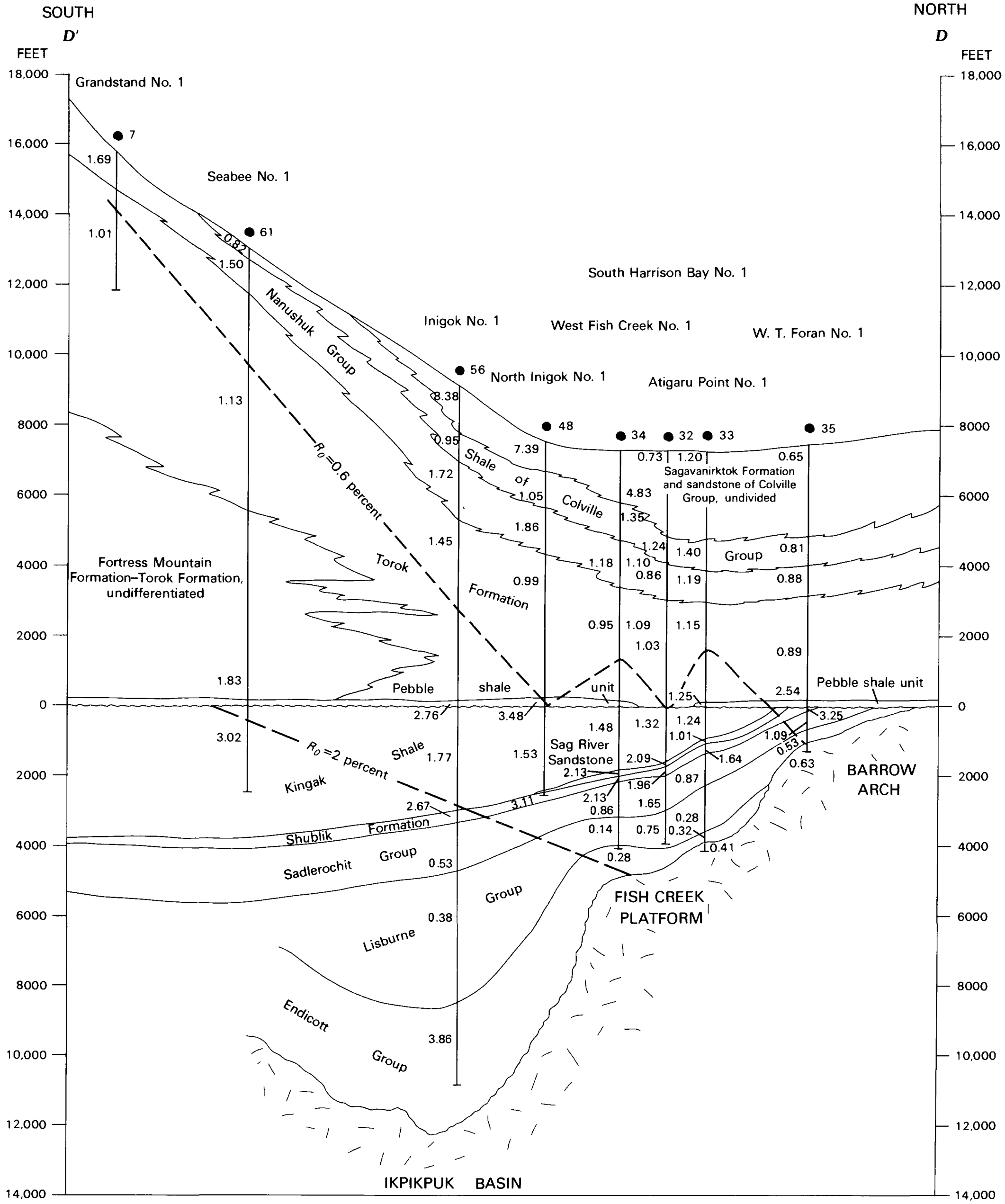


FIGURE 17.6.—Regional north-south cross section *D-D'*, showing average organic-carbon content for each rock unit and depths (dashed line) at which vitrinite reflectance equals 0.6 and 2.0 percent R_0. Numbering of wells corresponds to that in table 18.1.

the coal beds on the Meade River. Webber (1947) reported that thin slivers of cannel coal, which are in beds from 0.1 to 1.2 ft thick, "ignite readily with a match and burn with a petroliferous odor." Presumably, this cannel coal is composed of pollen and spores deposited in a swampy environment. Even though this material is associated with the thick Nanushuk Group, the cannel coal beds themselves are apparently thin and would be easily overlooked in cores that were routinely sampled at 5-ft intervals or in drill cuttings at 30-ft intervals. Therefore, these beds are not specifically evaluated here; only the general geochemical characteristics of the Nanushuk Group are considered. In addition, resinite has been considered a possible source of petroleum for the deltaic Mackenzie Basin (Snowdon, 1980; Snowdon and Powell, 1982), but in our study no effort was made to determine if resinite occurs in the Cretaceous and Tertiary deltaic rocks.

In this chapter, we evaluate the general geochemical characteristics of the 12 stratigraphic units penetrated by wells drilled in the NPRA; we do not consider the previously reported potential petroleum sources discussed above, or the Brooks Range outcrop information summarized recently by Brosgé and others (1981).

SAMPLE DISTRIBUTION

The reliability of any assessment of oil and gas source rocks depends on an adequate geochemical characterization of the stratigraphic interval(s) considered; this, in turn, depends on adequate sampling, a problem related to the thickness, areal extent, and internal geochemical variability. In this study, the stratigraphic intervals range in thickness from a few hundred to a few thousand feet, and most extend areally throughout the NPRA.

Areal sampling density is biased. Because of the southward increase in burial depth, pre-Cretaceous rocks are penetrated only in wells in the north third of the NPRA. Cretaceous and lower Tertiary rocks, at the east edge of the NPRA, are penetrated in wells in the northeast two-thirds of the area. Only a single well, Awuna No. 1, has been drilled in the southwest third of the NPRA (fig. 17.1 and well display, pl. 19.17).

The vertical sampling density is less biased than the areal sampling density. The 27 wells drilled since 1977 were sampled for geochemistry according to an established schedule. Conventional cores, sidewall cores, and cutting samples were analyzed from these wells. The 27 wells drilled before 1973 were sampled only from conventional cores. Samples from wells drilled from 1973 to 1977 include some drill cuttings and conventional cores. Because the pre-1977 wells were not continuously sampled with drill cuttings or cores, the sampling density for most stratigraphic intervals is considerably less for those wells than for post-1977 wells; thus, the characterization of strata in those earlier wells may be less reliable.

In each well, the selected stratigraphic interval or horizon is characterized by a single number, the mean value, for each parameter determined. The mean values from all wells are plotted on maps and contoured. Our goal was to discover regional trends that allowed extrapolation to areas with no control. In calculating the mean values, equal weight was given to each analysis, regardless of sample type or vertical spacing. Individual analyses that are thought to be nonrepresentative of the stratigraphic interval, on the basis of other lines of evidence, are indicated on the maps or tables. This problem of nonrepresentation is common for cutting samples in stratigraphic units that are thin in relation to the sample interval, at strata boundaries, or in formations easily eroded by the drilling mud.

The Lisburne No. 1 well is located in the southern part of the NPRA (fig. 17.1; pl. 19.23) in the disturbed belt—a structural province somewhat analogous to the overthrust belt of Wyoming. The Lisburne well is important to the evaluation of the hydrocarbon potential of this part of the NPRA, but it is not included on our geochemical maps because most of the stratigraphic units penetrated are different from those considered here (see Bird, chapter 15) and because most of the rocks have been tectonically transported northward from their sites of deposition. The geochemical data for this well are listed in table 17.14.

TYPES OF ANALYSES

The organic-carbon content (in weight percent) is a measure of the amount of carbon in the rock that originated from either terrestrial or marine organisms. The organic-carbon content, by itself, does not characterize the capacity of a rock to generate oil or gas, nor does it characterize the amount of oil and gas that may have been generated. The maps of organic carbon in this study are a first attempt to portray the richness of the organic matter on a regional scale. As a matter of approximation, rocks having values less than 0.5 weight percent are considered nonsource rocks (Welte, 1965), those having 0.5 to 2.0 weight percent have a fair potential of being source rocks, and those having more than 2.0 weight percent have a good potential of being source rocks, regardless of the type of organic matter.

The extractable-C_{15+}-hydrocarbon content (HC) is plotted against organic-carbon content (OC) to provide information on the ability of

TABLE 17.2.—*Organic-carbon, C_{15+}-hydrocarbon, visual-kerogen,*

[*, well not included on organic-carbon, visual-kerogen, or vitrinite-reflectance maps; NP, rock unit not penetrated; ND, not determined or insufficient data; 0, rock unit eroded or not deposited; OS, oil-stained sample; +, incomplete thickness. Rock-unit thicknesses, mean organic-carbon contents, mean C_{15+}-hydrocarbon contents, and visual-kerogen contents are posted on maps. Visual-kerogen contents (in percent): A-H, amorphous and herbaceous; W, woody; I, inertinite]

Well	API No.	Total depth (ft)	Rock unit thickness (ft)	Organic-carbon content (weight percent)										
				Cuttings			Sidewall core			Conventional core			Total samples	Mean value
				Min	Mean	Max	Min	Mean	Max	Min	Mean	Max		
Naval Petroleum Reserve No. 4 program (1944-53)														
North Simpson No. 1-------	50-023-10004	3,774	NP	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 1--------	50-023-10009	3,553	148+	-	-	-	-	-	-	-	1.40	-	1	1.40
South Barrow No. 2--------	50-023-10010	2,505	60+	-	-	-	-	-	-	-	2.92	-	1	2.92
South Barrow No. 3--------	50-023-10011	2,900	105+	-	-	-	-	-	-	.10	1.18	2.24	6	1.18
*South Barrow No. 4--------	50-023-10012	2,538	68+	-	-	-	-	-	-	-	.09	-	1	1.09
*Avak No. 1---------------	50-023-10013	4,020	1715+	-	-	-	-	-	-	.39	4.09	12.18	11	4.09
Grandstand No. 1----------	50-057-10001	3,939	NP	-	-	-	-	-	-	-	-	-	-	-
Fish Creek No. 1----------	50-103-10001	7,020	NP	-	-	-	-	-	-	-	-	-	-	-
Oumalik No. 1-------------	50-119-10005	11,872	NP	-	-	-	-	-	-	-	-	-	-	-
East Oumalik No. 1--------	50-119-10006	6,035	NP	-	-	-	-	-	-	-	-	-	-	-
Square Lake No. 1---------	50-119-10007	3,987	NP	-	-	-	-	-	-	-	-	-	-	-
*Wolf Creek No. 1----------	50-119-10008	1,500	NP	-	-	-	-	-	-	-	-	-	-	-
Wolf Creek No. 3----------	50-119-10010	3,760	NP	-	-	-	-	-	-	-	-	-	-	-
Titaluk No. 1-------------	50-119-10011	4,020	NP	-	-	-	-	-	-	-	-	-	-	-
Knifeblade No. 1----------	50-119-10012	1,805	NP	-	-	-	-	-	-	-	-	-	-	-
*Knifeblade No. 2A---------	50-119-10014	1,805	NP	-	-	-	-	-	-	-	-	-	-	-
Meade No. 1---------------	50-163-10002	5,305	NP	-	-	-	-	-	-	-	-	-	-	-
Simpson No. 1-------------	50-279-10032	7,002	467+	-	-	-	-	-	-	.03	.09	.15	6	.09
Topagoruk No. 1-----------	50-279-10033	10,503	458+	-	-	-	-	-	-	.35	.77	1.29	7	.77
East Topagoruk No. 1------	50-279-10034	3,589	NP	-	-	-	-	-	-	-	-	-	-	-
Umiat No. 1---------------	50-278-10001	6,005	NP	-	-	-	-	-	-	-	-	-	-	-
*Umiat No. 2---------------	50-287-10002	6,212	NP	-	-	-	-	-	-	-	-	-	-	-
Umiat No. 11--------------	50-287-10011	3,303	NP	-	-	-	-	-	-	-	-	-	-	-
Gubik No. 1---------------	50-287-10013	6,000	NP	-	-	-	-	-	-	-	-	-	-	-
*Gubik No. 2---------------	50-287-10014	4,620	NP	-	-	-	-	-	-	-	-	-	-	-
Kaolak No. 1--------------	50-297-10001	6,952	NP	-	-	-	-	-	-	-	-	-	-	-
Barrow program (1955-81)														
South Barrow No. 9--------	50-023-20003	2,450	NP	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 12-------	50-023-20006	2,285	20+	-	-	-	-	-	-	-	.83	-	1	.83
*South Barrow No. 13-------	50-023-20008	2,535	60+	-	9.81	-	-	-	-	-	9.96	-	2	9.89
*South Barrow No. 14-------	50-023-20009	2,257	NP	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 16-------	50-023-20010	2,400	60+	-	12.04	-	1.56	7.89	14.22	-	7.44	-	4	8.82
South Barrow No. 17-------	50-023-20011	2,382	37+	-	.99	-	-	-	-	-	2.57	-	2	1.78
*South Barrow No. 19-------	50-023-20012	2,300	35+	-	.94	-	-	-	-	-	-	-	1	.94
*South Barrow No. 20-------	50-023-20015	2,356	41+	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 15-------	50-023-20016	2,278	NP	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 18-------	50-023-20017	2,125	NP	-	-	-	-	-	-	-	-	-	-	-
Naval Petroleum Reserve No. 4 program (1973-77)														
Cape Halkett No. 1--------	50-103-20004	9,900	595+	-	-	-	-	-	-	-	-	-	0	ND
South Harrison Bay No. 1--	50-103-20007	11,290	NP	-	-	-	-	-	-	-	-	-	-	-
Atigaru Point No. 1-------	50-103-20008	11,535	325+	.16	.35	.56	-	-	-	-	.57	-	4	.41
West Fish Creek No. 1-----	50-103-20009	11,427	NP	-	-	-	-	-	-	-	-	-	-	-
W.T. Foran No. 1----------	50-103-20010	8,864	299+	.07	.63	1.02	-	-	-	-	-	-	5	.63
South Simpson No. 1-------	50-279-20001	8,795	50+	.55	.78	1.02	-	1.05	-	-	-	-	3	.87
National Petroleum Reserve in Alaska program (1977-81)														
Walakpa No. 1-------------	50-023-20013	3,666	36+	-	-	-	-	-	-	0.35	0.38	0.39	3	0.38
West Dease No. 1----------	50-023-20014	4,173	168+	1.25	1.31	1.37	-	-	-	-	.85	-	3	1.16
Tulageak No. 1------------	50-023-20018	4,015	55+	-	.96	-	-	-	-	1.24	1.67	2.10	3	1.43
Walakpa No. 2-------------	50-023-20019	4,360	60+	-	6.84	-	-	6.79	-	-	-	-	2	6.82
North Kalikpik No. 1------	50-103-20011	7,395	NP	-	-	-	-	-	-	-	-	-	-	-
North Inigok No. 1--------	50-103-20017	10,170	NP	-	-	-	-	-	-	-	-	-	-	-
Koluktak No. 1------------	50-119-20001	5,882	NP	-	-	-	-	-	-	-	-	-	-	-
*Lisburne No. 1------------	50-137-20003	17,000	NP	-	-	-	-	-	-	-	-	-	-	-
Awuna No. 1---------------	50-155-20001	11,200	NP	-	-	-	-	-	-	-	-	-	-	-
South Meade No. 1---------	50-163-20001	9,945	515+	.21	2.15	8.62	-	-	-	-	-	-	9	2.15
Kugrua No. 1--------------	50-163-20002	12,588	NP	-	-	-	-	-	-	-	-	-	-	-
Kuyanak No. 1-------------	50-163-20003	6,690	130+	.50	.55	.64	-	.14	-	.42	.43	.44	7	.44
Drew Point No. 1----------	50-279-20002	7,946	96+	.84	1.15	1.46	-	-	-	-	1.16	-	3	1.15
Inigok No. 1--------------	50-279-20003	20,102	NP	-	-	-	-	-	-	-	-	-	-	-
Ikpikpuk No. 1------------	50-279-20004	15,481	161+	1.81	4.26	6.44	-	-	-	-	-	-	3	4.26
East Simpson No. 1--------	50-279-20005	7,739	149+	.67	.75	.83	-	-	-	.12	.73	1.05	5	.74
Dalton No. 1--------------	50-279-20006	9,367	102+	.51	.60	.69	-	-	-	1.03	1.20	1.44	5	.96
East Simpson No. 2--------	50-279-20007	7,504	149+	5.06	17.25	29.45	-	-	-	.10	.34	.81	5	7.11
Seabee No. 1--------------	50-287-20007	15,611	NP	-	-	-	-	-	-	-	-	-	-	-
Tunalik No. 1-------------	50-301-20001	20,335	NP	-	-	-	-	-	-	-	-	-	-	-
Peard No. 1---------------	50-301-20002	10,225	585+	.17	.26	.49	-	-	-	.17	.23	.30	15	.26

[1] Sidewall-core data are included with conventional-core data.

and vitrinite-reflectance data for pre-Endicott Group rocks

C_{15+}-hydrocarbon content (ppm)									Visual-kerogen content								Vitrinite reflectance	
Cuttings samples				Core samples				Comments	Cuttings samples				Core samples				Top	Within
No.	Min	Mean	Max	No.	Min	Mean	Max		No.	A-H	W	I	No.	A-H	W	I		
Naval Petroleum Reserve No. 4 program (1944-53)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	1	63	9	27	.63	ND
-	-	-	-	-	-	-	-	-	-	-	-	-	1	60	10	30	.53	ND
-	-	-	-	2	268	290	311	-	-	-	-	-	3	23	5	72	.60	ND
-	-	-	-	-	-	-	-	-	-	-	-	-	1	0	1	99	ND	ND
-	-	-	-	-	-	-	-	-	-	-	-	-	4	11	6	83	.51	ND
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	4	32	77	150	-	-	-	-	-	6	64	4	32	.66	ND
-	-	-	-	3	44	52	57	-	-	-	-	-	5	42	14	44	1.18	1.3?
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Barrow program (1955-81)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	1	-	136	-	-	-	-	-	-	1	17	17	67	ND	ND
1	-	2,131	-	3	-	2,082	-	-	1	33	0	67	1	17	17	68	ND	4.9?
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	1	-	-	-	OS	1	50	0	50	1	50	0	50	.50	.6?
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.51	ND
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.55	ND
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	ND	ND
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Naval Petroleum Reserve No. 4 program (1973-77)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	ND	ND
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	2	46	19	35	ND	-	-	-	1.25	ND
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	104	112	116	-	-	-	-	-	4	45	26	29	ND	-	-	-	.60	.4?
2	97	135	174	-	-	-	-	-	2	44	24	32	*1	38	31	31	.95	1.3?
National Petroleum Reserve in Alaska program (1977-81)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	1	30	30	40	0.53	0.6?
1	-	188	-	-	-	-	-	-	1	61	31	8	[1]1	55	9	36	.74	ND
-	-	-	-	-	-	-	-	-	1	38	31	31	1	0	50	50	.74	2.8?
-	-	-	-	-	-	-	-	-	-	-	-	-	[1]1	11	44	44	.58	ND
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	2	6	44	50	-	-	-	-	3.4	ND
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	[1]2	54	18	28	.71	ND
-	-	-	-	-	-	-	-	-	1	27	36	36	1	33	22	44	.68	.6?
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.80	ND
-	-	-	-	-	-	-	-	-	2	43	32	25	1	46	18	36	.69	.8?
-	-	-	-	-	-	-	-	-	-	-	-	-	1	99	0	1	.67	.7?
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.77	.7?
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	4	36	32	32	1	50	25	25	1.05	1.3?

TABLE 17.3.—*Organic-carbon, C_{15+}-hydrocarbon, visual-*

[*, well not included on organic-carbon, visual-kerogen, or vitrinite-reflectance maps; NP, rock unit not penetrated; ND, not determined or insufficient data; 0, rock unit eroded or not deposited; OS, oil-stained sample; +, incomplete thickness. Rock-unit thicknesses, mean organic-carbon contents, mean C_{15+}-hydrocarbon contents, and visual-kerogen contents are posted on maps. Visual-kerogen contents (in percent): A-H, amorphous and herbaceous; W, woody; I, inertinite]

Well	API No.	Total depth (ft)	Rock unit thickness (ft)	Organic-carbon content (weight percent)										
				Cuttings			Sidewall core			Conventional core			Total samples	Mean value
				Min	Mean	Max	Min	Mean	Max	Min	Mean	Max		
Naval Petroleum Reserve No. 4 program (1944-53)														
North Simpson No. 1	50-023-10004	3,774	NP	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 1	50-023-10009	3,553	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 2	50-023-10010	2,505	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 3	50-023-10011	2,900	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 4	50-023-10012	2,538	0	-	-	-	-	-	-	-	-	-	-	-
*Avak No. 1	50-023-10013	4,020	0	-	-	-	-	-	-	-	-	-	-	-
Grandstand No. 1	50-057-10001	3,939	NP	-	-	-	-	-	-	-	-	-	-	-
Fish Creek No. 1	50-103-10001	7,020	NP	-	-	-	-	-	-	-	-	-	-	-
Oumalik No. 1	50-119-10005	11,872	NP	-	-	-	-	-	-	-	-	-	-	-
East Oumalik No. 1	50-119-10006	6,035	NP	-	-	-	-	-	-	-	-	-	-	-
Square Lake No. 1	50-119-10007	3,987	NP	-	-	-	-	-	-	-	-	-	-	-
*Wolf Creek No. 1	50-119-10008	1,500	NP	-	-	-	-	-	-	-	-	-	-	-
Wolf Creek No. 3	50-119-10010	3,760	NP	-	-	-	-	-	-	-	-	-	-	-
Titaluk No. 1	50-119-10011	4,020	NP	-	-	-	-	-	-	-	-	-	-	-
Knifeblade No. 1	50-119-10012	1,805	NP	-	-	-	-	-	-	-	-	-	-	-
*Knifeblade No. 2A	50-119-10014	1,805	NP	-	-	-	-	-	-	-	-	-	-	-
Meade No. 1	50-163-10002	5,305	NP	-	-	-	-	-	-	-	-	-	-	-
Simpson No. 1	50-279-10032	7,002	0	-	-	-	-	-	-	-	-	-	-	-
Topagoruk No. 1	50-279-10033	10,503	270	-	-	-	-	-	-	-	.10	-	1	.10
East Topagoruk No. 1	50-279-10034	3,589	NP	-	-	-	-	-	-	-	-	-	-	-
Umiat No. 1	50-278-10001	6,005	NP	-	-	-	-	-	-	-	-	-	-	-
*Umiat No. 2	50-287-10002	6,212	NP	-	-	-	-	-	-	-	-	-	-	-
Umiat No. 11	50-287-10011	3,303	NP	-	-	-	-	-	-	-	-	-	-	-
Gubik No. 1	50-287-10013	6,000	NP	-	-	-	-	-	-	-	-	-	-	-
*Gubik No. 2	50-287-10014	4,620	NP	-	-	-	-	-	-	-	-	-	-	-
Kaolak No. 1	50-297-10001	6,952	NP	-	-	-	-	-	-	-	-	-	-	-
Barrow program (1955-81)														
South Barrow No. 9	50-023-20003	2,450	NP	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 12	50-023-20006	2,285	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 13	50-023-20008	2,535	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 14	50-023-20009	2,257	NP	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 16	50-023-20010	2,400	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 17	50-023-20011	2,382	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 19	50-023-20012	2,300	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 20	50-023-20015	2,356	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 15	50-023-20016	2,278	NP	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 18	50-023-20017	2,125	NP	-	-	-	-	-	-	-	-	-	-	-
Naval Petroleum Reserve No. 4 program (1973-77)														
Cape Halkett No. 1	50-103-20004	9,900	0	-	-	-	-	-	-	-	-	-	-	-
South Harrison Bay No. 1	50-103-20007	11,290	NP	-	-	-	-	-	-	-	-	-	-	-
Atigaru Point No. 1	50-103-20008	11,535	390	.06	.32	.92	-	-	-	-	-	-	8	.32
West Fish Creek No. 1	50-103-20009	11,427	112+	-	.28	-	-	-	-	-	-	-	1	.28
W.T. Foran No. 1	50-103-20010	8,864	0	-	-	-	-	-	-	-	-	-	-	-
South Simpson No. 1	50-279-20001	8,795	155	.46	.52	.56	-	.19	-	-	-	-	5	.45
National Petroleum Reserve in Alaska program (1977-81)														
Walakpa No. 1	50-023-20013	3,666	0	-	-	-	-	-	-	-	-	-	-	-
West Dease No. 1	50-023-20014	4,173	0	-	-	-	-	-	-	-	-	-	-	-
Tulageak No. 1	50-023-20018	4,015	0	-	-	-	-	-	-	-	-	-	-	-
Walakpa No. 2	50-023-20019	4,360	0	-	-	-	-	-	-	-	-	-	-	-
North Kalikpik No. 1	50-103-20011	7,395	NP	-	-	-	-	-	-	-	-	-	-	-
North Inigok No. 1	50-103-20017	10,170	NP	-	-	-	-	-	-	-	-	-	-	-
Koluktak No. 1	50-119-20001	5,882	NP	-	-	-	-	-	-	-	-	-	-	-
*Lisburne No. 1	50-137-20003	17,000	NA	-	-	-	-	-	-	-	-	-	-	-
Awuna No. 1	50-155-20001	11,200	NP	-	-	-	-	-	-	-	-	-	-	-
South Meade No. 1	50-163-20001	9,945	0	-	-	-	-	-	-	-	-	-	-	-
Kugrua No. 1	50-163-20002	12,588	NP	-	-	-	-	-	-	-	-	-	-	-
Kuyanak No. 1	50-163-20003	6,690	0	-	-	-	-	-	-	-	-	-	-	-
Drew Point No. 1	50-279-20002	7,946	0	-	-	-	-	-	-	-	-	-	-	-
Inigok No. 1	50-279-20003	20,102	2,232+	.19	2.67	20.80	-	-	-	.26	13.36	26.11	45	3.86
Ikpikpuk No. 1	50-279-20004	15,481	770	.07	.46	1.24	-	-	-	.07	.08	.10	17	.37
East Simpson No. 1	50-279-20005	7,739	0	-	-	-	-	-	-	-	-	-	-	-
Dalton No. 1	50-279-20006	9,367	650	.26	.57	1.56	-	.71	-	-	-	-	12	.58
East Simpson No. 2	50-279-20007	7,504	0	-	-	-	-	-	-	-	-	-	-	-
Seabee No. 1	50-287-20007	15,611	NP	-	-	-	-	-	-	-	-	-	-	-
Tunalik No. 1	50-301-20001	20,335	NP	-	-	-	-	-	-	-	-	-	-	-
Peard No. 1	50-301-20002	10,225	0	-	-	-	-	-	-	-	-	-	-	-

kerogen, and vitrinite-reflectance data for the Endicott Group

C_{15+}-hydrocarbon content (ppm)								Comments	Visual-kerogen content								Vitrinite reflectance	
Cuttings samples				Core samples					Cuttings samples				Core samples				Top	Within
No.	Min	Mean	Max	No.	Min	Mean	Max		No.	A-H	W	I	No.	A-H	W	I		
Naval Petroleum Reserve No. 4 program (1944-53)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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-	-	-	-	1	-	28	-	-	-	-	-	-	-	-	-	-	1.12	1.18
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Barrow program (1955-81)--Continued																		
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Naval Petroleum Reserve No. 4 program (1973-77)--Continued																		
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-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1	-	158	-	-	-	-	-	-	3	44	31	25	ND	-	-	-	1.18	1.25
1	-	40	-	-	-	-	-	-	1	36	27	36	ND	-	-	-	.60	.60+
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	169	193	210	-	-	-	-	-	3	45	29	26	1	50	25	25	.93	.95
National Petroleum Reserve in Alaska program (1977-81)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	160	349	537	1	-	12	-	-	9	24	42	34	3	46	16	39	4.40	4.8+
-	-	-	-	-	-	-	-	-	2	57	9	34	1	60	0	40	2.60	2.8
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	156	277	397	-	-	-	-	OS	5	61	22	17	1	75	0	25	.67	.70
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TABLE 17.4.—*Organic-carbon, C_{15+}-hydrocarbon, visual-*

[*, well not included on organic-carbon, visual-kerogen, or vitrinite-reflectance maps; NP, rock unit not penetrated; ND, not determined or insufficient data; 0, rock unit eroded or not deposited; OS, oil-stained sample; +, incomplete thickness. Rock-unit thicknesses, mean organic-carbon contents, mean C_{15+}-hydrocarbon contents, and visual-kerogen contents are posted on maps. Visual-kerogen contents (in percent): A-H, amorphous and herbaceous; W, woody; I, inertinite)]

Well	API No.	Total depth (ft)	Rock unit thickness (ft)	Organic-carbon content (weight percent)										
				Cuttings			Sidewall core			Conventional core			Total samples	Mean value
				Min	Mean	Max	Min	Mean	Max	Min	Mean	Max		
Naval Petroleum Reserve No. 4 program (1944-53)														
North Simpson No. 1	50-023-10004	3,774	NP	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 1	50-023-10009	3,553	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 2	50-023-10010	2,505	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 3	50-023-10011	2,900	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 4	50-023-10012	2,538	0	-	-	-	-	-	-	-	-	-	-	-
*Avak No. 1	50-023-10013	4,020	0	-	-	-	-	-	-	-	-	-	-	-
Grandstand No. 1	50-057-10001	3,939	NP	-	-	-	-	-	-	-	-	-	-	-
Fish Creek No. 1	50-103-10001	7,020	NP	-	-	-	-	-	-	-	-	-	-	-
Oumalik No. 1	50-119-10005	11,872	NP	-	-	-	-	-	-	-	-	-	-	-
East Oumalik No. 1	50-119-10006	6,035	NP	-	-	-	-	-	-	-	-	-	-	-
Square Lake No. 1	50-119-10007	3,987	NP	-	-	-	-	-	-	-	-	-	-	-
*Wolf Creek No. 1	50-119-10008	1,500	NP	-	-	-	-	-	-	-	-	-	-	-
Wolf Creek No. 3	50-119-10010	3,760	NP	-	-	-	-	-	-	-	-	-	-	-
Titaluk No. 1	50-119-10011	4,020	NP	-	-	-	-	-	-	-	-	-	-	-
Knifeblade No. 1	50-119-10012	1,805	NP	-	-	-	-	-	-	-	-	-	-	-
*Knifeblade No. 2A	50-119-10014	1,805	NP	-	-	-	-	-	-	-	-	-	-	-
Meade No. 1	50-163-10002	5,305	NP	-	-	-	-	-	-	-	-	-	-	-
Simpson No. 1	50-279-10032	7,002	0	-	-	-	-	-	-	-	-	-	-	-
Topagoruk No. 1	50-279-10033	10,503	0	-	-	-	-	-	-	-	-	-	-	-
East Topagoruk No. 1	50-279-10034	3,589	NP	-	-	-	-	-	-	-	-	-	-	-
Umiat No. 1	50-278-10001	6,005	NP	-	-	-	-	-	-	-	-	-	-	-
*Umiat No. 2	50-287-10002	6,212	NP	-	-	-	-	-	-	-	-	-	-	-
Umiat No. 11	50-287-10011	3,303	NP	-	-	-	-	-	-	-	-	-	-	-
Gubik No. 1	50-287-10013	6,000	NP	-	-	-	-	-	-	-	-	-	-	-
*Gubik No. 2	50-287-10014	4,620	NP	-	-	-	-	-	-	-	-	-	-	-
Kaolak No. 1	50-297-10001	6,952	NP	-	-	-	-	-	-	-	-	-	-	-
Barrow program (1955-81)														
South Barrow No. 9	50-023-20003	2,450	NP	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 12	50-023-20006	2,285	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 13	50-023-20008	2,535	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 14	50-023-20009	2,257	NP	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 16	50-023-20010	2,400	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 17	50-023-20011	2,382	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 19	50-023-20012	2,300	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 20	50-023-20015	2,356	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 15	50-023-20016	2,278	NP	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 18	50-023-20017	2,125	NP	-	-	-	-	-	-	-	-	-	-	-
Naval Petroleum Reserve No. 4 program (1973-77)														
Cape Halkett No. 1	50-103-20004	9,900	435	-	-	-	-	-	-	-	-	-	0	-
South Harrison Bay No. 1	50-103-20007	11,290	1,055+	.27	.76	1.91	-	-	-	-	.74	-	14	.75
Atigaru Point No. 1	50-103-20008	11,535	1,310	.01	.28	2.56	.09	.25	.37	-	-	-	26	.28
West Fish Creek No. 1	50-103-20009	11,427	815	.10	.14	.18	-	-	-	-	-	-	7	.14
W.T. Foran No. 1	50-103-20010	8,864	370	.30	.45	.72	-	-	-	.51	.85	1.20	10	.53
South Simpson No. 1	50-279-20001	8,795	0	-	-	-	-	-	-	-	-	-	-	-
National Petroleum Reserve in Alaska program (1977-81)														
Walakpa No. 1	50-023-20013	3,666	0	-	-	-	-	-	-	-	-	-	-	-
West Dease No. 1	50-023-20014	4,173	0	-	-	-	-	-	-	-	-	-	-	-
Tulageak No. 1	50-023-20018	4,015	0	-	-	-	-	-	-	-	-	-	-	-
Walakpa No. 2	50-023-20019	4,360	0	-	-	-	-	-	-	-	-	-	-	-
North Kalikpik No. 1	50-103-20011	7,395	NP	-	-	-	-	-	-	-	-	-	-	-
North Inigok No. 1	50-103-20017	10,170	NP	-	-	-	-	-	-	-	-	-	-	-
Koluktak No. 1	50-119-20001	5,882	NP	-	-	-	-	-	-	-	-	-	-	-
*Lisburne No. 1	50-137-20003	17,000	NA	-	-	-	-	-	-	-	-	-	-	-
Awuna No. 1	50-155-20001	11,200	NP	-	-	-	-	-	-	-	-	-	-	-
South Meade No. 1	50-163-20001	9,945	0	-	-	-	-	-	-	-	-	-	-	-
Kugrua No. 1	50-163-20002	12,588	1,408+	.05	.15	.30	-	-	-	-	-	-	28	.15
Kuyanak No. 1	50-163-20003	6,690	0	-	-	-	-	-	-	-	-	-	-	-
Drew Point No. 1	50-279-20002	7,946	0	-	-	-	-	-	-	-	-	-	-	-
Inigok No. 1	50-279-20003	20,102	3,885	.04	.40	9.56	-	-	-	.09	.31	.86	92	.38
Ikpikpuk No. 1	50-279-20004	15,481	3,150	.08	.26	1.09	-	-	-	.08	.16	.29	61	.25
East Simpson No. 1	50-279-20005	7,739	0	-	-	-	-	-	-	-	-	-	-	-
Dalton No. 1	50-279-20006	9,367	310	.87	1.45	1.91	-	.87	-	.14	.72	1.62	20	.94
East Simpson No. 2	50-279-20007	7,504	0	-	-	-	-	-	-	-	-	-	-	-
Seabee No. 1	50-287-20007	15,611	NP	-	-	-	-	-	-	-	-	-	-	-
Tunalik No. 1	50-301-20001	20,335	3,235+	.16	.44	1.57	-	-	-	.04	.28	.72	66	.40
Peard No. 1	50-301-20002	10,225	0	-	-	-	-	-	-	-	-	-	-	-

kerogen, and vitrinite-reflectance data for the Lisburne Group

C_{15+}-hydrocarbon content (ppm)									Visual-kerogen content								Vitrinite reflectance	
Cuttings samples				Core samples				Comments	Cuttings samples				Core samples				Top	Within
No.	Min	Mean	Max	No.	Min	Mean	Max		No.	A-H	W	I	No.	A-H	W	I		
Naval Petroleum Reserve No. 4 program (1944-53)--Continued																		
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Barrow program (1955-81)--Continued																		
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Naval Petroleum Reserve No. 4 program (1973-77)--Continued																		
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2	61	73	85	-	-	-	-	-	6	51	28	21	2	62	20	18	.73	.90+
-	-	-	-	-	-	-	-	-	4	72	12	16	2	66	12	22	.97	1.18
7	10	32	57	-	-	-	-	-	8	53	22	25	ND	-	-	-	.58	.60
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National Petroleum Reserve in Alaska program (1977-81)--Continued																		
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3	19	39	75	1	-	24	-	-	16	35	29	36	6	29	33	38	2.80	4.40
1	-	52	-	-	-	-	-	-	9	30	35	35	3	83	9	8	2.15	2.60
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1	-	301	-	-	-	-	-	OS	4	68	20	12	3	61	22	17	.64	.67
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1	-	45	-	-	-	-	-	-	11	24	37	39	4	24	32	44	4.15	4.60+
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TABLE 17.5.—*Organic-carbon, C_{15+}-hydrocarbon, visual-*

[*, well not included on organic-carbon, visual-kerogen, or vitrinite-reflectance maps; NP, rock unit not penetrated; ND, not determined or insufficient data; 0, rock unit eroded or not deposited; OS, oil-stained sample; +, incomplete thickness. Rock-unit thicknesses, mean organic-carbon contents, mean C_{15+}-hydrocarbon contents, and visual-kerogen contents are posted on maps. Visual-kerogen contents (in percent): A-H, amorphous and herbaceous; W, woody; I, inertinite]

Well	API No.	Total depth (ft)	Rock unit thickness (ft)	Organic-carbon content (weight percent)										
				Cuttings			Sidewall core			Conventional core			Total samples	Mean value
				Min	Mean	Max	Min	Mean	Max	Min	Mean	Max		
				Naval Petroleum Reserve No. 4 program (1944-53)										
North Simpson No. 1	50-023-10004	3,774	NP	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 1	50-023-10009	3,553	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 2	50-023-10010	2,505	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 3	50-023-10011	2,900	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 4	50-023-10012	2,538	0	-	-	-	-	-	-	-	-	-	-	-
*Avak No. 1	50-023-10013	4,020	0	-	-	-	-	-	-	-	-	-	-	-
Grandstand No. 1	50-057-10001	3,939	NP	-	-	-	-	-	-	-	-	-	-	-
Fish Creek No. 1	50-103-10001	7,020	NP	-	-	-	-	-	-	-	-	-	-	-
Oumalik No. 1	50-119-10005	11,872	NP	-	-	-	-	-	-	-	-	-	-	-
East Oumalik No. 1	50-119-10006	6,035	NP	-	-	-	-	-	-	-	-	-	-	-
Square Lake No. 1	50-119-10007	3,987	NP	-	-	-	-	-	-	-	-	-	-	-
*Wolf Creek No. 1	50-119-10008	1,500	NP	-	-	-	-	-	-	-	-	-	-	-
Wolf Creek No. 3	50-119-10010	3,760	NP	-	-	-	-	-	-	-	-	-	-	-
Titaluk No. 1	50-119-10011	4,020	NP	-	-	-	-	-	-	-	-	-	-	-
Kniffeblade No. 1	50-119-10012	1,805	NP	-	-	-	-	-	-	-	-	-	-	-
*Knifeblade No. 2A	50-119-10014	1,805	NP	-	-	-	-	-	-	-	-	-	-	-
Meade No. 1	50-163-10002	5,305	NP	-	-	-	-	-	-	-	-	-	-	-
Simpson No. 1	50-279-10032	7,002	0	-	-	-	-	-	-	-	-	-	-	-
Topagoruk No. 1	50-279-10033	10,503	55	-	-	-	-	-	-	.08	.33	.72	8	.33
East Topagoruk No. 1	50-279-10034	3,589	NP	-	-	-	-	-	-	-	-	-	-	-
Umiat No. 1	50-278-10001	6,005	NP	-	-	-	-	-	-	-	-	-	-	-
*Umiat No. 2	50-287-10002	6,212	NP	-	-	-	-	-	-	-	-	-	-	-
Umiat No. 11	50-287-10011	3,303	NP	-	-	-	-	-	-	-	-	-	-	-
Gubik No. 1	50-287-10013	6,000	NP	-	-	-	-	-	-	-	-	-	-	-
*Gubik No. 2	50-287-10014	4,620	NP	-	-	-	-	-	-	-	-	-	-	-
Kaolak No. 1	50-297-10001	6,952	NP	-	-	-	-	-	-	-	-	-	-	-
				Barrow program (1955-81)										
South Barrow No. 9	50-023-20003	2,450	NP	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 12	50-023-20006	2,285	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 13	50-023-20008	2,535	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 14	50-023-20009	2,257	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 16	50-023-20010	2,400	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 17	50-023-20011	2,382	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 19	50-023-20012	2,300	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 20	50-023-20015	2,356	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 15	50-023-20016	2,278	NP	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 18	50-023-20017	2,125	NP	-	-	-	-	-	-	-	-	-	-	-
				National Petroleum Reserve No. 4 program (1973-77)										
Cape Halkett No. 1	50-103-20004	9,900	740	-	-	-	-	-	-	-	-	-	-	-
South Harrison Bay No. 1	50-103-20007	11,290	995	.97	1.65	2.55	-	-	-	-	-	-	11	1.65
Atigaru Point No. 1	50-103-20008	11,535	910	.07	.80	2.39	.24	1.65	4.29	.17	.19	.20	23	.87
West Fish Creek No. 1	50-103-20009	11,427	985	.34	.86	3.59	-	-	-	-	-	-	10	.86
W.T. Foran No. 1	50-103-20010	8,864	555	.59	1.09	1.82	-	-	-	-	-	-	13	1.09
South Simpson No. 1	50-279-20001	8,795	320	.18	.47	.09	-	1.30	-	-	-	-	8	.57
				National Petroleum Reserve in Alaska program (1977-81)										
Walakpa No. 1	50-023-20013	3,666	0	-	-	-	-	-	-	-	-	-	-	-
West Dease No. 1	50-023-20014	4,173	0	-	-	-	-	-	-	-	-	-	-	-
Tulageak No. 1	50-023-20018	4,015	0	-	-	-	-	-	-	-	-	-	-	-
Walakpa No. 2	50-023-20019	4,360	0	-	-	-	-	-	-	-	-	-	-	-
North Kalikpik No. 1	50-103-20011	7,395	NP	-	-	-	-	-	-	-	-	-	-	-
North Inigok No. 1	50-103-20017	10,170	NP	-	-	-	-	-	-	-	-	-	-	-
Koluktak No. 1	50-119-20001	5,882	NP	-	-	-	-	-	-	-	-	-	-	-
*Lisburne No. 1	50-137-20003	17,000	NA	-	-	-	-	-	-	-	-	-	-	-
Awuna No. 1	50-155-20001	11,200	NP	-	-	-	-	-	-	-	-	-	-	-
South Meade No. 1	50-163-20001	9,945	245	.14	.25	.33	-	-	-	.08	.14	.26	12	.18
Kugrua No. 1	50-163-20002	12,588	1,170	.18	.59	2.53	-	-	-	.11	.32	.97	50	.44
Kuyanak No. 1	50-163-20003	6,690	0	-	-	-	-	-	-	-	-	-	-	-
Drew Point No. 1	50-279-20002	7,946	280	.65	.82	1.04	.13	.98	3.94	.35	.54	.85	16	.78
Inigok No. 1	50-279-20003	20,102	1,555	.03	.41	1.34	-	-	-	.16	.67	1.56	53	.53
Ikpikpuk No. 1	50-279-20004	15,481	1,050	.21	.52	.92	-	-	-	.10	.33	.66	36	.40
East Simpson No. 1	50-279-20005	7,739	135	-	.62	-	-	-	-	.10	.50	2.36	20	.51
Dalton No. 1	50-279-20006	9,367	405	1.90	2.44	2.82	.90	1.03	1.17	.10	.86	4.83	58	1.06
East Simpson No. 2	50-279-20007	7,504	205	1.33	8.82	16.15	-	-	-	.15	5.12	20.87	36	5.61
Seabee No. 1	50-287-20007	15,611	NP	-	-	-	-	-	-	-	-	-	-	-
Tunalik No. 1	50-301-20001	20,335	2,275	.30	.71	1.91	-	-	-	.26	.45	.92	49	.64
Peard No. 1	50-301-20002	10,225	900	.18	.48	1.21	-	-	-	.14	.79	2.01	33	.63

kerogen, and vitrinite-reflectance data for the Sadlerochit Group

C_{15+}-hydrocarbon content (ppm)									Visual-kerogen content								Vitrinite reflectance	
Cuttings samples				Core samples				Comments	Cuttings samples				Core samples				Top	Within
No.	Min	Mean	Max	No.	Min	Mean	Max		No.	A-H	W	I	No.	A-H	W	I		
Naval Petroleum Reserve No. 4 program (1944-53)--Continued																		
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Barrow program (1955-81)--Continued																		
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Naval Petroleum Reserve No. 4 program (1973-77)--Continued																		
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1	-	819	-	-	-	-	-	-	4	67	18	15	ND	-	-	-	.68	.73
-	-	-	-	-	-	-	-	-	1	83	0	17	7	63	9	28	.87	.97
10	51	273	566	-	-	-	-	-	10	73	12	15	ND	-	-	-	.54	.58
3	290	441	718	-	-	-	-	OS	11	69	15	16	ND	-	-	-	.54	.57
3	134	201	250	-	-	-	-	-	6	53	20	27	1	55	36	4	.90	.93
National Petroleum Reserve in Alaska program (1977-81)--Continued																		
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2	26	26	26	-	-	-	-	-	10	43	29	28	11	58	16	26	1.60	2.10
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-	-	-	-	1	-	80	-	OS	1	58	17	25	10	69	14	17	.67	.68
-	-	-	-	2	23	30	37	-	5	42	23	35	7	26	37	37	2.35	2.80
1	-	97	-	2	68	77	85	-	5	31	33	36	4	62	19	19	1.50	2.15
-	-	-	-	2	37	61	85	-	ND	-	-	-	3	36	27	37	.67	.69
-	-	-	-	4	-	-	-	OS	1	62	23	15	6	96	2	2	.63	.65
-	-	-	-	5	167	511	1,042	coal	1	46	31	23	4	59	15	26	.73	.77
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	7	36	27	37	4	21	37	42	3.40	4.15
2	40	53	65	2	30	74	117	OS	5	40	28	32	2	37	34	29	.97	1.05

TABLE 17.6.—*Organic-carbon, C_{15+}-hydrocarbon, visual-kerogen,*

[*, well not included on organic-carbon, visual-kerogen, or vitrinite-reflectance maps; NP, rock unit not penetrated; ND, not determined or insufficient data; 0, rock unit eroded or not deposited; OS, oil-stained sample; +, incomplete thickness. Rock-unit thicknesses, mean organic-carbon contents, mean C_{15+}-hydrocarbon contents, and visual-kerogen contents are posted on maps. Visual-kerogen contents (in percent): A-H, amorphous and herbaceous; W, woody; I, inertinite]

Well	API No.	Total depth (ft)	Rock unit thickness (ft)	Organic-carbon content (weight percent)										
				Cuttings			Sidewall core			Conventional core			Total samples	Mean value
				Min	Mean	Max	Min	Mean	Max	Min	Mean	Max		
Naval Petroleum Reserve No. 4 program (1944-53)														
North Simpson No. 1	50-023-10004	3,774	NP	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 1	50-023-10009	3,553	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 2	50-023-10010	2,505	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 3	50-023-10011	2,900	185	-	-	-	-	-	-	.25	.61	1.21	10	.61
*South Barrow No. 4	50-023-10012	2,538	0	-	-	-	-	-	-	-	-	-	-	-
*Avak No. 1	50-023-10013	4,020	0	-	-	-	-	-	-	-	-	-	-	-
Grandstand No. 1	50-057-10001	3,939	NP	-	-	-	-	-	-	-	-	-	-	-
Fish Creek No. 1	50-103-10001	7,020	NP	-	-	-	-	-	-	-	-	-	-	-
Oumalik No. 1	50-119-10005	11,872	NP	-	-	-	-	-	-	-	-	-	-	-
East Oumalik No. 1	50-119-10006	6,035	NP	-	-	-	-	-	-	-	-	-	-	-
Square Lake No. 1	50-119-10007	3,987	NP	-	-	-	-	-	-	-	-	-	-	-
*Wolf Creek No. 1	50-119-10008	1,500	NP	-	-	-	-	-	-	-	-	-	-	-
Wolf Creek No. 3	50-119-10010	3,760	NP	-	-	-	-	-	-	-	-	-	-	-
Titaluk No. 1	50-119-10011	4,020	NP	-	-	-	-	-	-	-	-	-	-	-
Knifeblade No. 1	50-119-10012	1,805	NP	-	-	-	-	-	-	-	-	-	-	-
*Knifeblade No. 2A	50-119-10014	1,805	NP	-	-	-	-	-	-	-	-	-	-	-
Meade No. 1	50-163-10002	5,305	NP	-	-	-	-	-	-	-	-	-	-	-
Simpson No. 1	50-279-10032	7,002	265	-	-	-	-	-	-	.50	.76	1.27	6	.76
Topagoruk No. 1	50-279-10033	10,503	390	-	-	-	-	-	-	-	2.84	-	1	2.84
East Topagoruk No. 1	50-279-10034	3,589	NP	-	-	-	-	-	-	-	-	-	-	-
Umiat No. 1	50-278-10001	6,005	NP	-	-	-	-	-	-	-	-	-	-	-
*Umiat No. 2	50-287-10002	6,212	NP	-	-	-	-	-	-	-	-	-	-	-
Umiat No. 11	50-287-10011	3,303	NP	-	-	-	-	-	-	-	-	-	-	-
Gubik No. 1	50-287-10013	6,000	NP	-	-	-	-	-	-	-	-	-	-	-
*Gubik No. 2	50-287-10014	4,620	NP	-	-	-	-	-	-	-	-	-	-	-
Kaolak No. 1	50-297-10001	6,952	NP	-	-	-	-	-	-	-	-	-	-	-
Barrow program (1955-81)														
South Barrow No. 9	50-023-20003	2,450	NP	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 12	50-023-20006	2,285	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 13	50-023-20008	2,535	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 14	50-023-20009	2,257	NP	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 16	50-023-20010	2,400	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 17	50-023-20011	2,382	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 19	50-023-20012	2,300	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 20	50-023-20015	2,356	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 15	50-023-20016	2,278	NP	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 18	50-023-20017	2,125	NP	-	-	-	-	-	-	-	-	-	-	-
Naval Petroleum Reserve No. 4 program (1973-77)														
Cape Halkett No. 1	50-103-20004	9,900	275	-	-	-	-	-	-	-	-	-	0	-
South Harrison Bay No. 1	50-103-20007	11,290	285	1.85	1.96	2.08	-	-	-	-	-	-	2	1.96
Atigaru Point No. 1	50-103-20008	11,535	255	1.12	1.64	2.58	-	-	-	-	-	-	4	1.64
West Fish Creek No. 1	50-103-20009	11,427	230	1.41	2.13	2.86	-	-	-	-	-	-	2	2.13
W.T. Foran No. 1	50-103-20010	8,864	95	1.82	2.25	3.07	-	6.73	-	-	2.78	-	5	3.25
South Simpson No. 1	50-279-20001	8,795	585	.19	.65	.97	-	1.30	-	-	-	-	14	.70
National Petroleum Reserve in Alaska program (1977-81)														
Walakpa No. 1	50-023-20013	3,666	370	.56	.65	.78	-	1.11	-	.16	.47	1.07	19	.55
West Dease No. 1	50-023-20014	4,173	175	-	-	-	-	-	-	.29	.66	1.16	24	.66
Tulageak No. 1	50-023-20018	4,015	160	.61	.66	.79	-	-	-	.28	.54	.68	8	.60
Walakpa No. 2	50-023-20019	4,360	415	.26	.52	.68	-	.56	-	-	-	-	9	.52
North Kalikpik No. 1	50-103-20011	7,395	NP	-	-	-	-	-	-	-	-	-	-	-
North Inigok No. 1	50-103-20017	10,170	80+	2.11	3.11	4.12	-	-	-	-	-	-	2	3.11
Koluktak No. 1	50-119-20001	5,882	NP	-	-	-	-	-	-	-	-	-	-	-
*Lisburne No. 1	50-137-20003	17,000	NP	-	-	-	-	-	-	-	-	-	-	-
Awuna No. 1	50-155-20001	11,200	NP	-	-	-	-	-	-	-	-	-	-	-
South Meade No. 1	50-163-20001	9,945	325	.40	.69	.87	-	-	-	.26	.57	1.08	11	.61
Kugrua No. 1	50-163-20002	12,588	360	.58	.93	1.19	-	-	-	-	-	-	10	.93
Kuyanak No. 1	50-163-20003	6,690	225	.45	.57	.63	-	-	-	-	-	-	3	.57
Drew Point No. 1	50-279-20002	7,946	510	.72	.90	1.23	.39	.70	1.46	.65	.88	1.11	19	.79
Inigok No. 1	50-279-20003	20,102	240	2.34	2.67	3.25	-	-	-	-	-	-	4	2.67
Ikpikpuk No. 1	50-279-20004	15,481	490	.49	1.31	2.17	-	-	-	.50	2.51	4.26	16	1.98
East Simpson No. 1	50-279-20005	7,739	430	.26	.80	1.23	.81	.95	1.09	.46	1.82	4.22	13	1.06
Dalton No. 1	50-279-20006	9,367	260	1.82	2.10	2.85	1.58	1.92	2.24	-	-	-	9	2.00
East Simpson No. 2	50-279-20007	7,504	380	.44	1.21	1.79	-	-	-	-	-	-	6	1.21
Seabee No. 1	50-287-20007	15,611	NP	-	-	-	-	-	-	-	-	-	-	-
Tunalik No. 1	50-301-20001	20,335	315	1.29	1.64	2.30	-	-	-	-	-	-	10	.97
Peard No. 1	50-301-20002	10,225	275	.69	1.19	1.67	-	-	-	-	-	-	7	.77

and vitrinite-reflectance data for the Shublik Formation

C_{15+}-hydrocarbon content (ppm)									Visual-kerogen content								Vitrinite reflectance	
Cuttings samples				Core samples				Comments	Cuttings samples				Core samples				Top	Within
No.	Min	Mean	Max	No.	Min	Mean	Max		No.	A-H	W	I	No.	A-H	W	I		
Naval Petroleum Reserve No. 4 program (1944-53)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	1	-	724	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	ND	-	-	-	3	56	11	33	.60	.60
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	5	184	350	707	-	ND	-	-	-	5	36	32	32	.65	.66
-	-	-	-	-	-	-	-	-	ND	-	-	-	1	25	25	50	1.02	1.08
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Barrow program (1955-81)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Naval Petroleum Reserve No. 4 program (1973-77)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	ND	ND
-	-	-	-	-	-	-	-	-	1	70	10	20	ND	-	-	-	.67	.68
-	-	-	-	-	-	-	-	-	1	88	12	0	ND	-	-	-	.83	.87
2	1,176	1,193	1,210	-	-	-	-	-	2	100	0	0	ND	-	-	-	.54	.54
1	-	1,065	-	-	-	-	-	OS	2	62	21	17	2	77	11	12	.54	.54
6	119	434	673	-	-	-	-	OS	12	52	24	24	1	58	21	21	.85	.90
National Petroleum Reserve in Alaska program (1977-81)--Continued																		
1	-	48	-	2	32	93	154	-	2	51	28	21	2	36	34	30	.51	.53
-	-	-	-	1	-	248	-	OS	ND	-	-	-	4	44	23	33	.72	.74
-	-	-	-	1	-	45	-	-	ND	-	-	-	1	45	36	18	.73	.74
-	-	-	-	-	-	-	-	-	2	64	20	16	1	27	36	36	.56	.58
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1	-	86	-	-	-	-	-	-	1	67	22	11	ND	-	-	-	1.35	1.36+
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1	-	23	-	1	-	28	-	-	2	32	32	36	4	18	41	41	2.9	3.20
2	32	43	53	-	-	-	-	-	5	32	34	34	ND	-	-	-	1.32	1.60
-	-	-	-	-	-	-	-	-	1	38	31	31	ND	-	-	-	.70	.71
-	-	-	-	1	-	286	-	OS	1	58	17	25	11	46	26	28	.65	.67
2	29	36	147	-	-	-	-	-	3	57	20	23	ND	-	-	-	2.10	2.35
-	-	-	-	2	59	518	976	-	ND	-	-	-	3	71	11	18	1.25	1.50
2	39	394	397	1	-	482	-	-	4	52	29	19	2	58	24	18	.64	.66
2	390	412	434	-	-	-	-	-	2	60	31	9	4	55	21	24	.62	.63
-	-	-	-	-	-	-	-	-	1	88	12	0	ND	-	-	-	.71	.73
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1	-	33	-	-	-	-	-	-	2	31	34	35	1	20	40	40	3.25	3.40
-	-	-	-	1	-	157	-	OS	2	40	32	28	1	22	33	44	.95	.97

TABLE 17.7.—*Organic-carbon, C_{15+}-hydrocarbon, visual-kerogen,*

[*, well not included on organic-carbon, visual-kerogen, or vitrinite-reflectance maps; NP, rock unit not penetrated; ND, not determined or insufficient data; 0, rock unit eroded or not deposited; OS, oil-stained sample; +, incomplete thickness. Rock-unit thicknesses, mean organic-carbon contents, mean C_{15+}-hydrocarbon contents, and visual-kerogen contents are posted on maps. Visual-kerogen contents (in percent): A-H, amorphous and herbaceous; W, woody; I, inertinite]

Well	API No.	Total depth (ft)	Rock unit thickness (ft)	Organic-carbon content (weight percent)										
				Cuttings			Sidewall core			Conventional core			Total samples	Mean value
				Min	Mean	Max	Min	Mean	Max	Min	Mean	Max		
Naval Petroleum Reserve No. 4 program (1944-53)														
North Simpson No. 1-------	50-023-10004	3,774	NP	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 1--------	50-023-10009	3,553	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 2--------	50-023-10010	2,505	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 3--------	50-023-10011	2,900	25	-	-	-	-	-	-	-	.71	-	1	.71
*South Barrow No. 4--------	50-023-10012	2,538	0	-	-	-	-	-	-	-	-	-	-	-
*Avak No. 1----------------	50-023-10013	4,020	0	-	-	-	-	-	-	-	-	-	-	-
Grandstand No. 1----------	50-057-10001	3,939	NP	-	-	-	-	-	-	-	-	-	-	-
Fish Creek No. 1----------	50-103-10001	7,020	NP	-	-	-	-	-	-	-	-	-	-	-
Oumalik No. 1-------------	50-119-10005	11,872	NP	-	-	-	-	-	-	-	-	-	-	-
East Oumalik No. 1--------	50-119-10006	6,035	NP	-	-	-	-	-	-	-	-	-	-	-
Square Lake No. 1---------	50-119-10007	3,987	NP	-	-	-	-	-	-	-	-	-	-	-
*Wolf Creek No. 1----------	50-119-10008	1,500	NP	-	-	-	-	-	-	-	-	-	-	-
Wolf Creek No. 3----------	50-119-10010	3,760	NP	-	-	-	-	-	-	-	-	-	-	-
Titaluk No. 1-------------	50-119-10011	4,020	NP	-	-	-	-	-	-	-	-	-	-	-
Kniveblade No. 1----------	50-119-10012	1,805	NP	-	-	-	-	-	-	-	-	-	-	-
*Kniveblade No. 2A---------	50-119-10014	1,805	NP	-	-	-	-	-	-	-	-	-	-	-
Meade No. 1---------------	50-163-10002	5,305	NP	-	-	-	-	-	-	-	-	-	-	-
Simpson No. 1-------------	50-279-10032	7,002	240	-	-	-	-	-	-	.75	1.15	2.23	4	1.15
Topagoruk No. 1-----------	50-279-10033	10,503	165	-	-	-	-	-	-	-	-	-	0	ND
East Topagoruk No. 1------	50-279-10034	3,589	NP	-	-	-	-	-	-	-	-	-	-	-
Umiat No. 1---------------	50-278-10001	6,005	NP	-	-	-	-	-	-	-	-	-	-	-
*Umiat No. 2---------------	50-287-10002	6,212	NP	-	-	-	-	-	-	-	-	-	-	-
Umiat No. 11--------------	50-287-10011	3,303	NP	-	-	-	-	-	-	-	-	-	-	-
Gubik No. 1---------------	50-287-10013	6,000	NP	-	-	-	-	-	-	-	-	-	-	-
*Gubik No. 2---------------	50-287-10014	4,620	NP	-	-	-	-	-	-	-	-	-	-	-
Kaolak No. 1--------------	50-297-10001	6,952	NP	-	-	-	-	-	-	-	-	-	-	-
Barrow program (1955-81)														
South Barrow No. 9--------	50-023-20003	2,450	NP	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 12-------	50-023-20006	2,285	65	-	-	-	-	-	-	.70	1.49	1.97	3	1.49
*South Barrow No. 13-------	50-023-20008	2,535	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 14-------	50-023-20009	2,257	22+	.76	.76	.77	-	-	-	-	-	-	2	.76
South Barrow No. 16-------	50-023-20010	2,400	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 17-------	50-023-20011	2,382	70	.92	.96	1.0	-	-	-	1.08	1.82	2.57	5	1.30
*South Barrow No. 19-------	50-023-20012	2,300	70	-	1.22	-	-	-	-	1.05	1.51	2.10	4	1.44
*South Barrow No. 20-------	50-023-20015	2,356	85	-	-	-	-	-	-	1.19	2.20	3.49	16	2.20
*South Barrow No. 15-------	50-023-20016	2,278	NP	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 18-------	50-023-20017	2,125	NP	-	-	-	-	-	-	-	-	-	-	-
Naval Petroleum Reserve No. 4 program (1973-77)														
Cape Halkett No. 1--------	50-103-20004	9,900	125	-	-	-	-	-	-	-	-	-	0	ND
South Harrison Bay No. 1--	50-103-20007	11,290	110	1.65	2.09	2.90	-	-	-	-	-	-	4	2.09
Atigaru Point No. 1-------	50-103-20008	11,535	155	.38	1.01	2.08	-	-	-	-	-	-	4	1.01
West Fish Creek No. 1-----	50-103-20009	11,427	110	-	2.13	-	-	-	-	-	-	-	1	2.13
W.T. Foran No. 1----------	50-103-20010	8,864	0	-	-	-	-	-	-	-	-	-	-	-
South Simpson No. 1-------	50-279-20001	8,795	285	.23	.48	1.05	-	-	-	-	-	-	6	.48
National Petroleum Reserve in Alaska program (1977-81)														
Walakpa No. 1-------------	50-023-20013	3,666	40	-	.86	-	-	-	-	-	-	-	1	.86
West Dease No. 1----------	50-023-20014	4,173	30	-	-	-	-	-	-	.32	.47	.62	6	.47
Tulageak No. 1------------	50-023-20018	4,015	40	-	.41	-	-	-	-	.21	.49	.71	4	.47
Walakpa No. 2-------------	50-023-20019	4,360	40	-	.32	-	-	-	-	-	-	-	1	.32
North Kalikpik No. 1------	50-103-20011	7,395	NP	-	-	-	-	-	-	-	-	-	-	-
North Inigok No. 1--------	50-103-20017	10,170	40	-	-	-	-	-	-	-	-	-	0	ND
Koluktak No. 1------------	50-119-20001	5,882	NP	-	-	-	-	-	-	-	-	-	-	-
*Lisburne No. 1------------	50-137-20003	17,000	NA	-	-	-	-	-	-	-	-	-	-	-
Awuna No. 1---------------	50-155-20001	11,200	NP	-	-	-	-	-	-	-	-	-	-	-
South Meade No. 1---------	50-163-20001	9,945	90	.56	.71	.86	-	-	-	.15	.24	.33	12	.31
Kugrua No. 1--------------	50-163-20002	12,588	135	.82	.98	1.14	-	-	-	-	-	-	2	.98
Kuyanak No. 1-------------	50-163-20003	6,690	90	.81	.81	.82	-	-	-	.14	.24	.34	10	.31
Drew Point No. 1----------	50-279-20002	7,946	105	-	.90	-	.18	.54	1.41	.49	.53	.57	15	.56
Inigok No. 1--------------	50-279-20003	20,102	30	-	-	-	-	-	-	-	-	-	0	ND
Ikpikpuk No. 1------------	50-279-20004	15,481	60	-	.99	-	-	-	-	-	-	-	1	.99
East Simpson No. 1--------	50-279-20005	7,739	265	.57	1.02	1.21	-	-	-	.15	.56	2.86	27	.66
Dalton No. 1--------------	50-279-20006	9,367	0	-	-	-	-	-	-	-	-	-	-	-
East Simpson No. 2--------	50-279-20007	7,504	245	.68	1.22	2.24	-	2.38	-	.26	3.42	11.16	12	2.60
Seabee No. 1--------------	50-287-20007	15,611	NP	-	-	-	-	-	-	-	-	-	-	-
Tunalik No. 1-------------	50-301-20001	20,335	160	1.39	1.41	1.44	-	-	-	-	.35	-	3	1.06
Peard No. 1---------------	50-301-20002	10,225	125	-	.95	-	-	-	-	.38	.40	.43	4	.54

and vitrinite-reflectance data for the Sag River Sandstone

C_{15+}-hydrocarbon content (ppm)									Visual-kerogen content								Vitrinite reflectance	
Cuttings samples				Core samples				Comments	Cuttings samples				Core samples				Top	Within
No.	Min	Mean	Max	No.	Min	Mean	Max		No.	A-H	W	I	No.	A-H	W	I		
Naval Petroleum Reserve No. 4 program (1944-53)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	ND	-	-	-	1	50	17	34	.60	.60
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	3	178	257	312	-	ND	-	-	-	3	44	28	28	.65	.65
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	1.02
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Barrow program (1955-81)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	1	-	-	-	OS	-	-	-	-	-	-	-	-	ND	ND
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	1	40	30	30	ND	-	-	-	.48	.48+
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	3	-	-	-	OS	2	54	23	23	2	77	11	12	.51	.51
-	-	-	-	2	-	-	-	OS	1	64	18	18	1	57	14	29	.55	.55
-	-	-	-	1	-	-	-	OS	ND	-	-	-	1	75	25	0	ND	ND
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Naval Petroleum Reserve No. 4 program (1973-77)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	ND	ND
1	-	1,019	-	-	-	-	-	-	2	71	15	14	ND	-	-	-	.66	.67
1	-	261	-	-	-	-	-	-	1	64	18	18	ND	-	-	-	.82	.83
1	-	1,201	-	-	-	-	-	-	1	100	0	0	ND	-	-	-	.54	.54
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	197	231	289	-	-	-	-	-	5	51	26	23	ND	-	-	-	.83	.85
National Petroleum Reserve in Alaska program (1977-81)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.51	.51
-	-	-	-	1	-	-	-	OS	-	-	-	-	-	-	-	-	.72	.72
-	-	-	-	1	-	52	-	-	ND	-	-	-	1	45	36	18	.73	.73
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.56	.56
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.35	1.35
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	1	-	16	-	-	ND	-	-	-	1	20	40	40	2.8	2.9
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.22	1.32
-	-	-	-	-	-	-	-	-	ND	-	-	-	1	44	22	33	.70	.70
-	-	-	-	-	-	-	-	-	1	63	13	25	13	46	28	86	.64	.65
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.15	1.25
1	-	303	-	5	46	203	682	-	5	30	36	34	2	59	25	16	.63	.64
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	1	-	336	-	-	1	75	13	12	2	62	27	11	.69	.71
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	682	-	2	32	34	34	ND	-	-	-	3.15	3.25
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.94	.95

TABLE 17.8.—*Organic-carbon, C_{15+}-hydrocarbon, visual-*

[*, well not included on organic-carbon, visual-kerogen, or vitrinite-reflectance maps; NP, rock unit not penetrated; ND, not determined or insufficient data; 0, rock unit eroded or not deposited; OS, oil-stained sample; +, incomplete thickness. Rock-unit thicknesses, mean organic-carbon contents, mean C_{15+}-hydrocarbon contents, and visual-kerogen contents are posted on maps. Visual-kerogen contents (in percent): A-H, amorphous and herbaceous; W, woody; I, inertinite]

Well	API No.	Total depth (ft)	Rock unit thickness (ft)	Organic-carbon content (weight percent)										
				Cuttings			Sidewall core			Conventional core			Total samples	Mean value
				Min	Mean	Max	Min	Mean	Max	Min	Mean	Max		
Naval Petroleum Reserve No. 4 program (1944-53)														
North Simpson No. 1-------	50-023-10004	3,774	NP	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 1--------	50-023-10009	3,553	75	-	-	-	-	-	-	1.14	1.20	1.26	2	1.20
South Barrow No. 2--------	50-023-10010	2,505	115	-	-	-	-	-	-	.74	.97	1.12	5	.97
South Barrow No. 3--------	50-023-10011	2,900	925	-	-	-	-	-	-	.19	.75	1.73	37	.75
*South Barrow No. 4--------	50-023-10012	2,538	115	-	-	-	-	-	-	.30	.53	.63	7	.53
*Avak No. 1----------------	50-023-10013	4,020	955	-	-	-	-	-	-	.40	.70	1.36	31	.70
Grandstand No. 1----------	50-057-10001	3,939	NP	-	-	-	-	-	-	-	-	-	-	-
Fish Creek No. 1----------	50-103-10001	7,020	NP	-	-	-	-	-	-	-	-	-	-	-
Oumalik No. 1-------------	50-119-10005	11,872	712+	-	-	-	-	-	-	-	.52	-	1	.52
East Oumalik No. 1--------	50-119-10006	6,035	NP	-	-	-	-	-	-	-	-	-	-	-
Square Lake No. 1---------	50-119-10007	3,987	NP	-	-	-	-	-	-	-	-	-	-	-
*Wolf Creek No. 1----------	50-119-10008	1,500	NP	-	-	-	-	-	-	-	-	-	-	-
Wolf Creek No. 3----------	50-119-10010	3,760	NP	-	-	-	-	-	-	-	-	-	-	-
Titaluk No. 1-------------	50-119-10011	4,020	NP	-	-	-	-	-	-	-	-	-	-	-
Knifeblade No. 1----------	50-119-10012	1,805	NP	-	-	-	-	-	-	-	-	-	-	-
*Knifeblade No. 2A---------	50-119-10014	1,805	NP	-	-	-	-	-	-	-	-	-	-	-
Meade No. 1---------------	50-163-10002	5,305	NP	-	-	-	-	-	-	-	-	-	-	-
Simpson No. 1-------------	50-279-10032	7,002	530	-	-	-	-	-	-	.53	.60	.67	2	.60
Topagoruk No. 1-----------	50-279-10033	10,503	1,780	-	-	-	-	-	-	.20	.82	1.70	7	.82
East Topagoruk No. 1------	50-279-10034	3,589	NP	-	-	-	-	-	-	-	-	-	-	-
Umiat No. 1---------------	50-278-10001	6,005	NP	-	-	-	-	-	-	-	-	-	-	-
*Umiat No. 2---------------	50-287-10002	6,212	NP	-	-	-	-	-	-	-	-	-	-	-
Umiat No. 11--------------	50-287-10011	3,303	NP	-	-	-	-	-	-	-	-	-	-	-
Gubik No. 1---------------	50-287-10013	6,000	NP	-	-	-	-	-	-	-	-	-	-	-
*Gubik No. 2---------------	50-287-10014	4,620	NP	-	-	-	-	-	-	-	-	-	-	-
Kaolak No. 1--------------	50-297-10001	6,952	NP	-	-	-	-	-	-	-	-	-	-	-
Barrow program (1955-81)														
South Barrow No. 9--------	50-023-20003	2,450	100+	-	-	-	-	-	-	.43	.50	.67	6	.50
*South Barrow No. 12-------	50-023-20006	2,285	465	-	-	-	-	-	-	.39	.58	.80	11	.58
*South Barrow No. 13-------	50-023-20008	2,535	235	.75	2.87	6.95	-	-	-	.46	.56	.63	9	1.69
*South Barrow No. 14-------	50-023-20009	2,257	510	.93	1.19	1.72	-	.95	-	-	-	-	6	1.15
South Barrow No. 16-------	50-023-20010	2,400	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 17-------	50-023-20011	2,382	505	.59	.92	1.45	-	-	-	.36	.66	.96	13	.88
*South Barrow No. 19-------	50-023-20012	2,300	450	.82	1.00	1.52	-	-	-	-	.56	-	11	.96
*South Barrow No. 20-------	50-023-20015	2,356	495	-	-	-	-	-	-	-	-	-	0	-
*South Barrow No. 15-------	50-023-20016	2,278	368+	-	-	-	-	-	-	.37	.81	1.57	15	.81
*South Barrow No. 18-------	50-023-20017	2,125	365+	-	-	-	-	-	-	.28	.82	1.30	17	.82
Naval Petroleum Reserve No. 4 program (1973-77)														
Cape Halkett No. 1--------	50-103-20004	9,900	175	-	-	-	-	-	-	-	-	-	0	-
South Harrison Bay No. 1--	50-103-20007	11,290	1,555	.75	1.32	2.53	-	-	-	-	-	-	19	1.32
Atigaru Point No. 1-------	50-103-20008	11,535	870	1.08	1.24	1.67	-	-	-	-	-	-	14	1.24
West Fish Creek No. 1-----	50-103-20009	11,427	1,855	1.06	1.47	2.88	1.14	1.52	2.12	-	-	-	24	1.48
W.T. Foran No. 1---------	50-103-20010	8,864	0	-	-	-	-	-	-	-	-	-	0	-
South Simpson No. 1-------	50-279-20001	8,795	875	.78	1.57	3.95	.34	.68	1.15	-	-	-	27	1.37
National Petroleum Reserve in Alaska program (1977-81)														
Walakpa No. 1-------------	50-023-20013	3,666	1,130	.46	1.15	2.45	-	.68	-	.12	.75	3.10	59	.84
West Dease No. 1----------	50-023-20014	4,173	430	1.58	1.82	2.13	.50	.68	.86	.39	.70	1.50	23	.94
Tulageak No. 1------------	50-023-20018	4,015	805	.42	.73	1.37	-	-	-	.40	.47	.53	19	.66
Walakpa No. 2-------------	50-023-20019	4,360	1,205	2.34	1.26	3.92	.40	.97	1.99	.16	.72	6.78	51	.99
North Kalikpik No. 1------	50-103-20011	7,395	245+	-	1.01	-	1.03	1.04	1.05	.94	1.18	1.42	12	1.14
North Inigok No. 1--------	50-103-20017	10,170	2,400	.77	1.50	2.38	1.35	1.60	1.78	-	-	-	22	1.53
Koluktak No. 1------------	50-119-20001	5,882	NP	-	-	-	-	-	-	-	-	-	-	-
*Lisburne No. 1------------	50-137-20003	17,000	NA	-	-	-	-	-	-	-	-	-	-	-
Awuna No. 1---------------	50-155-20001	11,200	NP	-	-	-	-	-	-	-	-	-	-	-
South Meade No. 1---------	50-163-20001	9,945	2,035	.09	.99	2.14	.82	1.50	2.47	.42	.85	2.34	41	1.03
Kugrua No. 1--------------	50-163-20002	12,588	2,315	.48	1.55	2.58	.58	1.32	2.78	-	.58	-	57	1.46
Kuyanak No. 1-------------	50-163-20003	6,690	1,085	.41	.82	2.08	.51	.87	1.06	.19	.60	1.39	37	.73
Drew Point No. 1----------	50-279-20002	7,946	55	-	1.75	-	-	-	-	-	.54	-	2	1.14
Inigok No. 1--------------	50-279-20003	20,102	2,900	.52	1.99	6.47	.86	1.39	1.86	.53	1.28	2.05	80	1.77
Ikpikpuk No. 1------------	50-279-20004	15,481	2,365	.78	1.88	6.41	1.01	1.74	2.63	2.00	2.39	2.70	51	1.90
East Simpson No. 1--------	50-279-20005	7,739	180	1.37	1.58	1.90	.74	.75	.76	-	-	-	5	1.25
Dalton No. 1--------------	50-279-20006	9,367	0	-	-	-	-	-	-	-	-	-	-	-
East Simpson No. 2--------	50-279-20007	7,504	0	-	-	-	-	-	-	-	-	-	-	-
Seabee No. 1--------------	50-287-20007	15,611	2,411+	1.08	2.95	3.99	-	-	-	.34	3.20	5.23	58	3.02
Tunalik No. 1-------------	50-301-20001	20,335	3,450	.36	1.45	2.71	-	-	-	.17	.99	2.21	77	1.33
Peard No. 1---------------	50-301-20002	10,225	1,815	.84	1.41	2.20	1.26	2.19	3.64	.29	.71	1.56	48	1.30

kerogen, and vitrinite-reflectance data for the Kingak Shale

C_{15+}-hydrocarbon content (ppm)									Visual-kerogen content								Vitrinite reflectance	
Cuttings samples				Core samples				Comments	Cuttings samples				Core samples				Top	Within
No.	Min	Mean	Max	No.	Min	Mean	Max		No.	A-H	W	I	No.	A-H	W	I		
Naval Petroleum Reserve No. 4 program (1944-53)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	1	-	262	-	-	ND	-	-	-	2	71	10	19	.62	.63
-	-	-	-	1	-	238	-	-	ND	-	-	-	2	64	22	14	.53	.53
-	-	-	-	3	155	254	358	OS	ND	-	-	-	6	59	26	15	.55	.60
-	-	-	-	2	-	-	-	OS	-	-	-	-	-	-	-	-	ND	-
-	-	-	-	-	-	-	-	-	ND	-	-	-	3	57	17	26	.51	.51
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	2	185	195	206	-	-	-	-	-	-	-	-	-	1.50	1.65+
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	2	153	317	481	-	ND	-	-	-	2	67	22	11	.63	.65
-	-	-	-	4	77	358	933	-	ND	-	-	-	5	56	16	28	.82	1.00
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Barrow program (1955-81)--Continued																		
-	-	-	-	1	-	-	-	OS	ND	-	-	-	1	75	8	17	ND	ND
-	-	-	-	-	-	-	-	-	ND	-	-	-	3	64	18	18	ND	ND
2	298	310	321	6	127	358	568	OS	3	51	13	36	6	49	28	23	.45	.47+
-	-	-	-	-	-	-	-	-	2	66	19	15	ND	-	-	-	.47	.48
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	2	-	-	-	OS	2	83	8	9	2	73	13	14	.48	.51
2	340	381	422	1	-	-	-	OS	4	70	18	12	1	78	11	11	.54	.55
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	ND	ND
-	-	-	-	2	-	-	-	OS	ND	-	-	-	2	78	17	5	ND	ND
-	-	-	-	3	-	-	-	OS	ND	-	-	-	3	77	17	6	.50	.50
Naval Petroleum Reserve No. 4 program (1973-77)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	ND	ND
2	257	403	548	-	-	-	-	-	7	60	20	20	ND	-	-	-	.60	.66
1	-	385	-	-	-	-	-	-	3	58	21	21	ND	-	-	-	.73	.82
12	477	745	1,064	-	-	-	-	OS	19	87	9	4	4	85	5	10	.50	.54
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	346	489	654	-	-	-	-	-	17	67	20	13	5	61	16	23	.75	.83
National Petroleum Reserve in Alaska program (1977-81)--Continued																		
-	-	-	-	5	62	119	266	OS	2	64	29	7	6	55	26	19	.47	.51
-	-	-	-	1	-	84	-	OS	1	73	18	9	5	53	21	26	.63	.72
-	-	-	-	1	-	259	-	-	3	58	30	12	1	70	20	10	.71	.73
-	-	-	-	2	61	320	578	-	4	80	11	9	8	63	23	14	.50	.56
-	-	-	-	1	-	335	-	-	1	75	17	8	7	68	16	16	.78	.80+
-	-	-	-	-	-	-	-	-	8	76	13	11	6	43	35	22	.60	1.35
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	36	77	156	-	-	-	-	-	11	38	32	30	9	35	30	30	1.60	2.80
3	54	100	128	-	-	-	-	-	13	57	25	18	14	62	19	19	.85	1.22
-	-	-	-	-	-	-	-	-	4	68	25	7	4	57	24	19	.66	.70
-	-	-	-	1	-	52	-	-	ND	-	-	-	1	66	17	17	.63	.64
-	-	-	-	5	95	579	892	-	10	63	17	20	24	47	30	23	.72	2.10
3	188	306	413	-	-	-	-	-	11	53	30	17	6	59	25	16	.68	1.15
-	-	-	-	-	-	-	-	-	ND	-	-	-	1	54	27	18	.62	.63
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	65	107	165	1	-	31	-	-	9	59	23	18	3	69	14	17	1.85	2.65+
2	55	85	114	-	-	-	-	-	13	39	32	29	3	29	32	39	1.85	3.15
4	119	256	508	2	61	428	795	-	7	50	30	22	6	58	24	18	.80	.94

TABLE 17.9.—*Organic-carbon, C_{15+}-hydrocarbon, visual-*

[*, well not included on organic-carbon, visual-kerogen, or vitrinite-reflectance maps; NP, rock unit not penetrated; ND, not determined or insufficient data; 0, rock unit eroded or not deposited; OS, oil-stained sample; +, incomplete thickness. Rock-unit thicknesses, mean organic-carbon contents, mean C_{15+}-hydrocarbon contents, and visual-kerogen contents are posted on maps. Visual-kerogen contents (in percent): A-H, amorphous and herbaceous; W, woody; I, inertinite]

Well	API No.	Total depth (ft)	Rock unit thickness (ft)	Organic-carbon content (weight percent)										
				Cuttings			Sidewall core			Conventional core			Total samples	Mean value
				Min	Mean	Max	Min	Mean	Max	Min	Mean	Max		
Naval Petroleum Reserve No. 4 program (1944-53)														
North Simpson No. 1-------	50-023-10004	3,774	NP	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 1--------	50-023-10009	3,553	530	-	-	-	-	-	-	.38	1.20	1.71	15	1.20
South Barrow No. 2--------	50-023-10010	2,505	420	-	-	-	-	-	-	.84	1.39	1.75	21	1.39
South Barrow No. 3--------	50-023-10011	2,900	400	-	-	-	-	-	-	1.46	2.34	3.41	3	2.34
*South Barrow No. 4--------	50-023-10012	2,538	425	-	-	-	-	-	-	1.78	1.82	1.86	2	1.82
*Avak No. 1---------------	50-023-10013	4,020	1,250	-	-	-	-	-	-	.68	1.31	2.28	15	1.31
Grandstand No. 1----------	50-057-10001	3,939	NP	-	-	-	-	-	-	-	-	-	-	-
Fish Creek No. 1----------	50-103-10001	7,020	NP	-	-	-	-	-	-	-	-	-	-	-
Oumalik No. 1-------------	50-119-10005	11,872	280	-	-	-	-	-	-	-	3.38	-	1	3.38
East Oumalik No. 1--------	50-119-10006	6,035	NP	-	-	-	-	-	-	-	-	-	-	-
Square Lake No. 1---------	50-119-10007	3,987	NP	-	-	-	-	-	-	-	-	-	-	-
*Wolf Creek No. 1----------	50-119-10008	1,500	NP	-	-	-	-	-	-	-	-	-	-	-
Wolf Creek No. 3----------	50-119-10010	3,760	NP	-	-	-	-	-	-	-	-	-	-	-
Titaluk No. 1-------------	50-119-10011	4,020	NP	-	-	-	-	-	-	-	-	-	-	-
Knifeblade No. 1----------	50-119-10012	1,805	NP	-	-	-	-	-	-	-	-	-	-	-
*Knifeblade No. 2A---------	50-119-10014	1,805	NP	-	-	-	-	-	-	-	-	-	-	-
Meade No. 1---------------	50-163-10002	5,305	NP	-	-	-	-	-	-	-	-	-	-	-
Simpson No. 1-------------	50-279-10032	7,002	210	-	-	-	-	-	-	1.23	1.90	2.64	4	1.90
Topagoruk No. 1-----------	50-279-10033	10,503	200	-	-	-	-	-	-	1.92	2.45	2.98	2	2.45
East Topagoruk No. 1------	50-279-10034	3,589	NP	-	-	-	-	-	-	-	-	-	-	-
Umiat No. 1---------------	50-278-10001	6,005	NP	-	-	-	-	-	-	-	-	-	-	-
*Umiat No. 2---------------	50-287-10002	6,212	NP	-	-	-	-	-	-	-	-	-	-	-
Umiat No. 11--------------	50-287-10011	3,303	NP	-	-	-	-	-	-	-	-	-	-	-
Gubik No. 1---------------	50-287-10013	6,000	NP	-	-	-	-	-	-	-	-	-	-	-
*Gubik No. 2---------------	50-287-10014	4,620	NP	-	-	-	-	-	-	-	-	-	-	-
Kaolak No. 1--------------	50-297-10001	6,952	NP	-	-	-	-	-	-	-		-	-	-
Barrow program (1955-81)														
South Barrow No. 9--------	50-023-20003	2,450	415	-	-	-	-	-	-	1.21	1.38	1.52	11	1.38
*South Barrow No. 12-------	50-023-20006	2,285	415	-	-	-	-	-	-	-	-	-	0	-
*South Barrow No. 13-------	50-023-20008	2,535	535	.99	1.28	1.61	-	-	-	.80	1.53	1.93	12	1.41
*South Barrow No. 14-------	50-023-20009	2,257	360	1.21	1.59	2.13	-	1.85	-	-	-	-	4	1.66
South Barrow No. 16-------	50-023-20010	2,400	410	1.55	2.58	3.62	.63	1.48	2.31	-	-	-	10	1.70
South Barrow No. 17-------	50-023-20011	2,382	360	.04	1.87	3.05	-	-	-	-	-	-	8	1.87
*South Barrow No. 19-------	50-023-20012	2,300	395	1.41	1.90	2.53	-	-	-	-	-	-	7	1.90
*South Barrow No. 20-------	50-023-20015	2,356	425	-	-	-	-	-	-	-	-	-	0	-
*South Barrow No. 15-------	50-023-20016	2,278	430	-	-	-	-	-	-	.96	1.46	1.91	10	1.46
*South Barrow No. 18-------	50-023-20017	2,125	385	-	-	-	-	-	-	.54	1.46	2.89	17	1.46
Naval Petroleum Reserve No. 4 program (1973-77)														
Cape Halkett No. 1--------	50-103-20004	9,900	275	-	-	-	-	-	-	-	-	-	0	-
South Harrison Bay No. 1--	50-103-20007	11,290	0	-	-	-	-	-	-	-	-	-	-	-
Atigaru Point No. 1-------	50-103-20008	11,535	40	-	1.25	-	-	-	-	-	-	-	1	1.25
West Fish Creek No. 1-----	50-103-20009	11,427	40	-	-	-	-	-	-	-	-	-	0	-
W.T. Foran No. 1----------	50-103-20010	8,864	205	2.82	2.96	3.16	-	-	-	-	1.28	-	4	2.54
South Simpson No. 1-------	50-279-20001	8,795	210	1.56	1.93	2.37	-	-	-	-	-	-	4	1.93
National Petroleum Reserve in Alaska program (1977-81)														
Walakpa No. 1-------------	50-023-20013	3,666	390	1.55	1.93	2.73	-	-	-	.54	2.12	4.12	40	2.08
West Dease No. 1----------	50-023-20014	4,173	460	1.29	2.09	2.49	.79	1.40	1.91	-	-	-	10	1.81
Tulageak No. 1------------	50-023-20018	4,015	450	1.38	1.51	1.67	-	1.64	-	.25	1.08	2.05	15	1.43
Walakpa No. 2-------------	50-023-20019	4,360	435	1.06	1.80	2.36	2.04	2.32	2.61	.15	.95	4.98	17	1.51
North Kalıkpik No. 1------	50-103-20011	7,395	255	2.19	2.58	2.98	2.75	3.00	3.25	.86	1.86	3.24	11	2.20
North Inigok No. 1--------	50-103-20017	10,170	265	1.41	2.06	2.84	-	4.99	-	3.42	4.59	6.07	11	3.48
Koluktak No. 1------------	50-119-20001	5,882	NP	-	-	-	-	-	-	-	-	-	-	-
*Lisburne No. 1------------	50-137-20003	17,000	NA	-	-	-	-	-	-	-	-	-	-	-
Awuna No. 1---------------	50-155-20001	11,200	NP	-	-	-	-	-	-	-	-	-	-	-
South Meade No. 1---------	50-163-20001	9,945	260	.19	.39	.97	2.50	3.06	4.14	-	-	-	8	1.39
Kugrua No. 1--------------	50-163-20002	12,588	310	1.17	1.80	2.72	.22	2.01	3.14	.45	.47	.50	20	1.69
Kuyanak No. 1-------------	50-163-20003	6,690	520	1.22	2.38	2.90	.53	1.71	2.72	.08	1.72	4.35	52	1.84
Drew Point No. 1----------	50-279-20002	7,946	200	1.78	2.31	2.84	2.28	3.67	11.82	-	-	-	15	3.49
Inigok No. 1--------------	50-279-20003	20,102	220	2.50	2.76	2.90	-	-	-	-	-	-	3	2.76
Ikpikpuk No. 1------------	50-279-20004	15,481	250	.69	1.48	2.12	.65	1.84	3.92	1.17	2.61	4.77	14	1.87
East Simpson No. 1--------	50-279-20005	7,739	215	1.48	1.80	1.99	-	-	-	-	-	-	3	1.80
Dalton No. 1--------------	50-279-20006	9,367	160	1.66	2.36	3.43	-	-	-	-	3.95	-	4	2.76
East Simpson No. 2--------	50-279-20007	7,504	200	1.16	2.06	2.75	.83	2.24	3.73	1.07	3.12	4.30	15	2.53
Seabee No. 1--------------	50-287-20007	15,611	200	1.39	1.83	2.12	-	-	-	-	-	-	3	1.83
Tunalik No. 1-------------	50-301-20001	20,335	265	2.45	2.96	3.47	-	-	-	1.61	2.57	5.21	12	2.73
Peard No. 1---------------	50-301-20002	10,225	330	1.14	1.77	2.09	-	-	-	2.20	2.91	3.63	8	2.06

kerogen, and vitrinite-reflectance data for the pebble shale unit

C_{15+}-hydrocarbon content (ppm)									Visual-kerogen content								Vitrinite reflectance	
Cuttings samples				Core samples				Comments	Cuttings samples				Core samples				Top	Within
No.	Min	Mean	Max	No.	Min	Mean	Max		No.	A-H	W	I	No.	A-H	W	I		
Naval Petroleum Reserve No. 4 program (1944-53)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	1	-	257	-	-	ND	-	-	-	4	63	15	22	.60	.62
-	-	-	-	3	77	142	194	-	ND	-	-	-	4	61	23	16	.52	.53
-	-	-	-	2	286	319	352	-	ND	-	-	-	3	70	18	12	.54	.55
-	-	-	-	1	-	300	-	-	ND	-	-	-	1	63	25	13	ND	ND
-	-	-	-	-	-	-	-	-	ND	-	-	-	3	89	0	11	.51	.51
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	2	106	109	111	-	-	-	-	-	-	-	-	-	1.45	1.50
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	3	331	446	631	-	ND	-	-	-	3	70	17	13	.63	.63
-	-	-	-	2	483	592	701	-	ND	-	-	-	2	65	15	20	.82	.82
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Barrow program (1955-81)--Continued																		
-	-	-	-	2	133	137	140	-	ND	-	-	-	2	56	29	15	ND	ND
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	ND	ND
3	361	438	500	7	65	151	234	OS	5	62	12	26	6	53	27	20	.40	.45
-	-	-	-	-	-	-	-	-	1	64	18	18	ND	-	-	-	.46	.47
-	-	-	-	-	-	-	-	-	1	50	25	25	ND	-	-	-	.46	.50
1	-	552	-	-	-	-	-	-	4	65	23	12	ND	-	-	-	.46	.48
3	-	-	-	-	-	-	-	OS	3	74	16	10	ND	-	-	-	.52	.54
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	ND	ND
-	-	-	-	1	-	358	-	-	ND	-	-	-	1	80	20	0	ND	ND
-	-	-	-	2	216	480	744	-	ND	-	-	-	2	84	12	4	.50	.50
Naval Petroleum Reserve No. 4 program (1973-77)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	ND	ND
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.60	.60
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.72	.73
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.50	.50
2	535	594	652	-	-	-	-	OS	3	62	23	15	1	100	0	0	.52	.54
4	502	813	985	-	-	-	-	-	4	65	24	11	ND	-	-	-	.73	.75
National Petroleum Reserve in Alaska program (1977-81)--Continued																		
1	-	545	-	2	157	192	226	OS	2	68	24	8	3	76	17	7	.46	.47
3	151	227	284	-	-	-	-	-	4		20	18	4	66		11	.62	.63
-	-	-	-	1	-	277	-	-	2	61	29	10	2	64	20	16	.70	.71
-	-	-	-	1	-	491	-	-	1	58	17	25	3	82	16	2	.49	.50
-	-	-	-	2	-	-	-	OS	4	82	13	5	2	68	16	16	.75	.78
-	-	-	-	1	-	-	-	OS	1	63	25	13	2	76	22	4	.59	.60
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	107	125	143	-	-	-	-	OS	3	44	20	26	3	45	29	26	1.50	1.60
1	-	167	-	-	-	-	-	-	3	49	27	24	9	53	25	22	.84	.85
-	-	-	-	-	-	-	-	-	1	58	42	0	6	86	9	5	.64	.66
2	417	469	520	-	-	-	-	-	2	64	18	18	11	65	72	13	.62	.63
-	-	-	-	-	-	-	-	-	1	55	11	33	ND	-	-	-	.71	.72
2	136	565	994	-	-	-	-	-	1	42	33	25	8	46	30	24	.67	.68
2	422	488	554	-	-	-	-	-	2	57	25	18	ND	-	-	-	.61	.62
1	-	120	-	1	-	472	-	-	2	61	22	17	1	59	33	8	.60	.62
-	-	-	-	1	-	1,046	-	-	1	50	33	17	5	55	25	20	.69	.69
-	-	-	-	-	-	-	-	-	1	28	36	36	ND	-	-	-	1.80	1.85
1	-	47	-	-	-	-	-	-	2	67	19	14	2	26	38	38	1.80	1.85
2	193	203	212	1	-	400	-	-	2	63	25	12	1	66	25	8	.77	.80

TABLE 17.10.—*Organic-carbon, C_{15+}-hydrocarbon, visual-*

[*, well not included on organic-carbon, visual-kerogen, or vitrinite-reflectance maps; NP, rock unit not penetrated; ND, not determined or insufficient data; 0, rock unit eroded or not deposited; OS, oil-stained sample; +, incomplete thickness. Rock-unit thicknesses, mean organic-carbon contents, mean C_{15+}-hydrocarbon contents, and visual-kerogen contents are posted on maps. Visual-kerogen contents (in percent): A-H, amorphous and herbaceous; W, woody; I, inertinite]

Well	API No.	Total depth (ft)	Rock unit thickness (ft)	Organic-carbon content (weight percent)										
				Cuttings			Sidewall core			Conventional core			Total samples	Mean value
				Min	Mean	Max	Min	Mean	Max	Min	Mean	Max		
Naval Petroleum Reserve No. 4 program (1944-53)														
North Simpson No. 1-------	50-023-10004	3,774	1,004+	-	-	-	-	-	-	1.00	1.23	1.43	13	1.23
South Barrow No. 1--------	50-023-10009	3,553	2,110	-	-	-	-	-	-	.93	1.34	1.69	6	1.34
South Barrow No. 2--------	50-023-10010	2,505	1,830	-	-	-	-	-	-	.97	1.33	1.92	37	1.33
South Barrow No. 3--------	50-023-10011	2,900	1,195	-	-	-	-	-	-	.80	1.14	1.43	9	1.14
*South Barrow No. 4--------	50-023-10012	2,538	1,815	-	-	-	-	-	-	1.21	1.32	1.49	3	1.32
*Avak No. 1----------------	50-023-10013	4,020	0	-	-	-	-	-	-	-	-	-	-	-
Grandstand No. 1----------	50-057-10001	3,939	2,869+	-	-	-	-	-	-	.38	1.01	2.18	30	1.01
Fish Creek No. 1----------	50-103-10001	7,020	2,910+	-	-	-	-	-	-	.69	1.09	1.37	29	1.09
Oumalik No. 1-------------	50-119-10005	11,872	8,110	-	-	-	-	-	-	.54	1.24	2.49	45	1.24
East Oumalik No. 1--------	50-119-10006	6,035	3,085+	-	-	-	-	-	-	.92	1.22	1.49	13	1.22
Square Lake No. 1---------	50-119-10007	3,987	47+	-	-	-	-	-	-	.91	.91	.92	2	.91
*Wolf Creek No. 1----------	50-119-10008	1,500	NP	-	-	-	-	-	-	-	-	-	-	-
Wolf Creek No. 3----------	50-119-10010	3,760	185+	-	-	-	-	-	-	-	1.27	-	1	1.27
Titaluk No. 1-------------	50-119-10011	4,020	520+	-	-	-	-	-	-	.28	.98	2.52	7	.98
Knifeblade No. 1----------	50-119-10012	1,805	NP	-	-	-	-	-	-	-	-	-	-	-
*Knifeblade No. 2A---------	50-119-10014	1,805	NP	-	-	-	-	-	-	-	-	-	-	-
Meade No. 1---------------	50-163-10002	5,305	1,855+	-	-	-	-	-	-	.19	.87	1.35	10	.87
Simpson No. 1-------------	50-279-10032	7,002	4,310	-	-	-	-	-	-	.44	1.18	1.56	47	1.18
Topagoruk No. 1-----------	50-279-10033	10,503	4,535	-	-	-	-	-	-	.38	1.19	2.44	26	1.19
East Topagoruk No. 1------	50-279-10034	3,589	1,309+	-	-	-	-	-	-	1.01	1.30	1.76	8	1.30
Umiat No. 1---------------	50-278-10001	6,005	3,165+	-	-	-	-	-	-	-	-	-	0	-
*Umiat No. 2---------------	50-287-10002	6,212	5,152+	-	-	-	-	-	-	.45	1.28	3.82	28	1.28
Umiat No. 11--------------	50-287-10011	3,303	223+	-	-	-	-	-	-	-	-	-	0	-
Gubik No. 1---------------	50-287-10013	6,000	2,025+	-	-	-	-	-	-	.81	1.01	1.20	13	1.01
*Gubik No. 2---------------	50-287-10014	4,620	235+	-	-	-	-	-	-	1.07	1.11	1.15	4	1.11
Kaolak No. 1--------------	50-297-10001	6,952	1,747+	-	-	-	-	-	-	.19	1.40	2.95	12	1.40
Barrow program (1955-81)														
South Barrow No. 9--------	50-023-20003	2,450	1,835	-	-	-	-	-	-	-	-	-	0	-
*South Barrow No. 12-------	50-023-20006	2,285	1,220	-	-	-	-	-	-	-	-	-	0	-
*South Barrow No. 13-------	50-023-20008	2,535	1,605	.58	1.16	1.60	-	-	-	-	-	-	16	1.16
*South Barrow No. 14-------	50-023-20009	2,257	1,285	.48	1.33	1.90	-	-	-	-	-	-	11	1.33
South Barrow No. 16-------	50-023-20010	2,400	1,850	.47	1.08	2.03	-	-	-	-	-	-	10	1.08
South Barrow No. 17-------	50-023-20011	2,382	1,330	.02	1.38	2.58	-	-	-	-	-	-	24	1.38
*South Barrow No. 19-------	50-023-20012	2,300	1,270	.36	1.05	3.49	-	-	-	-	-	-	17	1.05
*South Barrow No. 20-------	50-023-20015	2,356	1,235	-	-	-	-	-	-	-	-	-	0	-
*South Barrow No. 15-------	50-023-20016	2,278	1,405	-	-	-	-	-	-	.60	1.30	2.00	17	1.30
*South Barrow No. 18-------	50-023-20017	2,125	1,300	-	-	-	-	-	-	1.26	1.49	1.64	4	1.49
Naval Petroleum Reserve No. 4 program (1973-77)														
Cape Halkett No. 1--------	50-103-20004	9,900	3,045	.46	1.04	2.44	-	-	-	-	-	-	11	1.04
South Harrison Bay No. 1--	50-103-20007	11,290	3,070	.73	1.03	1.35	-	-	-	.79	1.10	1.35	38	1.03
Atigaru Point No. 1-------	50-103-20008	11,535	2,880	.66	1.17	2.47	.47	1.09	1.76	-	-	-	50	1.15
West Fish Creek No. 1-----	50-103-20009	11,427	3,365	.67	.96	1.28	.53	.83	1.13	-	-	-	36	.95
W.T. Foran No. 1----------	50-103-20010	8,864	2,960	.38	.89	1.56	-	-	-	-	-	-	29	.89
South Simpson No. 1-------	50-279-20001	8,795	4,405	.20	2.03	1.49	.91	1.20	1.43	-	-	-	54	1.98
National Petroleum Reserve in Alaska program (1977-81)														
Walakpa No. 1-------------	50-023-20013	3,666	1,650	.38	1.06	2.39	-	-	-	.58	.91	1.16	32	1.03
West Dease No. 1----------	50-023-20014	4,173	2,755	.92	1.51	4.16	.61	1.09	1.47	.48	1.08	1.36	72	1.37
Tulageak No. 1------------	50-023-20018	4,015	2,405	.60	1.06	1.95	.67	1.20	1.49	-	-	-	51	1.08
Walakpa No. 2-------------	50-023-20019	4,360	2,155	.36	.61	1.51	-	-	-	-	-	-	41	.61
North Kalikpik No. 1------	50-103-20011	7,395	3,425	.45	1.39	2.34	1.26	1.70	3.33	.61	1.16	1.45	70	1.37
North Inigok No. 1--------	50-103-20017	10,170	4,120	.50	.98	1.62	.61	1.00	1.28	.97	1.13	1.13	93	.99
Koluktak No. 1------------	50-119-20001	5,882	1,672+	.72	1.15	1.53	.98	1.31	1.84	-	-	-	30	1.16
*Lisburne No. 1------------	50-137-20003	17,000	0	-	-	-	-	-	-	-	-	-	-	-
Awuna No. 1---------------	50-155-20001	11,200	2,930	.84	1.30	1.90	-	-	-	.29	.75	1.28	65	1.23
South Meade No. 1---------	50-163-20001	9,945	3,985	.14	.97	1.80	1.22	1.24	1.26	.40	1.19	1.80	87	1.00
Kugrua No. 1--------------	50-163-20002	12,588	4,560	.72	1.11	1.52	.93	1.24	1.50	-	-	-	91	1.13
Kuyanak No. 1-------------	50-163-20003	6,690	3,390	.50	1.01	2.11	1.09	1.21	1.44	-	-	-	71	1.03
Drew Point No. 1----------	50-279-20002	7,946	3,500	.66	1.60	3.92	.84	1.77	3.44	.36	1.18	1.83	39	1.48
Inigok No. 1--------------	50-279-20003	20,102	5,105	.90	1.47	12.23	.32	1.37	6.31	-	-	-	99	1.45
Ikpikpuk No. 1------------	50-279-20004	15,481	4,280	.53	.90	2.09	.49	.95	1.28	.38	.97	1.42	100	.92
East Simpson No. 1--------	50-279-20005	7,739	3,675	.81	1.26	5.26	.70	1.20	1.46	.39	.86	1.14	76	1.24
Dalton No. 1--------------	50-279-20006	9,367	3,340	.47	1.13	3.07	.92	1.43	1.99	.83	1.21	1.39	77	1.17
East Simpson No. 2--------	50-279-20007	7,504	3,625	.73	1.41	6.86	.77	1.13	1.47	.40	1.72	4.39	77	1.41
Seabee No. 1--------------	50-287-20007	15,611	6,245	.63	1.13	2.72	1.08	1.18	1.25	.74	1.05	1.32	114	1.13
Tunalik No. 1-------------	50-301-20001	20,335	4,385	.72	1.22	3.63	1.21	1.31	1.41	1.06	1.29	1.44	99	1.24
Peard No. 1---------------	50-301-20002	10,225	3,725	.81	1.22	2.97	-	-	-	.39	1.13	1.59	84	1.20

kerogen, and vitrinite-reflectance data for the Torok Formation

C_{15+}-hydrocarbon content (ppm)									Visual-kerogen content								Vitrinite reflectance	
Cuttings samples				Core samples				Comments	Cuttings samples				Core samples				Top	Within
No.	Min	Mean	Max	No.	Min	Mean	Max		No.	A-H	W	I	No.	A-H	W	I		
Naval Petroleum Reserve No. 4 program (1944-53)--Continued																		
-	-	-	-	4	222	260	296	-	ND	-	-	-	4	60	29	11	.53	.60+
-	-	-	-	-	-	-	-	-	ND	-	-	-	6	60	22	18	.48	.60
-	-	-	-	4	164	201	240	-	ND	-	-	-	9	57	25	18	.50	.52
-	-	-	-	2	233	399	564	-	ND	-	-	-	3	66	19	15	.50	.54
-	-	-	-	1	-	200	-	-	ND	-	-	-	1	63	13	25	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	ND	-	-	-	4	39	34	27	.56	.80+
-	-	-	-	23	126	198	314	OS	ND	-	-	-	25	49	27	24	.48	.64+
-	-	-	-	32	70	219	461	OS	ND	-	-	-	39	53	21	26	.56	1.45
-	-	-	-	-	-	-	-	-	ND	-	-	-	5	52	30	18	.56	.72+
-	-	-	-	-	-	-	-	-	ND	-	-	-	1	58	25	17	.58	.58+
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	1	-	240	-	-	ND	-	-	-	1	50	0	50	.65	.65+
-	-	-	-	-	-	-	-	-	ND	-	-	-	2	39	28	23	.66	.67+
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	3	292	330	382	-	ND	-	-	-	6	61	21	18	.67	1.05+
-	-	-	-	31	163	334	521	OS	ND	-	-	-	15	60	28	12	.57	.63
-	-	-	-	29	40	162	445	-	ND	-	-	-	21	56	18	26	.49	.82
-	-	-	-	-	-	-	-	-	ND	-	-	-	3	56	31	13	.53	.58+
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	9	158	234	297	-	ND	-	-	-	20	51	24	25	.51	.76+
-	-	-	-	-	-	-	-	-	ND	-	-	-	1	50	25	23	.51	.51+
-	-	-	-	-	-	-	-	-	ND	-	-	-	4	46	32	22	.51	.60+
-	-	-	-	-	-	-	-	-	ND	-	-	-	1	40	40	20	.51	.52+
-	-	-	-	3	113	174	228	-	ND	-	-	-	6	46	32	22	.93	1.15+
Barrow program (1955-81)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	ND	ND
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	ND	ND
8	223	360	465	-	-	-	-	OS	9	53	19	28	ND	-	-	-	.29	.40
-	-	-	-	-	-	-	-	-	4	64	18	18	ND	-	-	-	.42	.46
-	-	-	-	-	-	-	-	-	5	59	22	19	ND	-	-	-	.32	.46
-	-	-	-	-	-	-	-	-	6	50	32	18	ND	-	-	-	.40	.46
3	63	214	399	-	-	-	-	-	7	58	21	21	ND	-	-	-	.47	.52
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	ND	ND
-	-	-	-	1	-	110	-	OS	ND	-	-	-	2	66	29	5	ND	ND
-	-	-	-	-	-	-	-	OS	ND	-	-	-	1	80	20	0	-	.50
Naval Petroleum Reserve No. 4 program (1973-77)--Continued																		
-	-	-	-	-	-	-	-	-	2	39	31	30	ND	-	-	-	.38	ND
-	-	-	-	1	-	477	-	OS	14	54	25	21	2	40	30	30	.44	.60
1	-	117	-	-	-	-	-	-	7	50	28	22	8	54	19	27	.50	.72
24	85	272	490	-	-	-	-	OS	34	59	24	17	2	54	23	23	.44	.50
-	-	-	-	-	-	-	-	-	13	55	28	17	ND	-	-	-	.41	.52
2	228	232	236	-	-	-	-	OS	42	59	24	17	3	-	-	-	.48	.73
National Petroleum Reserve in Alaska program (1977-81)--Continued																		
-	-	-	-	3	136	279	424	-	5	53	29	18	4	46	34	20	.41	.46
1	-	136	-	3	104	144	204	-	9	52	30	18	12	53	29	18	.38	.62
-	-	-	-	-	-	-	-	-	8	55	28	17	5	45	33	22	.65	.70
-	-	-	-	-	-	-	-	-	8	65	23	12	ND	-	-	-	.40	.49
-	-	-	-	4	132	168	192	-	16	53	25	22	16	47	29	24	.50	.75
-	-	-	-	2	123	143	169	-	13	47	33	20	10	63	25	12	.40	.59
-	-	-	-	-	-	-	-	-	6	65	23	12	3	49	32	19	.40	.53+
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	2	299	400	499	-	32	50	28	22	2	65	30	5	.60	.85
4	159	194	230	4	99	138	208	-	19	55	24	21	10	49	27	24	.73	1.5
6	99	153	298	-	-	-	-	-	21	43	31	26	9	52	26	22	.57	.84
-	-	-	-	-	-	-	-	-	12	50	31	19	7	66	25	9	.53	.64
3	135	238	436	5	77	98	140	-	9	59	20	21	17	53	24	23	.49	.62
-	-	-	-	8	72	131	222	OS	17	47	30	23	17	42	30	23	.50	.71
-	-	-	-	7	32	88	221	-	17	39	34	27	12	54	27	19	.48	.67
5	41	109	161	-	-	-	-	-	13	48	35	17	6	40	34	26	.46	.61
3	102	137	185	2	69	81	93	-	12	43	31	26	5	44	35	21	.47	.60
-	-	-	-	-	-	-	-	coal	12	61	26	13	8	49	32	19	.44	.68
3	117	232	437	5	131	311	423	coal	41	43	34	23	14	52	27	21	.49	.80
3	74	122	178	2	186	218	249	-	17	42	30	28	11	46	31	23	.90	1.80
2	51	59	67	5	108	180	313	OS	15	43	34	23	5	49	29	22	.56	.77

TABLE 17.11.—*Organic-carbon, C_{15+}-hydrocarbon, visual-*

[*, well not included on organic-carbon, visual-kerogen, or vitrinite-reflectance maps; NP, rock unit not penetrated; ND, not determined or insufficient data; 0, rock unit eroded or not deposited; OS, oil-stained sample; +, incomplete thickness. Rock-unit thicknesses, mean organic-carbon contents, mean C_{15+}-hydrocarbon contents, and visual-kerogen contents are posted on maps. Visual-kerogen contents (in percent): A-H, amorphous and herbaceous; W, woody; I, inertinite]

Well	API No.	Total depth (ft)	Rock unit thickness (ft)	Organic-carbon content (weight percent)										
				Cuttings			Sidewall core			Conventional core			Total samples	Mean value
				Min	Mean	Max	Min	Mean	Max	Min	Mean	Max		
Naval Petroleum Reserve No. 4 program (1944-53)														
North Simpson No. 1	50-023-10004	3,774	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 1	50-023-10009	3,553	620	-	-	-	-	-	-	-	-	-	0	-
South Barrow No. 2	50-023-10010	2,505	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 3	50-023-10011	2,900	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 4	50-023-10012	2,538	0	-	-	-	-	-	-	-	-	-	-	-
*Avak No. 1	50-023-10013	4,020	0	-	-	-	-	-	-	-	-	-	-	-
Grandstand No. 1	50-057-10001	3,939	960	-	-	-	-	-	-	.12	1.69	8.10	19	1.69
Fish Creek No. 1	50-103-10001	7,020	1,220	-	-	-	-	-	-	.32	1.10	1.68	15	1.10
Oumalik No. 1	50-119-10005	11,872	2,740	-	-	-	-	-	-	.28	.97	3.68	16	.97
East Oumalik No. 1	50-119-10006	6,035	2,900	-	-	-	-	-	-	.22	1.08	2.57	16	1.08
Square Lake No. 1	50-119-10007	3,987	2,310	-	-	-	-	-	-	.14	2.03	32.26	46	2.03
*Wolf Creek No. 1	50-119-10008	1,500	1,490+	-	-	-	-	-	-	.50	.99	1.98	5	.99
Wolf Creek No. 3	50-119-10010	3,760	3,545	-	-	-	-	-	-	.15	.89	7.57	42	.89
Titaluk No. 1	50-119-10011	4,020	3,460	-	-	-	-	-	-	.23	4.54	44.28	25	4.54
Knifeblade No. 1	50-119-10012	1,805	1,799+	-	-	-	-	-	-	.17	.60	1.45	16	.60
*Knifeblade No. 2A	50-119-10014	1,805	1,790+	-	-	-	-	-	-	.19	.48	1.14	16	.48
Meade No. 1	50-163-10002	5,305	3,425	-	-	-	-	-	-	.22	2.03	16.51	14	2.03
Simpson No. 1	50-279-10032	7,002	955	-	-	-	-	-	-	.55	1.32	2.37	34	1.32
Topagoruk No. 1	50-279-10033	10,503	2,100	-	-	-	-	-	-	.80	1.18	2.01	6	1.18
East Topagoruk No. 1	50-279-10034	3,589	2,190	-	-	-	-	-	-	.31	1.16	2.44	18	1.16
Umiat No. 1	50-278-10001	6,005	1,925	-	-	-	-	-	-	.30	1.09	1.76	5	1.09
*Umiat No. 2	50-287-10002	6,212	990	-	-	-	-	-	-	.13	.90	3.18	33	.90
Umiat No. 11	50-287-10011	3,303	1,040	-	-	-	-	-	-	.32	1.50	4.06	14	1.50
Gubik No. 1	50-287-10013	6,000	905	-	-	-	-	-	-	.10	.77	2.02	14	.77
*Gubik No. 2	50-287-10014	4,620	1,055	-	-	-	-	-	-	.12	.73	2.01	35	.73
Kaolak No. 1	50-297-10001	6,952	5,095	-	-	-	-	-	-	.25	9.52	69.79	41	9.52
Barrow program (1955-81)														
South Barrow No. 9	50-023-20003	2,450	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 12	50-023-20006	2,285	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 13	50-023-20008	2,535	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 14	50-023-20009	2,257	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 16	50-023-20010	2,400	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 17	50-023-20011	2,382	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 19	50-023-20012	2,300	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 20	50-023-20015	2,356	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 15	50-023-20016	2,278	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 18	50-023-20017	2,125	0	-	-	-	-	-	-	-	-	-	-	-
Naval Petroleum Reserve No. 4 program (1973-77)														
Cape Halkett No. 1	50-103-20004	9,900	1,120	.41	1.11	2.86	-	-	-	-	-	-	5	1.11
South Harrison Bay No. 1	50-103-20007	11,290	1,000	.29	.86	1.57	-	-	-	-	-	-	14	.86
Atigaru Point No. 1	50-103-20008	11,535	930	.92	1.15	1.40	1.22	1.35	1.46	-	-	-	17	1.19
West Fish Creek No. 1	50-103-20009	11,427	1,365	.65	1.21	2.04	.82	1.07	1.33	-	-	-	9	1.18
W.T. Foran No. 1	50-103-20010	8,864	900	.36	.88	1.26	-	-	-	-	-	-	13	.88
South Simpson No. 1	50-279-20001	8,795	1,830	.69	5.77	52.36	-	-	-	-	-	-	15	5.77
National Petroleum Reserve in Alaska program (1977-81)														
Walakpa No. 1	50-023-20013	3,666	0	-	-	-	-	-	-	-	-	-	-	-
West Dease No. 1	50-023-20014	4,173	0	-	-	-	-	-	-	-	-	-	-	-
Tulageak No. 1	50-023-20018	4,015	0	-	-	-	-	-	-	-	-	-	-	-
Walakpa No. 2	50-023-20019	4,360	0	-	-	-	-	-	-	-	-	-	-	-
North Kalikpik No. 1	50-103-20011	7,395	1,075	.60	1.32	3.12	-	-	-	-	-	-	9	1.32
North Inigok No. 1	50-103-20017	10,170	1,345	.59	2.41	8.18	.11	.52	1.00	-	-	-	31	1.86
Koluktak No. 1	50-119-20001	5,882	4,135	.49	3.21	20.75	1.02	1.12	1.34	-	-	-	73	3.07
*Lisburne No. 1	50-137-20003	17,000	0	-	-	-	-	-	-	-	-	-	-	-
Awuna No. 1	50-155-20001	11,200	0	-	-	-	-	-	-	-	-	-	-	-
South Meade No. 1	50-163-20001	9,945	2,410	.16	2.40	10.79	-	-	-	-	-	-	18	2.40
Kugrua No. 1	50-163-20002	12,588	2,250	.31	3.12	18.03	-	-	-	-	-	-	15	3.12
Kuyanak No. 1	50-163-20003	6,690	1,175	.27	2.97	22.83	-	-	-	-	-	-	21	2.97
Drew Point No. 1	50-279-20002	7,946	1,970	.74	1.42	3.13	-	-	-	-	-	-	11	1.42
Inigok No. 1	50-279-20003	20,102	1,685	.26	1.97	9.13	-	-	-	.42	.86	1.30	40	1.72
Ikpikpuk No. 1	50-279-20004	15,481	2,850	.37	6.25	37.44	-	-	-	.40	.61	.80	43	5.60
East Simpson No. 1	50-279-20005	7,739	2,165	.52	3.48	25.82	-	-	-	1.14	1.32	1.65	39	3.32
Dalton No. 1	50-279-20006	9,367	1,480	.71	1.19	2.20	1.41	1.42	1.44	.92	1.09	1.26	23	1.20
East Simpson No. 2	50-279-20007	7,504	1,655	.52	2.82	14.32	.27	1.26	3.40	.29	.56	1.81	48	2.12
Seabee No. 1	50-287-20007	15,611	1,015	.45	.89	1.64	-	-	-	-	-	-	18	.89
Tunalik No. 1	50-301-20001	20,335	6,150	.73	9.86	60.11	.86	1.38	1.82	1.13	3.07	13.23	132	8.57
Peard No. 1	50-301-20002	10,225	2,390	1.16	8.85	50.06	-	-	-	-	-	-	42	8.85

kerogen, and vitrinite-reflectance data for the Nanushuk Group

C_{15+}-hydrocarbon content (ppm)									Visual-kerogen content								Vitrinite reflectance	
Cuttings samples				Core samples				Comments	Cuttings samples				Core samples				Top	Bottom
No.	Min	Mean	Max	No.	Min	Mean	Max		No.	A-H	W	I	No.	A-H	W	I		
Naval Petroleum Reserve No. 4 program (1944-53)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.46	.48
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	ND	-	-	-	1	45	27	27	.50	.56
-	-	-	-	9	128	209	468	OS	ND	-	-	-	1	52	26	22	.42	.48
-	-	-	-	12	66	128	220	OS	ND	-	-	-	14	59	23	18	.41	.56
-	-	-	-	-	-	-	-	-	ND	-	-	-	4	50	37	13	.45	.56
-	-	-	-	5	97	209	275	-	ND	-	-	-	9	61	25	14	.52	.58
-	-	-	-	2	194	218	242	-	ND	-	-	-	3	60	15	25	.53	.60+
-	-	-	-	3	261	407	677	-	ND	-	-	-	8	40	21	39	.46	.65
-	-	-	-	-	-	-	-	-	ND	-	-	-	5	46	26	28	.57	.66
-	-	-	-	2	272	254	236	-	ND	-	-	-	6	65	20	15	.50	.60+
-	-	-	-	2	227	233	239	-	ND	-	-	-	3	62	19	19	.62	.64+
-	-	-	-	2	211	228	244	coal	ND	-	-	-	6	52	26	22	.53	.67
-	-	-	-	17	171	387	678	OS	-	-	-	-	-	-	-	-	.55	.57
-	-	-	-	5	88	155	199	-	ND	-	-	-	5	68	13	19	.40	.49
-	-	-	-	-	-	-	-	-	ND	-	-	-	5	48	25	27	.46	.53
-	-	-	-	1	-	423	-	-	ND	-	-	-	2	68	20	12	.48	-
-	-	-	-	2	211	227	243	-	ND	-	-	-	5	61	20	19	.50	.51
-	-	-	-	1	-	459	-	OS	ND	-	-	-	6	45	28	27	.48	.51
-	-	-	-	-	-	-	-	-	ND	-	-	-	2	40	32	28	.50	.51
-	-	-	-	-	-	-	-	-	ND	-	-	-	2	43	36	21	.50	.51
-	-	-	-	6	127	160	208	coal	ND	-	-	-	21	51	27	22	.51	.93
Barrow program (1955-81)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	ND
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Naval Petroleum Reserve No. 4 program (1973-77)--Continued																		
-	-	-	-	-	-	-	-	-	1	70	10	20	ND	-	-	-	.32	.38
-	-	-	-	-	-	-	-	-	6	63	20	17	ND	-	-	-	.40	.44
-	-	-	-	-	-	-	-	-	3	56	22	22	3	59	18	23	.44	.50
7	82	175	244	-	-	-	-	-	7	64	16	20	2	72	9	19	.40	.44
1	-	264	-	-	-	-	-	-	5	57	29	14	ND	-	-	-	.37	.41
1	-	647	-	-	-	-	-	-	15	53	32	15	ND	-	-	-	.40	.48
National Petroleum Reserve in Alaska program (1977-81)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	3	49	34	19	ND	-	-	-	.44	.50
-	-	-	-	-	-	-	-	-	5	58	33	9	8	57	22	21	.33	.40
-	-	-	-	-	-	-	-	-	14	56	29	15	4	53	27	22	.38	.49
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	132	164	201	-	-	-	-	-	12	53	29	18	ND	-	-	-	.54	.73
5	51	131	289	-	-	-	-	-	11	58	25	17	ND	-	-	-	.48	.57
-	-	-	-	-	-	-	-	-	4	34	20	46	ND	-	-	-	.49	.53
1	-	81	-	-	-	-	-	-	6	57	23	20	ND	-	-	-	.36	.49
-	-	-	-	1	-	61	-	-	5	46	35	19	8	40	35	25	.45	.50
2	53	85	116	1	-	36	-	-	10	42	39	19	2	43	33	24	.40	.48
2	68	145	222	-	-	-	-	-	9	50	32	18	1	88	13	0	.39	.46
1	-	321	-	-	-	-	-	-	4	58	23	19	2	58	31	17	.42	.47
-	-	-	-	1	-	131	-	-	5	43	37	20	10	49	28	23	.36	.44
1	-	281	-	-	-	-	-	-	5	53	30	17	ND	-	-	-	.45	.49
5	88	132	159	-	-	-	-	-	24	45	32	23	13	44	31	25	.42	.90
-	-	-	-	-	-	-	-	-	7	52	29	19	ND	-	-	-	.45	.56

TABLE 17.12.—*Organic-carbon, C_{15+}-hydrocarbon, visual-*

[*, well not included on organic-carbon, visual-kerogen, or vitrinite-reflectance maps; NP, rock unit not penetrated; ND, not determined or insufficient data; 0, rock unit eroded or not deposited; OS, oil-stained sample; +, incomplete thickness. Rock-unit thicknesses, mean organic-carbon contents, mean C_{15+}-hydrocarbon contents, and visual-kerogen contents are posted on maps. Visual-kerogen contents (in percent): A-H, amorphous and herbaceous; W, woody; I, inertinite]

Well	API No.	Total depth (ft)	Rock unit thickness (ft)	Organic-carbon content (weight percent)										
				Cuttings			Sidewall core			Conventional core			Total samples	Mean value
				Min	Mean	Max	Min	Mean	Max	Min	Mean	Max		
Naval Petroleum Reserve No. 4 program (1944-53)														
North Simpson No. 1	50-023-10004	3,774	2,680	-	-	-	-	-	-	.43	1.09	1.40	11	1.09
South Barrow No. 1	50-023-10009	3,553	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 2	50-023-10010	2,505	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 3	50-023-10011	2,900	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 4	50-023-10012	2,538	0	-	-	-	-	-	-	-	-	-	-	-
*Avak No. 1	50-023-10013	4,020	0	-	-	-	-	-	-	-	-	-	-	-
Grandstand No. 1	50-057-10001	3,939	0	-	-	-	-	-	-	-	-	-	-	-
Fish Creek No. 1	50-103-10001	7,020	990	-	-	-	-	-	-	.89	1.35	2.85	5	2.85
Oumalik No. 1	50-119-10005	11,872	0	-	-	-	-	-	-	-	-	-	-	-
East Oumalik No. 1	50-119-10006	6,035	0	-	-	-	-	-	-	-	-	-	-	-
Square Lake No. 1	50-119-10007	3,987	930	-	-	-	-	-	-	.54	.82	1.11	8	1.11
*Wolf Creek No. 1	50-119-10008	1,500	0	-	-	-	-	-	-	-	-	-	-	-
Wolf Creek No. 3	50-119-10010	3,760	0	-	-	-	-	-	-	-	-	-	-	-
Titaluk No. 1	50-119-10011	4,020	0	-	-	-	-	-	-	-	-	-	-	-
Knifeblade No. 1	50-119-10012	1,805	0	-	-	-	-	-	-	-	-	-	-	-
*Knifeblade No. 2A	50-119-10014	1,805	0	-	-	-	-	-	-	-	-	-	-	-
Meade No. 1	50-163-10002	5,305	0	-	-	-	-	-	-	-	-	-	-	-
Simpson No. 1	50-279-10032	7,002	0	-	-	-	-	-	-	-	-	-	-	-
Topagoruk No. 1	50-279-10033	10,503	0	-	-	-	-	-	-	-	-	-	-	-
East Topagoruk No. 1	50-279-10034	3,589	0	-	-	-	-	-	-	-	-	-	-	-
Umiat No. 1	50-278-10001	6,005	715	-	-	-	-	-	-	.23	1.53	5.23	23	1.53
*Umiat No. 2	50-287-10002	6,212	0	-	-	-	-	-	-	-	-	-	-	-
Umiat No. 11	50-287-10011	3,303	1,495	-	-	-	-	-	-	.59	.82	1.3	10	.82
Gubik No. 1	50-287-10013	6,000	1,120	-	-	-	-	-	-	.72	.92	1.38	9	.92
*Gubik No. 2	50-287-10014	4,620	1,130	-	-	-	-	-	-	.65	1.00	1.40	3	1.00
Kaolak No. 1	50-297-10001	6,952	0	-	-	-	-	-	-	-	-	-	-	-
Barrow program (1955-81)														
South Barrow No. 9	50-023-20003	2,450	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 12	50-023-20006	2,285	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 13	50-023-20008	2,535	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 14	50-023-20009	2,257	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 16	50-023-20010	2,400	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 17	50-023-20011	2,382	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 19	50-023-20012	2,300	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 20	50-023-20015	2,356	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 15	50-023-20016	2,278	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 18	50-023-20017	2,125	0	-	-	-	-	-	-		-	-	-	-
Naval Petroleum Reserve No. 4 program (1973-77)														
Cape Halkett No. 1	50-103-20004	9,900	895	.32	.87	2.05	-	-	-	-	-	-	14	.87
South Harrison Bay No. 1	50-103-20007	11,290	1,160	.39	1.24	2.29	-	-	-	-	-	-	13	1.24
Atigaru Point No. 1	50-103-20008	11,535	1,050	1.01	1.40	2.01	-	-	-	-	-	-	12	1.40
West Fish Creek No. 1	50-103-20009	11,427	1,050	-	-	-	-	-	-	-	-	-	0	-
W.T. Foran No. 1	50-103-20010	8,864	880	.57	.81	1.20	-	-	-	-	-	-	11	.81
South Simpson No. 1	50-279-20001	8,795	0	-	-	-	-	-	-	-	-	-		-
National Petroleum Reserve in Alaska program (1977-81)														
Walakpa No. 1	50-023-20013	3,666	0	-	-	-	-	-	-	-	-	-	-	-
West Dease No. 1	50-023-20014	4,173	0	-	-	-	-	-	-	-	-	-		-
Tulageak No. 1	50-023-20018	4,015	0	-	-	-	-	-	-	-	-	-	-	-
Walakpa No. 2	50-023-20019	4,360	0	-	-	-	-	-	-	-	-	-	-	-
North Kalikpik No. 1	50-103-20011	7,395	695	.66	.87	1.20	-	-	-	-	-	-	7	.87
North Inigok No. 1	50-103-20017	10,170	1,035	.57	1.18	2.17	.18	.63	1.25	-	-	-	25	1.05
Koluktak No. 1	50-119-20001	5,882	0	-	-	-	-	-	-	-	-	-	-	-
*Lisburne No. 1	50-137-20003	17,000	0	-	-	-	-	-	-	-	-	-	-	-
Awuna No. 1	50-155-20001	11,200	0	-	-	-	-	-	-	-	-	-	-	-
South Meade No. 1	50-163-20001	9,945	0	-	-	-	-	-	-	-	-	-	-	-
Kugrua No. 1	50-163-20002	12,588	0	-	-	-	-	-	-	-	-	-	-	-
Kuyanak No. 1	50-163-20003	6,690	0	-	-	-	-	-	-	-	-	-	-	-
Drew Point No. 1	50-279-20002	7,946	490	1.51	1.55	1.60	-	-	-	-	-	-	2	1.55
Inigok No. 1	50-279-20003	20,102	870	.21	.95	3.41	-	-	-	-	-	-	16	.95
Ikpikpuk No. 1	50-279-20004	15,481	0	-	-	-	-	-	-	-	-	-	-	-
East Simpson No. 1	50-279-20005	7,739	445	1.23	5.86	14.44	-	-	-	-	-	-	5	5.86
Dalton No. 1	50-279-20006	9,367	600	.02	.28	1.09	-	-	-	-	-	-	10	.28
East Simpson No. 2	50-279-20007	7,504	965	.63	2.20	7.22	.97	1.06	1.12	-	-	-	19	2.02
Seabee No. 1	50-287-20007	15,611	180	.63	.87	.99	-	-	-	-	-	-	3	.87
Tunalik No. 1	50-301-20001	20,335	0	-	-	-	-		-	-	-	-	-	-
Peard No. 1	50-301-20002	10,225	0	-	-	-	-	-		-	-	-	-	-

kerogen, and vitrinite-reflectance data for the Colville Group

C_{15+}-hydrocarbon content (ppm)									Visual-kerogen content								Vitrinite reflectance	
Cuttings samples				Core samples				Comments	Cuttings samples				Core samples				Top	Within
No.	Min	Mean	Max	No.	Min	Mean	Max		No.	A-H	W	I	No.	A-H	W	I		
Naval Petroleum Reserve No. 4 program (1944-53)--Continued																		
-	-	-	-	5	123	203	312	-	ND	-	-	-	5	48	28	24	.42	.53
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.46
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.50
-	-	-	-	4	96	224	510	-	ND	-	-	-	4	55	26	19	.37	.42
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.41
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.45
-	-	-	-	2	99	116	132	-	ND	-	-	-	3	61	23	16	.50	.52
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.53
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.46
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.57
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.50
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.62
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.53
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.55
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.40
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.46
-	-	-	-	2	130	228	326	-	ND	-	-	-	4	59	30	11	.46	.48
-	-	-	-	-	-	-	-	-	ND	-	-	-	5	42	30	22	-	.50
-	-	-	-	1	-	166	-	-	-	-	-	-	-	-	-	-	.44	.48
-	-	-	-	-	-	-	-	-	ND	-	-	-	2	39	38	23	.46	.50
-	-	-	-	-	-	-	-	-	ND	-	-	-	2	54	31	15	.46	.50
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.51
Barrow program (1955-81)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Naval Petroleum Reserve No. 4 program (1973-77)--Continued																		
-	-	-	-	-	-	-	-	-	1	54	9	36	ND	-	-	-	.30	.32
-	-	-	-	-	-	-	-	-	5	49	33	18	ND	-	-	-	.35	.40
-	-	-	-	-	-	-	-	-	4	54	30	16	ND	-	-	-	.39	.44
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.38	.40
-	-	-	-	-	-	-	-	-	5	49	33	18	ND	-	-	-	.35	.37
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.40
National Petroleum Reserve in Alaska program (1977-81)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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-	-	-	-	-	-	-	-	-	2	45	35	20	ND	-	-	-	.41	.44
-	-	-	-	-	-	-	-	-	3	41	37	22	6	33	36	31	.31	.33
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.54
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.48
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	1	84	0	14	ND	-	-	-	.34	.36
2	31	60	91	-	-	-	-	-	6	65	26	9	ND	-	-	-	.43	.45
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.40
1	-	174	-	-	-	-	-	-	2	51	39	10	ND	-	-	-	.38	.39
-	-	-	-	-	-	-	-	-	2	37	42	21	ND	-	-	-	.40	.42
-	-	-	-	-	-	-	-	-	3	41	37	22	3	46	43	11	.34	.36
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.44	.45
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.42
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.45

TABLE 17.13.—*Organic-carbon, C_{15+}-hydrocarbon, visual-kerogen, and vitrinite-reflectance*

[*, well not included on organic-carbon, visual-kerogen, or vitrinite-reflectance maps; NP, rock unit not penetrated; ND, not determined or insufficient data; 0, rock unit eroded or not deposited; OS, oil-stained sample; +, incomplete thickness. Rock-unit thicknesses, mean organic-carbon contents, mean C_{15+}-hydrocarbon contents, and visual-kerogen contents are posted on maps. Visual-kerogen contents (in percent): A-H, amorphous and herbaceous; W, woody; I, inertinite]

Well	API No.	Total depth (ft)	Rock unit thickness (ft)	Organic-carbon content (weight percent)										
				Cuttings			Sidewall core			Conventional core			Total samples	Mean value
				Min	Mean	Max	Min	Mean	Max	Min	Mean	Max		
Naval Petroleum Reserve No. 4 program (1944-53)														
North Simpson No. 1-------	50-023-10004	3,774	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 1--------	50-023-10009	3,553	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 2--------	50-023-10010	2,505	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 3--------	50-023-10011	2,900	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 4--------	50-023-10012	2,538	0	-	-	-	-	-	-	-	-	-	-	-
*Avak No. 1---------------	50-023-10013	4,020	0	-	-	-	-	-	-	-	-	-		-
Grandstand No. 1----------	50-057-10001	3,939	0	-	-	-	-	-	-		-	-	-	-
Fish Creek No. 1----------	50-103-10001	7,020	1,835	-	-	-	-	-	-	.44	1.02	2.44	8	1.02
Oumalik No. 1-------------	50-119-10005	11,872	0	-	-	-	-	-	-	-	-	-	-	-
East Oumalik No. 1--------	50-119-10006	6,035	0	-	-	-	-	-	-	-	-	-	-	-
Square Lake No. 1---------	50-119-10007	3,987	665	-	-	-	-	-	-	.12	5.87	63.70	13	5.87
*Wolf Creek No. 1----------	50-119-10008	1,500	0	-	-	-	-	-	-	-	-	-	-	-
Wolf Creek No. 3----------	50-119-10010	3,760	0	-	-	-	-	-	-	-	-	-	-	-
Titaluk No. 1-------------	50-119-10011	4,020	0	-	-	-	-	-	-	-	-	-	-	-
Knifeblade No. 1----------	50-119-10012	1,805	0	-	-	-	-	-	-	-	-	-	-	-
*Knifeblade No. 2A---------	50-119-10014	1,805	0	-	-	-	-	-	-	-	-	-	-	-
Meade No. 1---------------	50-163-10002	5,305	0	-	-	-	-	-	-	-	-	-	-	-
Simpson No. 1-------------	50-279-10032	7,002	0	-	-	-	-	-	-	-	-	-	-	-
Topagoruk No. 1-----------	50-279-10033	10,503	0	-	-	-	-	-	-	-	-	-	-	-
East Topagoruk No. 1------	50-279-10034	3,589	0	-	-	-	-	-	-	-	-	-	-	-
Umiat No. 1---------------	50-278-10001	6,005	191	-	-	-	-	-	-	.14	.67	1.01	9	.67
*Umiat No. 2---------------	50-287-10002	6,212	0	-	-	-	-	-	-	-	-	-	-	-
Umiat No. 11--------------	50-287-10011	3,303	525	-	-	-	-	-	-	.04	12.57	49.66	12	12.57
Gubik No. 1---------------	50-287-10013	6,000	1,885	-	-	-	-	-	-	.23	2.93	13.44	10	2.93
*Gubik No. 2---------------	50-287-10014	4,620	2,090	-	-	-	-	-	-	.14	3.44	49.39	41	3.44
Kaolak No. 1--------------	50-297-10001	6,952	0	-	-	-	-	-	-	-	-	-	-	-
Barrow program (1955-81)														
South Barrow No. 9--------	50-023-20003	2,450	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 12-------	50-023-20006	2,285	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 13-------	50-023-20008	2,535	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 14-------	50-023-20009	2,257	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 16-------	50-023-20010	2,400	0	-	-	-	-	-	-	-	-	-	-	-
South Barrow No. 17-------	50-023-20011	2,382	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 19-------	50-023-20012	2,300	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 20-------	50-023-20015	2,356	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 15-------	50-023-20016	2,278	0	-	-	-	-	-	-	-	-	-	-	-
*South Barrow No. 18-------	50-023-20017	2,125	0	-	-	-	-	-	-	-	-	-	-	-
Naval Petroleum Reserve No. 4 program (1973-77)														
Cape Halkett No. 1--------	50-103-20004	9,900	2,120	.01	.33	1.42	-	-	-	-	-	-	31	1.42
South Harrison Bay No. 1--	50-103-20007	11,290	1,960	.04	.73	1.15	-	-	-	-	-	-	18	.73
Atigaru Point No. 1-------	50-103-20008	11,535	2,320	.28	1.20	4.42	-	-	-	-	-	-	20	1.20
West Fish Creek No. 1-----	50-103-20009	11,427	1,400	-	-	-	-	-	-	-	-	-	0	-
W.T. Foran No. 1----------	50-103-20010	8,864	2,500	.11	.65	1.72	-	-	-	-	-	-	24	.65
South Simpson No. 1-------	50-279-20001	8,795	0	-	-	-	-	-	-	-	-	-	-	-
National Petroleum Reserve in Alaska program (1977-81)														
Walakpa No. 1-------------	50-023-20013	3,666	0	-	-	-	-	-	-	-	-	-	-	-
West Dease No. 1----------	50-023-20014	4,173	0	-	-	-	-	-	-	-	-	-	-	-
Tulageak No. 1------------	50-023-20018	4,015	0	-	-	-	-	-	-	-	-	-	-	-
Walakpa No. 2-------------	50-023-20019	4,360	0	-	-	-	-	-	-	-	-	-	-	-
North Kalikpik No. 1------	50-103-20011	7,395	1,600	.29	2.31	8.03	-	-	-	-	-	-	14	2.31
North Inigok No. 1--------	50-103-20017	10,170	785	.93	8.38	24.19	.39	.43	.48	-	-	-	16	7.39
Koluktak No. 1------------	50-119-20001	5,882	0	-	-	-	-	-	-	-	-	-	-	-
*Lisburne No. 1------------	50-137-20003	17,000	0	-	-	-	-	-	-	-	-	-	-	-
Awuna No. 1---------------	50-155-20001	11,200	0	-	-	-	-	-	-	-	-	-	-	-
South Meade No. 1---------	50-163-20001	9,945	0	-	-	-	-	-	-	-	-	-	-	-
Kugrua No. 1--------------	50-163-20002	12,588	0	-	-	-	-	-	-	-	-	-	-	-
Kuyanak No. 1-------------	50-163-20003	6,690	0	-	-	-	-	-	-	-	-	-	-	-
Drew Point No. 1----------	50-279-20002	7,946	660	.66	1.53	2.48	-	-	-	-	-	-	4	1.53
Inigok No. 1--------------	50-279-20003	20,102	1,280	.19	8.38	27.06	-	-	-	-	-	-	20	8.38
Ikpikpuk No. 1------------	50-279-20004	15,481	0	-	-	-	-	-	-	-	-	-	-	-
East Simpson No. 1--------	50-279-20005	7,739	0	-	-	-	-	-	-	-	-	-	-	-
Dalton No. 1--------------	50-279-20006	9,367	1,850	.04	1.99	14.16	-	-	-	-	-	-	28	1.99
East Simpson No. 2--------	50-279-20007	7,504	0	-	-	-	-	-	-	-	-	-	-	-
Seabee No. 1--------------	50-287-20007	15,611	0	-	-	-	-	-	-	-	-	-	-	-
Tunalik No. 1-------------	50-301-20001	20,335	0	-	-	-	-	-	-	-	-	-	-	-
Peard No. 1---------------	50-301-20002	10,225	0	-	-	-	-	-	-	-	-	-	-	-

data for the Sagavanirktok Formation and sandstone of the Colville Group, undivided

C_{15+}-hydrocarbon content (ppm)									Visual-kerogen content								Vitrinite reflectance	
Cuttings samples				Core samples				Comments	Cuttings samples				Core samples				Top	Within
No.	Min	Mean	Max	No.	Min	Mean	Max		No.	A-H	W	I	No.	A-H	W	I		
Naval Petroleum Reserve No. 4 program (1944-53)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	No R_0 data	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	8	95	131	199	Coal	ND	-	-	-	9	42	33	25	.31	.37
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	2	120	158	196	Coal	ND	-	-	-	4	62	19	19	.48	.50
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	1	-	118	-	-	ND	-	-	-	2	42	22	36	.45	.46
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	Coal	ND	-	-	-	2	57	21	22	.42	.44
-	-	-	-	-	-	-	-	-	ND	-	-	-	5	31	33	36	.40	.46
-	-	-	-	-	-	-	-	-	ND	-	-	-	7	43	31	26	.40	.46
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Barrow program (1955-81)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Naval Petroleum Reserve No. 4 program (1973-77)--Continued																		
-	-	-	-	-	-	-	-	-	5	51	27	22	ND	-	-	-	.23	.30
-	-	-	-	-	-	-	-	-	8	56	22	22	ND	-	-	-	.30	.35
-	-	-	-	-	-	-	-	-	5	56	25	19	ND	-	-	-	.26	.39
-	-	-	-	-	-	-	-	-	8	44	29	17	ND	-	-	-	.35	.38
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.27	.35
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
National Petroleum Reserve in Alaska program (1977-81)--Continued																		
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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-	-	-	-	-	-	-	-	-	8	48	33	19	ND	-	-	-	.34	.41
-	-	-	-	-	-	-	-	-	3	57	28	15	2	39	33	28	.29	.31
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-	-	-	-	-	-	-	-	-	3	56	28	16	ND	-	-	-	.31	.34
1	-	40	-	-	-	-	-	Coal	5	56	31	13	ND	-	-	-	.39	.43
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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-	-	-	-	-	-	-	-	-	6	62	22	16	ND	-	-	-	.33	.40
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each rock unit to generate hydrocarbons (Hunt, 1979, fig. 7-1). Hunt's plot shows numerous petroleum source or nonreservoir rocks and how they compare, among other categories, with reservoir rocks. We have constructed a similar plot for each rock unit, and these are shown on each organic-carbon contour map. Two lines are shown on each plot. The lower line is from Hunt (1979) and represents the HC/OC ratio of 0.007, or the lower limit of petroleum source rocks. Rocks with values that plot below this line and above 5 weight percent are coals or coaly organic matter, and those samples that have a hydrocarbon content below 5 weight percent are nonsource rocks. The upper line, whose HC/OC value is 0.05, separates indigenous hydrocarbons (below) from migrated, expelled, or reservoired hydrocarbons (above). This line is placed empirically because the migrated hydrocarbons are not always detected visually. However, some shales or reservoir rocks have been extracted that obviously con-

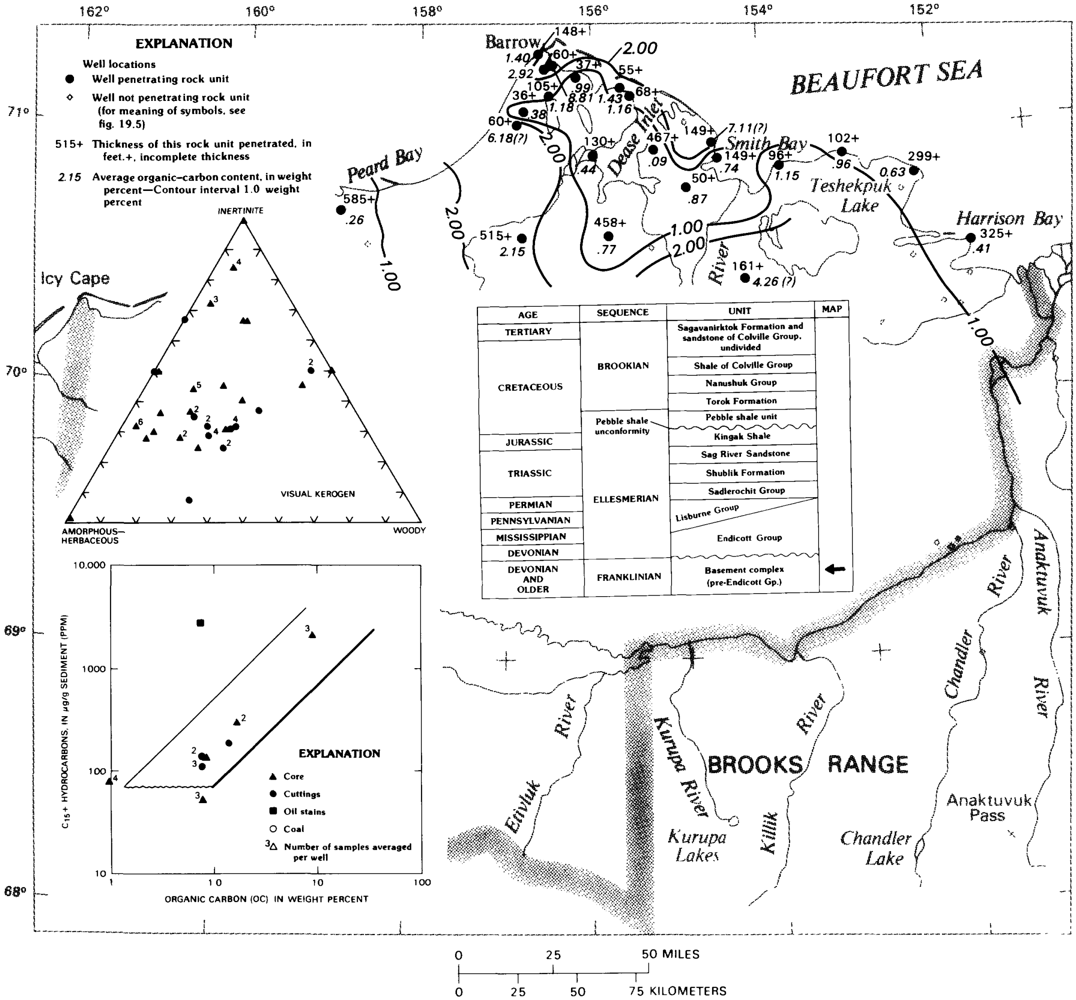
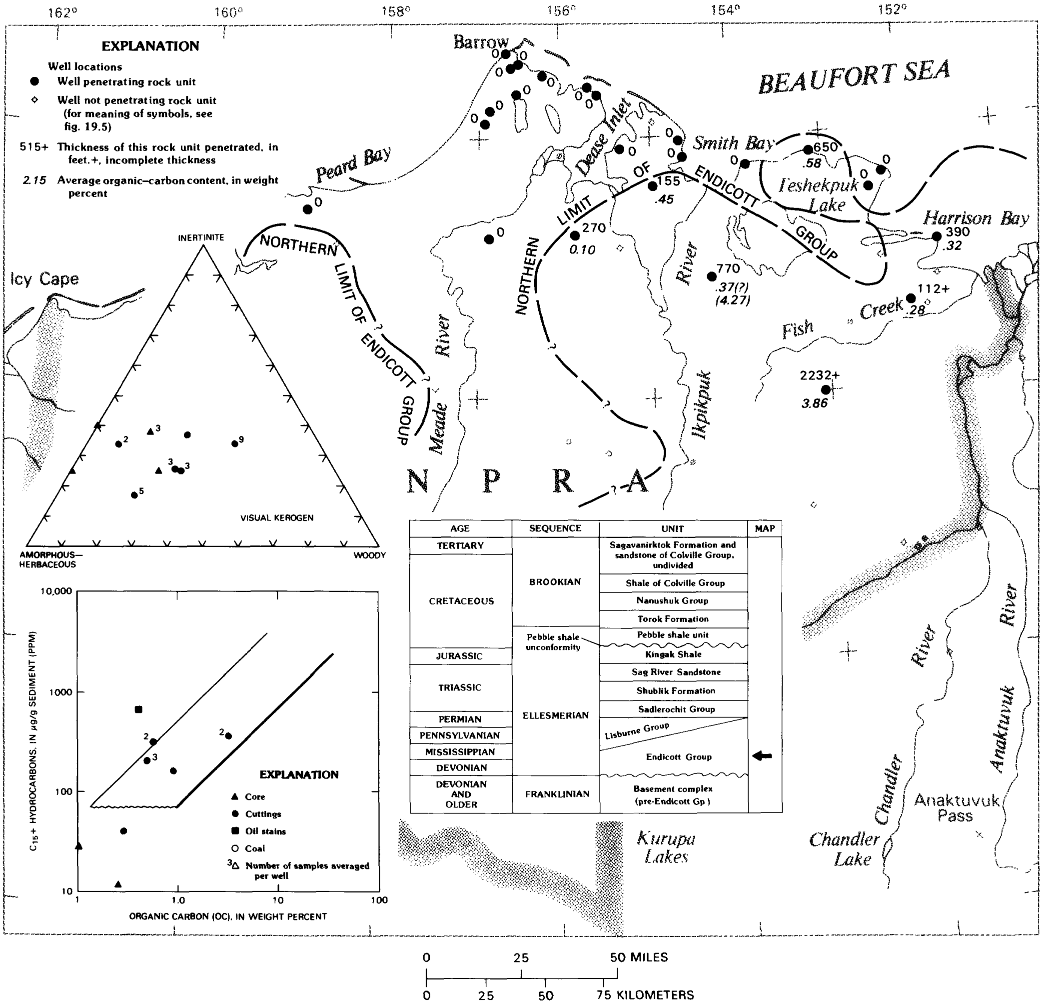


FIGURE 17.7.—Average organic-carbon content for the pre-Endicott Group, showing relation of organic-carbon content to content of extractable C_{15+} hydrocarbons and relative proportions of three kerogen types. Contour interval, 1 weight percent.

tain migrated hydrocarbons, and those HC/OC values were compared with any sample suspected of containing migrated hydrocarbons. The HC/OC data have been separated into four categories: (1) Mean HC/OC values for core samples have been plotted as solid triangles, with the number of samples from each well indicated near the symbol; (2) mean HC/OC values for cutting samples have been plotted as dots, with the number of samples from each well indicated near the symbol; (3) mean HC/OC values for coal samples (more than 5 weight percent OC and HC/OC<0.007) for core or cutting samples have been plotted as solid hexagons, with the number of samples from each well indicated; and (4) each HC/OC value for every sample suspected of being oil stained has been indicated as a solid square. In each of these categories, no sample has been counted twice.

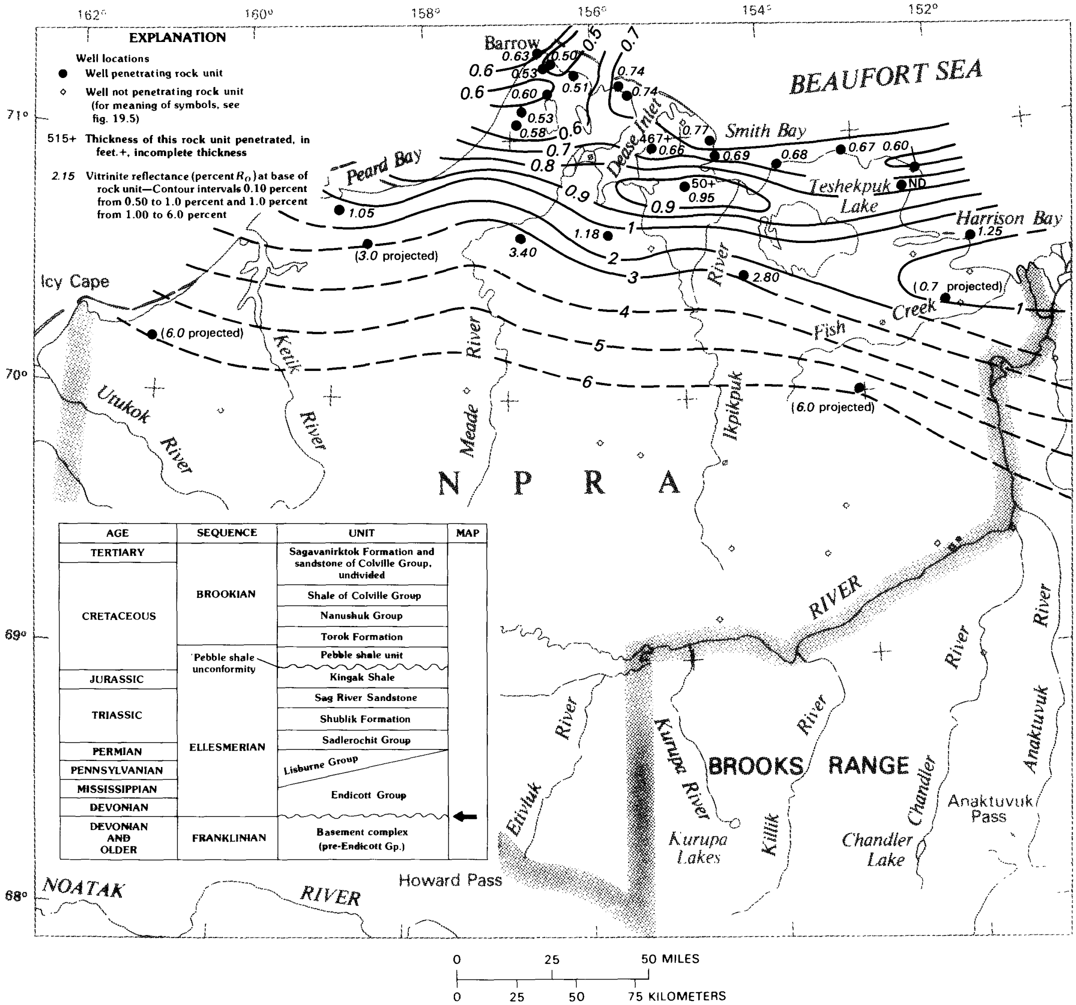
Visual kerogen (in percent) provides data about the relative abundance of different types of organic matter—(1) amorphous, (2) herba-



AGE	SEQUENCE	UNIT	MAP
TERTIARY	BROOKIAN	Sagavanirktok Formation and sandstone of Colville Group, undivided	
CRETACEOUS		Shale of Colville Group	
		Nanushuk Group	
		Torok Formation	
	Pebble shale unconformity	Pebble shale unit	
JURASSIC	ELLESMERIAN	Kingak Shale	
TRIASSIC		Sag River Sandstone	
		Shublik Formation	
PERMIAN		Sadlerochit Group	
PENNSYLVANIAN		Lisburne Group	
MISSISSIPPIAN		Endicott Group	←
DEVONIAN			
DEVONIAN AND OLDER	FRANKLINIAN	Basement complex (pre-Endicott Gp)	

FIGURE 17.8.—Average organic-carbon content for the Endicott Group, showing relation of organic-carbon content to content of extractable C_{15+} hydrocarbons and relative proportions of three kerogen types.

ceous, (3) woody, and (4) inertinite—included in the rock sample (see Bayliss and Magoon, chapter 20). The several types of kerogen have different potentials for contributing varying amounts of oil or gas. For example, amorphous material contributes mostly oil, whereas woody material contributes only gas (see Bayliss and Magoon, chapter 20). This hydrocarbon contribution can be related to the hydrogen content of the kerogen. According to Powell and others (1982), however, the correlation between hydrogen content (from elemental analyses) and kerogen type (from visual means) is not always good. The visual-kerogen maps and triangular plots on each organic-carbon map included in this study are used to help understand the regional variation of kerogen types regardless of their hydrogen content. Visual-kerogen maps were constructed only for shale units: the Shublik



AGE	SEQUENCE	UNIT	MAP
TERTIARY	BROOKIAN	Sagavanirktok Formation and sandstone of Colville Group, undivided	
CRETACEOUS		Shale of Colville Group	
		Nanushuk Group	
		Torok Formation	
	Pebble shale unconformity ELLESMERIAN	Pebble shale unit	
JURASSIC		Kingak Shale	
TRIASSIC		Sag River Sandstone	
		Shublik Formation	
PERMIAN		Sadlerochit Group	
PENNSYLVANIAN		Lisburne Group	
MISSISSIPPIAN		Endicott Group	
DEVONIAN			←
DEVONIAN AND OLDER	FRANKLINIAN	Basement complex (pre-Endicott Gp.)	

FIGURE 17.9.—Vitrinite-reflectance values at base of Ellesmerian sequence, contoured at intervals of 0.1 and 1.0 percent R_0. ND, no data.

Formation, the Kingak Shale, the pebble shale unit, and the Torok Formation. For each shale unit, three contour maps have been drawn: (1) oil-prone kerogen (amorphous and herbaceous), (2) gas-prone kerogen (woody), and (3) non-petroleum-prone kerogen (inertinite).

Vitrinite reflectance is an indirect measure of the maximum temperatures in the thermal history for rocks containing maceral vitrain (Castano and Sparks, 1974). To equate reflectance values with the generation of oil and gas, other geochemical analyses must be calibrated or correlated to vitrinite reflectance (percent R_0) measurements (see Bayliss and Magoon, chapter 20). Calibration for the NPRA shows that values of R_0 for the three stages of petroleum generation (Tissot and Welte, 1978) are as follows: (1) diagenetic stage for vitrinite reflectance values less than 0.6 percent, (2) catagenic stage

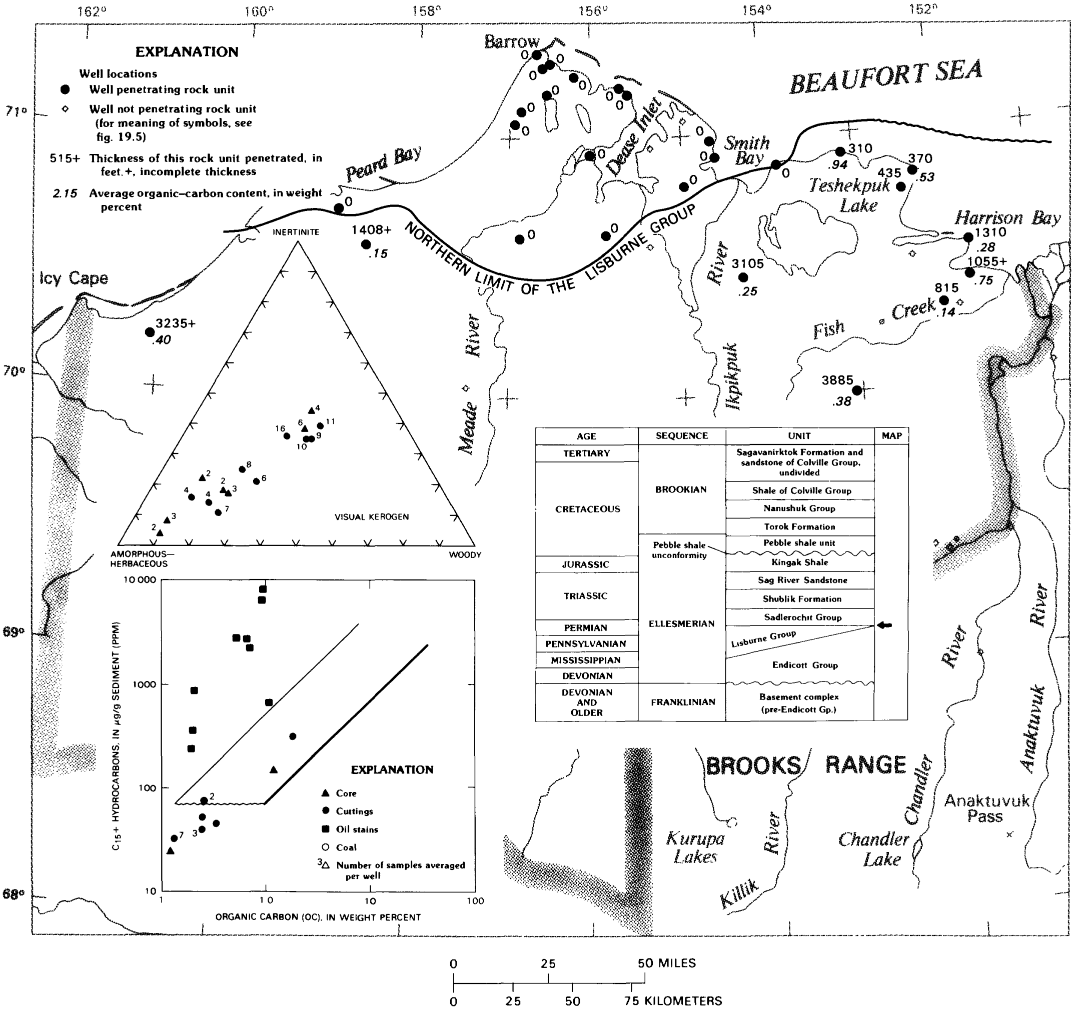


FIGURE 17.10.—Average organic-carbon content for the Lisburne Group, showing relation of organic-carbon content to content of extractable C_{15+} hydrocarbons and relative porportions of three kerogen types.

from 0.6 to 2.0 percent, and (3) metagenic stage above 2.0 percent (see Bayliss and Magoon, chapter 20).

ACKNOWLEDGMENTS

We acknowledge the following people who have contributed to the completion of this chapter. D. Weitzman, N. Palik, M. Martin, and G. Winger, all of Petroleum Information, provided the programming and computer support necessary to tabulate the data and create the preliminary maps. G.S. Bayliss and C. Bohnstedt of Geochem Research and D. DesAutels and S.J. Martin, formerly of Geochem Research, supervised the NPRA analytical program. The hydrocarbon content and visual kerogen were plotted by R.H. Thompson. Special appreciation is given to the technical reviewers D.E. Anders and G.E. Claypool, who provided many helpful suggestions.

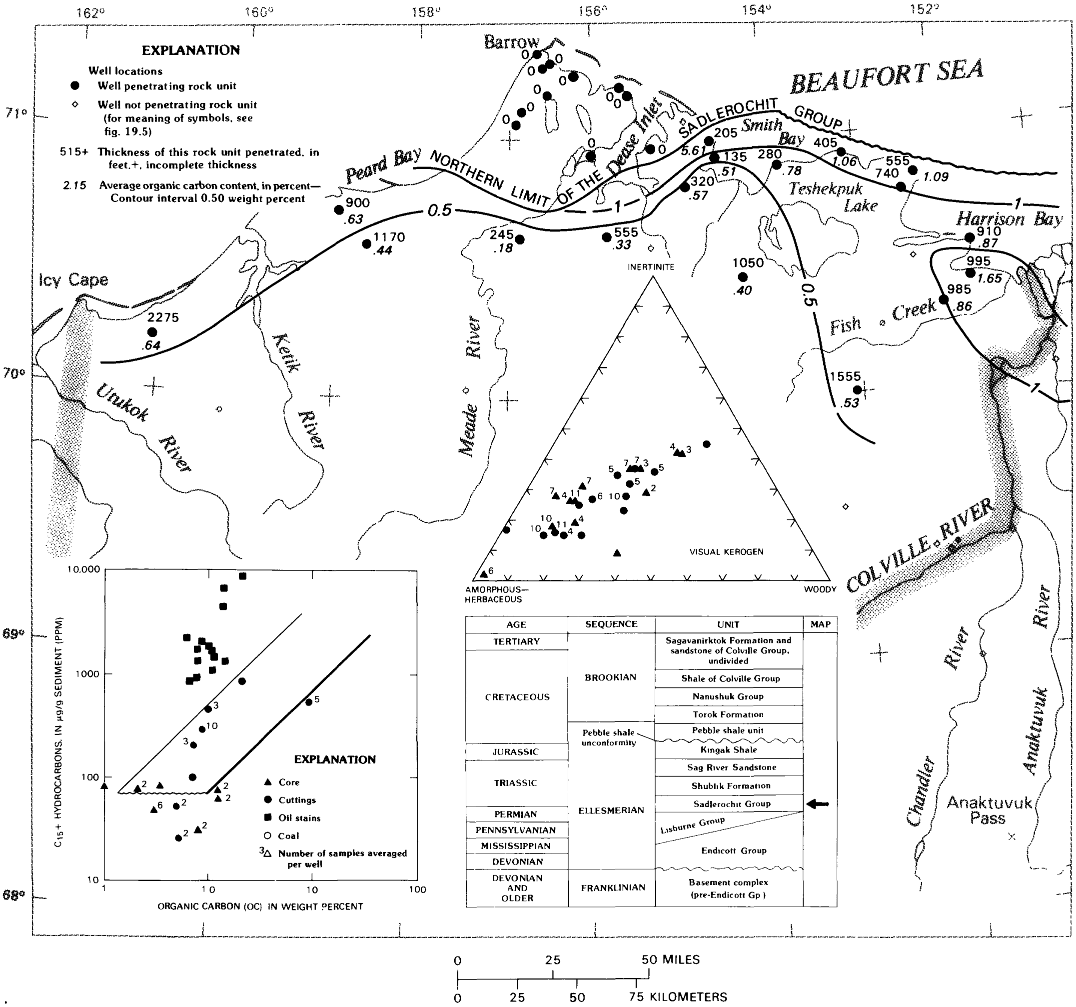


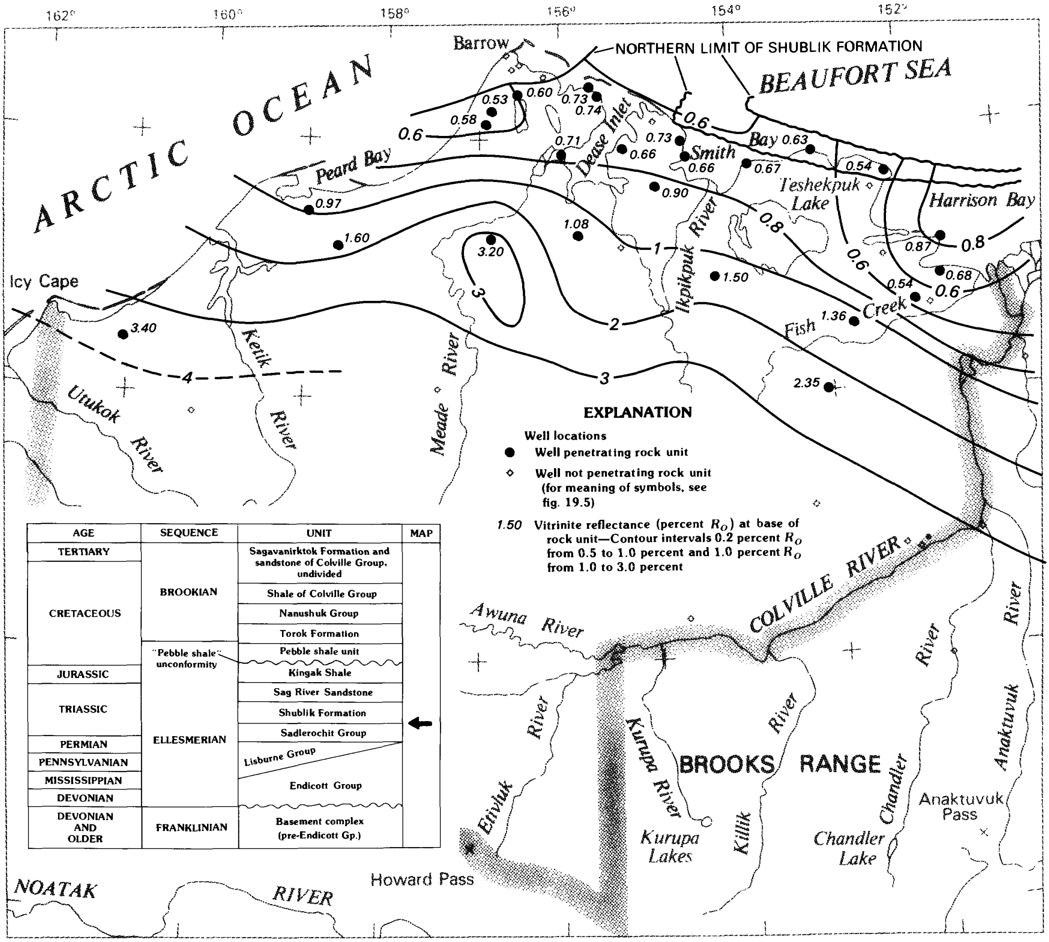
FIGURE 17.11.—Average organic-carbon content for the Sadlerochit Group, showing relation of organic-carbon content to content of extractable C_{15+} hydrocarbons and relative proportions of three kerogen types. Contour interval, 0.5 weight percent.

GEOCHEMISTRY OF STRATIGRAPHIC INTERVALS

The stratigraphic units in this section are discussed in sequence from oldest to youngest, following the history of basin development. The geochemical maps (figs. 17.7-17.27) may be compared to structure and isopach maps for the same stratigraphic units in the chapter by Bird (chapter 16). Results of these geochemical analyses are also summarized on four cross sections (figs. 17.3-17.6). Some wells have been omitted from the maps because of their close proximity to other wells with similar data (asterisks, table 18.1); however, data from all wells are listed in tables 17.2-17.14.

PRE-ENDICOTT GROUP

Rocks older than the Endicott Group in the NPRA north of the Brooks Range consist of deformed, slightly metamorphosed sedimentary rocks and rare igneous rocks that lie with angular unconformity beneath onlapping Mississippian and younger rocks. As penetrated in 29 wells, these pre-Endicott



AGE	SEQUENCE	UNIT	MAP
TERTIARY	BROOKIAN	Sagavanirktok Formation and sandstone of Colville Group, undivided	
CRETACEOUS		Shale of Colville Group	
		Nanushuk Group	
		Torok Formation	
	"Pebble shale" unconformity	Pebble shale unit	
JURASSIC	ELLESMERIAN	Kingak Shale	
TRIASSIC		Sag River Sandstone	
		Shublik Formation	←
		Sadlerochit Group	
PERMIAN		Lisburne Group	
PENNSYLVANIAN			
MISSISSIPPIAN		Endicott Group	
DEVONIAN			
DEVONIAN AND OLDER	FRANKLINIAN	Basement complex (pre-Endicott Gp.)	

FIGURE 17.12.—Vitrinite-reflectance values at base of the Shublik Formation, contoured at intervals of 0.2 and 1.0 percent R_0. In figures 17.12-17.14, the two wavy lines are the base (more seaward) and the top (more landward) of the Shublik Formation.

Group rocks consist predominantly of metamorphosed shale (argillite) of Ordovician and Silurian age (Carter and Laufeld, 1975). Also included are sandstone, conglomerate, siltstone, shale, and coal of Early and Middle Devonian age (Collins, 1958), and granite dated at 332 Ma (Bird and others, 1978). As shown on the pre-Endicott Group map by Brosgé and others (chapter 14), the basement rocks in the NPRA become younger to the south. Of the 29 wells that penetrated the pre-Endicott Group, 27 were sampled for petroleum geochemistry (table 17.2).

The organic-carbon content of the pre-Endicott Group rocks ranges from 0.09 to 9.89 weight percent, with a mean of 2.31 weight percent (table 17.2). Two anomalously high values (7.11 and 4.26 weight percent) from cutting samples can be attributed to coal cavings from younger strata (table 17.2; see East Simpson No. 2 and Ikpikpuk No. 1). Values are less than 1 weight percent around Dease Inlet but generally increase southward.

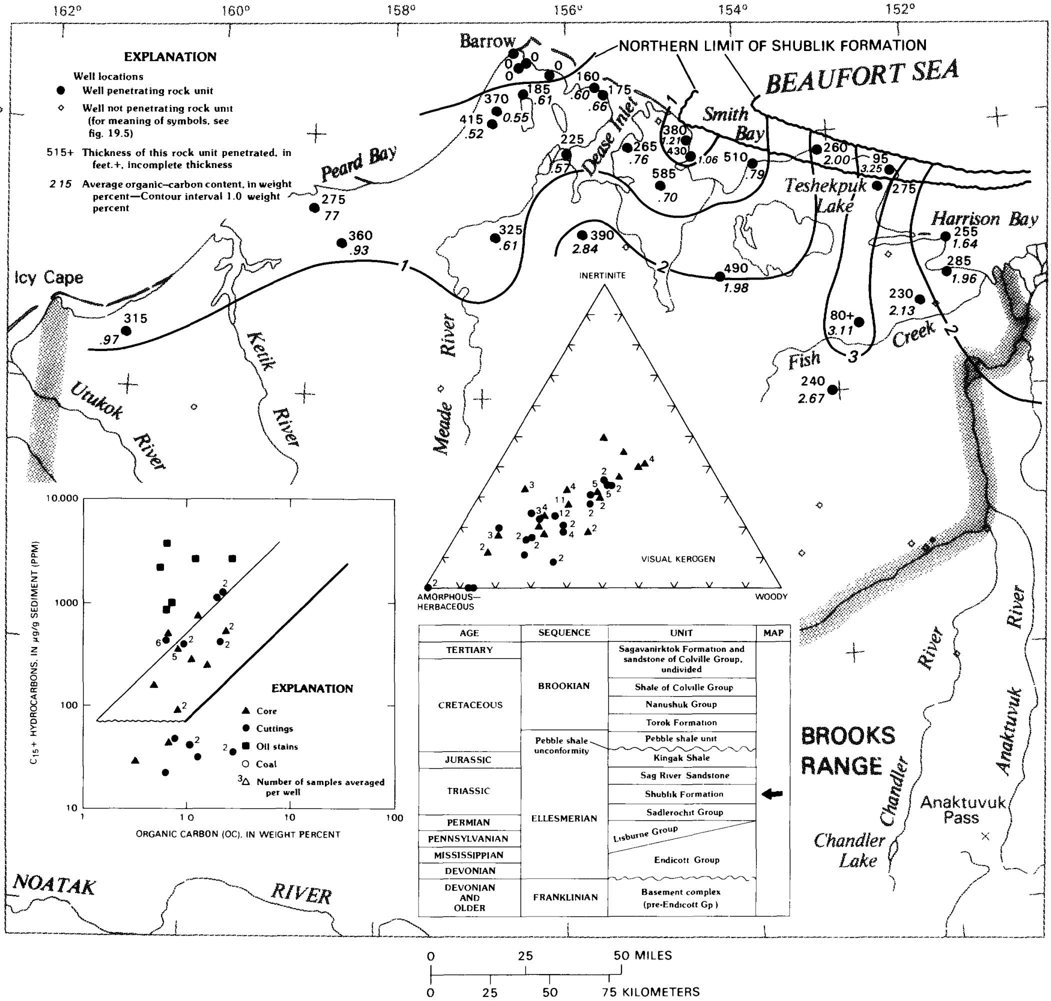
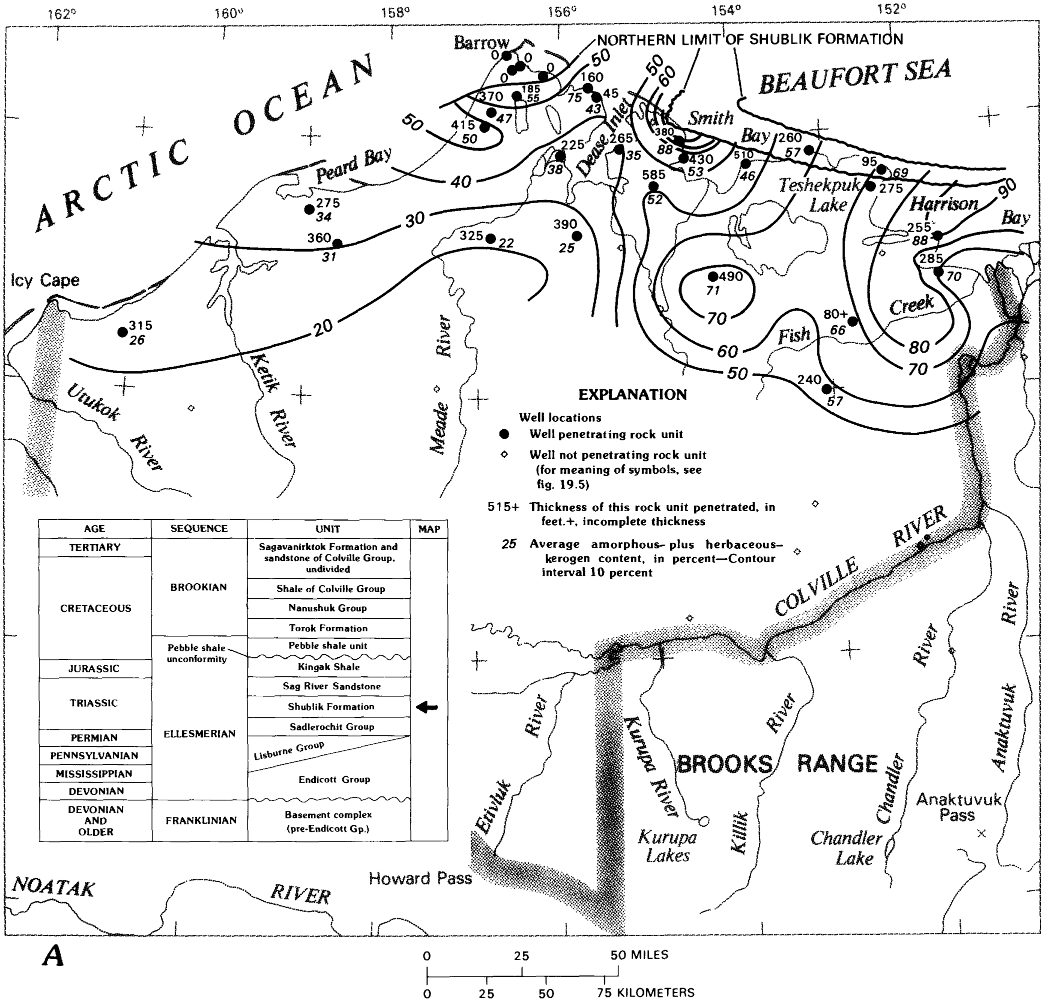


FIGURE 17.13.—Average organic-carbon content for the Shublik Formation, showing relation of organic-carbon content to content of extractable C_{15+} hydrocarbons and relative proportions of three kerogen types. Contour interval, 1 weight percent.

Organic-carbon content of about 2 weight percent or less is typical of the pre-Endicott Group rocks.

The HC/OC graph for the pre-Endicott Group rocks includes data from 9 wells, comprising 7 cutting samples, 13 core samples, and 1 oil-stained core sample (fig. 17.7). The oil-stained sample is from the South Barrow No. 16 well. In the Iko Bay No. 1 well, the pre-Endicott Group core is described in the well history as "bleeding oil from fractures." Most pre-Endicott Group rocks have HC/OC ratios between 0.007 and 0.05. Black sooty shales penetrated in the South Barrow No. 13 well have very high HC (possibly migrated oil) and OC values suggesting a good petroleum source rock. Except for the Topagoruk No. 1 well, which has nonsource characteristics, all other wells along the coastline contain sufficient hydrocarbons to be considered fair source rocks.

The vitrinite-reflectance values reported within this rock unit are considered suspect because vitrain macerals (woody, land-plant par-



EXPLANATION

Well locations
- ● Well penetrating rock unit
- ◇ Well not penetrating rock unit (for meaning of symbols, see fig. 19.5)

515+ Thickness of this rock unit penetrated, in feet.+, incomplete thickness

25 Average amorphous- plus herbaceous-kerogen content, in percent—Contour interval 10 percent

AGE	SEQUENCE	UNIT	MAP
TERTIARY	BROOKIAN	Sagavanirktok Formation and sandstone of Colville Group, undivided	
CRETACEOUS		Shale of Colville Group	
		Nanushuk Group	
		Torok Formation	
	Pebble shale unconformity	Pebble shale unit	
JURASSIC	ELLESMERIAN	Kingak Shale	
TRIASSIC		Sag River Sandstone	
		Shublik Formation	←
		Sadlerochit Group	
PERMIAN		Lisburne Group	
PENNSYLVANIAN			
MISSISSIPPIAN		Endicott Group	
DEVONIAN			
DEVONIAN AND OLDER	FRANKLINIAN	Basement complex (pre-Endicott Gp.)	

FIGURE 17.14.—Relative proportions of three visual kerogen types (in percent) for the Shublik Formation. A, Amorphous plus herbaceous. B, Woody. C, Inertinite.

ticles) are not likely to be present in pre-Upper Devonian rocks (Castaño and Sparks, 1974) and because of the caving problem in cutting samples. For these reasons, a vitrinite-reflectance map was not constructed. However, the vitrinite-reflectance data listed in table 17.2 for the top of the pre-Endicott Group section, which really represents the base of the Ellesmerian sequence, give a minimum reflectance value for the older rocks. The actual degree of organic metamorphism within pre-Endicott Group rocks is probably beyond the stage of gas generation.

Because metamorphism of the pre-Endicott Group rocks occurred before Late Devonian time, any hydrocarbons that may have originated from this rock unit are presumed to have been destroyed by the time deposition of Late Devonian and younger units began.

ENDICOTT GROUP

The Endicott Group, the basal unit of the Ellesmerian sequence

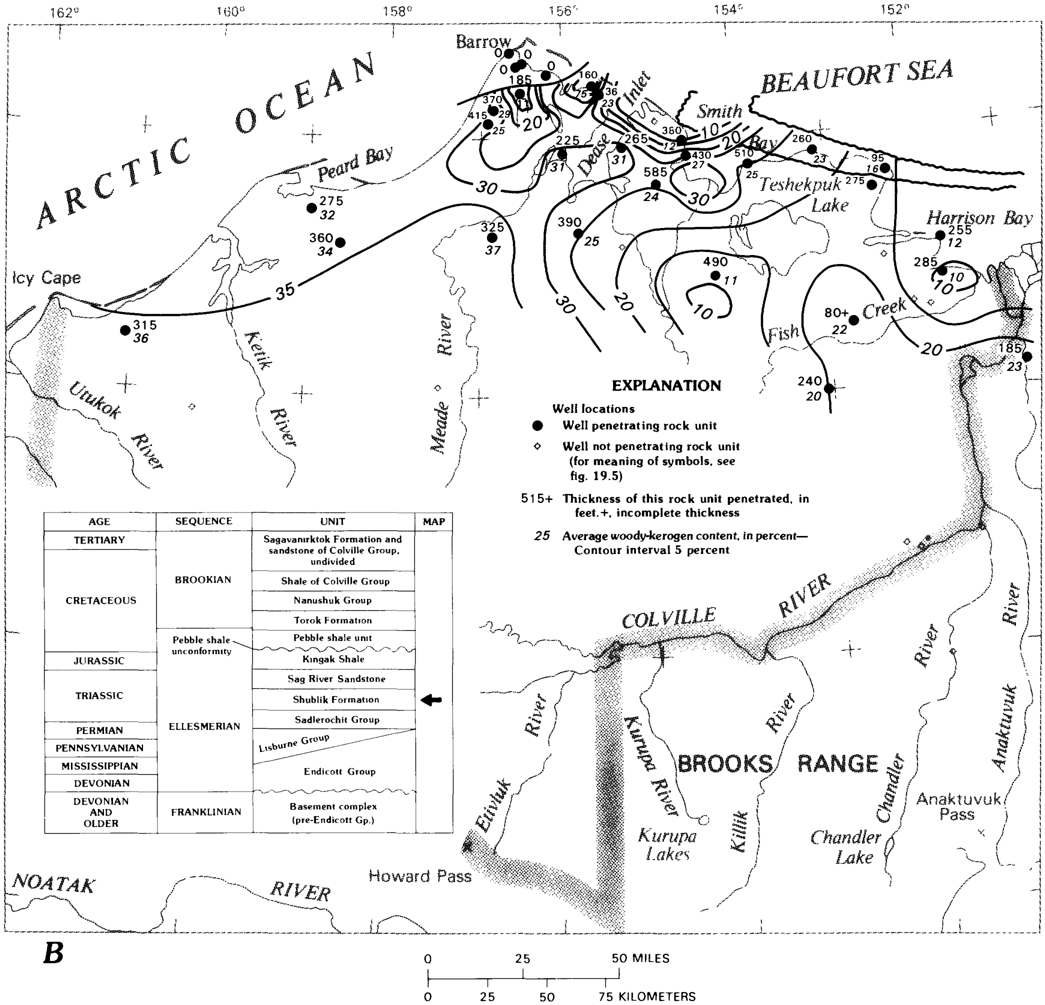
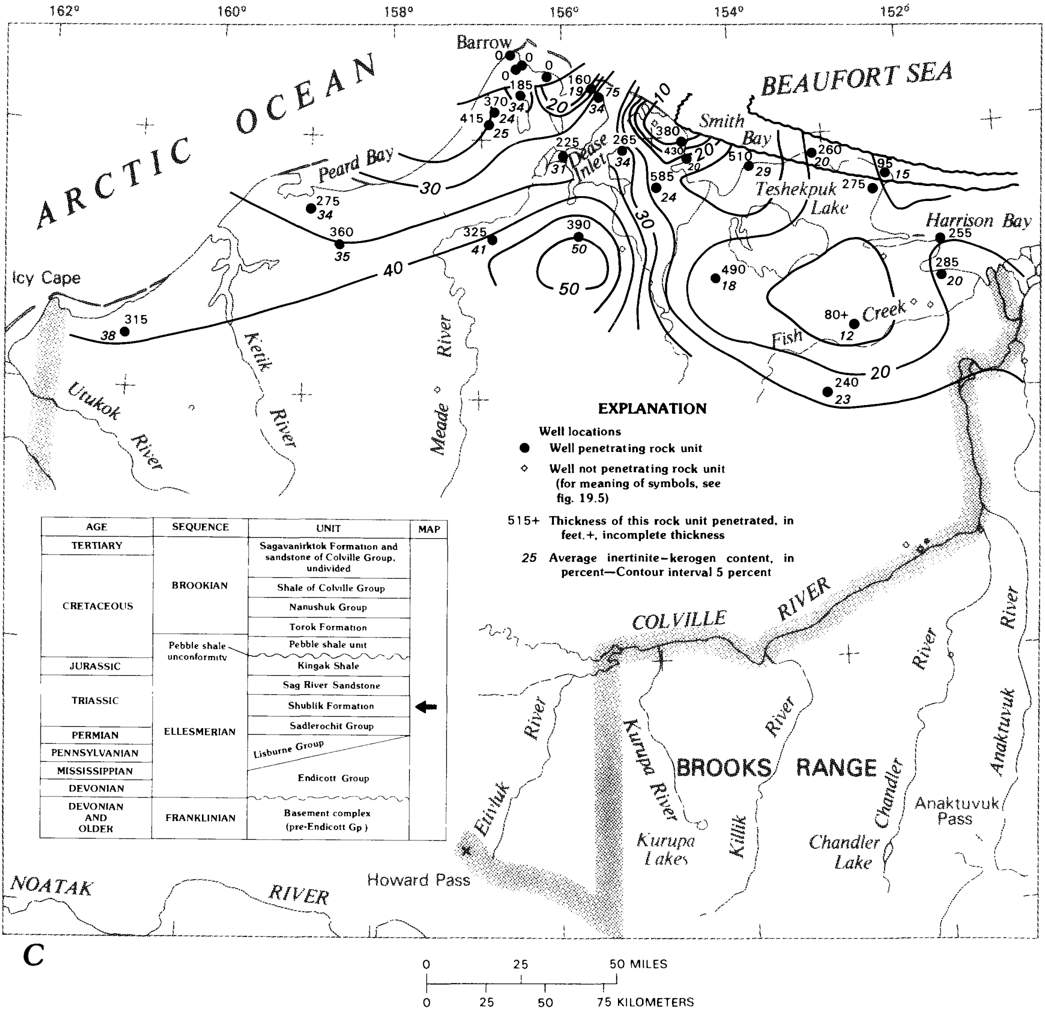


FIGURE 17.14.—Continued

(Lerand, 1973), includes in the subsurface Mississippian and Pennsylvanian clastic and carbonate rocks and coal. Deposition occurred in a series of partly fault-bounded basins where the unit's total thickness may exceed 3,000 m (10,000 ft) (see Bird, chapter 16). The lower part of the Endicott consists of nonmarine sandstone and shale and lesser amounts of conglomerate and coal. The upper part consists of dark-gray marine shale (red shale north of about lat 70° N.), increasing upward and with interbedded limestone. Geochemical data are limited to seven wells in the northeast quarter of the NPRA.

Organic-carbon values are less than 1 weight percent for all wells except the Inigok No. 1 (3.86 weight percent) and the Ikpikpuk No. 1 (4.26 weight percent), which encountered very high rank coal. The organic-carbon values for this unit range from 0.10 to 4.26 weight percent and average 0.85 weight percent (table 17.3; figs. 17.3-17.6, 17.8). The high value (4.26 weight percent) for the Ikpikpuk No. 1 well



AGE	SEQUENCE	UNIT	MAP
TERTIARY	BROOKIAN	Sagavanirktok Formation and sandstone of Colville Group, undivided	
CRETACEOUS		Shale of Colville Group	
		Nanushuk Group	
		Torok Formation	
	Pebble shale unconformity	Pebble shale unit	
JURASSIC	ELLESMERIAN	Kingak Shale	
TRIASSIC		Sag River Sandstone	
		Shublik Formation	←
PERMIAN		Sadlerochit Group	
PENNSYLVANIAN		Lisburne Group	
MISSISSIPPIAN			
DEVONIAN		Endicott Group	
DEVONIAN AND OLDER	FRANKLINIAN	Basement complex (pre-Endicott Gp.)	

FIGURE 17.14.—Continued

is shown on figure 17.8 in parentheses because coal horizons are at the base of the Endicott Group as indicated on the well display (pl. 19.15) and not at the top of the underlying rocks (fig. 17.7).

The HC/OC graph for the Endicott Group includes data from six wells comprising results from nine cuttings samples, two core samples, and one oil-stained cutting sample (table 17.3). The two core samples from the Topagoruk No. 1 and Inigok No. 1 wells indicate the Endicott Group is not a source-rock unit. However, average values on cutting samples from four wells imply that there may be a fair source facies within this rock unit. Two of the cutting samples from the Inigok No. 1 well do not compare favorably with the core analysis and suggest that caved material is being analyzed, some coal material is mixed with other material, or that the cores are from a different part of the section. High HC values from cutting samples in the Dalton No. 1 well result from oil staining. Values on drill cuttings from the

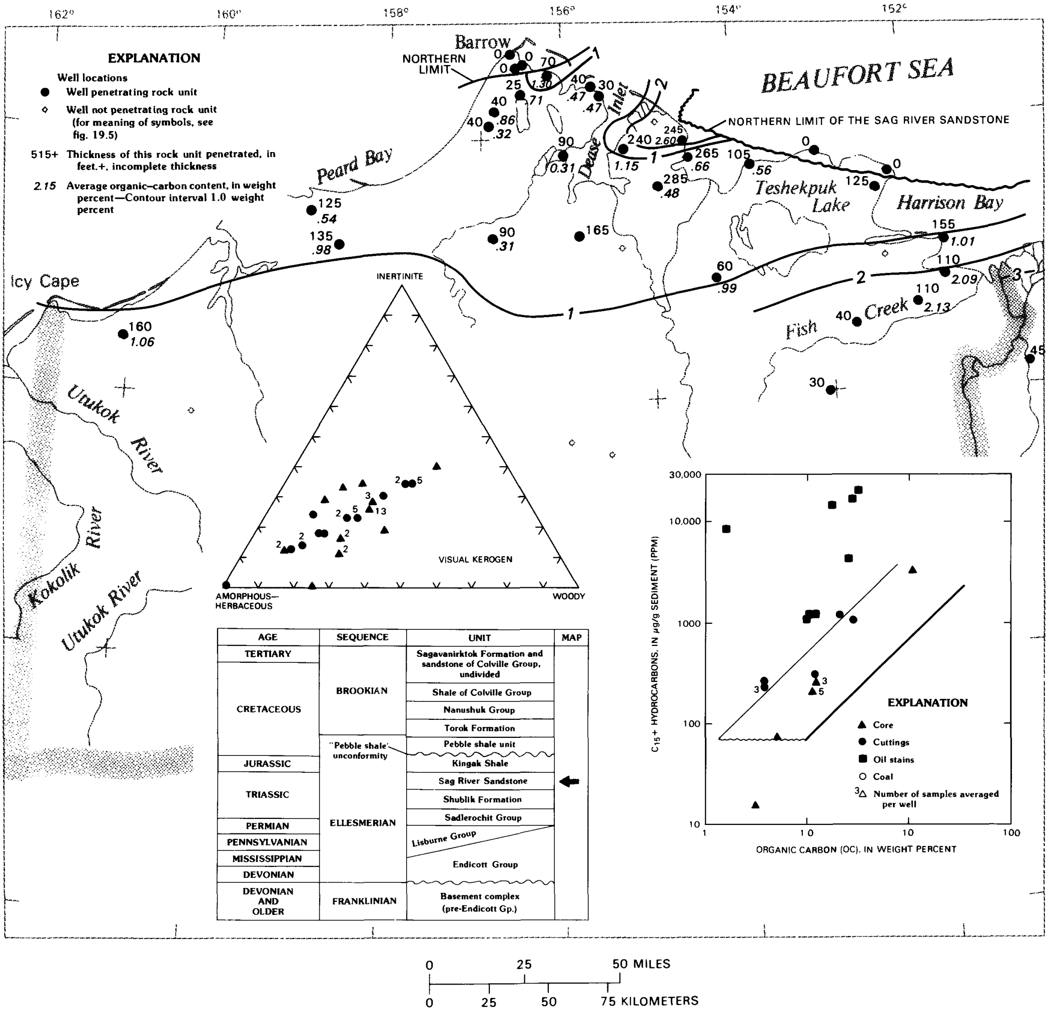


FIGURE 17.15.—Average organic-carbon content for the Sag River Sandstone, showing relation of organic-carbon content to content of extractable C_{15+} hydrocarbons and relative proportions of three kerogen types. Contour interval, 1 weight percent.

Atigaru Point No. 1 and South Simpson No. 1 wells indicate a fair source rock, but coal was reported in both wells. In summary, HC values on cutting samples from the Endicott Group suggest that it is a fair source rock, but low values from core samples indicate it is not.

Values of vitrinite reflectance, a measure of thermal maturity, are plotted and contoured at the base of the Ellesmerian sequence in figure 17.9. The horizon sampled is the base of the Endicott Group where that is present (table 17.2); elsewhere, it is the base of younger units where the sequence laps onto the Barrow high. The West Fish Creek No. 1 well, which showed anomalously low values (0.7 percent R_0) based entirely on cuttings, was disregarded in contouring. At the base of the Endicott Group, on an east-west trend from the Dalton No. 1 well, reflectance values are rather low (0.67 percent R_0), but they increase rapidly southward (2.80 percent R_0 in Ikpikpuk No. 1 well). To provide additional coverage to the south, vitrinite-reflec-

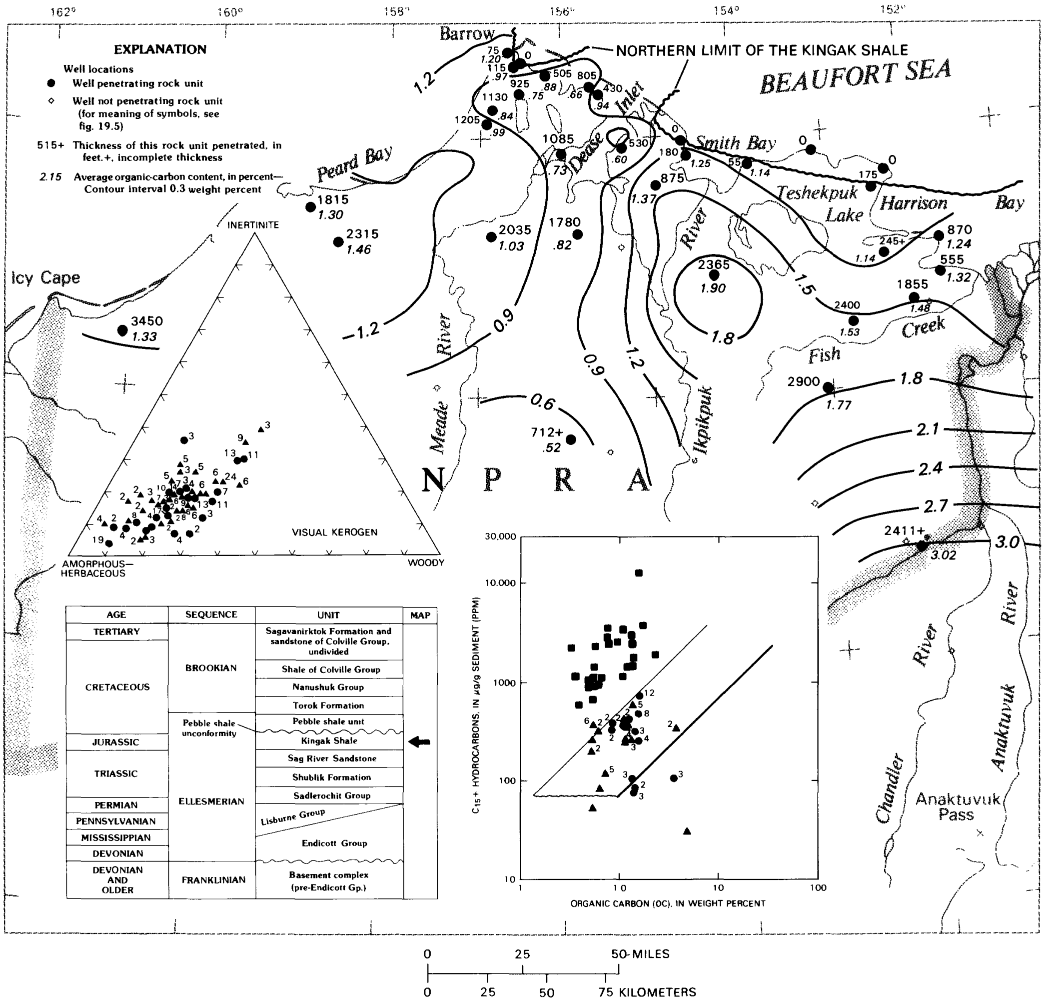
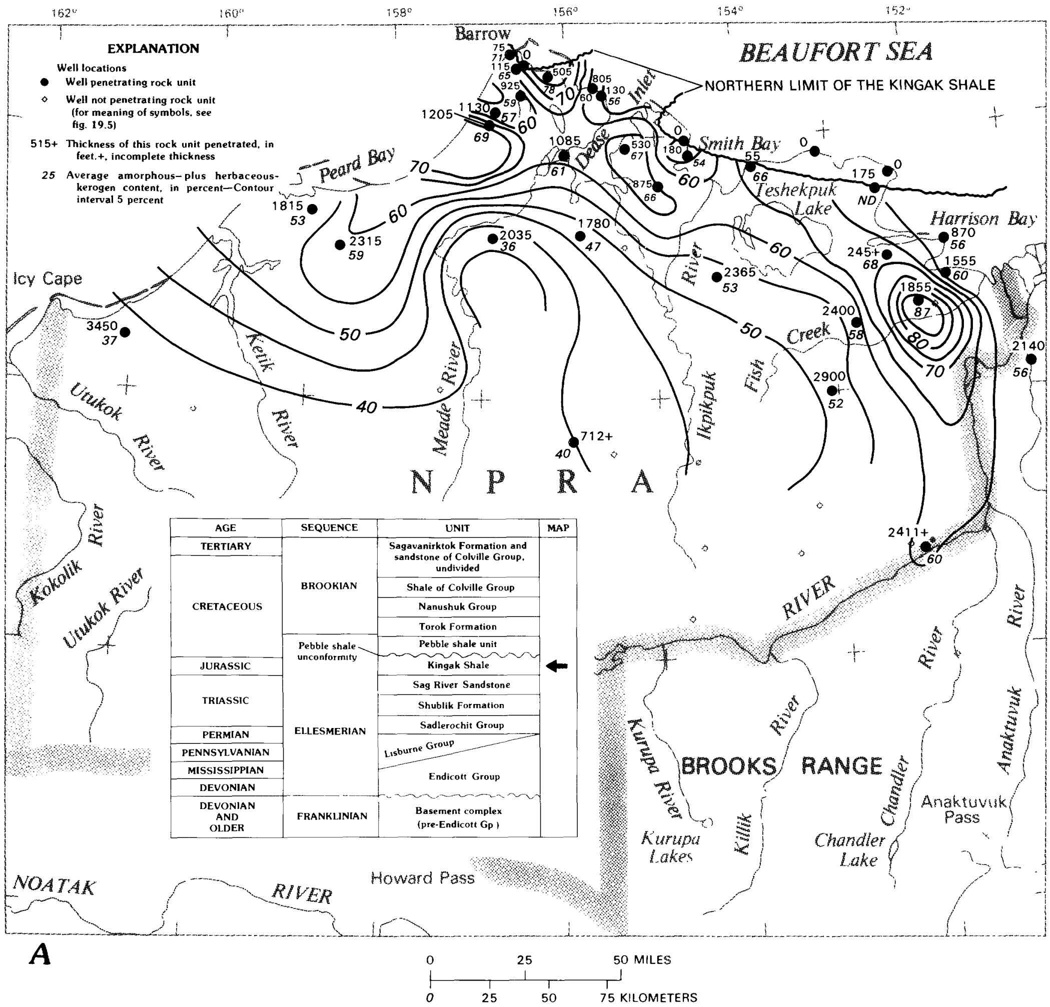


FIGURE 17.16.—Average organic-carbon content for the Kingak Shale, showing relation of organic-carbon content to content of extractable C_{15+} hydrocarbons and relative proportions of three kerogen types. Contour interval, 0.3 weight percent.

tance values in several wells were projected to the base of the Endicott Group. These wells—Inigok No. 1, Kugrua No. 1, and Tunalik No. 1—all have projected vitrinite-reflectance values that complement the regional trend.

The Endicott Group contains significant amounts of coal, as indicated on the lithology column of the large log displays for the Atigaru Point No. 1, Ikpikpuk No. 1, and Inigok No. 1 (pls. 19.12, 19.15, and 19.21, respectively); high organic-carbon values are evident in the last two wells. Most shales associated with coal (the exception is cannel coal, such as that in the Nanushuk Group) are gas prone even at vitrinite-reflectance values between 0.6 and 2.0 percent R_0. The Endicott Group in the northeastern part of the NPRA is considered a source of methane gas only. The Kayak Shale, a marine shale not associated with coal, is penetrated in the West Fish Creek



AGE	SEQUENCE	UNIT	MAP
TERTIARY	BROOKIAN	Sagavanirktok Formation and sandstone of Colville Group, undivided	
CRETACEOUS		Shale of Colville Group	
		Nanushuk Group	
		Torok Formation	
	Pebble shale unconformity	Pebble shale unit	
JURASSIC	ELLESMERIAN	Kingak Shale	←
TRIASSIC		Sag River Sandstone	
		Shublik Formation	
PERMIAN		Sadlerochit Group	
PENNSYLVANIAN		Lisburne Group	
MISSISSIPPIAN		Endicott Group	
DEVONIAN			
DEVONIAN AND OLDER	FRANKLINIAN	Basement complex (pre-Endicott Gp)	

FIGURE 17.17.—Relative proportions of three visual kerogen types (in percent) for the Kingak Shale. *A*, Amorphous plus herbaceous. *B*, Woody. *C*, Inertinite.

No. 1 and Inigok No. 1 wells (pls. 19.20, 19.21). One cutting sample from the former well and ten cutting samples from the latter have average OC values less than 1 weight percent. Because so few samples are available, the Kayak Shale cannot be adequately evaluated as a possible oil source.

LISBURNE GROUP

The Lisburne Group, a platform carbonate rock unit containing minor amounts of interbedded sandstone and shale (Bird and Jordan, 1977a), was deposited on a broad, shallow shelf that extended well beyond the boundaries of the NPRA. In the northern part of the NPRA, the Lisburne Group laps onto the Barrow high, but it is probably truncated offshore to the northeast. At the coastline, near this area of possible truncation, asphaltic oil was recovered from the Dalton No. 1 well, and significant oil shows were encountered in the

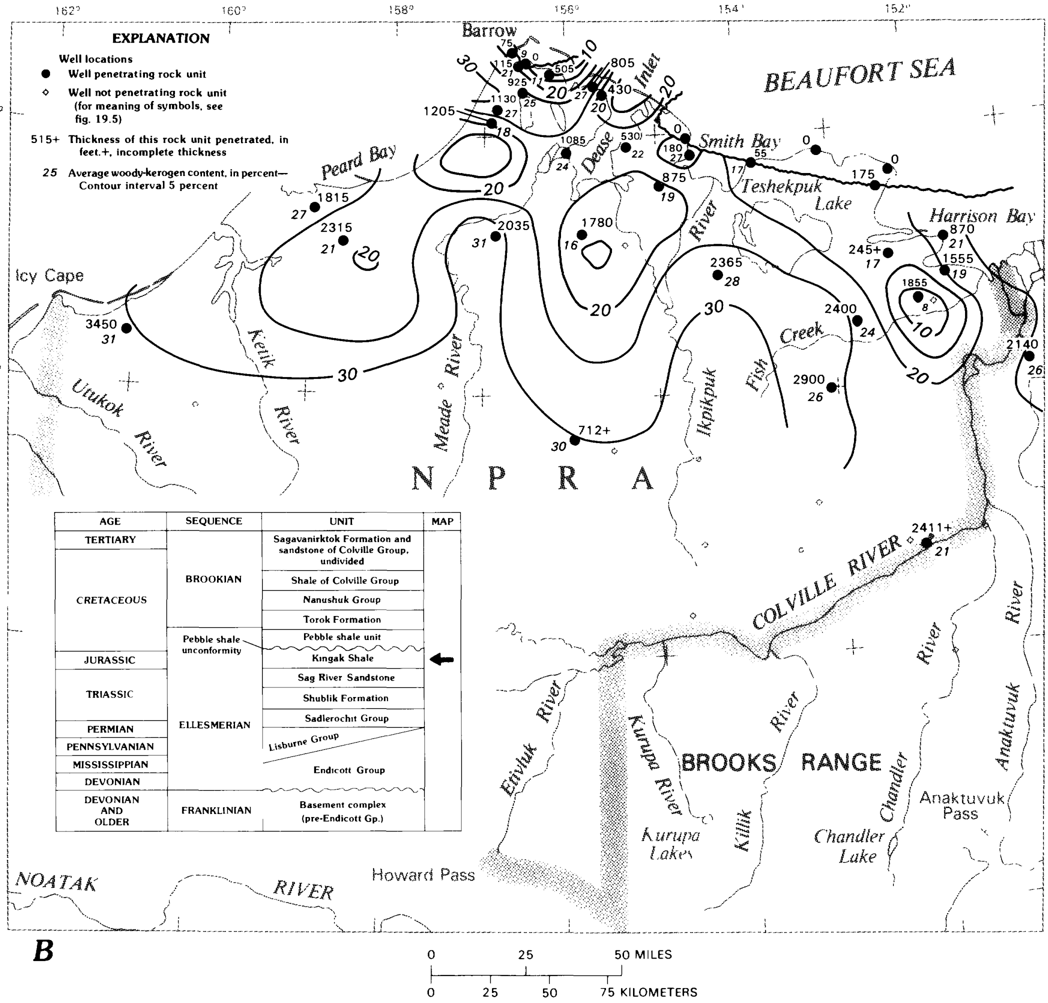
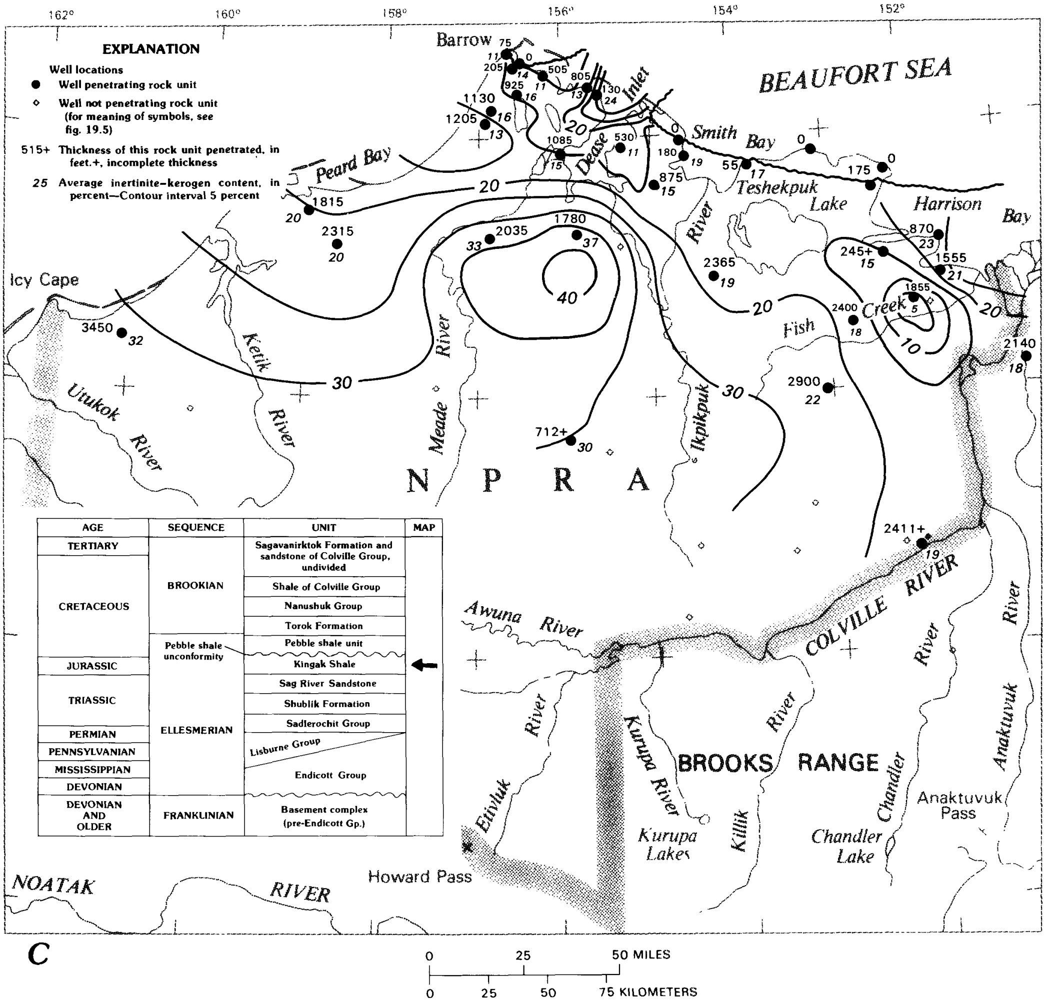


FIGURE 17.17.—Continued

W.T. Foran No. 1 well. Elemental sulfur and hydrogen sulfide gas were encountered at 5,355 m (17,570 ft) in the Inigok No. 1 well. Of the 10 wells that penetrate the Lisburne Group, 9 have been evaluated geochemically.

Data from the Lisburne No. 1 well, located in the southernmost part of the NPRA in the disturbed belt (see fig. 18.1), are not included in the contouring of the map for the Lisburne Group because those rocks are there entirely allochthonous and repeated by thrusting at least five times. The values for each thrust sheet are summarized on table 17.14, together with the average values for organic-carbon content (in weight percent) and visual-kerogen content (in percent) for the units penetrated in the entire well.

Of the 10 wells that penetrated the Lisburne Group in the northern part of the NPRA, 9 have organic-carbon values ranging from 0.14 to 0.94 weight percent and averaging 0.42 weight percent. Several high values (more than 1.0 weight percent) in the Dalton No. 1 and W.T.



AGE	SEQUENCE	UNIT	MAP
TERTIARY	BROOKIAN	Sagavanirktok Formation and sandstone of Colville Group, undivided	
CRETACEOUS		Shale of Colville Group	
		Nanushuk Group	
		Torok Formation	
	Pebble shale unconformity	Pebble shale unit	
JURASSIC	ELLESMERIAN	Kingak Shale	←
TRIASSIC		Sag River Sandstone	
		Shublik Formation	
PERMIAN		Sadlerochit Group	
PENNSYLVANIAN		Lisburne Group	
MISSISSIPPIAN		Endicott Group	
DEVONIAN			
DEVONIAN AND OLDER	FRANKLINIAN	Basement complex (pre-Endicott Gp.)	

FIGURE 17.17.—Continued

Foran No. 1 wells may be attributable to asphaltic oil contamination or, more likely, caving from the pebble shale unit or Shublik Formation. Omitting these suspect high values, the average value for this rock unit over the NPRA is 0.35 weight percent, below the richness required for a carbonate petroleum source rock (Hunt, 1979). The organic-carbon data are summarized in table 17.4 and figures 17.3-17.6 and 17.10.

The HC/OC graph for the Lisburne Group includes data from 7 wells comprising results from 15 cutting samples, 2 core samples, and 9 oil-stained samples (3 cores, 6 cuttings). Except for two samples from two wells, the Lisburne Group rocks fall into two categories—nonsource and oil stained. The oil-stained samples are from two wells, W.T. Foran No. 1 and J.W. Dalton No. 1, whereas the nonsource HC/OC ratios come from the remaining five wells. The two exceptions, a core and a cutting sample, are from the two wells that contain the oil stains, and so their

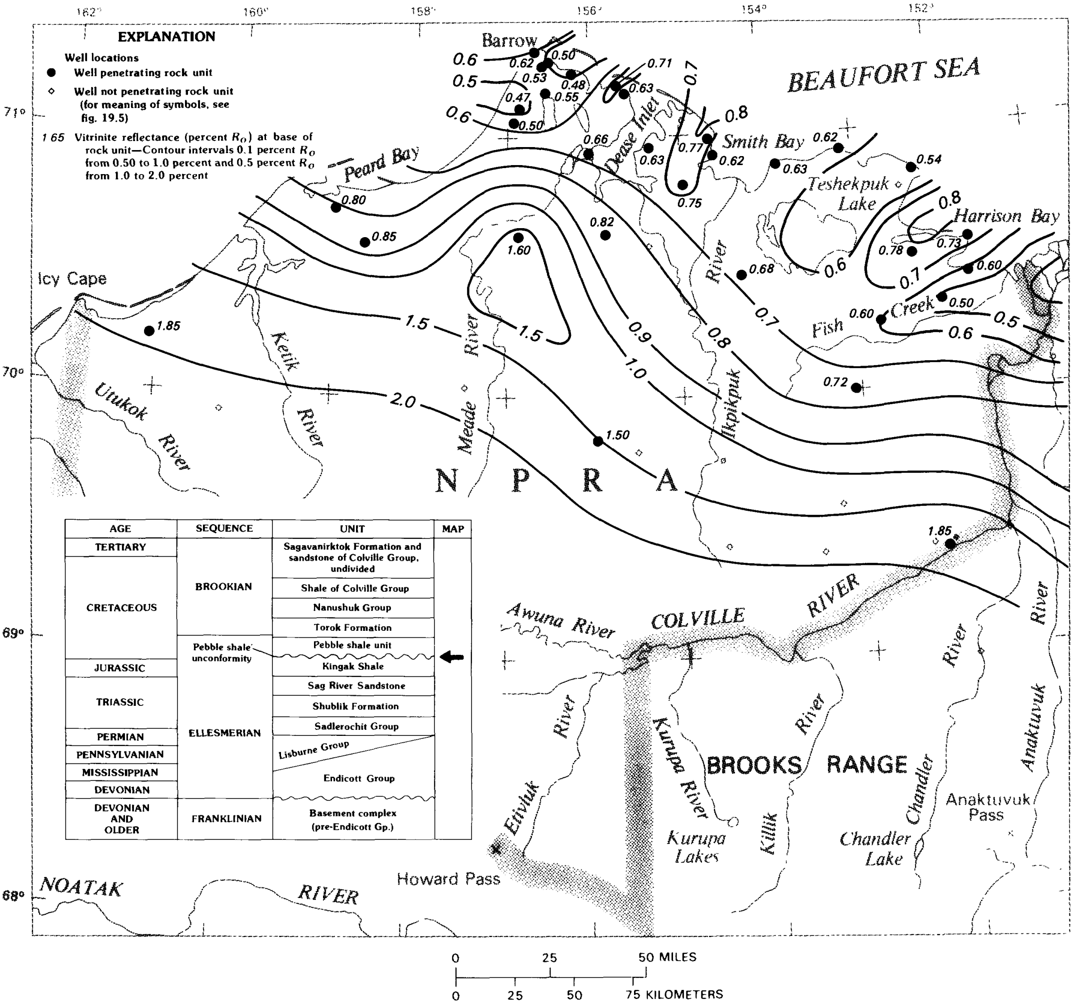
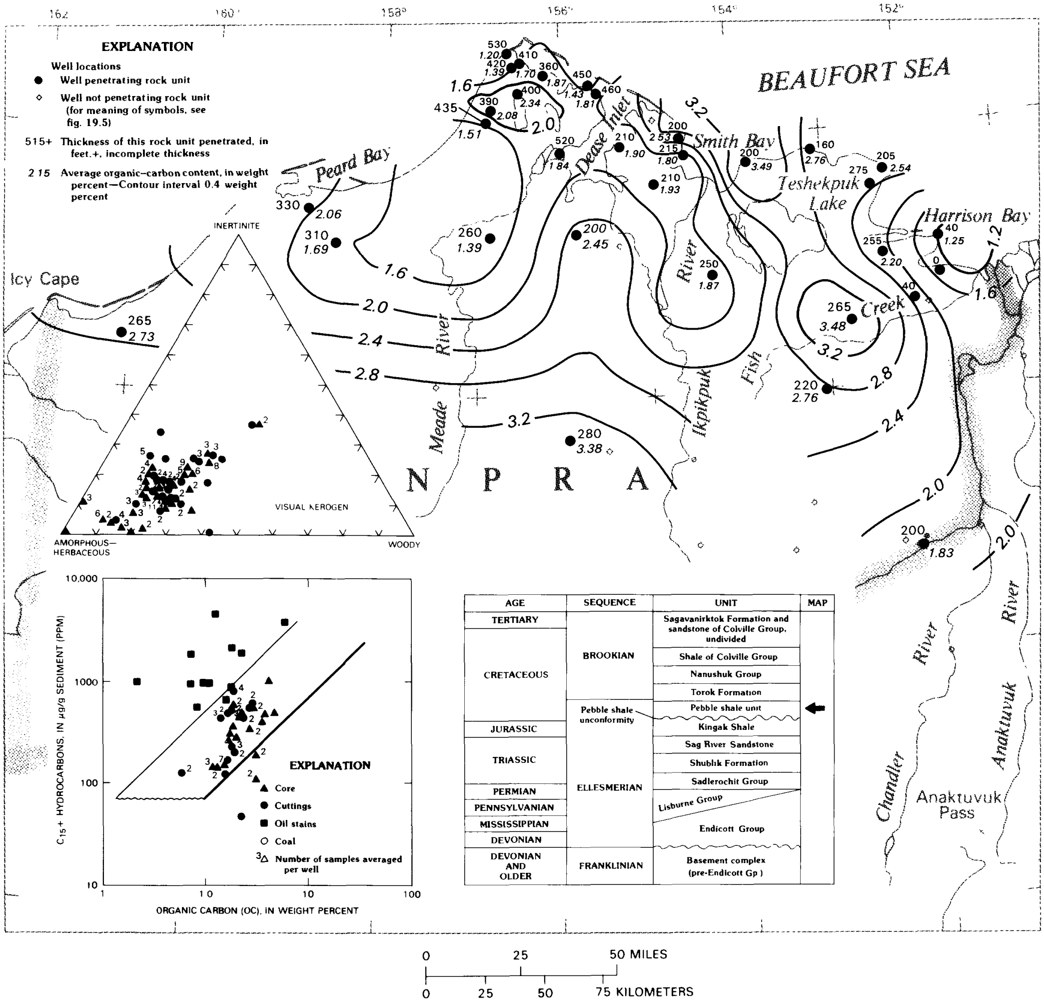


FIGURE 17.18.—Vitrinite-reflectance values at base of the pebble shale unit, contoured at intervals of 0.1 and 0.5 percent R_o.

high HC/OC values could also be attributed to migrated hydrocarbons.

Vitrinite-reflectance values in the Lisburne Group are suspect because carbonate rocks are generally devoid of vitrain macerals, but units above (fig. 17.12) and below (fig. 17.9) provide a basis for estimating the thermal history. The estimated vitrinite reflectance for the Lisburne Group is generally high (more than 1.5 percent R_0) over most of the NPRA except in the northeast near Teshekpuk Lake.

As a potential source for petroleum, the Lisburne Group cannot be entirely eliminated because areas in the Brooks Range contain favorable source-rock facies (Tailleur, 1964), indicating that source quality may improve downdip from the Inigok No. 1 and Tunalik No. 1 wells. The Lisburne Group underlies a large untested area of the NPRA in which the unit has passed through the liquid window and presently is in the gas window. This high-temperature thermal



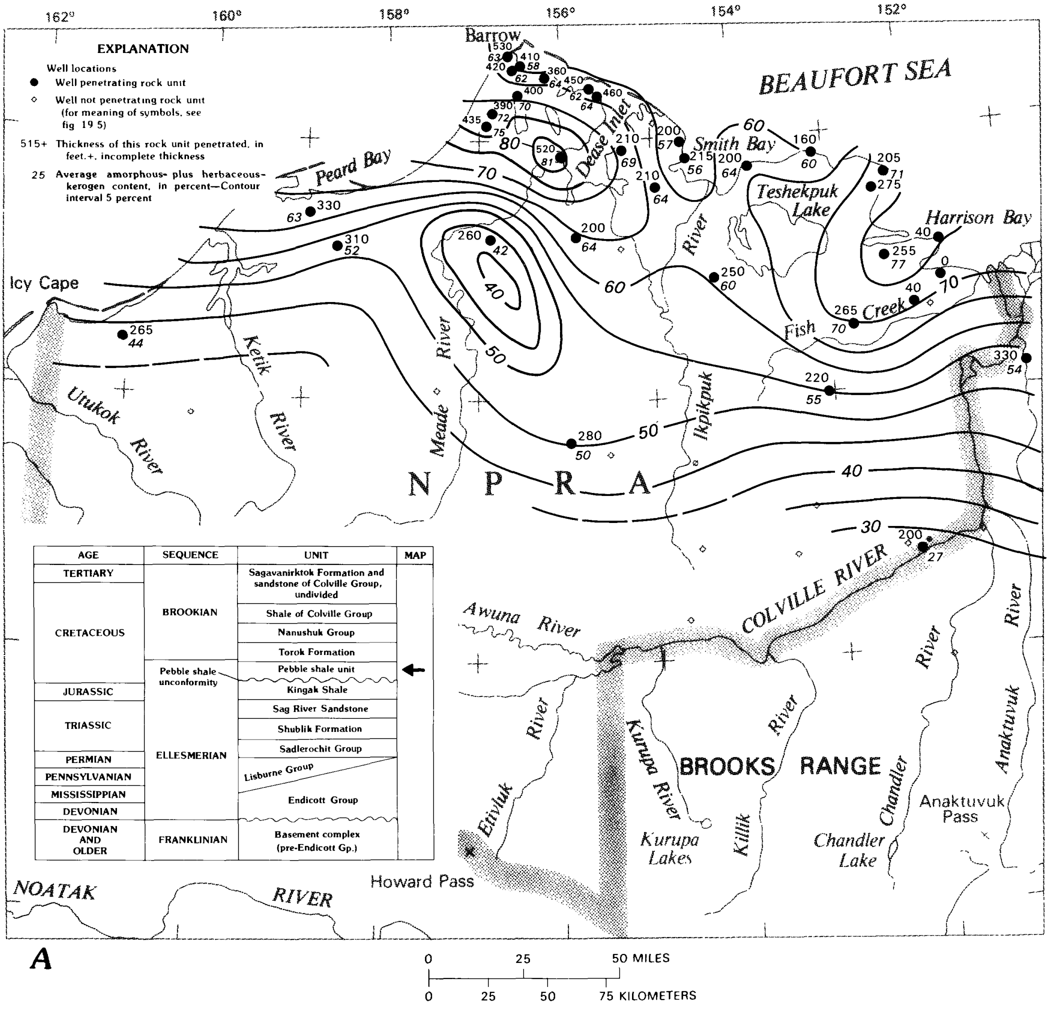
AGE	SEQUENCE	UNIT	MAP
TERTIARY	BROOKIAN	Sagavanirktok Formation and sandstone of Colville Group, undivided	
CRETACEOUS		Shale of Colville Group	
		Nanushuk Group	
		Torok Formation	
	Pebble shale unconformity	Pebble shale unit	⬅
JURASSIC	ELLESMERIAN	Kingak Shale	
TRIASSIC		Sag River Sandstone	
		Shublik Formation	
PERMIAN		Sadlerochit Group	
PENNSYLVANIAN		Lisburne Group	
MISSISSIPPIAN		Endicott Group	
DEVONIAN			
DEVONIAN AND OLDER	FRANKLINIAN	Basement complex (pre-Endicott Gp)	

FIGURE 17.19.—Average organic-carbon content for the pebble shale unit, showing relation of organic-carbon content to content of extractable C_{15+} hydrocarbons and relative proportions of three kerogen types. Contour interval, 0.4 weight percent.

history makes the Lisburne difficult to assess goechemically but indicates that oil could have been generated and migrated to the north, as in the Dalton and Prudhoe areas (Bird and Jordan, 1977a, b; Mull and others, 1982). Also, the oil produced from the Prudhoe Bay field has a moderately high sulfur content (0.9 weight percent), which is indicative of a carbonate or iron-deficient source (Magoon and Claypool, 1981).

SADLEROCHIT GROUP

The Sadlerochit Group—alluvial to nearshore-marine sandstone, conglomerate, and shale in the north—grades southward into entirely marine fine-grained sedimentary rocks (Jones and Speers, 1976). The Sadlerochit Group has a zero onlap edge in the north and thickens to 693 m (2,275 ft) in the Tunalik No. 1 well (see Bird, chapter 16). Of the 17 wells that penetrate this rock unit, 16 have been evaluated geochemically.

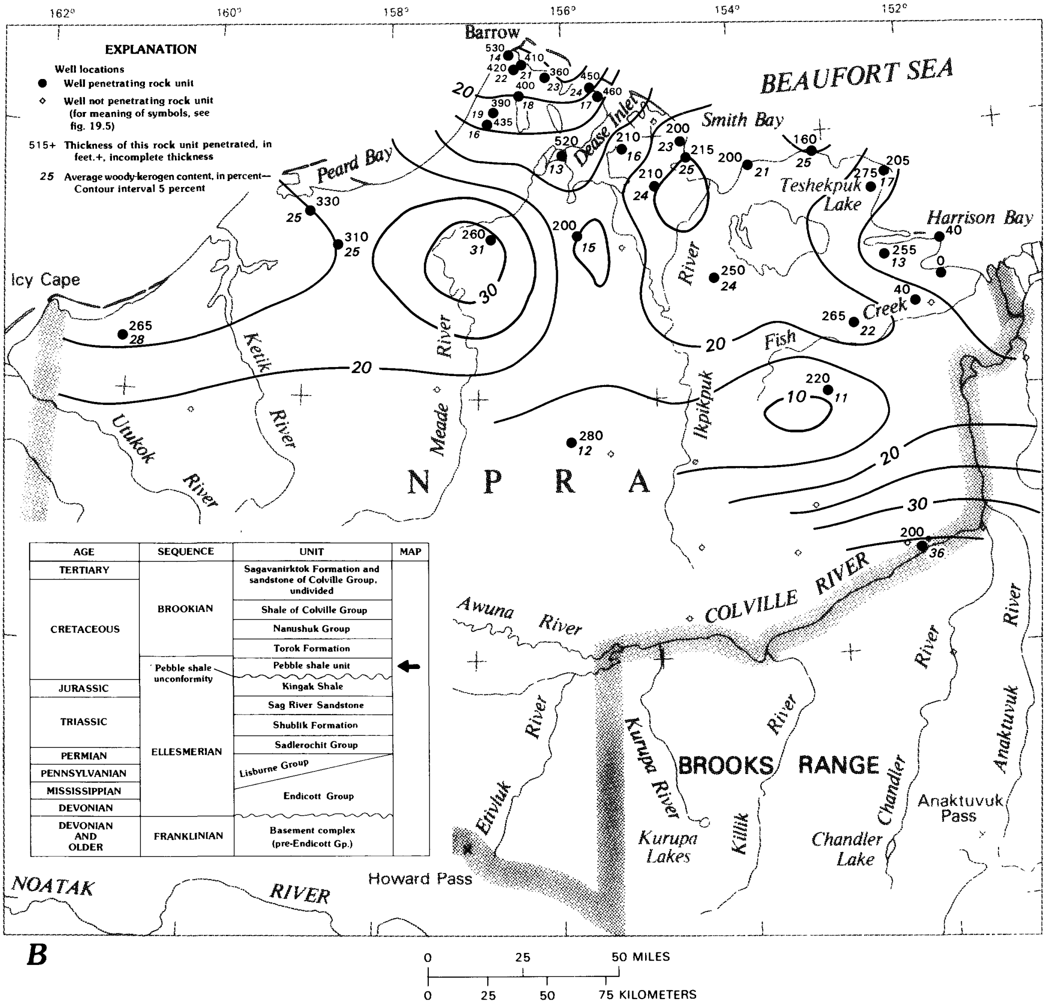


AGE	SEQUENCE	UNIT	MAP
TERTIARY	BROOKIAN	Sagavanirktok Formation and sandstone of Colville Group, undivided	
CRETACEOUS		Shale of Colville Group	
		Nanushuk Group	
		Torok Formation	
	Pebble shale unconformity	Pebble shale unit	←
JURASSIC	ELLESMERIAN	Kingak Shale	
TRIASSIC		Sag River Sandstone	
		Shublik Formation	
		Sadlerochit Group	
PERMIAN		Lisburne Group	
PENNSYLVANIAN			
MISSISSIPPIAN		Endicott Group	
DEVONIAN			
DEVONIAN AND OLDER	FRANKLINIAN	Basement complex (pre-Endicott Gp.)	

FIGURE 17.20.—Relative proportions of three visual kerogen types (in percent) for the pebble shale unit. *A*, Amorphous plus herbaceous. *B*, Woody. *C*, Inertinite.

The organic-carbon content, from 16 wells in the north half of the NPRA, has mean values that range from 0.18 to a high of 5.61 weight percent and average 1.01 weight percent. The high value (5.61 weight percent) occurs in the East Simpson No. 2 well, where a significant amount of coal was penetrated in the Sadlerochit Group (pl. 19.9). The data for the Sadlerochit Group are listed in table 17.5 and shown on figures 17.3-17.6 and 17.11.

The HC/OC graph for the Sadlerochit Group includes data from 14 wells, comprising results from 22 cutting samples, 20 core samples, 5 coal core samples, and 14 oil-stained samples (6 cores, 8 cuttings). Except for cutting samples from four wells, three categories of HC/OC ratio are evident: (1) coal from a core at East Simpson No. 1 well; (2) migrated hydrocarbons from the W.T. Foran No. 1, Drew Point No. 1, Dalton No. 1, and Peard No. 1 wells; and (3) core samples indicating nonsource rocks. The exceptions to these three



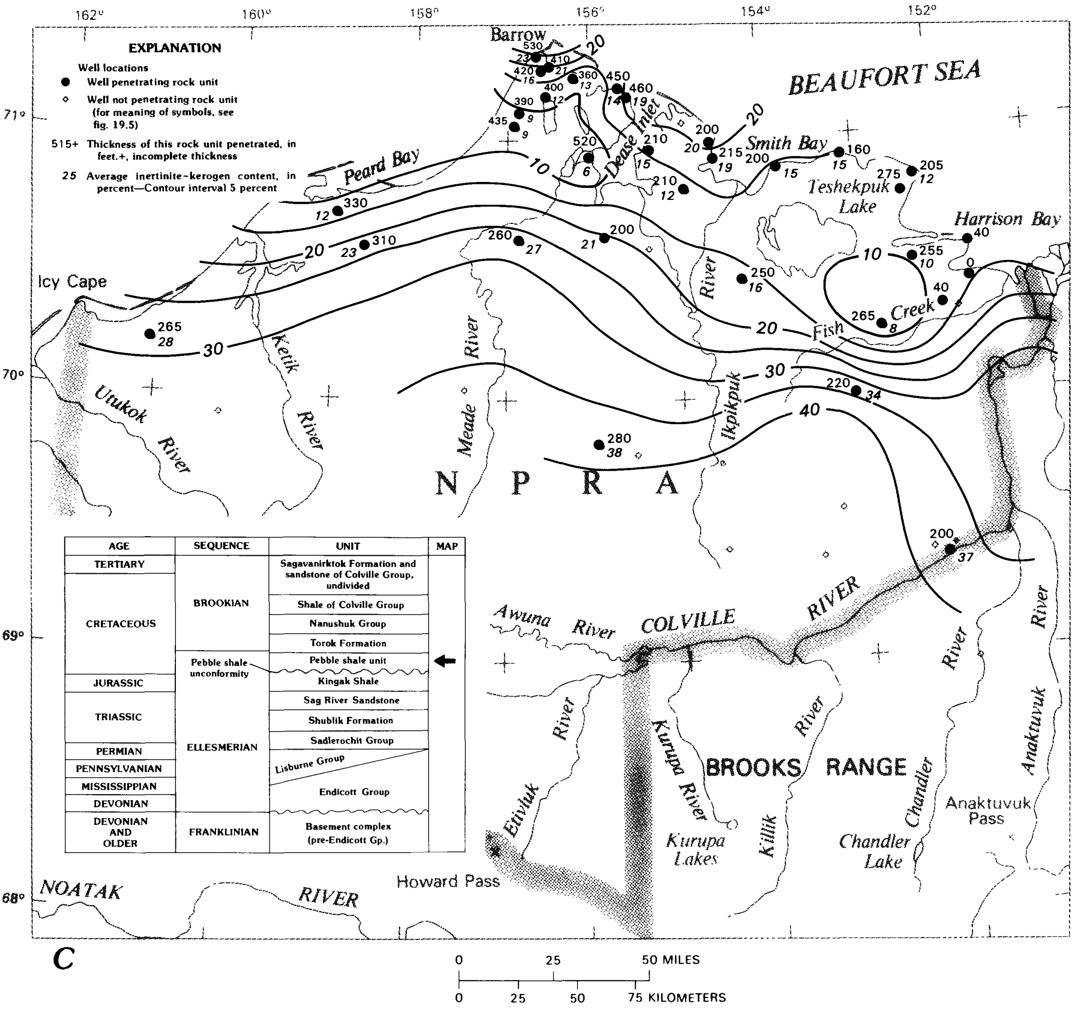
AGE	SEQUENCE	UNIT	MAP
TERTIARY	BROOKIAN	Sagavanirktok Formation and sandstone of Colville Group, undivided	
CRETACEOUS		Shale of Colville Group	
		Nanushuk Group	
		Torok Formation	
	Pebble shale unconformity	Pebble shale unit	←
JURASSIC	ELLESMERIAN	Kingak Shale	
TRIASSIC		Sag River Sandstone	
		Shublik Formation	
		Sadlerochit Group	
PERMIAN		Lisburne Group	
PENNSYLVANIAN			
MISSISSIPPIAN		Endicott Group	
DEVONIAN			
DEVONIAN AND OLDER	FRANKLINIAN	Basement complex (pre-Endicott Gp.)	

FIGURE 17.20.—Continued

categories are inferred to result from a combination of migrated oil, coaly material, and caved cuttings because the lithology of the Sadlerochit Group along the coastline represents nonmarine to transitional marine facies—not a depositional environment conducive to the preservation of hydrogen-rich organic matter.

All three stages of petroleum evolution (diagenesis, catagenesis, metagenesis) are represented in the uppermost part of the Sadlerochit Group, as shown on the contoured vitrinite-reflectance data in figure 17.12 and table 17.5. Exploratory wells located on the Fish Creek platform are in the late stage of diagenesis (less than 0.6 percent R_o) or early catagenesis (more than 0.6 percent R_o). Thermal maturity increases downdip into the Colville Trough—late catagenesis (less than 2.0 percent R_o) to metagenesis (2.0-4.5 percent R_o)—to a maximum measured value in the Tunalik No. 1 well of 4.15 percent R_o.

The Sadlerochit Group, on the basis of its organic carbon and



AGE	SEQUENCE	UNIT	MAP
TERTIARY	BROOKIAN	Sagavanirktok Formation and sandstone of Colville Group, undivided	
CRETACEOUS		Shale of Colville Group	
		Nanushuk Group	
		Torok Formation	
	Pebble shale unconformity	Pebble shale unit	⬅
JURASSIC	ELLESMERIAN	Kingak Shale	
TRIASSIC		Sag River Sandstone	
		Shublik Formation	
PERMIAN		Sadlerochit Group	
PENNSYLVANIAN		Lisburne Group	
MISSISSIPPIAN		Endicott Group	
DEVONIAN			
DEVONIAN AND OLDER	FRANKLINIAN	Basement complex (pre-Endicott Gp.)	

FIGURE 17.20.—Continued

hydrocarbon content, is a poor potential source rock and is probably gas prone in the northern part of the NPRA. Gas is anticipated for all the deeply buried (more than 2.0 percent R_O) parts of the Sadlerochit Group.

SHUBLIK FORMATION

The Shublik Formation consists of limestone, sandstone, siltstone, phosphatic shale, and calcareous shale that were deposited in a marine environment (Jones and Speers, 1976). Except for a very small area around Point Barrow where the unit thins to zero thickness by onlap, the Shublik is present throughout the NPRA. In the 25 wells where the Shublik Formation was penetrated, the unit ranges in thickness from 29 to 155 m (95-510 ft). Near the north limit of the Shublik Formation, the sandstone and siltstone content of the unit increases, making it difficult to distinguish it from the overlying Sag River Sandstone. The Shublik Formation was sampled and geochemically evaluated in 24 of the 25 wells in which it was penetrated.

The organic-carbon content of the Shublik Formation in the 24 wells

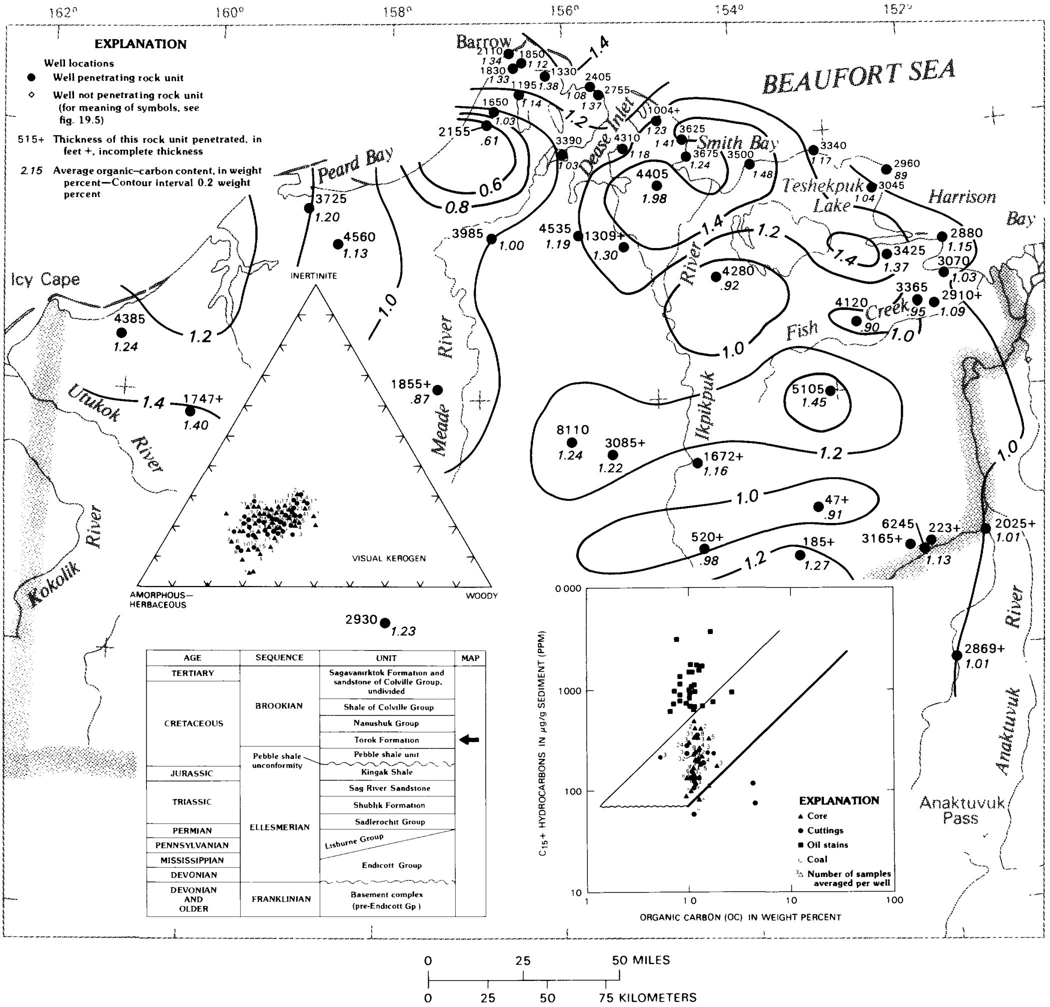


FIGURE 17.21.—Average organic-carbon content for the Torok Formation, showing relation of organic-carbon content to content of extractable C_{15+} hydrocarbons and relative proportions of three kerogen types. Contour interval, 0.2 weight percent.

ranges from 0.52 to 3.25 weight percent and averages 1.29 weight percent. It is lowest near the north depositional limit, probably because of the increased siltstone and sandstone content, and increases southward (downdip). From west to east, values are lowest (less than 1.0 weight percent) in the South Meade No. 1 well, located on the Meade arch, and increase to the east boundary of the NPRA. The only core sample in the Shublik from the Topagorak No. 1 well is anomalously high (2.84 weight percent) in organic-carbon content in comparison with the South Meade No. 1 (0.61 weight percent) and Kuyanuk No. 1 (0.57 weight percent) wells, but is closer to the average organic-carbon values from the Ikpikpuk No. 1 (1.98 weight percent) and Inigok No. 1 (2.67 weight percent) wells. The one value obtained from the Topagoruk No. 1 well was used on the contour map. The organic-carbon content is shown on the four cross sections (figs. 17.3-17.6) and on the contour map (fig. 17.13) and is listed in table 17.6.

The HC/OC graph for the Shublik Formation includes data from 18

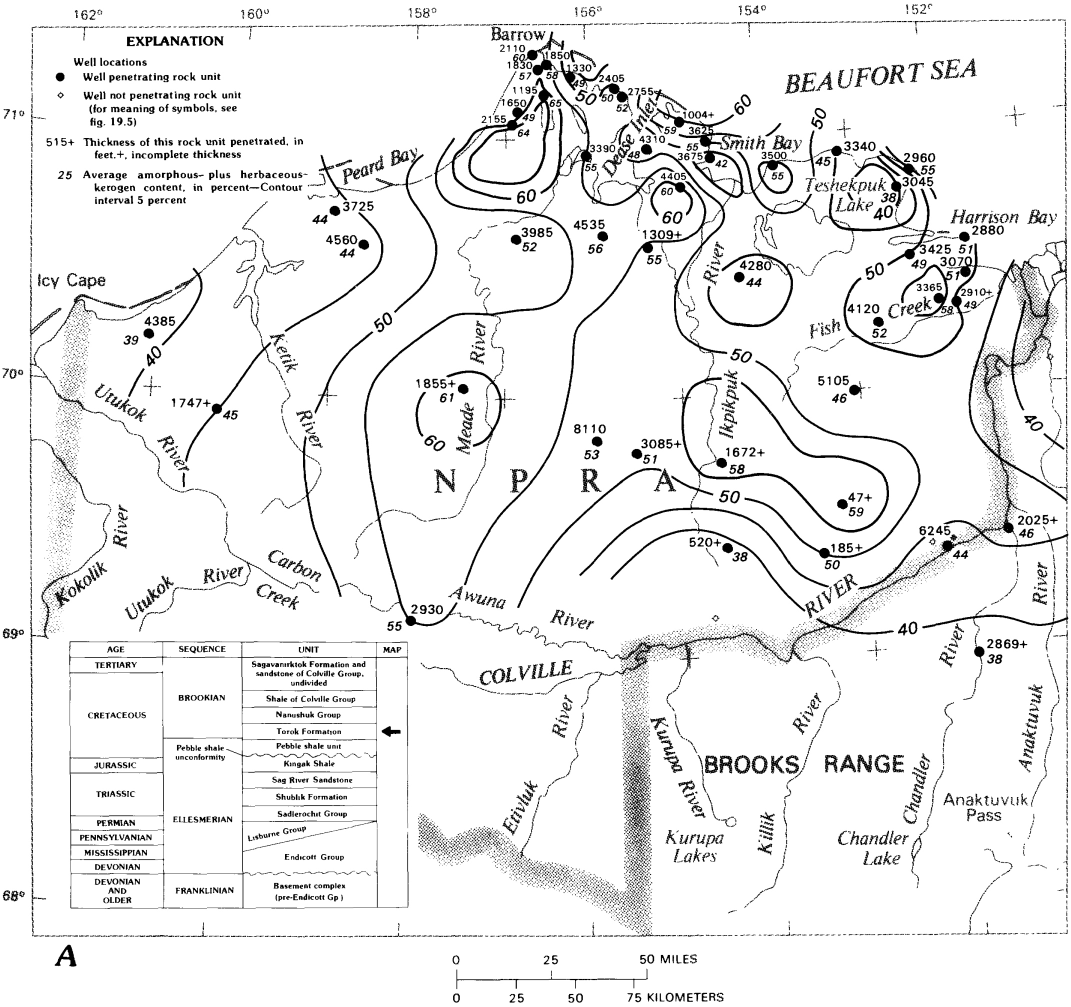
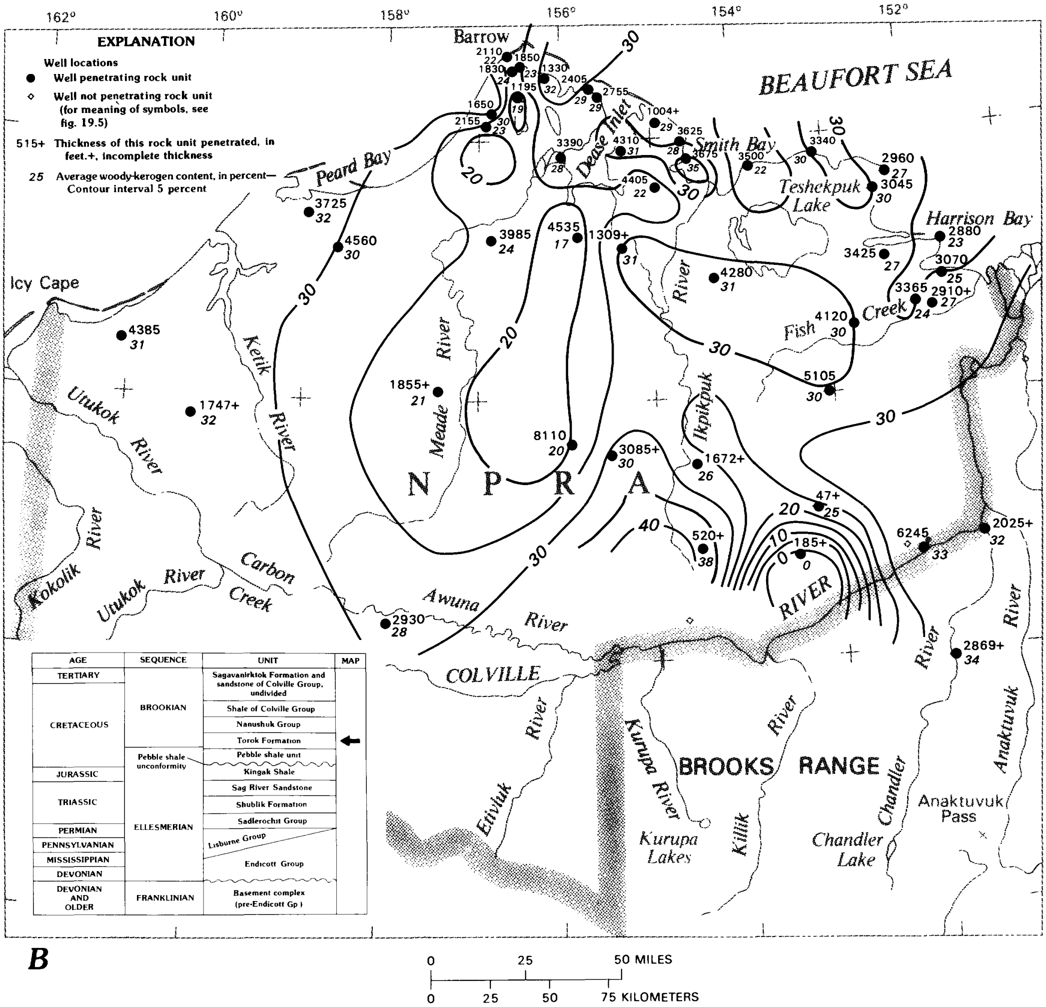


FIGURE 17.22.—Relative proportions of three visual kerogen types (in percent) for the Torok Formation. *A*, Amorphous plus herbaceous. *B*, Woody. *C*, Inertinite.

wells—21 cutting samples, 16 core samples, and 6 oil-stained samples (4 cores, 2 cuttings). There are three categories of HC/OC ratio: (1) nonsource facies, which in the case of the Inigok No. 1, South Meade No. 1, and Kugrua No. 1 wells may be because of maturity; (2) good source facies, which includes most of the core information; and (3) oil-stained rocks from the W.T. Foran No. 1, South Simpson No. 1, West Dease No. 1, Drew Point No. 1, and Peard No. 1 wells. HC/OC ratios slightly above 0.05 are difficult to interpret, as in the samples from the South Simpson No. 1, East Simpson No. 1, South Barrow No. 2, W.T. Foran No. 1, and West Fish Creek No. 1 wells. Even if these values are considered oil stains, however, there are sufficient values from the other wells to indicate that the Shublik Formation is a fair to good source for oil.

The visual-kerogen content for the Shublik Formation varies from west to east across the NPRA (figs. 17.13, 17.14). The amorphous and herbaceous content is less than 50



AGE	SEQUENCE	UNIT	MAP
TERTIARY	BROOKIAN	Sagavanirktok Formation and sandstone of Colville Group, undivided	
CRETACEOUS		Shale of Colville Group	
		Nanushuk Group	
		Torok Formation	⬅
	Pebble shale unconformity ELLESMERIAN	Pebble shale unit	
JURASSIC		Kingak Shale	
TRIASSIC		Sag River Sandstone	
		Shublik Formation	
		Sadlerochit Group	
PERMIAN		Lisburne Group	
PENNSYLVANIAN			
MISSISSIPPIAN		Endicott Group	
DEVONIAN			
DEVONIAN AND OLDER	FRANKLINIAN	Basement complex (pre-Endicott Gp)	

B

FIGURE 17.22.—Continued

percent west of the Meade arch and more than 50 percent east of the arch; it decreases toward the Colville Trough, west of the Meade arch, and increases into the Ikpikpuk Basin east of the Meade arch. The composition of woody material shows limited variation—between 0 and 30 percent—across the NPRA. The inertinite contour pattern is similar to the amorphous-plus-herbaceous pattern, but opposite in gradient; that is, when the percentage of inertinite increases, there is generally a corresponding decrease in the percentage of amorphous and herbaceous material. Both the inertinite composition and the vitrinite reflectance increase southward, implying a strong possibility that high maturity levels have altered the indigenous amorphous and herbaceous material so extensively that it is now interpreted as inertinite (see Bayliss and Magoon, chapter 20). The triangular plot for kerogen is shown on figure 17.13,

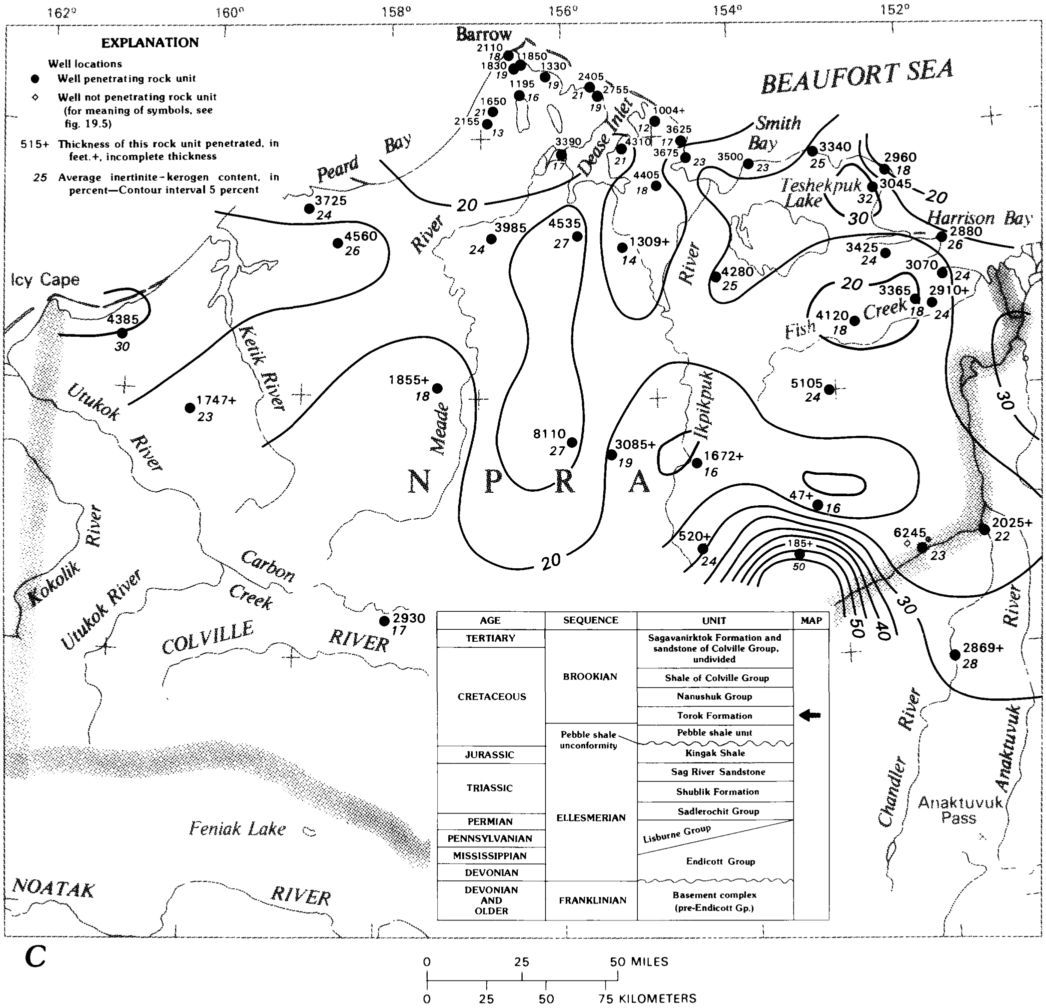
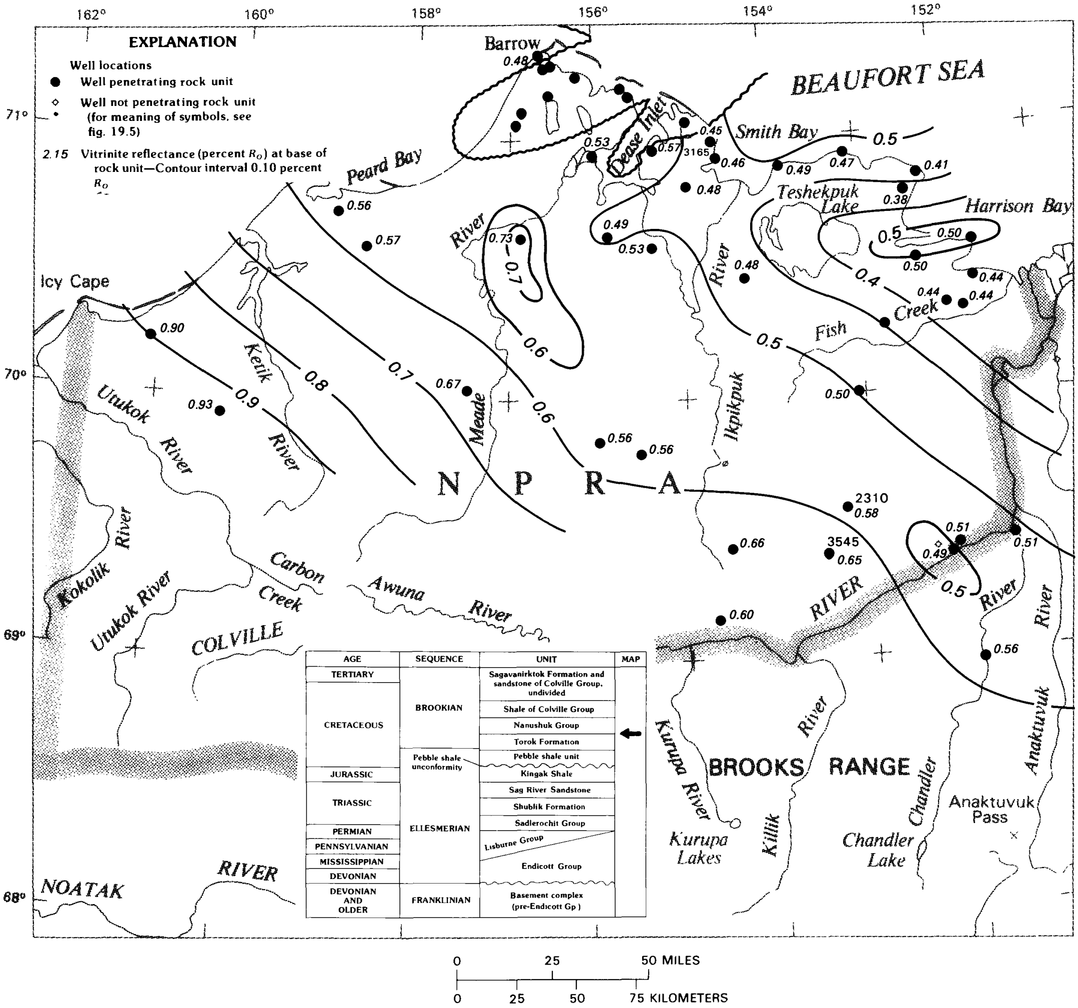


FIGURE 17.22.—Continued

and the visual-kerogen maps are shown in figure 17.14.

Vitrinite-reflectance data for the base of the Shublik Formation or the top of the Sadlerochit Group are contoured in figure 17.12. Only a small area of the Shublik Formation is in the diagenetic stage of petroleum generation (less than 0.6 percent R_o) on the west side of the Barrow high and on the Fish Creek platform. Vitrinite-reflectance values increase regularly downdip, except that the South Meade No. 1 well has an exceptionally high value (3.20 percent R_o). Even the present-day geothermal gradient is anomalously high (47 °C/km) in this well (see South Meade No. 1 well display, pl. 19.13; Blanchard and Tailleur, 1982).

The average organic-carbon content (1.3 weight percent), the significant amount of oil-prone kerogen (amorphous plus herbaceous), and the high-temperature thermal history (more than 2.0 per-



AGE	SEQUENCE	UNIT	MAP
TERTIARY	BROOKIAN	Sagavanirktok Formation and sandstone of Colville Group, undivided	
CRETACEOUS		Shale of Colville Group	
		Nanushuk Group	←
		Torok Formation	
	Pebble shale unconformity	Pebble shale unit	
JURASSIC	ELLESMERIAN	Kingak Shale	
TRIASSIC		Sag River Sandstone	
		Shublik Formation	
		Sadlerochit Group	
PERMIAN		Lisburne Group	
PENNSYLVANIAN			
MISSISSIPPIAN		Endicott Group	
DEVONIAN			
DEVONIAN AND OLDER	FRANKLINIAN	Basement complex (pre-Endicott Gp)	

FIGURE 17.23.—Vitrinite-reflectance values at base of the Nanushuk Group, contoured at interval of 0.1 percent R_o. In figures 17.23 and 17.24, the unconformity represented by a wavy line in the vicinity of Barrow and Dease Inlet truncates the Torok Formation and the Nanushuk Group (see fig. 18.3).

cent R_0) make the Shublik Formation a fair source for North Slope hydrocarbons. In addition, the stratigraphic relation of the Shublik Formation to two potential reservoir rock units—the Sadlerochit Group and the Sag River Sandstone—provides an updip conduit for expelled oil or gas.

SAG RIVER SANDSTONE

The Sag River Sandstone consists of a relatively thin, blanketlike deposit, less than 90 m (300 ft) thick, of glauconitic sandstone, including as much as 50 percent siltstone and shale, deposited in a shallow-marine environment (Reiser, 1970; Jones and Speers, 1976). The sandstone grades rapidly southward into siltstone and shale. Of the 28 wells that penetrated the Sag River Sandstone, 25 have been evaluated geochemically.

Organic-carbon values from the 24 wells analyzed range from 0.31 to 2.60 weight percent and have a

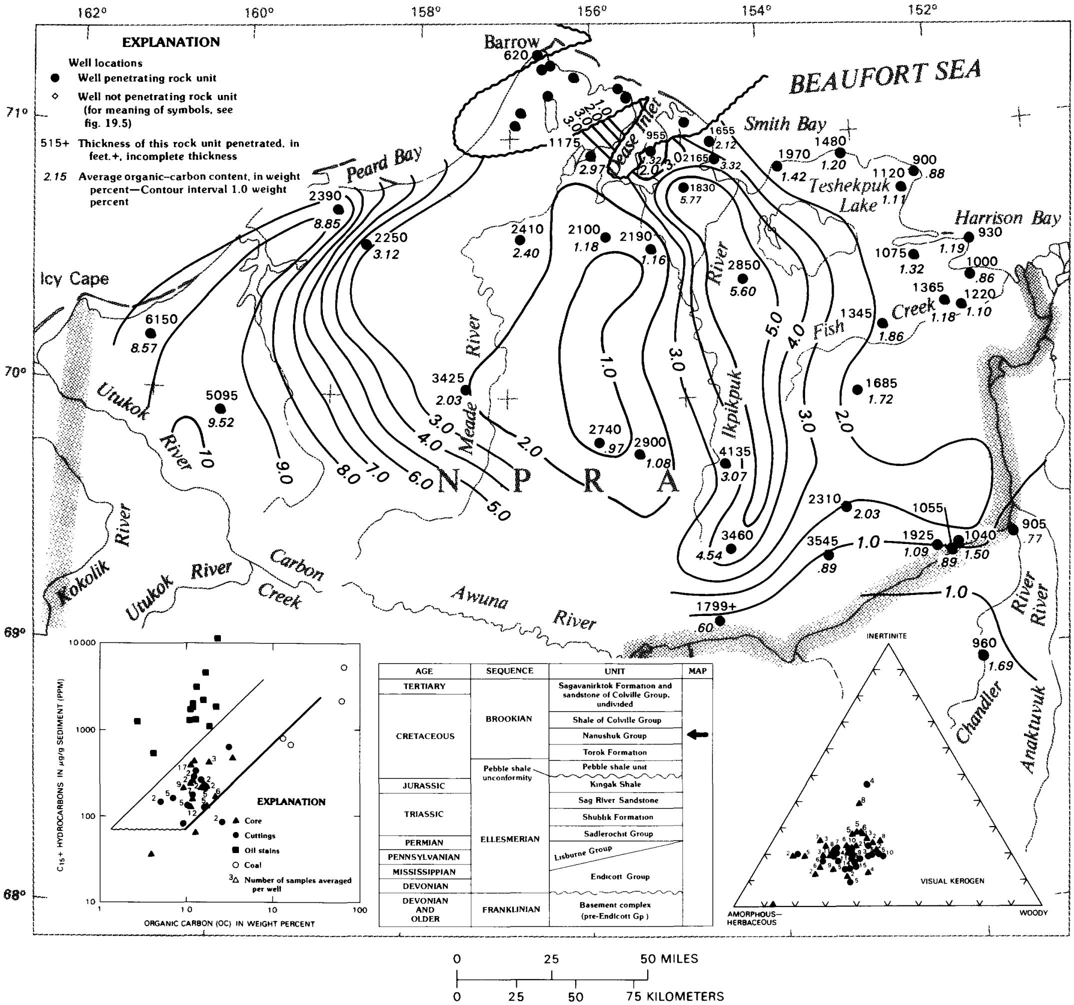


FIGURE 17.24.—Average organic-carbon content for the Nanushuk Group, showing relation of organic-carbon content to content of extractable C_{15+} hydrocarbons and relative proportions of three kerogen types. Contour interval, 1 weight percent.

mean of 1.04 weight percent. The organic-carbon content is shown in table 17.7 and figures 17.3-17.6 and 17.15.

The HC/OC graph for the Sag River Sandstone includes data from 14 wells—7 cutting samples, 19 core samples, and 8 oil-stained samples (6 cores, 2 cuttings). Except for one core sample, this unit falls into two categories: (1) fair to good petroleum source rock and (2) oil-stained rocks. The Sag River Sandstone beneath the Simpson shelf—Simpson No. 1, South Simpson No. 1, and East Simpson Nos. 1 and 2 wells—and the Fish Creek platform—South Harrison Bay No. 1 and West Fish Creek No. 1 wells—exhibits fair to good source-rock characteristics. Oil stains in the Sag River Sandstone are restricted to the Barrow high. The vitrinite-reflectance data, which are essentially identical to those in the Shublik Formation, are listed on table 17.7.

On the basis of organic-carbon content, hydrocarbon content, and thermal history, the Sag River

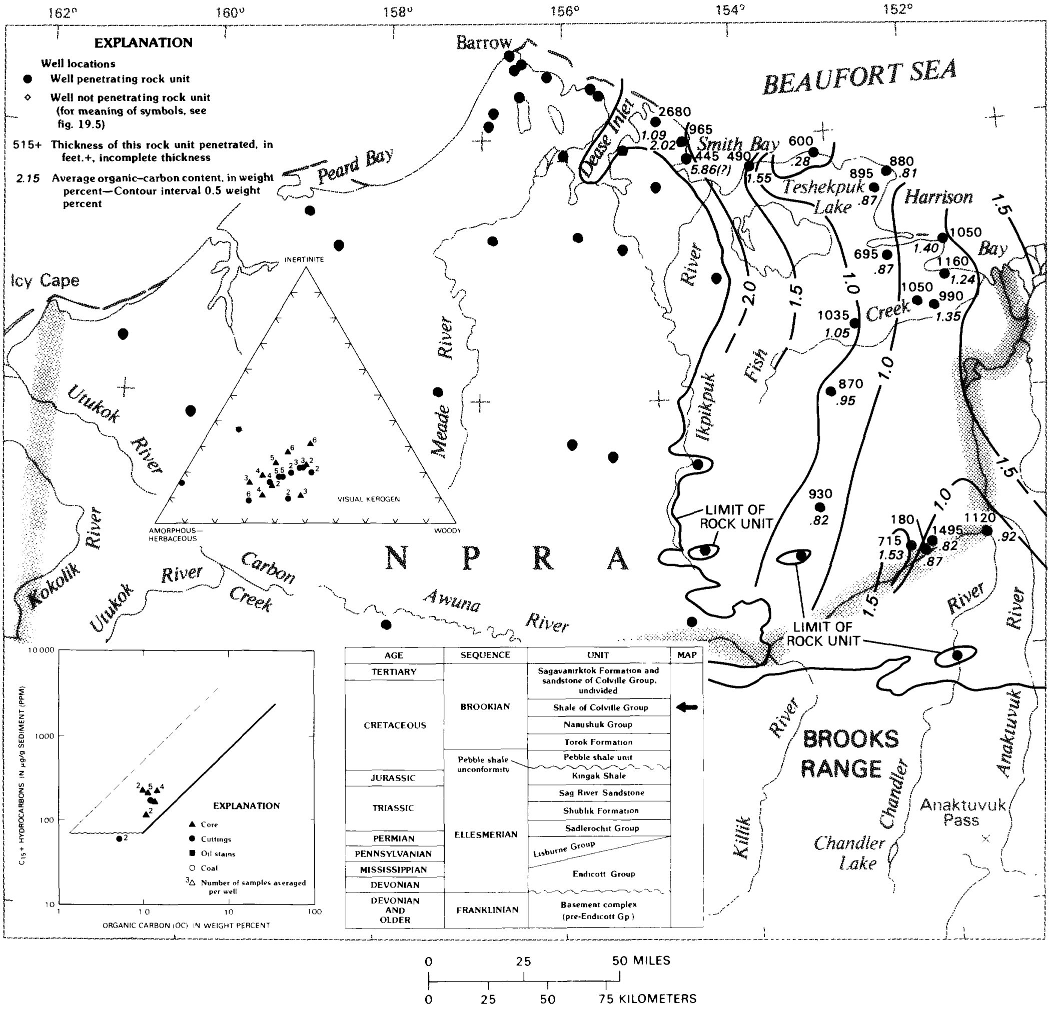


FIGURE 17.25.—Average organic-carbon content for informally named shale of the Colville Group, showing relation of organic-carbon content to content of extractable C_{15+} hydrocarbons and relative proportions of three kerogen types. Contour interval, 0.5 weight percent.

Sandstone, even though a thin unit, must be included as a potential source for North Slope oil or gas.

KINGAK SHALE

The Kingak Shale, one of the major marine shale units on the North Slope, consists of as much as 1,200 m (4,000 ft) of shale and minor amounts of siltstone and sandstone. The Kingak is overlain by a regional unconformity in the north half of the NPRA (see Molenaar, chapter 25). Except for a very small area in the northern part of the NPRA, the Kingak Shale occurs throughout the area and, where sampled, ranges in thickness from 17 to 1,050 m (55-3,450 ft). Of the 38 wells that penetrated the Kingak, 36 have been analyzed for petroleum geochemistry.

The organic-carbon content from 36 wells ranges from 0.50 to 3.02 weight percent and averages 1.11 weight percent. These values appear to be affected by regional structural features. Carbon values

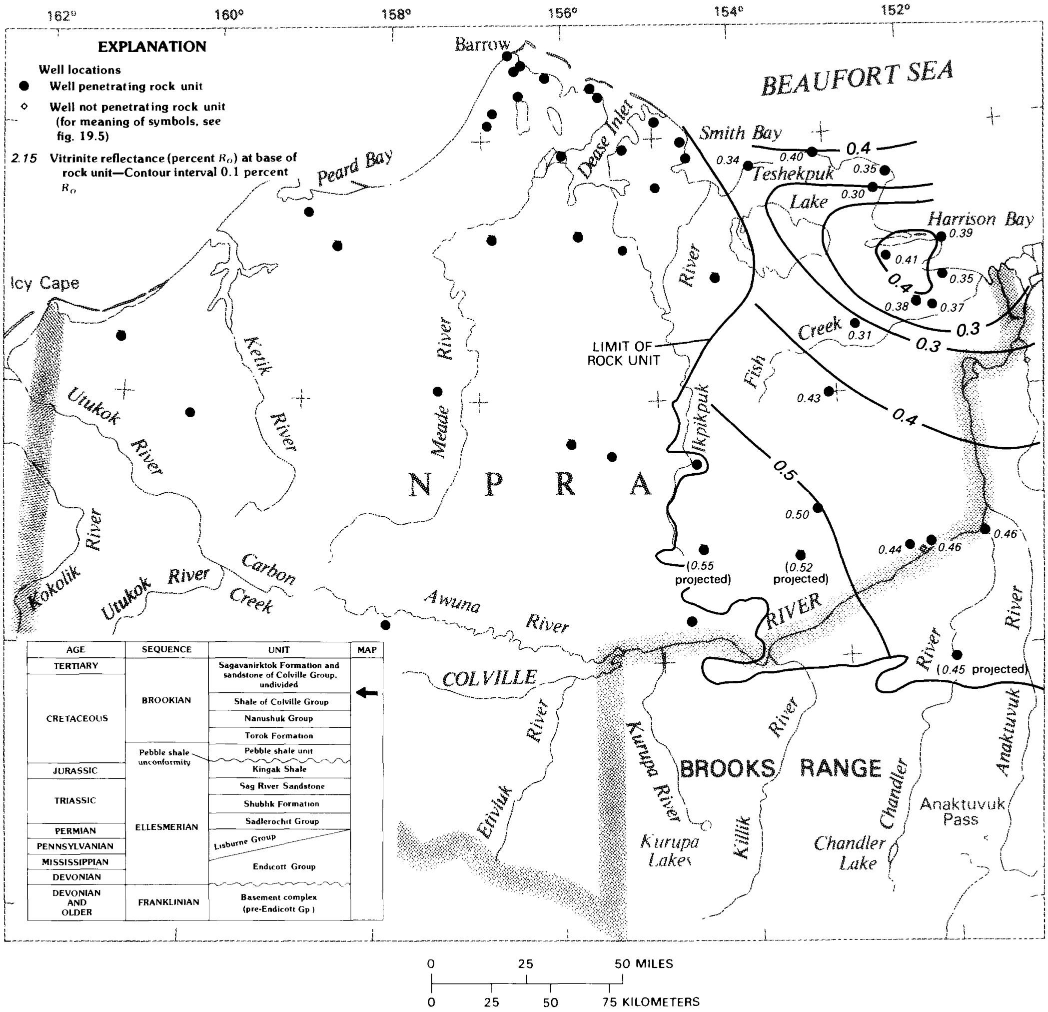


FIGURE 17.26.—Vitrinite-reflectance values at base of undivided Sagavanirktok Formation and sandstone of the Colville Group, contoured at interval of 0.1 percent R_o.

increase away from the Meade arch, and east of the arch values increase significantly into the Colville Trough. The organic-carbon values are shown on the four cross sections (figs. 17.3-17.6) and on the contour map (fig. 17.16) and are listed in table 17.8.

The HC/OC graph for the Kingak Shale includes data from 31 wells—45 cutting samples, 49 core samples, and 27 oil-stained samples (21 cores, 6 cuttings). Except for a few core and cutting samples, the Kingak Shale falls into two categories: (1) a good source rock with HC values that range from 200 to 600 ppm, and (2) oil-stained rocks in the Barrow area and in the West Fish Creek No. 1 well.

The contours of visual-kerogen content trend west-northwest, approximately parallel to the Barrow arch (fig. 17.17). The amorphous

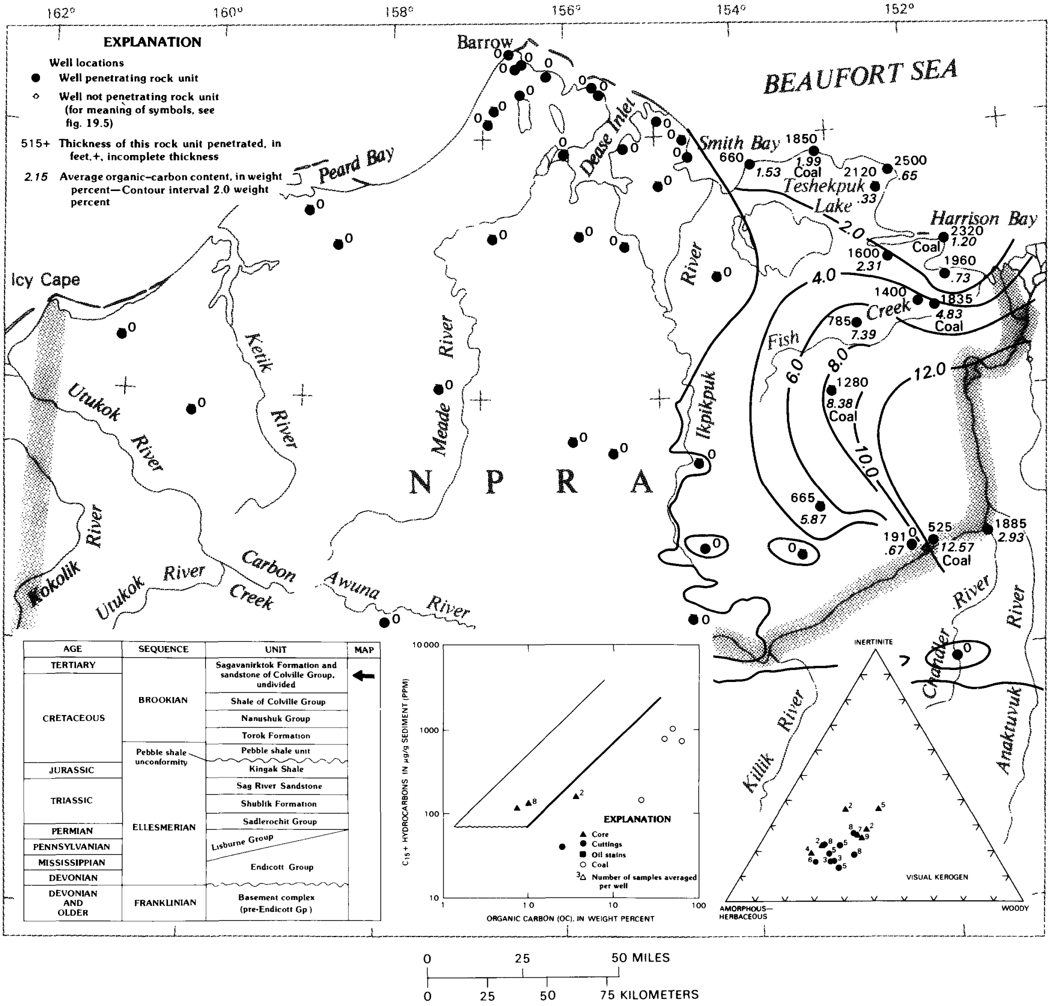


FIGURE 17.27.—Average organic-carbon content for undivided Sagavanirktok Formation and sandstone of the Colville Group, showing relation of organic-carbon content to content of extractable C_{15+} hydrocarbons and relative proportions of three kerogen types. Contour interval, 2 weight percent.

TABLE 17.14.—*Hydrocarbaon data for the Lisburne No. 1 well*

[Kerogen types: AM, amorphous; H, herbaceous; W, woody; I, inertinite. Well bottomed in Lisburne Group rocks at 17,000 ft]

Rock unit	Depth (ft)		Organic-carbon content (weight percent)				Samples	Average visual kerogen (percent) AM--H--W--I	Thrust sheet
	Top	Bottom	Number	Min	Max	Avg			
Etivluk Group-----	28	930	13	0.31	1.78	1.19	5	19-41-22-18	1
Okpikruak Group---	930	6,130	99	.36	2.05	.92	23	4-37-33-26	
Etivluk Group-----	6,130	7,410	29	.23	4.05	1.89	18	12-38-23-27	
Lisburne Group----	7,410	8,600	30	.13	.76	.46	13	24-30-24-22	
									Fault
Etivluk Group-----	8,600	9,670	18	.41	6.04	2.50	9	25-41-19-15	2
Lisburne Group----	9,670	10,900	19	.31	4.95	1.45	6	26-44-14-16	
									Fault
Etivluk Group-----	10,900	11,550	14	.48	5.00	2.42	6	16-35-24-25	3
Lisburne Group----	11,550	13,375	25	.40	1.68	1.12	12	19-43-17-20	
									Fault
Etivluk Group-----	13,375	13,730	5	.32	3.01	1.37	2	4-31-30-35	4
Lisburne Group----	13,730	15,315	26	.11	1.54	.79	6	12-43-23-22	
									Fault
Etivluk Group-----	15,315	15,395	4	.61	5.26	2.30	2	0-51-14-35	5
Lisburne Group----	15,395	17,000+	39	.14	3.25	.85	21	14-40-22-24	

and herbaceous content decreases from 60 to 70 percent of total kerogen in the northeast to less than 40 percent in the southwest. Both woody and inertinite constituents range from 10 percent in the northeast to 30 percent in the southwest. Except in the South Meade No. 1 well, where the percentage of amorphous plus herbaceous kerogen is low, there is no evidence of a shift of amorphous and herbaceous material to inertinite that is related to maturity; if one exists, it is too subtle to be mapped in the Kingak Shale.

The range of thermal maturity for the Kingak Shale is large, and all three stages of petroleum generation—diagenesis, catagenesis, and metagenesis—are represented. The vitrinite-reflectance values at the top of this rock unit have been contoured (fig. 17.18), and the data for both the top and base are listed in table 17.8.

The petroleum source-rock characteristics of the Kingak Shale indicate that this rock unit is a fair source, and the present-day thermal maturity indicates that hydrocarbons have been generated downdip from the Barrow arch.

PEBBLE SHALE UNIT

The pebble shale unit is an informally named stratigraphic unit. It consists of marine shale containing an occasional lenticular sandstone body (see Bird, chapter 15). The major regional unconformity that extends over much of the North Slope is at the base of the pebble shale unit, and at the top is a strong spike on the gamma-ray curve (more than 50 API units) referred to as the gamma-ray zone (Bird, 1982) or HRZ (Carman and Hardwick, 1982). In the NPRA, the pebble shale unit ranges in thickness from 50 to 160 m (160-520 ft) except in the area adjacent to Harrison Bay, where the pebble shale unit is drastically reduced in thickness or absent because of submarine slumping or scouring (see Bird, chapter 16). Of the 41 wells that penetrated the pebble shale unit, 38 have been analyzed geochemically.

The organic-carbon content for 37 wells ranges from 1.20 to 3.49 weight percent and averages 2.0 weight percent. It increases southward from 1.20 weight percent at Barrow to 3.28 weight percent at the Oumalik No. 1 well. However, there are exceptions to this trend in the Barrow area, along the northeast coastline, and at the Seabee No. 1 well, which may be the result of sample cavings or of local depositional settings. The organic-carbon content is depicted on the four cross sections (figs. 17.3-17.6) and on the contour map (fig. 17.19), and the values are listed in table 17.9.

The HC/OC graph for the pebble shale unit includes data from 30 wells—30 cutting samples, 36 core samples, and 12 oil-stained samples (6 cores, 6 cuttings). Except for a few core and cutting samples, the preponderance of the data fall into two categories: (1) fair to good petroleum source rock with OC values 1 weight percent higher than those of the underlying Kingak Shale, and (2) several oil-stained samples that apparently are randomly distributed across the NPRA.

Some components of the visual-kerogen composition of the pebble shale unit in the NPRA vary with the thermal history (fig. 17.20). The amorphous-plus-herbaceous kerogen content decreases, and the inertinite content increases, with increasing vitrinite-reflectance values. Along the northeast coast, the amorphous-plus-herbaceous kerogen composition is more than 60 percent, whereas in the Colville Trough the recorded values decrease to less than 30 percent. Woody kerogen content ranges from 10 to 30 percent throughout the NPRA, whereas the inertinite composition ranges from 10 percent along the coast to 40 percent in the Colville Trough. This inverse relation of amorphous-plus-herbaceous material to inertinite content appears to be related to the maturity level. The visual-kerogen data are contoured on figure 17.20.

As determined from vitrinite reflectance, most of the pebble shale unit is in the stage of catagenesis (0.6 to 2.0 percent R_o). A few areas along the northeast coastline, where oil shows are most prevalent, are below 0.6 percent R_o, or in the diagenetic stage of petroleum generation. Oil was recovered from a sandstone within the immature part of the pebble shale unit penetrated in the South Barrow No. 20 well; this oil probably migrated into the sandstone from below or from the flank of the Barrow high. The vitrinite-reflectance data for the base of the pebble shale unit are contoured on figure 17.18.

The pebble shale unit, which has a fairly high average content of organic carbon, composed mostly of amorphous and herbaceous kerogen that is mature over a large part of the NPRA, is an obvious potential source for oil and gas in the NPRA. The high proportion of amorphous and herbaceous kerogen indicates that the unit is oil prone. The gas recovered from sandstone in the pebble shale unit in the Walakpa Nos. 1 and 2 wells probably migrated from deeper in the Colville Trough because the pebble shale unit is immature in these wells. Analysis of the gas from the Walakpa No. 2 well shows light gas and isotopic compositions ($C_1/C_{1-5}=97$ percent; $\delta^{13}C=-37.9$ permil; $\delta D=-163$ permil) characteristic of thermal gas (see Bayliss and Magoon, chapter 20; Schoell, 1982). This gas may have migrated a long distance within the pebble shale unit because vitrinite-reflectance values greater than 2.0 percent R_o are not reached for 100 km (60 mi) downdip. The migration distance may have been much shorter if the gas originated from older rocks, such as the Kingak Shale or the Shublik Formation.

TOROK FORMATION

The Torok Formation consists of moderately deep to deep marine shale and siltstone, including minor amounts of sandstone; it is the deeper marine equivalent of the prograding deltaic Nanushuk Group (Bird and Andrews, 1979; Molenaar and Bird, 1980; Molenaar, 1981). The minimum preserved thickness is about 350 m (1,200 ft) on the Barrow arch, and its estimated maximum thickness from seismic profiles (including the Fortress Mountain Formation) in the southern part of the NPRA is approximately 6,000 m (20,000 ft). Total thickness of the Torok Formation in the 58 wells in which it was penetrated ranges from 365 to 2,470 m (1,195-8,110 ft); samples from 54 wells have been analyzed geochemically.

The organic-carbon content of the Torok Formation has the narrowest range for any of the NPRA units, 0.61 to 1.44 weight percent, and averages 1.16 weight percent. The contoured values over this narrow range form no specific pattern, implying either that the depositional environment was quite uniform over a long period of time or that the entire unit was deposited rapidly. The carbon content is shown on figures 17.3-17.6, contoured on figure 17.21, and listed in table 17.10.

The HC/OC graph for the Torok Formation includes data from 35 wells—68 cutting samples, 196 core samples, 28 oil-stained samples (14 cores, 14 cuttings), and 2 coal samples. Except for the two coal samples, which probably caved from the overlying Nanushuk Group, the Torok represents: (1) a fair source rock that has HC values ranging from 80 to 500 ppm and OC values from 1 to 2 weight percent; and (2) oil-stained samples from the Barrow high (East Barrow field), Simpson shelf, and Fish Creek platform, where oil shows have been recorded.

The visual-kerogen content of the Torok shows an irregular contour pattern for each of the kerogen components (figs. 17.22*A*, *B*, *C*). Unlike the rather thin Shublik Formation and pebble shale unit, where a relation between kerogen type and thermal history appears to exist, the Torok does not show a similar relation: it may be too thick, and the range of maturity too broad.

The thermal maturity of the Torok Formation is indicated by contours of vitrinite reflectance at the base and top of the formation (figs. 17.18 and 17.23, respectively). These maps and the data listed in table 17.10 indicate that most of the Torok Formation along the northeast coastline is immature and that all of the Torok is mature to overmature in the southwest half of the NPRA.

The Torok Formation is considered somewhat more gas prone than the pebble shale unit because of its content of amorphous-plus-herbaceous kerogen relative to woody kerogen. The level of thermal maturity indicates that the oil-generating capacity for part of this shale unit has been exceeded only in the southwest half of the NPRA.

NANUSHUK GROUP

The Nanushuk Group, a sequence of fluvial-deltaic to shallow-marine deposits formed by northeastward progradation, consists of sandstone, siltstone, shale, conglomerate, and coal (Ahlbrandt, 1979; Bird and Andrews, 1979; Molenaar, 1981). Two major deltas are recognized—the Corwin delta on the west and the Umiat delta to the east (Huffman and Ahlbrandt, 1979). Because of uplift and erosion of this rock unit in the western part of the NPRA and in the Barrow area, a complete section is missing over most of the west two-thirds of the area (see Kirschner and Rycerski, chapter 9). The Nanushuk Group was also removed in the Dease Inlet area by the Late Cretaceous erosion that formed Simpson Canyon. Total thickness from well penetrations range from 190 to 1,875 m (620-6,150 ft), and 41 of the 42 wells have been analyzed geochemically.

Organic-carbon content from 41 wells ranges from 0.48 to 9.52 weight percent and averages 2.3 weight percent. High organic-carbon values in two areas, one south of the Simpson shelf and the other in the northwest quarter of the NPRA, may represent woody (coaly) kerogen related to the two delta systems. These relations are shown on the four cross sections (figs. 17.3-17.6) and on the contour map (fig. 17.24) and are listed in table 17.11.

The HC/OC graph for the Nanushuk Group includes data from 27 wells—31 cutting samples, 72 core samples, 13 oil-stained core samples, and 4 coal samples. Except for a very few low HC values, three categories are represented: (1) coal in the Kaolak No. 1 and Meade No. 1 wells; (2) good source rocks for oil, with average HC values that range from 125 to 460 ppm and OC values that range from 1 to 2 weight percent; and (3) oil-stained samples from the Fish Creek No. 1, Oumalik No. 1, Simpson No. 1, and Umiat No. 11 wells.

The visual-kerogen estimates of the Nanushuk Group indicate that at least 50 percent of the constituents are herbaceous-plus-amorphous material, whereas woody and inertinite constituents each compose less than 25 percent of the total (Magoon and Claypool, 1979). Additional potential source-rock material reported in the Nanushuk includes amber (Langenheim and others, 1960) and cannel coal (boghead and algal coal) (Stadnichenko, 1929; White, 1929; Webber, 1947). In this study we have not specifically identified or analyzed these materials, although some may be included in the samples.

Vitrinite reflectance at the base of the Nanushuk Group is less than 1 percent R_0—an optimum value for oil-generating source rocks in both the Nanushuk and the underlying Torok Formation. Except for the anomalously high readings at South Meade No. 1, the Nanushuk in the northeast half of the NPRA is in the diagenetic stage of petroleum generation (less than 0.6 percent R_0); in the southwest half of the NPRA it is in the catagenic stage (more than 0.6 percent R_0). Oil that occurs in the unit in the northeast half of the NPRA, such as at Umiat, Fish Creek, and on the Simpson shelf, probably migrated from deeper (mature) units; it seems unlikely that it could have come from the mature part of the Nanushuk in the southwest half of the NPRA. Reflectance values decrease to the northeast, following the general direction of the Nanushuk and Torok progradation and mimicking the Nanushuk Group isopachs (see Bird, chapter 16; Molenaar, chapter 25). Apparently, the Nanushuk and Torok sediment load established the maturity trends for the underlying units. The Nanushuk Group is thickest and oldest in the southwest and thinnest and youngest in the northeast; thus, the deeper units matured earlier and to a higher degree in the southwest than in the northeast. The vitrinite-reflectance values at the base of the Nanushuk Group are contoured on figure 17.23.

From the depositional environment and lithology, we would generally conclude that the Nanushuk Group is not a source for oil but possibly a source for gas; however, the data indicate that good source rocks for oil are present and in submature to mature settings. The oil in known accumulations in the Nanushuk may have originated from within or, more likely, from underlying units.

SHALE OF COLVILLE GROUP

The shale of the Colville Group, an informal stratigraphic unit, consists of marine shale, siltstone, and minor amounts of sandstone (see Bird, chapter 15). In the NPRA, the shale of the Colville Group includes the Shale Wall Member of the Seabee Formation and most of the Schrader Bluff Formation. The shale of the Colville Group is limited to the east third of the

NPRA and, where penetrated, ranges in thickness from 55 to 815 m (180-2,680 ft). Of the 20 wells that penetrate this rock unit, 19 have been analyzed geochemically.

The organic-carbon content in 19 wells ranges from 0.28 to 5.86 weight percent and averages 1.43 weight percent. The contoured values are 1.0 to 1.5 weight percent except in the Simpson Canyon area, where the values exceed 2.0 weight percent. Exceptionally high values (more than 2.0 weight percent) obtained from the East Simpson Nos. 1 and 2 wells are from cutting samples that probably include coal from the underlying Nanushuk Group. Except in the Simpson Canyon and Umiat areas, the contours trend north-south, parallel to the depositional strike of the Colville Group. The organic-carbon data are displayed on four cross sections (figs. 17.3-17.6) and a contoured map (fig. 17.25) and listed in table 17.12.

The HC/OC graph for the shale of the Colville Group includes data from 7 wells—3 cutting samples and 14 core samples. Except for one low value, all the wells suggest that this unit is a fair source rock, with HC values ranging from 115 to 225 ppm.

The thermal history for the shale of the Colville Group as determined by vitrinite reflectance is in the diagenetic stage of petroleum generation, with values less than 0.6 percent R_o. The vitrinite reflectance for the shale of the Colville Group is listed in table 17.12 and contoured at the top of the unit in figure 17.26.

Even though this shale is judged a fair source rock, no oil would have been generated for want of an adequate thermal history. The catagenic stage may be reached in these rocks east of the NPRA, where depth of burial is greater (Pessel and others, 1978).

SAGAVANIRKTOK FORMATION AND SANDSTONE OF COLVILLE GROUP, UNDIVIDED

The Late Cretaceous and early Tertiary fluvial-deltaic to shallow-marine sequence of rocks in the NRPA consists of shale, siltstone, sandstone, conglomerate, coal, and bentonite (see Bird, chapter 16). Rocks in this sequence are assigned to three formations in the Colville Group and to the Sagavanirktok Formation. All of these units are grouped together for analysis here. This sequence is part of the northeastward-prograding clastic wedge that filled the Colville Trough. Where penetrated in the NPRA, this unit ranges in thickness from 58 to 760 m (190-2,500 ft). Of the 16 wells that penetrated this rock unit, 15 have been analyzed geochemically.

The organic-carbon content in 15 wells ranges from 0.65 to 12.57 weight percent and averages 3.47 weight percent. Coal, a common constituent, contributes significantly to the organic-carbon content. The organic-carbon content increases rapidly to the east and south toward Umiat. The data are shown on the four cross sections (figs. 17.3-17.6) and the contour map (fig. 17.2) and listed in table 17.15.

The HC/OC graph for the undivided Sagavanirktok Formation and sandstone of the Colville Group includes data from 5 wells—1 cutting sample, 11 core samples, and 4 coal samples (3 cores, 1 cutting). The data are insufficient to characterize this unit but indicate that the HC content is fair and the OC values are high.

The thermal history of this unit is entirely within the diagenetic stage of petroleum generation (less than 0.6 percent R_o). The vitrinite-reflectance values at the base of the unit increase to the southwest (fig. 17.27), an indication of previously greater burial and somewhat greater age of the rocks in the southwest.

The thermal history of this rock unit precludes its being a source for thermogenic hydrocarbons, but our data are inadequate to evaluate its overall source potential. Therefore, on the basis of the thermal history and high organic-carbon values, the undivided Sagavanirktok Formation and sandstone of the Colville Group can only be considered a possible source for microbial gas in the NPRA.

SUMMARY

This chapter provides a preliminary assessment of the sedimentary rocks in the NPRA as potential source rocks for oil and gas. This assessment is based on subsurface data from 63 wells. The rocks, including pre-Endicott Group rocks, are divided into 12 stratigraphic intervals according to their organic richness, kerogen type, and thermal maturity. Organic richness was measured by weight percent organic carbon and extractable (C_{15+}) hydrocarbons. The kerogen type was determined by estimating of the relative abundance of amorphous-plus-herbaceous, woody, and inertinitic kerogen particles on the basis of visual microscopic examination. Thermal maturity was measured by vitrinite reflectance. These analyses are displayed in a series of maps, graphs, and tables for each interval.

The organic-carbon content for each of the 12 units is summarized on figure 17.28. The extreme values are the lowest and highest mean values from individual wells (tables 17.2-17.13); the average value is the mean value for all wells. In all rock units except the Torok Formation, the average value is positively skewed, thus indicating that high values are the exception rather than the rule. All units except the

Lisburne Group (0.35 weight percent) have average organic carbon greater than 0.5 weight percent—a value commonly cited to distinguish source from nonsource rocks. The pebble shale unit is the only shale unit that averages as high as 2 weight percent organic carbon. The pre-Endicott Group rocks, Endicott Group, Nanushuk Group, and undivided Sagavanirktok Formation and sandstone of the Colville Group exceed 2 weight percent, but each contains coal that has a very high (more than 5 weight percent) organic-carbon content.

The C_{15+} hydrocarbon values indicate that the major shale units and the Nanushuk Group are good source rocks (fig. 17.29). These shale units are the Shublik Formation, Kingak Shale, pebble shale unit, Torok Formation, and shale of the Colville Group. Except for the Torok Formation, which does not extend far enough east of the NPRA, the first three shale units could have been the source of the oil being produced from the Prudhoe Bay oil pool (Seifert and others, 1980). The Sag River Sandstone and the undivided Sagavanirktok Formation and sandstone of the Colville Group unit include shales that have fair source characteristics. On the basis of core information, the Endicott, Lisburne, and Sadlerochit Groups are poor to fair source-rock units. The pre-Endicott Group rocks penetrated in the South Barrow No. 13 well have the characteristics of a good source-rock unit (fig. 17.7), but their thermal history indicates that they are more likely related to a pre-Late Devonian period of oil generation.

The information on kerogen type and relative abundance is given in

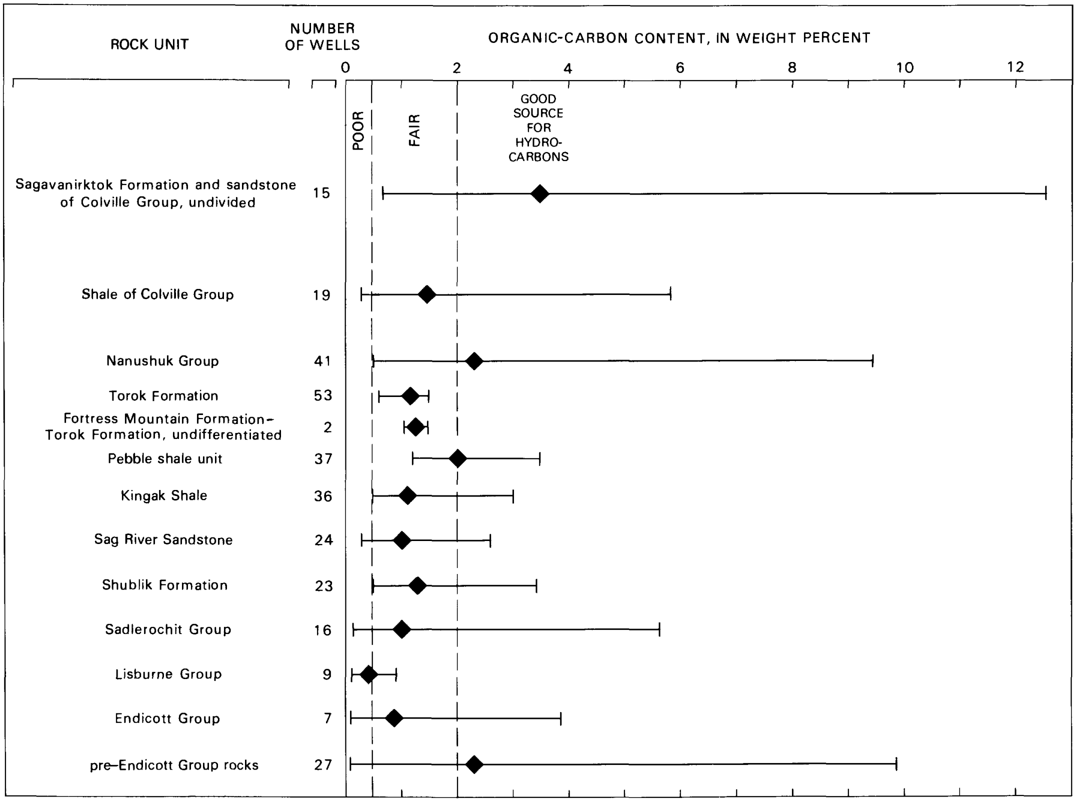


FIGURE 17.28.—Summary of organic-carbon content for each rock unit penetrated by wells within the National Petroleum Reserve in Alaska. Data from cutting and core samples are combined.

12 maps for the 4 shale units and as triangular diagrams on the maps of organic-carbon content. The kerogen maps summarize average values of amorphous-plus-herbaceous, woody, and inertinite kerogen for: (1) the Shublik Formation, (2) the Kingak Shale, (3) the pebble shale unit, and (4) the Torok Formation. The amorphous-plus-herbaceous kerogens are primarily oil prone, the woody material is primarily gas prone, and the inertinite contributes almost no hydrocarbons and is either reworked material or a metagenetic product (see Bayliss and Magoon, chapter 20). In three of these four rock units the percentage of inertinite appears to increase at the expense of amorphous-plus-herbaceous kerogen southward into the Colville Trough. The triangular diagrams on the maps of organic-carbon content are summarized on figure 17.30. The mean values for core samples and for cutting samples for each kerogen type are plotted for each unit. The pre-Endicott Group rocks and Endicott Group have the highest percentage of inertinite, whereas the pebble shale unit and Kingak Shale have the highest percentage of amorphous-plus-herbaceous kerogen. All other rock units show a remarkable clustering containing 40 to 60 percent amorphous-plus-herbaceous, 20 to 30 percent woody, and 20 to 30 percent inertinite kerogen.

Vitrinite-reflectance data have been contoured at five horizons and are summarized on figure 17.31 using the three stages of petroleum generation—diagenesis, catagenesis, and metagenesis (Tissot and Welte, 1978). The undivided Sagavanirktok Formation and sandstone of the Colville Group unit and the shale of the Colville Group in the NPRA are entirely within the diagenetic stage, indicating that these rock units could only be the source for microbially generated gas. Except for the Endicott Group and, probably, the pre-Endicott Group rocks, all other rock units have at least some small part still in the diagenetic stage. The Nanushuk Group and pebble shale unit have reached the catagenetic stage of petroleum generation (0.6-2.0 percent R_0); that is, oil and some gas could have been generated and preserved in these units. Except for the pebble shale unit, some parts of all units from the Torok Formation downward are in the catagenetic stage and thus could have generated oil and gas. Except again for the pebble shale unit, they are also partly in the metagenetic stage

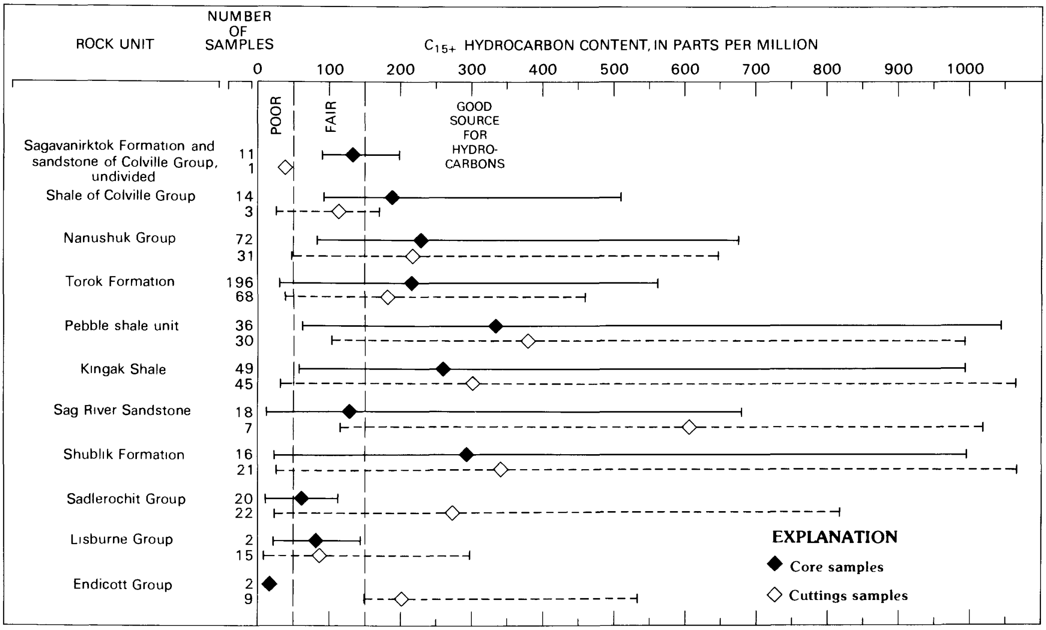


FIGURE 17.29.—Summary of content of extractable C_{15+} hydrocarbons for each rock unit penetrated by wells within the National Petroleum Reserve in Alaska.

(more than 2.0 percent R_0) and could have generated dry gas or thermally cracked oil to dry gas. Also, these rocks now in the metagenic stage could in the past have generated and expelled oil as they passed through the catagenetic stage of petroleum generation. If this oil migrated to presently cool areas, such as at Barrow, it would be preserved as a liquid.

Four marine shale units in the NPRA (Torok Formation, pebble shale unit, Kingak Shale, and Shublik Formation) are considered petroleum source-rock units on the basis of the four types of analyses described in this report. These shale units have an average organic-carbon content ranging from 1 to 2 percent, composed of 50 to 65 percent oil-prone (amorphous and herbaceous) and 20 to 30 percent gas-prone (woody) kerogen. Extractable C_{15+} hydrocarbons in amounts greater than 150 ppm confirm the good source-rock characteristics. These rocks are immature (diagenetic stage) in a relatively narrow zone paralleling the northeast coastline of the NPRA (along the crest of the Barrow arch). To the south these rocks are mature (catagenic stage) to overmature (metagenic stage) in the southern part of the NPRA. The richest source-rock unit, on the basis of all three criteria, is the pebble shale unit, the thinnest rock unit. The much thicker Torok Formation has the lowest average values.

Other rock units in the NPRA have had inadequate sampling to characterize their source-rock characteristics (Kayak Shale and Kekiktuk Conglomerate of the Endicott Group), or are coal bearing and (or) rich in sandstone. The coal-bearing rock units (Kekiktuk Conglomerate, Nanushuk Group, and undivided Sagavanirktok Forma-

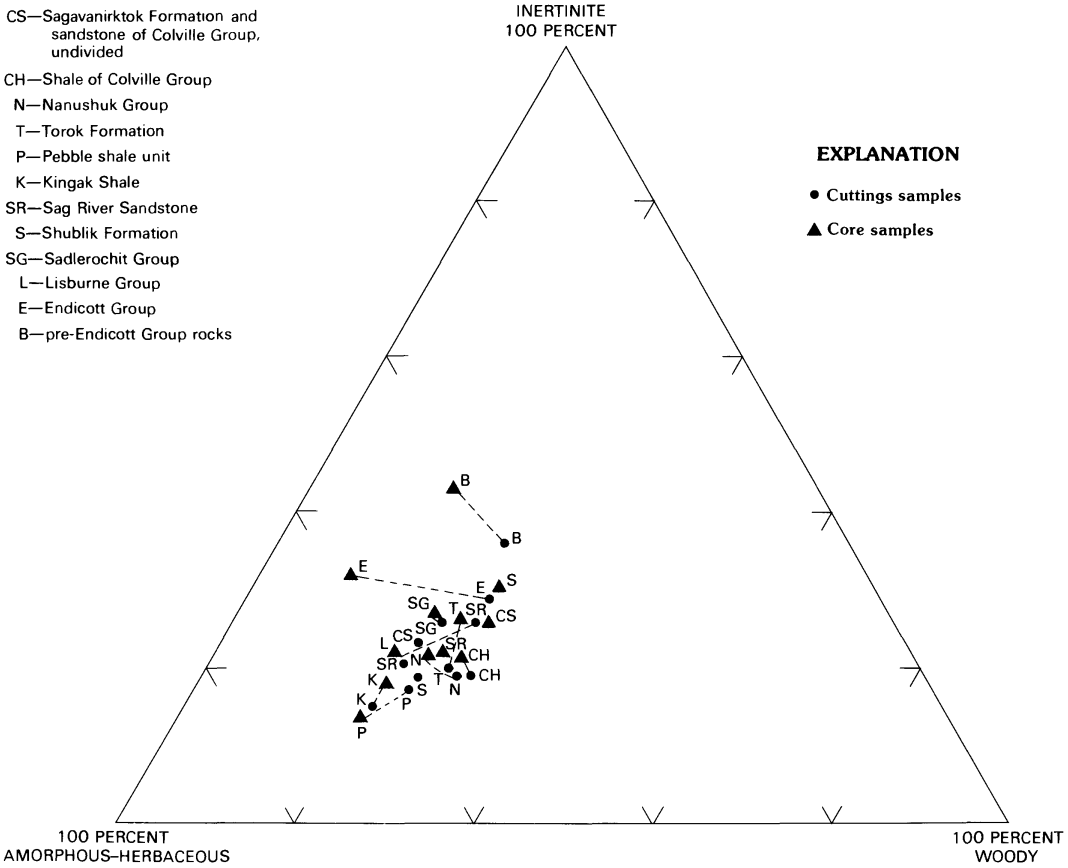


FIGURE 17.30.—Summary of relative proportions of three types of visual kerogen for each rock unit penetrated by wells within the National Petroleum Reserve in Alaska.

tion and sandstone of the Colville Group) are certainly sources for microbial or thermal gas, depending on their maturity.

REFERENCES CITED

Ahlbrandt, T.S., ed., 1979, Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, 163 p.

Bird, K.J., 1982, Rock unit reports of 228 wells drilled on the North Slope, Alaska: U.S. Geological Survey Open-File Report 82-278, 108 p.

Bird, K.J., and Andrews, Jack, 1979, Subsurface studies of the Nanushuk Group, North Slope, Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 32-41.

Bird, K.J., Conner, C.L., Tailleur, I.L., Silberman, M.L., and Christie, J.L., 1978, Granite on the Barrow arch, northeast NPRA, *in* Johnson, K.M., ed., The United States Geological Survey in

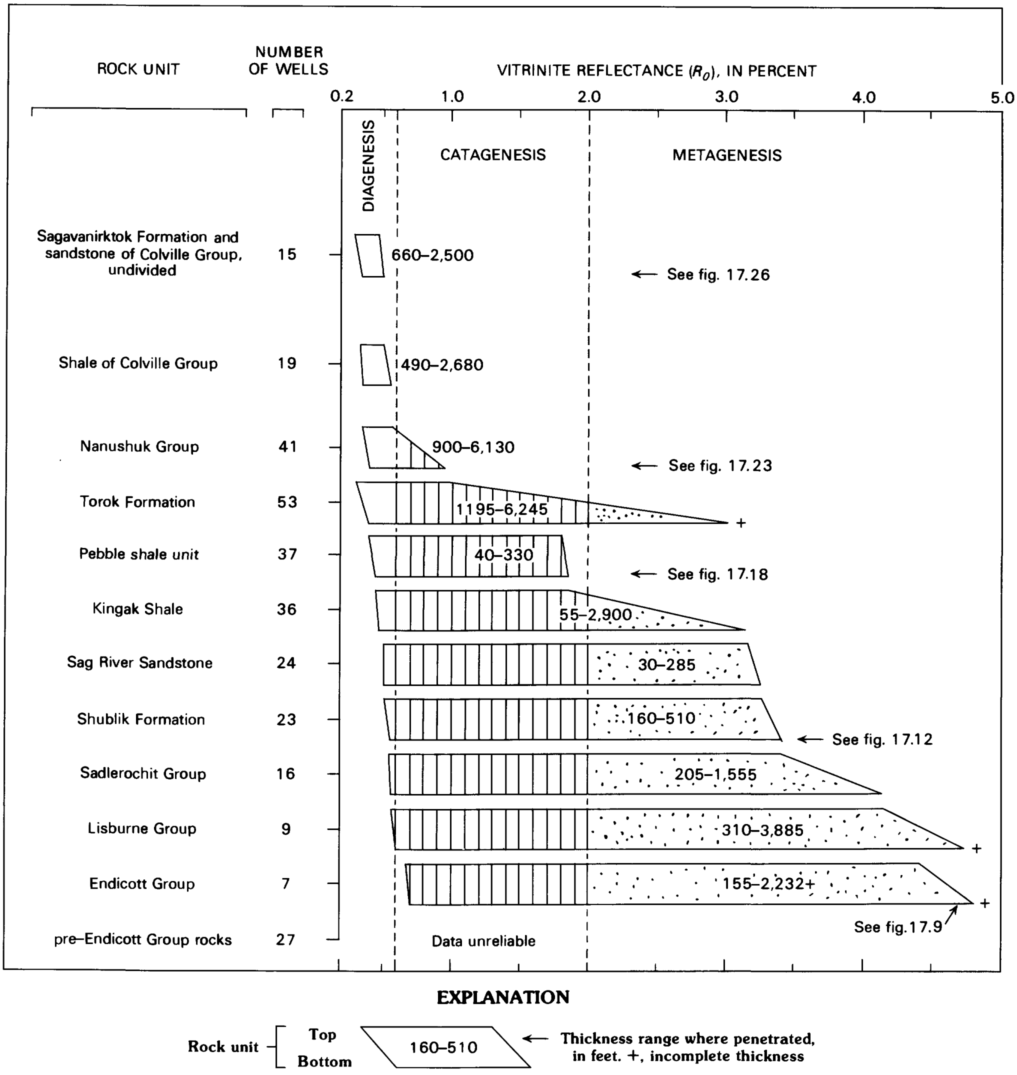


FIGURE 17.31.—Summary of vitrinite-reflectance values for each rock unit penetrated by wells within the National Petroleum Reserve in Alaska. Boundaries of diagenesis, catagenesis, and metagenesis in petroleum generation from Tissot and Welte (1978).

Alaska: Accomplishments during 1977: U.S. Geological Survey Circular 772-B, p. B24-B25.

Bird, K.J., and Jordan, C.F., 1977a, Lisburne Group (Mississippian and Pennsylvanian), potential major hydrocarbon objective of Arctic Slope, Alaska: American Association of Petroleum Geologists Bulletin, v. 61, no. 9, p. 1493-1512.

—— 1977b, Petroleum potential of the Lisburne Group, eastern Arctic slope, Alaska: Oil and Gas Journal, v. 75, no. 16 (Apr. 18, 1977), p. 90-94.

Blanchard, D.C., and Tailleur, I.L., 1982, Temperatures and interval geothermal-gradient determinations from wells in National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 82-391, 82 p.

Boneham, R.F., and Tailleur, I.L., 1972, *Leiosphaeridia* (Acritarcha) in the Mesozoic oil shales of northern Alaska, *in* Geological Survey research, 1972: U.S. Geological Survey Professional Paper 800-B, p. B17-B19.

Brosgé, W.P., Reiser, H.N., Dutro, J.T., Jr., and Detterman, R.L., 1981, Organic geochemical data for Mesozoic and Paleozoic shales, central and eastern Brooks Range, Alaska: U.S. Geological Survey Open-File Report 81-551, 18 p.

Burlingame, A.L., Wszolek, P.C., and Simoneit, B.R., 1969, The fatty acid content of tasmanites, *in* Schenck, P.A. and Havenaar, I., eds., Advances in organic geochemistry 1968: Oxford, Pergamon Press, p. 131-155.

Carman, G.J., and Hardwick, Peter, 1982, Geology and regional setting of the Kuparuk oil field, Alaska: Oil and Gas Journal, v. 80, no. 47 (Nov. 22, 1982), p. 153-158.

Carter, Claire, and Laufeld, Sven, 1975, Ordovician and Silurian fossils in well cores from North Slope of Alaska: American Association of Petroleum Geologists Bulletin, v. 59, no. 3, p. 457-464.

Castaño, J.R., and Sparks, D.M., 1974, Interpretation of vitrinite reflectance measurements in sedimentary rocks and determination of burial history using vitrinite reflectance and authigenic minerals, *in* Dutcher, R.R., Hacquebard, P.A., Schopf, J.M., and Simon, J.A., eds., Carbonaceous materials as indicators of metamorphism: Geological Society of America Special Paper 153, p. 31-52.

Collins, F.R., 1958, Test wells, Topagoruk area, Alaska: U.S. Geological Survey Professional Paper 305-D, p. 265-316.

Huffman, A.C., and Ahlbrandt, T.S., 1979, The Cretaceous Nanushuk Group of the western and central North Slope, Alaska, *in* Johnson, K.M., and Williams, J.R., eds., The United States Geological Survey in Alaska: Accomplishments during 1978: U.S. Geological Survey Circular 804-B, p. B46-B50.

Hunt, J.M., 1979, Petroleum geochemistry and geology: San Francisco, W.H. Freeman and Co., 617 p.

Jones, H.P., and Speers, R.G., 1976, Permo-Triassic reservoirs of Prudhoe Bay field, North Slope, Alaska, *in* Braunstein, Jules, ed., North American oil and gas fields: American Association of Petroleum Geologists Memoir 24, p. 23-50.

Kleist, J.R., Bard, T.R., Engstrom, D.B., Morrow, H.B., and Reber, S.J., 1983, Central Arctic foothills, Alaska—a unique challenge in frontier exploration [abs.]: American Association of Petroleum Geologists, v. 67, no. 3, p. 495-496.

Langenheim, R.L., Jr., Smiley, C.J., and Gray, Jane, 1960, Cretaceous amber from the Arctic Coastal Plain of Alaska: Geological Society of America Bulletin, v. 71, no. 9, p. 1345-1356.

Lerand, Monti, 1973, Beaufort Sea, *in* McCrossan, R.G., ed., Future petroleum provinces of Canada—their geology and potential: Canadian Society of Petroleum Geologists Memoir 1, p. 315-386.

Leythaeuser, D., Hagemann, H.W., Hollerbach, A., and Schaefer, R.G., 1980, Hydrocarbon generation in source beds as a function of type and maturation of their organic matter—a mass balance approach: World Petroleum Congress, 10th, Bucharest, 1979, Proceedings, v. 2, p. 31-41.

Magoon, L.B., and Claypool, G.E., 1979, Hydrocarbon source potential of the Nanushuk Group and the Torok Formation, a preliminary report, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 54-60.

—— 1981, Two oil types on North Slope of Alaska—implication for exploration: American Association of Petroleum Geologists Bulletin, v. 65, no. 4, p. 644-652.

Molenaar, C.M., 1981, Depositional history and seismic stratigraphy of Lower Cretaceous rocks, National Petroleum Reserve in Alaska and adjacent areas: U.S. Geological Survey Open-File Report 81-1084, 45 p.

Molenaar, C.M., and Bird, K.J., 1980, Stratigraphic relations of Nanushuk Group (Middle Cretaceous) and associated strata, North Slope of Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 64, no. 5, p. 752-753.

Mull, C.G., Tailleur, I.L., Mayfield, C.F., Ellersieck, Inyo, and Curtis, S.M, 1982, New Upper Paleozoic and Lower Mesozoic stratigraphic units, central and western Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 66, no. 3, p. 348-362.

Pessel, G.H., Tailleur, I.L., and Bird, K.J., 1978, Generalized structure map of top of the Colville Group, eastern North Slope petroleum province, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-928-C, scale 1:500,000.

Powell, T.G., Creaney, S., and Snowdon, L.R., 1982, Limitations of use of organic petrographic techniques for identification of petroleum source rocks: American Association of Petroleum Geologists Bulletin, v. 66, no. 4, p. 430-435.

Reiser, H.N., 1970, Northeast Brooks Range—a surface expression of the Prudhoe Bay section, *in* Adkison, W.L., and Brosgé, W.P., eds., Proceedings of the geological seminar on the North Slope of Alaska: American Association of Petroleum Geologists, Pacific Section, p. K1-K14.

Schoell, Martin, 1982, Application of isotopic analysis to petroleum and natural gas research: Spectra, v. 8, no. 2-3, p. 32-41.

Seifert, W.K., Moldowan, J.M., and Jones, R.W., 1980, Application of biological marker chemistry to petroleum exploration: World Petroleum Congress, 10th, Bucharest, 1979, v. 2, p. 425-440.

Snowdon, L.R., 1980, Resinite—a potential petroleum source in the Upper Cretaceous/Tertiary of the Beaufort-MacKenzie Basin, *in* Miall, A.D., ed., Facts and principles of world petroleum occurrence: Canadian Society of Petroleum Geologists Memoir 6, p. 509-521.

Snowdon, L.R., and Powell, T.G., 1982, Immature oil and condensate—modification of hydrocarbon model for terrestrial organic matter: American Association of Petroleum Geologists Bulletin, v. 66, p. 775-788.

Stadnichenko, Taisia, 1929, Microthermal studies of some "mother rocks" of petroleum from Alaska: American Association of Petroleum Geologists Bulletin, v. 13, p. 823-840.

Tailleur, I.L., 1964, Rich oil shale from northern Alaska, art. 148 *of* Short papers in geology and hydrology: U.S. Geological Survey Professional Paper 475-D, p. D131-D133.

Tissot, B.P., and Welte, D.H., 1978, Petroleum formation and occurrence: Berlin, Springer-Verlag, 538 p.

Webber, E.J., 1947, Stratigraphy and structure of the area of the Meade and Kuk

Rivers and Point Barrow, Alaska: U.S. Geological Survey, Geological Investigations of Naval Petroleum Reserve No. 4 and Adjacent Areas, Alaska, Regular Report 6, 14 p. [available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey].

Welte, D.H., 1965, Relation between petroleum and source rock: American Association of Petroleum Geologists Bulletin, v. 49, p. 2248-2268.

White, David, 1929, Description of fossil plants found in some "mother rocks" of petroleum from northern Alaska: American Association of Petroleum Geologists Bulletin, v. 13, p. 841-848.

18. OIL AND GAS SOURCE ROCKS IN THE NATIONAL PETROLEUM RESERVE IN ALASKA

By George E. Claypool and Leslie B. Magoon

INTRODUCTION

In 1977, the U.S. Geological Survey (USGS) was charged with continuing the most recent exploration program in the National Petroleum Reserve in Alaska (NPRA), which had been begun by the U.S. Navy in 1974. The history of this and earlier petroleum explorations in the NPRA and the North Slope of Alaska is summarized elsewhere in this volume (see Gryc, chapter 1; Schindler, chapter 2) and in other publications by USGS authors (see Gryc, 1982).

To support the programs of exploratory drilling and resource assessment in the NPRA, a study of petroleum geochemistry and source-rock geochemistry was initiated in 1977. Two important decisions were made at the beginning of this study. First, the large numbers of samples to be analyzed during the period 1977-82 could not be processed in USGS laboratories without a major impact on ongoing research programs. Accordingly, we designed an analytical program, developed specifications, and awarded a contract for the geochemical analyses to Geochem Research, Inc., of Houston, Tex., as prime contractor and Global Geochemistry Corp. of Canoga Park, Calif., as subcontractor. Second, the large volume of data that would be created by analyzing samples from all the wells in the NPRA made it imperative that we use a computer to store, retrieve, and graphically display these data. Data processing was carried out by Petroleum Information, Inc., of Denver, Colo., under an existing contract with the USGS.

The objectives of this source-rock study in the NPRA were somewhat broader than required to meet the immediate needs of the petroleum-exploration program. These objectives were as follows:

1. To provide rapid evaluation of wells then being drilled and of subsequent wells with respect to interpretation of thermal maturity, possible source-rock intervals, and presence of migrated hydrocarbons;
2. To provide geochemical data for more accurate petroleum-resource assessments;
3. To interrelate with and support the research program on the origin of petroleum conducted within the USGS; and
4. To evaluate the suitability of obtaining geochemical analyses by contract from commercial laboratories to support applied and basic research programs of the USGS.

Other organic geochemical studies have been conducted on oils and source rocks of the Alaskan North Slope. Morgridge and Smith (1972) concluded that the Cretaceous rocks were the main source for oil in the Prudhoe Bay field. They based this conclusion on the observed content of extractable hydrocarbons and on the fact that the Cretaceous rocks were the only possible source rocks in contact with all the reservoir-rock units. A study by Jones and Speers (1976) indicated that the oil produced from different reservoir units in the Prudhoe Bay field had a common origin. Young and others (1977) interpreted the varying proportions of different structural classes of hydrocarbons in crude oils as evidence for both Triassic and Late Cretaceous ages of oil in the Prudhoe Bay field. Seifert and others (1980) concluded that the major oil accumulation in the Prudhoe Bay field was derived from three source-rock units: the Triassic Shublik Formation, the Jurassic and Cretaceous Kingak Shale, and an unnamed Lower Cretaceous (post-Neocomian) shale. Magoon and Claypool (1981) summarized analytical data on 40 samples of crude oil from across the North Slope and recognized two distinct genetic types of oil. An expanded, updated version of that North Slope crude-oil study appears elsewhere in this volume (see Magoon and Claypool, chapter 21).

Results of organic geochemical analyses of rock samples from NPRA wells have been reported elsewhere (Magoon and Claypool, 1979, 1980a-f, 1983; Claypool and Magoon, 1980a-d). The visual kerogen analyses and vitrinite reflectance profiles in four selected wells are discussed by Bayliss and Magoon (chapter 20). The regional variation of selected properties (organic-carbon content, vitrinite reflectance, and visual identification of kerogen type) are shown on maps for the 12 major rock units by Magoon and Bird (chapter 17).

This report is a summary of the geochemical data obtained on rock samples collected from 63 boreholes drilled in and adjacent to the NPRA

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during the period from 1946 to 1981. The data are displayed on depth-profile plots and are interpreted with respect to content, type, and thermal maturity of organic matter. Possible oil and gas source rocks are identified, but correlations of oils with source rocks based on more detailed analyses are part of a separate study (Magoon and Claypool, 1985).

WELL CONTROL, SAMPLE COLLECTION, AND GEOCHEMICAL ANALYSES

The type and distribution of rock samples used are important to the success of any oil and gas source-rock study. The areal distribution of the wells within and adjacent to the NPRA that were used in this study is shown on plate 2.1. Thirty-four wells are concentrated along the coastline (Barrow high, 20 wells; Simpson shelf, 5 wells; Dalton area, 4 wells; Fish Creek platform, 5 wells); there, the basement complex is shallowest along the Barrow arch. The deepest wells, as much as 6,198 m (20,335 ft) deep in the Tunaiik No. 1 well, all lie within the west Arctic platform (6 wells) and the Ikpikpuk Basin (3 wells). Wells drilled in the northern foothills (16 wells) for Cretaceous deltaic sandstone reservoirs are less than 2,100 m (7,000 ft) deep except for Oumalik No. 1 and Seabee No. 1, which were drilled to test deeper horizons. The southern foothills region (3 wells) includes the Awuna No. 1 well; that well and the Seabee No. 1 well had the Fortress Mountain Formation as their objective. The shallow Knifeblade wells penetrated Cretaceous sandstone. The one well in the thrust belt (Brooks Range), Lisburne No. 1, penetrated at least five thrust sheets before it reached its total depth of 5,200 m (17,000 ft) (see Magoon and Bird, chapter 17; Mayfield and others, chapter 7).

The type of rock samples collected depended largely on the drilling program. Four different drilling programs were carried out in this area, as shown in table 18.1. Of the many wells and coreholes drilled during the first Naval Petroleum Reserve No. 4 (NPR-4) program (1946-53), 26 were sampled for this study. Many of these wells were continuously cored, and wherever cores existed, they were sampled at 6-m (20 ft) intervals for the entire core. Vertical sample distribution is shown on the well-summary diagram for that well (see table 18.1) The one well from the South Barrow program (1953-74) was sampled in this same manner (pl. 19.6A).

Nine wells from the second NPR-4 program (1974-77) were sampled for this study. Eight of these wells had drill cuttings collected and canned either every 9 or 15 m (30 or 50 ft). Because the USGS was not involved in the drilling program at that time, we do not know the method of sample preservation or collection that was used. Four of the wells had sidewall cores, and four others had conventional cores that were sampled wherever available.

Twenty-seven wells were sampled from the USGS NPRA program (1977-81). At 24 wellsites, drill cuttings were collected every 9 m (30 ft), washed, and sealed with bactericide in 0.95-L (1 qt) cans (table 18.1). Conventional cores from 26 wells were sampled every 1.5 m (5 ft), and sidewall cores were taken at selected depths from 20 wells; both types of core samples were also sealed in cans. Canned drill cuttings and canned core material from selected depths were analyzed according to the flowchart shown in figure 18.1. Depths for selection of the drill cuttings sampled for analysis were determined by the general thickness of the stratigraphic units. The two programs of sample selection are outlined in table 18.2. Analytical program A, specifying analysis at more widely spaced depth intervals, was applied to samples from rocks within stratigraphic units of mid-Cretaceous age and younger (Brookian sequence). Analytical program B, specifying analysis at more closely spaced depth intervals, was applied to generally thinner stratigraphic units of Late Devonian through Early Cretaceous age (Ellesmerian sequence). All cores were analyzed regardless of depth distribution.

The detailed procedures for performing the geochemical analyses outlined in table 18.2 were specified in contractual documents and are summarized in appendix 18.1.

MACHINE PROCESSING AND GRAPHICAL PRESENTATION OF GEOCHEMICAL DATA

The NPRA computer data and graphics system, developed as a specialized subset of the Well History Control System maintained by Petroleum Information (PI) Corp., is more completely described elsewhere (see Wilcox and others, chapter 39). The geochemistry file is one of several files developed by PI to store, retrieve, manipulate, plot, and report data for the NPRA petroleum-exploration and resource-assessment program. The results of the geochemical analyses performed by NPRA contract laboratories were transmitted to PI in prescribed format. Initially, the results of laboratory analyses were hand encoded on specially designed 80-column loading forms and mailed to PI for entry and processing on the computer terminal. Later, the geochemical data were typed into a computer terminal by the prime contractor (Geochem Research, Inc.) in Houston, then transmitted electronically to the PI computer in Denver for updating of the geochemical file.

In addition to the procedures for data storage, computer programs were written for retrieving, manipulating, plotting, and reporting the geochemical analytical data. We

TABLE 18.1.—*Test wells drilled in or adjacent to the National Petroleum Reserve in Alaska (Naval Petroleum Reserve No. 4 until 1977) during 1946-81 that are discussed in this report*

[Wells with numbers in brackets not included on maps of organic carbon, visual kerogen, or vitrinite reflectance in Magoon and Bird, chapter 17. API, American Petroleum Institute. For Oil and Gas Investigations Charts, see Claypool and Magoon (1980a-d) and Magoon and Claypool (1980a-f). WS, well summary diagram (plate number); VR, vitrinite reflectance and C_1-C_7 hydrocarbon display (plate or Oil and Gas Investigations Chart number); -, no samples, no display or chart because appropriate samples not available]

					Displays of data		Samples available		
	Well	API number	Region	Total depth (ft)	WS	VR	Conventional core	Sidewall core	Canned drill cuttings
Naval Petroleum Reserve No. 4 Program (1946-53)									
1	North Simpson No. 1	50-023-10004	Simpson shelf	3,774	19.7	-	X	-	-
2	South Barrow No. 1	50-023-10009	Barrow high	3,553	19.6A	-	X	-	-
3	South Barrow No. 2	50-023-10010	Barrow high	2,505	19.6B	-	X	-	-
4	South Barrow No. 3	50-023-10011	Barrow high	2,900	19.5	-	X	-	-
[5]	South Barrow No. 4	50-023-10012	Barrow high	2,538	19.6B	-	X	-	-
[6]	Avak No. 1	50-023-10013	Barrow high	4,020	19.6C	-	X	-	-
7	Grandstand No. 1	50-057-10001	Northern foothills	3,939	19.27	-	X	-	-
8	Fish Creek No. 1	50-103-10001	Fish Creek platform	7,020	19.20	-	X	-	-
9	Oumalik No. 1	50-119-10005	Northern foothills	11,872	19.18	-	X	-	-
10	East Oumalik No. 1	50-119-10006	Northern foothills	6,035	19.18	-	X	-	-
11	Square Lake No. 1	50-119-10007	Northern foothills	3,987	19.22	-	X	-	-
[12]	Wolf Creek No. 1	50-119-10008	Northern foothills	1,500	19.22	-	X	-	-
13	Wolf Creek No. 3	50-119-10010	Northern foothills	3,760	19.22	-	X	-	-
14	Titaluk No. 1	50-119-10011	Northern foothills	4,020	19.22	-	X	-	-
15	Knifeblade No. 1	50-119-10012	Southern foothills	1,805	19.24	-	X	-	-
[16]	Knifeblade No. 2A	50-119-10014	Southern foothills	1,805	19.24	-	X	-	-
17	Meade No. 1	50-163-10002	Northern foothills	5,305	19.13	-	X	-	-
18	Simpson No. 1	50-279-10032	Simpson shelf	7,002	19.8	-	X	-	-
19	Topagoruk No. 1	50-279-10033	West Arctic platform	10,503	19.14	-	X	-	-
20	East Topagoruk No. 1	50-279-10034	West Arctic platform	3,589	19.14	-	X	-	-
21	Umiat No. 1	50-287-10001	Northern foothills	6,005	19.24	-	X	-	-
[22]	Umiat No. 2	50-287-10002	Northern foothills	6,212	19.26	-	X	-	-
23	Umiat No. 11	50-287-10011	Northern foothills	3,303	19.26	-	X	-	-
24	Gubik No. 1	50-287-10013	Northern foothills	6,000	19.27	-	X	-	-
[25]	Gubik No. 2	50-287-10014	Northern foothills	4,620	19.27	-	X	-	-
26	Kaolak No. 1	50-297-10001	Northern foothills	6,952	19.17	-	X	-	-
South Barrow Program (1953-74)									
27	South Barrow No. 9	50-023-20003	Barrow high	2,450	19.6A	-	X	-	-
Naval Petroleum Reserve No. 4 Program (1974-77)									
[28]	South Barrow No. 12	50-023-20006	Barrow high	2,285	19.6C	-	X	-	-
[29]	South Barrow No. 13	50-023-20008	Barrow high	2,535	19.6B	-	X	-	X
[30]	South Barrow No. 14	50-023-20009	Barrow high	2,257	19.6D	OC-99	-	X	X
31	Cape Halkett No. 1	50-103-20004	Dalton area	9,900	19.11	OC-97	-	-	X
32	South Harrison Bay No. 1.	50-103-20007	Fish Creek platform	11,290	19.16	OC-93	X	-	X
33	Atigaru Point No. 1	50-103-20008	Fish Creek platform	11,535	19.12	OC-98	-	X	X
34	West Fish Creek No. 1	50-103-20009	Fish Creek platform	11,427	19.20	OC-95	-	X	X
35	W.T. Forman No. 1	50-103-20010	Dalton area	8,864	19.11	OC-94	X	-	X
36	South Simpson No. 1	50-279-20001	Simpson shelf	8,795	19.8	OC-92	-	X	X
National Petroleum Reserve in Alaska Program (1977-81)									
37	South Barrow No. 16	50-023-20010	Barrow high	2,400	19.6A	OC-99	X	X	X
38	South Barrow No. 17	50-023-20011	Barrow high	2,382	19.6D	OC-99	X	-	X
[39]	South Barrow No. 19	50-023-20012	Barrow high	2,300	19.6C	OC-99	X	-	X
40	Walakpa No. 1	50-023-20013	Barrow high	3,666	19.5	19.30	X	X	X
41	West Dease No. 1	50-023-20014	Barrow high	4,173	19.7	19.31	X	X	X
[42]	South Barrow No. 20	50-023-20015	Barrow high	2,356	19.6D	-	X	-	-
[43]	South Barrow No. 15	50-023-20016	Barrow high	2,278	19.6C	-	X	-	-
[44]	South Barrow No. 18	50-023-20017	Barrow high	2,125	19.6D	-	X	-	-
45	Tulageak No. 1	50-023-20018	Barrow high	4,015	19.7	19.31	X	X	X
46	Walakpa No. 2	50-023-20019	Barrow high	4,360	19.5	19.30	X	X	X
47	North Kalikpik No. 1	50-103-20011	Fish Creek platform	7,395	19.12	OC-96	X	X	X
48	North Inigok No. 1	50-103-20017	Ikpikpuk basin	10,170	19.19	19.36	X	X	X
49	Koluktak No. 1	50-119-20001	Northern foothills	5,882	19.19	19.36	-	X	X
[50]	Lisburne No. 1	50-137-20003	Thrust belt	17,000	19.23	19.38	X	-	X
51	Awuna No. 1	50-155-20001	Southern foothills	11,200	19.7	19.35	X	-	X
52	South Meade No. 1	50-163-20001	West Arctic platform	9,945	19.13	19.33	X	X	X
53	Kugrua No. 1	50-163-20002	West Arctic platform	12,588	19.3	OC-101	X	X	X
54	Kuyanuk No. 1	50-163-20002	Barrow high	6,690	19.4	19.29	X	X	X
55	Drew Point No. 1	50-279-20002	Dalton area	7,946	19.10	OC-100	X	X	X
56	Inigok No. 1	50-279-20003	Ikpikpuk basin	20,102	19.21	19.37	X	X	X
57	Ikpikpuk No. 1	50-279-20004	Ikpikpuk basin	15,481	19.15	19.34	X	X	X
58	East Simpson No. 1	50-279-20005	Simpson shelf	7,739	19.9	19.32	X	X	X
59	Dalton No. 1	50-279-20006	Dalton area	9,367	19.10	19.33	X	X	X
60	East Simpson No. 2	50-279-20007	Simpson shelf	7,504	19.9	19.32	X	X	X
61	Seabee No. 1	50-287-20007	Northern foothills	15,611	19.25	19.39	X	X	X
62	Tunalik No. 1	50-301-20001	West Arctic platform	20,335	19.2	19.28	X	X	X
63	Peard No. 1	50-301-20002	West Arctic platform	10,225	19.4	19.29	X	X	X

specified the several types of geochemical data we wished to be retrieved, provided general algorithms for calculations to be performed, and specified the formats to be used for tabular and graphical reports. Computer programs were developed by PI to accomplish these objectives; a complete listing of such programs is given by Wilcox and others (chapter 39, table 39.3).

BACKGROUND FOR INTERPRETATION OF RESULTS

GEOLOGIC FRAMEWORK

More thorough treatments of northern Alaskan geology are provided elsewhere in this volume (see chapters 7-16). A brief summary of the geologic framework is provided here only to serve as background for interpretation of the petroleum geochemical data.

The North Slope of Alaska can be subdivided into three major physiographic provinces (pl. 2.1): the Brooks Range (thrust belt), the foothills (southern and northern), and the coastal plain (west Arctic platform, Ikpikpuk Basin, Barrow high, Simpson shelf, Dalton area, and Fish Creek platform). Underlying structural elements in these provinces are, from south to north: (1) the Brooks Range orogen, (2) the Colville Trough or foredeep, and (3) the Barrow arch (Carter and others, 1977; Grantz and others, 1979; Bird, 1981f). Major stratigraphic sequences and their corresponding sediment source areas proposed by Lerand (1973) for the Yukon Territory in Canada were extended to northern Alaska by Grantz and others (1975). These sequences are the Franklinian (Cambrian through Middle Devonian), here referred to as the basement complex, the Ellesmerian, and the Brookian. The Ellesmerian sequence consists of sedimentary rocks that range in age from Late Devonian through Early Cretaceous (fig. 18.2). These sedimentary rocks include shelf carbonate rocks and both marine and nonmarine siliciclastic rocks. The sandstone within this sequence is rich in quartz; its provenance area generally lay north of the present coastline. Important reservoir rocks in this sequence are present within the Lisburne (carbonate) and Sadlerochit Groups (siliciclastic) and the Sag River Sandstone (siliciclastic). The Shublik Formation, the Kingak Shale, and the pebble shale unit include shale beds having an average organic-carbon content of 1 to 2 weight percent (see Magoon and Bird, chapter 17) and containing types of organic matter that generate oil. The basin geography during deposition of the Ellesmerian rocks was a simple ramp dipping south. The trend of the coastline was similar to that of the present but with the positions of water and land reversed (Grantz and others, 1975). Generally, all units within the Ellesmerian sequence thicken to the south and east, except where they have been eroded, and lap onto the Barrow arch to the west (fig. 18.3).

The Brookian sequence, of mid-Cretaceous through Tertiary age, comprises rock units whose provenance is the Brooks Range orogen (Grantz and others, 1975). The Brookian sequence consists of basinal, slope, shelf, and nonmarine deposits (Ahlbrandt, 1979) that prograded northeastward across the Colville Trough and over the Barrow arch in the Prudhoe Bay area and on into the Arctic Ocean basin. This progradational sequence is important because it provides the overburden necessary for thermal maturation of the deeper Brookian and underlying Ellesmerian shale units. The sandstone in the Brookian sequence is poor in quartz relative to sandstone in the Ellesmerian sequence (Bartsch-Winkler, 1979; Molenaar and

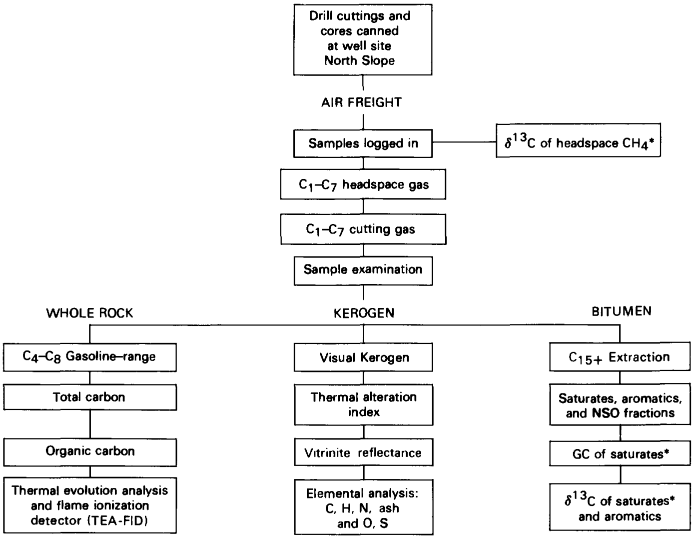

FIGURE 18.1.—Procedures for analyzing organic matter in well samples. Analyses marked with asterisk were done by Global Geochemistry Corp.; all others were done by Geochem Research, Inc.

others, 1981). Potential reservoir rocks in this sequence are included within the Fortress Mountain Formation and the Nanushuk and Colville Groups, all of Cretaceous age, and the Late Cretaceous and Tertiary Sagavanirktok Formation. Brookian shale units include at least two intervals of marine shale that contain about 1 weight percent organic carbon—the Torok Formation and Colville shale units. Both of these units contain significant amounts of nonmarine or terrestrial organic matter (see Magoon and Bird, chapter 17; Magoon and Claypool, 1979), which is typical of marine shale in a progradational deltaic sequence.

The rifting of the northern Alaska petroleum province during Early Jurassic to Early Cretaceous time (Grantz and others, 1979; Molenaar, 1981; Grantz and May, 1983) was an important event. The rifted margin initially was uplifted, block faulted, and eroded; then it subsided and was overlapped by the pebble shale unit—a marine shale and an important regional petroleum seal. This event was followed by prograding of the thick mid-Cretaceous through Tertiary siliciclastic rocks of the Brookian sequence. Rifting also may have favored formation of possible petroleum source rocks. For example, the pebble shale unit, deposited during the rifting, has a higher organic-carbon content and contains more oil-generating types of organic matter than the overlying Torok Formation. In this and in other ways, rifting in northern Alaska influenced conditions favorable for petroleum accumulation and preservation.

PETROLEUM FORMATION

The main reason for collecting and reporting these geochemical data is to provide a basis for evaluating if and where oil and gas

TABLE 18.2.—*Routine analytic programs for wells drilled in the National Petroleum Reserve in Alaska from 1977 to 1981*

[Program A is for the Brookian sequence mid-Cretaceous and younger; program B is for the Ellesmerian sequence Upper Devonian through Lower Cretaceous. Samples were collected at depth intervals of 30 ft (9.1 m)]

Analysis	Interval for analytic program (ft)	
	A	B
Sample preparation	60	60
C_1-C_7 headspace gas	60	60
C_1-C_7 cutting gas	60	60
C_4-C_8 gasoline range	300	300
Thermal evolution analysis/flame ionization detector.	300	60
Organic carbon	60	60
Total carbon	300	60
Vitrinite reflectance	600	300
Visual kerogen	300	300
Thermal-alteration index	300	300
C, H, N, and ash of kerogen	600	300
O, S of kerogen	600	300
$\delta^{13}C$ of CH_4 in headspace gas	600	300

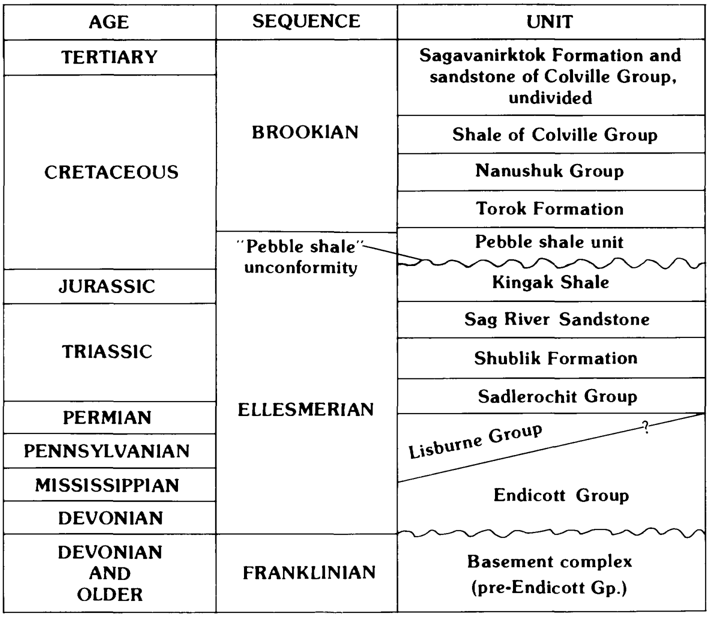

FIGURE 18.2.—Stratigraphy of the Ellesmerian and Brookian sequences. Two regional unconformities shown by wavy lines: one between the basement complex (Franklinian sequence) and the Endicott Group, and the other at the base of the pebble shale unit.

have been generated in commercial quantities and whether the hydrocarbons generated were preserved and trapped in the vicinity of a given well bore. This type of interpretation is based on understanding of and assumptions concerning the process of petroleum formation. The understanding and assumptions are briefly outlined below.

Organic matter of both marine and terrestrial origin is deposited with mineral particles in various aqueous environments. The amount of organic matter consumed by benthic organisms is determined by the availability of dissolved oxygen in the bottom water and the pore water of the sediment (Tissot and Welte, 1978). The oxygen is limited principally by the rate of sediment deposition and the rate at which oxygen is supplied by circulating marine currents. Very rapidly deposited sediment, such as in deltaic sequences, contains organic matter that is preserved because it is buried more rapidly than it can be consumed. Organic matter is consumed primarily in the near-surface zones where oxygen in the pore water is replenished by mixing (Ibach, 1982). At a given level of organic productivity, the content of organic matter preserved in rapidly accumulated sediment is limited by the degree of dilution caused by sediment influx. At the other extreme, sediment that has a very high content of organic matter generally accumulates under anoxic conditions (Demaison and Moore, 1980). Anoxic conditions develop where oxygen is consumed more rapidly than it can be replenished by mixing. Under oxygen-deficient conditions, part of the organic matter is not preserved in its original form, whether terrestrial or marine; it is subjected to intense reworking by anaerobic bacteria and is converted to a very fine grained, amorphous organic residue (Tissot and Welte, 1978). An important geochemical aspect of anoxic bacterial reworking of organic matter is an increase in the lipid content of the preserved organic matter. Oil is generated from the lipid fraction of the organic matter, and so rocks derived from organic-rich mud that accumulated slowly in oxygen-deficient environments are the best source rocks for oil (Demaison and Moore, 1980). Sediment deposited rapidly in well-oxygenated environments preserves some organic matter with hydrocarbon-generating capacity, but it is not enriched in the lipid fraction by intense activity of anaerobic bacteria. Rocks formed in this environment (rapid deposition under oxygenated conditions) are much poorer source rocks for oil. Gas can be generated from any type of preserved sedimentary organic matter, and so rocks containing organic matter that are the product of any depositional environment can be considered source rocks for gas.

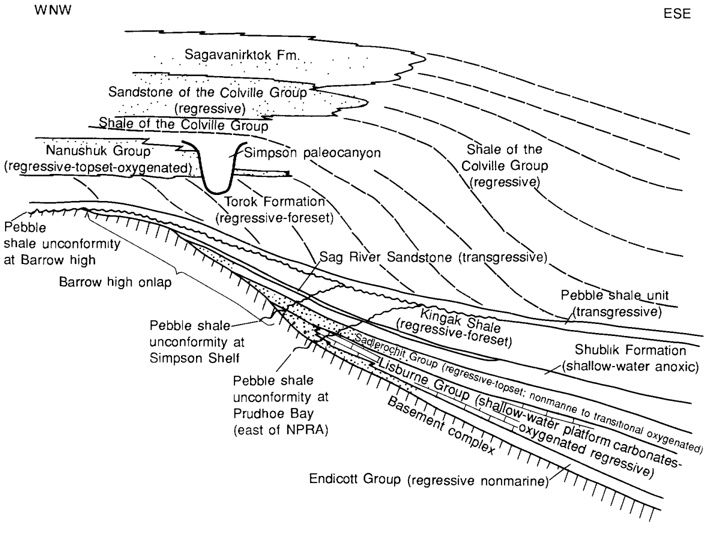

FIGURE 18.3.—West-to-east schematic stratigraphic cross section illustrating three important stratigraphic relations: (1) onlap of rock units that predate the pebble shale unit onto the Barrow high, (2) different regional positions of the pebble shale unconformity as it truncates older rock units to the east, and (3) stratigraphic position of Simpson paleocanyon.

The generation of oil and gas from organic matter is a natural consequence of burial in sedimentary basins. Under the primary influence of increased subsurface temperatures (and the secondary influence of time required for deeper burial), part of the solid organic matter is thermally decomposed to produce liquid and gaseous hydrocarbon products. Timing of the conversion from solid organic matter to petroleum (oil and gas) in source rocks can be predicted by reconstructing the burial history and thermal gradient (Waples, 1980). For most source rocks, significant oil generation begins to take place at temperatures of about 100 °C and is largely complete at temperatures above about 160 °C. Gas is generated before, during, and after oil generation and forms from various types of organic matter, including previously formed liquid hydrocarbons.

The generation of oil and gas from organic matter in source rocks is a continuous process if the subsidence history is continuous. Expulsion of petroleum may be episodic, however, depending on the rock properties that control expulsion. In any case, only part of the hydrocarbons present in the source rocks is expelled at any given time. Expelled hydrocarbons migrate, if possible, to shallower depths, where further temperature-dependent chemical changes occur at much slower rates. Hydrocarbons retained in the subsiding source rocks continue to undergo thermal degradation and are mixed with additional hydrocarbons produced by continued thermal decomposition of the solid organic matter. Hydrocarbons expelled at a later time will be slightly modified in composition, in comparison with the hydrocarbon mixtures generated earlier. In general, with increasing depth and temperature, the hydrocarbon mixtures are changed so that the distribution of molecular sizes is shifted more and more toward smaller molecules, and ultimately the hydrocarbon mixtures are completely dominated by methane, the hydrocarbon that is thermally most stable.

The main objectives of geochemical evaluation of source rocks are to determine for the sedimentary-rock sequence under investigation: (1) if the rocks contain enough organic matter to be a source of hydrocarbons on a commercial scale, (2) what is the oil-generating efficiency of the organic matter, and (3) what is the stage to which the petroleum-generation process has advanced. The answers to these questions should help determine where, how much, and what type of hydrocarbons might be found in the basin. In the following section, we explain how these objectives can, in principle, be achieved by the geochemical analyses employed in the NPRA geochemical program.

GEOCHEMICAL RESULTS

The results of analyses of rock samples from NPRA wells are presented in large format (pls. 19.1-19.39) of two types: illustrations (1) well-summary diagrams and (2) vitrinite-reflectance and C_1-C_7 hydrocarbon displays. Data are plotted as a function of sample depth in the borehole at a scale of 1:6,000 (1 in. = 500 ft). As indicated in table 18.1, the total drilled depth of the test wells ranges from 460 to 6,198 m (1,500-20,335 ft).

WELL-SUMMARY DIAGRAMS

Selected results of geochemical analyses are plotted against depth on a well-by-well basis in plates 19.1-19.27. These data are relevant in assessing the oil and gas potential of rock samples analyzed from the 63 test wells included in the 1946-81 petroleum reserve programs. Each well-summary diagram has a heading giving the well name, API (American Petroleum Institute) number, legal and latitude-longitude location, elevation of the kelly bushing on the drilling platform, and total depth of the well. Depth scales (in both meters and feet) are plotted at the left and right margins.

INDICATORS OF THERMAL HISTORY

The first four columns on the left side of the diagram are labeled "Indicators of Thermal History." Under this category are plotted: (1) the thermal-alteration index (TAI) based on the color of recognizable plant cuticle, rated on a subjective 1-to-5 scale (see Bayliss and Magoon, chapter 20); (2) the temperature at which the yield of pyrolysis products is at a maximum during temperature-programmed, thermal-evolution analysis monitored by a flame-ionization detector (TEA-FID); (3) the mean of a population ($n = 50$) of optical-reflectance measurements (in oil) on recognizable vitrinite particles; and (4) recorded values of subsurface temperature based on corrected wireline downhole measurements (Blanchard and Tailleur, 1982).

The indicators of thermal history are used for indirect evaluation of the stage to which the process of petroleum generation has advanced. In table 18.3, a general correlation is given for the relation among the stages of organic-matter transformation, the stages of hydrocarbon generation and preservation, and numerical values of the geochemical analyses plotted in the well-summary diagram. The relations listed in table 18.3 were independently developed and are based on geochemical observations in NPRA (Magoon and Claypool, 1983). However, the relations we observed in the NPRA among stages of organic-matter transformation, hydrocarbon generation and preservation, and numerical values for indirect indicators of thermal maturity are consistent with similar schemes proposed by Tissot and Welte (1978) and Waples (1980).

ROCK UNITS PENETRATED

Under the heading "Rock Units Penetrated" are the following 11 columns: geologic age; paleontologic zones; rock-unit names, some of which are informal terms from Bird (1982a); gamma-ray log; spontaneous-potential log; lithology symbols; resistivity log; interval-transit-time log; bulk-density log; differential-caliber log (Bird, 1981a-e, 1982b, c); and the

TABLE 18.3.—*Correlations among geochemical indicators of the thermal maturity of organic matter and stages of hydrocarbon generation and preservation, generalized from observations in NPRA oil and gas source-rock study*

[See text for discussion of geochemical indicators]

Stage of organic-matter transformation	Qualitative interpretation with respect to oil generation and preservation	Important stages of oil generation and preservation	Vitrinite reflectance (percent R_o)	Pyrolysis transformation ratio (vol. HC/total HC)	Sapropelic kerogen H/C ratio	Thermal alteration index	Temperature of maximum pyrolysis yield (TEA-FID) (°C)
Diagenesis	Immature						
		Onset of oil generation	0.6	0.1	1.1	2.2	440
	Mature						
Catagenesis		End of oil generation	1.3		.8	2.9	
		Oil preservation limit	1.75	.4	.65	3.2	490
	Overmature	Condensate, wet-gas preservation limit	2.0		.6	3.3	
Metagenesis							

type of sample (drill cuttings, conventional core, or sidewall core) analyzed at a given depth. The basis for the paleontologic dating of units is explained briefly by Magoon and others (chapter 19).

INDICATORS OF RICHNESS AND TYPE OF ORGANIC MATERIAL

The remaining 16 columns on the right side of the geochemical well-summary diagram are grouped under the major heading "Indicators of Richness and Type of Organic Material." In general, the geochemical data under this heading are grouped by type of analysis. Measurements indicating quantity (or amount) of organic matter are presented on the left, and those indicating quality (or type) of organic matter on the right.

The first two columns are grouped under the subheading "Carbon Content." Organic carbon is the basic measure of the content of organic matter and is determined on all rock samples analyzed. Carbonate carbon, determined on a more selective basis, is a geochemical indicator of lithology and has implications for the type and quality of organic matter in cutting samples.

Analytical data from TEA-FID (pyrolysis) are summarized in the next four columns. The content of volatile hydrocarbons (HC) is the low-temperature (below 300 °C) portion of thermally evolved organic matter, whereas total hydrocarbon is the sum of thermally evolved plus pyrolytically evolved (300-700 °C) organic matter. Also listed under the TEA-FID heading is volatile HC as a fraction of total HC, and total HC as a percentage of organic carbon.

The next five columns, under the heading "Solvent Extraction and C_{15+} Hydrocarbon Analysis," summarize the analysis of organic matter extractable by solvent (dichloromethane). The total content of C_{15+} (nonvolatile) hydrocarbons (saturated-plus-aromatic-hydrocarbon fraction) is given in parts per million. The ratio of saturated to aromatic hydrocarbons is plotted next, followed in the next two columns by the extractable total hydrocarbon fraction as a weight percentage of organic carbon and of bitumen. When the saturated-hydrocarbon fraction is analyzed by gas chromatography, a histogram of resolved *n*-alkanes plus pristane and phytane can be plotted. It is shown in the last column of this group.

Selected samples were analyzed for their content of gasoline-range (C_4-C_7) hydrocarbons and for the proportion (as a percentage) of cyclic saturated hydrocarbons (naphthenes) in the total C_7 isomers. These results are plotted in the next two columns labeled "Gasoline-range Hydrocarbons."

In the final three columns, the results of visual and elemental analyses of kerogen are plotted. The visual-kerogen analysis is described in some detail by Bayliss and Magoon (chapter 20). Under the heading "Elemental Analysis" are plotted the hydrogen-to-carbon and the carbon-to-nitrogen atomic ratios in the isolated solid organic matter.

A qualitative classification scheme for source rocks in the NPRA, based on selected geochemical measurements of the richness of organic matter, is listed in table 18.4. Four measurements are given, based on four different fractions of the organic matter: organic carbon, total pyrolysis yield, volatile fraction by pyrolysis, and C_4-C_7 hydrocarbons. The classifications listed in table 18.4 are limited with respect to the range of thermal maturity over which they can be applied. All measurements of organic richness are decreased at extremely high levels of thermal maturity and give minimum estimates of source-rock potential, both for equivalent rocks at lower degrees of maturity and for the same rocks at an earlier stage of transformation. Measurements of organic richness based on hydrocarbon content are applicable only within the oil-generating stage of thermal maturity (see table 18.3).

The type of organic matter must also be evaluated in relation to the degree of thermal maturity. The two principal geochemical indicators of bulk organic-matter type used in this study are the H/C atomic ratio in kerogen and the total yield of pyrolytic hydrocarbon as a percentage of organic carbon. The relation between type of organic matter, based on the H/C and pyrolytic HC/OC measurements, and thermal maturity based on vitrinite reflectance is shown in figure 18.4. That figure also shows the pathways of thermochemical evolution for two common end-member types of organic matter; sapropelic and humic compositions refer to the elemental H/C and normalized pyrolysis yield for organic matter in typical marine oil-source rocks and in coal, respectively. The evolutionary path of oil-shale kerogen, which is uncommon in rocks of the NPRA, is not shown, but it would plot above the path for sapropelic organic matter. The main purpose of figure 18.4 is to illustrate the changes in geochemical indicators of organic-matter type with changes in thermal maturity. Use of figure 18.4 to evaluate the original bulk chemical composition of organic matter is questionable at levels of thermal maturity equivalent to R_0 >2 percent because the analytical uncertainties are comparable in magnitude to the expected chemical differences between the end-member types of organic matter.

TABLE 18.4.—*Indicators of organic-matter content (richness) used in NPRA oil and gas source-rock study and qualitative rating of petroleum source-rock potential*

Petroleum source-rock quality	Organic carbon (percent)	Total yield pyrolysis assay (percent)	Pyrolysis volatile or extractable hydrocarbon content (ppm)	C_4-C_7 hydrocarbon content (ppm)
Inadequate	<1	<0.2	<100	<1000
Moderate	1-2	.2-.6	100-500	1000-10,000
Good	2-5	.6-2	500-1500	10,000-100,000
Excellent	>5	>2	>1500	>100,000

VITRINITE REFLECTANCE AND C_1-C_7 HYDROCARBON DISPLAYS

A separate display of selected geochemical data was prepared for test wells from which drill cuttings were washed, preserved, and sealed in cans at the wellsite. Eighteen of these displays are presented as plates 19.28-19.39 in this report. In addition, vitrinite reflectance and C_1-C_7 hydrocarbon displays for 13 more wells are available as Oil and Gas Investigations Charts OC-92 to OC-101 (Claypool and Magoon, 1980a-d; Magoon and Claypool, 1980a-f). The wells for which these displays are available are listed in Table 18.1; they correspond to exploration wells drilled after 1974.

On the vitrinite-reflectance and C_1-C_7 hydrocarbon displays, the wells are identified and described in the same manner as on the corresponding well-summary diagrams. Depth scales are plotted on the left edge of each column of analytical data. The first column on the left side of the display, under the heading "Vitrinite Reflectance," contains a plot of the mean vitrinite reflectance ($n = 50$) on a logarithmic scale (the same data are plotted in the third column of the well-summary diagrams, pls. 19.1-19.27). In this display of the log of vitrinite reflectance (percent R_0) versus sample depth, dashed vertical guidelines are drawn at R_0 values

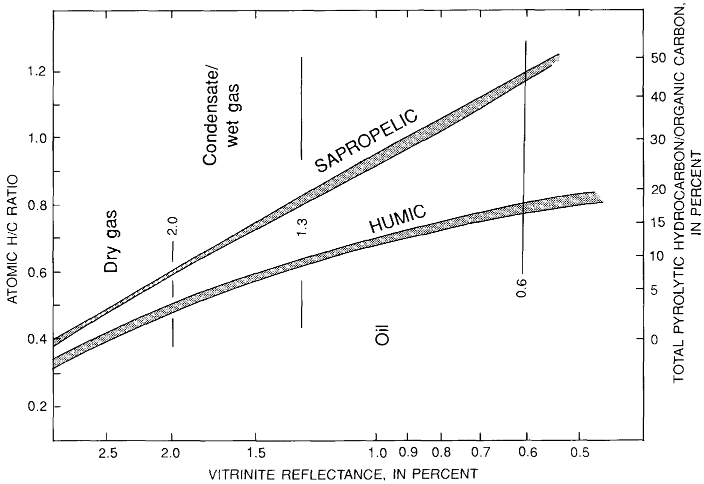

FIGURE 18.4.—Indicators of organic-matter type (H/C ratio of kerogen and pyrolytic hydrocarbon yield as a percentage of organic carbon) versus thermal maturity as indicated by vitrinite reflectance (modified from Dow, 1977).

of 0.6 and 2.0 percent. The symbols indicate the type of rock sample on which the measurement was made.

Under the heading "Rock Units Penetrated" are 10 of the same columns of stratigraphic, lithologic, and borehole logging information (omitting only that giving sample type) given under that heading on the well-summary diagrams (pls. 19.1-19.27). On the right half of the display are four plots of gas analyses under the heading "Total C_1-C_7 Hydrocarbon Headspace Plus Cuttings Gas." The first plot under this heading shows the content of C_1-C_4 hydrocarbons. The gas content is given in terms of standard volumes of gas per million volumes of sediment; the scale is logarithmic. Both the total C_1-C_4 and C_2-C_4 hydrocarbons are plotted. In the next column (third from the right), labeled "Wetness," the content of C_2-C_4 hydrocarbons as a percentage of C_1-C_4 hydrocarbons is plotted. In the last two columns on the right side of this display are shown the variation with depth of the C_5-C_7 hydrocarbon content on a logarithmic scale and the ratio of isobutane to *n*-butane.

The vitrinite-reflectance data are used to interpret thermal maturity, as discussed above, and as an indirect indicator of the stages of hydrocarbon generation and preservation. The C_1-C_4 hydrocarbon content is an indicator of gas richness. In general, a gas content of 100,000 ppm (or 0.1 standard volume of gas per volume of rock) is above average and indicates a significant potential for gas accumulation. The gas wetness, or the proportion of C_2-C_4 components in the C_1-C_4 gas, is a thermal-maturity indicator and a direct indicator of the stage of hydrocarbon generation, provided that the presence of significant amounts of migrated hydrocarbons can be excluded. A critical level of gas wetness for the rocks in the NPRA is 25 percent. The depth at which gas wetness increases from consistently less than 25 percent to consistently more than 25 percent marks the level of the onset of formation of thermogenic hydrocarbons from organic matter in the source rocks. Similarly, the depth at which gas wetness returns from being consistently above to being again consistently below 25 percent is the maximum depth for preservation of significant amounts of liquid hydrocarbons. The C_5-C_7 hydrocarbon content is another indicator of organic richness that may be useful in discriminating between so-called oil-prone and gas-prone source rocks. The ratio of isobutane to *n*-butane is primarily an indicator of thermal maturity; its value generally decreases with increasing thermal maturity.

The two types of geochemical displays produced for the NPRA program are intended to serve somewhat different purposes. The vitrinite-reflectance and C_1-C_7 hydrocarbon displays (pls. 19.28-19.39) were designed as the first rapid graphic output of geochemical data. The main purpose of these displays was to illustrate: (1) the stages of the hydrocarbon generation process as a function of depth in the rock sequence penetrated by the test well, and (2) the presence of migrated hydrocarbons in reservoir intervals. The well-summary diagrams (pls. 19.1-19.27) are a more complete graphic record of the geochemical analyses performed on samples from a given test well.

The results graphically presented in plates 19.1-19.39 and Oil and Gas Investigations Charts OC-92 to OC-101 (Claypool and Magoon, 1980a-d; Magoon and Claypool, 1980a-f) are discussed in the following section. Throughout the discussion we rely primarily on the content of organic carbon and of hydrocarbons for interpretation of organic-matter richness; on vitrinite reflectance for interpretation of thermal maturity; and on kerogen H/C ratio and normalized pyrolysis yield for interpretation of the type of organic matter.

DISCUSSION OF GEOCHEMICAL DATA FOR TEST WELLS IN THE NPRA

The results of organic geochemical analyses for evaluating petroleum source rocks in the NPRA are presented on plates 19.1-19.39. In this section, we discuss these results on a well-by-well basis, the wells being grouped by physiographic and structural region (see pl. 2.1).

THRUST BELT

The Brooks Range thrust belt in the southern part of the NPRA contains intensely deformed rocks (see Mayfield and others, chapter 7; Kirschner and Rycerski, chapter 9). One test well was drilled in this part of the reserve during the 1977-81 drilling program, at Lisburne.

LISBURNE NO. 1 WELL

Rock units penetrated by the Lisburne No. 1 test well are shown on plates 19.23 and 19.38. The well was spudded in apparently overturned beds of the Etivluk Group (Pennsylvanian to Jurassic). After penetrating 275 m (900 ft) of the Etivluk Group, the borehole passed through a 1,500-m (5,000 ft) section of the Okpikruak Formation (Early Cretaceous) that was recumbently folded and then entered another 400 m (1,300 ft) of the Etivluk Group. Limestones of the Lisburne Group (Mississippian to Permian) were first penetrated in this well at a depth of 2,250 m (7,410 ft). Thrust faults in this well at depths of 2,620, 3,320, 4,075, and 4,670 m (8,600, 10,900, 13,375, and 15,315 ft) separate stacked plates containing repeated sections of the Etivluk and Lisburne Groups.

Vitrinite-reflectance (R_o) data are shown in the appropriate columns on the left side of plates 19.23 and 19.38. Organic matter in rocks penetrated by the Lisburne No. 1 well from the surface down to a depth of about 450 m (1,500 ft) is thermally immature (R_o<0.6 percent). Below about 600 m (2,000 ft), organic matter seems, on the basis of vitrinite reflectance, sufficiently mature for the onset of oil generation. The lower depth limit for the preservation of liquid hydrocarbons in commercial amounts (1.75 percent R_o) occurs at about 2,750 m (9,000 ft) in this well. Vitrinite reflectance continues to increase with increasing depth to values of about 2.5 percent at about 3,500 m (12,000 ft). From there down to the total depth of 5,200 m (17,000 ft), vitrinite reflectance does not show any consistent increase, R_o values being between 2 and 3 percent. There are no apparent discontinuities in thermal maturity at the boundaries of thrust plates.

The C_1-C_4 hydrocarbon data for samples from the Lisburne No. 1 well (pl. 19.38) indicate abundant gas (more than 10^5 ppm) between depths of about 1,800 and 3,600 m (6,000 and 12,000 ft). The gas wetness (C_2-C_4/C_1-C_4) indicates wet gas (more than 25 percent C_2-C_4) in samples above about 2,750 m (9,000 ft) and dry gas (more than 75 percent C_1) in samples below this depth. These figures agree well with the estimated greatest depth of occurrence of liquid hydrocarbons based on vitrinite reflectance, as discussed above. The high content of wet gas and of C_5-C_7 hydrocarbons at shallow depths of 150 to 2,100 m (500-7,000 ft) in this well probably indicate the presence of migrated hydrocarbons. Oil shows were penetrated below 300 m (2,000 ft), and gas shows to 3,600 m (12,000 ft).

The content of organic carbon (pl. 19.23) is fairly high (1-2 weight percent, to as much as 4 weight percent) in the Etivluk Group and low (generally 0.5 weight percent or lower) in the Okpikruak Formation and Lisburne Group. High oil-generating capacity of the organic matter in the Etivluk Group is shown by values of the kerogen H/C atomic ratio greater than 1.0 and values of the pyrolytic hydrocarbon/organic carbon ratio greater than 0.3 at shallow depths of about 180 to 200 m (600-700 ft). The H/C ratio in the more deeply buried parts of the Etivuluk Group is lower because more kerogen is converted to hydrocarbons as more advanced degrees of thermal maturity are attained.

Significant amounts of liquid hydrocarbons are present in several zones of this well at depths shallower than 2,300 m (7,500 ft). These occurrences are evidenced both in the volatile-hydrocarbon yield from the pyrolysis assay (TEA-FID) and in the hydrocarbon yield from solvent extraction. The high content (more than 500 ppm) of heavy C_{15+} hydrocarbons is indigenous in the Etivluk Group but migrated in the Okpikruak Formation, as indicated by the extractable hydrocarbon/organic carbon proportions—values of more than 10 percent indicating migration. The C_{15+} *n*-alkane and isoprenoid histograms for solvent-extracted samples from the Lisburne No. 1 well are also shown in plate 19.23. The hydrocarbon distributions are oillike over the depth interval from 0 to 2,500 m (0-8,000 ft) in this well. At depths greater than 2,500 m (8,000 ft), there is significant depletion of *n*-alkanes having more than 20 carbon atoms. This change results from the advanced stage of thermal maturity at these depths and the apparent thermal decomposition of the larger hydrocarbon molecules to form gas and condensate-range hydrocarbons.

Source rocks of the Etivluk Group have an above-average content of oil-generating organic matter (more than 1 weight percent organic carbon, H/C>1 at R_o=0.6 percent). These rocks are present at the top and bottom of the oil window and also at greater depths in the Lisburne well, and they should have generated petroleum in the rock sequence penetrated. The presence of source rocks is a favorable factor for oil occurrence at this site. Other factors (reservoir, trap, seal, and timing) apparently are not so favorable, although hydrocarbon shows were noted.

SOUTHERN FOOTHILLS

The southern foothills in the NPRA contain moderately deformed rocks (see and Kirschner and Rycerski, chapter 9). One test well was drilled at Awuna during the 1977-81 drilling program. In addition, two shallow (less than 600 m [2,000 ft]) tests of the Nanushuk Group, Knifeblade Nos. 1 and 2A (see pl. 19.24), were drilled during the 1946-53 NPR-4 drilling program.

AWUNA NO. 1 WELL

Data for the Awuna No. 1 well are shown on plates 19.17 and 19.35. This well penetrated 900 m (3,000 ft) of the Torok Formation and about 3,500 m (11,000 ft) of the undivided Fortress Mountain and Torok Formations. Thermally mature organic matter is present in rocks just beneath the surface at Awuna, according to projected values of vitrinite reflectance. The base of the oil-condensate zone (R_o=1.75 percent) is about 2,300 m (7,500 ft) deep in this well.

The C_1-C_4 hydrocarbon data indicate the onset of rapid C_2-C_4 hydrocarbon generation (C_2-C_4/

C_1-C_4 >25 percent) at about 450 m (1,500 ft). On the basis of gas wetness, the bottom of the oil window is at about 2,000 m (6,500 ft). The overall gas content is not unusually high (less than 5×10^4 ppm).

The organic-carbon content is low (0.5-1 weight percent) in most of the rocks penetrated in this well. Below 3,000 m (10,000 ft) the organic-carbon content is slightly more than 1 weight percent. Moreover, the organic matter has a low capacity for hydrocarbon generation, as indicated by values of the kerogen H/C ratio of 0.8 or less and values of the pyrolytic hydrocarbon/organic carbon ratio of 0.1 or less. Only two samples were analyzed for extractable hydrocarbons. A sample of the Torok Formation at about 750 m (2,500 ft) contained 300 ppm of total (saturated plus aromatic) hydrocarbons. The *n*-alkane distribution, as determined by gas chromatography, showed a small but significant predominance of odd-numbered *n*-alkanes (carbon preference index or CPI=1.3). A deeper sample of the undivided Fortress Mountain and Torok Formations from about 1,800 m (6,000 ft) contained 500 ppm of total hydrocarbons. This sample was not analyzed by gas chromatography.

The rocks drilled in the Awuna well have unfavorable petroleum source potential.

KNIFEBLADE NOS. 1 AND 2A WELLS

Two shallow (550 m [1,805 ft]) wells were drilled to test the Nanushuk Group during the 1946-53 NPR-4 program. Thirty core samples from these wells were selected for geochemical analysis (pl. 19.24). Vitrinite reflectance in these samples was about 0.6 percent, and organic carbon content ranged from 0.2 to 0.8 weight percent. Eight of nine kerogen samples analyzed had an H/C ratio of 0.9 or less. Extractable hydrocarbons were in the range 200-300 ppm, and the *n*-alkane and isoprenoid distributions show distinct odd-carbon-number predominance and a high pristane/phytane ratio. The terrestrial organic matter in the rocks penetrated in these wells has a low probability of having generated oil or gas.

NORTHERN FOOTHILLS

The northern foothills structural province consists of Cretaceous rocks less intensely deformed than those in the Brooks Range thrust belt and southern foothills. This belt of shallow, elongate detachment folds was intensively drilled during the 1946-53 NPR-4 program. The Umiat oil field (Molenaar, 1982) and Gubik gas field are on this structural trend.

A total of 16 test wells at 12 different localities were drilled in the northern foothills belt. Most of these wells are shallow (14 are less than 2,100 m [7,000 ft]) tests of sandstone reservoirs in the Nanushuk Group. The wells all penetrate a similar sequence of stratigraphic units (see Bird, chapter 15).

KAOLAK NO. 1, MEADE NO. 1, EAST OUMALIK NO. 1, KOLUKTAK NO. 1, AND TITALUK NO. 1 WELLS

These five test wells are very similar in depth and in the stratigraphic sequence penetrated. The Meade No. 1 well is a noncommercial gas discovery. The undivided surficial deposits and Gubik Formation unit is from 8 to 34 m (25-110 ft) thick in the shallowest parts of these wells, and the Nanushuk Group ranges from about 900 to 1,500 m (3,000-5,000 ft) thick. All five of the wells bottomed in the Torok Formation after penetrating 150 m (500 ft; at Titaluk) to 900 m (3,000 ft; at East Oumalik) of this unit.

Gradients of increasing vitrinite reflectance are highest in wells in the western part of the northern foothills belt of the NPRA. At the Kaolak No. 1 well (pl. 19.17) the depth of 0.6 percent R_o is about 600 m (2,000 ft), and values of 1.2 to 1.3 percent are present in the deepest samples at about 2,100 m (6,900 ft). At the Meade No. 1 well (pl. 19.13) the depth of 0.6 percent R_o is about 750 m (2,500 ft), and 1.1-1.2 percent R_o is reached at the total depth of 1,600 m (5,300 ft). In samples from the East Oumalik No. 1 (pl. 19.18) and Titaluk No. 1 (pl. 19.22) wells, 0.6 percent R_o values occur at about 1,050 m (3,500 ft). The gradient of increasing vitrinite reflectance in these holes is very gentle, values of only 0.7-0.75 percent R_o being reached at the total depth (1,800 m [6,000 ft] at East Oumalik). The Koluktak No. 1 well (pls. 19.19, 19.36) shows only a slight increase in vitrinite reflectance with depth. Vitrinite reflectance ranges from only about 0.5 to 0.6 percent R_o throughout the 1,750 m (5,800 ft) thickness sampled. Koluktak No. 1 is the only well in this group of five that was drilled during the 1977-81 program and for which canned cutting samples were collected and analyzed. The C_1-C_4 hydrocarbon data (pl. 19.36) show a very high content (more than 10^5 ppm) of dry gas at shallow depths from 150 to 450 m (500-1,500 ft). This same depth interval also contains numerous coal beds with a high organic content of carbon (more than 10 weight percent). The immaturity of the organic matter in the Koluktak No. 1 well is confirmed by the gas-wetness profile; values of C_2-C_4/C_1-C_4 ratio consistently greater than 0.25 are not reached except in rocks from the bottom of the hole.

The content of organic carbon is low (0.5-0.8 weight percent) in the Nanushuk Group and Torok Formation in these five wells, except where coal beds are present or where a few shale intervals in the Torok contain as much as 1.5-2 weight percent carbon. The organic matter has a uniformly low hydrogen content, as indicated by values of the kerogen H/C ratio of 0.8 or less and values of the pyrolytic hydrocarbon/organic carbon ratio of 0.15 or less. Isolated H/C values of 1 or more in immature rocks are not confirmed by correspondingly high pyrolytic hydrocarbon/organic carbon values and thus are regarded as spurious values.

In this group of five wells, extractable organic matter was analyzed only in samples from the Kaolak No. 1 and Meade No. 1 wells. In both of these wells the extractable hydrocarbon concentrations range from 100 to 350 ppm, except where coal beds were analyzed. The *n*-alkane distributions show odd-carbon-number preference in samples shallower than 900 m (3,000 ft). The more mature hydrocarbon distributions at greater depths are consistent with the higher vitrinite-reflectance values (0.7-1.2 percent) observed in these rocks.

Rocks penetrated in these wells have a poor potential for being a hydrocarbon source; that is, they have a low content of hydrogen-deficient organic matter. The organic matter in rocks from these shallow wells in the northern foothills is thermally mature in the west half of the NPRA and immature to marginally mature in the east half of the NPRA.

OUMALIK NO. 1 WELL

The Oumalik No. 1 well is a medium-depth test (3,619 m [11,872 ft]) in the central part of the northern foothills structural trend. The 0.6 percent R_0 value occurs at about 1,050 m (3,500 ft) in the Torok Formation (pl. 19.18). The most mature samples have a vitrinite reflectance of about 1.5 percent in the Kingak Shale at the bottom of the well. The organic-carbon content of the Nanushuk Group and the upper part of the Torok Formation is 0.5 to 0.8 weight percent, except for one isolated Nanushuk sample that contains 2 weight percent. The lower part of the Torok Formation, deeper than 2,750 m (9,000 ft), contains 1 to 1.5 weight percent organic carbon. Samples of the pebble shale unit and the Kingak Shale contain 2.1 and 0.4 weight percent organic carbon, respectively.

The kerogen H/C ratio in rocks of the Oumalik well is low (0.65-0.85), indicating that the original organic matter was hydrogen deficient and that some hydrogen loss was due to hydrocarbon generation in rocks deeper than about 1,200 m (4,000 ft). The rather low capacity for generation of hydrocarbons from organic matter in the rocks penetrated in this well is confirmed by the low values of pyrolytic hydrocarbon/organic carbon ratio—0.15 or less for most of the samples analyzed.

The content of extractable hydrocarbons is low (100-250 ppm) except for three possible oil-stained intervals, two in the Nanushuk Group and one in the upper part of the Torok Formation. The *n*-alkane hydrocarbon distributions show odd-carbon-number predominance clearly down to 1,200 m (4,000 ft) but greatly diminished at 1,800 m (6,000 ft). The *n*-alkanes in the deep sample of the Kingak Shale at 3,618 m (11,870 ft) have a distribution that is truncated at about n-C_{19} because of the advanced stage of thermal maturity.

The Oumalik No. 1 well differs from the other northern foothills wells so far discussed in that it penetrated a thick sequence of the Torok Formation, the pebble shale unit, and the upper 210 m (700 ft) of the Kingak. The content of organic matter in the lower part of the Torok and the pebble shale unit is significantly higher than in the samples of the Nanushuk Group and upper part of the Torok Formation. These data lead to a slightly higher estimate of the petroleum potential than was derived from the previously discussed northern foothills wells. However, the kerogen H/C value of 0.6 at vitrinite-reflectance values of 1.5 percent indicate an original humic composition of the kerogen in the samples from both the lower part of the Torok and the pebble shale unit. Although the presence of kerogen with humic chemical composition does not preclude generation and accumulation of liquid hydrocarbons, it does greatly diminish the expected yield, other factors (such as effective source-rock volume, expulsion and migration efficiencies, drainage area, and trap volume) being approximately equal.

The lower part of the Torok and the pebble shale unit are at an optimum depth with respect to the oil-window limits of thermal maturity, which are based on relative rates of liquid hydrocarbon generation and destruction processes. Absence of adequate reservoir beds or migration pathways may be the limiting factor to oil accumulation at this location.

SQUARE LAKE NO.1, WOLF CREEK NOS. 1 AND 3, GUBIK NOS. 1 AND 2, AND GRANDSTAND NO. 1 WELLS

Six shallow test wells to depths of 1,800 m (6,000 ft) or less confirmed three gas fields at the east edge of the northern foothills region in the NPRA. The Square Lake No. 1 well, a 1,200-m (4,000 ft) test, penetrated the Colville Group, the Nanushuk Group, and the upper part of the Torok Formation. The rocks sampled range from thermally immature to marginally mature at the bottom of the well. The organic-carbon content of shale in the Colville and Nanushuk Groups ranges from 0.5 to 1.5 weight percent (pl. 19.22). A higher content of organic carbon in the sandstone sequences in the upper parts of the Colville and Nanushuk Groups reflects the presence of coaly interbeds. The organic matter in shale from this well is humic in composition, as indicated by values of the kerogen H/C ratio of 0.6 to 0.9 and values of the pyrolytic hydrocarbon/organic carbon ratio of 0.15 or less. The extractable hydrocarbon content is 100 to 300 ppm, except in one coal bed where a value of 700 ppm was observed. The *n*-alkane and isoprenoid distributions indicate mainly hydrocarbons that were derived from terrestrial organic matter at an immature stage of thermal alteration—values of the pristane/phytane ratio are high, and odd-carbon-number *n*-alkanes predominate.

The Grandstand No. 1 and Wolf Creek Nos. 1 and 3 wells, drilled to depths of 1,200, 460, and 1,150 m (3,939, 1,500, and 3,760 ft), respectively, were shallow tests of the Nanushuk Group (pls. 19.22, 19.27). In addition, about 60 m (200 ft) of the upper part of the Torok Formation was drilled in the Wolf Creek No. 3 well (pl. 19.22). The results of geochemical analyses of samples from these wells are comparable in all respects to those from the Square Lake No. 1 well. The organic matter is hydrogen deficient and thermally immature.

The Gubik gas field, just east of the Colville River boundary of the NPRA, was discovered during the 1946-53 program. The Gubik Nos. 1 and 2 wells penetrate the Colville, the Nanushuk, and the upper part of the Torok (pl. 19.27). The geochemical analyses of samples from these wells gave, for the most part, results comparable to those from the Square Lake No. 1 and Wolf Creek No. 1 wells. A major difference is observed in the ratio of volatile hydrocarbon to total hydrocarbon from the pyrolysis assay. Most of the samples from the Gubik Nos. 1 and 2 wells have values above 0.3 for this ratio, and some are above 0.5. These figures undoubtedly indicate the presence of migrated hydrocarbons that account for the gas accumulation. Extractable hydrocarbons were not determined for samples from the Gubik wells, and so the molecular weights of the migrated hydrocarbons cannot be evaluated. It is interesting that the migrated hydrocarbons seem to permeate both sandstone and shale at the Gubik gas field. However, sandstone intervals were the most heavily cored and thus were more available for subsequent analysis.

The analyses of samples from these five wells generally corroborate the unfavorable characterization of the potential of the Colville, Nanushuk, and upper part of the Torok for liquid-hydrocarbon generation. The organic matter in these rocks is hydrogen deficient, thermally immature, and present in only low to average concentration.

SEABEE NO. 1 AND UMIAT NOS. 1, 2, AND 11 WELLS

A group of four wells is located at the Umiat oil field, a noncommercial field in the northern foothills at the east boundary of the NPRA. The Seabee No. 1 well, a dry hole on the south flank of the Umiat thrust-faulted anticline, was a deep test (4,758 m or 15,611 ft) of either the Torok or Fortress Mountain Formation (pls. 19.25, 19.39).

The Umiat Nos. 1, 2, and 11 wells, sampled for geochemical analysis, are also nonproducible wells (pls. 19.24, 19.26). The Umiat Nos. 1 and 11 wells were off the structure, whereas the Umiat No. 2 well did not produce because of formation damage by freshwater-based drilling mud (Molenaar, 1982). The offstructure wells at the Umiat field (Nos. 1 and 11) penetrated surficial deposits, the lower part of the Colville Group, the Nanushuk Group, and the upper part of the Torok Formation. The Colville Group was eroded in the Umiat No. 2 well. The Umiat wells sampled were of shallow to intermediate depths—No. 11, 1,007 m (3,303 ft); No. 1, 1,830 m (6,005 ft); and No. 2, 1,893 m (6,212 ft). The main reservoir unit at the Umiat field is the Grandstand Formation of the Nanushuk Group, which produces at depths of less than 135 m (450 ft) subsea (oil-water contact) within the closed contours of the Umiat anticline (Molenaar, 1982).

The results of geochemical analyses of rock samples from shallower than 1,800 m (6,000 ft) in these wells are generally quite similar. The depth of 0.6 percent vitrinite reflectance is about 900 m (3,000 ft) except in the Umiat No. 11 well, where values of 0.5 percent are observed at the total depth of 1,007 m (3,303 ft). However, the Umiat No. 11 well was drilled north of a thrust fault into the lower plate (Molenaar, 1982). Nanushuk Group strata on the upper plate are structurally about 600 m (2,000 ft) higher than the same beds on the lower plate. Thus, the shallower depth of 0.6 percent R_0 in wells drilled south of the thrust fault into upper-plate rocks reflects the higher temperatures associated with former deeper burial. The gradients of increasing vitrinite reflectance with increasing depth of burial between 760 and 1,800 m (2,500-6,000 ft) in the Umiat No. 2 and Seabee No. 1 wells are also consistent with structural discontinuities associated with thrust faulting. The structural cross sections by Molenaar (1982) show that the Umiat No. 2 well penetrated thrust faults at about 760 m (2,500 ft; upper/middle plates) and about 1,615 m (5,300 ft; middle/lower plates). In the Seabee No. 1 well the same thrust faults are present at 975 and 1,400 m (3,200 and 4,600 ft). At these depths in both of these wells, the vitrinite-reflectance gradient is consistent with a minor reversal, absence of increase, or increase with a different slope. The main value of comparing these minor anomalies in the vitrinite-reflectance profiles with known structural displacements is that it constitutes a test of the reliability and sensitivity of this technique as an indicator of thermal history. In these rocks and in this particular study, vitrinite reflectance seems to be an extremely useful technique for this type of interpretation.

The organic-carbon contents of the Colville Group and the Nanushuk Group are essentially the same as those observed for these rock units from other wells in the northern foothills region. Colville Group rocks generally contain 0.5 to 0.8 weight percent organic carbon; only a few values are as high as 2 weight percent. Coal beds in the Colville Group containing as much as 50 weight percent organic carbon were sampled in the Umiat No. 11 well. The Nanushuk Group and the upper part of the Torok Formation generally contain 0.5 to 1 weight percent organic carbon; a few samples contain as much as 2 or 3 weight percent.

The Seabee No. 1 well penetrated the Torok Formation, the pebble shale unit, and the upper half of the Kingak Shale. Vitrinite reflectance increases from about 0.7 percent in the lower part of the Torok to about 2.3 percent in the Kingak at the total depth of 4,758 m (15,611 ft). Thus, peak oil generation (1 percent R_o) should be occurring in the lower part of the Torok at about 3,000 m (10,000 ft), the base of the oil-preservation zone (1.75 percent R_o) should be at about 4,000 m (13,000 ft), and the depth limit for preservation of wet-gas condensate should be at about 4,400 m (14,500 ft) according to the vitrinite reflectance.

The stages of hydrocarbon generation inferred from C_1-C_7 hydrocarbon data in the Seabee No. 1 well (pl. 19.39) agree reasonably well with those inferred from vitrinite reflectance. Because of the presence of migrated hydrocarbons at shallow depth, it is impossible to see the onset of oil generation reflected in the gas-wetness (C_2-C_4/C_1-C_4) profile. The gas wetness drops below 25 percent at a depth of about 3,450 m (11,300 ft). This point on the gas-wetness curve generally corresponds to the depth of the oil-preservation limit, which was estimated from vitrinite reflectance to occur at a depth of about 4,000 m (13,000 ft). The latter estimate (based on R_o) is probably a better guideline because the gas-wetness curve is inconsistent with the curve of C_5-C_7 hydrocarbon content, which shows a significant content of C_5-C_7 hydrocarbons (more than 100 ppm) down to 4,250 m (14,000 ft). The low content of wet-gas components (less than 25 percent) between 3,450 and 4,000 m (11,300-13,000 ft) in the Seabee No. 1 well is a result more of dilution by the generation of abundant amounts of C_1 in the lower part of the Torok than of the thermal destruction of C_2-C_4 hydrocarbons.

The content of organic carbon is significantly higher in the lower part of the Torok Formation, the pebble shale unit, and the Kingak Shale than in the upper part of the Torok and the Nanushuk. The value in the lower part of the Torok is consistently about 1 weight percent, although one sample at about 3,650 m (12,000 ft) contained more than 3 weight percent organic carbon. The pebble shale unit and the Kingak Shale down to 4,250 m (14,000 ft) contain 1 to 1.5 weight percent organic carbon, whereas the Kingak Shale below 4,250 m (14,000 ft) contains 2 to 2.5 weight percent.

The organic matter in the Nanushuk, Torok, and pebble shale units is consistently hydrogen deficient or humic in composition, as indicated by the values of the H/C ratio. One sample of the Torok at 3,900 m (12,800 ft) has a kerogen H/C ratio of 0.8 and a vitrinite reflectance of about 2 percent. However, this value is suspect because such an amount of residual hydrogen at that level of maturity would indicate an original hydrogen content greater than that of immature oil-shale kerogen. Samples of Torok shale at about 3,650 m (12,000 ft) have combinations of kerogen H/C ratio and vitrinite reflectance (fig. 18.4) that indicate an original humic composition of the organic matter. Kerogen elemental analyses were not performed on samples of the pebble shale unit from the Seabee No. 1 well, but the kerogen H/C ratio in the Kingak Shale ranges from 0.45 to 0.6. At a level of thermal maturity indicated by the vitrinite-reflectance range of 2 to 2.3 percent in the Kingak, the Kingak may have originally contained more hydrogen rich (that is, oil-generating) organic matter.

Source-rock evaluation based on the geochemical analyses of samples from the Seabee No. 1 and Umiat Nos. 1, 2, and 11 wells does not markedly differ from that based on data from other wells in the northern foothills. Organic matter in the Colville and Nanushuk Groups and in the upper part of the Torok Formation is thermally immature, present in low concentration, and humic in composition. These characteristics make it unlikely that these rocks have been a major source of hydrocarbons. The lower part of the Torok and the pebble shale unit contain thermally mature organic matter at average concentration levels (1 weight percent organic carbon) and of a humic bulk composition. These units (lower part of the Torok and the pebble shale unit) can be rated as only marginally adequate source rocks, judging from analyses of samples from the Seabee No. 1 well. The results of analyses of samples of the Kingak Shale from the Seabee No. 1 well indicate somewhat more favorable source-rock characteristics. The Kingak Shale is overmature with respect to the preservation of liquid hydrocarbons, but the organic-carbon content is high (2 weight percent) and was somewhat higher before maturation. There is also evidence that the Kingak Shale contained hydrogen-rich organic matter. Thus, the Kingak Shale may have generated oil at an earlier stage of thermal maturity.

WEST ARCTIC PLATFORM

Rocks underlying the coastal plain in the western part of the NPRA are here designated as the west Arctic platform province. Except for the slight regional dip to the south toward the Colville Trough, Cretaceous rocks are devoid of structure in this region. Underlying pre-Cretaceous rocks contain broad arches and basins (see Kirschner and Rycerski, chapter 9).

TUNALIK NO. 1 WELL

The Tunalik No. 1 well was drilled in the deep part of the Colville Trough west of the Wainwright arch to test a deep structure and older rocks just above the basement complex (see Kirschner and Rycerski, chapter 9). The well bottomed in the Lisburne Group at 6,198 m (20,335 ft); it is currently the deepest test in Alaska. The organic matter in the Nanushuk Group is thermally immature to a depth of about 1,050 m (3,500 ft), as indicated by vitrinite-reflectance values of less than 0.6 percent and gas-wetness values of less than 25 percent at shallow depths from 3 to 1,050 m (10-3,500 ft). The level of thermal maturity required for rapid hydrocarbon generation from organic matter (vitrinite reflectance, 0.6-1.3 percent) is present in the lower part of the Nanushuk Group and in the Torok Formation between about 1,050 and 3,000 m (3,500-10,000 ft). Rocks from depths greater than about 3,650 m (12,000 ft) in the Tunalik No. 1 well are characterized by a level of thermal maturity that is inconsistent with the preservation of significant amounts of liquid hydrocarbons. The gas-wetness values are consistently less than 25 percent, and the vitrinite reflectance is greater than 2.2 percent.

The Nanushuk Group and Torok Formation in the Tunalik No. 1 well are generally low in organic matter (less than 1 weight percent organic carbon) except for a 750-m (2,500 ft) interval with numerous low-rank coal beds (lignite, subbituminous) in the upper part of the Nanushuk Group. Samples from the pebble shale unit contain 1.5 to 3 weight percent organic carbon. The Kingak Shale, the Sag River Sandstone, and the Shublik Formation contain from 0.5 to 1.5 weight percent organic carbon, whereas the Sadlerochit and Lisburne Groups contain less than 0.5 weight percent organic carbon.

The Nanushuk Group and the Torok Formation, which are still in the hydrocarbon-generating stage of thermal maturity, generally contain hydrogen-deficient organic matter, as indicated by values of the kerogen H/C ratio of less than 1.0 and pyrolysis yield/organic carbon values of 0.15 or less. Thus, the rocks that are at the hydrocarbon-generating stage of thermal maturity do not contain significant amounts of oil-generating organic matter. Organic matter in the pebble shale unit has been largely converted to hydrocarbons ($R_o = 1.6\text{-}2.1$ percent). A single kerogen H/C ratio of 0.55 at this level of maturity is consistent with an originally humic type of organic matter in the pebble shale unit. The original type of organic matter in the Kingak Shale and the deeper rock units penetrated in this well cannot be estimated with any degree of confidence on the basis of these data because of the advanced levels of thermal maturity. Kerogen H/C data for the Sadlerochit and Lisburne samples are unreliable, as indicated by several spurious values of the H/C ratio of 1.0 or more.

The content of liquid hydrocarbon is at a maximum in the depth interval 2,300 to 3,000 m (7,500-10,000 ft), as indicated by the volatile-hydrocarbon estimate from pyrolysis assays (TEA-FID) and from the content of extractable C_{15+} hydrocarbons. However, the liquid-hydrocarbon content normalized by organic carbon is not high, indicating that the type of organic matter present has a fairly low efficiency for generating hydrocarbons. The *n*-alkane and pristane-phytane distributions are consistent both with a dominantly land-plant source for the organic matter in the Nanushuk Group and Torok Formation (high pristane/phytane and CPI) and with advanced stages of thermal maturity in the Kingak Shale and deeper rock units (*n*-alkane distributions truncated above C_{20}).

Evaluation of samples from the Tunalik No. 1 well on the basis of geochemical analysis indicates that they are unfavorable source rocks for oil but favorable for gas. Organic matter in the Nanushuk Group and the Torok Formation is present in low concentration (less than 1 weight percent organic carbon except for shallow coal beds) and is humic in composition. These rock units seem to be inadequate source units for oil and only marginal source units for gas. The shallow coal beds are immature and would not be expected to contribute to the occurrence of gas. The pebble shale unit and the Kingak Shale have an above-average content of organic matter and are at optimum maturity for gas generation. These rock units can be rated as favorable source units for gas.

PEARD NO. 1 AND KUGRUA NO. 1 WELLS

The Peard No. 1 and Kugrua No. 1 wells were drilled in the west Arctic platform, on the east edge of the Wainwright arch and updip in the Meade Basin, respectively (pls. 19.3, 19.4, 19.29). The depth of 0.6-percent vitrinite reflectance is within the upper part of the Torok Formation at about 1,125 m (3,700 ft) in the Peard No. 1 well and about 1,200 m (4,000 ft) in the Kugrua No. 1 well. The gas-wetness curves are generally consistent with the vitrinite reflectance, in the sense that the C_2-C_4/C_1-C_4 ratio in cuttings gas exceeds 0.25 below these depths. The oil window with respect to the thermal maturity required for generation and preservation of hydrocarbons in source rocks is from 1,125 to 2,900 m (3,700-9,500 ft) in the Peard No. 1 well and from 1,200 to 3,000 m (4,000-10,000 ft) in the Kugrua No. 1 well. Many coal beds are present in the Nanushuk Group in the Peard No. 1 well, and the Torok Formation in that well is low in organic carbon (0.5-0.8 weight percent). In the Kugrua No. 1 well, both the Nanushuk Group and the Torok Formation have a low content of organic carbon (0.5-0.8 weight percent). The pebble shale unit and the upper part of the Kingak Shale in both wells have an organic carbon content ranging from 1 to 2 weight percent. The lower part of the Kingak Shale, the Sag River Sandstone, and the Shublik Formation in both the Peard and Kugrua wells have a low content of organic carbon (0.5-0.6 weight percent). The Sadlerochit Group in the Peard well and both the Sadlerochit and Lisburne Groups in the Kugrua well are very low in organic carbon (0.1-0.5 weight percent).

The organic matter in rocks penetrated by both the Peard No. 1 and Kugrua No. 1 wells is not the hydrogen-rich, oil-generating type except possibly in the Shublik Formation. The few observed values of the H/C ratio greater than 1 are supported only in the Shublik Formation by values of the pyrolytic hydrocarbon/organic carbon ratio greater than 0.3. The extractable hydrocarbon content is generally low (less than 200 ppm) in the Kugrua No. 1 well and in most analyzed intervals of the Peard No. 1 well. However, some samples from the Kingak Shale, the Shublik Formation, and the Sadlerochit Group in the Peard No. 1 well contained 500 ppm or more. The *n*-alkane distributions are most oillike in samples from the lower part of the Torok Formation, pebble shale unit, and upper part of the Kingak Shale from both of these wells.

Geochemical evaluation of samples from the Peard No. 1 and Kugrua No. 1 wells as possible petroleum source rocks indicates that they are unfavorable for major occurrences of oil. The content of organic matter in the rocks penetrated is low, and the rocks do not contain abundant organic matter of the oil-generating type. However, the rock units that are prospective source beds elsewhere on the North Slope are in a favorable position in these wells with regard to the oil window determined by the degree of thermal maturity required for oil generation. Furthermore, there is evidence that these rocks have also generated hydrocarbons in the region of these two wells, but the quantity and quality of the organic matter are such that the effective availability of hydrocarbons for petroleum accumulation is much less than the hydrocarbon yields from these same rock units farther east in the NPRA.

SOUTH MEADE NO. 1 WELL

The South Meade No. 1 well was drilled on top of the Meade arch, the basement structural feature that divides the Meade basin from the Ikpikpuk basin. The rock-unit sequence penetrated at South Meade No. 1 (pls. 19.13 and 19.33) is virtually the same as that in the nearby Peard No. 1 and Kugrua No. 1 wells.

The South Meade No. 1 well has a very high thermal gradient (50 °C/km) that is reflected in the profiles of the indicators of thermal maturity. The depth of 0.6-percent vitrinite reflectance is at about 450 m (1,500 ft) in the Torok Formation, as is the increase in gas wetness to greater than 25 percent. The base of the oil window in the South Meade No. 1 well is at about 2,300 m (7,500 ft), as indicated by the interpreted trend in vitrinite reflectance. This trend is based on the analysis of core samples, which give consistently higher vitrinite-reflectance values than cutting samples. The depth profile of gas wetness does not agree with the depth profile of vitrinite reflectance—the gas-wetness curve drops below 25 percent at a depth of about 2,010 m (6,600 ft). However, in the South Meade No. 1 well the decrease in gas wetness is not due to a diminishing content of C_2-C_4 hydrocarbons in the depth range 1,980 to 2,300 m (6,500-7,500 ft) but to a greatly increased content of methane (C_1) in the depth interval 2,040 to 2,400 m (6,700-8,000 ft). The major decrease in C_2-C_4 hydrocarbons occurs at a depth of about 2,400 m (8,000 ft). Apparently, there has been significant generation of gas in the Kingak Shale, which is downdip from the Walakpa and Barrow gas accumulations.

The content of organic matter in rock samples analyzed from the South Meade No. 1 well is generally below average (1 weight percent organic carbon). Coaly units containing 2 to 11 weight percent organic carbon are present in the upper part of the Nanushuk Group, but the lower part of the Nanushuk Group and the Torok Formation contains only 0.4 to 0.9 weight percent organic carbon. The pebble shale unit and the upper part of the Kingak Shale have above-average contents of organic carbon (1-2.5 weight percent), whereas the lower part of the Kingak Shale (deeper than 2,400 m [8,000 ft]), the Sag River Sandstone, the Shublik Formation, and the Sadlerochit Group have an organic carbon content of 0.5 weight percent or less. The basement complex includes rocks with a high content of organic carbon (2-9 weight percent).

The Nanushuk Group and the upper part of the Torok Formation contain hydrogen-deficient organic matter, as indicated by values of the kerogen elemental H/C ratio of less than 1 and values of the total pyrolytic hydrocarbon/organic carbon ratio of less than 0.3. In contrast, the lower part of the Torok Formation, the pebble shale unit, and the upper part of the Kingak Shale in the South Meade No. 1 well contain a significant proportion of originally hydrogen rich, oil-generating organic matter. Organic matter in the lower part of the Kingak Shale, the Sag River Sandstone, the Shublik Formation, and the Sadlerochit Group is at such an advanced stage of thermal maturity (more than 2 percent vitrinite reflectance) that the original chemical composition and hydrocarbon-generating capacity are impossible to estimate on the basis of the available geochemical evidence.

Hydrocarbon content based on pyrolysis assay (TEA-FID), volatile hydrocarbons, and C_{15+} extractable hydrocarbons is only at average levels (100-300 ppm) for the thermally mature rocks and at low levels (less than 100 ppm) for the rocks that are advanced in maturity beyond the oil-generating stage. The *n*-alkane distributions are most oillike in the lower part of the Torok Formation and the pebble shale unit. The Kingak Shale and deeper (older) rock units have *n*-alkane distributions that are depleted in *n*-alkanes above *n*-C_{20} because of the advanced degree of thermal maturity.

The implications of the organic geochemical analyses for possible petroleum source rocks in the immediate vicinity of the South Meade No. 1 well are generally unfavorable. However, the high thermal gradient on the Meade arch and the position of the rock sequence with respect to the oil window or depth stages of hydrocarbon generation have important implications for petroleum occurrence north of the South Meade No. 1 well in the Walakpa-Barrow region. The Barrow sandstone of local usage within the Kingak Shale is the major producing reservoir in this region, and the Kingak Shale has advanced to the main gas-generating stage of thermal maturity in the region of the South Meade No. 1 well. Most of the gas at the Barrow and Walakpa fields probably has migrated updip from the region of the South Meade well.

TOPAGORUK NO. 1 AND EAST TOPAGORUK NO. 1 WELLS

Two wells about 16 km (10 mi) apart are located in the eastern part of the area designated as the northern platform structural province and are 19 km (12 mi) south of Admiralty Bay (see pl. 2.1). The Topagoruk No. 1 well is a deep test of total depth 3,201 m (10,503 ft), whereas the East Topagoruk No. 1 is a shallow test of total depth 1,094 m (3,589 ft).

Organic geochemical indicators of thermal maturity in the Nanushuk Group and the upper part of the Torok Formation are similar in the two wells; values of vitrinite reflectance range from 0.45 to 0.6 percent. The thermal-maturity profiles in the upper 1,050 m (3,500 ft) of these wells are similar, even though the present geothermal gradients are quite different. The Topagoruk No. 1 well has a geothermal gradient of 27 °C/km, whereas the East Topagoruk No. 1 well has a geothermal gradient of 44 °C/km. In the Topagoruk No. 1 well, the depth of 0.6-percent vitrinite reflectance is in the Torok Formation at about 1,200 m (4,000 ft). The deepest observed values of vitrinite reflectance in rocks above the basement complex are only about 0.9 to 1.1 percent in the Topagoruk No. 1 well. Therefore, the oil window in the Topagoruk well extends from about 1,200 m (4,000 ft) to the basement complex at 3,060 m (10,045 ft).

The organic-carbon content of a few samples from the lower part of the Nanushuk Group and the upper part of the Torok Formation exceeds 1 weight percent, but most samples of these units from the Topagoruk and East Topagoruk wells contain from 0.5 to 0.7 weight percent organic carbon. In the deeper part of the Topagoruk well, only the pebble shale unit, the upper part of the Kingak Shale, and the Shublik Formation yielded samples containing more than 0.5 weight percent organic carbon.

The proportion of hydrogen-rich organic matter in the rocks analyzed from these two wells is low, as indicated by the kerogen H/C ratio and pyrolysis assays. The content of generated hydrocarbons in the rocks is generally low except for the pebble shale unit in the Topogoruk No. 1 well, where extractable C_{15+} hydrocarbons at levels of 800 to 900 ppm were observed. The *n*-alkane distributions for samples below 2,300 m (7,500 ft) in the Topagoruk No. 1 well are not meaningful because of contamination from treated cloth sample bags, which impart a distinct predominance of even-carbon-number *n*-alkanes.

The pebble shale unit and, possibly, the Shublik Formation in the Topagoruk No. 1 well contain sufficient organic carbon (1.8 weight percent) and are thermally mature enough to have contributed to petroleum accumulation.

IKPIKPUK BASIN

The Ikpikpuk Basin is a large basement depression bounded on the west by a fault of large displacement. The depression was filled with a thick section consisting of the Endicott Group and, in part, the Lisburne Group. Probably by the end of Lisburne time and certainly by the end of Sadlerochit time, the Ikpikpuk Basin had been filled. Deposition after Sadlerochit time implies that the basin was, at most, a slight depression. Three wells—Inigok No. 1, North Inikok No. 1 and Ikpikpuk No. 1—have been drilled into and through the basin fill. The stratigraphic section penetrated is thick and characteristic in many ways of the entire Arctic platform.

INIGOK NO. 1 WELL

The Inigok No. 1 well is the deepest well in the eastern NPRA; it penetrated a section that ranges in age from Late Cretaceous to Late Devonian (pl. 19.21). The organic geochemistry of this well was discussed by Magoon and Claypool (1983). All the major rock units are represented, and most are close to their maximum thicknesses. Therefore, the Inigok No. 1 was used as a key well in the study of visual kerogen (see Bayliss and Magoon, chapter 20).

The thermal maturity, as indicated by vitrinite reflectance, goes through all the stages of petroleum generation. Vitrinite reflectance (R_o) values of 0.6 percent at 1,980 m (6,500 ft) and 2.0 percent at about 3,600 m (12,000 ft) define the limits of the zone of catagenesis in this well. The maximum reflectance value at total depth is 4.8 percent R_o. The C_1-C_7 gas analysis data (pl. 19.37) and the gas-wetness curve confirm the main stages of petroleum generation shown by vitrinite reflectance. The gas-wetness values of more than 25 percent at shallow depths of 900 to 1,200 m (3,000-4,000 ft) are interpreted as indicating migrated hydrocarbons (see Bayliss and Magoon, chapter 20; Magoon and Claypool, 1983).

The organic-carbon content of strata in the Colville, Nanushuk, and Endicott Groups is very high (more than 5 weight percent) because of abundant coal. Organic-carbon values for shales within the Colville Group are less than 0.5 weight percent, and in the Torok Formation they generally range from 0.5 to 1 weight percent. The pebble shale unit, Kingak Shale, and Shublik Formation have the highest values of organic-carbon content in this well, ranging from 1 to 2 weight percent. The Sadlerochit and Lisburne Groups are at very advanced stages of maturity and have an organic-carbon content of less than 0.5 weight percent except in a thin shale at the base of the Sadlerochit Group, where it approaches 1 weight percent.

In the submature to mature (0.5-0.8 percent R_o) Colville Group, Nanushuk Group, and Torok Formation, the organic matter is dominantly humic in bulk chemical composition, as indicated by values of the H/C ratio of less than 0.9 and values of the pyrolytic hydrocarbon/organic carbon ratio of less than 0.3. The thermally mature to overmature (0.8-2 percent R_o) lowest part of the Torok Formation, pebble shale unit, Kingak Shale, and Shublik Formation may contain organic matter of more sapropelic composition because the H/C ratio ranges from 0.7 to 0.8. In addition, the Kingak Shale has values of the pyrolytic hydrocarbon/organic carbon ratio of 0.4 to 0.5.

The only rock units in which the content of extractable hydrocarbons exceeded 500 ppm were the lowermost part of the Torok Formation and the Kingak Shale. The pebble shale unit was not analyzed for extractable hydrocarbons, but the results of the pyrolysis assays (TEA-FID) indicate that the content of extractable hydrocarbons is similar to that in the Kingak Shale. The *n*-alkane composition of the extractable organic matter is oillike only for samples within the Kingak Shale.

Evaluation of rocks in the Inigok No. 1 well as petroleum source rocks is generally favorable. The pebble shale unit and the Kingak Shale contain above-average amounts of oil-generating organic matter at an optimum stage of thermal maturity.

NORTH INIGOK NO. 1 AND IKPIKIPUK NO. 1 WELLS

The North Inigok No. 1 well (pls. 19.19, 19.36) bottomed in the Shublik Formation at 3,100 m (10,170 ft), and the Ikpikpuk No. 1 well (pls. 19.15, 19.34) was drilled all the way into the basement complex at a total depth of 4,719 m (15,481 ft). The stratigraphic sequence in both wells is similar, except that the Ikpikpuk No. 1 penetrated the Sadlerochit, Lisburne, and Endicott Groups.

Organic matter is thermally mature with respect to oil generation in rocks deeper than about 1,800 m (6,000 ft) in the North Inigok No. 1 well and deeper than about 1,500 m (5,000 ft) in the Ikpikpuk No. 1 well. These depths, corresponding to the top of the liquid-hydrocarbon window, are interpreted from the values of vitrinite reflectance and gas wetness. Using the same geochemical evidence, the deepest limit for the preservation of liquid hydrocarbons (1.75 percent R_0) is at about 3,500 m (11,500 ft) in the Ikpikpuk No. 1 well and is approached but not reached at the total depth of 3,100 m (10,170 ft) in the North Inigok No. 1 well. Vitrinite-reflectance values are 2 to 2.8 percent in rocks from the Ikpikpuk No. 1 well below 3,600 m (12,000 ft), but other geochemical indicators of maturity do not consistently corroborate such high degrees of thermal maturity. In particular, values of the H/C ratio greater than 1 and values of the pyrolytic hydrocarbon/organic carbon ratio greater than 0.4 were observed in strata of the Lisburne and Endicott Groups. Samples that are inconsistent with the interpreted degree of thermal maturity mostly contain very small amounts of organic carbon (less than 0.2 weight percent). Organic geochemical analyses on rocks with such a low carbon content are suspect.

The high content of organic carbon (more than 10 weight percent) in rocks at depths shallower than 900 m (3,000 ft) in these wells are a result of the presence of coal beds in the Colville and Nanushuk Groups. The lower part of the Nanushuk Group and the Torok Formation in both wells have an organic-carbon content in the range 0.5 to 0.8 weight percent. Samples from the pebble shale unit contain 1 to 3 weight percent organic carbon in both wells. The Kingak Shale in the North Inigok No. 1 well contains between 0.5 and 1 weight percent organic carbon except for some basal Kingak beds that contain 2 weight percent. In the Ikpikpuk No. 1 well, the Kingak Shale is significantly richer in organic carbon; values are generally above 1 weight percent, and some zones contain as much as 3 weight percent organic carbon. The Shublik Formation contains 2 to 2.5 weight percent organic carbon in both wells. In the Ikpikpuk No. 1 well, the strata of the Sadlerochit, Lisburne, and Endicott Groups are uniformly low (less than 0.5 weight percent) in organic carbon.

Each well contains two zones of high gas content (pls. 19.34, 19.36)—a shallow zone above 600 m (2,000 ft) where high gas content is associated with low-rank coal beds, and a deeper zone from 2,100 to 3,000 m (7,000-10,000 ft) where high gas content is associated with thermally mature source rocks of the pebble shale unit and the Kingak Shale.

In both wells, the Colville and Nanushuk Groups and the Torok Formation contain organic matter that has a relatively low potential for the generation of liquid hydrocarbons, as indicated by values of the H/C ratio of 0.9 or less and values of the pyrolytic hydrocarbon/organic carbon ratio of less than 0.2 at low levels of thermal maturity. In the North Inigok No. 1 well, samples from the lower part of the Torok Formation and the Kingak Shale contain organic matter with an H/C ratio greater than 1; however, these rock units were not confirmed as containing oil-generating organic matter by the pyrolysis index (total pyrolytic hydrocarbon/organic carbon), because the values are generally less than 0.2. In contrast, the pebble shale unit and the Kingak Shale in the Ikpikpuk No. 1 well contain fairly large amounts of thermally mature, oil-generating organic matter, as indicated by values of both the H/C ratio and the pyrolytic hydrocarbon/organic carbon ratio. It is difficult to evaluate the type of organic matter in the Shublik Formation in both wells, and in the Sadlerochit, Lisburne, and Endicott Groups in the Ikpikpuk No. 1 well, because of the advanced degree of thermal maturity and generally low content of organic matter.

Rocks from the Ikpikpuk No. 1 well were analyzed for content and *n*-alkane distribution of extractable hydrocarbons. The Nanushuk Group and the upper part of the Torok Formation have a fairly low content (less than 200 ppm) of extractable and TEA-FID volatile hydrocarbons. The hydrocarbon distributions are not oillike; they show a significant predominance of odd-carbon-number *n*-alkanes. In the lower part of the Torok Formation, where the onset of thermal maturity coincides with the presence of more oil-generating organic matter, the TEA-FID volatile hydrocarbon content increases to more than 500 ppm. The pebble shale unit and the Kingak Shale have hydrocarbon contents of more than 1,000 ppm, and their *n*-alkane distributions are oillike.

The geochemical properties of organic matter in these two wells provide the basis for a very favorable evaluation of the rocks as petroleum source rocks. Organic-rich prospective source-rock units (lower part of the Torok, pebble shale unit, Kingak Shale, Shublik Formation) are optimally situated with respect to the burial history required for generation and preservation of oil. The type of organic matter in the Kingak Shale is significantly better for oil generation in the Ikpikpuk No. 1 well than in the North Inigok No. 1 well.

FISH CREEK PLATFORM

The Fish Creek platform is a generally flat area on the basement complex northeast of the Ikpikpuk Basin and south of the Barrow arch (see pl. 2.1). The platform is a structural saddle of the Barrow arch between the Barrow high on the west and the Prudhoe Bay oil field on the east. The five exploratory wells drilled on this platform have been included in the petroleum geochemical study.

The stratigraphic units represented in this area are more numerous, though not thicker, than in any other area in the NPRA. Not only is the entire Ellesmerian sequence represented, but also the youngest units of the Brookian sequence, the Late Cretaceous and Tertiary Sagavanirktok Formation and the late Cretaceous Colville Group, which include the deltaic units that prograde over the Prudhoe Bay oil field to the east.

The pebble shale unit is missing in the South Harrison Bay No. 1 well because of a submarine slump (see Molenaar, chapter 25). In the remaining wells where the pebble shale unit is penetrated, it is unusually thin, presumably because the platform was topographically a slightly positive submarine feature. Because the pebble shale unit is absent or very thin, an adequate geochemical evaluation of this unit is not possible.

FISH CREEK NO. 1 AND WEST FISH CREEK NO. 1 WELLS

The Fish Creek No. 1 (pl. 19.20) and the West Fish Creek No. 1 (pl. 19.20; Magoon and Claypool, 1980d) are important wells because the former recovered oil from the Nanushuk Group and the latter found oil indications in the Torok Formation (see Magoon and Claypool, chapter 21, for analyses). The Fish Creek No. 1 well was drilled during the first U.S. Navy exploration program, and so only conventional cores are available; the West Fish Creek No. 1 well was drilled during the latest U.S. Navy program, and only a few sidewall cores and canned drill cuttings were collected. The Fish Creek No. 1 well bottomed in the Torok Formation, and the West Fish Creek No. 1 bottomed in the Endicott Group.

Interpretation of the thermal maturity of the rock units penetrated by the Fish Creek No. 1 and nearby West Fish Creek No. 1 wells on the basis of vitrinite reflectance is somewhat complex. From analyses of core samples in the Fish Creek No. 1 well, the 0.6-percent R_0 value is projected to be slightly deeper than 1,800 m (6,000 ft); analyses of drill cuttings in the West Fish Creek No. 1 well indicate that the depth there is 3,500 m (11,500 ft). Analysis of C_1-C_7 cutting gas (Magoon and Claypool, 1980d) indicates a gas wetness of 25 percent at about 1,200 m (4,000 ft). From other maturity indicators, such as the kerogen thermal-alteration index (TAI) and peak II of the TEA-FID pyrolysis analysis, the most likely top of the oil window is at the shallower depth of 1,200 to 1,800 m (4,000-6,000 ft).

The organic-carbon content of the Colville Group in the Fish Creek No. 1 well averages 0.5 weight percent. Two samples approach 2 weight percent, and one coal sample contains about 40 weight percent. The organic-carbon content in the Nanushuk Group and Torok Formation ranges from 0.5 to 1 weight percent in both wells. In the Kingak Shale in the West Fish Creek No. 1, it approaches 2 weight percent toward the base; the overall average content is about 1 weight percent. No analyses were made on samples from the thin Sag River Sandstone in the West Fish Creek No. 1 well, and only two analyses were made of the Shublik Formation; those indicate 1 to 2 weight percent organic carbon. The upper part of the Sadlerochit Group has one value of about 2.0 weight percent; otherwise, the rest of the Ellesmerian section in the West Fish Creek No. 1 well contains less than 0.5 weight percent organic carbon.

The organic matter in thermally immature rock units penetrated by these two wells is hydrogen deficient, or humic in composition, as indicated by the H/C ratio. For the thermally mature units of the Ellesmerian sequence, the H/C ratio remains close to 1.0; thus, if the effect of maturity is taken into account, the Kingak Shale could contain oil-generating organic matter.

The pyrolysis assay (TEA-FID) and the C_{15+} hydrocarbon content indicate clearly where migrated oil is present, especially in the Nanushuk Group from Fish Creek No. 1, where oil was actually recovered. The values of hydrocarbon richness generally parallel those of organic-carbon content. The C_{15+} hydrocarbons increase significantly in the Kingak Shale, indicating that this unit not only is thermally mature but also is generating and expelling oil.

The Fish Creek No. 1 well does not penetrate rocks with favorable oil-generating potential, although oil is present in sandstones of the Nanushuk Group. The Kingak Shale and the Shublik Formation, as sampled in the West Fish Creek No. 1 well, have a favorable oil-source potential: their organic richness is above average, their organic matter is hydrogen rich, and their thermal maturity is nearly optimal.

ATIGARU POINT NO. 1, SOUTH HARRISON BAY NO. 1, AND NORTH KALIKPIK NO. 1 WELLS

The Atigaru Point No. 1 (pl. 19.12) and South Harrison Bay No. 1 (pl. 19.16) wells were drilled during the most recent U.S. Navy exploration program. Canned drill cuttings and two conventional cores are available from each well, as well as sidewall cores from the Atigaru Point No. 1 well. The North Kalikpik No. 1 well (pl. 19.12), drilled during the USGS exploration program, has all three types of samples available for study. A similar rock sequence was penetrated in each of these three wells. The combined thickness of the Colville Group, Nanushuk Group, and the Torok Formation is 2,150 to 2,225 m (7,100-7,300 ft) in the three wells. The thickness of the Ellesmerian sequence is about 150 m (500 ft) in the North Kalikpik No. 1 well and about 1,200 m (4,000 ft) in the Atigaru Point No. 1 and South Harrison Bay No. 1 wells.

The thermal maturity interpreted from vitrinite reflectance for the rock units penetrated in these wells indicates that the top of the liquid window (0.6 percent R_o) is at a depth of about 1,500 to 2,300 m (5,000-7,500 ft). The maximum reflectance value of 1.4 percent R_o is observed in the Atigaru Point well at 3,350 m (11,000 ft). The gas-wetness curves from the C_1-C_7 gas analysis (Claypool and Magoon, 1980a; Magoon and Claypool, 1980b, e) indicate that the top of the liquid window is between 1,500 and 1,800 m (5,000-6,000 ft) in all three wells, in agreement with the vitrinite-reflectance results. Because the Fish Creek platform is structurally high relative to the Colville Basin, vertical migration of the gas could be affecting the C_2-C_4 content of cutting gas and masking the onset of rapid thermal generation of hydrocarbons.

The organic-carbon content of sandstones of the Sagavanirktok Formation and Colville Group generally ranges from 0.5 to 1.0 weight percent. Scattered coaly intervals are present in the North Kalikpik No. 1 well and in the Atigaru Point No. 1 well. The Upper Cretaceous Colville shale, the Nanushuk Group, and the Torok Formation also range from 0.5 to 1 weight percent in organic-carbon content. Values of organic carbon as high as 2 weight percent are common within the pebble shale unit in the North Kalikpik No. 1 well, but the values drop off again to slightly more than 0.5 weight percent in the Kingak Shale. In the South Harrison Bay No. 1 and Atigaru Point No. 1 wells, the organic-carbon content of the Kingak Shale increases downsection from 0.5 weight percent at the top to more than 1.5 weight percent at the base. The Sag River Sandstone is thin and mostly sandstone, and it is not evaluated in these wells. The organic-carbon content in the Shublik Formation ranges from 1 to 1.5 weight percent. Surprisingly high values are observed in the Sadlerochit Group, possibly because of caving from the overlying Shublik Formation. Similarly, the values of organic carbon above 0.5 weight percent in the Lisburne Group of the South Harrison Bay No. 1 well are high for a limestone and are attributed to caved drill cuttings from overlying rock units. The Endicott Group and the basement complex in the Atigaru Point No. 1 well have a low organic-carbon content.

Hydrogen-rich organic matter is present in the basal part of the Nanushuk Group, parts of the Torok Formation, and the Kingak Shale, as indicated by pyrolysis yields and values of the kerogen H/C ratio in samples from the South Harrison Bay No. 1 and Atigaru Point No. 1 wells. Organic matter seems to be hydrogen deficient in the entire rock sequence penetrated by the North Kalikpik No. 1 well; an exception may be the deepest samples of the pebble shale unit and the Kingak Shale.

Migrated hydrocarbons are present in the Torok Formation and the Nanushuk and Colville Groups in all three wells, as indicated by values of the volatile HC/total HC ratio from the pyrolysis assay. A high content (more than 500 ppm) of nonmigrated extractable C_{15+} hydrocarbons was observed in the pebble shale unit at the North Kalikpik No. 1 well and in the lower part of the Torok Formation, Kingak Shale, and Shublik Formation at the South Harrison Bay No. 1 well.

Geochemical analysis of organic matter in the rock units penetrated by the wells drilled on the Fish Creek platform has confirmed the presence of thermally mature, oil-generating source rocks. In particular, the pebble shale unit, the Kingak Shale, and the Shublik Formation have characteristics favorable for petroleum source rocks. Oil was recovered from the Nanushuk Group in the Fish Creek No. 1 well and at a surface seep in the area (see Magoon and Claypool, chapter 21).

DALTON AREA

The Dalton area is on the Arctic Coastal Plain between Smith Bay and Harrison Bay, structurally straddling the Barrow arch. Four wells (Cape Halkett No. 1, W.T. Foran No. 1, J.W. Dalton No. 1, and Drew Point No. 1) were drilled in this area in an attempt to discover oil beneath the pebble shale unconformity, in a geologic setting similar to that of the Prudhoe Bay oil field (fig. 18.3). Several barrels of heavy oil were recovered from the J.W. Dalton No. 1 well on a drill-stem test. This oil was trapped in the Sadlerochit and Lisburne Groups beneath the regional unconformity.

The thickness of the Ellesmerian sequence in this area is reduced because of regional thinning toward the sediment source area and truncation under the pebble shale unconformity. The Torok Formation within the Brookian sequence is thin because of depositional onlap towards the Barrow arch. The pebble shale unconformity at the J.W. Dalton No. 1 well does not cut entirely through the Shublik Formation, and we must look offshore to find the pebble shale unit in direct contact with the Sadlerochit Group.

Geochemical information on the Cape Halkett No. 1 well (pl. 19.11; Claypool and Magoon, 1980b) is so meager it will not be discussed. The remaining three wells in this area, W.T. Foran No. 1 (pl. 19.11; Magoon and Claypool, 1980c), J.W. Dalton No. 1 (pl. 19.10, 19.33), and Drew Point No. 1 (pl. 19.10; Claypool and Magoon, 1980c), have three types of sample material—canned cuttings and conventional and sidewall core samples. All three wells penetrated the entire section to the basement complex at a depth of less than 2,850 m (9,300 ft); the section includes about 2,050 to 2,300 m (6,700-7,500 ft) of the Brookian sequence and 350 to 625 m (1,150-2,025 ft) of the Ellesmerian sequence.

The rocks sampled in these three wells, as indicated by the vitrinite reflectance, range from immature to thermally mature (0.3-0.75 percent R_o). The onset of oil generation, based on a C_2-C_4/C_1-C_4 ratio greater than 0.25, mostly agrees with the interpreted trend of vitrinite reflectance. In the Drew Point No. 1 well, the transition from immature to mature rocks occurs at a depth of about 1,675 to 1,800 m (5,500-6,000 ft). This same transition occurs at about 1,980 m (6,500 ft) in the J.W. Dalton No. 1 well and at about 2,200 m (7,200 ft) in the W.T. Foran No. 1 well. Thus, the lower part of the Torok Formation, the pebble shale unit, and the Ellesmerian sequence are thermally mature in the Dalton area.

The organic-carbon content in sandstones of the Sagavanirktok Formation and Colville Group is low (0.2-0.6 weight percent) in the W.T. Foran No. 1 well but is rather high (max 15 weight percent) in the J.W. Dalton No. 1 well because of the presence of coal. The organic-carbon content of the Colville shale is generally about 0.5 weight percent but does get as high as 1.0 weight percent in the Drew Point No. 1 well. Organic-carbon values of 0.5 to 1.0 weight percent are common for the Nanushuk Group and Torok Formation. The values increase to 2.0 weight percent in the pebble shale unit. For the rest of the Ellesmerian sequence, organic-carbon content averages about 0.5 weight percent in the W.T. Foran and Drew Point wells but gets as high as 3.0 weight percent in the J.W. Dalton No. 1 well. In that well, the Sadlerochit and Lisburne Groups are unusually rich in organic carbon, partly because of much oil staining.

The organic matter in the J.W. Dalton No. 1 and Drew Point No. 1 wells is mainly hydrogen deficient or humic in composition, as indicated by the H/C ratio. The values of the H/C ratio that do exceed 1.0 are the result of migrated hydrocarbons.

The pyrolysis assays (TEA-FID) and the C_{15+} solvent-extraction data for the Drew Point well show that the ratio of volatile hydrocarbons to total hydrocarbons within the Torok Formation is high, indicating migrated oil. This seems to be true of the entire Brookian sequence. The Shublik Formation may contain oil-generating organic matter.

Migrated oil is common throughout the Ellesmerian and Brookian sequences, as indicated by the volatile HC/total HC ratio and the C_{15+} extraction data. The presence of migrated oil is not surprising because these wells are located on the Barrow arch and heavy oil was recovered from the J.W. Dalton No. 1 well. Even though the Ellesmerian sequence is thermally mature and the pebble shale unit and Shublik Formation are sufficiently rich in organic matter to generate hydrocarbons, the bulk of the migrated oil probably came from the Ellesmerian sequence downdip in the Colville Basin.

SIMPSON SHELF

The Simpson shelf is part of the south-dipping Arctic platform on the south flank of the Barrow arch, a regional feature that extends offshore northwest of the Barrow high and continues east of the NPRA to at least the Prudhoe Bay field. Geographically, the shelf is restricted to the Simpson peninsula, on which numerous shallow coreholes and five exploratory wells were drilled (see Bird, chapter 4). Petroleum geochemical analyses were carried out on the five wells.

Three stratigraphic relations important to the source-rock evaluation of the Simpson shelf are illustrated in figure 18.3. The first relation is the onlap of sedimentary-rock units below the pebble shale unit from older to younger in a southeast-to-northwest direction. For example, in the South Simpson No. 1 well the Endicott Group overlies the basement complex, whereas in the Simpson No. 1 well the Shublik Formation overlies the basement. Onlapping continues into the Barrow high area to the northwest until a very thin Jurassic sandstone overlies the basement. Near their onlapping edges, most sedimentary-rock units are sandy or silty and lower in their content of oil-generating organic matter.

The second stratigraphic relation is the truncation by the pebble shale unconformity of successively older rock units to the north. For example, below the uncomformity at the South Simpson No. 1 well, a thick section of the Kingak Shale is present, whereas the older Sag River Sandstone immediately underlies the unconformity farther north in the East Simpson No. 2 well. This regional truncation of rock units by the pebble shale unconformity creates updip seals for potential hydrocarbon accumulations, such as that at Prudhoe Bay (Morgridge and Smith, 1972; Jones and Speers, 1976).

The third relation shown is the stratigraphic position of the Simpson paleocanyon, which underlies the peninsula. This canyon was cut into the Nanushuk Group and Torok Formation and subsequently filled with shale of the Colville Group (see Kirschner and Rycerski, chapter 9; Bird, chapter 16). These canyon shale beds act as a seal to the stratigraphically trapped oil in the Nanushuk Group (see Magoon and Claypool, chapter 21).

NORTH SIMPSON NO. 1, SIMPSON NO. 1, SOUTH SIMPSON NO. 1, AND EAST SIMPSON NOS. 1 AND 2 WELLS

The North Simpson No. 1 (pl. 19.7) and Simpson No. 1 (pl. 19.8) wells were drilled during the first U.S. Navy exploration program, and only conventional cores are available for geochemical analysis (Collins, 1958). The South Simpson No. 1 well (pl. 19.8; Magoon and Claypool, 1980a) was drilled during the second U.S. Navy program, and only drill cuttings and a few sidewall cores are available for study. The East Simpson Nos. 1 and 2 wells (pls. 19.9, 19.32) were drilled during the USGS exploration program, and drill cuttings, sidewall cores, and conventional cores were obtained.

Except for North Simpson No. 1, all wells penetrated the basement complex at moderate depths of less than 2,700 m (8,800 ft). Vitrinite reflectance ranges from about 0.4 percent to a high of approximately 1 percent R_o, indicating a range from immature to thermally mature. Canned cutting samples were collected for C_1-C_7 hydrocarbon analyses from three of the latest wells to be drilled, the South Simpson No. 1 (pl. 19.8) and the East Simpson Nos. 1 and 2 (pls. 19.9, 19.32). Gas-wetness curves generally agree with the data on vitrinite reflectance in indicating that the onset of thermal maturity occurs at depths of about 1,500 m (5,000 ft), in the lower part of the Torok Formation.

The content of organic carbon is given below for the rock units penetrated in these wells, from youngest to oldest. In the Colville shale and the Torok Formation, organic-carbon content ranges from 0.5 to 1.0 weight percent, except for the high values (less than 4.5 weight percent) in the East Simpson Nos. 1 and 2 wells, which are caused by the presence of caved coaly material in the Nanushuk Group. Many samples of coal from the Nanushuk Group have a high (more than 5 weight percent) organic-carbon content, but generally the shale and siltstone within the Nanushuk Group are similar to those of the underlying Torok Formation. The pebble shale unit in wells on the Simpson shelf is richer in organic carbon (1-2 weight percent) than at localities farther west. Where core samples exist from the Kingak Shale, the organic-carbon content is found to be low (0.5 weight percent), even though the wells are some distance from the unit's truncation edge. The Sag River Formation is too sandy to be considered a possible source rock, and the organic-carbon content in core samples is only 0.2 to 0.4 weight percent. Except in the East Simpson No. 1 well, the Shublik Formation is very silty and low in organic-carbon content (0.5 weight percent). The Endicott Group is coaly, conglomeratic, and sandy and is not considered a source rock, containing less than 0.5 weight percent organic carbon. A high content of organic carbon in the Endicott Group at East Simpson No. 2 well is explained by the observation of numerous hydrocarbon indications and the presence of coal. The Endicott Group in the South Simpson No. 1 contains as much as 0.6 weight percent organic carbon.

The organic matter in rocks penetrated by wells on the Simpson Shelf is hydrogen deficient, or humic in composition, as indicated by the H/C ratio. The organic matter in the Torok Formation at the South Simpson No. 1 well is an exception, with an H/C ratio higher than 1. A single sample of the Kingak Shale contains organic matter with an H/C ratio greater than 1, but this one value is not considered significant.

The pyrolysis assay (TEA-FID) and the C_{15+} solvent-extraction data confirm the data on richness and type of organic matter and indicate whether or not the hydrocarbons are indigenous. The values of the TEA-FID volatile HC/total HC ratio greater than 0.1 associated with vitrinite-reflectance values below 0.6 percent R_o indicate that migrated hydrocarbons are present in the Nanushuk Group at the North Simpson No. 1 and Simpson No. 1 wells. The Simpson peninsula oil accumulation occurs in the Nanushuk Group and is sealed by Colville shale, into which hydrocarbons also have migrated. Similar indications of migrated hydrocarbons seem to occur in all the Simpson peninsula wells. Migrated hydrocarbons also were detected in the Endicott Group penetrated in the East Simpson No. 2 well.

In summary, the thermal maturity of the lower part of the Torok Formation and the Ellesmerian sequence in the Simpson shelf area is sufficient to have generated oil. Except for a few isolated examples, however, the amount of organic matter is low to moderate; it also is hydrogen deficient except for the Torok in the South Simpson No. 1 well. Migrated hydrocarbons are present in the Nanushuk Group.

BARROW HIGH

The Barrow high is a domal (doubly plunging) high that developed after deposition of the Nanushuk Group (mid-Cretaceous) and that brings basement-complex rocks to within 750 m (2,500 ft) of the surface. The Torok Formation is exposed on the surface, and the upper Paleozoic and lower Mesozoic sedimentary rocks lap onto the basement high from south to north (see Bird, chapter 16, figs. 16.4, 18.3). Three gas fields are located within this area. Two are of a structural type—the South Barrow field (west) and the South Barrow field (east); one is a stratigraphic trap—the Walakpa gas field (Walakpa Nos. 1 and 2 wells). The Avak structural feature between the two Barrow gas fields has been interpreted as an impact crater or a submarine canyon similar to Simpson Canyon (see Kirchner and Rycerski, chapter 9).

SOUTH BARROW NOS. 1, 3, AND 16, AVAK NO. 1, TULAGEAK NO. 1, AND WEST DEASE NO. 1 WELLS

Six dry exploratory wells were drilled on the Barrow high to depths of about 750 m (2,500 ft). Most of these wells penetrated the basement complex (Argillite; see Brosgé and others, chapter 14). The northernmost well, South Barrow No. 1, indicates a northward dip of the structural basement high, whereas the South Barrow No. 3 well farther south indicates a southward dip. The Tulageak No. 1 and West Dease No. 1 wells indicate an eastward dip, but no wells show a westward dip. Offshore seismic data, however, indicate a small saddle farther west on the high (see Grantz and others, chapter 11). The Barrow high is important because the basement is shallowest there, the location is closest to the northern sediment source of the Ellsemerian rock units, and the area overlies a structural and stratigraphic trap for hydrocarbons.

South Barrow No. 1 (pl. 19.6A) and No. 3 (pl. 19.5) and Avak No. 1 (pl. 19.6C) were drilled during the 1946-53 NPR-4 exploration program, and only conventional core material is available for analysis (table 18.1). The South Barrow No. 16 (pl. 19.6A; Magoon and Claypool, 1980f), Tulageak No. 1 (pls. 19.7, 19.31), and West Dease No. 1 (pls. 19.7, 19.31) wells were drilled during the NPRA exploration program, and both canned cuttings and core samples are available. The rock units in the section penetrated above the basement complex in these wells are immature on the structural high and moderately mature down its east flank, as indicated by vitrinite reflectance (less than 0.65 percent R_0) and gas wetness (less than 25 percent). The vitrinite-reflectance profiles in the South Barrow No. 3 and West Dease No. 1 wells indicate much lower reflectance values (0.4 percent R_0) in the Kingak Shale than in the rock units above and below (0.6 percent R_0). The reason for this discrepancy is unknown, but the same phenomenon has been noticed in other wells. These data seem to imply that the section in the Tulageak No. 1 well either has been uplifted or has undergone a higher temperature thermal history than in the West Dease No. 1 well. The 25 percent gas-wetness threshold in the Tulageak No. 1 well is approximately 150 m (500 ft) shallower than in the West Dease No. 1 well.

Only moderate amounts (1-2 weight percent) of organic matter have been preserved in these rock units. The ranges of organic-carbon content for the units penetrated are as follows: (1) the Torok Formation, 0.5 to 1.0 weight percent; (2) the pebble shale unit, 0.6 to 2 weight percent—this unit contains the most consistently rich (1.5 weight percent) rocks penetrated in the West Dease No. 1 well; (3) the Kingak Shale, 0.2 to 1.5 weight percent—the rich upper part of this unit at West Dease is probably caved material from the overlying pebble shale unit because the Kingak Shale is silty at this site; (4) the Sag River Formation—too thin to evaluate; and (5) the Shublik Formation, 0.1 to 1.0 weight percent—but since this unit is also silty, the rocks here generally contain less than 0.5 weight percent. The type of organic matter in rocks penetrated by exploratory wells on the Barrow high varies from hydrogen deficient ($H/C<1$) to hydrogen rich ($H/C>1$), as indicated by elemental analysis. The immature Torok Formation and pebble shale unit contain hydrogen-deficient ($H/C<1$) organic matter except at South Barrow No. 11, whereas organic matter in the Kingak Shale and the Shublik Formation is hydrogen-rich in the South Barrow No. 3 and Tulageak No. 1 wells.

Pyrolysis data (TEA-FID) and C_{15+} solvent-extraction data indicate that migrated hydrocarbons are present in the rock units underlying the pebble shale unconformity—the Torok Formation (South Barrow Nos. 1 and 3, Tulageak No. 1, and West Dease No. 1 wells) and the pebble shale unit (South Barrow No. 1 well). Indications of migrated hydrocarbons encountered in the South Barrow No. 1 well are important because this well is located on the north flank of the structure, implying that these hydrocarbons may have originated in a downdip source offshore.

These five exploratory wells drilled on or near the Barrow regional high are important for several reasons: (1) The four major shale units (Torok, pebble shale unit, Kingak, and Shublik) can be evaluated for type and richness of organic matter in an immature to marginally mature setting; (2) the facies for the Ellesmerian sequence are closest to their source area; (3) thermal maturity indicates that the Barrow high has always been positive relative to the areas previously discussed; and (4) long-range migration of hydrocarbons has occurred, as indicated by the presence of oil and gas in thermally immature rocks.

SOUTH BARROW NOS. 2, 4, 9, AND 13 WELLS

Of the 10 wells that were drilled to develop the South Barrow gas field (west), 4 were selected for petroleum geochemical analysis. The South Barrow Nos. 2, 4, 9, and 13 wells (pls. 19.6A, B), after passing through the Gubik Formation of Pleistocene age, penetrated the Torok Formation, pebble shale unit, Kingak Shale, and finally the basement complex. The Kingak Shale is here composed almost entirely of the gas-producing Barrow sandstone of local usage; the gas is of thermal origin ($\delta^{13}C = -39$ permil). The petroleum geochemistry is virtually identical to that of the South Barrow Nos. 3 and 16 wells, previously discussed. The section penetrated is thermally immature; has a range of organic-carbon content for the Torok Formation and pebble shale unit of from 0.5 to 1.0 weight percent; and has, with a few exceptions, a hydrogen-deficient ($H/C<1.0$) type of kerogen. Pyrolysis (TEA-FID) and C_{15+} solvent-extraction data indicate the presence of migrated hydrocarbons, especially in the pebble shale unit and Kingak Shale.

SOUTH BARROW NOS. 12, 14, 15, 17, 18, 19, AND 20 WELLS

Seven wells drilled to develop the South Barrow gas field (east) were sampled and analyzed for petroleum geochemistry. These wells include South Barrow Nos. 12, 14, 15, and 17 through 20 (pls. 19.6C, D), all drilled during the latest (1974-81) exploration program. Canned samples were collected for the South Barrow Nos. 14, 17, and 19 wells and analyzed for C_1-C_7 hydrocarbon gases (Magoon and Claypool, 1980f). The rock units penetrated in these wells, and their thicknesses, are virtually identical to those in the South Barrow gas field, except that more of the onlapped section below the pebble shale unconformity is present, the Kingak Shale is thicker, and the Sag River Sandstone is present above the basement complex.

The petroleum geochemistry of these development wells is very similar to that of the exploratory wells and the four wells analyzed in the South Barrow gas field. The major difference is that oil was recovered at South Barrow No. 20 well from a sandstone within the pebble shale unit and at the South Barrow Nos. 12, 17, and 19 wells from the Sag River Sandstone (see Magoon and Claypool, chapter 21). Only core samples of the Sag River Formation were analyzed from the South Barrow No. 20 well. These samples are oil stained, as indicated by the pyrolysis and C_{15+} solvent-extraction data. The petroleum geochemistry indicates oil staining in all samples of the Sag River Sandstone, as well as migrated hydrocarbons in other parts of the section in the area of the Barrow gas field. In summary, the hydrocarbon geochemistry of this region mainly shows the presence of migrated petroleum.

WALAKPA NOS. 1 AND 2 WELLS

The Walakpa gas field was discovered during the latest (1977-81) exploratory drilling within the NPRA. The rock units penetrated in the two wells (pl. 19.5) are identical, except that the Kingak Shale and Torok Formation are thicker in the Walakpa No. 2 well. In the Walakpa area the Shublik Formation is present below the Sag River Sandstone, whereas it is absent in the section penetrated at the South Barrow (east) gas field. The Shublik Formation is coarser grained here than over most of the NPRA (K.J. Bird, oral commun., 1980), and source-rock geochemical data indicate that it is marginally mature and has a poor source-rock potential. Pyrolysis data indicate no migrated hydrocarbons within the Shublik Formation. The petroleum geochemical indicators of organic richness are higher for the pebble shale unit; the organic-carbon content is 1 to 3 weight percent in both wells. The organic-carbon content for the Torok Formation (0.7-1.5 weight percent) and the Shublik Formation (0.3-0.5 weight percent) is similar to that observed in these rock units in other wells on the Barrow high. The H/C ratio of kerogen for all rock units is about 0.9; one value is more than 1.0 in the Kingak Shale. The sandstone reservoir for gas in the Walakpa field is within the immature Kingak Shale, but the gas is thermogenic in origin ($\delta^{13}C = -38$ permil, $\delta D = -163$ permil, C_1/C_1-$C_4 = 0.98$).

SUMMARY AND CONCLUSIONS

Drilling programs conducted from 1946 to 1981 by agencies of the U.S. Government in the petroleum reserve on the North Slope of Alaska have provided sample material for a geochemical evaluation of oil and gas source rocks. Organic matter in rock samples from 63 test wells and representing all major stratigraphic units has been characterized with respect to content, thermal maturity, and type (oil and gas generating or mainly gas generating), and the petroleum source-rock geochemistry of individual wells or closely related groups of wells has been summarized. Regional syntheses are the subject of other chapters in this volume (for example, Magoon and Bird, chapter 17). However, on the basis of the foregoing well-by-well review of the petroleum source-rock potential of the NPRA test wells, the following generalizations can be made:

1. Rock units of the Brookian sequence (Torok Formation and Nanushuk and Colville Groups) contain a dominantly humic type of organic matter in low concentrations, except where coal beds are developed. A possible exception is the lowermost part of the Torok Formation in some wells; this part of the Torok is a basinal facies that contains more oil-generating organic matter.
2. Some rock units within the Ellesmerian sequence, especially the Shublik Formation and the Kingak Shale, contain significant amounts of sapropelic, oil-generating organic matter. The pebble shale unit in the NPRA contains organic matter of dominantly humic composition.
3. Possible oil source rocks of the Ellesmerian sequence have undergone deep burial and have advanced beyond the oil-generating stage of thermal maturity in most of the western and southern parts of the NPRA.
4. Gas source rocks are present throughout the NPRA. A high gas content in canned cutting samples was observed in association with low-rank coal beds and disseminated humic organic matter in the Colville and Nanushuk Groups and in the upper part of the Torok Formation. Overmature strata of the pebble shale unit and the Kingak Shale are important gas source rocks in the central parts of the NPRA. The Meade arch is a region with a high thermal gradient, which may cause gas generation and migration toward the accumulations on the Barrow high.
5. Compared with source rocks in other petroleum provinces, the prospective source-rock units present in the NPRA are qualitatively rated as only adequate to good. This conclusion is somewhat surprising because the region is adjacent to Prudhoe Bay, the largest oil and gas field in the United States. There is a definite regional trend of improving source-rock quality in the direction of the major petroleum occurrences. However, it seems that the magnitude of the reserves in those occurrences is due not so much to exceptional source-rock richness as to a favorable combination of effective source-rock volume, drainage area, migration conduits, regional seals, and timing of oil generation.

REFERENCES

Ahlbrandt, T.S., 1979, Introduction to geologic studies of the Nanushuk Group, North Slope, Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 1-4.

Bartsch-Winkler, Susan, 1979, Textural and mineralogical study of some surface and subsurface sandstones from the Nanushuk Group, western North Slope, Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 61-76.

Bird, K.J., 1981a, Machine-generated displays of well logs and lithology from selected wells on the North Slope of Alaska—11 wells from the northeastern part of the National Petroleum Reserve in Alaska (NPRA): U.S. Geological Survey Open-File Report 81-1034, 7 p., 11 sheets.

——— 1981b, Machine-generated displays of well logs and lithology from selected wells on the North Slope of Alaska—15 wells from the southeastern part of the National Petroleum Reserve in Alaska (NPRA): U.S. Geological Survey Open-File Report 81-1035, 7 p., 15 sheets.

——— 1981c, Machine-generated displays of well logs and lithology from selected wells on the North Slope of Alaska—7 wells from the east-central North Slope: U.S. Geological Survey Open-File Report 81-1036, 7 p., 7 sheets.

——— 1981d, Machine-generated displays of well logs and lithology from selected wells on the North Slope of Alaska—10 wells from the western part of the National Petroleum Reserve in Alaska (NPRA): U.S. Geological Survey Open-File Report 81-1032, 7 p., 10 sheets.

——— 1981e, Machine-generated displays of well logs and lithology from selected wells on the North Slope of Alaska—26 wells from the northern part of the National Petroleum Reserve in Alaska (NPRA): U.S. Geological Survey Open-File Report 81-1033, 7 p., 26 sheets.

——— 1981f, Petroleum exploration of the North Slope in Alaska, U.S.A.: U.S. Geological Survey Open-File Report 81-0227, 43 p.

——— 1982a, Catalog of digital log data for government-drilled wells in and adjacent to the National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 82-800, 31 p.

——— 1982b, Machine-generated displays of well logs and lithology from 12 wells on the North Slope of Alaska: U.S. Geological Survey Open-File Report no. 82-290, 6 p, 12 sheets.

——— 1982c, Rock unit reports of 228 wells drilled on the North Slope, Alaska: U.S. Geological Survey Open-File Report 82-278, 108 p.

Blanchard, D.C., and Tailleur, I.L., 1982, Temperatures and interval geothermal-gradient determinations from wells in National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 82-391, 82 p.

Carter, R.D., Mull, C.G., Bird, K.J., and Powers, R.B., 1977, The petroleum geology and hydrocarbon potential of Naval Petroleum Reserve No. 4, North Slope, Alaska: U.S. Geological Survey Open-File Report 77-475, 62 p.

Claypool, G.E., and Magoon, L.B., 1980a, Vitrinite reflectance and C_1-C_7 hydrocarbon data for North Kalikpik No. 1 well, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-96.

——— 1980b, Vitrinite reflectance and C_1-C_7 hydrocarbon data for Cape Halkett No. 1 well, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-97.

——— 1980c, Vitrinite reflectance and C_1-C_7 hydrocarbon data for Drew Point No. 1 well, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-100.

——— 1980d, Vitrinite reflectance and C_1-C_7 hydrocarbon data for Kugrua No. 1 well, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-101.

Collins, F.R., 1958, Test wells, Topagoruk area, Alaska: U.S. Geological Survey Professional Paper 305-D, p. 265-316.

Demaison, G.J., and Moore, G.T., 1980, Anoxic environments and oil source bed genesis: American Association of Petroleum Geologists Bulletin, v. 64, no. 8, p. 1179-1209.

Dow, W.G., 1977, Kerogen studies and geological interpretations: Journal of Geochemical Exploration, v. 7, no. 2, p. 79-99.

Grantz, Arthur, Eittreim, Stephen, and Dinter, D.A., 1979, Geology and tectonic development of the continental margin north of Alaska: Tectonophysics, v. 59, p. 263-291.

Grantz, Arthur, Holmes, M.L., and Kososki, B.A., 1975, Geologic framework of the Alaskan continental terrace in the Chukchi and Beaufort Seas, *in* Yorath, C.J., Parker, E.R., and Glass, D.J., eds., Canada's continental margins and offshore petroleum exploration: Canadian Society of Petroleum Geologists Memoir 4, p. 669-700.

Grantz, Arthur, and May, S.D., 1983, Rifting history and structural development of the continental margin north of Alaska, *in* Watkins, J.S., and Drake, C.L., eds., Studies in continental margin geology: American Association of Petroleum Geologists Memoir 34, p. 77-100.

Gryc, George, 1982, Petroleum exploration in the National Petroleum Reserve in Alaska: U.S. Geological Survey Circular 875, p. 14-21.

Ibach, L.E.J., 1982, Relationship between sedimentation rate and total organic carbon content in ancient marine sediments: American Association of Petroleum Geologists Bulletin, v. 66, no. 2, p. 170-188.

Jones, H.P., and Speers, R.G., 1976, Permo-Triassic reservoirs of Prudhoe Bay field, North Slope, Alaska, *in* Braunstein, Jules, ed., North American oil and gas fields: American Association of Petroleum Geologists Memoir 24, p. 23-50.

Lerand, Monti, 1973, Beaufort Sea, *in* McCrossan, R.G., ed., The future petroleum provinces of Canada—their geology and potential: Canadian Society of Petroleum Geologists Memoir 1, p. 315-386.

Magoon, L.B., and Claypool, G.E., 1979, Hydrocarbon source potential of the Nanushuk Group and the Torok Formation, a preliminary report, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 54-60.

——— 1980a, Vitrinite reflectance and C_1-C_7 hydrocarbon data for South Simpson No. 1 well, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-92.

——— 1980b, Vitrinite reflectance and C_1-C_7 hydrocarbon data for South Harrison Bay No. 1 well, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-93.

——— 1980c, Vitrinite reflectance and C_1-C_7 hydrocarbon data for W.T. Foran No. 1 well, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-94.

——— 1980d, Vitrinite reflectance and C_1-C_7 hydrocarbon data for West Fish Creek No. 1 well, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-95.

——— 1980e, Vitrinite reflectance and C_1-C_7 hydrocarbon data for Atigaru Point No. 1 well, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-98.

——— 1980f, Vitrinite reflectance and C_1-C_7 hydrocarbon data for South Barrow Nos. 14, 16, 17, and 19 wells, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-99.

——— 1981, Two oil types on North Slope of Alaska—implications for exploration: American Association of Petroleum Geologists Bulletin, v. 65, no. 4, p. 644-652.

——— 1983, Petroleum geochemistry of the North Slope of Alaska—time and degree of thermal maturity, *in* Byorøy, M., and others, eds., Advances in organic geochemistry 1981: Chichester, U.K., Wiley Heyden, p. 28-38.

——— eds., 1985, Alaska, North Slope oil/rock correlation study: American Association of Petroleum Geologists Special Studies in Geology 20, 682 p.

Molenaar, C.M., 1981, Depositional history and seismic stratigraphy of Lower Cretaceous rocks, National Petroleum Reserve in Alaska and adjacent areas: U.S. Geological Survey Open-File Report 81-1084, 42 p.

——— 1982, Umiat field, an oil accumulation in a thrust-faulted anticline, North Slope of Alaska, *in* Powers, R.B., ed., Geologic studies of the Cordilleran thrust belt: Denver, Rocky Mountain Association of Geologists, v. 2, p. 537-548.

Molenaar, C.M., Egbert, R.M., and Krystinik, L.F., 1981, Depositional facies, petrography, and reservoir potential of the Fortress Mountain Formation (Lower Cretaceous), central North Slope, Alaska: U.S. Geological Survey Open-File Report 81-967, 32 p.

Morgridge, D.L., and Smith, W.B., Jr., 1972, Geology and discovery of Prudhoe Bay field, eastern Arctic Slope, Alaska, *in* King, R.E., ed., Stratigraphic oil and gas fields: Classification, exploration methods, and case histories: American Association of Petroleum Geologists Memoir 16, p. 489-501.

Seifert, W.K., Moldowan, J.M., and Jones, R.W., 1980, Application of biological marker chemistry to petroleum exploration: World Petroleum Congress, 10th, Bucharest, 1980, Proceedings, v.2, p. 425-440.

Tissot, B.P., and Welte, D.H., 1978, Petroleum formation and occurrence: New York, Springer-Verlag, 538 p.

Waples, D.W., 1980, Time and temperature in petroleum formation: Application of Lopatin's method to petroleum exploration: American Association of Petroleum Geologists Bulletin, v. 64, no. 6, p. 916-926.

Young, Allen, Monaghan, P.H., and Schweisberger, R.T., 1977, Calculation of ages of hydrocarbons in oils—physical chemistry applied to petroleum geochemistry I: American Association of Petroleum Geologists Bulletin, v. 61, no. 4, p. 573-600.

APPENDIX 18.1. ANALYTICAL PROCEDURES

Organic geochemical procedures for petroleum source rock evaluation were specified in the request-for-proposal (RFP) document. Actual procedures employed are described in the proposals submitted by Geochem Research, Inc., and Global Geochemistry Corp. The description of analytical procedures given below is modified from these proposals.

SAMPLE COLLECTION AND SUBMITTAL

Wells drilled in the NPRA (table 18.1) were sampled by the wellsite geologists and other personnel according to a standard program. Drill cuttings were collected every 9 m (30 ft), washed, and placed in 1-quart cans with friction lids. The cans were filled three-fourths full with drill cuttings and then to within 2.5 cm (1 in.) of the top with tap water to which a bactericide (zephrin chloride) had been added. The can was closed with a friction lid held in place by three can clips.

Conventional cores were sampled at the top, the bottom, and every 1.5 m (5 ft) in between. Enough dry core chips were collected at each sample depth to fill a 1-quart can. Sidewall core samples were sealed without water in half-pint cans.

All three types of sample were shipped from the wellsite to Camp Lonely or Point Barrow, and from there to Anchorage. Samples were shipped by airfreight to Geochem Research, Inc., in Houston for analysis.

When a group of NPRA samples arrived, containers were examined for integrity and to determine the source and composition of the sample. Samples from the same well (or grouped on some other basis) were assigned a unique three-digit sequential job number, and samples from within the well or group (usually in order of increasing depth) were given sequential sample numbers. Information on the date of receipt, type of sample and container, and condition of sample and container were encoded in standard format to create a sample header entry for the geochemistry data file.

C_1-C_7 HEADSPACE GAS

After receipt of the canned samples at Geochem Research and after completion of the sample header information, a silicone rubber septum was attached to the top of the canned sample and allowed to cure overnight. The can was then agitated, a hole pierced through the septum into the can, and the pressure inside the can equilibrated to sea-level atmospheric pressure by adding degassed water through a needle. This procedure was necessary because subatmospheric pressure often developed within the can because of cooling of the canned drill cuttings. A gas sample was withdrawn for analysis by injecting an additional 2 mL of degassed water after pressure equilibration, then withdrawing a 2-mL sample of the headspace gas. The gas sample was injected into a calibrated 1-mL sample loop attached to the inlet of a Varian 1400 gas chromatograph that was equipped with an alumina-packed column 2.4 m by 3.2 mm ID and a flame-ionization detector. The gas was analyzed for methane, ethane, propane, *n*-butane and isobutane, and, if present, the C_2, C_3, and C_4 olefinic hydrocarbons. After elution of the *n*-butane peak, the C_5-C_{7+} hydrocarbons were eluted as a single-backflush composite chromatographic peak.

C_1-C_7 CUTTING GAS

After measurement of the volumes of airspace, water, and cuttings present in the can, an aliquot of 10 mL of the gross contents was transferred to a double-walled container fitted with a polytron blending assembly. The design of the dual container and the surrounding water-filled jacket prevented air from leaking in and maintained the 10-mL airspace at the top of the blender.

After 2 to 3 minutes of blending, a 2-mL sample of degassed water was injected into the constant-volume headspace at the top of the blender, and an equal amount of the gas sample was withdrawn. This sample of gas was then injected into the 1-mL sample attached to the Varian gas chromatograph, and the C_1-C_7 cuttings gas analyses were carried out in a manner identical to that described in the previous section on C_1-C_7 headspace gas.

After completion of the cuttings C_1-C_7 light-gas analysis, a correction was made if complete disaggregation and maceration of the rock sample had not occurred.

C_4-C_8 GASOLINE-RANGE HYDROCARBONS

After the cutting gas analysis, another 10-mL aliquot of the can contents was immediately transferred into a stainless-steel ball mill with a ball 2.5 cm in diameter. The ball mill was filled with degassed water and sealed by a screw cap. The concave surface in the screw-cap fitting holds exactly 10 mL of airspace. The ball mill was placed in a boiling-water bath for a further 10-minute period, and the milling and disaggregation operation was repeated. After equilibration of the temperature to 95±2 °C, a sample of the headspace gas was removed by injecting 2 mL of degassed water through the withdrawal system fitted to the ball mill and removing a 2-mL measured amount of headspace gas. This aliquot was injected into a low dead-volume sample loop chilled in liquid nitrogen (−190 °C). The sample loop was attached to a Varian 1400 gas chromatograph equipped with an HHK (hexadecane-hexadecene-Kel F) column, 61 m long by 0.25 mm ID, maintained at ambient temperature (21 °C). The C_4-C_8 hydrocarbons were injected onto the HHK column by heating the loop. The column resolves the the following C_4-C_7 gasoline-range hydrocarbons commonly present in petroleum: isobutane, *n*-butane, neopentane, isopentane, *n*-pentane, 2,2-dimethylbutane, cyclopentane, 2,3-dimethylbutane, 2-methylpentane, 3-methylpentane, *n*-hexane, methylcyclopentane, 2,2-dimethylpentane, benzene, 2,4-dimethylpentane, 2,2,3-trimethylbutane, cyclohexane, 3,3-dimethylpentane, 1,1-dimethylcyclopentane, 2-methylhexane, 2,3-dimethylpentane, 1,*cis*-3-dimethylcyclopentane, 3-methylhexane, 1,*trans*-3-dimethylcyclopentane, 1,*trans*-2-dimethylcyclopentane, 3-ethylpentane, 2,2,4-trimethylpentane, *n*-heptane, 1,*cis*-2-dimethylcyclopentane, methylcyclohexane, 1,1,3-trimethylcyclopentane, 2-2-dimethylhexane and ethylcyclopentane.

The concentrations of individual hydrocarbons were estimated on a weight-weight basis, using response factors based on analysis of known concentrations of hydrocarbon standards.

ROCK-SAMPLE PREPARATION

After the analyses of C_1-C_7 light hydrocarbons and C_4-C_8 gasoline-range hydrocarbons, the samples were washed and air dried for 24 h. The dried cutting samples were then transferred into clear plastic Zip-lock bags, labeled with the sample number, and examined to determine the dominant and subordinate lithologies, the overall quality of the samples, and the amount of drilling mud and caved material.

After the lithologic and sample quality description, representative splits of samples requiring additional analyses were crushed to an average grain size of less than 2 mm in an Angstrom concentric-ring grinder. The samples were then stored in labeled clear-plastic Zip-lock bags until needed for subsequent analyses.

TOTAL CARBON

A 2- to 5-g aliquot of the rock sample was oven dried at 105 °C. A portion of this subsample was ground to a very fine particle size by hand, using an agate mortar and pestle. A weighed amount of the finely ground material was transferred to a Leco crucible, and the total carbon content was measured by combustion in a Leco induction furnace. The weight of carbon dioxide was determined gravimetrically after reaction with Ascarite.

ORGANIC CARBON

A second aliquot of each sample weighing 0.2729 g was used for determination of organic carbon. The sample was transferred into a standard porous Leco filtering crucible and placed in a specially designed suction rack, where the rock powder was acidified with 2 to 3 mL of cold 2*N* hydrochloric acid. If carbonate was present and vigorous reaction took place, more cold acid was added until the visible reaction stopped. Acidification with cold 2*N* hydrochloric acid was followed by the addition of 2*N* hydrochloric acid heated to 60 °C. If magnesium and iron carbonates were present, the reaction was driven to completion by continued addition of hydrochloric acid until no further evolution of carbon dioxide was detected. On completion of acidification, the liquid was filtered through the porous crucible by suction, and the remaining contents thoroughly washed with distilled water to remove soluble salts and any remaining traces of the acid.

The crucibles were dried at 200 °C for a 4-hour period. The amount of organic carbon was determined by burning the residue in a Leco induction furnace, as previously outlined for total carbon.

PYROLYSIS ASSAY (TEA-FID)

A subsample of the powdered whole-rock material used for analyses of total and organic carbon was used for pyrolysis assay. The rock sample was dried, weighed, and analyzed in a custom-designed pyrolysis apparatus. The sample chamber of the pyrolysis apparatus consisted of a 15-cm length of 0.7-mm-OD quartz tubing surrounded by a resistance furnace. The furnace contained a thermocouple and was driven by a temperature programmer. The sample was heated at a constant rate of temperature increase (40 °C/min) while the system was swept with helium carrier gas. The volatile reduced carbon compounds evolved from the rock were swept through a connecting line heated to 300 °C and monitored by means of a flame-ionization detector (FID). The FID analog response was digitized, integrated, and converted to a hydrocarbon weight, based on a calibration curve generated by analysis of known weights of a pure hydrocarbon standard (n-C_{20}). The results of the pyrolysis assay are expressed in terms of (1) the volatile hydrocarbon content in parts per million (milligrams per gram) and (2) the total hydrocarbon yield in weight percent. The volatile-hydrocarbon content represents the hydrocarbon weight equivalent to the FID response at temperatures below 300 °C. The total hydrocarbon yield is the equivalent hydrocarbon weight for the total FID response. In addition, the temperature at which the yield of pyrolysis products is at a maximum was also reported.

CONCENTRATION OF SOLID ORGANIC MATTER

The dried subsample was inspected carefully under a microscope to determine whether it contained any drilling mud contaminants. If the sample contained contaminants, such as straw or walnut shells, these contaminants were removed by flotation in a zinc bromide solution with a specific gravity of 2.0. After removal of the contaminants, the rock constituents were washed free of the heavy liquid used in the separation and air dried below 40 °C. A 30- to 50-g portion of the sample was impact crushed to a particle size of 1 to 2 mm, and the fines removed by sieving.

The samples were reacted with 6N hydrochloric acid at 50 °C for 2 hours to ensure the reaction of any dolomite present. Afterward, the material was centrifuged, and the acid decanted from the rock residue material. The rock residue was washed three times with distilled water. Concentrated (70 volume percent) hydrofluoric acid was cautiously added to the rock residue, which again was agitated by careful stirring for complete suspension within the acid. The rock residue was allowed to stand for 12 hours in the cold concentrated hydrofluoric acid. After this treatment, the test tube and its contents were again centrifuged to segregate the solids from the liquid, which was then decanted from the residue. The residue was washed three times with distilled water, and the solid was suspended in a zinc bromide solution with a specific gravity of 2.0 to 2.2 that contained trace amounts of hydrochloric acid to prevent discoloration of the zinc bromide solution. After agitation of the residue sufficient to obtain complete suspension, the test tubes and contents were centrifuged at 1,800 r/min for 20 minutes. The heavy-minerals separate from the kerogen concentrate was removed from the top of the layer by a disposable dropping pipette. The kerogen concentrate was thoroughly washed three times with distilled water and stored under water until used for subsequent analyses.

VITRINITE REFLECTANCE

A representative aliquot of the organic kerogen concentrate was mixed with bioplastic on a glass microscope slide. This mixture was transferred carefully into a hole drilled in a Lucite plug, and the bioplastic was allowed to cure overnight in a drying oven. The vitrinite plug surface was then polished, using differing grades of coarse and fine alumina powder (the standard vitrinite preparation technique). The plug, containing randomly oriented vitrinite, was examined under reflected light, and the first-cycle vitrinite measured. A minimum of 50 vitrinite readings were made for each sample if the amount of vitrinite permitted. In samples sparse in vitrinite, the maximum number of available grains were rated. Each reading of percent R_o was reported in the format prescribed. Additional descriptive information, such as the quality of the polish, the ease of selecting first-cycle vitrinite, and the abundance of pyrite, was also noted.

VISUAL KEROGEN

A small aliquot of the isolated kerogen concentrate was mounted on a cover slip, using Clearcol or polyvinyl alcohol as the mounting medium. Mounting on the cover slip ensured that the phytoclast constituents were in a single plane, making it possible to carry out the visual-kerogen assessment and the determination of alteration rank more conveniently. After drying of the Clearcol or polyvinyl alcohol mix, the cover slip was inverted and permanently mounted on the glass slide, using Fisher Permount mounting solution. The slide was allowed to cure overnight before visual examination under the microscope. Each slide of the kerogen concentrate was examined under a high-powered microscope. The abundances of the prime kerogen constituents (amorphous sapropel, spore pollen, herbaceous cuticle, membranous debris, woody-structured plant debris, and black opaque inertinite) were measured by using a ×10 eyepiece and ×10 and ×40 high-powered objective lenses. The abundance of each type of phytoclast present was visually estimated and expressed in the format requested. A chart listing the kerogen types and describing the classification scheme had been provided. In addition, a representative field of each sample analyzed was photographed using a ×10 objective and ×10 eyepiece; the result was a 35-mm color slide showing the nature of the kerogen concentrate.

The alteration indices were also calculated at the same time that the composition of the visual kerogen was determined and were based entirely on the coloration of the recognizable plant cuticle. The alteration rank was based on the standard stages 1 through 5 and, as requested, was converted into a decimal alteration-rank scale.

ELEMENTAL ANALYSIS (C, H, N, ASH) OF KEROGEN

A split of the kerogen concentrate was also used for elemental and ash analysis. The weight percentages of C, H, N, and ash were determined on a Perkin-Elmer 240 elemental analyzer.

After the elemental analyzer's operating conditions were met (its combustion and reduction tubes reaching temperatures of approximately 950 and 650 °C, respectively), the instrument was conditioned, then calibrated using 1- to 3-mg standards of very pure acetanilide. In the calibration procedure, at least two standards and two blanks were run alternately. When at least two blank values fell within an acceptable range, average blank values for C, H, and N were calculated. These average blank values were then used to calculate the sensitivity constants K_C, K_H, and K_N from the acetanilide standards. When three standards yielded sensitivity constants that deviated from their average by an amount no more than would yield an accuracy of 0.3 percent for the instrument (±0.10 for K_C, 3.58 for K_H, and 0.3 for K_N), an average value for the sensitivity factors was calculated.

After the calibration procedure, samples were run. Standards were run after every five samples to check on the consistency of the sensitivity factors. The 240 elemental analyzer was operated according to the standard procedures described in the instruction manual.

C_{15+} EXTRACTABLE ORGANIC MATTER

The C_{15+} bitumen was extracted from the ground rock samples by using a ball mill. A previously cleaned bottle and 20 ceramic marbles were washed with CH_2Cl_2 (30 mL) by rotating on the ball mill for 5 minutes.

About 100 g of dry, powdered rock sample and 125 mL of CH_2Cl_2 were added to the bottle and sealed with a Teflon-lined cap. The bottle and its contents were rotated at a rate of about 75 r/min on rollers for 20 to 24 hours.

After the extraction, about 12 mL of distilled water was added to aggregate the sample. The bottle and its contents were returned to the ball mill and rolled for 5 minutes to promote the displacement by water of solvent from the sediment. The CH_2Cl_2 solution was decanted from the bottle into a 250-mL flask. An additional 40 mL of CH_2Cl_2 was then added to the sediment, and the bottle and its contents were rotated for 5 minutes more on the ball mill. The rinse was added to the contents of the 250-mL flask.

Elemental sulfur was removed from the bitumen by percolating the solution through a column of activated copper and collecting the desulfurized solution in a flask. Water was removed by adding anhydrous sodium sulfate (15 g). The flask was swirled several times, covered tightly with aluminum foil, and left standing overnight. The CH_2Cl_2 solution, containing particulate materials, powdered copper, and sodium sulfate, was filtered through a Celite column, concentrated to about 20 mL under vacuum in a rotary evaporator at 50 °C, and further evaporated to about 3 mL under nitrogen at 50 °C. The solution was transferred to a preweighed 10-mL tapered vial and concentrated under nitrogen at about 50 °C until all visible solvent was removed. After the solvent was removed, the vial, containing the C_{15+} bitumen, was weighed. The vial was then heated at 40 °C under nitrogen for an additional 15 minutes and reweighed; the weight loss was recorded. If the weight loss after any 15-minute evaporation period was greater than 5 percent of the initial weight or 0.5 mg (whichever was smaller), the sample was heated again under nitrogen for 15 minutes, and the final weight of the sample recorded.

C_{15+} HYDROCARBON FRACTIONS

The C_{15+} bitumen (about 10-30 mg) obtained from solvent extraction was separated into three fractions by liquid chromatography. A microcolumn (length 20 times its diameter) was packed with two grades of activated silica gel (previously with hexane)—Davison Grade 923 (60-200 mesh) for the lower half of the column and Davison Grade 62 (60-200 mesh) for the upper half.

The microcolumn was rinsed thoroughly with *n*-hexane, and the C_{15+} bitumen dissolved or suspended in *n*-hexane was added to the top of the column. The part of the bitumen that was insoluble in the nonpolar solvent was dispersed in the solvent by stirring, and as much as possible was transferred to the top of the column.

A total amount of *n*-hexane equal to three bed volumes (6 mL) was eluted through the column. The eluant, containing the saturated hydrocarbons, was collected in a preweighed vial.

The vial that had contained the C_{15+} bitumen was rinsed again with about 1 mL of toluene, and the rinse added to the top of the column. The receiver was changed, and the aromatic hydrocarbon fraction was eluted by passing three bed volumes (6 mL) of toluene through the column. The eluant was collected in a second preweighed vial. The nonhydrocarbon asphaltic fraction was obtained by eluting with three bed volumes (6 mL) of 6:4 CH_2Cl_2:methanol (this eluant has the same solvent polarity as 1:1 benzene:methanol) and collected in a third preweighed vial.

Each fraction was concentrated under nitrogen at 40 °C. The procedure previously specified for drying and weighing of C_{15+} bitumen was used. Care had to be taken to prevent excessive evaporation of the fractions. The percentage recovery of the three fractions was calculated as 100 times the sum of the weight of the three fractions divided by the weight of the total bitumen placed on the column.

C_{15+} SATURATED HYDROCARBONS

The saturated-hydrocarbon fractions were dissolved in methylene chloride and then measured using a Varian Model 3700 dual-column gas chromatograph equipped with dual flame-ionization detectors. The column was a 15-m fused silica or glass capillary (0.25 mm ID) coated with OV-101. Detector output was processed through a converter and recorded on magnetic tape; the tape was then reprocessed through a reverse converter and read into a DEC PDP-11 computer. The software integrated all recognizable peaks, the unresolved component, and the total resolved area. Data were tabulated through a hardcopy printer/plotter along with the original chromatogram, which was reduced to 8.5 by 11 in. and labeled to publication specifications with the required sample information. All the computer output was manually scanned to verify accuracy.

19. ORGANIC GEOCHEMISTRY, HYDROCARBON OCCURRENCE, AND STRATIGRAPHY OF GOVERNMENT-DRILLED WELLS, NORTH SLOPE, ALASKA

By LESLIE B. MAGOON, KENNETH J. BIRD, GEORGE E. CLAYPOOL, DENNIS E. WEITZMAN,[1]
and RICHARD H. THOMPSON

INTRODUCTION

The basic data for evaluation of the petroleum source-rock potential in the National Petroleum Reserve in Alaska are summarized on the accompanying 39 plates (pls. 19.1–19.39). These data consist of organic geochemical analyses and observed hydrocarbon occurrences in 63 Government-drilled wells located in and adjacent to the NPRA (fig. 19.1). To relate the geochemistry to the geology, we have also included geophysical well logs, lithology, rock units, paleontologic zones, and ages. Two additional wells, Iko Bay No. 1 and Teshekpuk No. 1, are included here even though they lack geochemical data because they were drilled during the latest exploration program and provide information on subsurface geology and hydrocarbon occurrences.

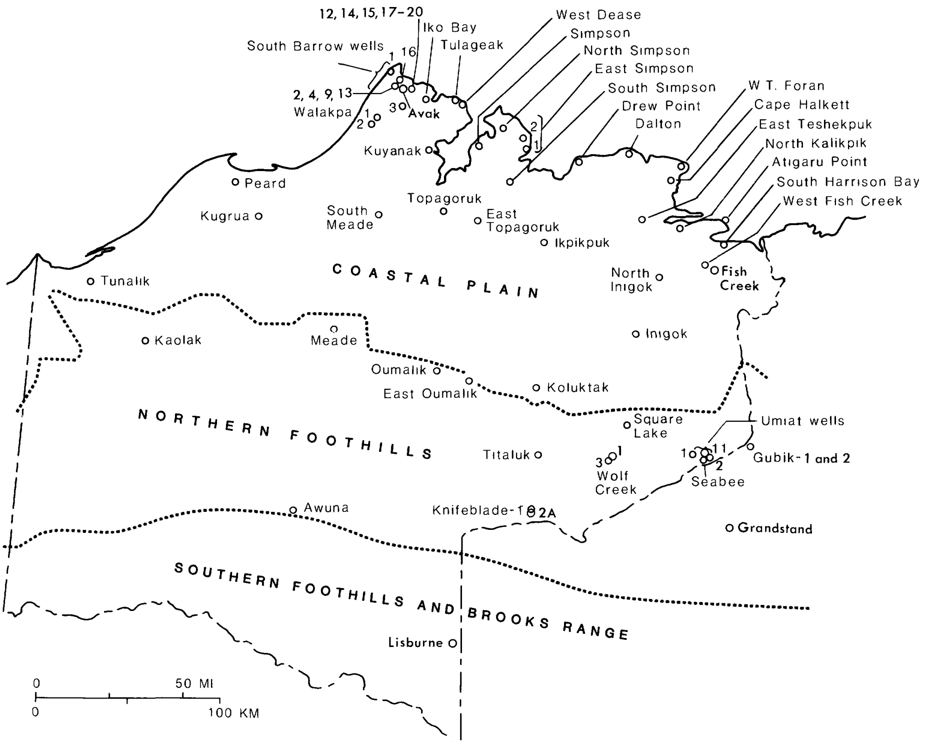

FIGURE 19.1.—Location of wells drilled by the U.S. Government in or adjacent to the National Petroleum Reserve in Alaska (boundary shown by dashed line) from 1944 to 1981. Dotted lines show boundaries of provinces discussed by Claypool and Magoon (chapter 18).

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[1] Petroleum Information Corporation, Denver, CO 80201.

These displays, in addition to being the culmination of a considerable team effort, also demonstrate the capabilities of the NPRA computer system (see Wilcox and others, chapter 39). All of the data displayed are stored in various computerized files. All data were computer-plotted except for the columns showing age, paleontologic zones, and stratigraphic names. Magoon and Claypool are responsible for the geochemical data and plate format design, Bird for the geologic and paleontologic summary, Weitzman for the computer programming and file construction, and Thompson for the data on hydrocarbon occurrence.

GEOCHEMICAL DATA

These data are discussed and interpreted in papers by Bayliss and Magoon (chapter 20), Magoon and Bird (chapter 17), Magoon and Claypool (chapter 21), and Claypool and Magoon (chapter 18). The petroleum-geochemical data are available from NOAA (National Oceanic and Atmospheric Administration), National Geophysical Data Center, Boulder, CO 80303, and Petroleum Information Corporation, P.O. Box 2612, Denver, CO 80201.

PALEONTOLOGIC DATA

The geologic ages for most wells are based on the study of microfossils reported in Witmer and others (1981) and Haga and Mickey (1983a, b). Biostratigraphic zones based on foraminifers (F and Z zones) and pollen, spores, dinoflagellates (PM and PT zones) are shown in relation to ages in figure 19.2. For each well, the basic paleontologic data consisting of distribution charts of fossil identifications and abundances are available from NOAA. Paleontologic data for wells lacking zone determinations may be found in Bergquist (1966). Samples studied for microfossils include drill cuttings, sidewall cores, and conven-

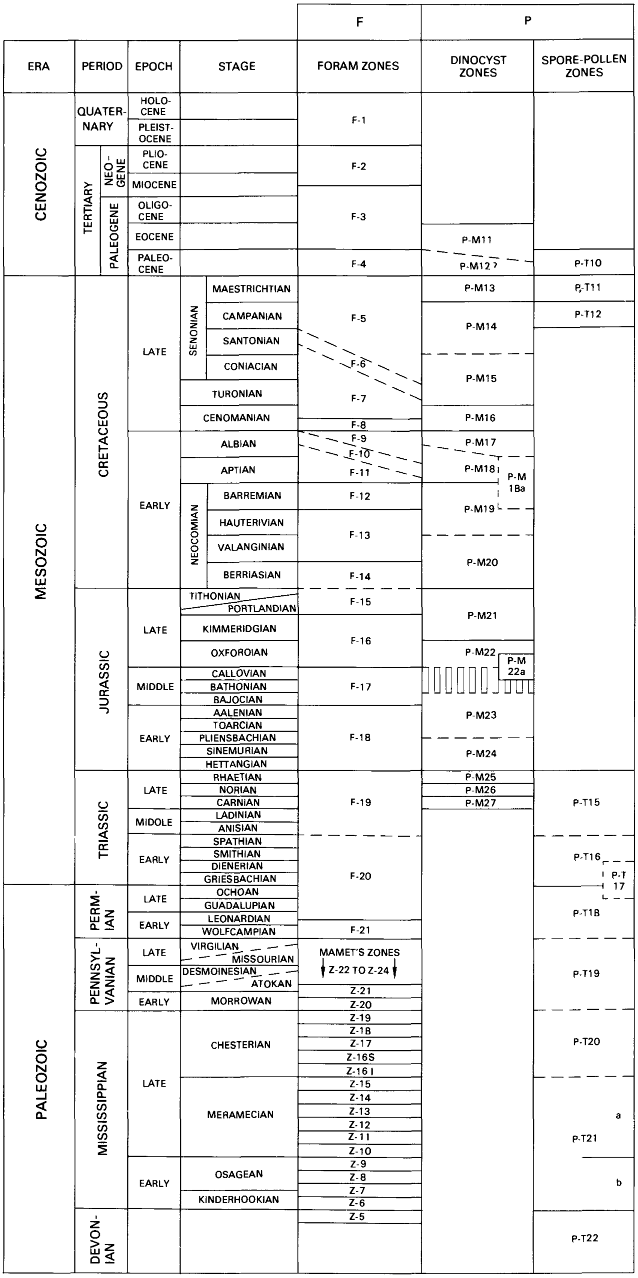

FIGURE 19.2.—Relation of geologic age to the paleontologic zones (adapted from Witmer and others, 1981).

tional cores. Although not shown on the displays, the sampling interval employed was 30 ft for foraminiferal analysis and 90 ft for pollen, spore and dinoflagellate analysis. An interval of slanted lines (fig. 19.3) illustrates differences in age boundary placement resulting from the use of the two zonation schemes. Ages shown here may differ somewhat from those previously published for some rock units. Such discrepancies may be the result of the relatively broad sampling interval, contamination, or actual age differences. We are presenting the zone determinations and interpreted ages but are not proposing changes in ages of any of the rock units based on these displays.

ROCK UNITS

The stratigraphic nomenclature and depths are from Bird (chapter 15).

GEOPHYSICAL WELL LOGS AND LITHOLOGY

The well log curves and lithologies are from the reports by Bird (1981a, b, c, d, e; 1982). The basic well logs are also available from NOAA as well as commercial well log distributors. The lithologic symbols are explained in figure 19.4.

HYDROCARBON OCCURRENCES AND WELL SYMBOLS

Occurrences of oil or gas in a well are loosely referred to as "shows." These shows may be observed in the samples, in the drilling mud, or actually measured in a test. The criteria we employed in determining significant from insignificant hydrocarbon occurrences are shown in figure 19.5. The basic observations or test results are reported on the mud log, the lithology log, and in the well history. These logs and histories are available from NOAA. A set of well symbols has been designed by Bird to show the status of the well and the nature of any hydrocarbon occurrences. These are utilized in the title block of each well in these displays and explained in figure 19.5. Figures 19.1–19.5 are repeated on plate 19.1 for ease of reference.

REFERENCES

Bergquist, H.R., 1966, Micropaleontology of the Mesozoic rocks of northern Alaska: U.S. Geological Survey Professional Paper 302-D, 227 p.

Bird, K.J., 1981a, Machine-generated displays of well logs and lithology from selected wells on the North Slope of Alaska: 10 wells from the western part of National Petroleum Reserve in Alaska (NPRA): U.S. Geological Survey Open-File Report 81-1032, 6 p., 10 pls.

——— 1981b, Machine-generated displays of well logs and lithology from selected wells on the North Slope of Alaska: 26 wells from the northern part of National Petroleum Reserve in Alaska (NPRA): U.S. Geological Survey Open-File Report 81-1033, 6 p., 26 pls.

——— 1981c, Machine-generated displays of well logs and lithology from selected wells on the North Slope of Alaska: 11 wells from the northeastern part of National Petroleum Reserve in Alaska (NPRA): U.S. Geological Survey Open-File Report 81-1034, 6 p., 11 pls.

——— 1981d, Machine-generated displays of well logs and lithology from selected wells on the North Slope of Alaska: 15 wells from the southeastern part of National Petroleum Reserve in Alaska (NPRA): U.S. Geological Survey Open-File Report 81-1035, 6 p., 15 pls.

——— 1981e, Machine-generated displays of well logs and lithology from selected wells on the North Slope of Alaska: 7 wells from the east-central part of National Petroleum Reserve in Alaska (NPRA): U.S. Geological Survey Open-File Report 81-1036, 6 p., 7 pls.

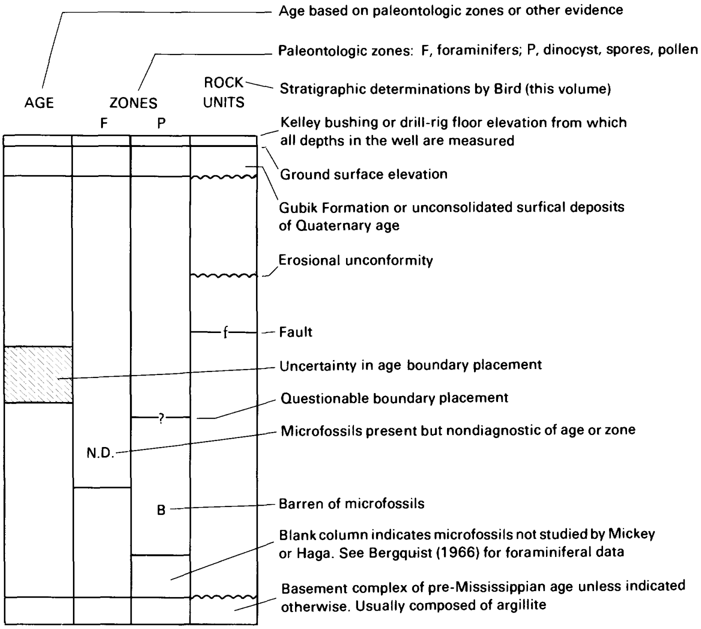

FIGURE 19.3.—Explanation of paleontologic and stratigraphic details shown on plates 19.1–19.39.

—— 1982, Machine-generated displays of well logs and lithology from 12 wells on the North Slope of Alaska: U.S. Geological Survey Open-File Report 82-290, 5 p., 12 pls.

Bird, K.J., Conner, C.L., Tailleur, I.L., Silberman, M.L., and Christie, J.L., 1978, Granite on the Barrow Arch, northeast NPRA, *in* Johnson K.M., ed., The United States Geological Survey in Alaska: Accomplishments during 1977: U.S. Geological Survey Circular 772-B, p. B24-B25.

Brosgé, W.P., and Tailleur, I.L., 1970, Depositional history of northern Alaska, *in* Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska: Los Angeles, American Association of Petroleum Geologists, Pacific Section, p. D1-D17.

Carter, Claire, and Laufeld, Sven, 1975, Ordovician and Silurian fossils in well cores from North Slope of Alaska: American Association of Petroleum Geologists Bulletin, v. 59, no. 3, p. 457-464.

Collins, F.R., 1958, Test wells, Topagoruk area, Alaska: U.S. Geological Survey Professional Paper 305-D, p. 265-316.

Haga, Hideyo, and Mickey, M.B., 1983a, South Barrow area Neocomian biostratigraphy: A report of work performed for the U.S. Geological Survey by Biostratigraphics Inc., San Diego, CA, 48 p., 20 pls. [Available from National Geophysical Data Center, 325 Broadway, E/GC1, Dept. CNP, Boulder, CO 80303].

—— 1983b, Jurassic-Neocomian seismic stratigraphy, NPRA: A report of work performed for the U.S. Geological Survey by Biostratigraphics, Inc., San Diego, CA, 133 p. [Available from National Geophysical Data Center, 325 Broadway, E/GC1, Dept. CNP, Boulder, CO 80303].

Lanphere, M.A., and Tailleur, I.L., K-Ar ages of bentonites in the Seabee Formation, northern Alaska: A Late Cretaceous (Turonian) time-scale point: Cretaceous Research, v. 4, p. 361-370.

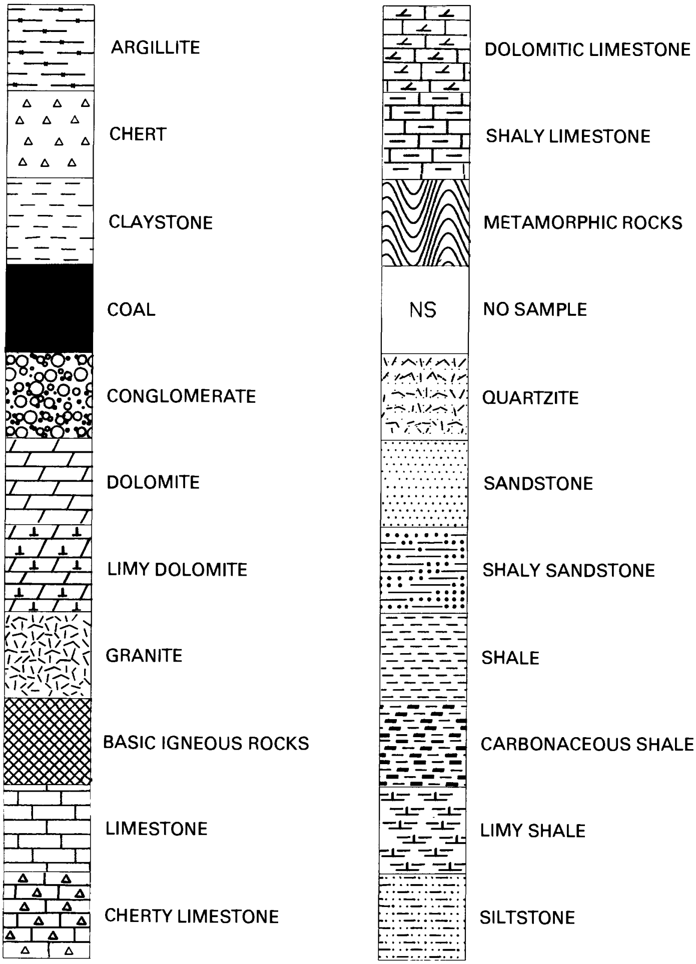

FIGURE 19.4.—Lithologic symbols used on plates 19.1-19.39.

Witmer, R.J., Haga, Hideyo, Mickey, M.B., 1981, Biostratigraphic report of thirty-three wells drilled from 1975 to 1981 in National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 81-1166, 47 p.

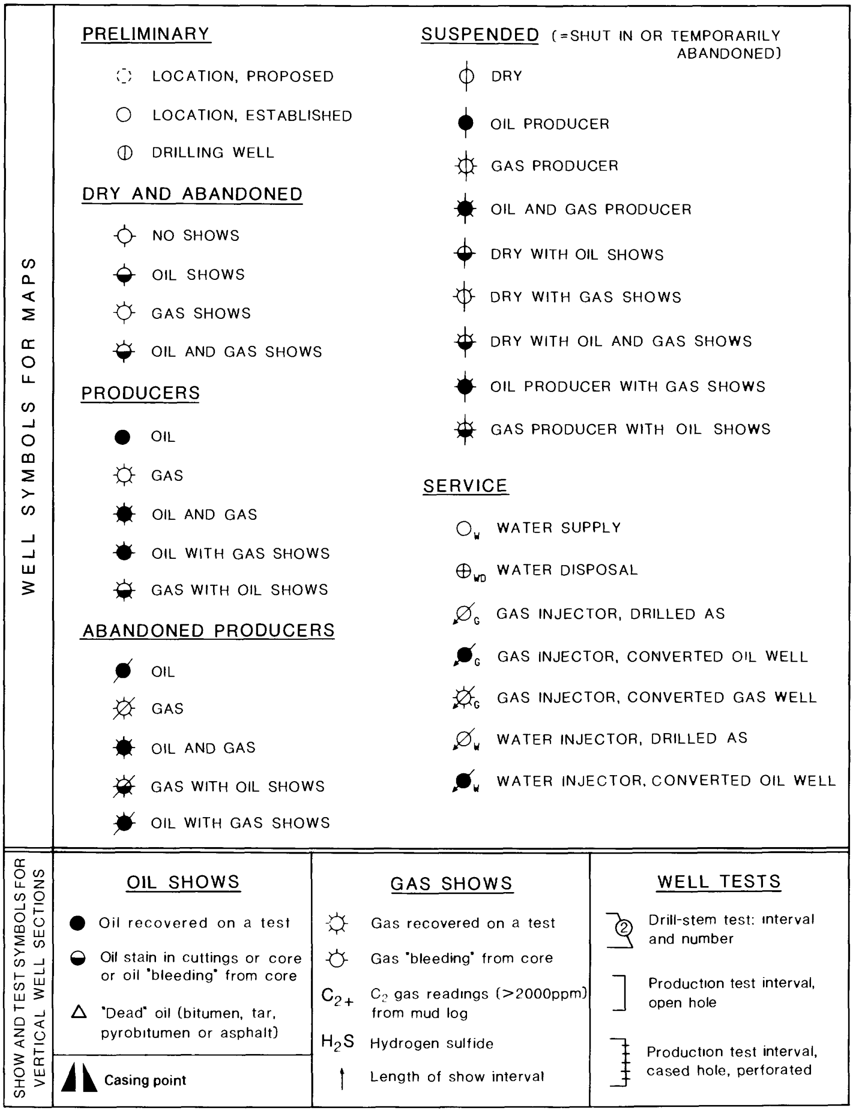

FIGURE 19.5.—Symbols used on plates 19.1–19.39 for wells (on maps and displays) and for hydrocarbon occurrences (on well sections).

20. ORGANIC FACIES AND THERMAL MATURITY OF SEDIMENTARY ROCKS IN THE NATIONAL PETROLEUM RESERVE IN ALASKA

By GEOFFREY S. BAYLISS[1] and LESLIE B. MAGOON

INTRODUCTION

In 1977, the U.S. Geological Survey (USGS) initiated a contract with GeoChem Research, Inc., to carry out petroleum geochemical analyses on drill cuttings, conventional and sidewall cores, and hydrocarbon samples collected from wells drilled in the National Petroleum Reserve in Alaska (NPRA). The geochemical file from this work is one of the most complete and comprehensive publicly available data sets for evaluating the regional variation of geochemical processes as related to oil and gas exploration and resource assessment (see Claypool and Magoon, chapter 18).

The focus of attention in this regional study was on three important goals: (1) identification of organic facies for 11 rock units, (2) determination of the richness (organic-carbon content) of these organic facies, and (3) establishment of thermal-maturation profiles in relation to the stages of petroleum generation within the geologic framework for the NPRA.

To better understand the vertical and areal variations of these three important aspects, the analytical results from four widely spaced wells in the NPRA have been interpreted in considerable detail. The geochemical analyses discussed in this chapter are of organic-carbon content, visual kerogen, thermal-alteration index (TAI), vitrinite reflectance (percent R_0), and C_1-C_4 hydrocarbon composition. Although various geochemical measurements can be used to demonstrate thermal-maturity trends or degrees of geothermal stress undergone by the sedimentary rocks (Abelson, 1963; Hedberg, 1964; Welte, 1965; Cordell, 1972; Hood and Castaño, 1974; Tissot and Welte, 1978; Hunt, 1979), it is not the purpose of this chapter to use all such geochemical criteria. Instead, we interpret the thermal maturity and the content and type of organic matter from examination of the inplace kerogen, using transmitted-light (Wilson, 1961; Gutjahr, 1966; Staplin, 1969; Burgess, 1974; Powell and others, 1982) and reflected-light microscopic techniques (Bostick, 1971; Castaño and Sparks, 1974).

The large number of data available for the four wells considered affords an excellent opportunity to compare the use of different maturation techniques, specifically: (1) to compare increase in thermal-alteration index with increase in vitrinite reflectance, (2) to compare values from drill cuttings with those from conventional and sidewall cores, and (3) to compare these two maturity techniques with light-hydrocarbon geochemistry to establish limits for oil and gas generation and preservation.

ACKNOWLEDGMENTS

We thank Ann B. Reaugh, GeoChem Laboratories, Inc., for her useful discussions and for taking the photographs used in figures 20.2-20.5, and Rick Harding of GeoChem Laboratories, Inc., and H.B. Lo (formerly of GeoChem Laboratories, Inc.), who carried out all the vitrinite-reflectance measurements reported herein. We also thank Charles F. Bohnstedt, Louis Simms, and Rudy Schwarzer of GeoChem Research, Inc., who coordinated much of the analytical work, and Stephen J. Martin and David DesAutels (both formerly with GeoChem Research, Inc.) for their efforts during the first 4 years of this program.

SAMPLING, ANALYTICAL PROCEDURE, AND INTERPRETATIVE FRAMEWORK

At the wellsite, washed drill cuttings were collected in quart cans. If enough cuttings were available, the can was filled about two-thirds full. Enough water was then added to submerge the cuttings and leave 1.25 cm (0.5 in.) of airspace (called the headspace) at the top of the can. Zephiran chloride was added to the water to prevent biologic activity in the samples. Conventional and sidewall cores were canned in a similar manner but without water or zephiran chloride. The cans were shipped by air freight to GeoChem Research, Inc., in Houston, Texas, for analysis.

C_1-C_4 HYDROCARBON GAS

A 2-mL sample of headspace gas was analyzed on a 1-mL gas-sample loop attached to a gas chromatograph equipped with an alumina-

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[1] GeoChem Research, Inc., Houston, TX 77043.

packed column, 3 mm (0.125 in.) by 2.4 m (8 ft), and a flame ionization detector. The gas was analyzed for methane (C_1), ethane (C_2), propane (C_3), isobutane and normal butane (*iso*-C_4 and *n*-C_4), and, if present, C_2, C_3, and C_4 olefinic hydrocarbons. After *n*-butane elution, the C_5-C_7 hydrocarbons were eluted as a single backflush composite chromatographic peak. The concentration of each hydrocarbon was computed from the area of its peak. The volumes of airspace, water, and rock (drill cuttings) in the can were used to calculate the concentration of each hydrocarbon component in standard volumes of gas per million volumes of sediment (ppm).

After the composition of the headspace gas was determined, the can was opened, and a 10-mL aliquot of wet cuttings was taken for the C_1-C_7 cuttings-gas analysis. This sample was disaggregated in a specially designed blender for 2 to 3 minutes. Degassed water (2 mL) was injected with a syringe into the 10-mL airspace at the top of the blender, and an equal amount (2 mL) of the gas was withdrawn; this 2-mL gas sample was analyzed in the manner described previously. The 10-mL aliquot of cuttings and about 10 mL of the airspace were used for calculation of the standard volumes of C_1-C_7 hydrocarbon components released per million volumes of rock disaggregated.

The wetness value is based on the combined headspace and cuttings-gas analyses of the C_1-C_4 data; the C_5-C_7 data are not used in this chapter. Gas wetness (in percent) is calculated as

$$100 \times \frac{(C_2\text{-}C_4 \text{ headspace gas}) + (C_2\text{-}C_4 \text{ cuttings gas})}{(C_1\text{-}C_4 \text{ headspace gas}) + (C_1\text{-}C_4 \text{ cuttings gas})}$$

ORGANIC CARBON

A weighed sample of ground rock material that had been dried at 105 °C for 10 hours was placed into a standard porous Leco crucible. The crucible and contents were transferred into a specially designed vacuum system, and the rock powder cautiously acidified with 2*N* hydrochloric acid. On completion of the acidification, the liquid was filtered from the crucible by vacuum suction, and the remaining contents thoroughly washed with distilled water to remove any traces of the acid. The crucible was then dried at 200 °C for a 4-hour period.

After drying, the acid-insoluble carbon content was determined by combustion in a Leco induction furnace in a 1-L/min flow of purified oxygen gas. The weight of carbon dioxide formed was measured by reaction with Ascarite in a preweighed gravimetric absorption bulb. Organic carbon is reported in weight percent of original rock.

PALYNOLOGIC KEROGEN

Although the term "kerogen" is used to define the solvent- and acid-insoluble carbonaceous residue in shale and carbonate rocks, not all the residual carbonaceous material can be isolated in particulate form for microscopic examination. The use of the term "palynologic kerogen" is suggested as a means to identify more specifically the particulate and microscopically identifiable kerogen isolated from sedimentary rocks in the manner described below.

A coarsely ground, unextracted rock sample was treated with an excess of cold hydrochloric acid to dissolve carbonate and to remove calcium and magnesium ions, which during processing would otherwise form insoluble calcium and magnesium fluorides that are difficult to remove. The decarbonated sample was digested with cold concentrated hydrofluoric acid to remove the silicates and release the kerogen. The kerogen concentrate was isolated as a powder after thorough washings with water and separation from heavy minerals by flotation, using a zinc bromide solution with a specific gravity of 2.0. The kerogen float was mounted wet onto a cover slip and made into a permanently bonded strew slide by standard palynologic techniques (Brown, 1960). The strew slide was examined under transmitted light for both assessment of the visual kerogen and determination of the thermal-alteration index (TAI).

VISUAL KEROGEN

For assessment of visual kerogen, the strew slide was evaluated in transmitted light, using a high-powered microscope fitted with appropriate light filters. In general, a ×10 objective lens and ×10, ×40, and ×100 condenser lenses were used for this examination.

The simplest classification of kerogen as viewed under the microscope divides it into four main types: amorphous sapropel (Am), herbaceous (H), woody (W), and inertinite (I). During the course of the NPRA study, these four categories of palynologic kerogen were routinely scanned in each sample or strew slide. The description of and genetic basis for each of these kerogen populations are outlined in table 20.1.

The relative amounts of the different kerogen populations were subjectively quantified as estimated percent abundances for each kerogen type in the total kerogen. This technique of population assessment by numerical percentages has certain advantages when averaging characteristics for a formation or zone for computerized data storage and mapping, but it does not always adequately define subtle organic facies changes between samples.

THERMAL-ALTERATION INDEX

Values of the thermal-alteration index (TAI) have been assigned to the kerogen samples in this study by using a subjective numerical scale from 1 through 5 based on color changes (table 20.2) in the plant cuticle. These colors range from greenish yellow, through yellow, yellow orange, orange brown and various other degrees of brown, to black. Descriptive terms for the degrees of thermal alteration represented by these colors are: immature, moderately immature, moderately mature, very mature, and severely altered, respectively. GeoChem Research, Inc., refined this preliminary maturity scale by using a + and − notation for each scale integer from 1 to 5. In practice, these values are much easier to reproduce than numerical fractions and can be readily converted to the numerical scale shown in table 20.2 after the rating has been completed. The TAI numerical scale is also compared to the vitrinite-reflectance maturity scale in table 20.2; the relation between TAI and R_0 shown there is empirical and is based on the selected NPRA wells discussed below.

TABLE 20.1.—*Characteristics of the four kerogen types recognized and assessed in this study*

Symbol	Organic-matter characteristics
Am	**Amorphous sapropel** is material that has an amorphous or nonstructured appearance. It can be derived from the lipid-rich degraded remains of marine algae or can be the result of bacterial degradation of herbaceous and spore remains of terrestrial origin. The physical appearance may be diaphanous, finely disseminated, globular, or relict at high levels of diagenesis.
H	**Herbaceous** kerogen encompasses all membraneous plant materials of terrestrial origin, such as cuticle, spore, pollen, and, in general, the softer parts of plants annually regenerated, such as leaves and grasses.
W	**Woody** plant detritus consists of plant remains in which a ribbed structure, or an overall twig-wood appearance, is pronounced. Woody detritus is commonly associated with herbaceous-membraneous material.
I	**Inertinite** is a term used for black opaque particulate debris that generally has a definite angularity related to a herbaceous-wood type of precursor. The term "coaly" (C) is sometimes used because of the black appearance; however, no relation to coal should be inferred. The term "inertinite" is more appropriate because this material is inert and does not contribute to the generation of hydrocarbons.

VITRINITE REFLECTANCE

To determine vitrinite reflectance (percent R_0), a representative aliquot of the kerogen concentrate was mixed with bioplastic and mounted in a hole drilled in a Lucite plug. After the vitrinite plug was cured overnight in a drying oven, its surface was polished, using different grades of alumina powder from coarse to fine.

The polished surface of the plug was examined by a coal petrographer under reflected light in a microscope system that permitted digital photometric measurement of the reflected-light intensity. The randomly oriented vitrinite was inspected, and the optical reflectance of recognizable first-cycle vitrinite particles was measured. Wherever the abundance of first-cycle vitrinite permitted, 50 vitrinite readings were recorded for each sample. If a sample contained little vitrinite, all the vitrinite particles were measured, even if they appeared to be second- or third-cycle material. A description of the plug is part of the vitrinite report and includes (1) the quality of the polish, (2) the ease of selecting first-cycle vitrinite, (3) a list of all reflectance measurements, and (4) a qualitative estimate of pyrite abundance.

RESULTS—ORGANIC FACIES, THERMAL MATURITY, AND HYDROCARBON COMPOSITION

A total of 63 wells have been sampled and analyzed in the NPRA. These wells have depths ranging from less than 600 m (2,000 ft) to more than 6,400 m (21,000 ft). The analytical and geochemical data on rocks from these wells are voluminous and varied, and a complete interpretation is beyond the scope of this chapter. Therefore, organic-carbon content, visual kerogen, thermal-alteration index (TAI), vitrinite reflectance (percent R_0), and C_1-C_4 hydrocarbon results from four wells have been selected for discussion purposes. The four wells penetrated geographically representative sedimentary sections in the NPRA: in the west, the Tunalik No. 1 well, with a total depth of 6,198 m (20,335 ft); in the north-central part, the Walakpa No. 1 well, with a total depth of 1,117 m (3,666 ft); in the midcentral part, the Oumalik No. 1 well, with a total depth of 3,619 m (11,872 ft); and in the east, the Inigok No. 1 well, with a total depth of 6,127 m (20,102 ft). The locations of the selected wells are shown in figure 20.1.

ORGANIC FACIES AND RICHNESS

A total of 340 samples obtained from drill cuttings, sidewall cores, and conventional cores have been rated by assessment of visual kerogen and measurement of organic-carbon content to determine the

TABLE 20.2.—*Color of plant cuticle in transmitted light in relation to thermal maturity as indicated by thermal-alteration index and vitrinite reflectance*

[Do, ditto; only selected values of vitrinite reflectance shown]

Color of plant cuticle in transmitted light	Maturity	Thermal-alteration index (TAI)		Vitrinite reflectance (percent R_o)	
		Geochem Laboratories scale	Numerical scale	Geochem Laboratories	This study
Greenish light yellow	Immature	1	1.0	---	---
Do	--do--	$\underline{1}$ to 1+	1.1	---	---
Do	--do--	1 to 1+	1.2	---	---
Do	--do--	1 to $\underline{1+}$	1.3	.3	---
Yellow	--do--	1+	1.4	---	---
Do	--do--	$\underline{1+}$ to 2-	1.5	---	.2
Do	--do--	1+ to 2-	1.6	.4	---
Do	--do--	1+ to $\underline{2-}$	1.7	---	.3
Yellow-orange	Moderately immature	2-	1.8	---	.4
Do	--do--	$\underline{2-}$ to 2	1.9	---	---
Do	--do--	2- to 2	2.0	.5	.5
Do	--do--	2- to $\underline{2}$	2.1	---	.6
Orange-brown	Moderately mature	2	2.2	.6	.7
Do	--do--	$\underline{2}$ to 2+	2.3	.7	.8
Do	--do--	2 to 2+	2.4	---	---
Do	--do--	2 to $\underline{2+}$	2.5	.8	.9
Light brown	Mature	2+	2.6	.9	---
Do	--do--	$\underline{2+}$ to 3-	2.7	---	1.0
Do	--do--	2+ to 3-	2.8	---	---
Do	--do--	2+ to $\underline{3-}$	2.9	---	---
Medium brown	--do--	3-	3.0	1.0	1.5
Do	--do--	$\underline{3-}$ to 3	3.1	---	---
Do	--do--	3- to 3	3.2	---	---
Do	--do--	3- to $\underline{3}$	3.3	---	2.0
Dark brown	--do--	3	3.4	1.5	---
Do	--do--	$\underline{3}$ to 3+	3.5	---	2.5
Do	Very mature	3 to 3+	3.6	---	3.0
Do	--do--	3 to $\underline{3+}$	3.7	---	---
Very dark brown	--do--	3+	3.8	2.0	3.5
Do	--do--	$\underline{3+}$ to 4-	3.9	---	---
Do	--do--	3+ to 4-	4.0	4.0	---
Do	--do--	3+ to $\underline{4-}$	4.1	---	4.5
Black	Severely altered	4-	4.2	2.5	---
Do	--do--	$\underline{4-}$ to 4	4.3	---	5.0
Do	--do--	4- to 4	4.4	3.0	---
Do	--do--	4- to $\underline{4}$	4.5	---	---
Do	--do--	4	4.6	4.0	---
Do	--do--	$\underline{4}$ to 5	4.7	---	---
Do	--do--	4 to 5	4.8	---	---
Do	--do--	4 to $\underline{5}$	4.9	---	---
Do	Metamorphosed	5	5.0	---	---

type and amount of organic matter in the four study wells. The resulting data are listed in tables 20.3-20.8. Photographs showing the color and appearance of the kerogen populations for each rock unit penetrated by each well make up figures 20.2-20.5.

Microscopic examination of palynologic kerogen in transmitted and reflected light can provide the geochemist and geologist with a wealth of information related to oil and gas resource assessment (Correia, 1967; Landes, 1967; Pusey, 1973; Burgess, 1974; Castaño and Sparks, 1974). The plant and other organic detritus (kerogen) in sedimentary rocks is the material that, when heated, generates oil and gas (Burgess, 1974). The importance of examining this kerogen to identify organic facies can be summarized by the following comments: (1) The kerogen material has been physically entrapped within the sediment from the moment of deposition; (2) the bulk of the organic carbon measured in sedimentary rock consists of the kerogen; (3) the degree of preservation or destruction of the discrete kerogen particles commonly reflects the depositional environment or diagenetic history of the sediment; (4) the kerogen, through its color changes from the time of deposition, records the thermal conditions that the rock has been subjected to in its history; and (5) the nature and relative abundance of the various types of kerogen determine both the yield and type of hydrocarbons (oil, condensate, or gas) that can be generated from that particular sedimentary rock.

The content of organic carbon, in weight percent of total rock weight, gives a measure of the amount of organic matter present, which, if it is the proper type, could generate oil or gas. However, organic matter includes elements other than carbon, such as hydrogen, sulfur, and nitrogen, in varying amounts, and the percentage of organic carbon present in a rock does not necessarily equal a certain percentage of organic matter. For example, inertinite is a type of organic matter that contains mostly carbon and very little hydrogen, and so the carbon content rather closely reflects the amount of organic matter present. Amorphous sapropel, on the other hand, can contain much hydrogen, and in this case the organic-carbon content could represent as little as 80 percent of the organic matter present. Use of the visual-kerogen data in conjunction with organic-carbon content allows for a much more complete assessment of organic facies than using either independently.

The visual-kerogen assessment and organic-carbon content are discussed below by rock unit for each of the four wells. The number of samples analyzed for each rock unit is noted in parentheses.

TUNALIK NO. 1 WELL

The Tunalik No. 1 well penetrated the Nanushuk Group (37 samples), Torok Formation (28 samples), the informally named pebble shale unit (4 samples), Kingak Shale (16 samples), Sag River Sandstone (3 samples), Shublik Formation (2 samples), and Sadlerochit Group (11 samples) and bottomed in the Lisburne Group (15 samples) (fig. 20.2). A total of 116 samples were assessed for organic-matter type (visual kerogen) and organic-carbon content. The color of plant cuticle in this well changes progressively with increasing depth of burial from light yellow in the Nanushuk Group to very dark brown to black in the Lisburne Group. The amount of contained kerogen, based on the total content of organic carbon, is above the minimum required to be a source for hydrocarbons in all the rock units (table 20.7). The Nanushuk Group contains much coal, which is reflected in the mean organic-carbon content of 6.60 weight percent. The pebble shale unit is the richest shale unit (2.64 weight percent), followed by the Torok Formation (1.35 weight percent), Kingak Shale (1.21 weight percent), and Shublik Formation (0.95 weight percent).

The kerogen contained in the sedimentary rocks penetrated by this well shows a remarkable degree of homogeneity; terrestrially derived herbaceous and woody-structured detritus predominate (fig. 20.2; tables 20.3, 20.8). Preservation of the kerogen constituents is excellent. There was very good overall agreement in identifying the kerogen populations between different sample types (drill cuttings, conventional cores, sidewall cores). Amorphous sapropel was sparse in the sedimentary rocks analyzed,

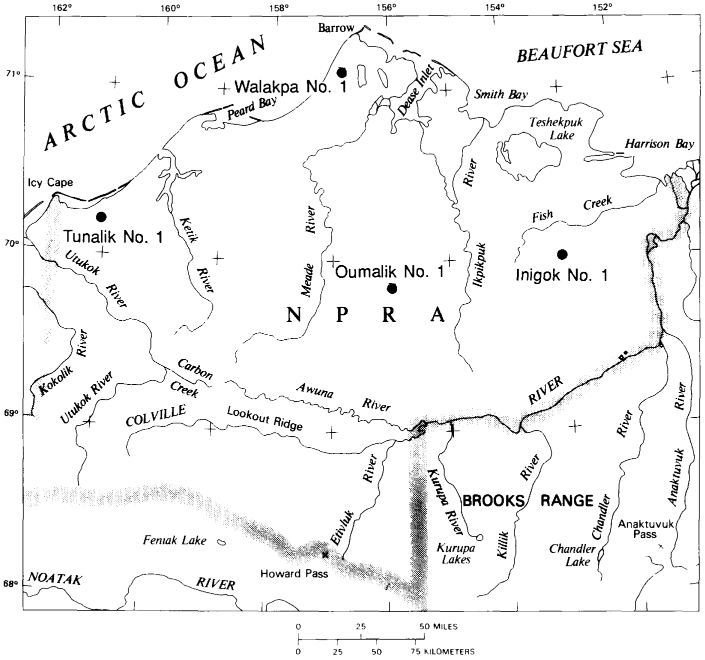


FIGURE 20.1.—National Petroleum Reserve in Alaska (NPRA), showing location of four wells discussed in this chapter.

TABLE 20.3—*Geochemical data for the Tunalik No. 1 well*

[Sample types: CO, conventional core; SW, sidewall core; CT, cuttings. Lithologic types: Sh, shale; St, siltstone; Ss, sandstone; C, coal; Cb, carbonate; Ot, other. Kerogen types: Am, amorphous-sapropel; H, herbaceous; W, woody; I, inertinite. TAI, thermal-alteration index; $\underline{R}_o$, vitrinite reflectance (determined for some samples only)]

Sample	Type	Depth (ft)	Lithologic composition (percent)						Organic carbon (weight percent)	Kerogen composition (percent)				TAI	$\underline{R}_o$ (percent)	Hydrocarbon factor (percent)
			Sh	St	Ss	C	Cb	Ot		Am	H	W	I			
									Nanushuk Group							
013	CT	420-450	30	--	--	50	20	--	8.36	--	63	25	13	2.0	--	47
023	CT	720-750	--	--	--	40	60	--	4.36	--	56	33	11	2.0	0.47	45
033	CT	1020-1050	20	--	--	60	20	--	7.05	--	40	40	20	2.0	--	38
043	CT	1320-1350	20	--	--	40	40	--	5.62	--	36	36	27	2.1	.49	35
053	CT	1620-1650	--	--	--	100	--	--	56.66	--	25	25	50	2.1	--	28
063	CT	1920-1950	--	--	--	90	--	10	43.02	--	44	33	22	2.1	.56	38
073	CT	2220-2250	--	--	--	100	--	--	58.33	--	44	33	22	2.2	--	38
083	CT	2520-2550	40	--	--	60	--	--	10.43	--	36	36	27	2.2	.57	35
093	CT	2820-2850	40	--	25	20	15	--	2.87	18	27	36	18	2.3	--	47
103	CT	3120-3150	80	--	20	--	--	--	1.75	8	42	33	17	2.3	.57	45
109	CO	3280	100	--	--	--	--	--	13.23	10	50	30	10	2.4	.62	50
116	CT	3300-3320	50	35	--	15	--	--	1.05	--	40	40	20	2.3	.51	38
560	SW	3319	100	--	--	--	--	--	1.74	9	36	36	18	2.3	--	43
561	SW	3438	--	100	--	--	--	--	.86	--	45	36	18	2.3	--	40
131	CT	3600-3620	80	--	10	--	--	10	2.18	10	30	40	20	2.3	.61	42
145	CO	3829	100	--	--	--	--	--	1.13	--	36	36	27	2.4	.62	35
146	CT	3840-3860	80	--	20	--	--	--	1.27	--	63	25	13	2.3	.50	47
149	CT	3900-3920	90	--	10	--	--	--	1.23	--	36	36	27	2.3	--	35
562	SW	4112	100	--	--	--	--	--	1.24	--	42	33	25	2.4	--	38
563	SW	4193	100	--	--	--	--	--	1.07	--	45	27	27	2.4	--	38
164	CT	4200-4220	75	--	25	--	--	--	1.02	--	36	36	27	2.3	.53	35
564	SW	4215	100	--	--	--	--	--	1.24	--	45	27	27	2.4	--	38
179	CT	4500-4520	85	--	15	--	--	--	.94	--	45	27	27	2.3	--	38
565	SW	4550	100	--	--	--	--	--	1.82	--	38	31	31	2.5	--	35
190	CT	4750-4820	90	--	5	--	--	5	1.67	--	45	27	27	2.3	.56	38
566	SW	4904	100	--	--	--	--	--	1.49	--	38	31	31	2.6	--	35
567	SW	4916	100	--	--	--	--	--	1.40	--	38	31	31	2.6	--	35
198	CT	5030-5060	90	--	5	--	--	5	.97	--	45	36	18	2.3	.53	40
568	SW	5046	100	--	--	--	--	--	1.55	8	38	31	23	2.7	--	42
200	CT	5090-5120	85	--	15	--	--	--	.92	--	45	27	27	2.3	--	38
569	SW	5128	100	--	--	--	--	--	1.24	--	38	31	31	2.7	--	35
570	SW	5158	100	--	--	--	--	--	1.46	--	45	27	27	2.7	--	38
210	CT	5390-5420	100	--	--	--	--	--	.94	--	40	40	20	2.3	.55	38
212	CT	5450-5480	100	--	--	--	--	--	1.02	--	50	30	20	2.3	.60	41
214	CT	5510-5540	100	--	--	--	--	--	.98	--	56	22	22	2.3	.61	42
220	CT	5690-5720	100	--	--	--	--	--	1.14	--	42	33	25	2.4	--	38
230	CT	5990-6020	80	10	--	--	--	10	1.18	--	50	13	38	2.4	.60	38
									Torok Formation							
240	CT	6290-6320	80	20	--	--	--	--	1.40	15	38	23	23	2.4	--	47
242	CT	6350-6380	70	10	--	--	--	20	1.02	--	45	27	27	2.4	0.64	38
248	CO	6504-6512	100	--	--	--	--	--	1.37	--	38	31	31	2.7	.74	35
251	CT	6590-6620	70	20	--	--	--	10	1.14	--	27	36	36	2.4	.63	31
261	CT	6890-6920	80	20	--	--	--	--	1.06	--	40	30	30	2.4	--	36
571	SW	6998	--	100	--	--	--	--	1.27	--	45	27	27	2.7	--	38
572	SW	7008	100	--	--	--	--	--	1.41	--	38	31	31	2.7	--	35
271	CT	7190-7220	90	--	--	--	--	10	1.38	--	27	36	36	2.4	.61	31
273	CT	7250-7280	90	--	--	--	--	10	1.23	--	45	27	27	2.4	.75	38
573	SW	7258	100	--	--	--	--	--	1.41	8	25	33	33	2.7	--	36
574	SW	7299	100	--	--	--	--	--	1.33	8	25	33	33	2.7	--	36
281	CT	7490-7520	80	--	--	--	--	20	1.20	8	33	33	25	2.4	--	40
575	SW	7563	100	--	--	--	--	--	1.21	--	36	27	36	2.8	--	33
291	CT	7790-7820	90	--	--	--	--	10	1.36	--	36	36	27	2.4	.58	35
295	CO	7875	100	--	--	--	--	--	1.38	17	33	25	25	2.7	1.03	47
576	SW	7951	100	--	--	--	--	--	1.37	9	45	27	18	2.8	--	46
577	SW	7954	100	--	--	--	--	--	1.23	--	50	30	20	2.8	--	41

TABLE 20.3—*Geochemical data for the Tunalik No. 1 well*—Continued

Sample	Type	Depth (ft)	Lithologic composition (percent)						Organic carbon (weight percent)	Kerogen composition (percent)				TAI	$\underline{R}_o$ (percent)	Hydrocarbon factor (percent)
			Sh	St	Ss	C	Cb	Ot		Am	H	W	I			
Torok Formation--Continued																
302	CT	8030-8060	80	20	--	--	--	--	1.00	9	36	27	27	2.4	--	41
311	CT	8300-8330	20	--	--	5	75	--	3.63	8	42	33	17	2.1	0.56	45
321	CT	8600-8630	100	--	--	--	--	--	1.47	--	38	31	31	2.3	--	35
329	CO	8792	100	--	--	--	--	--	1.25	8	33	25	33	2.7	1.27	39
342	CT	9010-9040	100	--	--	--	--	--	.95	--	42	33	25	2.3	--	38
352	CT	9310-9340	100	--	--	--	--	--	1.27	--	38	31	31	2.3	--	35
362	CT	9610-9640	100	--	--	--	--	--	1.25	--	42	33	25	2.3	--	38
372	CT	9910-9940	100	--	--	--	--	--	1.42	--	40	40	20	2.4	1.24	38
382	CT	10210-10240	45	50	--	--	--	5	1.26	--	27	36	36	2.7	1.58	31
392	CO	10472	100	--	--	--	--	--	1.35	--	27	36	36	2.9	1.86	31
399	CT	10510-10540	95	5	--	--	--	--	1.25	--	27	36	36	2.7	1.62	31
Pebble shale unit																
406	CO	10676-10681	100	--	--	--	--	--	3.76	--	27	36	36	2.9	2.06	31
407	CO	10681-10686	100	--	--	--	--	--	1.86	--	20	40	40	3.2	1.67	28
415	CT	10810-10840	100	--	--	--	--	--	2.47	33	33	17	17	2.7	1.82	60
417	CT	10870-10900	100	--	--	--	--	--	2.45	33	33	22	11	3.2	1.84	60
Kingak Shale																
423	CO	10925-10930	--	100	--	--	--	--	0.21	--	40	20	40	3.1	2.11	34
433	CT	11110-11140	20	80	--	--	--	--	.39	--	38	31	31	2.7	1.96	35
443	CT	11410-11440	40	20	40	--	--	--	.81	8	25	33	33	2.7	1.90	36
453	CO	11672-11677	100	--	--	--	--	--	1.99	--	27	36	36	3.2	2.41	31
459	CT	11710-11740	100	--	--	--	--	--	1.45	--	36	27	36	2.7	2.17	33
469	CT	12010-12040	100	--	--	--	--	--	.97	8	25	33	33	2.7	2.10	36
471	CT	12070-12100	90	--	--	--	--	10	1.21	15	23	31	31	3.4	1.86	41
473	CT	12130-12160	100	--	--	--	--	--	1.71	25	42	17	17	3.5	1.94	57
479	CT	12310-12340	90	10	--	--	--	--	1.46	--	27	36	36	2.7	2.16	31
494	CO	12572	--	100	--	--	--	--	.93	--	20	40	40	3.5	2.48	28
506	CT	12910-12940	40	--	--	--	50	10	1.01	23	31	31	15	3.3	2.54	52
517	CT	13240-13270	60	--	--	--	--	40	1.03	25	25	33	17	3.3	--	52
527	CT	13540-13570	100	--	--	--	--	--	.92	--	20	40	40	3.3	2.86	28
537	CT	13840-13870	80	--	--	--	--	20	1.17	17	25	33	25	3.3	2.91	44
547	CT	14140-14170	75	--	--	--	--	25	2.28	21	21	29	29	3.4	2.85	45
551	CT	14260-14290	100	--	--	--	--	--	1.89	--	27	36	36	3.5	2.59	31
Sag River Sandstone																
555	CT	14380-14410	100	--	--	--	--	--	1.44	8	25	33	33	3.6	2.58	36
557	CT	14440-14470	100	--	--	--	--	--	1.39	--	27	36	36	3.7	2.84	31
559	CT	14500-14530	100	--	--	--	--	--	1.34	8	25	33	33	3.6	2.56	36
Shublik Formation																
580	CO	14518	100	--	--	--	--	--	.60	--	20	40	40	3.9	3.42	28
589	CT	14560-14590	100	--	--	--	--	--	1.29	--	27	36	36	3.6	2.64	31
Sadlerochit Group																
586	CO	14851	100	--	--	--	--	--	0.72	--	20	40	40	3.9	3.54	28
606	CT	15070-15100	60	--	--	--	--	40	1.68	--	27	36	36	3.7	--	31
617	CT	15400-15430	60	--	--	--	--	40	1.49	--	27	36	36	3.8	--	31
626	CT	15670-15700	95	--	--	--	--	5	.46	--	40	20	40	3.5	3.70	34
636	CT	15970-16000	95	--	--	--	--	5	.51	--	40	20	40	3.6	3.71	34
648	CO	16251-16256	100	--	--	--	--	--	.27	--	22	33	44	4.1	4.04	28
649	CO	16256-16261	100	--	--	--	--	--	.29	--	20	40	40	3.8	3.58	28

TABLE 20.3—*Geochemical data for the Tunalik No. 1 well*—Continued

Sample	Type	Depth (ft)	Lithologic composition (percent)						Organic carbon (weight percent)	Kerogen composition (percent)				TAI	R_o (percent)	Hydrocarbon factor (percent)
			Sh	St	Ss	C	Cb	Ot		Am	H	W	I			
Sadlerochit Group--Continued																
651	CT	16270-16300	95	--	--	--	--	5	.56	8	33	25	33	3.6	3.76	39
661	CT	16570-16600	100	--	--	--	--	--	.41	--	36	27	36	3.7	4.00	33
671	CT	16870-16900	100	--	--	--	--	--	.87	--	36	27	36	3.7	4.32	33
677	CO	16929-16934	100	--	--	--	--	--	.32	--	22	33	44	4.1	4.31	28
Lisburne Group																
683	CO	17145	100	--	--	--	--	--	0.31	--	22	33	44	4.1	4.32	28
691	CT	17230-17260	100	--	--	--	--	--	.37	--	--	50	50	4.1	4.28	20
693	CO	17255	100	--	--	--	--	--	.72	--	--	50	50	4.2	4.64	20
707	CT	17500-17530	100	--	--	--	--	--	.29	--	--	50	50	4.2	4.47	20
723	CT	17800-17830	100	--	--	--	--	--	.26	--	11	44	44	3.7	4.27	24
720	CO	17878-17883	100	--	--	--	--	--	.14	--	17	17	67	4.1	--	22
721	CO	17883-17888	100	--	--	--	--	--	.12	--	57	29	14	2.6	4.64	44
735	CT	18160-18190	95	--	--	--	--	5	.75	18	27	18	36	4.1	4.63	43
747	CT	18520-18550	10	--	--	--	90	--	.35	11	22	22	44	4.1	4.67	35
757	CT	18820-18850	20	--	--	--	80	--	.42	--	25	25	50	4.1	4.65	28
767	CT	19120-19150	30	--	--	--	70	--	.32	--	11	44	44	3.9	4.76	24
777	CT	19420-19450	10	--	--	--	85	5	.33	--	20	40	40	4.0	5.02	28
787	CT	19720-19750	20	--	--	--	40	40	.61	--	27	36	36	4.0	--	31
789	CT	19780-19810	10	--	--	--	80	10	.24	--	20	40	40	4.1	4.65	28
805	CT	20260-20290	10	--	--	--	70	20	.35	--	20	40	40	4.2	--	28

generally being observed in only secondary or trace amounts. Two samples in the interval between 3,295 and 3,322 m (10,810-10,900 ft) in the pebble shale unit and the underlying Kingak Shale contain noticeably more amorphous sapropel. Herbaceous material is almost twice as abundant in the shallow rock units as in the deepest rock units, but the reverse is true for inertinitic material. The abundance of woody and inertinitic material throughout the section may indicate a continuous and substantial influx of reworked or recycled organic matter. Probably, most of the sedimentary organic matter accumulated in a nearshore neritic depositional environment.

WALAKPA NO. 1 WELL

The Walakpa No. 1 well reached the basement complex (1 sample), after penetrating the Torok Formation (9 samples), pebble shale unit (5 samples), Kingak Shale (9 samples), Sag River Sandstone (no samples), and Shublik Formation (5 samples) at this location (fig. 20.3). A total of 29 samples were analyzed; again, well-preserved kerogen was found, and there was excellent agreement between different sample types taken at adjacent depths (fig. 20.3; table 20.4). The average organic-carbon content for each unit is similar to that in the Inigok No. 1 well (table 20.7). The uppermost part of the Torok Formation generally contains predominant amounts of herbaceous and woody kerogen as does the Shublik Formation, whereas the pebble shale unit and Kingak Shale again contain large amounts of amorphous sapropel and herbaceous material (table 20.8). The kerogen color for the entire section in this well was mostly yellow to yellow orange.

OUMALIK NO. 1 WELL

The Oumalik No. 1 well was cored extensively from the surface to its total depth, and so the 53 samples analyzed from this well afforded excellent kerogen ratings for the Nanushuk Group (14 samples), Torok Formation (37 samples), pebble shale unit (1 sample), and Kingak Shale (1 sample) (fig. 20.4; table 20.5). The overall kerogen populations present in the fine-grained sedimentary rocks are similar to those observed in the Tunalik No. 1 well in that herbaceous plant remains are predominant and secondary amounts of woody-structured debris and inertinitic fragments are present. Amorphous-sapropel kerogen is sporadically dispersed throughout

TABLE 20.4—*Geochemical data for the Walakpa No. 1 well*

[Sample types: CO, conventional core; SW, sidewall core; CT, cuttings. Lithologic types: Sh, shale; St, siltstone; Ss, sandstone; C, coal; Cb, carbonate; Ot, other. Kerogen types: Am, amorphous-sapropel; H, herbaceous; W, woody; I, inertinite. TAI, thermal-alteration index; $\underline{R}_o$, vitrinite reflectance (determined for some samples only)]

Sample	Type	Depth (ft)	Lithologic composition (percent)						Organic carbon (weight percent)	Kerogen composition (percent)				TAI	$\underline{R}_o$ (percent)	Hydrocarbon factor (percent)
			Sh	St	Ss	C	Cb	Ot		Am	H	W	I			
Torok Formation																
006	CO	257	100	--	--	--	--	--	1.16	--	42	33	25	1.9	0.44	38
007	CO	262	100	--	--	--	--	--	.99	--	45	36	18	2.0	.43	40
008	CO	267	100	--	--	--	--	--	.58	10	40	30	20	1.7	.42	45
009	CO	272	100	--	--	--	--	--	.87	--	45	36	18	2.0	.42	40
015	CT	390-420	90	--	--	--	--	10	1.00	10	40	30	20	2.8	--	45
025	CT	690-720	90	--	--	--	--	10	1.56	9	36	36	18	2.8	--	43
035	CT	990-1020	100	--	--	--	--	--	1.10	40	40	10	10	2.8	--	68
045	CT	1290-1320	100	--	--	--	--	--	.99	--	27	36	36	2.8	.50	31
055	CT	1590-1620	50	50	--	--	--	--	1.14	15	46	31	8	1.9	.45	53
Pebble shale unit																
059	CT	1710-1740	90	--	--	--	--	10	2.73	33	33	25	8	2.1	.40	61
112	CO	1877-1882	100	--	--	--	--	--	2.26	27	45	18	9	2.1	.59	60
065	CT	1890-1920	100	--	--	--	--	--	2.19	31	38	23	8	2.0	.51	61
121	CO	2006-2011	100	--	--	--	--	--	4.11	44	33	22	--	2.1	.57	70
131	CO	2080	--	--	100	--	--	--	.75	44	33	11	11	2.1	.50	68
Kingak Shale																
082	CT	2400-2430	70	20	--	--	--	--	2.45	29	36	29	7	2.0	.55	60
174	SW	2602	100	--	--	--	--	--	.68	8	50	33	8	2.0	--	49
093	CT	2700-2730	90	--	--	--	--	10	1.26	14	50	29	7	2.0	.40	53
140	CO	2812	100	--	--	--	--	--	1.11	50	25	13	13	2.3	.42	70
145	CO	2945-2950	100	--	--	--	--	--	.63	--	44	44	11	2.2	.42	41
152	CO	2980-2985	100	--	--	--	--	--	.69	8	54	23	15	2.1	.41	49
155	CO	2990-2995	100	--	--	--	--	--	.60	15	31	23	31	2.2	.43	44
165	CO	3065-3070	--	100	--	--	--	--	.31	36	27	18	18	2.2	.42	59
173	CO	3105-3110	100	--	--	--	--	--	.55	--	42	33	25	2.1	.42	38
Shublik Formation																
186	CT	3330-3360	50	40	--	--	--	10	0.66	15	31	31	23	3.2	0.72	45
197	CO	3365-3370	100	--	--	--	--	--	1.07	7	36	29	29	2.3	.51	40
204	CO	3400-3405	100	--	--	--	--	--	.59	--	30	40	30	2.2	.55	33
192	CT	3540-3570	70	--	--	--	30	--	.78	8	50	25	18	2.2	.55	47
175	CT	3543	100	--	--	--	--	--	1.11	31	31	23	15	2.3	--	58
Basement complex																
209	CT	3656-3661	100	--	--	--	--	--	0.39	--	30	30	40	3.8	0.64	31

the sedimentary rocks and is dominant at 923 and 2,790 m (3,030 and 9,150 ft) in the Torok Formation. The one sample from the pebble shale unit in this well has an organic carbon content of 3.38 weight percent and contains largely herbaceous kerogen and some woody and inertinitic remains. It is therefore quite different from the pebble shale unit in the Walakpa No. 1 well to the north and in the Tunalik No. 1 well to the west, at both of which more amorphous sapropel was present (table 20.8).

INIGOK NO. 1 WELL

The Inigok No. 1 is the deepest and most extensively studied well in the NPRA. These studies provide information on sandstone of the Colville Group (5 samples), shale of the Colville Group (6 samples), Nanushuk Group (13 samples), Torok Formation (34 samples), pebble shale unit (1 sample), Kingak Shale (34 samples), Sag River Sandstone (no samples), Shublik Formation (3 samples), Sadlerochit Group

TABLE 20.5—*Geochemical data for the Oumalik No. 1 well*

[Sample type: CO, conventional core. Lithologic types: Sh, shale; St, siltstone; Ss, sandstone; C, coal; Cb, carbonate; Ot, other. Kerogen types: Am, amorphous-sapropel; H, herbaceous; W, woody; I, inertinite. TAI, thermal alteration index; R_o, vitrinite reflectance (determined for some samples only)]

Sample	Type	Depth (ft)	Lithologic composition (percent)						Organic carbon (weight percent)	Kerogen composition (percent)				TAI	R_o (percent)	Hydrocarbon factor (percent)
			Sh	St	Ss	C	Cb	Ot		Am	H	W	I			
Nanushuk Group																
001	CO	517-528	--	--	--	--	--	--	0.58	--	80	20	--	1.9	0.41	54
014	CO	725	20	40	20	--	--	--	1.05	--	63	25	12	1.3	--	46
015	CO	915	50	20	--	--	30	--	.84	--	56	22	22	1.3	--	42
016	CO	985	60	20	--	--	20	--	.94	--	71	14	14	1.3	--	48
017	CO	1000	20	20	40	--	--	--	.28	14	71	14	--	1.4	--	61
018	CO	1010	80	10	--	--	10	--	.80	--	62	13	26	1.4	.49	44
019	CO	1035	70	20	--	--	10	--	.94	--	50	30	20	1.5	--	41
020	CO	1200	20	20	40	--	--	--	.39	13	50	13	25	1.5	--	49
002	CO	1410-1422	--	--	--	--	--	--	1.22	--	36	36	28	1.9	.48	35
024	CO	1800	50	10	--	40	--	--	3.68	17	42	25	17	1.7	.57	51
026	CO	2165	80	20	--	--	--	--	1.20	--	50	30	20	1.7	--	41
027	CO	2365	70	30	--	--	--	--	.43	--	57	14	29	1.8	.53	41
028	CO	2530	70	30	--	--	--	--	.98	15	38	23	23	1.9	--	47
029	CO	2760	80	20	--	--	--	--	.81	--	42	42	17	1.9	--	39
Torok Formation																
030	CO	2780	80	20	--	--	--	--	0.98	9	36	37	18	1.9	--	43
031	CO	2800	90	10	--	--	--	--	1.06	--	50	30	20	2.0	--	41
003	CO	2829-2836	--	--	--	--	--	--	1.19	--	36	27	37	1.9	0.55	33
032	CO	3030	90	10	--	--	--	--	1.22	44	33	11	11	2.0	--	68
033	CO	3225	90	10	--	--	--	--	1.13	17	33	33	17	2.0	.66	48
034	CO	3255	80	20	--	--	--	--	.54	--	50	38	13	2.0	--	43
035	CO	3280	80	20	--	--	--	--	1.07	--	63	13	25	2.0	--	44
036	CO	3460	100	--	--	--	--	--	1.24	--	56	33	11	2.0	--	45
004	CO	3500-3510	--	--	--	--	--	--	1.23	25	50	--	25	1.9	.60	58
037	CO	3755	60	40	--	--	--	--	1.19	22	56	11	11	2.0	--	60
038	CO	3815	80	20	--	--	--	--	.95	9	45	27	18	2.0	--	46
039	CO	4000	70	20	--	--	10	--	1.04	18	36	27	18	2.1	.65	49
040	CO	4430	90	10	--	--	--	--	1.19	--	56	22	22	2.1	--	42
005	CO	4670-4690	--	--	--	--	--	--	1.33	33	44	--	23	2.0	.60	62
041	CO	4930	90	10	--	--	--	--	1.35	--	56	22	22	2.1	--	42
042	CO	5140	80	20	--	--	--	--	1.36	--	45	36	18	2.1	.69	40
043	CO	5360	90	10	--	--	--	--	1.14	--	50	25	25	2.1	--	40
006	CO	5605-5625	--	--	--	--	--	--	1.20	25	50	12	13	2.1	.71	60
044	CO	6050	80	20	--	--	--	--	1.18	--	56	22	22	2.1	.77	42
045	CO	6290	90	10	--	--	--	--	1.42	--	56	22	22	2.2	--	42
046	CO	6500	80	20	--	--	--	--	.96	15	38	23	23	2.3	.76	47
047	CO	6670	80	20	--	--	--	--	1.10	13	50	13	25	2.3	--	49
007	CO	7250-7258	--	--	--	--	--	--	.81	--	67	17	16	2.2	.76	47
008	CO	7452-7467	--	--	--	--	--	--	1.13	--	40	30	30	2.2	.83	36
048	CO	8090	80	20	--	--	--	--	1.05	--	44	11	44	2.3	1.02	34
049	CO	8290	90	10	--	--	--	--	1.30	9	36	18	36	2.3	--	40
009	CO	8488-8498	--	--	--	--	--	--	1.31	--	50	12	38	2.3	.93	37
050	CO	8695	80	20	--	--	--	--	1.32	--	44	11	44	2.3	--	34
051	CO	8920	90	10	--	--	--	--	1.21	--	40	30	30	2.4	1.23	36
052	CO	9150	90	10	--	--	--	--	1.22	31	23	31	15	2.5	--	56
053	CO	9295	60	20	--	20	--	--	2.06	17	42	17	25	2.5	.98	50
054	CO	9540	80	20	--	--	--	--	1.04	--	40	20	40	2.6	--	34
010	CO	9824-9841	--	--	--	--	--	--	1.22	--	44	11	45	2.5	1.26	34
055	CO	10010	70	20	--	10	--	--	.79	--	44	11	44	2.7	--	34
056	CO	10235	80	20	--	--	--	--	1.82	--	44	11	44	2.7	1.48	34
011	CO	10453-10473	--	--	--	--	--	--	2.49	--	27	36	37	2.5	1.49	31
057	CO	10675	70	30	--	--	--	--	1.88	15	31	23	31	2.8	1.35	44
Pebble shale unit																
012	CO	10992-11007	--	--	--	--	--	--	3.38	--	50	12	38	2.7	1.38	37
Kingak Shale																
013	CO	11852-11872	--	--	--	--	--		0.52	--	40	30	30	1.3	1.38	36

TABLE 20.6—*Geochemical data for the Inigok No. 1 well*

[Sample types: CO, conventional core; SW, sidewall core; CT, cuttings. Lithologic types: Sh, shale; St, siltstone; Ss, sandstone; C, coal; Cb, carbonate; Ot, other. Kerogen types: Am, amorphous-sapropel; H, herbaceous; W, woody; I, inertinite. TAI, thermal alteration index; $\underline{R}_o$, vitrinite reflectance (determined for some samples only)]

Sample	Type	Depth (ft)	Lithologic composition (percent)						Organic carbon (weight percent)	Kerogen composition (percent)				TAI	$\underline{R}_o$ (percent)	Hydrocarbon factor (percent)
			Sh	St	Ss	C	Cb	Ot		Am	H	W	I			
Colville Group sandstone																
012	CT	410-440	35	--	--	--	--	--	20.95	--	56	33	11	2.3	--	45
022	CT	710-740	--	--	--	20	--	75	21.35	10	50	30	10	2.3	0.42	50
028	CT	890-920	--	--	--	5	--	85	2.55	--	57	29	14	1.9	.42	44
032	CT	1310-1340	--	--	--	--	--	80	.56	--	56	33	11	2.3	--	45
Colville Group shale																
052	CT	1610-1640	--	--	--	--	--	90	0.50	--	44	44	11	2.3	--	41
062	CT	1910-1940	--	--	--	--	--	90	.21	29	43	14	14	2.3	--	60
064	CT	1970-2000	--	--	--	--	--	85	.71	22	56	22	--	1.6	0.44	62
066	CT	2030-2060	--	--	--	--	--	80	.54	--	63	25	13	1.7	.40	47
070	CT	2150-2180	--	--	--	--	--	90	.31	--	57	29	14	1.8	.41	44
072	CT	2210-2240	--	--	--	--	--	85	1.80	--	67	33	--	2.3	--	50
Nanushuk Group																
082	CT	2510-2540	--	--	--	--	--	95	0.56	--	67	22	11	2.3	--	48
087	CO	2632-2662	100	--	--	--	--	--	.46	--	36	27	36	2.0	0.46	33
476	CO	2632	100	--	--	--	--	--	1.20	--	40	40	20	2.0	.45	38
478	CO	2642	100	--	--	--	--	--	1.15	--	40	40	20	2.0	.47	38
480	CO	2652	100	--	--	--	--	--	1.30	--	40	40	20	2.0	.46	38
482	CO	2661	100	--	--	--	--	--	.98	9	36	36	18	2.0	.45	43
094	CT	2820-2850	30	--	25	20	--	5	3.29	--	44	44	11	2.1	.40	41
103	CO	3072-3082	100	--	--	--	--	--	.42	--	36	27	36	2.1	.46	33
483	CO	3072	100	--	--	--	--	--	1.02	--	40	40	20	2.0	.49	38
485	CO	3080	100	--	--	--	--	--	.61	8	31	31	31	2.0	.46	39
105	CT	3120-3150	20	--	70	--	--	--	.34	--	36	36	27	2.3	--	35
118	CT	3400-3420	65	--	15	--	--	--	1.44	--	40	40	20	2.3	.42	38
131	CT	3700-3730	75	--	5	--	--	--	1.18	--	36	36	27	2.3	--	35
141	CT	4000-4030	75	--	20	--	--	--	1.14	--	40	40	20	2.3	.51	38
148	CO	4206-4216	100	--	--	--	--	--	.37	--	40	40	20	2.1	.47	38
486	CO	4206	100	--	--	--	--	--	1.58	--	40	40	20	2.1	.47	38
487	CO	4211	100	--	--	--	--	--	1.69	--	40	40	20	2.2	.51	38
488	CO	4216	100	--	--	--	--	--	1.47	--	33	44	22	2.1	.50	35
152	CT	4300-4330	90	--	--	--	--	--	1.16	--	38	31	31	2.3	--	35
162	CT	4600-4630	100	--	--	--	--	--	1.21	--	33	44	22	2.3	.55	35
172	CT	4900-4930	100	--	--	--	--	--	1.39	--	40	30	30	2.3	--	36
176	CO	5000	100	--	--	--	--	--	1.27	--	36	36	27	2.1	.52	35
178	CO	5010	100	--	--	--	--	--	1.40	33	33	17	17	2.1	.58	60
185	CT	5200-5230	90	--	--	--	--	--	1.32	--	40	40	20	2.3	.58	38
195	CT	5500-5530	55	35	--	--	--	--	1.13	--	45	36	18	1.9	--	40
205	CT	5800-5830	--	100	--	--	--	--	1.12	--	45	36	18	1.9	.60	40
215	CT	6100-6130	100	--	--	--	--	--	1.16	--	42	33	25	1.9	--	38
225	CT	6400-6430	80	--	--	--	--	--	1.79	17	33	25	25	1.9	.60	47
235	CT	6700-6730	60	20	--	--	--	--	1.40	22	44	11	22	1.9	--	54
245	CT	7000-7030	70	20	--	--	--	--	1.09	--	50	30	20	1.9	.65	41
247	CO	7054-7064	--	--	--	--	--	100	1.27	33	44	11	11	2.1	.67	64
249	CO	7054-7064	--	--	--	--	--	100	1.08	9	36	27	27	2.1	.66	41
489	CO	7054	100	--	--	--	--	--	1.81	--	40	40	20	2.1	.63	38
491	CO	7064	100	--	--	--	--	--	1.17	--	36	36	27	2.1	.70	35
258	CT	7300-7330	80	10	--	--	--	--	1.12	--	40	40	20	2.0	--	38
268	CT	7600-7630	65	25	--	--	--	--	.97	--	36	36	27	2.0	.61	35
278	CT	7900-7930	70	25	--	--	--	--	.90	8	33	33	25	2.0	--	40
288	CT	8200-8230	70	25	--	--	--	--	.96	--	45	27	27	2.0	.62	38
289	CO	8210	--	100	--	--	--	--	.40	--	27	36	36	2.2	.68	31

TABLE 20.6—*Geochemical data for the Inigok No. 1 well*—Continued

Sample	Type	Depth (ft)	Lithologic composition (percent)						Organic carbon (weight percent)	Kerogen composition (percent)				TAI	$\bar{R}_o$ (percent)	Hydrocarbon factor (percent)
			Sh	St	Ss	C	Cb	Ot		Am	H	W	I			
Nanushuk Group--Continued																
291	CO	8220	--	100	--	--	--	--	0.42	10	40	20	30	2.2	0.72	43
293	CO	8230	--	100	--	--	--	--	.32	--	40	20	40	2.3	.69	34
295	CO	8240	--	100	--	--	--	--	.32	--	44	22	33	2.3	.77	36
305	CT	8500-8530	45	15	--	--	35	--	1.49	22	44	11	22	2.1	--	54
315	CT	8800-8830	65	--	--	--	15	--	1.28	36	36	9	18	2.2	.78	62
316	CO	8842-8852	--	30	--	--	--	70	1.94	9	36	36	18	2.3	.75	43
492	CO	8842	100	--	--	--	--	--	6.31	38	50	13	--	2.3	.53	72
494	CO	8852	100	--	--	--	--	--	1.54	9	36	36	18	2.3	.52	43
Pebble shale unit																
326	CT	9100-9180	70	15	--	--	5	--	2.87	11	44	11	33	2.3	--	44
Kingak Shale																
333	CO	9338-9348	100	--	--	--	--	--	1.39	33	33	25	8	2.3	1.04	61
337	CT	9430-9460	90	--	--	--	--	--	2.04	25	42	17	17	2.3	.70	57
338	CO	9448-9458	--	--	--	--	--	100	1.49	--	67	22	11	2.7	1.06	48
495	CO	9448	100	--	--	--	--	--	1.58	25	33	33	8	2.3	.66	55
496	CO	9453	100	--	--	--	--	--	1.58	11	56	33	--	2.7	1.11	54
497	CO	9458	100	--	--	--	--	--	2.05	31	31	23	15	2.3	.73	58
463	SW	9564	100	--	--	--	--	--	1.69	--	63	25	13	2.3	.77	47
348	CT	9730-9760	90	--	--	--	--	--	1.85	27	36	27	9	2.3	--	58
464	SW	9742	100	--	--	--	--	--	1.60	13	50	25	13	2.3	--	52
465	SW	9814	100	--	--	--	--	--	1.64	--	44	44	11	2.3	1.06	41
358	CT	10030-10060	95	--	--	--	--	--	1.74	36	27	18	18	2.5	.80	59
367	CO	10295-10306	--	--	--	--	--	100	.75	9	45	27	18	2.3	.95	46
498	CO	10295	100	--	--	--	--	--	.53	9	36	36	18	2.4	.77	43
500	CO	10306	100	--	--	--	--	--	.69	8	42	25	25	2.5	1.37	43
369	CT	10330-10360	70	10	--	--	--	--	4.03	44	44	--	11	2.5	--	71
383	CT	10630-10660	45	50	--	--	--	--	2.09	27	36	18	18	2.5	.94	56
468	SW	10870	100	--	--	--	--	--	.86	--	27	36	36	2.5	--	31
397	CT	10930-10960	70	15	--	--	--	--	2.11	33	33	17	17	2.5	--	60
402	CO	10998-11008	--	--	--	--	--	100	1.17	8	25	33	33	2.5	1.67	36
501	CO	10998	100	--	--	--	--	--	1.21	8	42	25	25	2.8	1.03	43
503	CO	11008	--	--	--	--	--	100	1.23	33	25	25	17	2.8	1.02	57
469	SW	11015	100	--	--	--	--	--	1.04	--	27	36	36	2.8	--	31
470	SW	11100	100	--	--	--	--	--	.96	--	27	36	36	2.9	--	31
414	CT	11230-11260	90	--	--	--	--	--	1.64	--	50	20	30	2.8	.93	39
471	SW	11285	100	--	--	--	--	--	1.41	8	33	33	25	2.9	--	40
428	CT	11530-11560	90	--	--	--	--	--	1.47	17	33	25	25	3.1	--	47
436	CO	11704-11714	100	--	--	--	--	--	1.43	8	25	33	33	2.7	1.73	36
504	CO	11704	100	--	--	--	--	--	1.60	15	38	23	23	3.1	1.05	47
506	CO	11714	100	--	--	--	--	--	1.35	17	33	25	25	3.1	1.49	47
472	SW	11776	100	--	--	--	--	--	1.31	--	45	36	18	3.1	1.64	40
443	CT	11830-11860	100	--	--	--	--	--	2.54	29	29	21	21	2.1	--	55
473	SW	11893	100	--	--	--	--	--	1.86	18	36	27	18	2.7	2.18	49
474	SW	12095	100	--	--	--	--	--	1.23	--	27	36	36	3.1	--	31
457	CT	12130-12160	100	--	--	--	--	--	3.22	31	31	8	31	2.8	--	55
Shublik Formation																
510	CT	12220-12250	90	--	--	--	--	--	3.25	--	40	20	40	3.1	2.05	34
515	CT	12340-12370	90	--	--	--	--	--	2.34	7	36	29	29	3.1	2.17	40
517	CT	12400-12430	90	--	--	--	--	--	2.48	44	44	11	--	3.2	1.75	74

(12 samples), Lisburne Group (21 samples), and Endicott Group (13 samples). A total of 142 samples of drill cuttings, conventional cores, and sidewall cores were assessed, using visual-kerogen techniques and organic-carbon content. Again, the organic-matter populations from the different sample types

TABLE 20.6—*Geochemical data for the Inigok No. 1 well*—Continued

Sample	Type	Depth (ft)	Lithologic composition (percent)						Organic carbon (weight percent)	Kerogen composition (percent)				TAI	R_o (percent)	Hydrocarbon factor (percent)
			Sh	St	Ss	C	Cb	Ot		Am	H	W	I			
									Sadlerochit Group							
521	CO	12500-12529	100	--	--	--	--	--	0.56	9	36	18	36	3.5	2.56	40
529	CT	12700-12730	45	45	--	--	--	--	1.34	--	50	25	25	2.2	--	40
528	CO	12705-12735	100	--	--	--	--	--	.20	18	36	9	36	3.5	2.51	46
539	CT	13000-13030	15	--	75	--	--	--	.16	33	11	11	44	3.6	1.99	47
549	CT	13300-13330	25	--	65	--	--	--	.21	17	25	25	33	3.5	--	43
556	CO	13480-13485	100	--	--	--	--	--	.49	--	40	20	40	3.2	2.52	34
558	CO	13490-13495	100	--	--	--	--	--	.53	8	33	25	33	3.6	2.53	39
566	CT	13570-13600	65	--	--	--	--	25	.26	27	18	18	36	3.6	2.39	47
579	CO	13845-13850	--	--	--	--	--	100	.63	--	20	40	40	3.6	2.64	28
584	CO	13870-13875	100	--	--	--	--	--	1.56	9	18	36	36	3.6	2.77	34
588	CT	13870-13900	90	--	10	--	--	--	.65	--	27	36	36	3.5	2.40	31
586	CO	13880	100	--	--	--	--	--	.94	--	20	40	40	3.6	2.72	28
									Lisburne Group							
594	CO	14030-14035	100	--	--	--	--	--	0.26	--	20	40	40	3.6	2.84	28
599	CO	14055-14060	--	--	--	--	100	--	.13	--	20	40	40	3.8	2.73	28
607	CT	14110-14140	50	--	--	--	--	50	.36	--	27	36	36	3.8	2.73	31
609	CT	14170-14200	50	--	--	--	--	50	.35	--	11	44	44	3.5	2.40	24
619	CT	14470-14500	--	--	--	--	100	--	.11	33	25	17	25	3.6	2.37	56
629	CT	14770-14800	--	--	--	--	100	--	.12	44	22	11	22	3.7	2.38	63
639	CT	15070-15100	25	--	--	--	75	--	.18	9	18	36	36	3.1	2.51	34
643	CO	15185-15215	--	--	--	--	100	--	.12	33	22	11	33	3.7	--	53
650	CT	15370-15400	--	--	--	--	100	--	.10	--	20	40	40	3.1	2.48	28
660	CT	15670-15700	--	--	--	--	100	--	.07	--	27	36	36	3.1	2.34	31
670	CT	15970-16000	10	--	--	--	90	--	.13	15	31	31	23	3.1	--	45
680	CO	16190-16195	--	--	--	--	100	--	.14	--	--	50	50	4.0	--	20
681	CO	16195-16198	--	--	--	--	100	--	.17	33	11	22	33	3.7	--	49
684	CT	16270-16300	--	--	--	--	100	--	.06	15	31	23	31	3.2	2.51	44
693	CT	16540-16570	50	--	--	--	50	--	.16	--	33	--	67	4.0	3.71	26
699	CT	16720-16750	60	--	--	--	40	--	.19	--	40	20	40	4.0	3.37	34
703	CT	16840-16870	30	--	--	--	70	--	.15	--	27	36	36	4.0	3.21	31
713	CO	17061-17068	--	--	--	--	100	--	.23	17	17	33	33	3.9	3.82	40
719	CT	17140-17170	--	--	--	--	100	--	.13	21	21	29	29	4.0	4.01	45
729	CT	17440-17470	--	--	--	--	100	--	.22	18	9	36	36	3.6	3.46	38
732	CT	17530-17560	--	--	--	--	100	--	.20	--	20	40	40	4.1	4.30	28
									Endicott Group							
738	CT	17710-17740	--	--	--	--	10	90	6.59	22	11	22	44	3.7	3.28	40
748	CT	18010-18040	40	--	--	--	60	--	.97	18	18	27	36	3.7	4.36	41
757	CT	18280-18310	60	--	10	10	--	10	4.52	--	27	36	36	4.1	4.14	31
759	CT	18340-18370	100	--	--	--	--	--	1.27	--	--	50	50	4.2	4.22	20
767	CT	18580-18610	100	--	--	--	--	--	1.90	--	20	40	40	4.2	4.22	28
769	CT	18640-18670	95	--	--	5	--	--	5.13	--	--	50	50	4.2	4.42	20
779	CT	18940-18970	30	--	30	40	--	--	20.80	11	--	44	44	4.2	4.67	29
789	CT	19240-19270	40	--	60	--	--	--	1.10	--	--	50	50	4.2	4.77	20
794	CO	19360	--	--	100	--	--	--	.26	--	50	--	50	4.2	--	35
796	CO	19370	100	--	--	--	--	--	2.44	36	9	18	36	4.1	4.40	50
802	CT	19540-19570	--	--	100	--	--	--	1.31	--	--	43	57	4.2	4.61	19
813	CT	19870-19900	10	--	90	--	--	--	3.82	11	--	44	44	4.2	4.84	29
821	CO	20091-20033	--	--	100	--	--	--	19.05	23	15	31	31	4.2	--	44

agreed closely (fig. 20.5; table 20.6). Overall, the kerogen is well preserved to depths of 3,650 m (12,000 ft), but below this depth there is an increase in inertinite. This change is undoubtedly related to the high degree of carbonization, which tends to make the kerogen harder to identify (table 20.8).

The rock units penetrated by this well are fairly thick; the organic facies, as one would expect, vary considerably within each unit. However, the sandstone and shale of the Colville Group have kerogen compositions which are very similar (table 20.8). The Nanushuk Group and Torok Formation are also

TABLE 20.7—*Average content of organic carbon for each rock unit penetrated in the four test wells*

[Values in weight percent. ab., absent (eroded or not deposited); --, not penetrated; n.d., no data]

Unit	Tunalik No. 1	Walakpa No. 1	Oumalik No. 1	Inigok No. 1
Sandstone of the Colville Group---	ab.	ab.	ab.	9.24
Shale of the Colville Group-------	ab.	ab.	ab.	.68
Nanushuk Group--------------------	6.60	ab.	1.01	1.07
Torok Formation-------------------	1.35	1.04	1.27	1.32
Pebble shale unit-----------------	2.64	2.41	3.38	2.87
Kingak Shale----------------------	1.21	.92	.52	1.60
Sag River Sandstone---------------	1.39	n.d.	--	n.d.
Shublik Formation-----------------	.95	.84	--	2.69
Sadlerochit Group-----------------	.69	ab.	--	.58
Lisburne Group--------------------	.37	ab.	--	.17
Endicott Group--------------------	--	ab.	--	5.32
Basement complex------------------	--	.39	--	--

similar to each other but differ from the Colville Group. This relation is reasonable because the Colville rock units are part of one deltaic and interdeltaic system, whereas the Nanushuk Group and Torok Formation are in a separate deltaic and interdeltaic system. In the Sadlerochit Group, thin zones rich in amorphous kerogen are interspersed throughout the herbaceous-woody and woody-inertinitic facies. As in the Tunalik No. 1 well, the amount of herbaceous material in the Inigok No. 1 well decreases with depth from 54 percent in the Colville Group to 12 percent in the Endicott Group, whereas the inertinite increases from 13 to 44 percent.

In all the NPRA wells examined, almost every sample analyzed contained some clearly measurable amount of black inertinite material. The inertinite is mainly reworked material, most certainly from the surface to a depth of about 3,650 m (12,000 ft). Below 3,650 m (12,000 ft), the high degree of carbonization of the kerogen precludes any definitive differentiation between reworked and indigenous inertinite by using techniques of visual-kerogen assessment.

THERMAL-MATURATION PROFILES

Measurements of cuticle coloration or thermal-alteration index (TAI) and vitrinite reflectance (percent R_0) on palynologic kerogen provide maturation profiles for the sedimentary rocks. Two main microscopic methods have been used: (1) observation of color changes in either recognizable spore-pollen palynomorphs or plant cuticle within the isolated kerogen concentrates and (2) measurement of vitrinite reflectance. Throughout the analytical program of the NPRA study, all evaluations of thermal maturation have been made according to the scheme shown in table 20.2, which illus-

TABLE 20.8—*Average composition of kerogen for each rock unit penetrated in the four test wells*

[Kerogen types: Am, amorphous sapropel; H, herbaceous; W, woody; I, inertinite. Figures in percent of total kerogen. ab., absent (eroded or not deposited); --, not penetrated; n.d., no data]

Unit	Tunalik No. 1 (Am/H/W/I)	Walakpa No. 1 (Am/H/W/I)	Oumalik No. 1 (Am/H/W/I)	Inigok No. 1 (Am/H/W/I)
Sandstone of the Colville Group--	ab.	ab.	ab.	2/54/31/13
Shale of the Colville Group------	ab.	ab.	ab.	9/54/28/ 9
Nanushuk Group-------------------	2/42/32/24	ab.	4/55/23/18	1/41/35/23
Torok Formation------------------	3/37/31/29	9/41/31/19	8/44/21/27	7/40/30/23
Pebble shale unit----------------	17/28/29/26	36/36/20/ 7	0/50/12/38	11/44/11/33
Kingak Shale---------------------	9/28/32/31	18/40/27/15	0/40/30/30	15/37/27/21
Sag River Sandstone--------------	3/26/35/34	n.d.	---	n.d.
Shublik Formation----------------	0/24/38/38	12/35/30/23	---	17/40/20/23
Sadlerochit Group----------------	1/29/31/39	ab.	---	10/28/25/37
Lisburne Group-------------------	2/19/36/43	ab.	---	11/22/30/37
Endicott Group-------------------	---	ab.	---	9/12/35/44
Basement complex-----------------	---	0/30/30/40	---	---

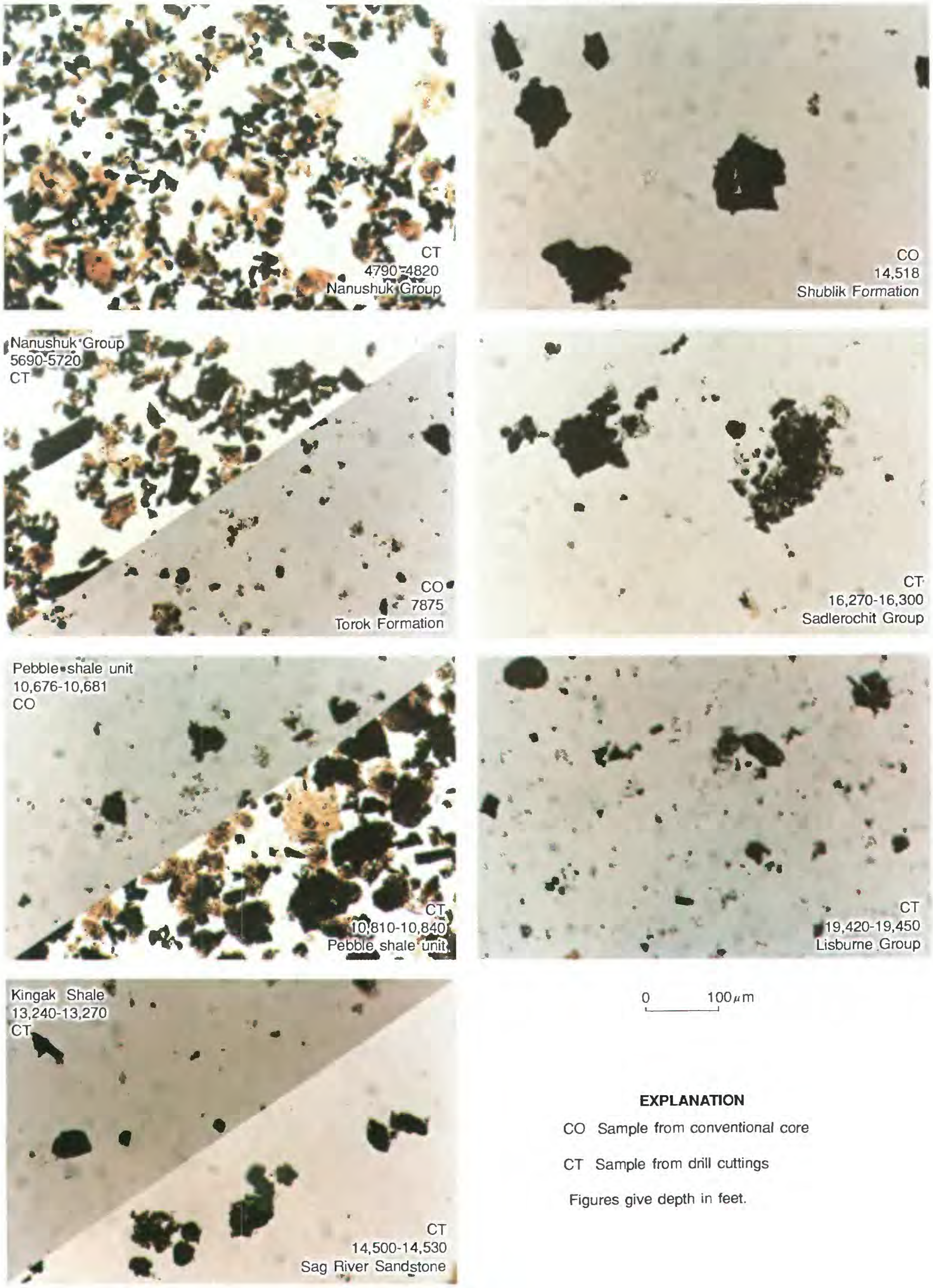


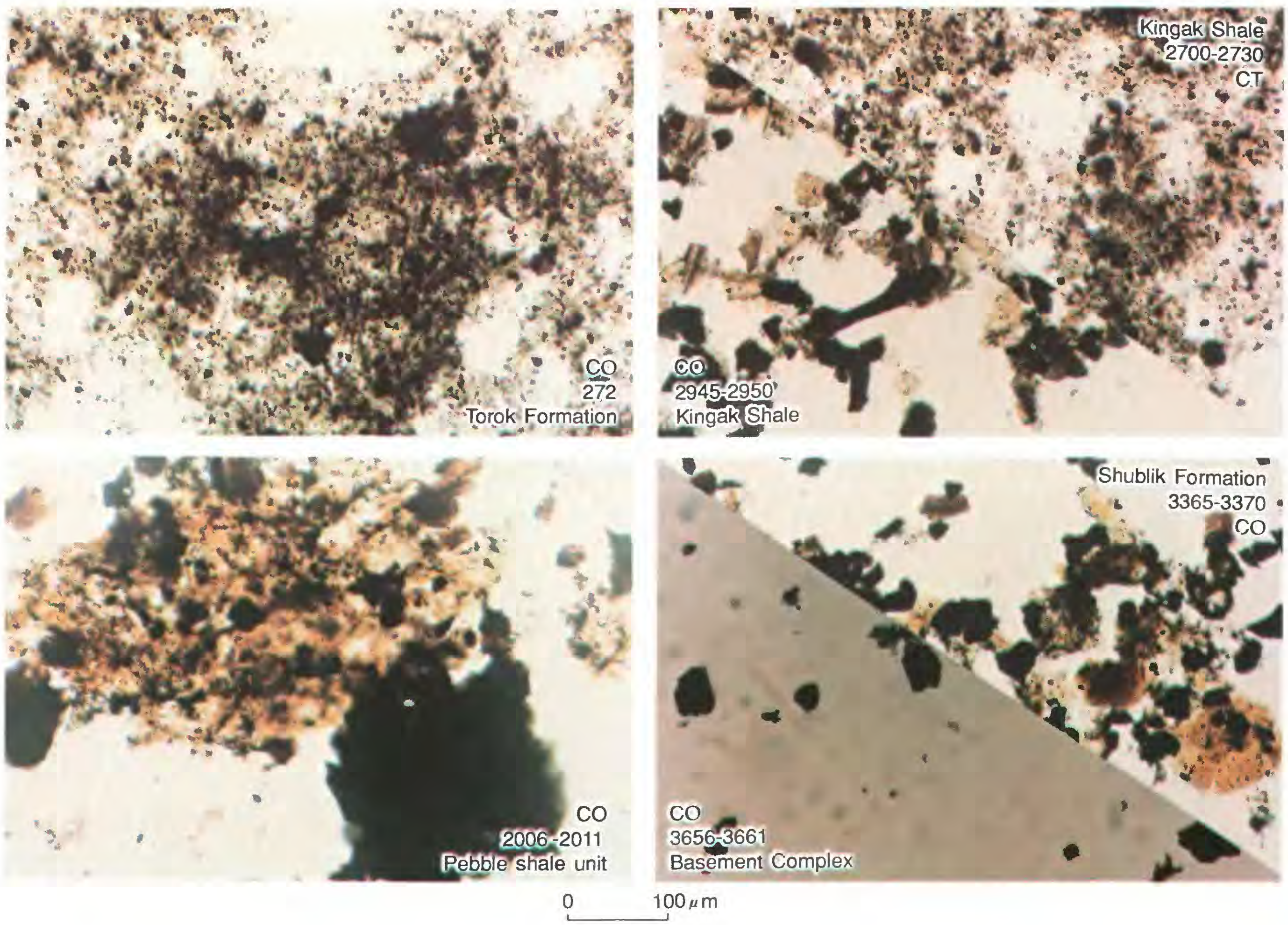
FIGURE 20.2.—Transmitted-light photographs of representative kerogen facies of rock units penetrated in the Tunalik No. 1 well.

trates the relation between vitrinite reflectance (percent R_o) and TAI derived from the data of this study.

TUNALIK NO. 1 WELL

The 116 kerogen analyses available for the Tunalik No. 1 well made possible a comparison of visual-kerogen and vitrinite-reflectance data from both drill cuttings (79 samples) and conventional and sidewall cores (37 samples) (fig. 20.6; table 20.3). Values of the TAI plotted on a linear scale from both types of sample show similar changes with increasing depth, ranging from 2.0 (moderately immature) at 300 m (1,000 ft) to 4.2 (very mature to severely altered) at the total depth. Although some scatter is shown in the TAI data, particularly for the cutting samples, both data sets are consistent with a sharp change in the apparent rate of increase in TAI with depth. This change in slope occurs at a depth of approximately 3,650 m (12,000 ft) in the Kingak Shale.

A similar linear plot of the mean values of vitrinite reflectance (percent R_o) for the indigenous vitrinite population is shown for both the drill cuttings (53 samples) and the cores (21 samples) analyzed (fig. 20.6). Again, two different slopes of apparent thermal alteration are evident. The trend of reflectance values (percent R_o) is from 0.5 at



EXPLANATION

CO Sample from conventional core

CT Sample from drill cuttings

Figures give depth in feet.

FIGURE 20.3.—Transmitted-light photographs of representative kerogen facies of rock units penetrated in the Walakpa No. 1 well.

300 m (1,000 ft) to 0.8 at 2,900 m (9,500 ft) and from 1.5 at 3,000 m (10,000 ft) to 5.0 at the total depth. The break in slope of vitrinite reflectance occurs in the Torok Formation. The slope of the reflectance profile in the deeper part of this well, in comparison with the slope of the TAI curve over the same depth range, indicates that the process responsible for increasing vitrinite reflectance is proceeding at approximately twice the rate of the coloration changes in kerogen. In contrast, the reverse is true for the shallower data, in which vitrinite reflectance increases much more slowly than TAI. The geologic significance (if any) of these observations is not known. Because a casing point in this well is at 3,744 m (12,283 ft), caved materials might account for the difference in TAI, although a similar effect would be expected for the vitrinite-reflectance data.

WALAKPA NO. 1 WELL

The thermal-maturation profiles determined for the Walakpa No. 1 well indicate primarily that the sedimentary rocks have undergone very low geothermal conditions; both cuttings (11 samples) and cores (11 samples) yield TAI values generally ranging from 1.8 to 2.3 (fig. 20.7; table 20.4). Four cutting samples from the Torok Formation were rated with TAI values of 2.8, much higher than expected on the basis of the other data for this well. We have no explanation for this difference, but the much darker kerogen color can be readily observed in the photograph of one of these samples in figure 20.3.

The vitrinite-reflectance values (percent R_o) measured on the cuttings (7 samples) and cores (12 samples) from the Walakpa No. 1 well agree excellently with each other (fig. 20.7) and, except for the Torok samples, also with the TAI values. The beginning of hydrocarbon generation appears at this location only in the small interval represented by the Shublik Formation from 975 m (3,200 ft) to the basement complex at 1,105 m (3,630 ft).

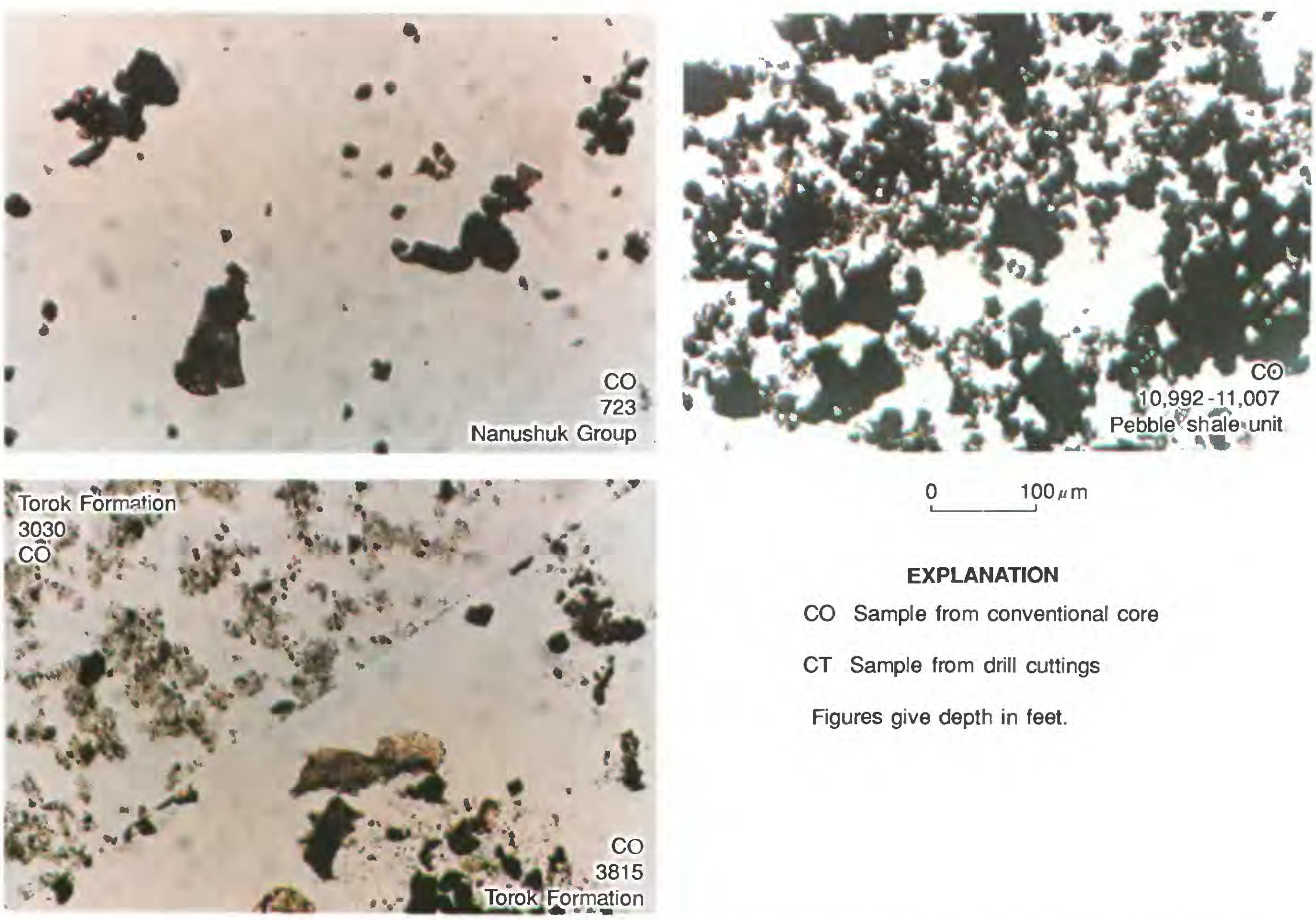


FIGURE 20.4.—Transmitted-light photographs of representative kerogen facies of rock units penetrated in the Oumalik No. 1 well.

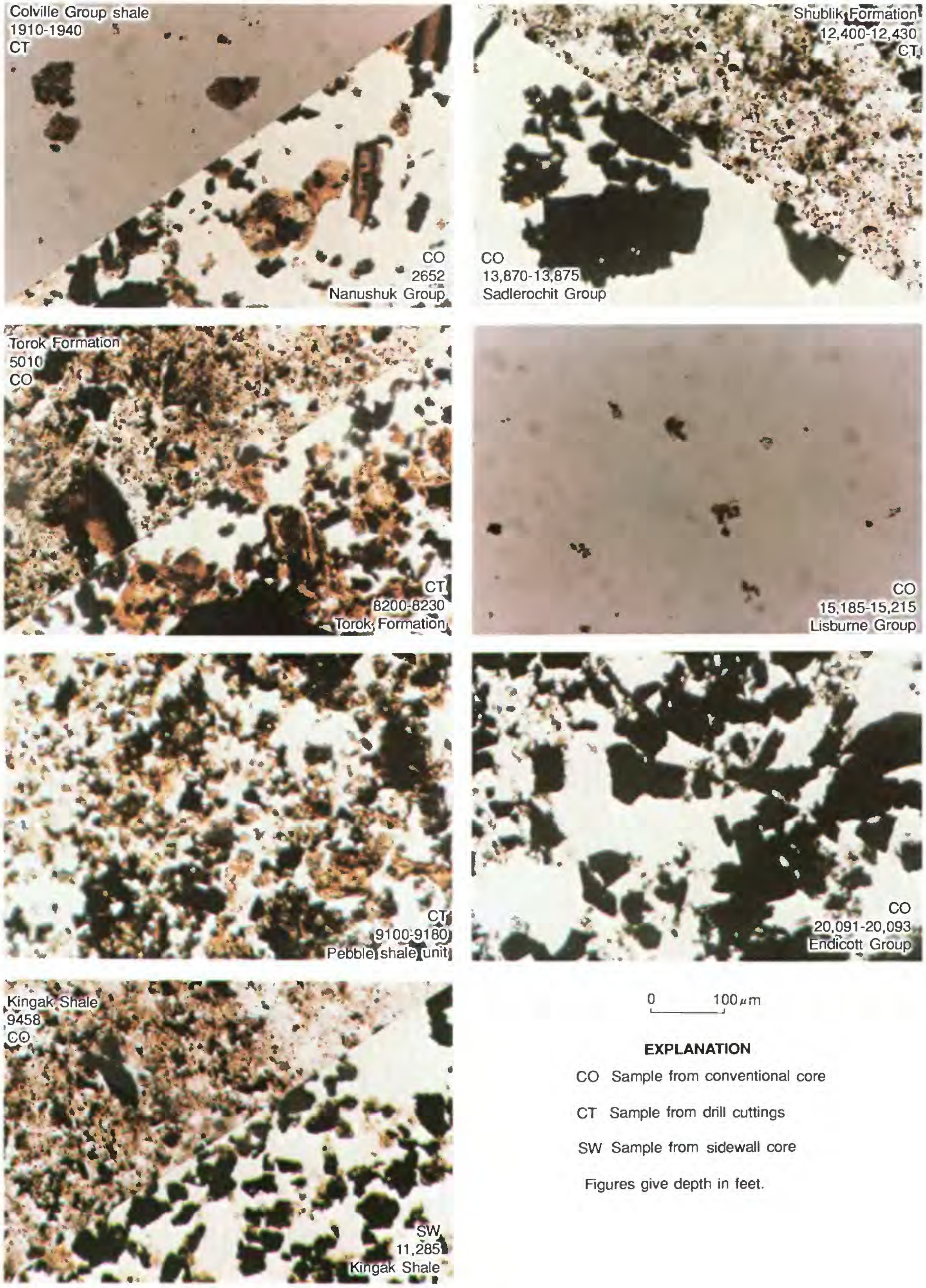


FIGURE 20.5.—Transmitted-light photographs of representative kerogen facies of rock units penetrated in the Inigok No. 1 well.

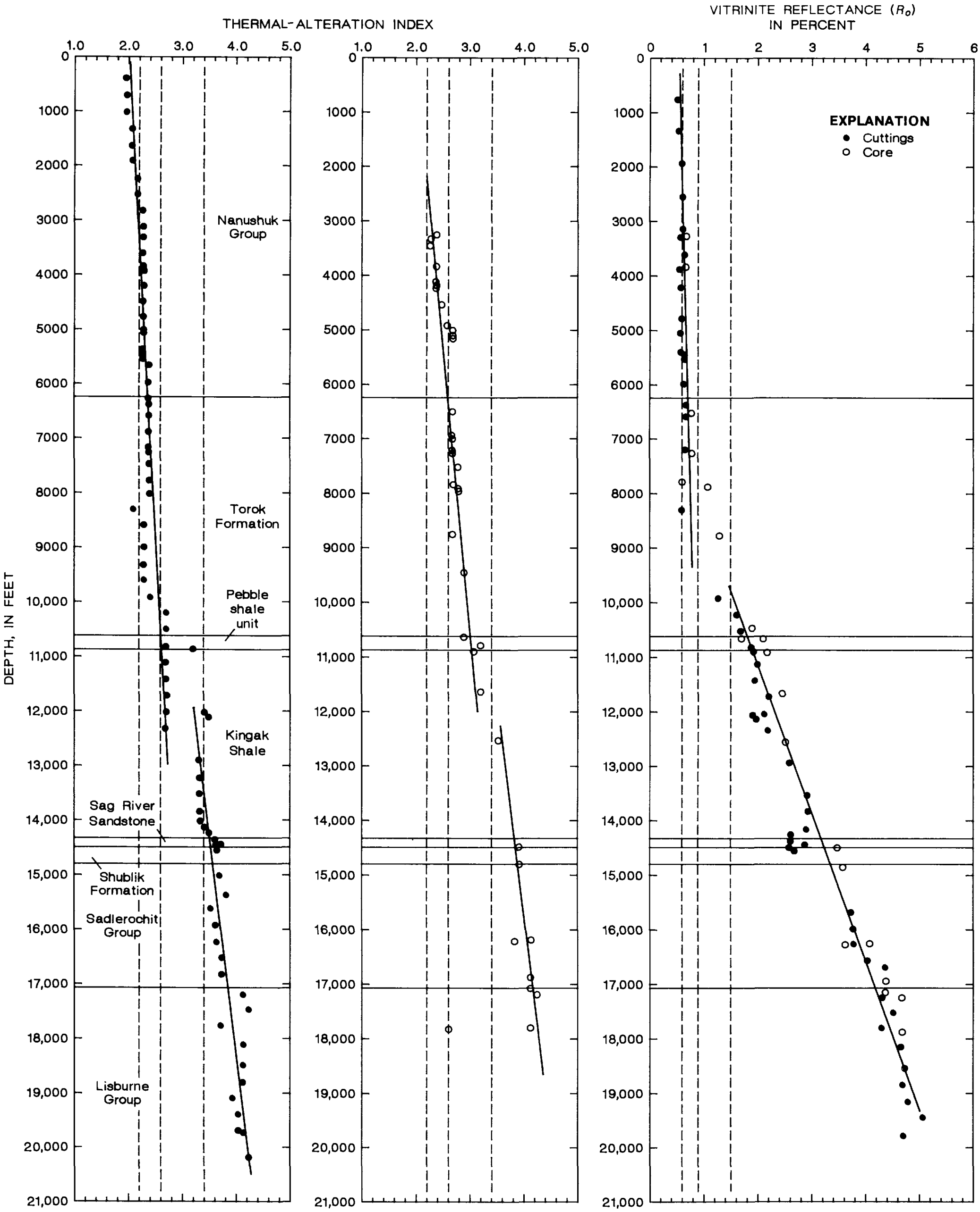


FIGURE 20.6.—Variation of thermal-alteration index and vitrinite reflectance with depth in the Tunalik No. 1 well. Dashed lines show thermal-alteration-index values of 2.2, 2.6, and 3.4 and vitrinite-reflectance values of 0.6, 0.9, and 1.5 percent.

OUMALIK NO. 1 WELL

The 45 samples from the Oumalik No. 1 well were, as previously mentioned, all from excellent-quality cores, not drill cuttings, which could include caved material from shallower levels. Thus, the kerogen concentrates isolated from these samples must be representative of the stratigraphic horizons cored. Except for the scatter in values below 450 m (1,500 ft), TAI's determined on these conventional cores show a gradual, almost linear increase from 1.6 to 2.8 at the total depth (fig. 20.8; table 20.5). The degree of thermal alteration thus appears to increase linearly with increasing depth of burial.

Similar results were obtained from vitrinite-reflectance measurements carried out on the cores (26 samples); values of percent R_0 range from 0.4 at 158 m (517 ft) to 1.5 deeper than 3,000 m (10,000 ft). As in the shallow interval in the Tunalik No. 1 well, the increase in vitrinite reflectance with depth appears to have proceeded at approximately twice the rate of maturation implied by the cuticle-coloration ranking in the TAI assessment.

INIGOK NO. 1 WELL

Thermal-alteration measurements on the Inigok No. 1 well, using both cuttings (73 samples) and conventional and sidewall cores (48 samples), show the same complete range of hydrocarbon generation as was noted in the Tunalik No. 1 well, that is, from biogenic gas, through oil and condensate, to thermally derived methane gas at the total depth. There is excellent agreement between the TAI assessments from drill cuttings and from cores. The data indicate two distinct geothermal profiles, the break in maturity occurring from 3,350 to 3,650 m (11,000-12,000 ft) (fig. 20.9; table 20.6). The shallower maturity slope, determined from the core samples, shows a smooth and progressive rate of increase in TAI with increasing depth, from 2.0 at 750 m (2,500 ft) in the Nanushuk Group to 2.5 at 3,350 m (11,000 ft) in the middle of the Kingak Shale. Examination of the upper TAI values for the shallower part of the drill-cutting data indicates two curves, a value of 2.3 being noted from the surface to 1,585 m (5,200 ft), followed by an abrupt drop to 1.7 at 1,615 m (5,300 ft) and then a rise to 2.5 at 3,350 m (11,000 ft) in the Kingak Shale. The reason for this anomalous change in profile is not known; it cannot be attributed to casing points (fig. 20.9) but may be the result of an abrupt change in sample quality. However, the TAI values from 1.8 to 2.1 theoretically encompass the entire moderately immature degree of diagenesis, and variations within this range have little effect on interpretation of the depth for oil generation (table 20.2).

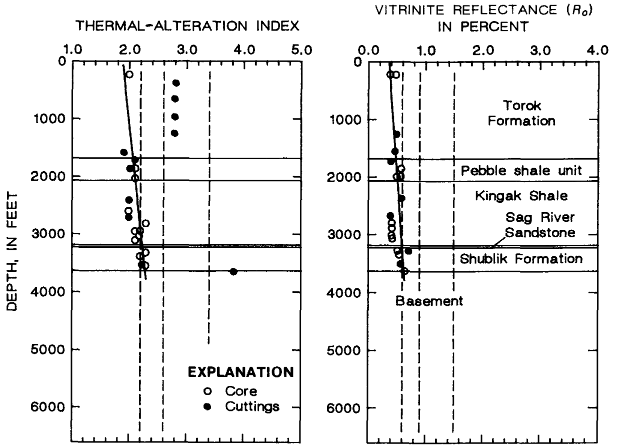


FIGURE 20.7.—Variation of thermal-alteration index and vitrinite reflectance with depth in Walakpa No. 1 well. Dashed lines show thermal-alteration-index values of 2.2, 2.6, and 3.4 and vitrinite-reflectance values of 0.6, 0.9, and 1.5 percent.

Below 3,350 m (11,000 ft) and, more specifically, below the base of the Shublik Formation, both sets of data indicate a smooth maturation profile; TAI increases progressively from 3.4 to 4.2 at 6,000 m (20,000 ft). Because casing was set at 3,744 m (12,283 ft) in the Shublik Formation, there should have been no caving of drill cuttings from above. There is considerable scatter in the data throughout the Lisburne Group for the cutting samples, possibly attributable to the differing rock types or, more likely, to caving from the Shublik Formation. Similar variations were noted in the vitrinite-reflectance data for drill cuttings from this interval, confirming that the measured TAI and vitrinite-reflectance values are representative of the samples analyzed.

The vitrinite-reflectance measurements on the cores (41 samples) and cuttings (50 samples) similarly agree with the TAI data, two maturation profiles again being clearly discernible. From the surface to 3,350 m (11,000 ft), the reflectance values (percent R_0) change from 0.4 to 1.0. Values for samples from below 11,000 ft range from 1.5 to 4.9 at the total depth. As mentioned previously, cuttings samples from throughout the Lisburne Group showed a considerable scattering of values, but data are sufficient to project the curve shown in figure 20.9 as the best straight-line fit. Again, the rate of increase in vitrinite reflectance agrees with the alteration rate implied by the TAI data for the shallow slope, but it is twice that rate for the deeper slope.

To our knowledge, this observation of different rates of change with depth in TAI and percent R_0 has not been reported previously, possibly because the phenomenon becomes apparent only when the higher vitrinite ranks (more than 1.5 percent R_0) are encountered. The basis for this relation may be one or all of the following. First, the cause may be inherent in the different measurement techniques being used, especially the different numerical scales employed. The TAI values reported are based on the coloration rank of the lightest colored identifiable indigenous cuticle or spore, whereas the vitrinite values reported are means, not minimums. Second, the TAI ranking is made on the exinite-related maceral components of the kerogen (cuticle and spore pollen), whereas the vitrinite reflectance is measured on the vitrinized woody-plant material. These different maceral types may undergo differing rates of thermal alteration under similar time and temperature conditions. Third, the perceived color in transmitted light can vary with the particle thickness, whereas the reflectance is totally a surface phenomenon. Fourth, some variation between TAI and percent R_0 values could be attributed to the original particle size of the kerogen. Because alteration through geologic time proceeds from the exterior of the particle inward, subsequent breakdown of the kerogen particle during processing can give a range of maturities from the less altered interior of the particle to the more altered outer part. Fifth, if the chemical reactions responsible for changes in vitrinite reflectance occur at rates analogous to most other organic chemical reactions (that is, first-order kinetics with exponential temperature dependence) and the TAI color change has been arbitrarily calibrated to show linear change with depth on a numerical scale of 1 to 5, then these two thermal-maturity indicators could well show markedly different rates of increase with increasing depth of burial.

Regardless of the reasons, a consistent relation between TAI and percent R_0 can be demonstrated (fig. 20.10*A*). A general relationship is clear on the plot, even though the data points show some obvious deviations from the interpreted relation between TAI and percent R_0. For example, the Oumalik well shows a much higher percent R_0 for a corresponding TAI value in

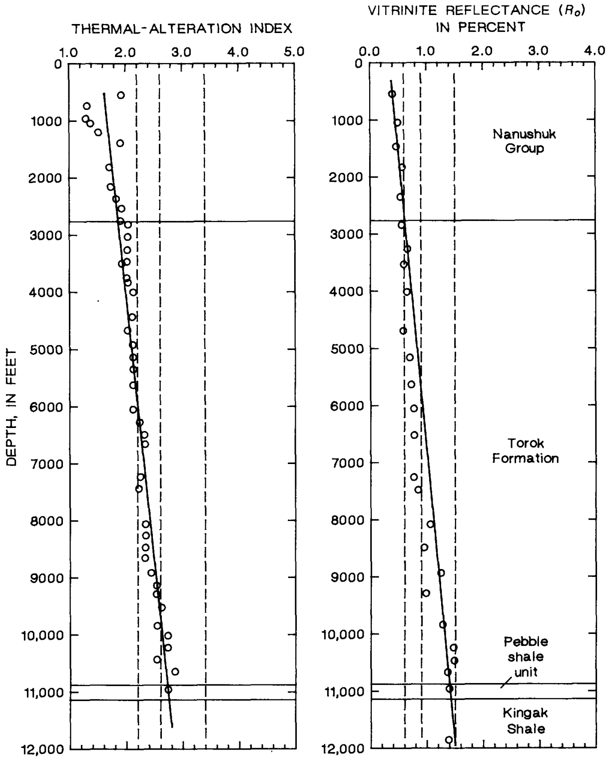


FIGURE 20.8.—Variation of thermal-alteration index and vitrinite reflectance with depth in Oumalik No. 1 well. Dashed lines show thermal-alteration-index values of 2.2, 2.6, and 3.4 and vitrinite-reflectance values of 0.6, 0.9, and 1.5 percent.

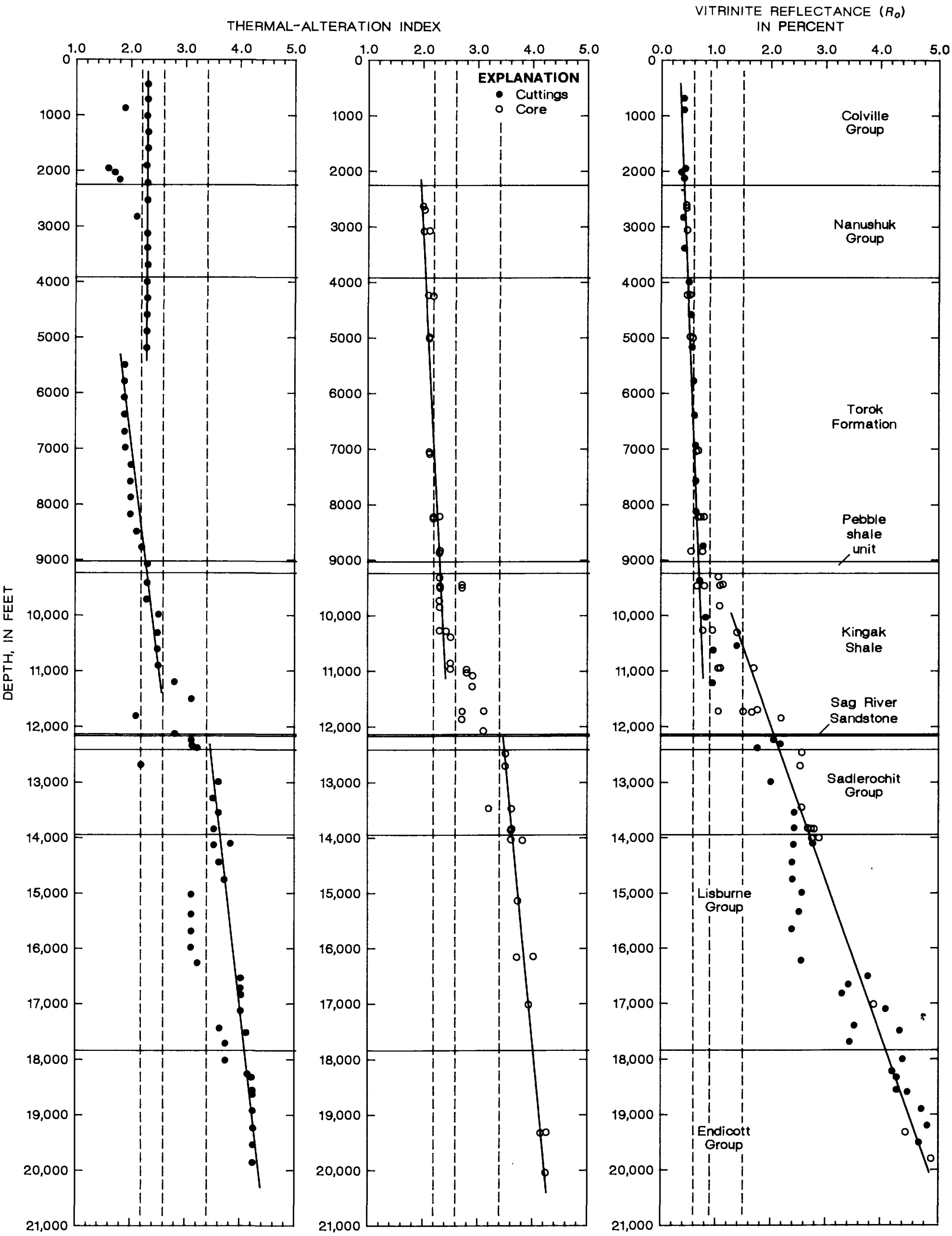


FIGURE 20.9.—Variation of thermal-alteration index and vitrinite reflectance with depth in Inigok No. 1 well. Dashed lines show thermal-alteration-index values of 2.2, 2.6, and 3.4 and vitrinite-reflectance values of 0.6, 0.9, and 1.5 percent.

comparison with the interpreted value. Two reasons for this may be (1) that the Oumalik No. 1 well was one of the first three wells completed in 1977, whereas the other three wells were completed in 1981; and (2) that the cores from the Oumalik No. 1 well were stored since 1950, whereas the other sample material was freshly canned in 1979-81. Although the data from the other three wells also show idiosyncrasies, the dashed line drawn visually represents the best-fit relation between TAI and percent R_0 for this study.

The relation between TAI and percent R_0 varies between operators and between geologic basins (fig 20.10*B*). In the study by Waples (1980), the TAI values for any given R_0 below 4.0 percent are consistently higher than those in the NPRA study. Similarly, the TAI scale developed by GeoChem Research, Inc., is even higher than that of Waples (1980) for R_0 values greater than 1.5 percent but lower than those of both Waples (1980) and in this study for reflectance values less than 1.0 percent. We cannot say that any scale is incorrect or correct, but a separate calibration curve should be defined for each geologic basin and by each palynologist or petrographer.

GEOCHEMISTRY OF LIGHT HYDROCARBONS

In the previous discussion, the thermal-maturity indicators TAI and vitrinite reflectance were shown to have a consistent relation in four NPRA wells. The relation between these maturity indicators and the stages of hydrocarbon generation and destruction can be established by the relative contents of the C_1-C_4 hydrocarbons (figs. 20.11-20.14). Light hydrocarbons are direct indicators of petroleum generation because C_2-C_{10} alkanes are present only in trace amounts in rocks at shallow depths of burial. At temperatures below about 60 °C, biogenic methane (C_1) is the only hydrocarbon generated at a significant rate. As the subsurface temperature increases above 60 °C, especially above about 100 °C, a range of hydrocarbons including

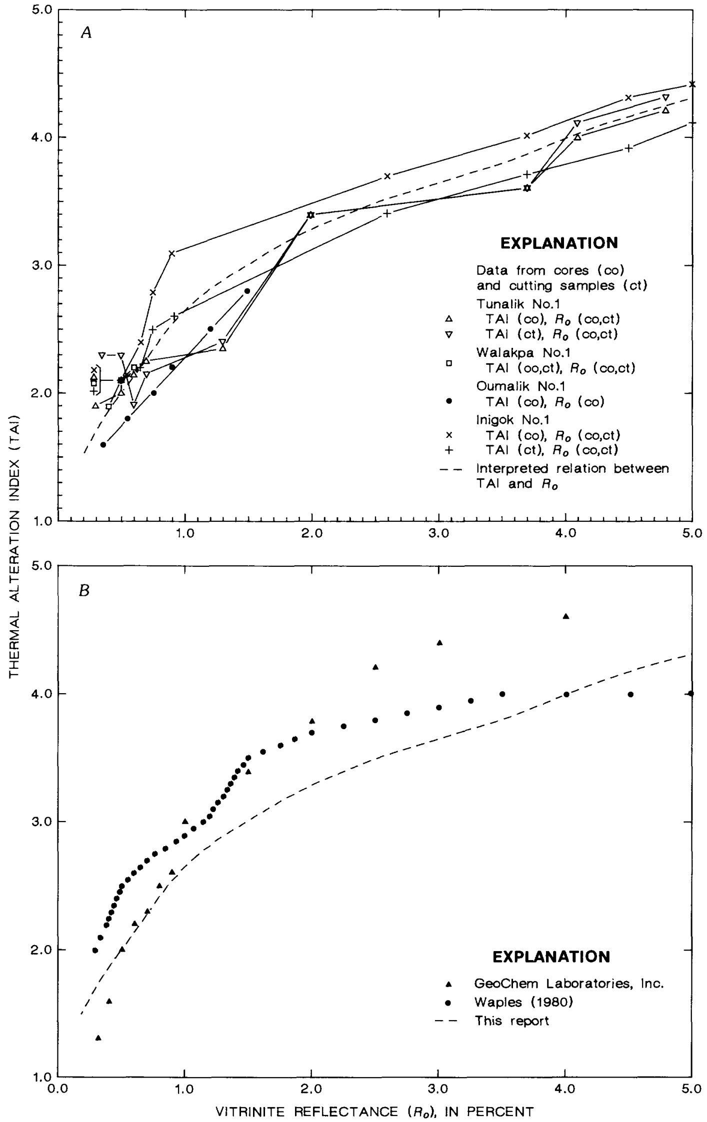


FIGURE 20.10.—Relation of thermal-alteration index (TAI) to vitrinite reflectance (R_0). *A*, Plots for each of the four wells in this study and inferred average relation for NPRA. *B*, Average relation from this study compared with those from other studies.

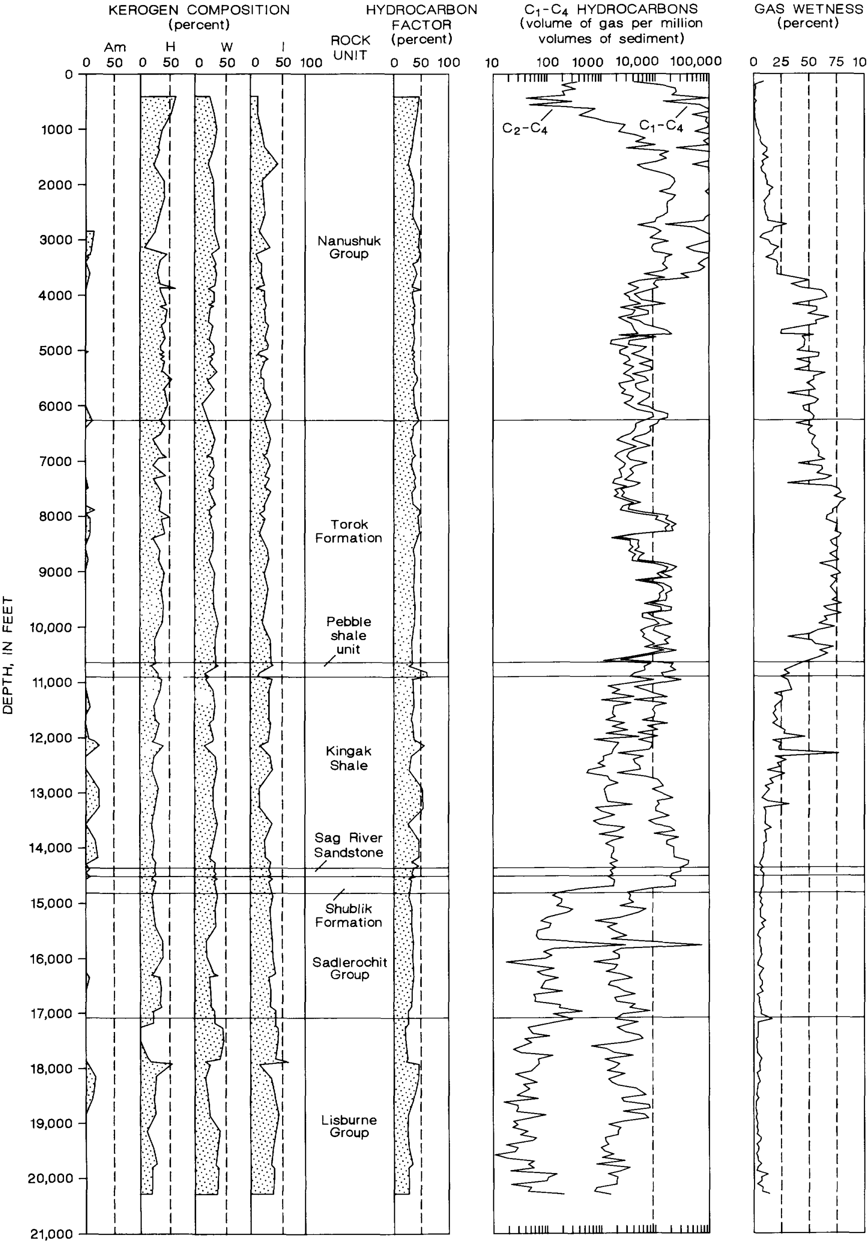


FIGURE 20.11.—Variation of kerogen composition, hydrocarbon factor, C_1-C_4 hydrocarbon data, and gas wetness with depth in the Tunalik No. 1 well. Kerogen data for amorphous sapropel (Am), herbaceous (H), woody (W), and inertinite (I) are percentages present on strew slide. See text for calculation of hydrocarbon factor.

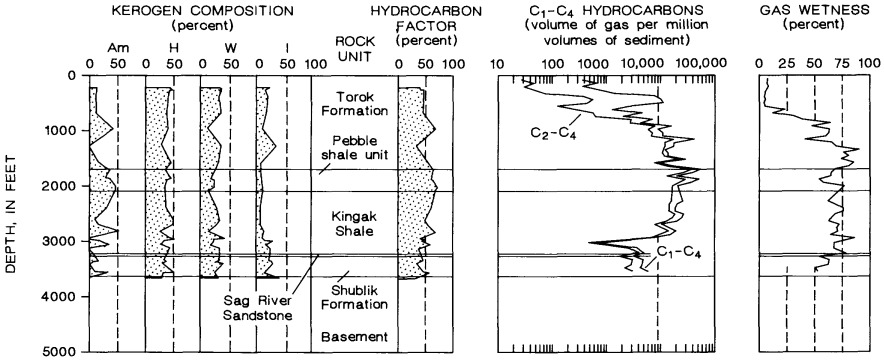


FIGURE 20.12.—Variation of kerogen composition, hydrocarbon factor, C_1-C_4 hydrocarbon data, and gas wetness with depth in the Walakpa No. 1 well. Kerogen data for amorphous sapropel (Am), herbaceous (H), woody (W), and inertinite (I) are percentages present on strew slide. See text for calculation of hydrocarbon factor.

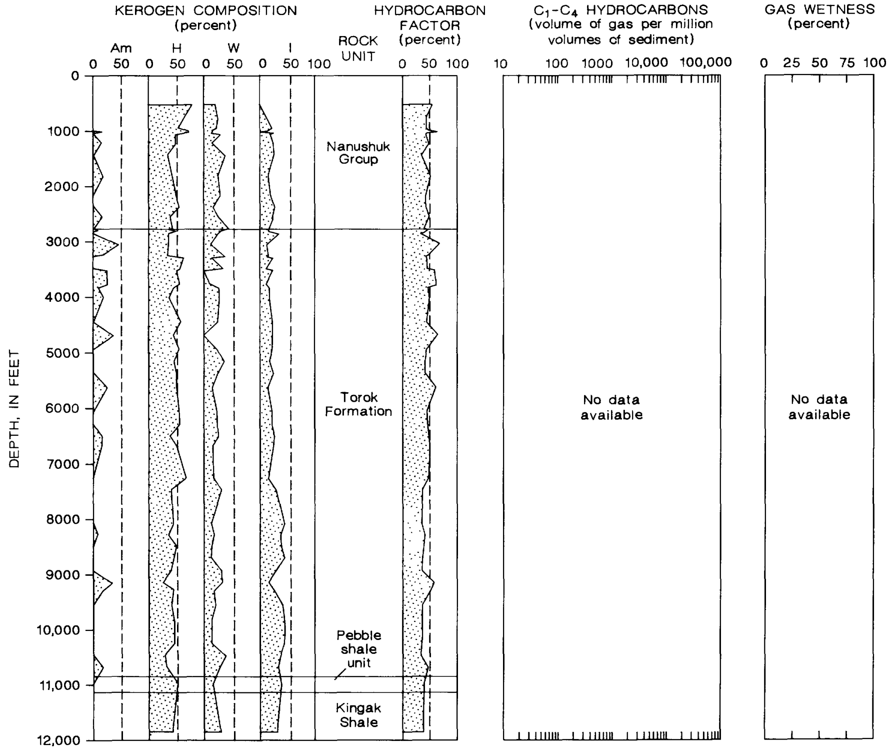


FIGURE 20.13.—Variation of kerogen composition and hydrocarbon factor with depth in the Oumalik No. 1 well. Kerogen data for amorphous sapropel (Am), herbaceous (H), woody (W), and inertinite (I) are percentages present on strew slide. See text for calculation of hydrocarbon factor.

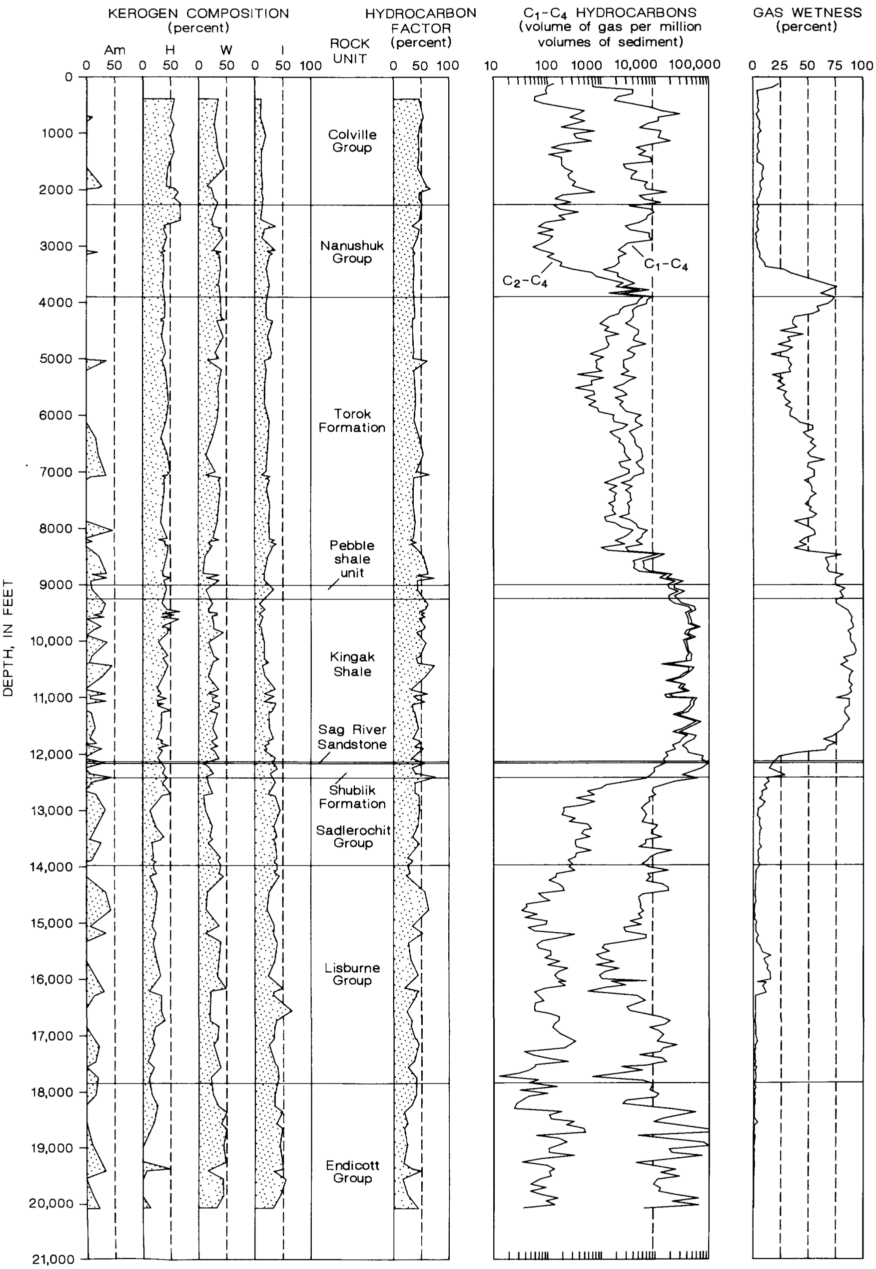


FIGURE 20.14.—Variation of kerogen composition and hydrocarbon factor, C_1-C_4 hydrocarbon data, and gas wetness with depth in the Inigok No. 1 well. Kerogen data for amorphous sapropel (Am), herbaceous (H), woody (W), and inertinite (I) are percentages present on strew slide. See text for calculation of hydrocarbon factor.

C_2-C_4 hydrocarbons are generated at geologically rapid rates. At even higher temperatures (above about 175 °C), C_2-C_4 hydrocarbons are destroyed more rapidly than they are formed. Thus, the temperature-dependent rates of hydrocarbon generation and destruction define the subsurface transitions from the biogenic gas zone, through the oil zone and the wet-gas condensate zone, to the dry-gas/thermal-C_1 zone. One geochemical measurement that illustrates these transitions is the percentage of C_2-C_4 hydrocarbons in the total C_1-C_4 fraction from canned cuttings (referred to as gas wetness).

TUNALIK NO. 1 AND INIGOK NO. 1 WELLS

The C_1-C_4 light hydrocarbons were analyzed in canned cutting samples taken every 18 m (60 ft) in the Tunalik No. 1 and Inigok No. 1 wells. The results of these analyses are shown in the two columns on the right-hand side of figures 20.11 and 20.14. In the column labeled "C_1-C_4 Hydrocarbons," the two curves indicate the abundance of C_2-C_4 alkanes (left) and of C_1-C_4 alkanes (right), in units of standard gas volumes per million volumes of rock, plotted on a logarithmic scale. The difference between the curves indicates the abundance of the C_1 alkane (methane). In general, the gas contents are low near the surface, peak at an intermediate depth, and decrease again near the total depth.

In the column labeled "Percent Wetness," the gas-wetness curve also starts low, builds up to a maximum, and then declines with increasing depth in response to the main stages of organic-matter evolution. Percent wetness is compared with TAI and percent R_o in figure 20.15. Through the diagenetic stage, percent wetness remains low, while TAI increases to 2.1 and percent R_o increases to 0.6. At this level, gas wetness begins to increase rapidly to peak generation at a TAI value of about 2.4 and percent R_o of about 0.8. Peak generation continues until the TAI is more than 3.0 and the percent R_o is more than 1.5, but gas wetness drops off very rapidly when the TAI value reaches 3.3 and the percent R_o reaches 2.0. This interval in which gas-wetness values are significant is considered the catagenetic stage or the liquid-hydrocarbon window. At greater depths, only dry gas is preserved; this is called the metagenetic stage.

WALAKPA NO. 1 WELL

The light-hydrocarbon profile for the Walakpa No. 1 well (fig. 20.12) shows a very different pattern from those of the two deep wells because migrating hydrocarbons have affected this discovery well for gas in sandstone of the pebble shale unit. Anomalously high gas-wetness values occur in the immature zone when any hydrocarbon reservoir is in the vicinity, for example, in the South Barrow area (Magoon and Claypool, 1980). Thus, in such cases the gas-wetness profile cannot be used to substantiate maturity, but it can be used to indicate a proximity to a hydrocarbon reservoir.

DISCUSSION—ORGANIC FACIES, THERMAL MATURITY, AND HYDROCARBON COMPOSITION

The beginning of hydrocarbon generation, peak generation, and the base for oil occurrence were discussed in the preceding section in relation to the data available for the Tunalik No. 1 and Inigok No. 1 wells. However, whereas temperature and time are major factors controlling hydrocarbon generation, the nature of the kerogen still largely determines the composition of hydrocarbons derived from any given organic facies. The generation of hydrocarbons is part of a continuous process beginning with the initial preservation of organic matter in sediment. Generation and destruction of specifically identifiable hydrocarbon precursors and products occur as the levels of maturation increase with time and with depth of burial. Continued maturation above the point of peak hydrocarbon generation results in disproportionation of those hydrocarbons already generated, and ultimately only dry methane gas survives in appreciable concentration both in the rock and in any hydrocarbon accumulation.

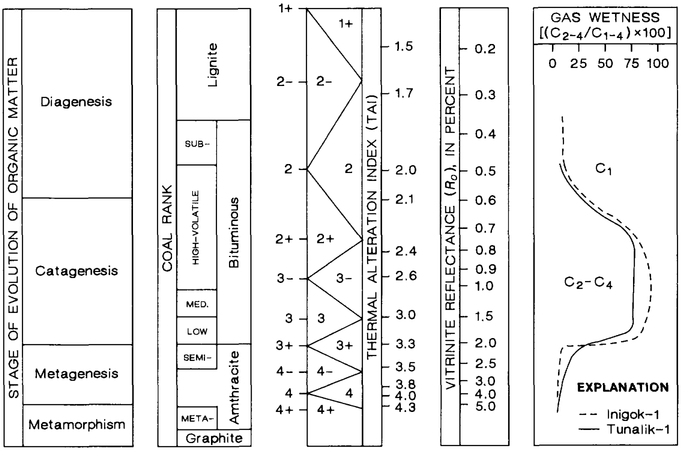


FIGURE 20.15.—Comparison of correlated values of thermal-alteration index and vitrinite reflectance (from fig. 20.10*A*) with gas wetness, coal ranks, and main stages of evolution of organic matter.

In general, both oil and gas are generated from the amorphous-sapropel and herbaceous types of organic matter. Only gas and possible minor oil is generated from woody and inertinite organic matter. The main stages of evolution of organic matter and the equivalent ranks of coal are shown in figure 20.15, which is modified from Tissot and Welte (1978, p. 71). The relation between organic-matter evolution and TAI was established by GeoChem Research, Inc. The correlation of vitrinite reflectance and gas wetness in figure 20.15 is based on the present study.

The predominant kerogen population (more than 40 percent) reflects the depositional environment. Accordingly, open-water marine and lacustrine environments tend to have an aqueous-derived amorphous-sapropel kerogen, whereas nearshore environments tend to have terrestrially derived herbaceous and woody kerogens. By determining these organic facies (or observed kerogen populations) and evaluating their thermal ranks, we can predict the probable composition of the hydrocarbons generated from that facies at a particular degree of catagenesis. The range of thermal maturities in the Tunalik No. 1 and Inigok No. 1 wells (fig. 20.15) indicate that all three types of hydrocarbon (oil, condensate, and thermal gas) should have been generated in the NPRA. Oil, condensate, and thermal gas have, in fact, been found in the South Barrow field and in other parts of the NPRA.

The potential of the organic facies penetrated by the study wells for generating oil and gas can be theoretically calculated. This potential can be quantified by calculating an estimated hydrocarbon-yield factor based on the yield factor determined for each specific kerogen type. Amorphous sapropel (Am) yields the greatest amount of oil and gas during catagenesis, and the hydrocarbon yield of other kerogen types diminishes in the order herbaceous (H), woody (W), and inertinite (I) (Bailey, 1981). Abelson (1963) inferred yield values on the order of 90, 50, 25, and 0 percent convertibility for Am, H, W, and I types of kerogen, respectively. Under conditions simulating complete thermal alteration of the organic matter to the stage in which only gas is generated, the completely unaltered kerogen types Am, H, W, and I afforded hydrocarbon yields of 95, 60, 30, and 10 percent, respectively. Without reference to the organic-carbon content or thermal maturity of the rocks, therefore, a hydrocarbon factor (in percent) can be computed from the data on kerogen types by the equation:

$$\text{hydrocarbon factor} = (P_{\text{Am}} \times 0.9) + (P_{\text{H}} \times 0.6) + (P_{\text{W}} \times 0.3) + (P_{\text{I}} \times 0.1),$$

where P_{Am}, P_{H}, P_{W}, and P_{I} are the respective percentages of the kerogen types in the total kerogen.

The visual-kerogen data from tables 20.3-20.6 are graphically portrayed in figures 20.11-20.14 as normalized percent compositions for the four basic kerogen types identified in this study. The hydrocarbon factor, calculated as described above, is shown on these figures next to the kerogen compositions. The content of C_1-C_4 light-gas hydrocarbons and percent wetness are given in profile on the far right of figures 20.11-20.13. No C_1-C_4 data are available for the Oumalik No. 1 well.

The hydrocarbon factor ranges from 30 to 60 percent in all four wells, indicating that whenever sufficient organic matter is present, the kerogen always has the potential to yield a measurable volume of hydrocarbons. The hydrocarbon factor can be empirically checked by using the C_1-C_4 hydrocarbon data, which here indicate that at least some hydrocarbons are present in all canned samples, although maturity levels affect hydrocarbon composition. For example, in the Tunalik No. 1 and Inigok No. 1 wells at shallow depths, where gas wetness is low (less than 25 percent), methane is the predominant gas (zone of diagenesis); at greater depths, where gas wetness is again low (less than 25 percent), high maturity (zone of metagenesis) is the cause for the dominance of dry gas. Between these two zones of less than approximately 25 percent gas wetness, more than 80 percent of the ethane and heavier hydrocarbons are present. The laboratory work of Abelson (1963) and one of us (GSB) on hydrocarbon yields is empirically corroborated by comparing the hydrocarbon factor with the C_1-C_4 hydrocarbon data acquired from these deep wells.

Several features on figures 20.11 to 20.14 can be noted that are consistent with previous interpretations. In general, the sedimentary sections penetrated by the four wells seem to contain fairly homogeneous populations of organic matter, the kerogen appearing to be primarily composed of terrestrially derived herbaceous and woody-plant remains. Only minor amounts of amorphous sapropel were noted in the Tunalik No. 1 well. The light-gas hydrocarbon analyses for the Tunalik No. 1 well (fig. 20.11) indicate large amounts of biogenic methane gas from the surface to 1,050 m (3,500 ft), where low-temperature hydrocarbon generation starts. Peak hydrocarbon generation is at about 2,300 m (7,500 ft). These depths correspond to wet-gas (C_2-C_4) proportions of 25 percent and more than 50 percent, respectively. The base for significant preservation of liquid hydrocarbons is estimated to be at 3,870 m (12,700 ft) because the wet-gas proportion of less than 25 percent content indicates rapid hydrocarbon disproportionation below this level.

Two important observations can be made from the kerogen and hydrocarbon summary for the sedimentary section in the Walakpa No. 1 well (fig. 20.12). First, the organic facies present in this well contain significantly more amorphous-sapropel kerogen and thus have a favorable, oil-prone character. Second, although the thermal-maturity profile for this well shows low TAI values (2.0-2.2), this maturity level may be adequate for the amorphous-sapropel kerogen to have generated some hydrocarbons. Such generation may have contributed to the observed high value of gas wetness noted for the cutting-gas analysis of the samples from below 300 m (1,000 ft), rather than its being entirely attributable to migrating hydrocarbons. However, the Walakpa No. 2 well was the discovery well for a gas field whose compositional characteristics ($C_1/C_{1\text{-}5}=97$ percent; $\delta^{13}C=-37.9$ permil; $\delta D=-163$ permil) strongly suggest that these wells, located at the updip end of the Meade arch, is on the hydrocarbon-migration path between the Colville Trough and the Barrow gas field.

A similar evaluation of the hydrocarbon data cannot be made for the Oumalik No. 1 well (fig. 20.13) because no data on C_1-C_4 light-gas hydrocarbons are available for this well. Nevertheless, the organic facies penetrated by this well appear to be more closely comparable to those of the Tunalik No. 1 well, only sporadic amorphous sapropel in minor amounts being noted throughout. The hydrocarbon-yield factor appears favorable for both oil and gas to a depth of 2,300 m (7,500 ft) but indicates a more gas-prone character from there to the total depth. The thermal-maturity profiles from TAI and percent R_o indicate that hydrocarbon generation most likely begins below 1,800 m (6,000 ft); the type of organic matter present would generate gas at this well location.

The Inigok No. 1 well (fig. 20.14) shows the greatest degree of organic-facies variation among the four wells analyzed; significantly more amorphous-sapropel kerogen are interdispersed throughout the predominantly herbaceous-woody facies. The hydrocarbon-yield factor fluctuates around 50 percent from the surface to near the base of the Kingak Shale at 3,650 m (12,000 ft). The content and composition of light-hydrocarbon gas support the interpretation of rapid hydrocarbon generation beginning at 1,585 m (5,200 ft), peak generation occurring at about 2,560 m (8,400 ft), and the base of oil liquids being sharply defined near the base of the Kingak at 3,690 m (12,100 ft). Below 3,650 m (12,000 ft), irrespective of the nature of the organic facies, the sedimentary rocks will be gas generating because of the high levels of maturation.

SUMMARY

Three important factors—organic facies, richness, and thermal maturity—were characterized by means of five types of petroleum geochemical analyses on rock samples from four widely spaced wells in the NPRA. Visual-kerogen assessment and organic-carbon content were used to characterize the organic facies and richness of 11 rock units penetrated by the 4 wells. The thermal maturity for the entire stratigraphic section was determined by using the values of thermal-alteration index (TAI), vitrinite reflectance (percent R_o), and C_1-C_4 hydrocarbon gas wetness. Two wells, Tunalik No. 1 and Inigok No. 1, penetrated rocks in all three stages of the evolution of organic matter—diagenesis, catagenesis, and metagenesis.

The organic facies penetrated by these wells accumulated near shore on a shallow shelf where marine currents were minimal, so that the influx of terrestrially derived herbaceous and woody-plant detritus could be deposited. The content of amorphous-sapropel kerogen is highest for the Shublik Formation, Kingak Shale, and pebble shale unit in some of the wells. The average amorphous-sapropel content in the Inigok well is 17 percent, but it is 0 percent in the Tunalik well. These same two deep wells show an inverse trend in the herbaceous and inertinite kerogens with depth: Herbaceous content decreases, and inertinite increases.

The average richness of each kerogen facies, based on organic-carbon content, is sufficient for all 11 rock units to meet the minimum requirements as source rocks for hydrocarbons. Three rock units, the Endicott Group, the Nanushuk Group, and sandstone of the Colville Group, are rich in organic carbon in the form of coal (5.32, 6.60, and 9.24 weight percent, respectively); these units are considered gas prone. Rock units that are considered to be important potential source of hydrocarbons are the Shublik Formation (2.69 weight percent), the Kingak Shale (1.60 weight percent), the pebble shale unit (2.87 weight percent), and the Torok Formation (1.35 weight percent).

The thermal maturity of certain rock units in these four wells is sufficiently high to generate oil, condensate, and thermal gas. The measures of thermal maturity, TAI and percent R_o, were compared in three ways: (1) for both TAI and percent R_o, results were compared between sample types (drill cuttings and core material); the results agreed well; (2) the TAI was compared with percent R_o for each well to determine an average relation between the two analytical techniques; and (3) the results were compared with Waples' (1980) curve in figure 20.10*B*.

The C_1-C_4 hydrocarbon composition of headspace and cuttings gas was compared with the values of the TAI and percent R_o to determine thresholds for the stages of evolution for organic matter. The threshold values for the beginning of catagenesis are 2.1 for TAI, 0.6 percent for R_o, and 25 percent (increasing) for gas wetness, and for the beginning of metagenesis they are 3.3, 2.0 percent, and 25 percent (decreasing), respectively.

Comparison of hydrocarbon yields obtained in the laboratory for Am, H, W, and I kerogens with the C_1-C_4 hydrocarbon data acquired from a well indicates that as long as some organic matter is present, there will always be some hydrocarbons generated during catagenesis and metagenesis. Therefore, the gas-wetness curve can be used as a direct indicator for maturity, provided the C_1-C_4 hydrocarbons have not migrated.

REFERENCES CITED

Abelson, P.H., 1963, Organic geochemistry and the formation of petroleum: World Petroleum Congress, 6th, Frankfurt, 1963, Proceedings, Section 1, p. 397-407.

Bailey, N.J.L., 1981, Hydrocarbon potential of organic matter, *in* Brooks, J., ed., Organic maturation studies and fossil fuel exploration: London, Academic Press, p. 283-302.

Bostick, N.H., 1971, Thermal alteration of clastic organic particles as an indicator of contact and burial metamorphism in sedimentary rocks: Geoscience and Man, v. 3, p. 83-92.

Brown, C.A., 1960, Palynological techniques: Baton Rouge, La., 188 p.

Burgess, J.D., 1974, Microscopic examination of kerogen (dispersed organic matter) in petroleum exploration, *in* Dutcher, R.R., Hacquebard, P.A., Schopf, J.M., and Simon, J.A., eds., Carbonaceous materials as indicators of metamorphism: Geological Society of America Special Paper 153, p. 19-30.

Castaño, J.R., and Sparks, D.M., 1974, Interpretation of vitrinite reflectance measurements in sedimentary rocks and determination of burial history using vitrinite reflectance and authigenic minerals, *in* Dutcher, R.R., Hacquebard, P.A., Schopf, J.M., and Simon, J.A., eds., Carbonaceous materials as indicators of metamorphism: Geological Society of America Special Paper 153, p. 31-52.

Cordell, R.J., 1972, Depths of oil origin and primary migration: A review and critique: American Association of Petroleum Geologists Bulletin, v. 56, no. 10, p. 2029-2067.

Correia, M., 1967, Relations possibles entre l'état de conservation des éléments figurés de la matière organique (microfossiles palynoplanctologiques) et l'existence de gisements d'hydrocarbures: Institut Français du Pétrole Revue, v. 22, p. 1285-1306.

Gutjahr, C.C.M., 1966, Carbonization of pollen grains and spores and their application: Leidse Geologische Mededelingen, v. 38, p. 1-29.

Hedberg, H.D., 1964, Geologic aspects of origin of petroleum: American Association of Petroleum Geologists Bulletin, v. 48, no. 11, p. 1755-1803.

Hood, A., and Castaño, J.R., 1974, Organic metamorphism: Its relationship to petroleum generation and application to studies of authigenic minerals: United Nations ESCAP, CCOP Technical Bulletin, v. 8, p. 85-118.

Hunt, J.M., 1979, Petroleum geochemistry and geology: San Francisco, W.H. Freeman and Co., 617 p.

Landes, K.K., 1967, Eometamorphism, and oil and gas in time and space: American Association of Petroleum Geologists Bulletin, v. 51, no. 6, p. 828-841.

Magoon, L.B., and Claypool, G.E., 1980, Vitrinite reflectance and C_1-C_7 hydrocarbon data for South Barrow Nos. 14, 16, 17, and 19 wells, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-99.

Powell, T.G., Creaney, S., and Snowdon, L.R., 1982, Limitations of use of organic petrographic techniques for identification of petroleum source rocks: American Association of Petroleum Geologists Bulletin, v. 66, no. 4, p. 430-435.

Pusey, W.C., 1973, The ESR method: A new technique of estimating the organic maturity of sedimentary rocks: Petroleum Times, January 12, 1973, p. 21-24, 32.

Staplin, F.L., 1969, Sedimentary organic matter, organic metamorphism and oil and gas occurrence: Bulletin of Canadian Petroleum Geology, v. 17, p. 47-66.

Tissot, B.P., and Welte, D.H., 1978, Petroleum formation and occurrence: Berlin, Springer-Verlag, 538 p.

Waples, D.W., 1980, Time and temperature in petroleum formation: Application of Lopatin's method to petroleum exploration: American Association of Petroleum Geologists Bulletin, v. 64, no. 6, p. 916-926.

Welte, D.H., 1965, Relation between petroleum and source rock: American Association of Petroleum Geologists Bulletin, v. 49, no. 12, p. 2246-2268.

Wilson, L.R., 1961, Palynological fossil response to low-grade metamorphism in Arkoma basin: Tulsa, Okla., Tulsa Geological Society Digest, v. 29, p. 131-140.

21. GEOCHEMISTRY OF OIL OCCURRENCES, NATIONAL PETROLEUM RESERVE IN ALASKA

By LESLIE B. MAGOON and GEORGE E. CLAYPOOL

INTRODUCTION

The North Slope of Alaska is a proven petroleum province containing numerous seeps; several small undeveloped oil fields, which are for the most part in the National Petroleum Reserve in Alaska (NPRA); and the largest oil field on the North American continent, the Prudhoe Bay field, located east of the NPRA.

Except for studies of the Prudhoe Bay field, little has been published concerning the origin of North Slope oil. In 1959, McKinney and others (1959) reported on the quantity and quality of products obtainable from Alaska crude-oil occurrences using the U.S. Bureau of Mines (USBM) distillation techniques. Morgridge and Smith (1972) suggested that the source of Prudhoe Bay oil is Cretaceous marine shale. On the basis of crude-oil analyses, Jones and Speers (1976) concluded that oil from their Ivishak Sandstone (Sadlerochit Group), Kuparuk River Formation, and Upper Cretaceous sandstone has a common origin. Young and others (1977) calculated ages for Prudhoe Bay oil. They assigned an age of 87 Ma to the oil in an Upper Cretaceous reservoir unit and an age of about 220 Ma to the oil in Pennsylvanian and Triassic reservoirs. These ages imply source rocks of both Triassic and Late Cretaceous age for oil in the Prudhoe Bay field. Seifert and others (1979) compared a suite of samples of Prudhoe Bay oil from reservoirs of Mississippian through Early Cretaceous age with bitumens extracted from possible source rocks representing the same age span. Analysis of biologic marker compounds in the oil and the shale extracts led them to believe that the major sources of the principal oil accumulations were the Triassic Shublik Formation, a phosphatic-calcareous shale; the Jurassic and Cretaceous Kingak Shale; and deeply buried (3,480 m) Cretaceous shale (post-Neocomian shale). In addition, they determined that the encasing shale was the only source for the oil recovered from a sandstone within the Kingak Shale.

Recently we (Magoon and Claypool, 1981) extended the geochemical characterization of North Slope oils beyond the Prudhoe Bay field. We suggested that two types or genetic families of oil exist, a Barrow-Prudhoe type and a Simpson-Umiat type.

In this chapter, we update and expand the geochemical characterization of crude oil from the NPRA. Several oil samples from drill-stem tests and production tests are included here that were unavailable for the earlier study (Magoon and Claypool, 1981). In addition, we extracted oil from oil-stained cores.

The purpose of this study is to apply petroleum geochemical data to group the different NPRA oil occurrences into genetically related types or families. Genetically related oil types are those that are derived from the same source rock or source-rock sequence. The analytical techniques used in this study are described in appendix 21.1. The five kinds of geochemical analyses used in the present study are: (1) stable isotope abundances (C, S, N), (2) percent sulfur and nitrogen, (3) hydrocarbon molecular distributions, (4) compound-type analysis, and (5) API gravity. In general, the order of this list is from more to less dependence on specific properties of the parent organic matter in the source rock, and from lesser to greater sensitivity to the effects of such secondary processes as migration, biodegradation, or degree of maturation.

ACKNOWLEDGMENT

We thank Phil Woodward for painstakingly normalizing and photographing the chromatograms.

OIL SAMPLES

The geographic location and stratigraphic position of the oil samples analyzed in this study are summarized in figures 21.1-21.3. The samples are from 24 localities (22 wells and 2 seeps) and from 8 different stratigraphic units (fig. 21.1; table 21.1). Of the 67 oil samples analyzed, 48 were of oil recovered from wells or seeps, and 19 were extracted from core samples of reservoir rocks. Twenty-five different oil occurrences are represented in the 48 oil analyses, because many oils were analyzed in duplicate or triplicate. These duplicated results have not been averaged but are reported as separate oil analyses on

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the figures and tables. The complete list of oil samples analyzed is given in table 21.1. The rock-unit symbols and station numbers are used together on all appropriate figures to indicate the stratigraphic unit and collecting location for each oil sample. Duplicated analyses can be identified in table 21.1 by the common depth interval or API number.

The oil samples were obtained from a variety of sources and carry various amounts of source information. Samples collected during the first U.S. Navy exploration program (1945-1951) were provided by Irvin Tailleur of the USGS. Many of these samples were identified only by core test or test well, without notation of the exact sampling point, technique, depth interval, or location. We were able, however, to obtain much of this information from published reports by Collins (1958, 1961) Robinson (1958, 1959, 1964), and Robinson and Collins (1959).

In order to extend the sample coverage and to verify the origin of some of the older samples used in previous studies, oil was extracted from oil-stained cores with an

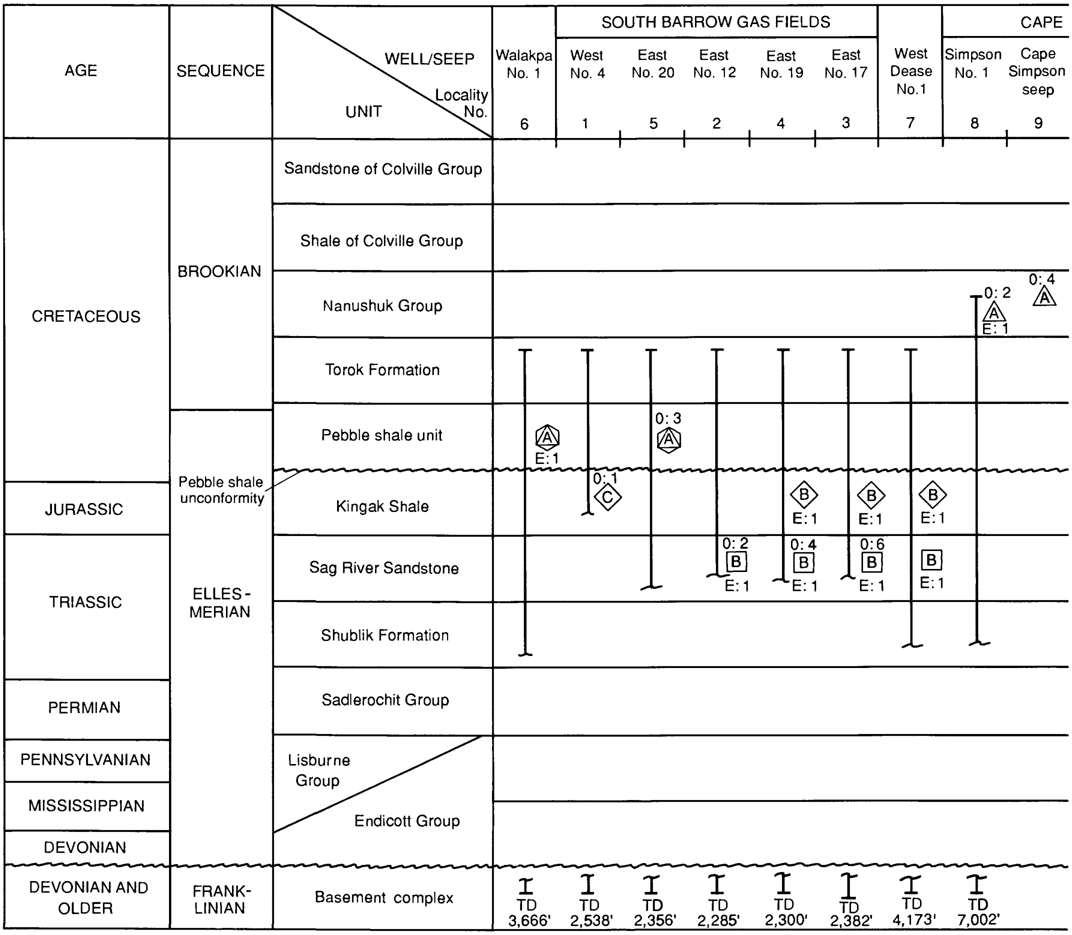


FIGURE 21.1.—Age of rock units, position of pebble shale unconformity relative to Brookian and Ellesmerian sequences, and total depth (TD, in feet) and relative stratigraphic position of drilled interval for selected NPRA wells. For each locality, rock-unit symbol indicates stratigraphic interval where oil is reservoired. Letter within rock-unit symbol indicates oil type. Above each symbol is number of free-oil

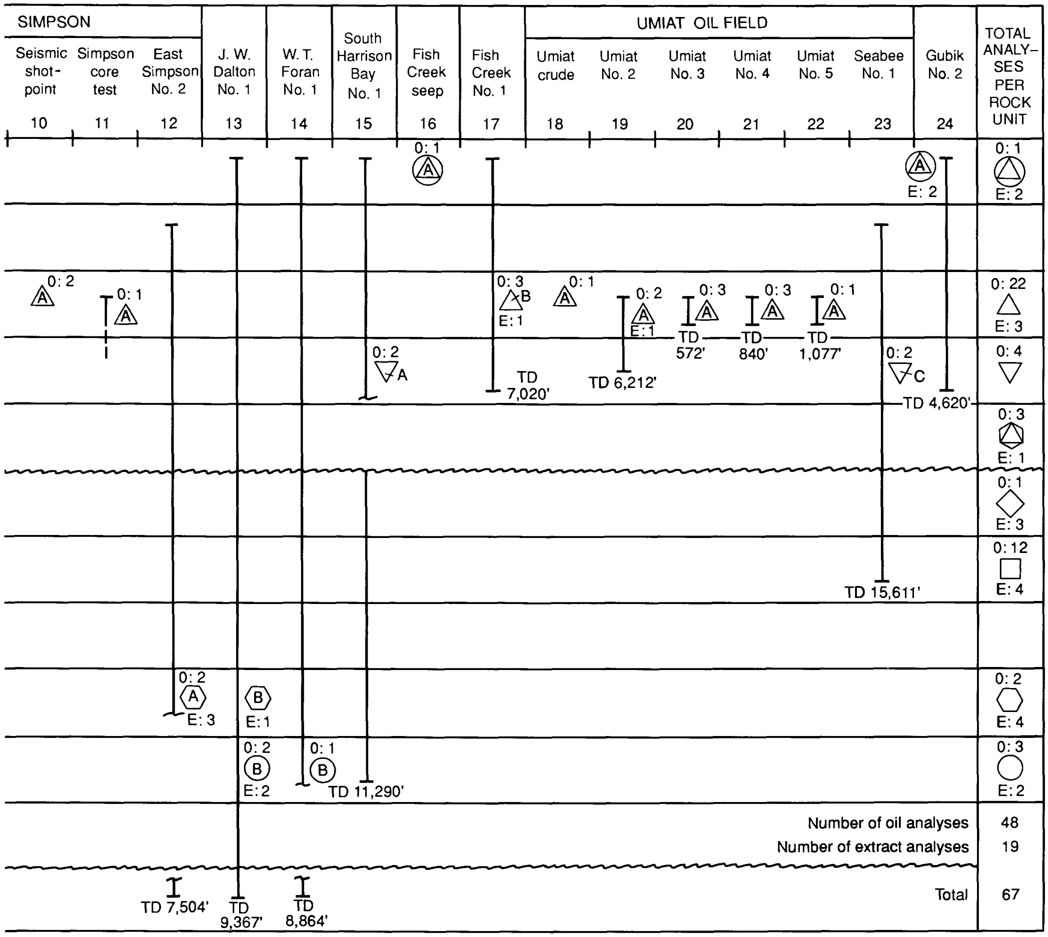
organic solvent. When sufficient extracted oil was obtained, the sample was analyzed and compared with the test oil from the same well.

Oil samples from the more recent exploration programs of the Navy (1974-1977) and the USGS (1977-1981) had sufficient information available at the time of sampling that, except as noted below, their origin is certain.

The samples are discussed below individually, arranged by area. The number in parentheses following the name of each seep or well is the station number for the sample location and corresponds to the numbers given in figures 21.1-21.3 and table 21.1. Results of analyses from our previous paper (Magoon and Claypool, 1981) are included for samples R165-001 through R165-020.

BARROW AREA

South Barrow No. 4 (1).—One condensate sample (R165-059) was obtained from this well, presumably from a well head or flow line. The well was completed in the Barrow sands at 718-735 m (2,355-2,410 ft) within the Kingak Shale. An open-hole production test from 714 to 763 m (2,343-2,502 ft) yielded more than 1.5 x 10^6 ft/d of gas (Collins, 1961).



samples (for example, O: 2) analyzed; below is number of extracted-oil samples (for example, E: 2). On far right is total number of free- and extracted-oil analyses for each stratigraphic unit. Locality numbers are keyed to table 21.1, which lists the analytical results.

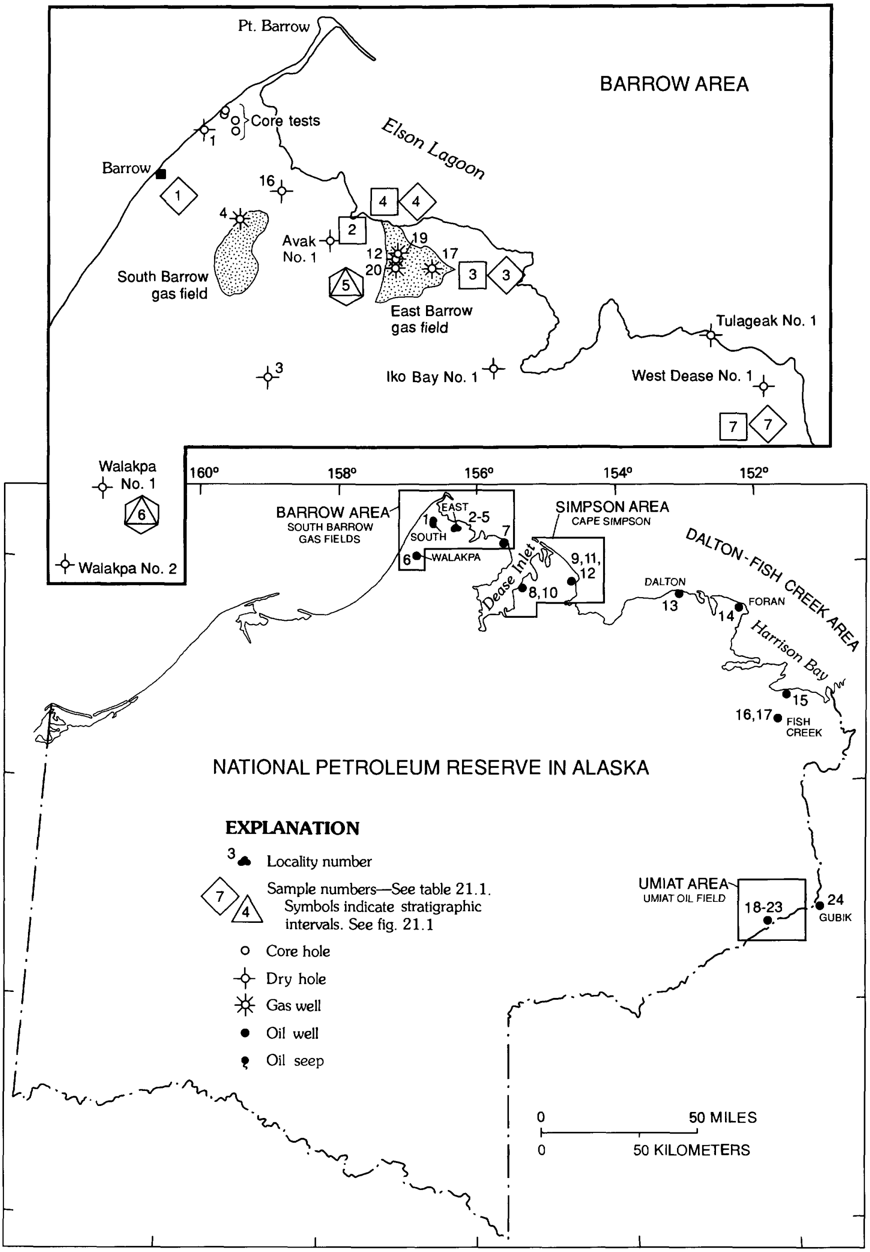
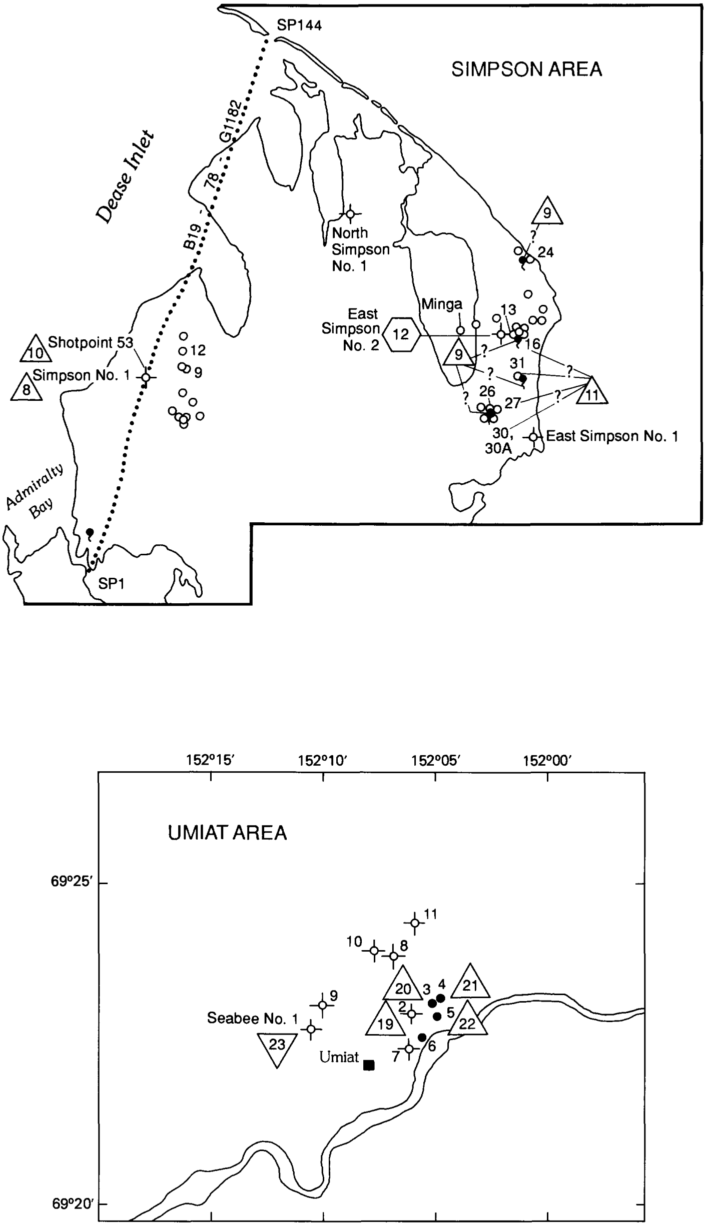


FIGURE 21.2.—Localities for oil samples from the National Petroleum Reserve in Alaska. Inset maps show details of Barrow, Simpson, and Umiat areas. Inset map of Barrow area shows the two gas pools and localities 1 through 7. Inset map of Simpson Peninsula shows sites of core tests, wells, and seeps and the seismic-reflection line with shotpoint 53 and end shotpoints (SP1 and SP144); localities 8 through 12 are on this peninsula. Information on



samples 9 and 11 is insufficient to determine from which seep or core test, respectively, the oil sample originated. Inset map of Umiat area shows localities 19 through 23; locality 18, crude from Umiat airstrip, is not shown on inset map.

The condensate sample presumably came from traps on the gas line during this test.

South Barrow No. 12 (2).—Three analyses were carried out on two different samples: one oil sample from a drill-stem test (DST) was analyzed twice, and another sample of oil was extracted from a core. The former was collected in 1974 from DST 4, which tested depths from 640 to 686 m (2,100-2,250 ft) in the Sag River Sandstone and in which oil and gas-cut muddy salt-water rose 290 m (950 ft) in the drill pipe (Bird, chapter 15). Analyses R165-007 and R165-008 are from this oil, whereas R165-023 is of oil extracted from oil-stained core no. 8 at 685 m (2,248 ft) (no stains reported in core description).

South Barrow No. 17 (3).—Eight analyses were carried out on four different sets of oil samples—two from DST's and two extracted from cores. Oil samples were collected from DST 3, which recovered 24 barrels of mud cut with gas and oil from the depth interval from 674 to 708 m (2,212-2,323 ft), and DST 4, which tested the depth interval from 674 to 715 m (2,212-2,345 ft) and recovered 24 barrels of mud cut with gas and oil (Bird, chapter 15). Samples R165-069, R165-079, and R165-080 are from DST 3; samples R165-065, R165-081, and R165-082 are from DST 4; and sample R220-172 is oil extracted from core no. 4 covering the depth interval from 708 to 715 m (2,322-2,345 ft). All three of these sets of samples are from the Sag River Sandstone. An additional oil sample (R220-168) was extracted from core 1 at depths of 639 to 648 m (2,096-2,126 ft) taken in the Barrow sandstone of local usage within the Kingak Shale (Bird, chapter 15).

South Barrow No. 19 (4).—Six analyses were carried out on three different oil samples—one collected from a DST and two extracted from cores. DST 1, which tested the

TABLE 21.1.—*Geochemical data for samples of oil and core extract from the National Petroleum Reserve in Alaska*

[Sample types: O, oil; E, extract from core. Fractions: Sat., saturated hydrocarbons; Arom., aromatic hydro-
?, questionable result; do, ditto. Biodegradation: N, normal; B, biodegraded. $\underline{R}_o$, vitrinite reflec-

Sample						API gravity (°)	Normalized fractions (percent)			
API No.	Lab. No.	Depth (ft)	Type	Unit	Age		Sat.	Arom.	NSO	Recovery
1. South Barrow No. 4										
50-023-10012	R165-059	2,343-2,502	O	Kingak Shale--------	Cretaceous and Jurassic.	40.7	65.7	12.3	21.9	72.3
2. South Barrow No. 12										
50-023-20006	R165-007	2,100-2,250	O	Sag River Sandstone-	Triassic------	24.2	52.2	36.2	11.7	65.0
50-023-20006	R165-008	2,100-2,250	O	do----------------	do----------	24.2	53.6	33.4	12.9	67.3
50-023-20006	R220-023	2,248	E	do----------------	do----------	---	49.5	32.9	17.6	94.5
3. South Barrow No. 17										
50-023-20011	R220-168	2,096-2,126	E	Kingak Shale--------	Cretaceous---- and Jurassic.	---	72.2	20.2	7.7	95.3
50-023-20011	R165-080	2,212-2,322	O	Sag River Sandstone-	Triassic------	18.3	54.3	34.2	11.5	95.7
50-023-20011	R165-069	2,212-2,322	O	do----------------	do----------	20.0	44.5	24.1	31.4	71.4
50-023-20011	R165-079	2,212-2,322	O	do----------------	do----------	18.0	54.9	28.2	16.9	66.7
50-023-20011	R165-065	2,212-2,345	O	do----------------	do----------	18.0	50.9	38.0	11.2	96.7
50-023-20011	R165-081	2,212-2,345	O	do----------------	do----------	16.0	46.9	23.7	29.4	98.3
50-023-20011	R165-082	2,212-2,345	O	do----------------	do----------	19.0	57.0	31.3	11.7	97.1
50-023-20011	R220-172	2,322-2,345	E	do----------------	do----------	---	44.5	35.1	20.4	98.2
4. South Barrow No. 19										
50-023-20012	R220-173	2,039-2,069	E	Kingak Shale--------	Cretaceous and Jurassic.	---	74.6	16.8	8.7	96.7
50-023-20012	R165-083	2,161-2,245	O	Sag River Sandstone-	Triassic------	21.1	57.4	30.3	12.3	96.9
50-023-20012	R165-084	2,161-2,245	O	do----------------	do----------	18.0	59.7	17.3	23.0	96.5
50-023-20012	R165-086	2,161-2,245	O	do----------------	do----------	18.0	60.2	24.0	15.8	95.2
50-023-20012	R165-087	2,161-2,245	O	do----------------	do----------	21.4	58.9	27.7	13.4	96.3
50-023-20012	R220-176	2,230-2,245	E	do----------------	do----------	---	55.5	33.6	10.9	97.3
5. South Barrow No. 20										
50-023-20015	R165-095	1,556-1,639	O	Pebble shale unit---	Cretaceous----	30.5	71.5	19.8	8.7	81.8
50-023-20015	R165-096	1,556-1,639	O	do----------------	do----------	32.2	71.5	20.0	8.5	88.2
50-023-20015	R165-102	1,556-1,639	O	do----------------	do----------	30.1	73.4	12.8	13.8	69.5
6. Walakpa No. 1										
50-023-20013	R220-193	2,070	E	Pebble shale unit---	Cretaceous----	---	64.2	28.2	7.6	88.2
7. West Dease No. 1										
50-023-20014	R220-197	3,720-3,725	E	Kingak Shale--------	Jurassic------	---	82.1	14.2	3.7	87.6
50-023-20014	R220-198	3,805-3,810	E	Sag River Sandstone-	Triassic------	---	61.4	30.7	7.9	73.7
8. Simpson No. 1										
50-279-10032	R165-001	115-413	O	Nanushuk Group------	Cretaceous----	20.1	65.2	25.0	9.8	80.5
50-279-10032	R165-113	115-413	O	do----------------	do----------	19.6	66.8	23.7	9.5	99.1
50-279-10032	R220-088	400	E	do----------------	do----------	---	49.0	15.4	35.6	98.3
9. Cape Simpson Seep										
50-279-95001	R165-002	Surface	O	Nanushuk Group------	Cretaceous----	20.0	51.7	23.5	24.8	99.2
50-279-95001	R165-114	Surface	O	do----------------	do----------	(20.0)	---	---	---	---
50-279-95002	R165-011	Surface	O	do----------------	do----------	18.8	54.9	25.8	19.3	78.2
50-279-95002	R165-118	Surface	O	do----------------	do----------	18.5	65.1	20.4	14.5	95.1
10. Seismic shotpoint 53										
50-279-95003	R165-035	45	O	Nanushuk Group------	Cretaceous----	23.7	81.5	14.3	4.2	99.2
50-279-95003	R165-063	45	O	do----------------	do----------	23.8	75.8	19.2	5.1	98.0
11. Simpson core test										
50-279-95004	R165-088	---	O	Nanushuk Group------	Cretaceous----	22.8	71.0	18.6	10.4	89.7
12. East Simpson No. 2										
50-279-20007	R165-092	7,165-7,197	O	Sadlerochit Group---	Permian and Triassic.	25.3	65.7	24.6	9.7	92.6
50-279-20007	R165-106	7,165-7,197	O	do----------------	do----------	(25.3)	69.1	18.7	12.2	79.3

TABLE 21.1.—*Geochemical data for samples of oil and core extract from the National Petroleum Reserve in Alaska*—Continued

carbons; NSO, nonhydrocarbons. API, American Petroleum Institute. x, analysis performed; ---, no data available; tance of reservoir rock. Figures in parentheses are estimates from comparison with nearby samples]

Sulfur		Nitrogen		$\delta^{13}C$ (permil)			Gas chromatography		Biodegradation	R_o (percent)
Content (percent)	$\delta^{34}S$ (permil)	Content (percent)	$\delta^{15}N$ (permil)	Whole oil	C_{15+}sat.	C_{15+}arom.	C_{15+}	C_7-C_{35}		
(sec. 14, T. 22N., R. 18W.)										
0.12	+8.73	0.003	+14.17	-26.03	-27.11	-26.49	x	x	N	0.5
(sec. 23, T. 22N., R. 17W.)										
1.15	+1.84	0.13	+2.71	-30.07	-29.95	-29.97	---	x	N	0.5
1.38	+2.11	.43	+1.10	-30.04	-30.03	-30.12	---	x	N	.5
1.49	+0.45	---	---	-29.84	-29.84	-29.65	x	---	N	.5
(sec. 30, T. 22N., R. 16W.)										
0.49	-3.88	---	---	-29.62	-29.40	-29.25	x	---	N	0.5
1.95	+.50	0.10	+7.05	-29.60	-29.17	-29.72	x	x	N	.5
1.30	---	---	---	-29.4	-29.4	-29.5	x	---	N	.5
1.57	+2.8	---	---	29.8	-29.6	-29.6	x	---	N	.5
---	---	---	---	-29.18	-29.10	-28.70	x	x	N	.5
1.54	---	---	---	-29.7	-29.50	-29.50	x	---	N	.5
1.90	+.50	.13	+6.85	-29.43	-29.34	-29.21	x	x	N	.5
1.36	.00	---	---	-29.47	-29.51	-29.60	x	---	N	.5
(sec. 23, T. 22N., R. 17W.)										
1.29	-30.32?	---	---	-29.72	-29.53	-29.06	x	---	N	0.5
1.72	+.73	0.05	+7.21	-29.65	-29.49	-29.48	x	x	N	.5
1.17	---	---	---	-29.7	-29.50	-29.60	---	---	---	.5
.08?	---	---	---	-29.6	-29.50	-29.50	x	x	N	.5
1.71	+.26	.07	+7.32	-29.83	-29.51	-29.37	x	x	N	.5
1.00	-11.34	---	---	-29.94	-29.80	-29.87	x	---	N	.5
(sec. 26, T. 22N., R. 17W.)										
0.11	+7.7	---	---	-29.2	-29.11	-28.81	x	---	N	0.5
.10	+5.5	---	---	-29.6	-28.93	-28.97	x	---	N	.5
.20	+9.61	---	---	-29.36	-29.49	-28.88	x	x	N	.5
(sec. 9, T. 20N., R. 19W.)										
---	---	---	---	-29.9	-28.81	-29.57	x	---	N	0.5
(sec. 21, T. 21N., R. 14W.)										
0.91	-36.18?	---	---	-29.17	?	?	---	---	---	0.6
.62	+.27	---	---	-29.55	-29.11	-29.50	---	---	---	.7
(sec. 32, T. 19N., R. 13W.)										
0.20	-8.43	0.04	+10.45	-28.71	-29.51	-28.52	x	x	B	0.5
.31	-7.07	---	---	-28.72	-28.95	-28.28	---	x	B	.5
.35	-4.58	---	---	-28.75	-29.03	-28.35	---	---	---	.5

0.08	-5.46	0.03	+3.81	-28.94	-29.31	-28.19	---	x	B	0.5
.33	-7.03	---	---	-28.80	-28.98	-28.00	---	x	B	.5
.32	-6.11	.05	+2.85	-29.09	-29.34	-28.48	---	x	B	.5
.32	-7.37	---	---	-28.94	-29.13	-28.08	---	x	B	.5
(sec. 32, T. 19N., R. 13W.)										
0.20	-5.86	0.03	+0.95	-30.07	-28.44	-27.96	---	x	B	0.5
.19	-4.89	.05	+1.83	-28.28	-28.51	-28.08	x	x	B	.5

0.22	-7.61	0.01	+2.25	-27.82	-28.44	-27.31	x	x	N	0.5
(sec. 23, T. 19N., R. 11W.)										
0.78	-5.68	0.02	+1.73	-26.87	-27.95	-26.60	x	x	N	0.7
.74	-2.63	---	---	-27.99	-27.95	-27.29	x	---	N	.7

TABLE 21.1.—*Geochemical data for samples of oil and core extract from the National Petroleum Reserve in Alaska*—Continued

Sample						API gravity (°)	Normalized fractions (percent)			
API number	Lab. number	Depth (ft)	Type	Unit	Age		Sat.	Arom.	NSO	Recovery
12. East Simpson No. 2										
50-279-20007	R220-194	7,175	E	Sadlerochit Group---	Permian and Triassic.	---	65.4	26.4	8.2	94.2
50-279-20007	R220-195	7,248	E	do----------------	do----------	---	84.0	12.8	3.2	91.5
50-279-20007	R220-196	7,260	E	do----------------	do----------	---	35.9	41.1	23.0	94.3
13. J.W. Dalton No. 1										
50-279-20006	R220-180	7,967	E	Sadlerochit Group---	Permian and Triassic.	---	53.9	33.7	12.4	99.5
50-279-20006	R220-185	8,333	E	Lisburne Group------	Permian and Carboniferous.	---	40.5	48.0	11.5	93.0
50-279-20006	R165-062	8,482-8,538	O	do----------------	do----------	12.6	31.1	53.4	15.5	99.9
50-279-20006	R220-186	8,520-8,525	E	do----------------	do----------	---	25.1	44.6	30.3	96.3
50-279-20006	R165-058	8,568-8,665	O	do----------------	do----------	6.5	30.2	54.8	15.0	72.3
14. W.T. Foran No. 1										
50-103-20010	R165-076	8,206-8,283	O	Lisburne Group------	Permian and Carboniferous.	---	48.4	35.5	16.1	88.1
15. South Harrison Bay No. 1										
50-279-20007	R165-070	7,119-7,207	O	Torok Formation-----	Cretaceous----	25.4	73.6	21.1	5.3	99.1
50-103-20007	R165-120	7,119-7,207	O	do----------------	do----------	(25.4)	71.2	20.3	8.5	97.0
16. Fish Creek Seep										
50-103-90001	R165-061	Surface	O	Sandstone of the Colville Group.	Cretaceous----	---	43.2	21.9	34.9	100.0
17. Fish Creek No. 1										
50-103-10001	R165-006	2,925-3,060	O	Nanushuk Group------	Cretaceous----	15.5	46.6	42.6	10.8	71.3
50-103-10001	R165-010	2,925-3,060	O	do----------------	do----------	13.0	41.1	34.4	24.5	51.8
50-103-10001	R165-089	2,925-3,060	O	do----------------	do----------	15.4	39.7	50.9	9.4	88.7
50-103-10001	R220-030	3,020	E	do----------------	do----------	---	35.4	33.0	32.5	100.9
18. Umiat crude										
50-287-90006	R165-012	---	O	Nanushuk Group------	Cretaceous----	34.6	67.9	19.2	13.0	47.0
19. Umiat No. 2										
50-287-10002	R165-003	103-544	O	Nanushuk Group------	Cretaceous----	19.8	60.9	25.6	13.5	81.3
50-287-10002	R165-015	103-544	O	do----------------	do----------	19.4	68.1	21.4	10.5	95.3
50-287-10002	R220-199	390-940	E	do----------------	do----------	---	65.0	22.2	12.9	97.7
20. Umiat No. 3										
50-287-10003	R165-004	72-457	O	Nanushuk Group------	Cretaceous----	31.6	74.2	17.9	7.9	58.1
50-287-10003	R165-090	72-457	O	do----------------	do----------	33.0	73.0	19.9	7.1	89.9
50-287-10003	R165-116	72-457	O	do----------------	do----------	31.0	76.9	20.3	2.8	87.0
21. Umiat No. 4										
50-287-10004	R165-005	33-840	O	Nanushuk Group------	Cretaceous----	31.2	74.2	17.7	8.1	62.0
50-287-10004	R165-091	33-840	O	do----------------	do----------	30.6	72.9	20.5	6.6	96.2
50-287-10004	R165-136	299	O	do----------------	do----------	36.5	79.7	17.1	3.2	88.8
22. Umiat No. 5										
50-287-10005	R165-064	32-1,077	O	Nanushuk Group------	Cretaceous----	33.2	77.2	18.9	4.0	88.6
23. Seabee No. 1										
50-287-20007	R165-093	5,366-5,394	O	Torok Formation-----	Cretaceous----	54.1	60.0	6.3	33.8	8.0
50-287-20007	R165-122	5,366-5,394	O	do----------------	do----------	42.0	63.3	16.3	20.4	9.8
24. Gubik No. 2										
50-287-10014	R220-139	1,855	E	Sandstone of the Colville Group.	Cretaceous----	---	63.1	25.8	11.1	97.0

TABLE 21.1.—*Geochemical data for samples of oil and core extract from the National Petroleum Reserve in Alaska*—Continued

Sulfur		Nitrogen		$\delta^{13}C$ (permil)			Gas chromatography		Biodeg-radation	$\underline{R}_o$ (percent)
Content (percent)	$\delta^{34}S$ (permil)	Content (percent)	$\delta^{15}N$ (permil)	Whole oil	C_{15+}sat.	C_{15+}arom.	C_{15+}	C_7-C_{35}		
(sec. 23, T. 19N., R. 11W.)--Continued										
---	---	---	---	-28.80	-28.62	-28.69	x	---	N	0.7
---	---	---	---	-27.90	-27.50	-27.95	x	---	N	.7
---	---	---	---	-28.00	-28.14	-27.97	x	---	N	.7
(sec. 14, T. 18N., R. 5W.)										
1.92	+3.67	---	---	-29.45	-29.56	-29.50	x	---	N	0.7
2.18	+3.60	---	---	-29.74	-29.73	-29.89	x	---	B	.7
2.50	+4.54	---	---	-29.85	-29.05	-29.42	---	x	B	.7
1.60	+4.39	---	---	-31.04	-29.92	-30.06	x	---	B	.7
2.62	+5.16	0.003	+0.91	-29.58	-29.00	-29.42	x	x	B	.7
(sec. 13, T. 17N., R. 2W.)										
1.94	-1.27	---	---	-28.40	-28.54	-28.36	x	x	B	0.7
(sec. 6, T. 12N., R. 2E.)										
0.62	-11.50	---	---	-27.48	-27.60	-27.16	x	x	B	0.5
.43	-9.56	---	---	-27.17	-27.84	-27.75	---	---	---	.5

0.31	-5.8	---	---	-28.5	-28.36	-28.19	---	x	B	0.4
(sec. 15, T. 11N., R. 1E.)										
1.71	-1.50	0.22	+4.24	-29.78	-30.15	-29.81	---	x	B	0.5
1.76	-2.04	.21	+5.34	-30.09	-29.88	-29.80	---	x	B	.5
2.00	-3.46	.05	+4.78	-29.70	-29.35	-29.36	x	x	B	.5
1.78	-4.65	---	---	-29.95	-30.03	-29.57	x	---	B	.5

0.04	-5.15	0.01	+10.81	-27.91	-28.63	-27.30	---	x	N	0.5
(sec. 3, T. 1S., R. 1W.)										
0.22	-5.44	0.05	+2.84	-28.82	-29.40	-28.28	---	x	B	0.5
.33	-7.54	---	---	-28.70	-29.03	-28.12	---	x	B	.5
.23	+.32	---	---	-28.42	-28.64	-27.49	x	---	N	.5
(sec. 3, T. 1S., 1W.)										
0.05	-1.71	0.01	+1.61	-27.88	-28.50	-27.07	---	x	N	0.5
.08	-3.50	.003	-1.54	---	---	---	x	---	N	.5
.09	-2.60	---	---	-27.82	-28.44	-26.82	---	x	N	.5
(sec. 3, T. 1S., 1W.)										
0.06	-4.62	0.03	+9.47	-27.80	-28.76	-27.08	---	x	N	0.5
.08	-2.65	.03	+5.35	-27.60	-28.00	-28.60	x	---	N	.5
.05	---	---	---	---	---	---	x	x	N	.5
(sec. 3, T. 1S., 1W.)			---							
0.06	-3.89	.005	+7.67	-26.97	-27.94	-26.89	x	x	N	0.5
(sec. 5, T. 1S., R. 1W.)										
0.05	-3.58	---	---	-25.98	-26.56	-26.96	x	x	N	0.6
.02	+.17	---	---	-25.74	-26.66	-26.59	---	x	N	.6
(sec. 20, T. 1N., R. 3E.)										
0.39	-8.81	---	---	-28.59	-28.77	-27.82	x	---	N	0.4

TABLE 21.2.—*Summary of geochemical data for oil types in the National Petroleum Reserve in Alaska*

[n.d., no data; i.d., insufficient data; bio., biodegraded samples]

Oil type	A			B	C
Subtype Locality	Pebble shale (5)	Simpson (8,9,10)	Umiat (20,21,22)	Barrow (2,3,4)	Condensates (1,23)
API gravity (API°)	30-32	18-24	30-36	18-21	40-54
Sulfur (weight percent)	.14	.22	.07	1.6	.1
$\delta^{34}S$ (permil)	+7.6	-6.3	-2.7	+1.06	-3.6 to +8.7
$\delta^{13}C$ (permil)					
Whole oil	-29.4	-29.0	-27.7	-29.7	-25.9
C_{15+} saturates	-29.2	-29.0	-28.4	-29.5	-26.8
C_{15+} aromatics	-28.9	-28.2	-27.0	-29.6	-26.8
C_7 hydrocarbons (percent)					
Normal	n.d.	i.d.	8	17	i.d.
Branched	n.d.	i.d.	30	34	i.d.
Cyclic	n.d.	i.d.	62	49	i.d.
C_{15+} fractions (percent)					
Saturates	72	64	75	53	63
Aromatics	19	21	19	30	12
Nonhydrocarbons	9	15	6	17	25
C_{15+} and C_7-C_{35} chromatograms					
CPI C_{22}-C_{24}	1.0-1.1	bio.	.93-1.0	.9-1.0	.9
Pristane/phytane ratio	1.2-1.4	bio.	2.2-2.3	1.3-1.4	7.6

depth interval 659 to 684 m (2,161-2,245 ft) in the Sag River Formation, recovered 7 gallons of gassy and very slightly oil-cut emulsified drilling fluid (Bird, chapter 15). Four analyses (R165-083, R165-084, R165-086, and R165-087) were made at different times on material from two separate containers. Additional analyses were made on oil extracted from two oil-stained cores, core 2 (R220-173) from the depth interval of 621 to 631 m (2,039-2,069 ft) in the Barrow sandstone within the Kingak Shale and core 5 (R220-176) from the depth interval of 680 to 684 m (2,230-2,245 ft) in the Sag River Sandstone.

South Barrow No. 20 (5).—An oil sample was collected during a production test that recovered 2.6 bar-

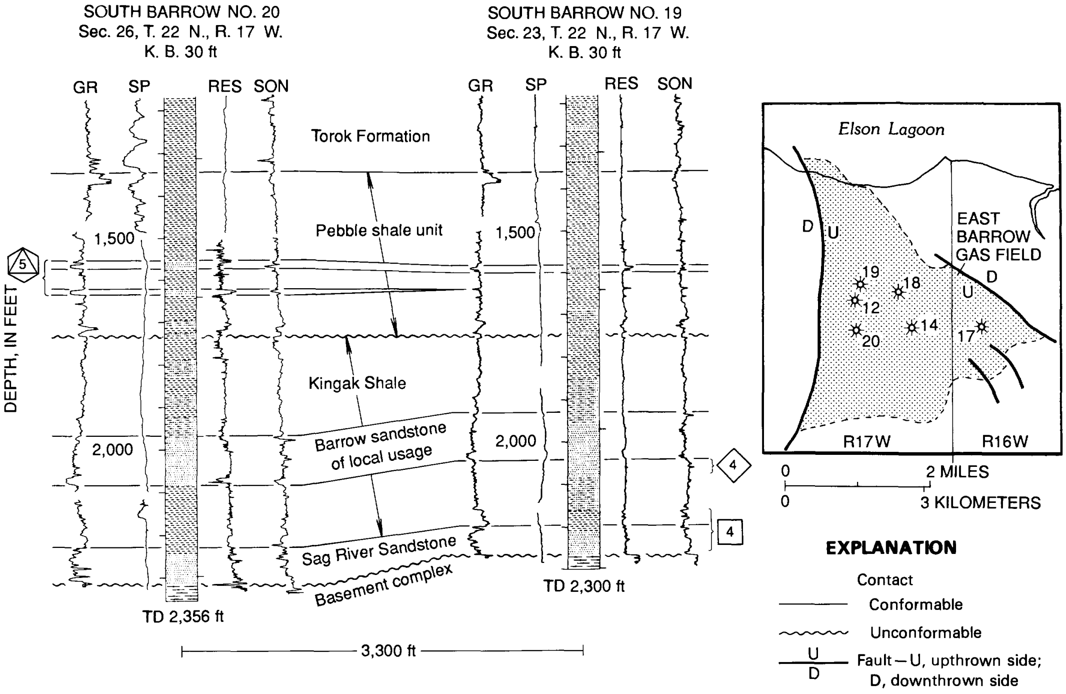


FIGURE 21.3.—Map and well sections of East Barrow gas field, showing stratigraphic location of pebble shale oil (5), Barrow oil (4), and extracted Barrow sandstone (of local usage) within the Kingak Shale. Sections from South Barrow Nos. 19 and 20 wells, with location and elevation of kelly bushing given; geophysical logs are gamma ray (GR), self-potential (SP), resistivity (RES), and interval transit time (SON). Modified from Bird (chapter 15, fig. 15.2), in which lithologic symbols are explained. TD, total depth.

rels of oil cut with water and gas. The perforated depth intervals are from 474 to 480 m (1,556-1,574 ft) and from 497 to 500 m (1,629-1,639 ft) in the pebble shale unit. This sample from the pebble shale unit was analyzed three times (R165-095, R165-096, and R165-102).

Walakpa No. 1 (6).—One analyzed oil sample (R220-193) was extracted from core 6 at 631 m (2,070 ft). within the pebble shale unit.

West Dease No. 1 (7).—Two oil samples were extracted from two different cores. Sample R220-197 was extracted from core 5 from a depth interval of 1,134 to 1,136 m (3,720-3,725 ft) within the Barrow sandstone in the Kingak Shale; sample R220-198 was extracted from core 7 from a depth interval of 1,159 to 1,161 m (3,805-3,810 ft) within the Sag River Sandstone.

SIMPSON AREA

Simpson No. 1 (8).—Two different oil samples were analyzed. The first sample (R165-001, R165-113), labeled "Simpson Test Well," was presumably from DST 2, which recovered one gallon of oil (Robinson, 1964). The second analyzed sample (R220-088) was extracted from an oil-saturated core recovered from a depth of 120 m (400 ft).

Cape Simpson seep (9).—Two different samples, labeled "Cape Simpson Oil Seep" and "Simpson Oil Seep—Collected 6/21/49," were both presumably collected during the Navy's core test program on the Simpson Peninsula during the years 1945 to 1951 (Robinson, 1964). Each of these samples was analyzed twice (R165-002, -011, -014, -118). The first two analyses were included in our previous study (Magoon and Claypool, 1981). Probably these samples were obtained from one or two of the four oil seeps on the east side of the peninsula (fig. 21.2; Robinson, 1964).

Seismic shotpoint 53 (10).—Oil flowed from a seismic shot hole drilled in 1978 to a depth of 45 ft near Simpson No. 1 well (fig. 21.2) on line B19-SP53. A sample collected for geochemical analysis a short time later was analyzed twice (R165-035 and R165-063). This oil

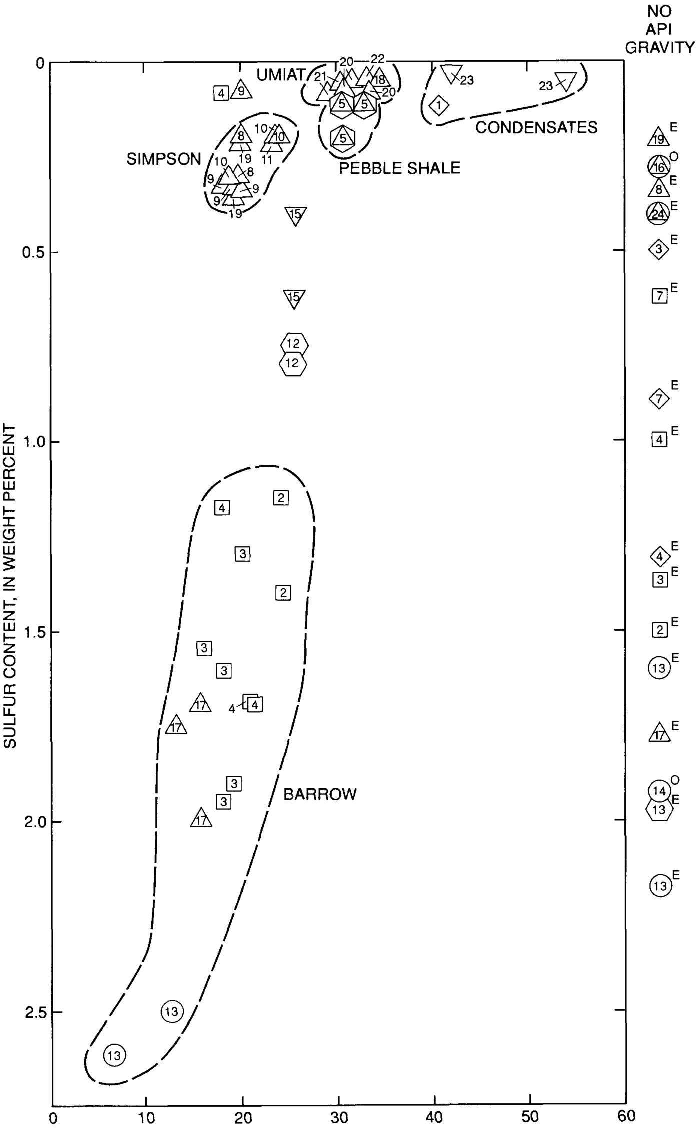


FIGURE 21.4.—Relation between sulfur content and API gravity for analyzed NPRA oil samples. Oil that was extracted or too heavy to acquire API gravity is plotted along right side of graph. Numbers are sample numbers from table 21.1; symbols surrounding numbers indicate stratigraphic interval of sample (see fig. 21.1 for explanation); E, extracted oil; O, recovered free oil.

sample is important because it is the only sample collected during the recent exploration program from the Simpson area whose depth and location could be positively verified.

Simpson core test (11).—Analysis (R165-088) is of an oil sample presumably from one of the 33 core holes drilled on the Simpson Peninsula during the years 1945 to 1951 (fig. 21.2; Robinson, 1964). Oil was recovered from Simpson core tests 16, 26, 27, 30, 30A, and 31 (Robinson, 1964). Because this sample is incompletely labeled, it could have originated from any of these core tests or it could even be a mixture of oil from the Simpson and Umiat areas (Collins, 1958).

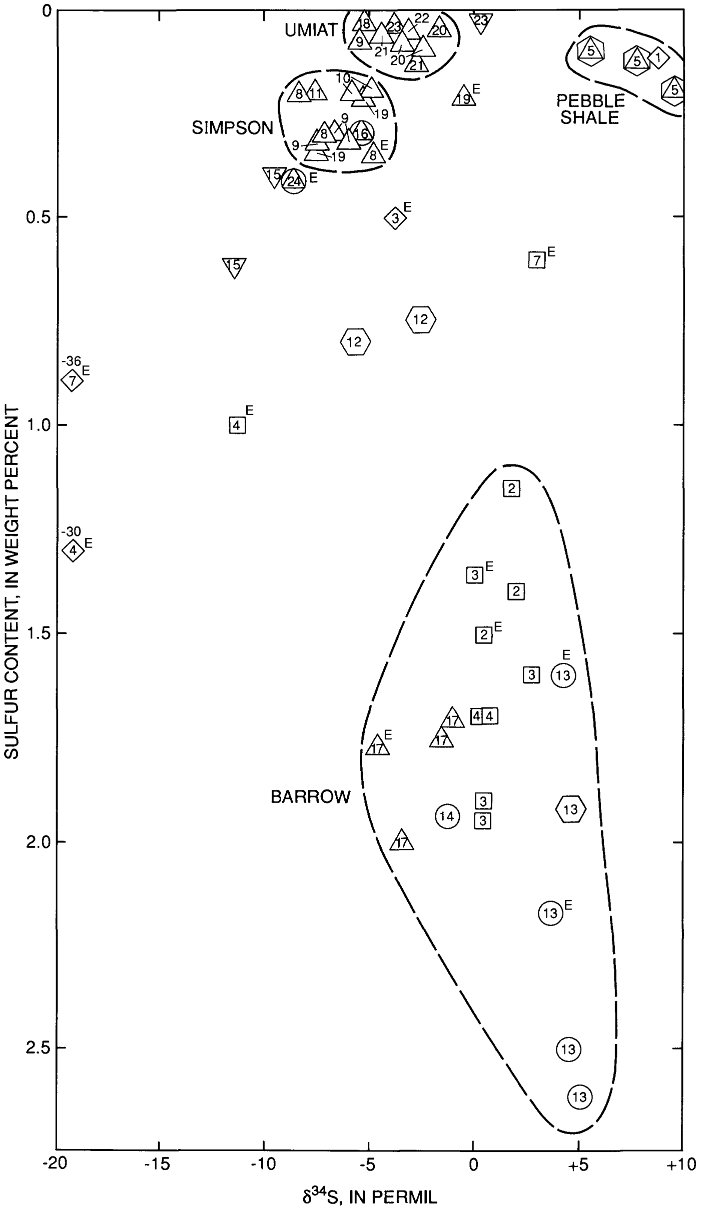


FIGURE 21.5.—Relation between sulfur content and sulfur-isotope value ($\delta^{34}S$) for NPRA whole-oil and extract samples. Oil subtypes are outlined. Same symbols as in figure 21.4.

East Simpson No. 2 (12).—Five analyses were obtained: two of oil from a drill-stem test and three of oil extracted from cores. R165-092 and R165-106 are duplicate analyses of oil recovered from DST 1 across the depth interval 2,184 to 2,194 m (7,165-7,197 ft) in the Sadlerochit Group. This test recovered gas, in amounts too small to measure, and saltwater with a trace of oil at a rate of 960 barrels per day, declining later to 576 barrels per day. The trace of oil recovered from DST 1 was believed to be contamination either from the rig site or from one of the Cape Simpson seeps. Therefore, three oil samples were extracted from oil-stained cores of the Sadlerochit group: R220-194 (2,187 m; 7,175 ft) is from core 5 (2,185-2,194 m; 7,167-7,197 ft), R220-195 (2,209 m; 7,248 ft) and R220-196 (2,213 m; 7,260 ft) are from core 7 (2,209 m; 7,248-7,278 ft).

DALTON-FISH CREEK AREA

J.W. Dalton No. 1 (13).—Five oil samples were analyzed: two from drill-stem tests and three extracted from cores. One sample (R165-058) is from DST 2 (2,612-2,641 m; 8,568-8,665 ft), which recovered small amounts of gas, 5 barrels of heavy oil, 3.3 barrels of water cushion, 29 barrels of mud filtrate, and 80 barrels of saltwater from the lower part of the Lisburne Group and the upper part of the Endicott Group (Bird, chapter 15). A second sample (R165-062) is from DST 3 (2,585-2,602 m; 8,482-8,538 ft) which recovered 5 barrels of heavy oil, 6.8 barrels of watery mud, and 22 barrels of oily water from the Lisburne Group. The three samples extracted from cores are R220-180

(2,428 m; 7,967 ft) from core 6 (2,428-2,445 m; 7,967-8,021 ft) taken in the Sadlerochit Group, R220-185 (2,540 m; 8,333 ft) from core 11 (2,535-2,544 m; 8,317-8,345 ft) taken in the Lisburne Group, and R220-186 (2,597-2,599 m; 8,520-8,525 ft) from core 12 (2,595-2,604; 8,515-8,544 ft) also taken in the Lisburne Group (Bird, chapter 15).

W.T. Foran No. 1 (14).—One oil sample (R165-076) was analyzed from DST 3 (2,501-2,525 m; 8,206-8,283 ft) in the Lisburne Group, which recovered 1,010 m (3,313 ft) of water, 623 m (2,044 ft) of mud, and 191 m (628 ft) of formation water, as measured by the rise of fluids in the drill pipe. However, the sample chamber recovered 61,400 cm^3 (2.17 ft^3) of mud, 76 cm^3 of oil, and 1,691 cm^3 of water.

South Harrison Bay No. 1 (15).—One oil sample, which was analyzed twice (R165-070, R165-120) is believed to be from DST 1 (2,170-2,197 m (7,119-7,207 ft) at the base of the Torok Formation, which recovered water in amounts too small to measure.

Fish Creek seep (16).—One sample (R165-061) of oil-soaked tundra was collected by an unknown field party in 1949. The surface seep is reported by Ebbley (1944, p. 418): "About 25 miles southwest of the mouth of the Colville River, this area is 4 miles N. 60° W. of the confluence of Ovolotuk Creek and Fish River."

Fish Creek No. 1 (17).—Four analyses were made: Oil recovered from DST 1 within the Nanushuk Group from 892 to 933 m (2,925-3,060 ft) was analyzed three times (R165-006, -010, -089), and one oil sample was extracted from a core (R220-030) to confirm the origin of the DST oil sample. The DST oil was in two old samples labeled "Fish Creek Test Well #1" and "Fish Creek Test Well', which are without depth intervals but are presumed to be separate samples of DST 1.

UMIAT AREA

Umiat Crude (18).—The Umiat crude oil sample (R165-012) was collected from a storage tank on the Umiat air strip in 1975.

Umiat No. 2 (19).—The oil sample from the Umiat No. 2 well is labeled "Umiat #2-Simpson Seeps by W. W. Gifford." Presumably, this oil sample was obtained from DST 4 (31-166 m; 103-544 ft), which recovered at least one pint of oil per trip (Collins, 1958). The other four tests of this well produced, at best, a skim of oil. No oil was used in the mud to drill this well, but it was not

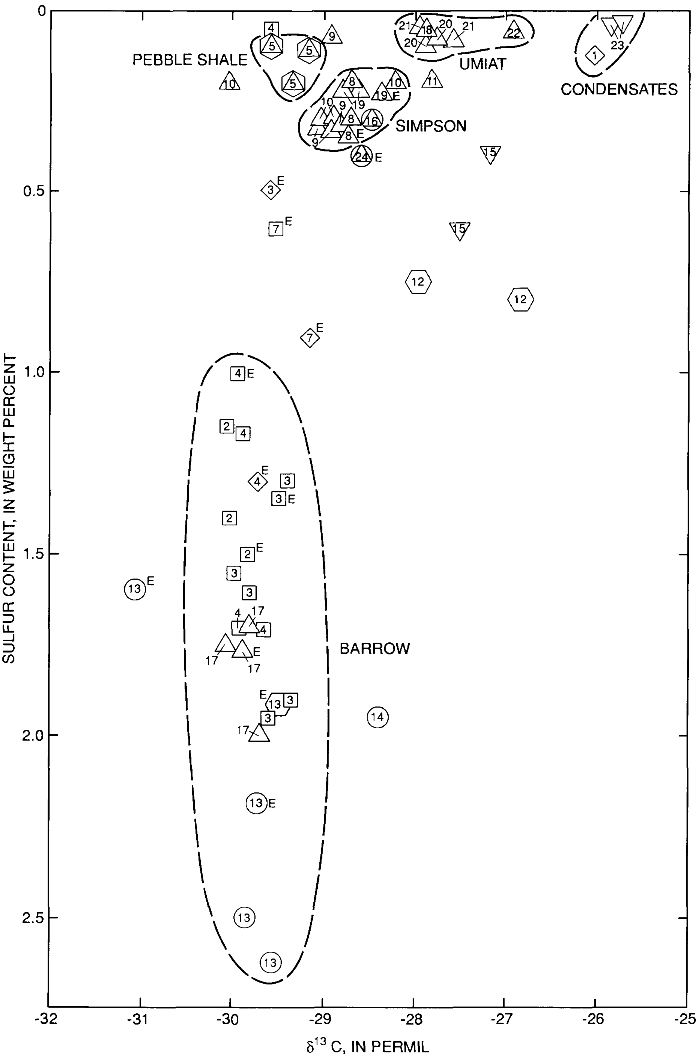


FIGURE 21.6.—Relation between sulfur content and carbon-isotope value ($\delta^{13}C$) for NPRA whole-oil and extract samples. Oil subtypes are outlined. Same symbols as in figure 21.4.

uncommon to use Simpson oil as a mud additive in drilling other Umiat wells (Collins, 1958). Oil was extracted from the Umiat No. 2 core from a depth of 119 to 287 m (390-940 ft). and analyzed (R220-199).

Umiat No. 3 (20).—One oil sample from the Umiat No. 3 well was analyzed three times (R165-004, R165-090, R165-116). The origin of this oil sample is uncertain. The container is labeled "Umiat Core Test 1," subsequently renamed Umiat No. 3 (Collins, 1958), so we are unable to determine if the oil came from one of the two bailing tests or was collected when the well was pumped (Collins, 1958). No oil was used in the drilling mud, and the API gravity and sulfur content are similar to those reported by the Bureau of Mines (Collins, 1958); the oil is therefore probably from the Umiat area.

Umiat No. 4 (21).—Three oil analyses are available for the Umiat No. 4 well. One old oil sample was analyzed twice (R165-091), and some oil was bailed from the well (R165-136) in 1982 by the first author from a depth of 91 m (299 ft). The old oil sample was labeled "Umiat-Ruby #1"; subsequently the well was renamed Umiat No. 4 (Collins, 1958). No depth interval was indicated on the sample. Because a brine was used in the drilling mud, Simpson oil is not suspected as a mud additive. The well was tested at a depth interval of 10 to 256 m (33 through 840 ft) six times and produced substantial volumes of oil on many of the tests (Collins, 1958). The high API gravity and low sulfur content are similar to the values reported by the Bureau of Mines (Collins, 1958) for this same oil.

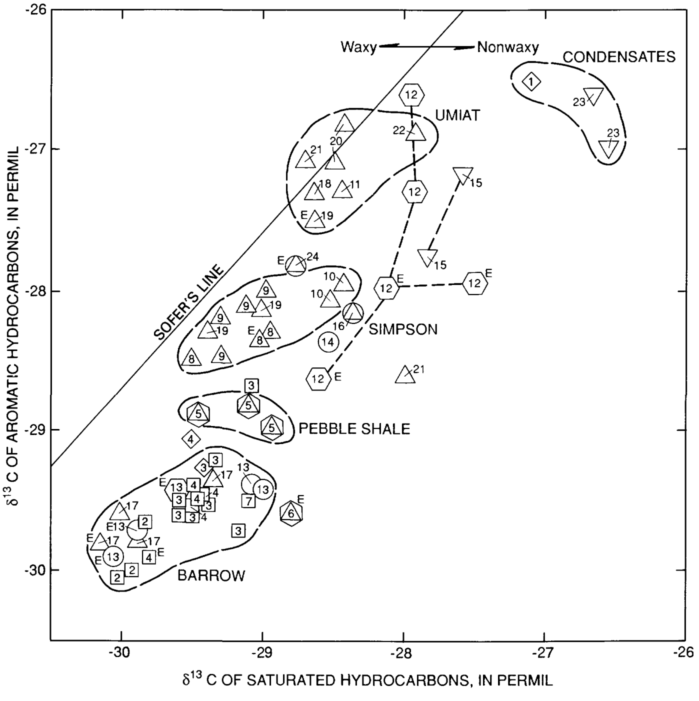


FIGURE 21.7.—Relation between carbon-isotope values ($\delta^{13}C$) for saturated and aromatic hydrocarbons in analyzed NPRA oil samples. Long-dashed lines enclose oil subtypes; short-dashed lines connect multiple analyses of same sample. Same symbols as in figure 21.4.

Umiat No. 5 (22).—One oil sample (R165-064) was analyzed from the Umiat No. 5 well, which produced 400 barrels of oil per day (Collins, 1958). Brine mud, not oil-based mud, was used to drill this well, which offset the nonproductive Umiat No. 2 well (Collins, 1958).

Seabee No. 1 (23).—One condensate sample from the Seabee No. 1 well was analyzed twice (R165-093, R165-122). This sample was collected during DST 3, which recovered gas at 4.0-6.7 × 10^6 ft^3 per day at various choke sizes, but rates and pressures were declining (Bird, chapter 15). The condensate was collected from a container along the flow line.

Gubik No. 2 (24).—Two oil samples (R220-139, R220-197) from the Gubik No. 2 well were extracted from oil-stained core 49 (563-569 m; 1,848-1,868 ft) at a depth of 565 m (1,855 ft) and from core 97 (1,148-1,151 m (3,768-3,777 ft) in sandstone of the Colville Group.

ANALYTICAL RESULTS

The analytical results are discussed from two points of view. First, the oil-extract data are compared in order to establish which oil samples are representative of a particular station number and rock unit. Secondly, analytical criteria are described and used to determine the major oil types.

OIL-EXTRACT COMPARISON

In our earlier study (Magoon and Claypool, 1981), the oil samples used were only from the first Navy exploration program and were of varying quality. For this subsequent study, additional oil samples have been acquired and analyzed in the same manner as before. In addition, eight of the oil samples included here were used for our study of Alaska North Slope oil-rock correlation (Magoon and Claypool, 1985). The relative confidence we have in the quality of each of these sets of oil samples is important to the interpretation of the analytical results from this study.

BARROW AREA

Three stratigraphic horizons yielded oil samples in the Barrow area— pebble shale unit (localities 5, 6), Kingak Shale (1, 3, 4, 7), and Sag River Sandstone (2, 3, 4, 7). In

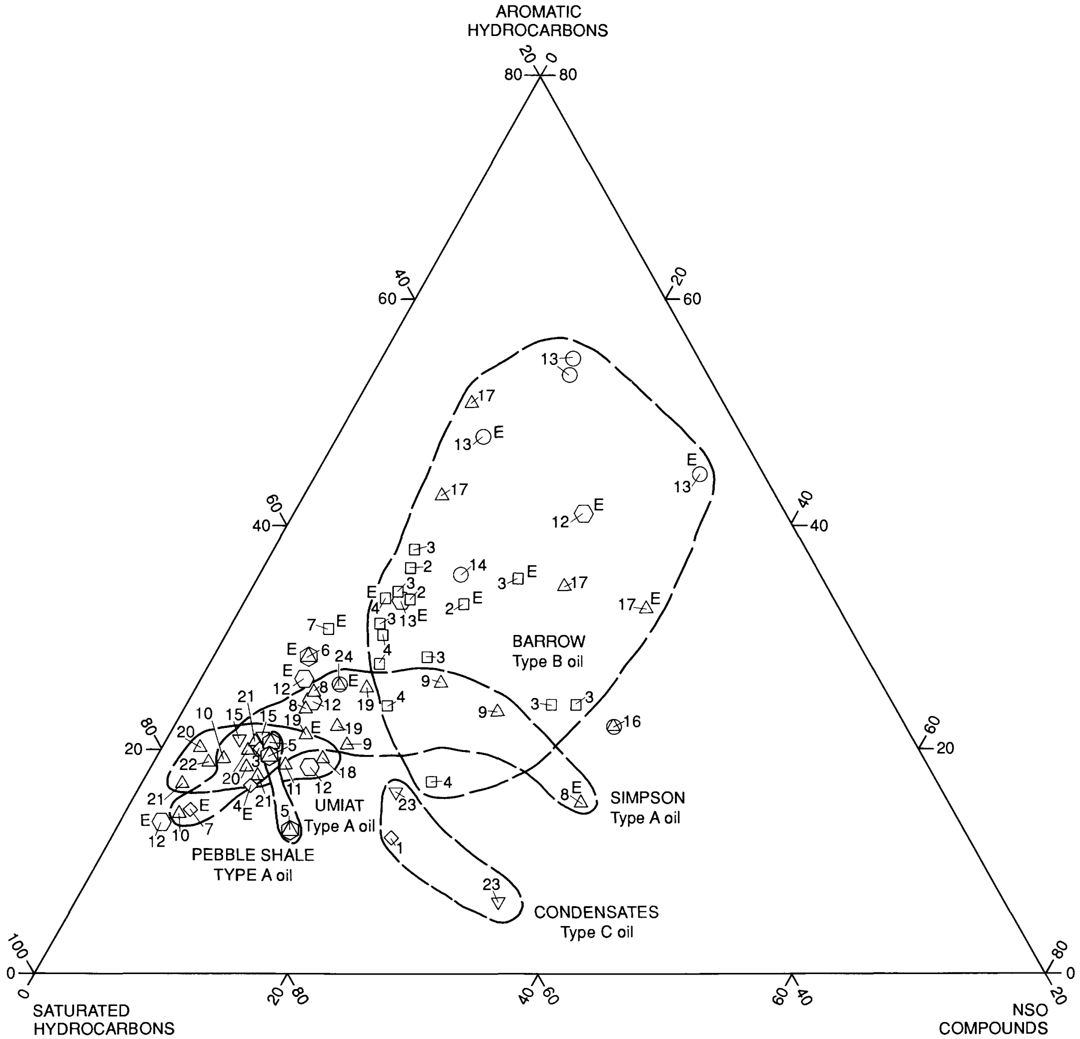


Figure 21.8.—Triangular plot of proportions of C_{15+} saturated hydrocarbons, aromatic hydrocarbons, and nonhydrocarbon compounds in NPRA oil samples, showing overlap between various oil subtypes (outlined). Same symbols as in figure 21.4.

TABLE 21.3.—*Content of gasoline-range (C_4-C_8) hydrocarbons in oil from the National Petroleum Reserve in Alaska*

[All values in volume percent]

Locality number	Lab. number	C_4		C_5			C_6	C_5	C_6							C_7		C_6
		i-C_4 (1)	n-C_4 (2)	neo-C_5 (3)	i-C_5 (4)	n-C_5 (5)	2,2-DMB (6)	CP (7)	2,3-DMB (8)	2-MP (9)	3-MP (10)	n-C_6 (11)	MCP (12)	2,2-DMD (13)	BZ (14)	2,4-DP (15)	2,2,3-TMP (16)	CH (17)
1	R220-059	0	0.1	0	0	0.1	0	0	0.1	0.1	0.2	0.3	0.6	0.7	0.9	0	0.5	7.3
2	R220-007	5.0	13.4	0	17.6	11.4	1.1	1.4	2.1	5.9	3.9	5.9	4.4	.5	0	1.0	.6	4.2
	R220-008	5.0	15.2	0	22.3	13.9	1.1	1.3	2.2	6.4	3.9	6.4	4.2	.2	0	.6	.1	3.9
3	R220-065	.1	.1	0	91.2	2.4	.4	.1	.2	.7	.2	.4	.1	.1	.2	0	0	0.3
	R220-069	3.9	5.7	0	10.4	9.6	1.1	1.1	1.7	6.6	4.9	8.7	5.5	.5	.3	.7	.2	7.7
	R220-079	.6	.1	0	6.6	5.4	1.8	.2	2.5	8.9	6.5	11.2	4.4	1.0	0	1.4	.2	5.3
	R220-080	7.9	2.3	0	14.4	11.8	1.3	1.8	1.7	6.7	4.8	7.8	5.7	.4	.7	.6	.2	8.7
	R220-081	.3	2.5	0	5.3	5.4	1.9	.1	2.1	8.8	7.0	13.5	7.0	.8	0	1.1	.3	5.
	R220-082	2.2	5.2	0	6.4	5.8	.8	1.3	1.3	5.1	4.0	7.1	5.6	.6	.7	.9	.3	10.3
4	R220-083	.2	1.2	0	3.5	4.7	.6	.8	1.0	5.0	3.4	8.7	5.1	.5	.8	.8	.2	9.1
	R220-084	.1	1.2	0	3.4	3.7	.9	.1	1.4	7.6	7.0	17.2	10.7	.8	0	1.0	.2	4.2
	R220-086	.7	.2	0	7.1	8.2	1.0	.5	1.5	7.4	5.1	11.2	6.4	.6	.4	.8	.2	7.8
	R220-087	1.0	5.4	0	8.2	9.4	1.0	.5	1.5	7.1	4.6	10.3	5.2	.6	.6	.9	.3	8.0
5	R220-095	.2	.1	0	2.8	9.9	.6	.1	.8	2.2	2.3	56.6	2.0	.3	.5	0	.1	4.9
	R220-096	0	.4	0	55.1	0	.2	0	.4	.8	.9	18.1	.8	.2	.4	0	.1	3.8
	R220-102	0	5.3	0	5.0	1.3	0	1.7	.5	.5	.5	7.8	1.6	0	1.2	0	0	4.6
8	R220-001	1.5	6.6	0	6.7	9.7	.5	2.0	.9	6.6	4.2	7.3	7.9	.5	1.1	1.1	.2	3.5
	R220-113	1.5	15.0	0	4.2	8.1	9.2	.7	2.8	5.8	7.3	9.5	16.6	.4	.4	.2	.6	8.3
9	R220-002	1.5	7.0	0	6.7	11.1	.3	1.7	.7	5.4	3.9	7.9	8.9	.4	.7	.7	.6	3.7
	R220-114	0	1.6	0	1.0	76.5	0	1.6	.1	.2	.3	.4	0	0	.2	0	0	0
	R220-011	.4	4.5	0	13.7	13.7	.6	2.9	2.9	8.8	5.4	10.2	8.0	.2	1.0	1.2	.2	4.7
	R220-118	.8	3.0	0	25.6	24.4	.2	1.2	1.2	4.0	2.8	12.8	4.7	.1	.4	.6	.1	3.4
10	R220-035	.4	.9	.7	3.2	3.3	1.1	1.0	1.4	4.1	3.8	5.6	6.2	.6	1.5	0	.9	8.1
	R220-063	1.4	1.9	0	8.1	2.6	4.1	.6	3.3	5.4	6.6	1.2	4.9	1.1	2.1	0	1.6	6.7
11	R220-088	6.4	12.2	0	3.9	3.4	.8	1.0	8.8	4.0	3.1	3.3	2.4	.2	.9	0	3.0	4.9
12	R220-092	(values not determined)																
	R220-106	0	17.8	0	18.3	19.8	.3	.7	2.3	3.9	6.8	8.5	.3	.2	.2	.1	2.6	.1
13	R220-058	3.5	11.3	0	13.5	12.2	.7	1.7	2.2	7.9	6.9	7.9	3.2	.4	4.2	0	0	5.7
	R220-062	.2	.4	0	67.8	0	0	.5	.9	5.1	.5	.6	1.9	0	1.3	0	.1	3.2
14	R220-076	1.0	2.6	0	4.2	12.9	.3	.2	1.7	.8	1.4	.9	1.8	0.7	1.0	0	.9	61.3
15	R220-070	4.5	6.6	0	15.4	33.0	0	.4	.4	2.8	1.8	3.1	2.6	0	3.1	0	0	14.7
	R220-120	(values not determined)																
16	R220-061	.6	14.6	0	.2	.3	0	.5	1.2	5.7	10.4	28.1	28.1	.4	0	.2	.1	2.8
17	R220-006	2.6	9.4	0	9.8	4.3	4.3	.9	4.8	3.3	2.7	2.9	3.4	0.9	0	1.2	1.6	1.6
	R220-010	1.9	8.6	0	21.6	13.6	1.4	1.2	2.3	5.5	3.4	5.2	4.8	.4	.3	.8	.7	2.6
	R220-089	3.0	4.8	0	9.1	3.7	6.6	.8	10.0	4.8	4.1	2.9	2.0	1.1	2.3	0	2.9	1.4
18	R220-012	0	.1	0	3.8	5.2	2.3	2.7	3.8	7.9	5.4	8.6	8.8	1.3	1.9	0	.5	19.9
19	R220-003	.7	4.1	0	5.0	14.9	3.3	6.5	.6	4.7	3.1	6.0	7.5	.4	.5	.7	.4	4.0
	R220-115	3.3	63.0	0	.3	.3	.1	.1	.8	2.8	4.6	8.5	9.8	.2	0	.2	0	2.4
20	R220-004	.3	1.5	0	1.4	2.4	.2	.5	.3	1.2	1.1	1.8	2.1	.1	.3	.3	.1	1.8
	R220-090	1.8	1.0	0	.4	0	.2	1.5	.7	2.3	0	13.1	7.0	.8	1.5	.7	.8	8.2
	R220-116	0	33.8	0	.1	.1	.1	0	.5	2.0	3.4	6.1	8.5	.2	.1	.1	.1	1.8
21	R220-005	.9	.1	0	4.9	.5	7.1	.8	5.8	3.7	3.5	.8	4.7	2.4	0	2.2	1.2	21.1
	R220-091	1.0	.7	0	4.5	.2	5.5	.6	4.2	3.1	3.0	1.0	.1	3.5	2.1	2.3	.9	23.3
	R220-136	2.8	4.9	0	6.1	4.9	1.4	2.4	1.8	4.0	3.2	5.7	6.4	.6	2.9	.3	1.0	16.4
22	R220-064	.3	.2	0	1.5	1.3	1.2	1.1	1.8	2.6	2.1	3.5	5.0	1.1	1.5	2.1	1.0	18.4
23	R220-093	(values not determined)																
	R220-122	0	.1	0	2.6	0	.1	.2	.2	2.5	2.4	.8	7.1	.3	2.2	1.1	.5	14.9

TABLE 21.3.—*Content of gasoline-range (C_4-C_8) hydrocarbons in oil from the National Petroleum Reserve in Alaska*—Continued

C_7													C_8		C_7	
3,3-DMP (18)	11-DMCP (19)	2-MH (20)	2,3-DMP (21)	1-*cis*-3-DMCP (22)	3-MH (23)	1-*trans*-3-DMCP (24)	1-*trans*-2-DMCP (25)	3-EP (26)	2,2,4-TMP (27)	*n*-C_7 (28)	1-*cis*-2-DMCP (29)	MCH (30)	1,1,3-TMCP (31)	2,2-DMH (32)	ECP (33)	T (34)
1.3	2.7	10.4	0	1.3	10.6	0	7.3	2.6	0.7	4.3	1.6	26.0	6.7	0	4.6	8.8
.5	1.0	1.6	1.0	.9	1.6	.7	1.3	.5	1.7	2.1	.7	5.1	.8	.2	.8	1.0
.1	.3	1.4	.6	.6	1.5	.6	.9	.1	1.2	1.4	.1	4.0	.1	0	.2	.2
.1	0	.1	.1	0	.1	.3	.2	.1	.1	.5	.1	1.1	.2	.1	.1	.3
.3	.7	3.8	.6	1.0	3.9	1.6	1.1	.2	.1	5.2	.2	11.3	.4	.1	.4	.7
.5	.9	4.8	2.4	1.3	6.9	1.3	1.4	.4	.1	8.0	.2	13.8	.7	.3	.4	.1
.3	.6	2.8	0	.7	2.3	.7	1.4	.2	0	3.1	.2	8.6	.3	0	.4	1.6
.5	.9	3.8	2.8	1.3	7.0	1.0	1.5	.4	.1	7.2	.3	10.7	.6	.2	.5	.2
.5	.9	5.4	0	1.3	5.7	0	2.5	.4	.1	6.4	.3	15.9	.6	0	.8	2.0
.4	.8	5.6	0	1.3	6.0	0	2.4	.4	.1	10.1	.3	20.3	.7	0	1.1	4.9
.4	.7	4.6	2.0	1.0	5.6	1.6	1.2	.4	.1	8.8	.4	12.2	.6	.3	.4	.2
.4	.8	3.6	1.9	1.1	4.6	1.9	1.3	.3	.1	7.9	.2	14.2	.5	.2	.5	1.2
.4	.7	4.7	0	1.0	4.8	0	1.7	.4	.1	6.8	.2	11.8	.5	0	.6	2.0
.3	.5	.5	1.1	.4	1.6	0	1.5	.4	0	1.3	1.4	5.3	.5	2.2	.4	1.3
.4	.5	.5	.9	.4	1.5	0	1.5	.3	0	2.9	.2	6.5	.5	.1	.4	2.2
0	0	3.3	0	.4	4.0	0	.4	0	0	45.0	0	13.1	0	0	0	3.7
.7	1.1	2.1	1.6	2.8	3.5	2.4	5.5	1.1	.7	5.0	1.8	5.0	1.1	1.6	2.6	1.2
.2	.6	.9	.3	1.1	2.4	.1	.4	.6	.2	1.7	.6	.2	0	0	0	.2
.5	.8	1.9	1.3	3.1	3.3	2.8	6.4	1.1	0	5.3	1.8	5.4	1.2	.2	2.2	1.4
0	0	0	0	0	0	0	.1	.1	0	.1	.1	.2	.1	0	0	17.4
.1	.6	1.9	1.0	1.3	2.0	1.2	2.2	.2	2.1	3.3	.2	4.1	.4	0	.2	.6
.1	.4	1.1	.6	.8	1.2	.7	1.4	1.3	2.2	.1	.2	3.8	.2	0	.2	.5
.6	1.7	3.0	2.4	2.6	4.5	2.4	4.9	1.2	.3	6.4	1.1	18.1	2.2	.4	1.8	3.4
.7	1.8	1.2	2.9	2.5	3.4	2.4	4.4	.9	0	1.1	1.1	17.4	2.5	.9	1.6	3.3
.5	.7	2.1	0	.8	2.9	0	2.0	.5	0	3.3	.4	17.9	1.0	0	1.2	8.4
.2	0	.2	.1	.1	.2	.1	.3	.1	.2	.4	.9	2.9	0	0	0	12.4
.4	.4	3.5	0	.4	3.5	0	1.5	.6	.1	2.9	.2	4.1	.3	0	.4	.3
0	.4	1.0	0	.3	1.1	0	1.1	.6	.2	1.8	.5	7.0	.8	0	1.4	1.3
.8	0	0	0	0	0	0	0	0	0	.4	0	.6	0	0	0	6.4
0	.3	1.1	0	.5	1.5	0	1.1	0	0	1.2	0	2.9	0	0	0	2.8
.1	.1	.2	.1	.1	.2	.1	.2	.1	.1	.6	.1	1.1	.2	.1	.1	1.2
1.3	2.5	1.1	1.6	2.0	1.8	1.6	3.3	1.9	1.0	3.1	1.8	5.3	3.0	.7	2.1	2.2
.4	1.3	1.3	1.1	1.9	2.2	1.7	3.4	.7	1.0	3.4	.4	5.2	1.0	0	.5	.2
1.3	7.3	4.5	0	2.6	2.5	2.5	2.8	1.1	.9	1.1	.4	4.2	5.6	0	.8	2.4
.6	1.5	2.7	1.2	1.3	3.3	1.1	2.6	.3	0	1.6	.2	10.4	.4	0	.3	.2
.4	1.1	1.7	1.3	2.9	2.9	2.6	5.8	1.2	0	4.8	2.1	5.3	1.4	.3	2.6	1.6
0	.1	.1	.3	0	0	0	.1	.2	0	.4	.1	1.1	.1	.2	0	.9
.1	.6	1.1	.7	1.2	2.2	1.2	2.9	.9	.3	8.1	.9	47.6	4.1	1.7	2.5	8.3
.8	1.1	3.9	0	.8	3.2	.6	1.4	.4	0	7.1	.4	22.3	1.0	2.2	1.8	12.7
0	.2	.4	.2	.2	.6	.2	.5	.1	.2	2.7	.3	18.8	1.5	.7	.9	15.6
1.4	3.4	1.7	2.3	1.1	3.0	1.0	3.8	.4	.1	.9	.5	17.0	2.1	.8	.4	.6
1.3	3.3	4.0	1.2	0	2.4	1.4	4.1	.4	.1	.9	.5	21.7	1.7	.8	0	.3
.7	1.3	2.2	1.0	1.1	3.5	.3	0	2.3	0	3.4	.3	12.2	1.2	.2	.6	4.7
1.2	2.4	2.5	2.1	1.6	3.8	1.5	3.8	1.3	.4	4.7	1.0	17.8	2.2	.8	1.1	6.9
.8	1.1	7.5	0	1.3	3.9	2.9	2.2	.7	0	10.8	.4	24.1	.6	.9	.4	7.2

all cases, the analytical results for the extracted oil compare favorably with those for the DST oil samples.

SIMPSON AREA

In the Simpson area, different groups of oil samples collected by four different methods—DST, seep, shothole, and core test. Because our confidence is highest in the seismic shotpoint 53 sample (10), we compare all other samples in the Simpson area to it. The extracted oil (R220-088) from the Simpson No. 1 well (8), compares favorably, especially in the carbon isotope data, with the Simpson No. 1 oil (R165-001, R165-113) and the shotpoint oil (10). Cape Simpson seep (9) oil also compares favorably with the shotpoint oil (10). However, the Simp-

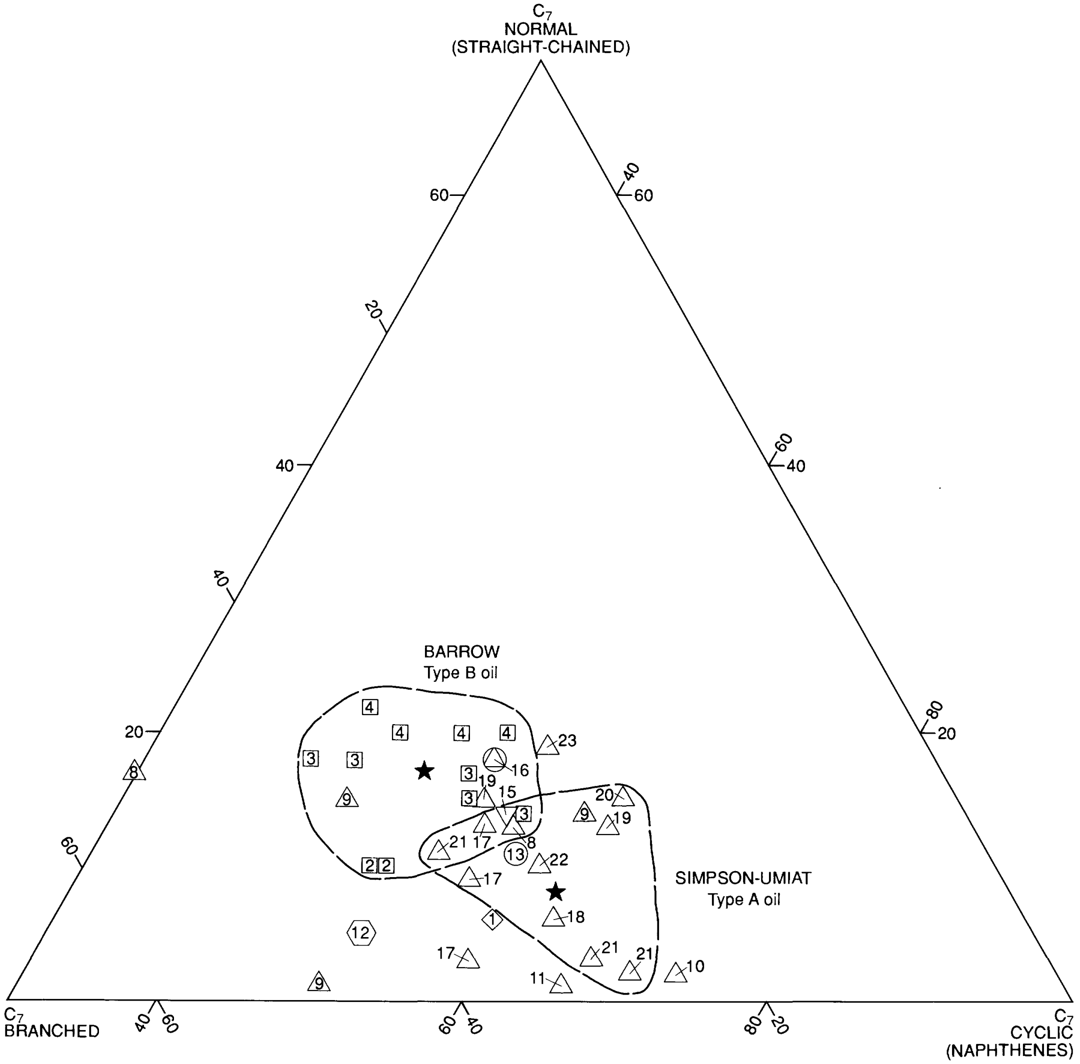


FIGURE 21.9.—Triangular plot of proportions of C_7 hydrocarbon types (normal, branched, and cyclic) in NPRA oil samples, showing slight difference between Barrow (B) and Simpson-Umiat (A) oil types (enclosed by long-dashed lines). Stars indicate average compositions of the two oil types. Same symbols as in figure 21.4.

son core test (11) oil does not compare favorably, because this oil (11) is not biodegraded like all other Simpson area oils. Whole-oil and fraction values of $\delta^{13}C$ for the core test (11) are similar to those of the Umiat oil. Most other geochemical data (for example, API gravity, $\delta^{34}S$, and sulfur content) are consistent with this oil (11) being from the Simpson area. It is probable that this oil (11) is a mixture of Simpson and Umiat oil.

The oil recovered from DST 1 in the East Simpson No. 2 well is not contaminated because it is similar in carbon isotopes to the oil extracted from the cores.

DALTON-FISH CREEK AREA

Oil from the Dalton No. 1 well (13) and the Fish Creek No. 1 well (17) correlate well with the DST oil and their respective extracted oils.

UMIAT AREA

Of the oil samples from the five Umiat localities (18-22), we have most confidence in the bailed Umiat No. 4 oil (R165-136). All the Umiat DST oil and extracted oil compare favorably with this oil sample (R165-136) except for the Umiat No. 2 oil (R165-003, R165-115). The analytical results for the Umiat No. 2 oil indicate that this is Simpson oil rather than Umiat oil.

CRITERIA FOR OIL TYPES

The analytical results from this study justify recognition of three types of oil in the NPRA: Type A includes three subtypes—the pebble shale, Simpson, and Umiat; type B includes the Barrow subtype, which compares with the Prudhoe subtype; and type C comprises the condensates. The results of all the supporting analyses, except for the gas chromatographic analyses, are given in table 21.1, and the three oil types and their subtypes are outlined in table 21.2.

SULFUR CONTENT

Except for the condensate sample from South Barrow No. 4 well (1), all test oil samples recovered in the NPRA from rocks beneath the pebble shale unconformity in the Ellesmerian sequence have a high sulfur content (>0.6 wt pct). By contrast, except for the samples from the Fish Creek No. 1 well (17), all test oil samples recovered from rocks above the pebble shale unconformity have a low sulfur content (<0.6 wt pct). The oil samples extracted from cores also follow this generalization; the only exception is the sample from the Barrow sandstone within the Kingak Shale, which derives from beneath the pebble shale unconformity but is at the high end of the low-sulfur group (0.5 wt pct).

API GRAVITY

A plot of API gravity against sulfur content (fig 21.4) permits a further grouping of oil samples on a stratigraphic and regional basis. The oil recovered from rock units of the Ellesmerian sequence below the unconformity along the Barrow Arch forms the Barrow group (type B), which has a high sulfur content

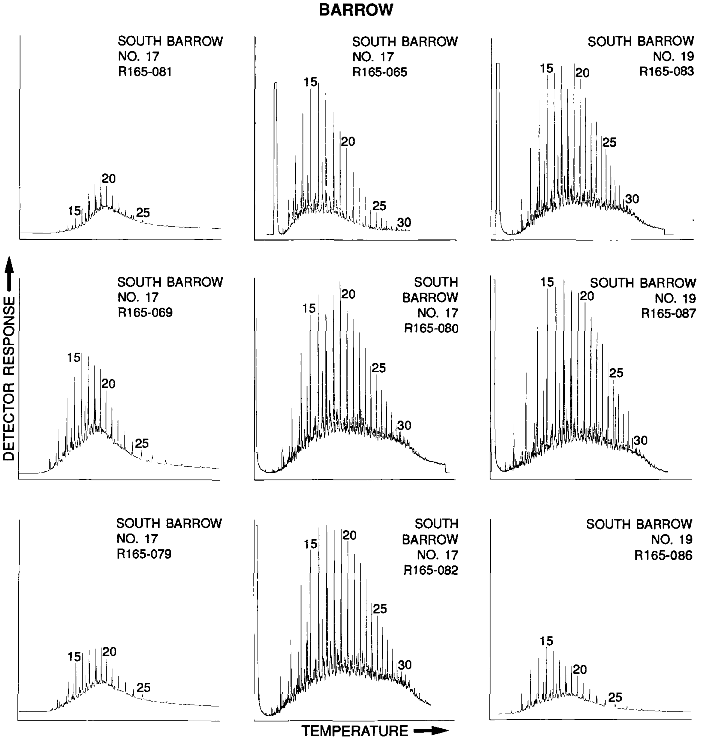


FIGURE 21.10.—C_{15+} chromatograms, identified by well name and analysis number, for samples of Barrow oil. Selected peaks are labeled by carbon number.

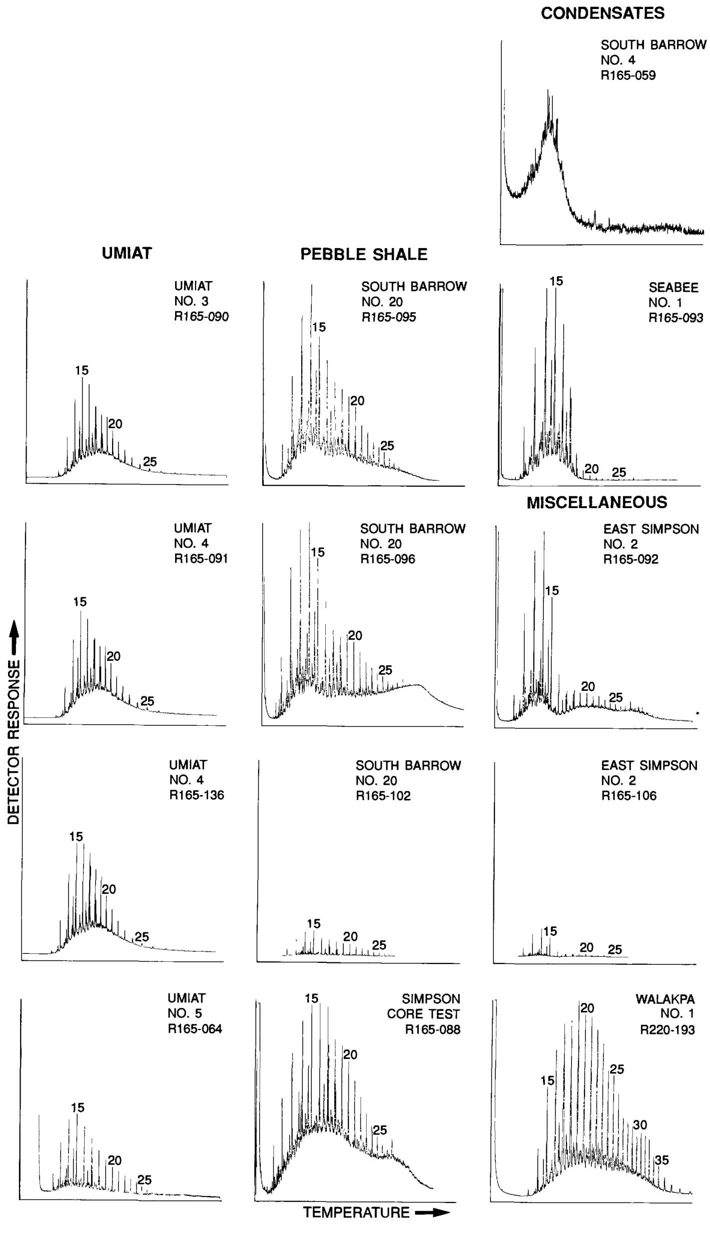


FIGURE 21.11.—C_{15+} chromatograms, identified by well name and analysis number, for samples of Umiat oil, pebble shale oil, condensates, and miscellaneous sources. Selected peaks are labeled by carbon number.

(1-2.6 wt pct) and the lowest range of gravity (API 6-25°). The Fish Creek oil also belongs with this group, as does the oil from the Sadlerochit and Lisburne Groups recovered from the Dalton No. 1 well (13). Oil samples from Nanushuk Group rock units of the Brookian sequence in the Cape Simpson area (type A) all have low sulfur content (0.22-0.35 wt pct) and a low range of gravity (API 18-24°). Samples from the Umiat oil field and South Barrow No. 20 well also have very low sulfur content (<0.1 wt pct) and higher gravities (API 30-36°). These samples form the Umiat, Simpson, and pebble shale subtypes. The condensate samples stand apart in that they have a low sulfur content and very high gravity (API >40°), but these properties undoubtedly reflect compositional changes produced when liquids were dissolved in the gas phase rather than being an imprint of the original source rock.

SULFUR ISOTOPES

A plot of $\delta^{34}S$ against sulfur content appears in figure 21.5. The distribution of the data on this plot supports the groupings recognized on the basis of API gravity and sulfur content. In addition, another stratigraphic subgroup is indicated for the pebble shale oil (5), which has the heaviest $\delta^{34}S$ values (+6 to +10 permil).

CARBON ISOTOPES

The $\delta^{13}C$ of each whole oil is plotted against its sulfur content in figure 21.6. This plot again delimits the same groups proposed above.

The $\delta^{13}C$ values for the C_{15+} saturated and aromatic hydrocarbon fractions are plotted against each other in figure 21.7. The aromatic hydrocarbon $\delta^{13}C$ effectively separates the groups proposed earlier on the basis of sulfur content, API gravity, and $\delta^{34}S$. When extracted oil is compared with conventionally recovered oil, the extracted oil appears to be systematically heavier by about 0.5 to 1 permil, although a spread of more than 2 permil is observed for oil from the Sadlerochit Group at the East Simpson No. 2 well.

NITROGEN ISOTOPES

The $\delta^{15}N$ value for whole oil could not be measured for all samples and so was not useful for grouping oil samples in this study. However, such values were reported in our previous study (Magoon and Claypool, 1981).

C_{15+} FRACTIONS

The relative proportions of the three C_{15+} fractions separated by column chromatography are listed in table 21.1 and shown in figure 21.8. The type B oil samples recovered from rock units of the Ellesmerian sequence plus the Fish Creek oil (17) are generally enriched in aromatics and nitrogen-, sulfur-, and oxygen-containing (NSO) compounds when compared to type A oil. The biodegraded oil (8, 9, 10) from the Nanushuk Group in the Simpson area forms a band that overlaps both the Umiat oil and the few Type B oil samples that are richest in saturated hydrocarbons. Considering the compositional effects of biodegradation and gas solution on oil and condensate, two median compositions can be inferred for type A and type B oil. The type A oil centers around the Umiat oil at 75 percent saturated hydrocarbons, 20 percent aromatic hydrocarbons, and 5 percent NSO compounds; the broad scattering of Type B oil centers at about 55 percent saturates, 30 percent aromatics, and 15 percent NSO's (fig. 21.8).

C_4-C_8 HYDROCARBONS

The analyses of gasoline-range hydrocarbon do not provide confirmation for the groupings based on the results presented above. Analytical problems of unknown cause may be partially responsible for the limited usefulness of these data. Of the 45 samples analyzed, 10 gave apparently spurious results, having anomalously high values for a single compound (R165-065, -095, -096, -102, -114, -035, -062, -076, -004, and -116; see table 21.3). The relative proportions of the C_7 saturated-hydrocarbon

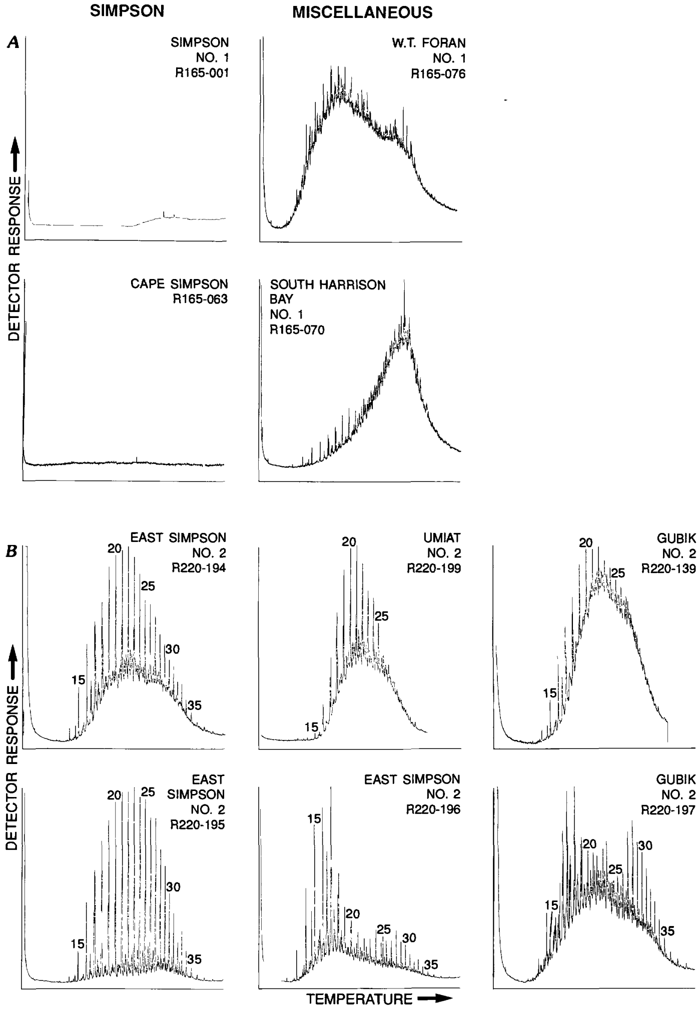


FIGURE 21.12.—C_{15+} chromatograms, identified by well name and analysis number, for various NPRA oil samples. Selected peaks are labeled by carbon number. *A*, Biodegraded oil from Simpson area and oil from W.T. Foran No. 1 and South Harrison Bay No. 1 wells. *B*, Extracted oil from East Simpson No. 2, Umiat No. 2, and Gubik No. 2 wells.

structural types (normal, branched, naphthenes) are plotted in figure 21.9. In general, type A oil from the Umiat field is enriched in C_7 naphthenes compared with the oil from Ellesmerian sequence rock units.

C_{15+} AND C_7-C_{25} GAS CHROMATOGRAMS

Chromatograms of C_{15+} saturated hydrocarbons are shown in figures 21.10-21.13, and chromatograms of C_7-C_{35} saturated hydrocarbons are shown in figures 21.14-21.16. Three types of differences are apparent from these data: (1) biodegraded oil can be distinguished from nonbiodegraded oils by the absence or small content of *n*-alkanes; (2) extracted oils (figs. 21.12, 21.13) can be distinguished from produced oil by the low proportions of hydrocarbons with fewer than 20 carbon atoms; and (3) the groupings previously noted (Barrow, Umiat, pebble shale) in terms of other geochemical results are also indicated by subtle differences in molecular distributions.

All of the Simpson oil samples (fig. 21.12), with the exception of the Simpson core test (R165-088 in fig. 21.11), are biodegraded. The oil from the Umiat No. 2 well (fig. 21.10; R165-003 in fig. 21.16), also biodegraded, is believed to be a Simpson oil. Fish Creek No. 1 oil (R165-089, R220-030, in figs. 21.13, 21.14), J.W. Dalton No. 1 oil (R165-058, R220-180, -185, -186 in fig. 21.13, R165-058, 062 in fig. 21.14), W.T. Foran No. 1 oil (R165-076 in fig. 21.12), and South Harrison Bay No. 1 oil (R165-070 in fig. 21.12) are also biodegraded.

For detailed comparison of the saturated hydrocarbons from C_{15} to C_{32}, that portion of the *n*-alkane profile from both the C_{15+} (figs. 21.10-21.13) and C_7-C_{35} (figs. 21.14-21.16) chromatograms were plotted as relative percent (normalized to 100 percent) against carbon number in figures 21.17 (recovered oil) and 21.18 (extracted oil) for the C_{15+} saturated hydrocarbons and in figure 21.19 (recovered oil) for the C_7-C_{35} hydrocarbons. The major differences among the oil samples are in the range C_{15} to C_{21}. Because the extracted samples have not retained hydrocarbons in this range, the C_{15+} saturated hydrocarbon distributions cannot be used to group extracted oils. This difference in molecular distribution may, how-

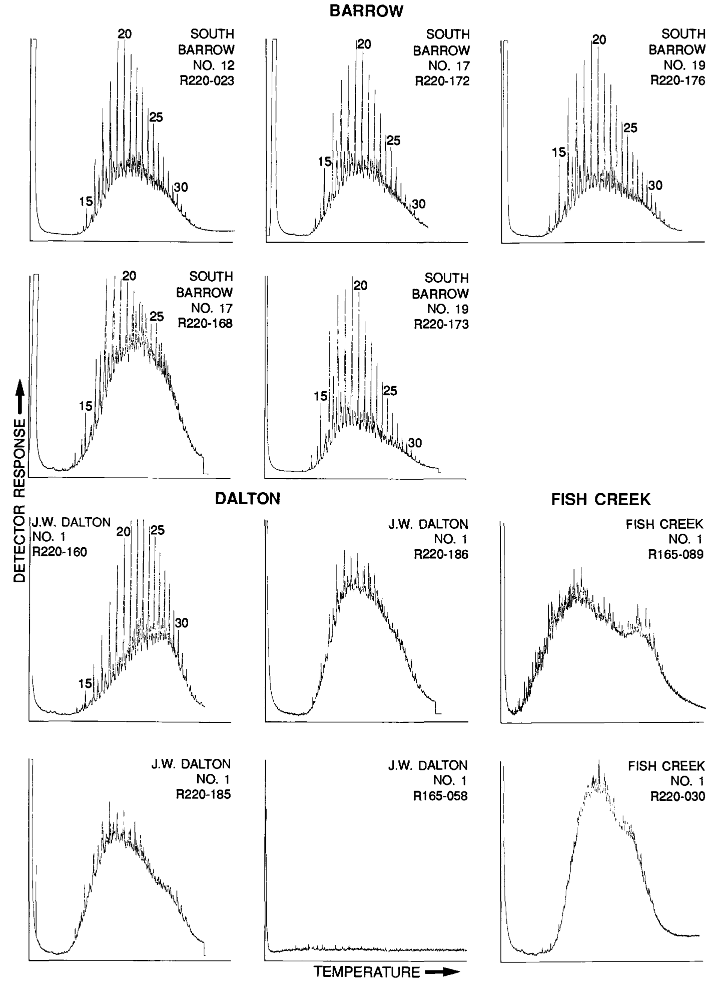


FIGURE 21.13.—C_{15+} chromatograms, identified by well name and analysis number, for samples of extracted oil from Barrow area and from Dalton and Fish Creek wells. Selected peaks are labeled by carbon number.

ever, explain some of the systematic differences observed earlier between extracted and conventional test oils (for example, the shift in $\delta^{13}C$ values for the saturated and aromatic fractions).

The C_{15}-C_{32} *n*-alkane profiles of selected oil samples are plotted in figures 21.17 and 21.19. Oil samples from the South Barrow Nos. 17 and 19 wells are plotted in figures 21.17*A* and 21.19*A*. The apparent difference between the two types of *n*-alkane profiles within each figure (figs 21.17*A* and 21.19*A*) is caused by variations in the analytical procedures and the degree of C_{15}-C_{18} evaporation, rather than by differences between the Barrow oil samples. When only those samples are compared that do not appear to have suffered extreme evaporation losses (figs. 21.17, 21.19), the differences are as follows:

1. Oil from the South Barrow Nos. 17 and 19 wells (figs. 21.17*A*, 21.19*A*) differs from the Umiat field oil (figs. 21.17*B* and 21.19*B*) in having smaller amounts of C_{15}-C_{20} *n*-alkanes and larger amounts of C_{21}-C_{32} *n*-alkanes.
2. The South Barrow No. 20 oil (fig. 21.17*C*, 21.19*C*), obtained from the sandstone encased in the pebble shale unit, has smaller amounts of C_{16}-C_{20} than the Umiat oil (figs. 21.17*B*, 21.19*B*) and larger amounts of C_{21}-C_{30} alkanes than the South Barrow Nos. 17 and 19 oil (figs. 21.17*A*, 21.19*A*).
3. The condensate sample from Seabee No. 1 well (fig 21.17*D*) is depleted in *n*-alkanes above *n*-C_{20}.

ODD *n*-ALKANE PREDOMINANCE AND PRISTANE/PHYTANE RATIOS

From the *n*-alkane data reported in tables 21.4 and 21.5, we have calculated the carbon preference index (CPI) (Bray and Evans, 1961). All samples have CPI values (table 21.6) of about 1, indicating no pre-

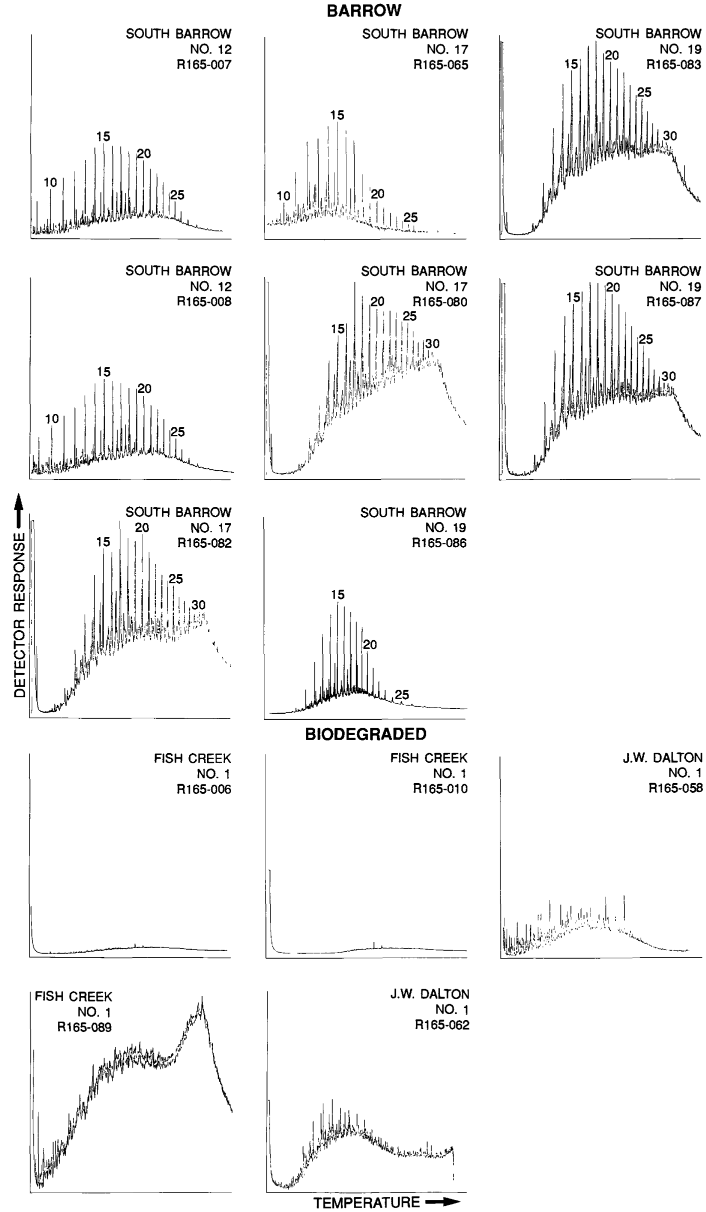


FIGURE 21.14.—C_7-C_{35} chromatograms, identified by well name and analysis number, for samples of oil from Barrow area and of biodegraded oil from Fish Creek and Dalton wells. Selected peaks are labeled by carbon number.

dominance of either odd-numbered or even-numbered *n*-alkanes. Values of the pristane/phytane ratio are listed in table 21.6. Umiat field oil has values of 2.2 to 2.3, while the rest of the oil samples have values of less than 1.5.

DISCUSSION

The NPRA oil occurrences that are described in this chapter are mainly subeconomic oil shows, seeps, drill-stem tests, or core tests. Only the Umiat field has a significant conventional accumulation (30-100 million barrels; Molenaar, 1982). However, study of the oil samples constitutes one of the best available means to evaluate the oil-generating capabilities of the sedimentary rock sequence on the North Slope of Alaska. In our earlier study (Magoon and Claypool, 1981), we divided North Slope oil into two types or genetically related families—the Simpson-Umiat type and the Barrow-Prudhoe type. For the present study, which is limited to the NPRA region, more oil samples are available and a greater variety of analyses have been performed and evaluated. Forty-four different oil occurrences have been analyzed, some in duplicate or triplicate, so data are reported for a total of 67 analyses. Nineteen of the oil samples were extracted from oil-stained reservoir rocks.

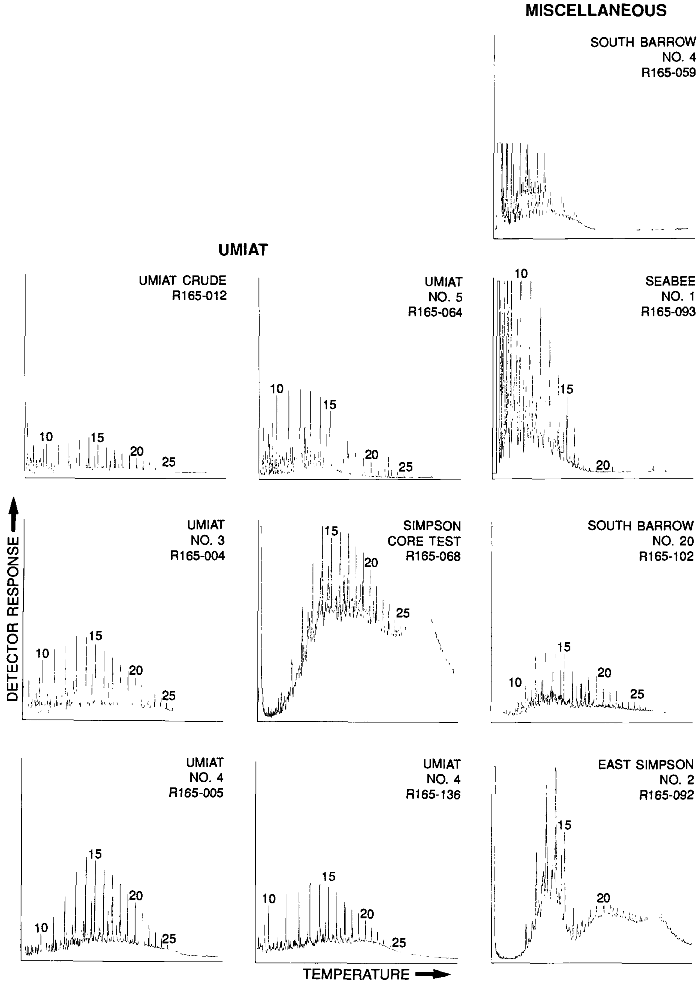


FIGURE 21.15.—C_7-C_{35} chromatograms, identified by well name and analysis number, for samples of Umiat oil and miscellaneous sources. Selected peaks are labeled by carbon number.

The analytical results presented above require us to extend our previous conclusions (Magoon and Claypool, 1981) to include the pebble shale oil (5) and the differences between the Simpson (8, 9, 10) and Umiat (20, 21, 22) oil. These oil types are not restricted to any particular stratigraphic interval, which is not surprising considering that oil is a mobil fluid. In order to avoid stratigraphic connotations and to minimize biasing the classification with a compound or compositional designation, we call the oil types simply type A, B, or C.

Within the NPRA, type A oil is usually in reservoir rocks stratigraphically above the pebble shale unconformity; it includes the pebble shale (5), Simpson (8, 9, 10), South Harrison Bay (15), Fish Creek seep (16), and Umiat oil (20, 21, 22). The East Simpson No. 2 (12) oil is Type A but reservoired below the pebble shale unconformity. Type B oil is generally in reservoir rocks below the pebble shale unconformity; it includes the Barrow (2, 3, 4) and Dalton oils (13). The one type B occurrence reservoired above the unconformity is the Fish Creek oil (17).

The geochemical criteria for designating these major types are generally based on the order outlined in the introduction; stable isotope abundances (C, S) and the percentage of sulfur are the most important, while API gravity is the least significant.

The most distinguishing characteristic among the NPRA oil samples studied is low (type A) versus high (type B) sulfur content, about 0.6 weight percent sulfur being the dividing point. With one or two possible exceptions, oil occurrences in rocks beneath the pebble shale unconformity have a high sulfur content. In addition, they also group together in terms of other geochemical properties that have genetic significance, such as the pristane/phytane ratio and stable-isotope abundances (C, S). The evidence is strong that the composition of this oil is inherited from the organic matter in the source rocks and was not introduced during migration.

We interpret the South Barrow No. 20 oil (5), a type A oil, to be a pebble shale oil because it was recovered from sandstone encased in the pebble shale unit (fig. 21.3). The pebble shale unit is immature (see values of percent R_o in table 21.1) at this location, so this oil had to migrate to its present position either from within this unit or from other units. This South Barrow No. 20 oil differs from other pre-unconformity oils in having a low sulfur content; it differs from the Simpson and Umiat oil in having a more positive $\delta^{34}S$ value and a more negative $\delta^{13}C$ value. Some properties of the South Barrow No. 20 oil are transitional between the oil on either side of the unconformity. Possible reasons for this transitional character are that (1) the oil is a complex mixture from different sources or (2) the oil is a product of organic matter accumulated in its own distinctive environment of deposition.

The oil that seeped (9) from, or is reservoired (8, 10) in, the Nanushuk Group in the Cape Simpson area is now believed to be sufficiently different from the Umiat oil (Magoon and Claypool, 1981) to be classified as a separate subtype within the type A group. The Simpson oil is biodegraded and differs sufficiently from the Umiat field oil that the Simpson oil cannot be considered biodegraded Umiat oil; in fact, except for the $\delta^{34}S$, the Simpson oil is more like a biodegraded pebble shale oil. We now believe that both Simpson oil and Umiat oil are derived from source rocks above the pebble shale unconformity (PSU), but the sources are significantly different. The chemical differences may be the result of (1) different sources, (2) lateral facies changes in a rock unit such as the Torok Formation or pebble shale unit, or (3) generation and expulsion of the oil at different stages of thermal maturity. The fact that the Simpson oil, located on the Barrow Arch, is stratigraphically and geologically close to the pebble shale unit and is geochemically similar to the oil from the sand within the pebble shale unit indicates that a pebble shale source for the Simpson oil is geologically reasonable.

The Umiat oil differs from the other oil groups primarily in having the lowest sulfur content and the most positive δC value. Moreover, the difference between the $\delta^{13}C$ values for C_{15+} saturated and aromatic hydrocarbons (fig. 21.7) is the largest among the four oil types

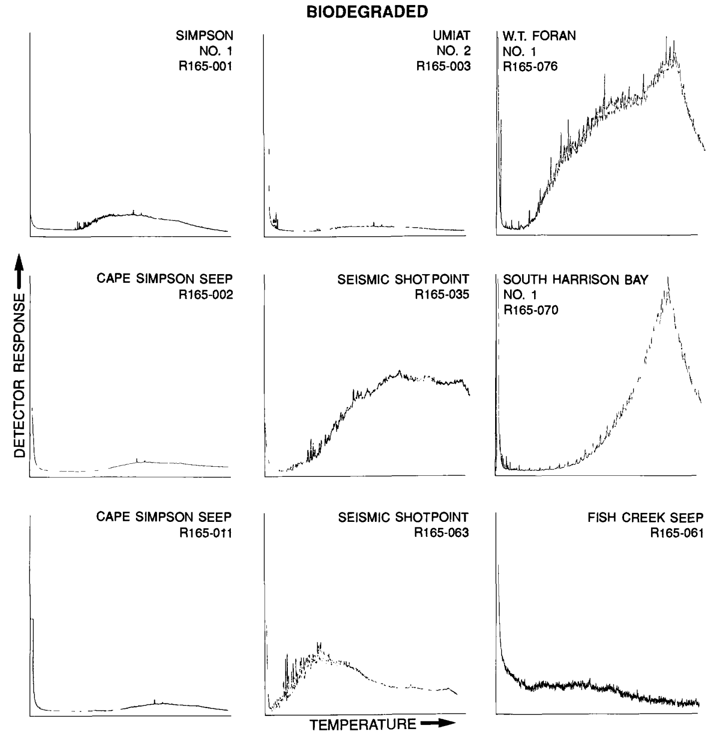


FIGURE 21.16.—C_7-C_{35} chromatograms, identified by source and analysis number, for samples of biodegraded oil from Simpson and other areas.

(table 21.2), and has a magnitude that implies the greatest terrestrial influence in the original organic matter, according to the interpretation proposed by Sofer (1984).

The two type C condensate samples also differ consistently from the other oil groups in terms of most of the geochemical measurements performed. However, we believe that these differences do not indicate genetically different source material as much as a different migration history for the hydrocarbon mixtures. These condensate samples are hydrocarbon mixtures that were dissolved in gas and then precipitated at the surface during gas production or testing. Solution in gas imposes significant compositional fractionation, and the resulting mixtures cannot therefore be directly compared with related crude oils.

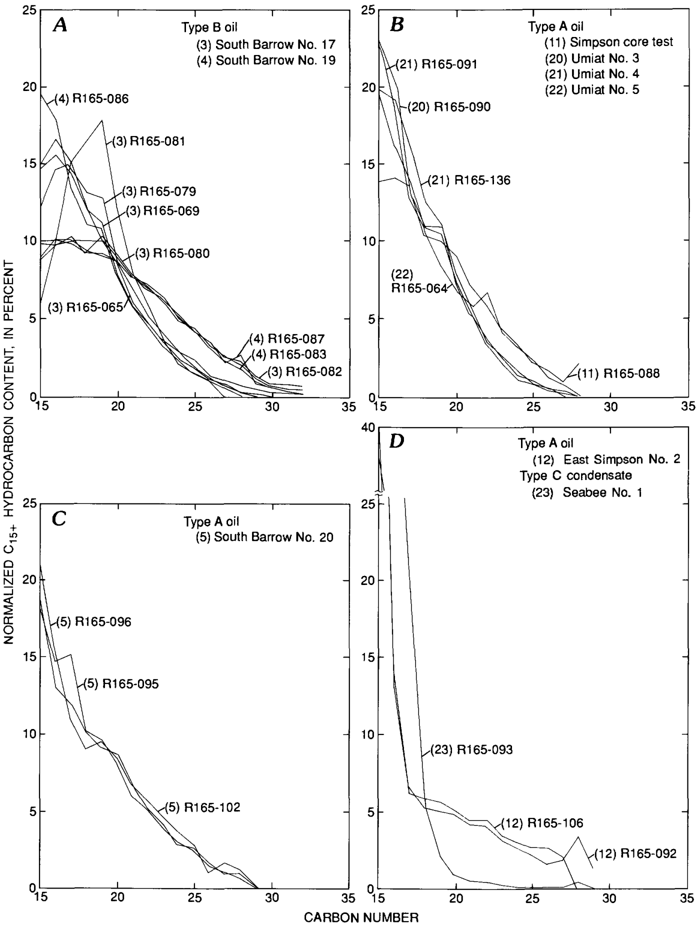


FIGURE 21.17.—Normalized C_{15+} hydrocarbon data, plotted by carbon number from C_{15} to C_{32}, for various NPRA oil samples. Locality numbers are given in parentheses. *A*, Barrow area, Sag River Sandstone. *B*, Umiat area. *C*, Barrow area, pebble shale unit. *D*, East Simpson No. 2 and Seabee No. 1 wells.

CONCLUSIONS

1. Geochemical analyses of oil occurrences from NPRA indicate the existence of three oil types, here called A, B, and C.
2. Within each major oil type, distinct subtypes are recognizable. The type B oil, found beneath the pebble shale unconformity (PSU), contains the oil group referred to as the Barrow-Prudhoe type (Magoon and Claypool, 1981). The post-PSU type A oil contains the Simpson, Umiat, and pebble shale subtypes.
3. The condensate samples cannot be grouped with the major oil types A and B on the basis of the geochemical evidence presented in this report, so they are considered a separate type C.

REFERENCES CITED

Bray, E.E., and Evans, E.D., 1961, Distribution of *n*-paraffins as a clue to recognition of source beds: Geochimica et Cosmochimica Acta, v. 22, no. 1, p. 2-15.

Collins, F.R., 1958, Test wells, Umiat area, Alaska: U.S. Geological Survey Professional Paper 305-B, p. 71-206.

——— 1961, Core tests and test wells, Barrow area, Alaska: U.S. Geological Survey Professional Paper 305-K, p. 569-644.

Ebbley, Norman, Jr., 1944, Oil seepages on the Alaskan Arctic slope: Mining and Metallurgy, v. 25, p. 415-419.

Jones, H.P., and Speers, R.G., 1976, Permo-Triassic reservoirs of Prudhoe Bay field, North Slope, Alaska, *in* Braunstein, Jules, ed., North American oil and gas fields: American Association of Petroleum Geologists Memoir 24, p. 23-50.

McKinney, C.M., Garton, E.L., and Schwartz, F.G., 1959, Analyses of some crude oils from Alaska: U.S. Bureau of Mines Investigation 5447, 29 p.

Magoon, L.B., and Claypool, G.E., 1981, Two oil types on North Slope of Alaska—implication for exploration: American Association of Petroleum Geologists Bulletin, v. 65, no. 4, p. 644-652.

——— eds., 1985, Alaska North Slope oil-rock correlation study: American Association of Petroleum Geologists Special Studies in Geology, no. 20, 678 p.

Molenaar, C.M., 1982, Umiat field, an oil in a thrust-faulted anticline, North Slope of Alaska, *in* Powers, R.B., ed., Geologic studies of the Cordilleran thrust belt: Denver, Rocky Mountain Association of Geologists, v. 2, p. 537-548.

Morgridge, D.L., and Smith, W.B., 1972, Geology and discovery of Prudhoe Bay field, eastern Arctic Slope, Alaska, *in* King, R.E., ed., Stratigraphic oil and gas fields: American Association of Petroleum Geologists Memoir 16, p. 489-501.

Robinson, F.M., 1958, Test wells, Gubik area, Alaska: U.S. Geological Survey Professional Paper 305-C, p. 207-264.

——— 1959, Test wells, Simpson area, Alaska, U.S. Geological Survey Professional Paper 305-J, p. 523-568.

——— 1964, Core tests, Simpson area, Alaska, U.S. Geological Survey Professional Paper 305-L, p. 645-730.

Robinson, F.M., and Collins, F.R., 1959, Core test, Sentinel Hill area, and test well, Fish Creek area, Alaska: U.S. Geological Survey Professional Paper 305-I, p. 485-521.

Seifert, W.K., Moldowan, J.M., and Jones, R.W., 1980, Application of biological marker chemistry to petroleum exploration: World Petroleum Congress, 10th, Bucharest, 1980, Proceedings, p. 425-440.

Sofer, Zvi, 1984, Stable carbon isotope compositions of crude oils; application to source depositional environments and petroleum alteration: American Association of Petroleum Geologists Bulletin, v. 68, p. 31-49.

Young, Allen, Monaghan, P.H., and Schweisberger, R.T., 1977, Calculation of ages of hydrocarbons in oils—physical chemistry applied to petroleum geochemistry I: American Association of Petroleum Geologists Bulletin, v. 61, no. 4, p. 573-600.

APPENDIX 21.1

ANALYTICAL TECHNIQUES

The oil analyses reported here were done under contract to the U.S. Geological Survey by Geochem Research, Inc. (GRI), and their subcontractor Global Geochemistry Corp. All oil and rock samples were sent directly from the NPRA to GRI for analysis. The numbers on the following headings correspond to those on the flow chart for all the analytical techniques, figure 21.20.

1. API GRAVITY

The sample of crude oil, as received in the laboratory, was centrifuged and treated with anhydrous sodium sulphate in order to separate and remove any water; this procedure also removed any particulate material. The API gravity was measured using a Mettler/Paar Digital Density Meter (DMA 40) with constant temperature control. The method requires a minimum sample size (0.7 mL) and is very precise (±0.1 mg/mL).

The sample was introduced into a U-shaped sample tube that was rigidly supported at its open ends, and the sample tube was then electromagnetically excited to vibrate at its natural frequency. From the frequency change caused by the particular sample inside the sample tube, the density of the sample was determined. Because the mass of the sample participating in the vibration was established in this way, there was no need for measuring either weight or volume. The viscosity and surface tension of the sample do not affect the result. The density value was converted to specific gravity and API gravity at 15.5 °C (60 °F) and 101 kPa (one atmosphere) pressure by standard calculation.

2. C_4-C_8 GASOLINE-RANGE

The sample of oil, centrifuged and treated with the anhydrous sodium sulphate, was

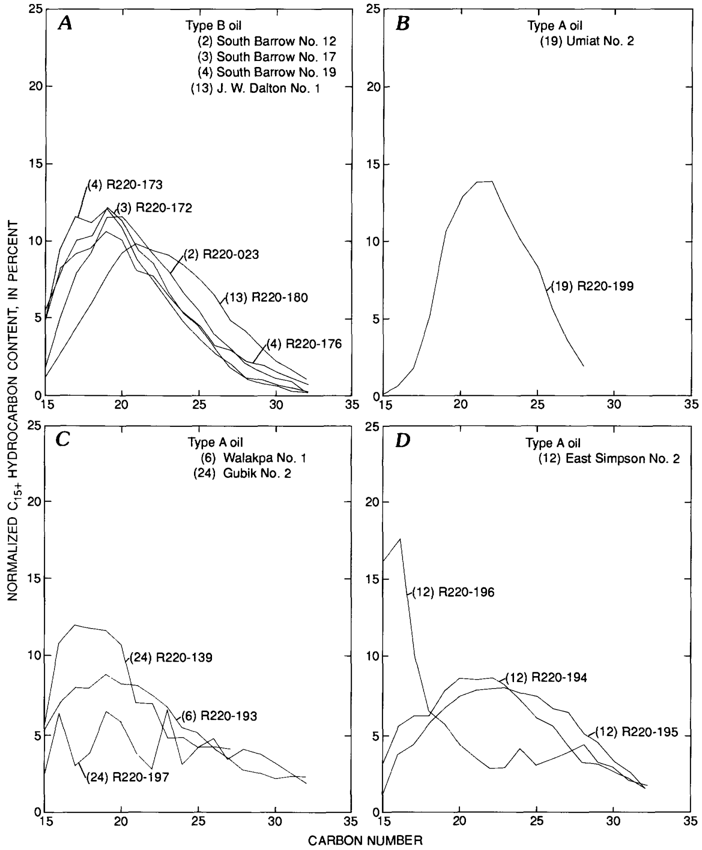


FIGURE 21.18.—Normalized C_{15+} hydrocarbon data, plotted by carbon number from C_{15} to C_{32}, for various extracted-oil samples from NPRA. Locality numbers are given in parentheses. *A*, Barrow area, Sag River Sandstone; and J.W. Dalton No. 1 well. *B*, Umiat No. 2 well. *C*, Gubik No. 2 and Walakpa No. 1 wells. *D*, East Simpson No. 2 well.

used for the analysis of gasoline-range hydrocarbons. A small aliquot of approximately 100 mL was transferred into a disposable pipette having its narrow end sealed by torch flaming. The top of the pipette was then sealed with a septum cap suitable for the removal of a gas sample. The pipette and contents were immersed in boiling water for a 20-minute period, and a sample of the headspace gas was then injected into a Varian Aerograph 1400 Gas Chromatograph by way of a sample loop cooled by liquid nitrogen. The gas chromatograph is fitted with a 200-ft, 0.01-in. (i.d.) HHK (hexadecane-hexadecene-Kel F) column maintained at ambient temperature (21 °C). Following the admittance of the sample to the liquid-nitrogen-cooled sample loop, the C_4-C_8 hydrocarbons were injected onto the HHK column by passing a current of electricity through the loop in such a manner that over a period of 15 s, the loop was heated, and complete volatilization of the sample occurred. During the analysis, the column was maintained and operated isothermally at ambient temperature. Initial preconditioning was carried out so that a complete separation results between the C_7 isomers, 2-methylhexane and 2,3-dimethylpentane. This particular column resolved 33 of the C_4-C_7 gasoline-range hydrocarbon components and only a few of the C_8 compounds.

The concentrations of the individual hydrocarbons were determined on a weight-weight basis as measured against known concentrations of cyclopentane, methylcyclopentane, cyclohexane, methylcyclohexane (Mixture No. 7, Scott Analyzed Gases) and of isobutane, 2-methylbutane, 2,2-dimethylpropane, 2-methylpentane, 3-methylpentane and 2,2-dimethylbutane (Mixture No. 2, Scott Analyzed Gases).

The peak areas for the individual components present in the C_4-C_8 hydrocarbons were digitized using an Infotronic Integrator and expressed as weight percents of individual hydrocarbons with respect to the whole oil.

3. C_{15+} SATURATES, AROMATICS, AND NONHYDROCARBONS

About 1 mL of the oil sample was dissolved in 5 mL of n-hexane in a 10-mL vial. Anhydrous sodium sulfate (0.5 g) was added to remove water. The *n*-hexane solution was passed through a filtering microcolumn of celite. The vial was rinsed twice with 1-mL portions of *n*-hexane and the rinse added to the top of the column. The celite was rinsed with 2 mL of *n*-hexane. The eluant was collected in a preweighed tapered vial, evaporated to dryness, and weighed. The vial was heated at 40 °C under nitrogen for an additional 15 min and reweighed. The weight loss was recorded. If the weight loss after the 15 min evaporation period was greater than 5 percent of the initial weight or 0.5 mg (whichever was smaller), the sample was heated again under nitrogen for 15 min and the sample weight recorded. The tapered vial was then tightly capped. A 30-mg aliquot of the oil in *n*-hexane was separated by liquid chromatography into saturated hydrocarbon, aromatic hydrocarbon, and nonhydrocarbon fractions under the conditions described below.

A microcolumn (length 20 times diameter) was packed with two grades of activated silica gel (pre-wetted with hexane)—Davison Grade 923 (60-200 mesh) for the lower half of the column and Davison Grade 62 (60-200 mesh) for the upper half.

The microcolumn was rinsed thoroughly with *n*-hexane. The 30-mg aliquot of oil in *n*-hexane was added to the top of the column. The portion of the aliquot which was insoluble in the nonpolar solvent was dispersed in the solvent by stirring, and as much as possible transferred to the top of the

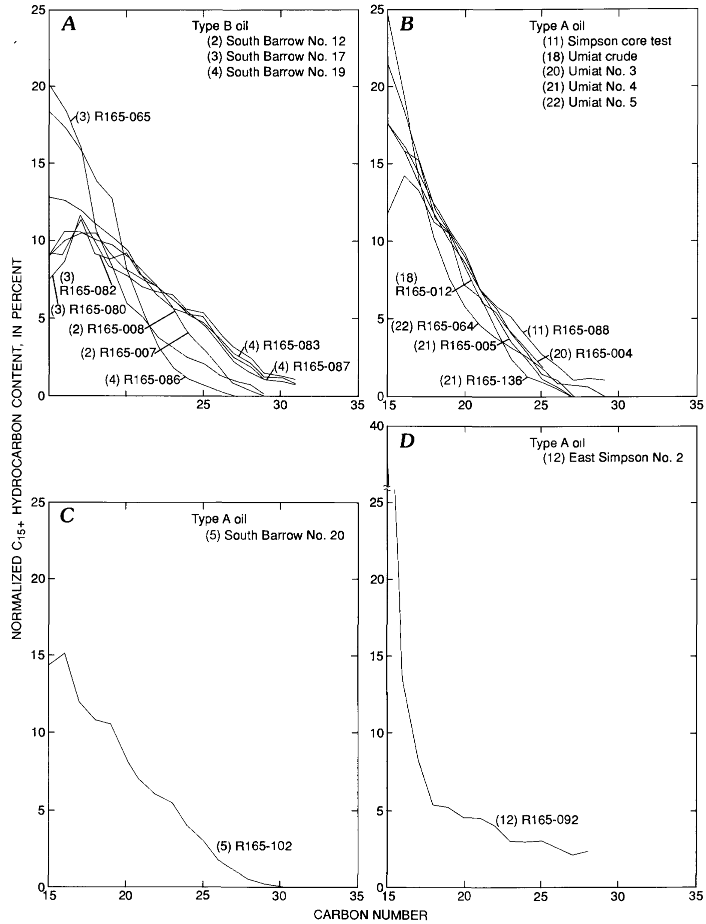


FIGURE 21.19.—Normalized C_{15+} hydrocarbon data, plotted by carbon number from C_{15} to C_{32}, for varous NPRA oil samples. Locality numbers are given in parentheses. *A*, Barrow area. *B*, Umiat area. *C*, South Barrow No. 20 well, pebble shale unit. *D*, East Simpson No. 2 well.

TABLE 21.4.—*Content of C_{15}-C_{32} saturated hydrocarbons from chromatograms of C_{15+} extraction for oil from the National Petroleum Reserve in Alaska*

[Values derived from measured peak heights, normalized to percents of total C_{15-32} hydrocarbon content; -, not detected]

Locality number	Lab. number	Carbon number																	
		15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
2	R220-023	1.8	5.0	7.9	9.1	11.6	11.6	10.4	9.2	8.0	6.6	5.5	4.0	3.2	2.3	1.6	1.3	0.9	0.1
3	R165-080	8.9	10.0	10.3	9.4	10.3	9.2	8.0	7.1	6.1	5.0	4.5	3.5	2.7	2.1	1.2	.8	.6	.5
	R165-069	15.3	16.5	15.2	12.0	11.4	7.9	6.0	4.8	3.6	2.5	1.9	1.3	.8	.5	.3	0	0	0
	R165-079	12.4	14.7	15.0	13.1	12.8	8.9	7.0	5.0	4.0	2.8	1.9	1.2	.8	.5	0	0	0	0
	R165-065	14.8	15.6	14.4	12.1	10.2	8.6	6.2	4.8	3.6	2.8	2.0	1.4	1.1	.8	.6	.4	.4	.3
	R165-081	5.8	9.7	15.3	16.6	17.9	12.2	8.1	5.8	3.9	2.2	1.6	1.2	0	0	0	0	0	0
	R165-082	8.9	10.0	9.9	9.3	9.3	8.8	7.9	7.3	6.5	5.0	4.3	3.5	2.7	2.4	1.4	1.0	1.0	.8
	R220-172	4.5	8.2	10.1	10.4	12.2	11.4	9.4	8.5	6.8	5.4	4.5	3.0	1.9	1.3	.9	.7	.4	.4
4	R165-083	9.9	9.9	10.1	10.2	10.1	9.2	7.9	7.1	6.2	5.3	4.4	3.2	2.3	1.9	1.0	.6	.5	.4
	R165-086	19.5	17.8	13.5	11.0	10.9	7.9	6.0	4.5	3.4	2.3	1.5	1.0	.7	0	0	0	0	0
	R165-087	10.1	10.1	10.3	9.5	9.2	8.8	7.9	7.0	6.4	5.4	4.4	3.5	2.4	2.8	1.0	.6	.4	.3
	R220-176	4.8	8.3	9.3	9.5	10.5	10.2	8.3	7.8	6.5	5.5	4.7	3.5	3.1	2.4	2.1	1.6	1.2	.7
	R220-173	4.8	9.5	11.6	11.2	12.0	11.0	8.9	7.5	6.1	4.9	3.8	2.8	2.1	1.3	1.0	.8	.5	.4
5	R165-095	17.9	14.7	15.3	10.1	9.6	8.1	6.2	5.0	3.9	3.1	2.6	1.7	1.1	.7	0	0	0	0
	R165-096	21.0	14.9	11.0	9.1	9.6	8.6	7.0	5.3	4.3	3.0	2.6	1.8	1.0	1.0	0	0	0	0
	R165-102	18.0	13.1	11.9	10.0	9.1	8.7	6.8	5.8	4.7	3.8	2.9	2.2	1.6	1.2	0	0	0	0
6	R220-193	5.4	7.1	8.2	8.1	9.0	8.4	8.3	7.6	6.9	5.5	5.2	4.2	3.5	2.8	2.7	2.3	2.5	2.5
11	R165-088	14.0	14.1	13.6	10.5	10.1	9.2	7.3	6.0	4.5	3.5	2.4	1.7	1.0	2.2	-	-	-	-
12	R165-092	38.5	13.9	6.6	5.4	5.2	4.9	4.3	4.2	3.3	2.6	2.4	1.7	1.9	3.5	1.5	-	-	-
	R165-106	40.3	13.0	6.4	5.9	5.7	5.0	4.6	4.6	3.6	3.2	2.7	2.7	2.3	0	0	0	0	0
	R220-194	3.3	5.6	6.4	6.4	8.0	8.7	8.6	8.7	8.2	7.1	6.0	5.6	4.5	3.4	3.1	2.6	2.2	1.6
	R220-195	1.4	3.8	4.5	5.9	6.8	7.6	8.0	8.0	8.2	7.7	7.6	6.7	6.7	5.2	4.6	3.4	2.6	1.7
	R220-196	16.5	17.7	10.1	6.7	5.6	4.5	3.5	2.9	3.0	4.3	3.1	3.5	3.9	4.5	3.4	3.0	2.1	1.8
13	R220-180	1.3	2.8	4.5	6.0	7.8	9.3	9.9	9.4	9.2	8.5	7.5	6.4	4.9	4.4	3.1	2.3	1.7	1.2
19	R220-199	.4	.8	1.9	5.2	10.1	12.9	13.8	13.8	11.77	10.0	8.4	5.7	3.5	2.0	-	-	-	-
20	R165-090	22.8	20.1	13.1	10.8	10.6	7.4	5.3	3.7	2.6	1.5	1.0	.6	.5	0	0	0	0	0
21	R165-091	22.8	19.0	12.9	11.2	11.2	8.1	5.8	3.5	2.6	1.7	.9	.5	0	0	0	0	0	0
	R165-136	19.8	19.1	16.4	12.7	11.0	7.4	5.3	3.4	2.1	1.2	.8	.5	.3	0	0	0	0	0
22	R165-064	19.4	16.3	13.8	10.6	8.4	6.7	5.9	6.9	4.2	3.4	2.3	1.2	.8	0	0	0	0	0
23	R165-093	37.9	31.4	18.9	5.5	2.2	1.0	.6	.5	.4	.3	.3	.2	.1	.6	0	0	0	0
24	R220-139	5.7	11.0	12.1	11.9	11.8	11.0	7.2	7.1	4.8	4.8	4.2	4.5	4.1	-	-	-	-	-
	R220-197	2.4	6.4	3.2	3.7	6.7	5.9	3.8	2.9	6.7	3.2	4.1	4.8	8.8	10.1	8.5	7.7	6.4	4.8

column. The tapered vial was rinsed with 1 mL of *n*-hexane, and the rinse was added to the top of the column. An additional amount of *n*-hexane equal to 3 bed volumes (6 mL) was eluted through the column. The eluant composed of the saturated hydrocarbons was collected in a preweighed tapered vial and capped.

The vial that contained the 30-mg aliquot of oil was rinsed again with about 1 mL of toluene and this rinse was also added to the top of the column. The receiver was charged and the aromatic hydrocarbon fraction was obtained by passing 3 bed volumes (6 ml) of toluene through the column. The eluant was collected in a preweighed tapered vial and capped. The nonhydrocarbon asphaltic fraction was obtained by eluting with 3 bed volumes (6 mL) of 6:4 CH_2Cl_2:methanol into a preweighed tapered vial (the 6:4 CH_2Cl_2:methanol has the same solvent polarity as 1:1 benzene:methanol.)

Each fraction was concentrated under nitrogen at 40 °C. The procedure previously specified for the drying and weighing was used. Care was taken to prevent excessive evaporation of the fractions. The percentage of recovery was calculated as the sum of the weights of the three fractions divided by the weight of the total oil placed on the column.

4. C_{15+} SATURATED HYDROCARBONS—GAS CHROMATOGRAM

Solution of the saturated hydrocarbon fraction was effected by using methylene chloride. The column was a 15-m fused silica or glass capillary (0.25 mm i.d.). Such columns, manufactured by J&W Scientific, Inc. provided compound separations of up to 70,000 theoretical phases. A Varian Model 3700 dual column gas chromatograph equipped with dual flame ionization detectors was used. Detector output was processed through an alternating-field converter and recorded on magnetic tape. The tape was

TABLE 21.5.—*Content of C_{15}-C_{32} saturated hydrocarbons from chromatograms of C_7-C_{35} extraction for oil from the National Petroleum Reserve in Alaska*

[Values derived from measured peak heights, normalized to percents of total C_{15-32} hydrocarbon content; -, not detected]

Locality number	Lab. number	Carbon number																	
		15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
2	R165-007	12.9	12.5	12.1	11.1	10.4	9.5	7.8	7.1	5.8	4.3	3.0	1.8	1.0	0.5	0	0	0	0
	R165-008	12.9	12.6	12.0	10.9	10.3	9.6	7.8	7.0	5.8	4.3	3.2	2.0	1.0	.6	0	0	0	0
3	R165-080	7.7	8.5	11.8	10.0	8.5	7.7	7.1	6.8	6.5	5.6	5.4	4.3	3.3	2.7	1.6	1.43	1.3	-
	R165-065	20.1	18.6	16.2	10.7	8.6	6.0	5.1	3.7	3.2	2.5	2.2	1.4	1.0	.9	0	0	0	0
	R165-082	9.4	9.1	11.27	9.2	8.7	9.2	7.7	6.7	5.9	5.4	4.9	3.7	2.9	2.4	1.3	1.3	.9	-
4	R165-083	9.0	10.0	10.5	10.6	9.1	8.3	7.6	7.1	6.3	5.4	5.0	3.7	2.5	1.9	1.1	1.1	.7	-
	R165-086	18.4	17.4	15.9	13.9	12.9	8.4	5.6	3.4	2.0	1.1	.7	.4	0	0	0	0	0	0
	R165-087	9.5	10.6	10.5	10.2	9.8	9.0	8.1	7.3	6.3	5.5	4.7	3.6	2.3	1.6	1.1	-	-	-
5	R165-102	14.5	15.1	11.9	10.7	10.5	8.4	6.9	6.0	5.5	3.9	3.0	1.8	1.1	.5	.3	0	0	0
11	R165-088	12.0	14.3	13.3	11.4	10.6	8.7	6.9	5.7	5.0	3.9	2.7	1.9	1.2	1.3	1.0	0	0	0
12	R165-092	37.5	13.4	8.2	5.5	5.4	4.7	4.6	4.0	3.2	3.1	3.2	2.6	2.3	2.5	-	-	-	-
18	R165-012	17.5	15.9	15.2	11.5	10.6	8.3	6.2	5.5	4.0	2.8	1.5	1.1	0	0	0	0	0	0
20	R165-004	17.7	15.9	14.0	11.9	10.1	8.7	6.9	5.8	4.2	3.1	1.9	-	-	-	-	-	-	-
21	R165-005	17.6	16.2	14.5	12.2	10.7	9.1	6.7	5.2	3.5	2.4	1.2	.6	0	0	0	0	0	0
	R165-136	21.3	18.4	15.2	12.2	10.6	7.2	5.6	4.3	2.5	1.3	.9	.5	0	0	0	0	0	0
22	R165-064	24.5	19.2	13.9	10.3	7.6	5.9	4.6	3.8	3.2	2.6	1.9	1.0	.6	0	0	0	0	0

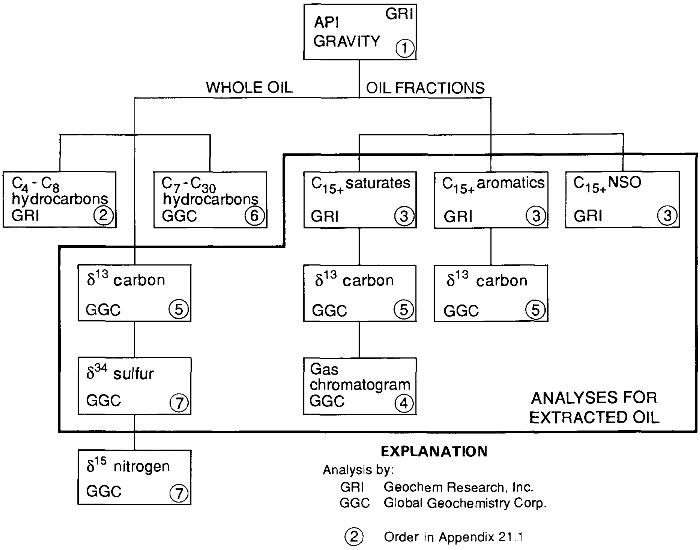


FIGURE 21.20.—Flow chart showing geochemical analyses performed for this study on recovered and extracted NPRA oil samples.

then reprocessed through a reverse converter and read into a PDP-11 DEC computer, the software of which integrated all recognizable peaks, the unresolved component, and the total resolved area. The data were tabulated through a hard copy printer plotter along with the original chromatogram, which was reduced to 8½ x 11 in. and labeled. All computer output data were manually scanned to verify accuracy.

5. $\delta^{13}C$ OF C_{15+} SATURATED, AROMATIC, AND WHOLE-OIL FRACTIONS

Analyses were performed on purified extracts of C_{15+} saturated-and aromatic-hydrocarbon fractions. Approximately 1 mg of sample was placed on a precleaned 1-cm-square piece of silver foil 0.1 mm thick and then transferred into a 9-mm (o.d.) quartz tube together with 1 g of cupric oxide. The tube was connected to a vacuum-line system, the sample was cooled to LN_2 (liquid nitrogen) temperature, and the air was evacuated. The tube was then sealed under a vacuum and heated for 4 h at 850 °C in a Thermolyne furnace. Following slow cooling to room temperature (25 °C), the quartz tube was broken in a vacuum-line system and the resultant (CO_2 and H_2) collected with an

TABLE 21.6.—*Carbon preference index (CPI) and selected hydrocarbon ratios for oil from the National Petroleum Reserve in Alaska*

[-, no data; Pr = pristane; Ph = phytane]

Locality number	Lab. number	From C_{15+} chromatograms (data in table 21.4)				From C_7–C_{35} chromatograms (data in table 21.5)			
		CPI C_{22-24}	Pr/ Ph	Pr/ $\underline{n}$-C_{17}	Ph/ $\underline{n}$-C_{18}	CPI C_{22-24}	Pr/ Ph	Pr/ $\underline{n}$-C_{17}	Ph/ $\underline{n}$-C_{18}
2	R165-007	-	-	-	-	1.01	1.34	0.39	0.32
	R165-008	-	-	-	-	.91	1.37	.39	.31
	R220-023	1.02	1.01	0.69	0.59	-	-	-	-
3	R165-080	1.01	1.22	.56	.51	1.05	1.32	.46	.42
	R165-069	.98	1.50	.59	.50	-	-	-	-
	R165-079	1.01	1.55	.60	.45	-	-	-	-
	R165-065	.94	1.41	.45	.38	.90	1.89	.43	.34
	R165-081	.97	1.03	.68	.61	-	-	-	-
	R165-082	1.06	.91	.59	.69	.97	1.45	.59	.50
	R220-172	.97	5.90	.76	.58	-	-	-	-
4	R165-083	1.00	1.26	.50	.40	1.02	1.32	.52	.39
	R165-086	1.00	1.57	.54	.42	.88	1.41	.48	.39
	R165-087	1.03	1.24	.51	.44	.99	1.37	.51	.39
	R165-176	.98	1.21	.60	.48	-	-	-	-
	R165-173	.99	1.21	.75	.64	-	-	-	-
5	R165-095	.96	1.32	.61	.70	-	-	-	-
	R165-096	1.04	1.51	.79	.63	-	-	-	-
	R165-102	.98	1.36	.55	.48	1.11	1.20	.61	.56
6	R220-193	1.05	1.47	.69	.47	-	-	-	-
11	R165-088	.95	1.73	.70	.53	1.04	1.79	.80	.52
12	R165-092	.96	1.13	1.12	1.21	.90	1.19	.89	1.11
	R165-106	.94	.96	.96	1.08	-	-	-	-
	R220-194	1.04	1.53	3.81	.61	-	-	-	-
	R220-195	1.04	2.69	.71	.20	-	-	-	-
	R220-196	.84	2.11	1.94	1.39	-	-	-	-
13	R220-180	1.03	.77	.43	.42	-	-	-	-
18	R165-012	-	-	-	-	.97	2.20	.68	.41
19	R220-199	.99	.49	.35	1.05	-	-	-	-
20	R165-004	-	-	-	-	.94	2.10	.71	.40
	R165-090	.99	2.36	1.00	.51	-	-	-	-
21	R165-005	-	-	-	-	.93	2.01	.67	.39
	R165-091	1.00	2.23	1.01	.50	-	-	-	-
	R165-136	.89	2.20	.82	.48	.87	2.33	.85	.45
22	R165-064	.82	2.25	.60	.35	.98	3.12	.60	.26
23	R165-093	.86	7.64	.87	.39	-	-	-	-
24	R220-139	.80	1.31	.75	.58	-	-	-	-
	R220-197	2.20	1.08	4.43	3.47	-	-	-	-

LN_2 trap while nitrogen was evacuated. The LN_2 was replaced by dry ice/acetone, and the liberated CO_2 was collected with a gas collection bulb with LN_2 and stored for the mass-spectographic determination.

The purified CO_2 was analyzed on a Varian Mat 250 triple collecting instrument and the result was reported as permil relative to the PDB standard.

6. C_7-C_{30} HYDROCARBON ANALYSIS—GAS CHROMATOGRAM

The gas chromatographic analysis was carried out with the column first cooled to <-20 °C to optimize the determination of the hydrocarbons of intermediate molecular weight (C_8-C_{15}), the C_7-C_{30} *n*-alkanes, and the isoprenoid compounds: ipC_{11}, ipC_{13}, ipC_{14}, ipC_{15}, ipC_{16}, ipC_{18}, and ipC_{20}. Absolute and relative concentrations of *n*-alkanes and isoprenoid hydrocarbons were determined and reported. The compounds were identified from the chromatograms by comparing their retention times with the retention times of pure compounds.

7. $\delta^{34}S$, PERCENT S, $\delta^{15}N$, AND PERCENT N OF WHOLE OIL

Sulfur in bitumen was oxidized in a standard Parr bomb in an oxygen atmosphere. The resulting sulfate was precipitated at a pH of 4 as barium sulfate, using a 10-percent solution of $BaCl_2$. The $BaSO_4$ was collected on a tared millipore filter, air dried, and weighed, and the value was converted to percentage S.

A known weight of the barium sulfate was then mixed with an equivalent weight of cleaned and powdered quartz, placed in a quartz tube sealed at one end, covered with quartz wool, and heated in a furnace for 1 h at 800 °C to remove organic contaminants.

The quartz tube was then connected to a vacuum system, was pumped down to <0.01-Pa pressure, and heated to >1,000 °C with a hand-held torch. The effluent gases were passed through a dry-ice/acetone trap to remove water, and the oxygen was pumped away. The liberated SO_2 was then condensed in an LN_2 trap and frozen out in a gas sample tube for mass spectroscopy.

Nitrogen in bitumen was analyzed using a dry-combustion technique. This method involved the thermal combustion (at 850 °C for 4 h) of a known weight of dried bitumen with 1 g of CuO and in the presence of silver metal in an evacuated quartz tube. The reaction vessel was allowed to cool and the gases were trapped in LN_2. The organic nitrogen was entirely converted to N_2 gas during this combustion. This purified gas was pumped into a manometer, its volume measured, and the value converted to a percentage of N in the bitumen. The N_2 was next pumped into a gas sample tube for mass spectroscopy.

The purified SO_2 and N_2 were analyzed in a Nuclide Corp. dual-collecting mass spectrometer of 6-in. radius, 60° sector.

22. GEOCHEMISTRY OF OIL-FIELD WATER FROM THE NORTH SLOPE

By YOUSIF K. KHARAKA and WILLIAM W. CAROTHERS

INTRODUCTION

Knowledge of the chemical composition of oil-field water is important in understanding the origin and migration of petroleum (Hitchon and Horn, 1974; Carothers and Kharaka, 1978) as well as the water-mineral reactions that affect the porosity and permeability of the reservoir rocks. This knowledge is essential in interpreting electric logs and in determining potential pollution, corrosion, and disposal problems of water produced with oil and gas. Finally, the chemical composition of water is an important factor in determining the conditions (temperature, pressure) for the formation of clathrates.

Chemical analyses of surface water (from lakes, rivers, streams, and springs) from the North Slope of Alaska (Childers and others, 1977, 1979) show that it is generally of calcium-bicarbonate types having salinity usually less than 500 mg/L total dissolved solids. Information on the chemical composition of formation water from this area, on the other hand, is sparse. However, chemical analyses of water obtained from various formation tests are available for a number of exploration wells in the National Petroleum Reserve in Alaska (NPRA) (for example, Collins, 1958a-c; Robinson, 1959a, b). For many of these wells the reported analyses do not give the true chemical composition of their formation water because of mixing and contamination with drilling fluids. The reported salinities of water from these tests range from about 1,000 to 27,000 mg/L dissolved solids; the lower salinities probably result from the mixing of formation water with drilling fluids.

This chapter reports detailed chemical analyses of seven formation-water samples from wells within the NPRA and one surface- and two formation-water samples from the Prudhoe Bay oil field. We also report δD and $\delta^{18}O$ values for eight of the water samples as well as analyses for gases from six wells. The formation-water samples were obtained from depths ranging from about 700 to 2,800 m and from reservoir rocks ranging in age from Mississippian (Lisburne Group) to Triassic. The reservoir rocks are sandstone except for sample 79-AK-5, which was obtained from a limestone interbedded with sandstone. Generally, the pre-Cretaceous sandstone reservoir rocks on the North Slope have a similar mineral composition (Rickwood, 1970; van de Kamp, 1979). Van de Kamp (1979) gave the following description of these sandstones: Quartz (usually monocrystalline) and chert are the major components; carbonate and clay are variable. Carbonate occurs as detrital grains and as cement, siderite being the most common type. Siderite can form as much as 30 percent of the rock. Clay occurs as a common matrix, generally making up less than 10 percent of the rock. Accessory minerals include pyrite, plagioclase, microcline, glauconite, zircon, sphene, tourmaline, and muscovite.

ACKNOWLEDGMENTS

We thank the employees of the Atlantic Richfield Oil Co. for their cooperation and assistance in obtaining samples from the Prudhoe Bay oil field. A number of chemical analyses were performed by Victoria A. Wright and Michael S. Lico.

COLLECTION AND ANALYSIS OF FLUIDS

Proper methods must be used for the collection, preservation, and chemical analyses of fluids produced from petroleum wells in order to obtain reliable data. The methods described by Lico and others (1982) were used for the analysis of all the samples of table 22.1. In addition, the first six samples of table 22.1 were collected and preserved according to those methods; the last four samples, however, were obtained from drill-stem tests and were shipped to our laboratory unfiltered and untreated. Chemical data from drill-stem tests are generally not reliable because of contamination and mixing with the drilling fluid and mud (White, 1965; Kharaka and others, 1977). For our samples these problems were minimized because the samples were selected from a series obtained during the progress of each of the four drill-stem tests. Chemical data from these four samples, nevertheless, should only be used to indicate the general chemical composition of the formation water.

Another difficulty that affects the sampling and analysis of formation water from relatively shallow (low

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TABLE 22.1.—*Chemical analyses, well data, and stable-isotope values for samples of oil-field and surface waters from the North Slope*

[n.d., not measured or determined]

	Barrow			Prudhoe Bay			Pitt Point			Simpson Bay
Sample	78-AK-51	78-AK-52	78-AK-53	78-AK-54[1]	78-AK-55[2]	78-AK-56[3]	79-AK-1	79-AK-5	79-AK-8	80-AK-53
				Well data						
Well	S.Barrow 11	S.Barrow 5	S.Barrow 7	Arco 13 D.S. 1	Arco 8 D.S.3		Dalton 1			E.Simpson 2
Location	Sec. 14, T.22N., R.18W.			Sec.8, T.10N., R.15E.	Sec. 11, T.10N., R.15E.	Webster Lake	Sec. 14, T.18.N, R.5W.			Sec. 23, T.19N., R.11W.,
Reservoir unit	Barrow sandstone[4]			Sadlerochit Group	Sadlerochit Group		Sadlerochit Group	Lisburne Group	Sadlerochit Group	Sadlerochit Group
Sampled depth (m)	666-716	707-749	503-683	2,804-2,835	2,682-2,782	Surface	2,381-2,481	2,012-2,641	2,430-2,436	2,181-2,195
In-place temperature (°C)	17	16	13	94	90	4	n.d.	n.d.	n.d.	n.d.
				Chemical analyses (constituents in Mg/L)						
Total dissolved solids	20,600	22,100	19,000	21,900	17,000	730	23,000	21,800	21,900	24,200
Na	7,260	7,980	7,070	7,600	5,720	6.4	8,720	8,360	8,130	8,700
Li	1.3	2.1	1.5	4.0	3.3	.02	6.1	2.6	4.3	1.5
K	3.3	3.0	19	86	68	1.1	57	43	49	35
Rb	.2	.3	.1	.5	.5	<.01	.5	.23	.5	.2
Cs	.8	1.6	.8	1.1	.9	<.3	3.3	1.6	3.0	.9
Mg	66	67	57	20	16	8.3	22	2.7	22	54
Ca	224	119	166	182	151	71	140	31	185	280
Sr	13.4	16.1	12.5	20.2	13.1	.28	27	1.6	26	30
Ba	53	175	51	3.8	3.1	<.5	3.1	4.2	n.d.	6.3
Fe	138	5.5	4.6	63	57	1.9	<.1	2.3	.6	<.1
Cl	10,700	11,800	10,400	10,600	7,940	14	12,600	12,100	12,100	13,900
F	.7	1.6	1.1	1.5	.2	<.1	1.2	.1	.7	1.5
Br	49	62	36	54	40	1.2	61	n.d.	59	53
I	11	28	11	19	14	.1	30	n.d.	31	29
B	20	42	19	158	115	n.d.	130	n.d.	120	112
NH_3	9	19	9	17	5	<.3	15	n.d.	n.d.	18
H_2S	<.1	<.1	<.1	<.1	<.1	<.1	n.d.	n.d.	n.d.	n.d.
HCO_3	320	1,480	720	2,680	2,560	205	[5]1,100	[5]1,280	[5]1,150	[5]870
CH_3COO	1,660	230	290	250	240	n.d.	n.d.	n.d.	n.d.	n.d.
SO_4	3.1	n.d.	2.2	69	33	18	31	n.d.	n.d.	34
SiO_2	9	11	16	62	23	.8	42	n.d.	n.d.	26
pH	6.8	7.2	7.3	6.5	6.3	n.d.	[5]8.6	[5]8.1	[5]8.0	[5]6.7
				Stable isotopes (in permil relative to SMOW)						
$\delta^{18}O$	n.d.	-1.66	-.94	+6.06	+2.61	-18.54	+2.78	+1.85	+1.55	+2.57
δD	n.d.	-44.8	-50.5	-34.4	-38.9	-149.6	-35.5	-40.8	-40.2	-34.9

[1] Sample taken below oil-water contact.

[2] Water sample diluted by 30 percent condensed water vapor (see text for details).

[3] Water sample collected from lake containing 40 percent ice (see text for details).

[4] Informal unit of local usage.

[5] Measured in the laboratory.

temperature) reservoirs of the North Slope is the presence of a zone of permafrost that extends from the surface to a depth that exceeds 600 m in certain areas. Ethyl alcohol is injected into wells at Barrow to prevent the freezing of formation water as it ascends through this zone. Samples 78-AK-51, -52, and -53 contained 6, 0.2, and 11 percent ethyl alcohol by volume, respectively, at the time of sampling. Results of laboratory experiments, using the method of addition, showed that the effect of ethyl alcohol on various chemical analyses is different and is not proportional to the volume of alcohol in the water. Chemical analyses for these three samples were corrected for the presence of alcohol.

Sample 78-AK-56 was collected from Webster Lake on April 28, 1978, when the lake was partly frozen. Computations, using the thickness of ice and the chemical composition of lake water before the freeze and at the time of sampling, show that ice constituted about 40±10 percent of the total volume of the lake. Chemical analyses for this sample (table 22.1) have not been corrected for the volume of ice.

Finally, sample 78-AK-55 was collected from a gas separator that is used for collecting fluids from several wells. We concluded that this sample was obtained from well DS3-8 because, according to the field operator, only this well was producing an appreciable amount of water, and for 3 hours before the sampling all the other wells were excluded from this separator. The following lines of evidence, however, indicate that the chemical composition reported (table 22.1) for sample 78-AK-55 is a modified composition for the formation water from that well:

1. The concentration of silica is lower than expected from the solubility of quartz with water at the reported subsurface temperature (90 °C). The concentration of silica in oil-field (Kharaka and others, 1977) and geothermal (Kharaka and Mariner, 1988) waters is controlled by the solubility of quartz at subsurface temperatures higher than about 70 °C.
2. Unpublished chemical analyses of formation water from two wells producing from the same zone as that of this sample, one from Atlantic Richfield's side and the other from British Petroleum's side of the field, show a total content of dissolved solids of about 22,000 mg/L. Jones and Speers (1976, p. 49) report that the average total content of dissolved solids from this formation is slightly in excess of 20,000 mg/L, which is remarkably similar to that of sample 78-AK-54 (table 22.1).

We consider it most likely that the chemical composition of sample 78-AK-55 represents formation water mixed with about 30±10 percent freshwater, probably from condensation of the water vapor that is produced with natural gas. This dilution factor is obtained by averaging the 34±4 percent calculated by assuming equilibrium with quartz and the 25±5 percent based on the ratios of many dissolved constituents between samples 78-AK-55 and -54. Chemical analyses for sample 78-AK-55 have not been corrected for this dilution factor.

ORIGIN OF FORMATION WATER

Stable-isotope analyses of oil-field water from many basins have been used to show that the water is predominantly of local meteoric origin—the original connate water of deposition having been lost by compaction and subsequent flushing (Clayton and others, 1966; Hitchon and Friedman, 1969; Kharaka and others, 1973; Kharaka and Carothers, 1986). Stable isotope analyses of water from many major geothermal systems of the world have shown that such water is also dominantly meteoric in origin (Craig, 1963, 1966; White and others, 1973). Kharaka and others (1978), on the other hand, used stable isotopes and fluid potentials to show that formation waters from the northern Gulf of Mexico basin were connate waters representing the original marine water of deposition. White and others (1973) showed that water from thermal springs in the northern California Coast Ranges was metamorphic in origin.

A mixture of meteoric water and standard mean ocean water (connate?) is ruled out as a source for the water samples of this study because of an absence of correlation between the isotope values and water salinities or concentrations of chloride. Also, such a mixing model would require about the same proportions of meteoric and ocean water for all the water samples of this study, a condition considered very unlikely because of the large differences in the depth and areal extent of the reservoir rocks.

The plot of δD versus $\delta^{18}O$ (fig. 22.1) shows the least-squares line drawn through the isotope values of the formation-water samples of table 22.1. Corrected values were used for δD and $\delta^{18}O$ of sample 78-AK-55 (although no appreciable change is seen when original values are used). For this correction, we used mixing of formation water with 30 percent condensed water vapor, as calculated in the previous section. The water vapor was assumed to be in isotopic equilibrium with formation water at the reservoir temperature (90 °C). The fractionation factor between water and vapor was obtained from Friedman and O'Neil (1977). The isotope values and the least-squares line from figure 22.1 have been replotted in figure 22.2 together with the line for all meteoric water (Craig, 1961) and isotope values for formation water from well 1-C-1 from Kuparak field, Webster Lake, standard mean ocean water (SMOW), and precipitation at Point Barrow. The values for Point Barrow are for the yearly weighted average composition of precipitation (Burk and Stuiver, 1981). The least-squares line for formation water intersects the line for all meteoric water (Craig, 1961) at δD and δ^{18}O values of about −65 and −7 permil, respectively. We note that the line for formation water (fig. 22.2) does not pass through the points giving isotope values for SMOW or for Webster Lake and Point Barrow.

The most likely conclusion to be drawn from figures 22.1 and 22.2 is that all the formation water is meteoric in origin. The meteoric water had original δD and δ^{18}O values of about −65 and −7 permil, respectively. The shifts in the values of δD and D^{18}O from those of the original meteoric water are not related to water salinity or concentration of chloride, but they are related (fig. 22.3) to the depth (temperature) of the reservoir rocks and probably resulted from exchange reactions with minerals that had contacted the water (White and others, 1973; O'Neil and Kharaka, 1976; Yeh and Savin, 1977) and from the membrane behavior of shale (Coplen and Hanshaw, 1973; Kharaka and Carothers, 1986).

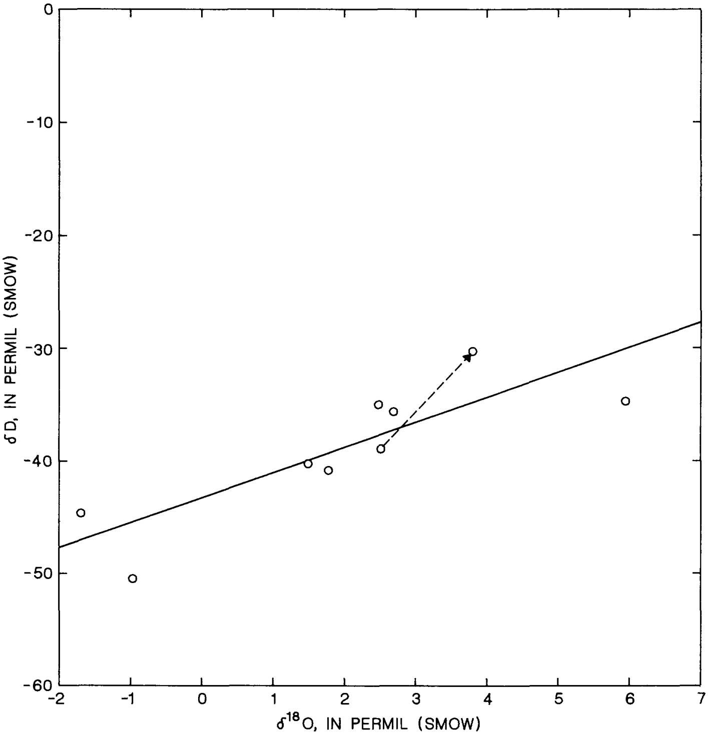

FIGURE 22.1.—Stable-isotope values for samples of formation water from the North Slope. Dashed arrow goes from raw isotope values of sample 78-AK-55 to corrected values (see text for details). Solid line is least-squares line drawn through data points, using corrected values for sample 78-AK-55.

The isotope values for present-day meteoric water on the North Slope are much lighter than the values for the presumed original meteoric water. Sample 78-AK-56 was collected from Webster Lake, the water supply for the Prudhoe Bay Camp. The water comes from the Sagavanirktok River, which originates in the Brooks Range. We estimate that the volume of ice at Webster Lake at the time of sampling was 40 ± 10 percent (see previous section for details). Correcting for this volume of ice by using fractionation factors between water and ice reported by Friedman and O'Neil (1977) and assuming a closed system for the lake, we derive δD and δ^{18}O values of −160 and −20 permil, respectively. These values appear reasonable for meteoric water from the Brooks Range when compared with isotope values for meteoric water reported by Burk and Stuiver (1981) for Point Barrow, by Miller and others (1975) for west-central Alaska, by Hitchon and Krouse (1972) for the McKenzie River basin, Canada, and by Brown (1970) for Alaska, Canada, and Greenland. Values for δD and δ^{18}O of present-day meteoric water for Point Barrow are higher (heavier) than those from the Brooks Range (fig. 22.2) because of the lower elevations and the closeness to the Arctic Ocean.

The most likely conclusion that can be drawn from the isotope data of this study is that the formation water in all the sites sampled is meteroic in origin but that recharge took place when the North Slope had an entirely different climate. Dansgaard (1964) has shown that present-day meteroic water changes in δD and δ^{18}O by 5.6 and 0.7 permil, respectively, for every 1-°C change in mean annual temperature. Using these data, we infer that the mean annual temperatures at the Brooks Range (the probable recharge area) would have had to be 15-20 °C higher at the time of recharge than at present.

There are two possible ways to produce meteoric water on the North Slope with the isotope values of the presumed recharge water. The first assumes climatic and topographic conditions at the time of recharge that were similar to those of the present day but requires a latitude for the North Slope different from its present position. The distribution of isotope values for present-day meteoric water in North America (Taylor and Magaritz, 1978, fig. 1) indicate that the North Slope would have been south of lat 48° N.; at about that latitude, the contour line of isotope values equal to those of the presumed recharge water crosses from the continent to the Pacific Ocean. Placing northern Alaska at such a more southerly latitude than its present position may not be in disagreement with current theories on the tectonic framework of Alaska (Tailleur and Brosgé, 1970; Grantz and others, 1979; Coney and others, 1980). These theories indicate a very complex tectonic framework that involves rifting in the Arctic Basin and the building of Alaska from numerous allochthonous blocks that collided and accreted the North American cratonic margin mostly during Mesozoic and early Cenozoic time.

A more plausible explanation, however, would keep northern Alaska in its present location but change the climatic conditions so that mean annual temperatures were 15-20 °C higher than at present. Mean annual temperatures during parts of interglacial periods may have been higher in northern Alaska than now, but less so than would be required to explain the water samples of this study (Habicht, 1979; D.M. Hopkins, oral commun., 1981). However, paleoclimatic indicators show that North America (including northern Alaska) had warmer climates than at present through most of Mesozoic and Tertiary time (Smiley, 1967; Hopkins and others, 1971; Irving, 1978; Habich, 1979; Wolfe, 1980). These studies show that the mean annual temperatures in northern Alaska required to account for the recharge water inferred in this study (15-20 °C higher than at present) were reached as early as

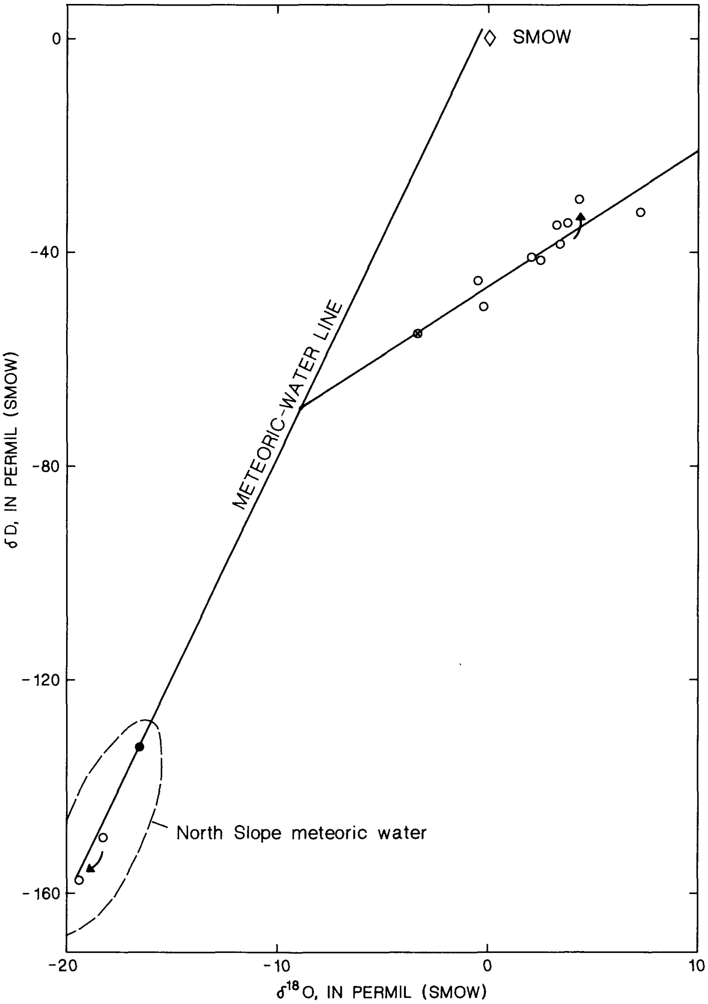

FIGURE 22.2.—Stable-isotope values for samples of formation water from the North Slope (from fig. 22.1), together with values for position of SMOW (diamond) and values for a sample (crossed circle) from the Kuparak field. Approximate field for meteoric water from North Slope is based on values for precipitation at Point Barrow (dot) and raw and corrected isotopes for Webster Lake (circles). Arrows go from raw to corrected isotope values (see text for details).

Miocene and continued throughout most of early Cenozoic time. The actual time of recharge cannot be determined, but it is clear that the formation waters of this study, even though meteoric, are extremely old. The permafrost probably helped to preserve the ancient water in the sedimentary rocks by preventing any new recharge.

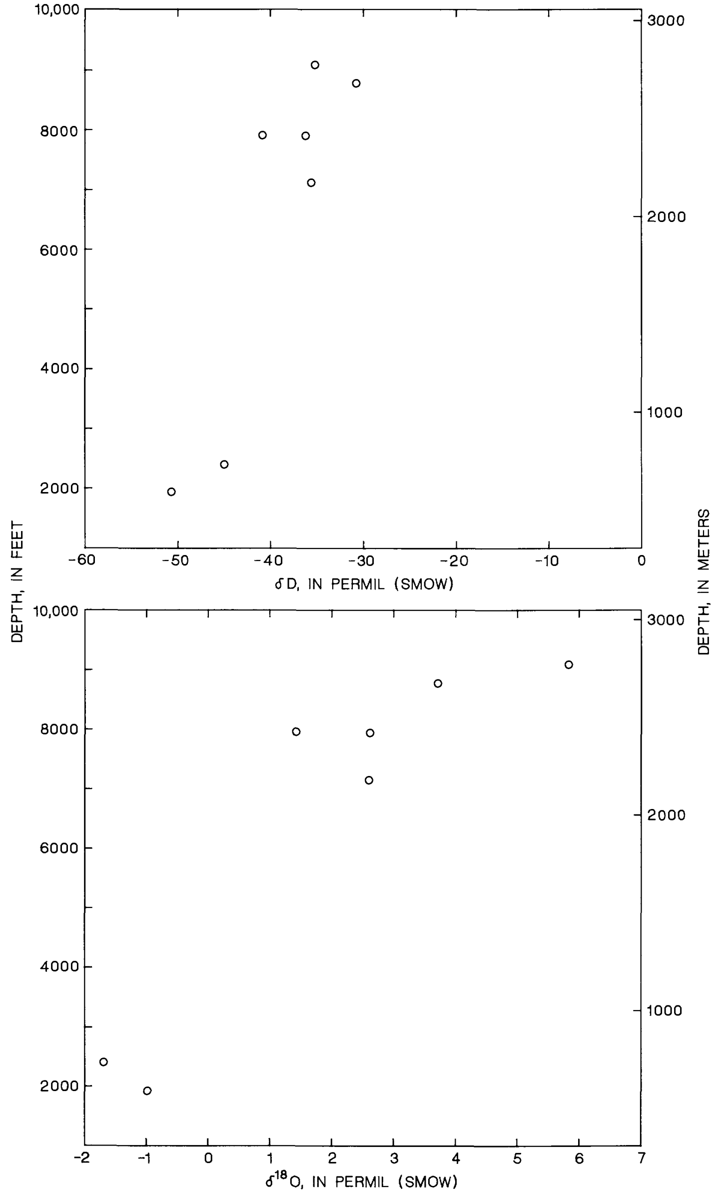

FIGURE 22.3.—Variation of stable-isotope values of formation water with depth of reservoir rocks. Note general increase of both δD and $\delta^{18}O$ with increasing depth.

CHEMICAL COMPOSITION OF THE WATERS

Chemical analyses of formation water from the North Slope (table 22.1) show relatively low salinities that range from 19,000 to 24,000 mg/L total dissolved solids. This extremely narrow range of salinities is remarkable considering the wide areal distribution of the wells, the great differences in the depths (700 to 2,800 m) of the reservoir rocks, and the different lithologies (table 22.1).

The distribution of major cations and anions in the formation water (fig. 22.4) is also rather uniform. All the samples are of Na-Cl type, Na constituting more than 95 percent of the total cations and Cl generally constituting more than 90 percent of the anions. The concentration of HCO_3^- is moderately high, especially at Prudhoe Bay oil field, but the concentration of SO_4^{2-} is extremely low in comparison with seawater or oil-field water from

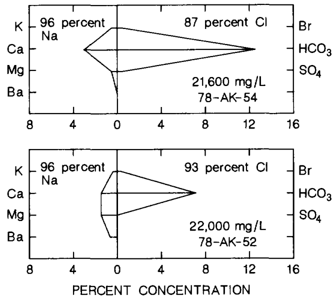

FIGURE 22.4.—Modified Stiff diagrams for two formation-water samples (table 22.1), showing the remarkable similarity in salinity as well as concentrations of major cations and anions of formation waters from South Barrow (sample 78-AK-52) and Prudhoe Bay fields (sample 78-AK-54).

other basins. The concentration of boron is extremely high in all the formation water of this study, and that of Ba is moderately high. Concentration of Fe is high in the samples that were acidified in the field. Samples from the J.W. Dalton and East Simpson wells were not acidified, and their low Fe values probably result from precipitation of $Fe(OH)_3(s)$ after the samples were collected.

The rather high concentrations of boron (toxic to plants) and ammonia (toxic to fish) in the formation water of this study may preclude its disposal into surface water, even though the salinity of the formation water is relatively low and concentrations of H_2S and other toxic constituents are very low. Disposal of the water by injection probably would not result in precipitation of large quantities of minerals because all the waters of this study, regardless of depth, are reasonably compatible in composition.

It is tempting, but probably not very instructive, to explain in detail how the change in the chemical composition of the presumed original meteoric water to that of the observed formation water occurred. The limited number of wells sampled, the limited usefulness of chemical data from drill-stem tests, and the fact that we have no values for concentrations of Al or subsurface pH preclude any meaningful quantitative analyses of these data. Nevertheless, the similarity in chemical composition of all the samples indicates, assuming a common meteoric origin, that they have been subjected to the same water-rock interactions (including dissolution, precipitation, and membrane phenomena) that modified the original composition. Chloride/bromide ratios show the water to be slightly enriched in Br with respect to the evaporation line for seawater, indicating no contact with evaporites.

TABLE 22.2.—*Changes in porosity of reservoir rocks resulting from incongruent dissolution of minerals.*

[Percent volume change calculated by dividing change in the volume of solid phases by volume or volumes of dissolving minerals; result is multiplied by 100]

Reaction	Percent pore volume change
$2CaAl_2Si_2O_8 + 4SiO_2 + 2HCO_3^- + 2Na^+ + H_2O \longrightarrow$ $2NaAlSi_3O_8 + Al_2Si_2O_5(OH)_4 + 2CaCO_3$	-28
$2Na_{.5}Ca_{.5}Al_{1.5}Si_{2.5}O_8 + HCO_3^- + H^+ + H_2O \longrightarrow$ $NaAlSi_3O_8 + Al_2Si_2O_5(OH)_4 + CaCO_3$	-17
$4Na_{.75}Ca_{.25}Al_{1.25}Si_{2.75}O_8 + HCO_3^- + H^+ + H_2O \longrightarrow$ $NaAlSi_3O_8 + 2Al_2Si_2O_5(OH)_4 + 4SiO_2 + CaCO_3$	- 6
$CaMgSi_2O_6 + 2HCO_3^- + 2H^+ \longrightarrow$ $CaMg(CO_3)_2 + 2SiO_2 + 2H_2O$	-68
$KAlSi_3O_8 + 2H^+ + H_2O \longrightarrow$ $Al_2Si_2O_5(OH)_4 + 4SiO_2 + 2K^+$	+13
$5KAlSi_3O_8 + 4H^+ \longrightarrow KAl_5Si_7O_{20}(OH)_4 + 8SiO_2 + 4K^+$	+30
$2CaCO_3 + Mg^{++} \longrightarrow CaMg(CO_3)_2 + Ca^{++}$	+12

The differences in the concentrations of the alkali metals (table 22.1) can be explained by temperature-dependent exchange reactions with clay and feldspar (see, for example, White, 1965; Ellis and Mahon, 1967; Kharaka and others, 1985). Computations with the updated chemical model SOLMNEQ (Kharaka and Barnes, 1973; Kharaka and others, 1985), using data of samples 78-AK-52 and 78-AK-54 (table 22.1), show that both of these samples are supersaturated with carbonates of Ca, Sr, Fe, and Ba and sulfate of Ba. Computations using chemical data from other sedimentary basins have shown (Kharaka and others, 1978) that these minerals control the concentration of divalent cations. For the water samples of this study, no such definitive conclusions about divalent carbonates can be made, because the pH values of table 22.1 were measured at surface conditions and data are insufficient to compute subsurface pH values.

The porosity and permeability of reservoir rocks are greatly affected by the water that comes in contact with them. Water supersaturated with a particular mineral may cause porosity loss because that mineral is precipitated. Secondary porosity, on the other hand, is caused by congruent and, in some cases, incongruent dissolution of minerals by water undersaturated with respect to the dissolving minerals. Table 22.2 shows some incongruent reactions that affect the porosity of reservoir rocks. Albitization of plagioclase feldspar results in porosity loss, but dolomitization of limestone and the formation of clay from K-feldspar result in secondary porosity. Another important reaction in the sandstones of the North Slope is the dissolution of chert and precipitation of quartz as overgrowths (van de Kamp, 1979). The rate of this reaction increases as temperature increases, and it results in enhanced porosity because of the higher density of quartz as compared to chert.

Exposure of reservoir rocks to surface conditions at any time provides ideal conditions for development of secondary porosity by percolating meteoric water. Recharging meteoric water will dissolve chert, pyrite, siderite, and other detrital and diagenetic minerals in potential reservoir rocks, but this water, as it percolates through the rocks, becomes saturated with these minerals and then dissolution ceases. The zone of secondary porosity will increase in thickness as more meteoric water recharges and percolates downdip. Basins with recharge areas at high elevation and low-lying discharge areas are ideal for development of good-quality reservoir rocks by this process. The limited chemical and isotopic data of this study are too ambiguous for the delineation of recharge areas. Besides, it is likely that fluid-flow directions in the North Slope were different in pre-Cretaceous time from those of today.

FORMATION OF CLATHRATES

Methane hydrates require relatively low temperatures but high pressures for their formation. These conditions are present in two basically different environments: the first is the ocean bottom, and the second is in or near areas of terrestrial permafrost like those on the North Slope. Chemical compositions of water and associated gases are factors in determining the conditions for the formation of clathrates. The temperature for the formation of methane hydrate at a pressure of 6.9 MPa (1,000 psia), for example, is lowered by 1 and 3 °C if the salinity of the water is increased from 0 to 35,000 (seawater) and 100,000 mg/L dissolved solids, respectively (fig. 22.5). The temperature for the formation of methane hydrate at this pressure, on the other hand, is increased by 1 and 2 °C if, respectively, 10 percent and 20 percent CO_2 gas is added to methane; this temperature is increased by 2 and 6 °C if 1 percent and 5 percent H_2S gas is added to the methane (fig. 22.5).

The chemical data from this study (table 22.1) show that the salinities of formation water from the North Slope are rather uniform, ranging from about 19,000 to 24,000 mg/L total dissolved solids. A larger range of salinities (1,000 to 27,000 mg/L) has been reported (see, for example, Collins, 1958a-c; Robinson, 1959a, b, 1964) for water obtained from various formations in the NPRA, but those data, as already stated, are difficult to evaluate. All these chemical data indicate that the most probable range for salinity in formation water for the formation of clathrates in the NPRA is 10,000 to 25,000 mg/L total dissolved solids. These salinities will lower the temperature at which methane hydrates form by a maximum of 2 °C (fig. 22.5) from that for pure water and methane at a given pressure (depth).

The composition of gases obtained from six wells on the North Slope is listed in table 22.3. Nitrogen is the only gas present in appreciable quantities in natural gas that lowers the temperature for the formation of methane hydrate (fig. 22.5). The amount of nitrogen present in natural gases from North Slope wells (table 22.3) is small and will not significantly affect the formation of clathrates, even though a given proportion of this gas increases the temperature of clathrate formation by a larger amount than the same proportion of any other gas (fig. 22.5). Neither the gas analyses (table 22.3) nor the water analyses (table 22.1) from the North Slope detected H_2S. We believe that the high concentration of iron in formation water will precipitate any H_2S as pyrite or other sulfides of iron.

The CO_2 content of separator gas from the Prudhoe Bay field is very high, averaging about 16 percent (table 22.3). The addition of this amount of CO_2 to methane increases the temperature for hydrate formation by about 2 °C. The CO_2 content of gas from test and producing wells in the NPRA, on the other hand, is less than 2 percent (table 22.3), which will increase this temperature by less than 0.5 °C.

The presence of ethane, propane, and isobutane will increase the temperature (see fig. 22.5 for ethane and propane) for the formation of methane hydrate (Katz and others, 1959; Hand and others, 1974). Ethane is almost always (biogenic gas being an exception) an important constituent of natural gas (Tissot and Welte, 1978). On the North Slope, the ethane content of gas ranges from a low of about 1 percent in the thermogenic ($\delta^{13}C$ of methane is about -40 permil) dry gas at Barrow to more than 10 percent in gas associated with oil at Prudhoe Bay (table 22.3). Even 1 percent of ethane at Barrow increases the temperature for clathrate formation by 2 °C; 15 percent ethane (assuming C_2-C_6 gas is all ethane) at Prudhoe Bay increases that temperature by 10 °C. The propane and isobutane content of gas at Barrow is very small (<0.1 mol percent), but at Umiat (Collins, 1958a) it is about 1 percent, which will increase the temperature for clathrate formation by at least 6 °C.

Combining the effects of water salinity and gas composition shows that at Barrow the two effects cancel each other out, and one can calculate the temperature and pressure for clathrate formation by using the values for pure water and methane; at Prudhoe Bay the total effect will be to increase the temperature for the formation of methane hydrate by at least 10 °C. In addition to this higher temperature of possible formation, conditions in the Prudhoe Bay area are more conducive to clathrate formation than in the Barrow area because the thickness of the zone of permafrost (⩾600 m) is more than twice that at Barrow.

CONCLUSIONS

The limited chemical data of this study show that the composition of formation water from sampled wells on the North Slope, regardless of the age, depth, or lithology of the reservoir rocks, is remarkably uniform both in total dissolved solids (19,000-24,000 mg/L) and in

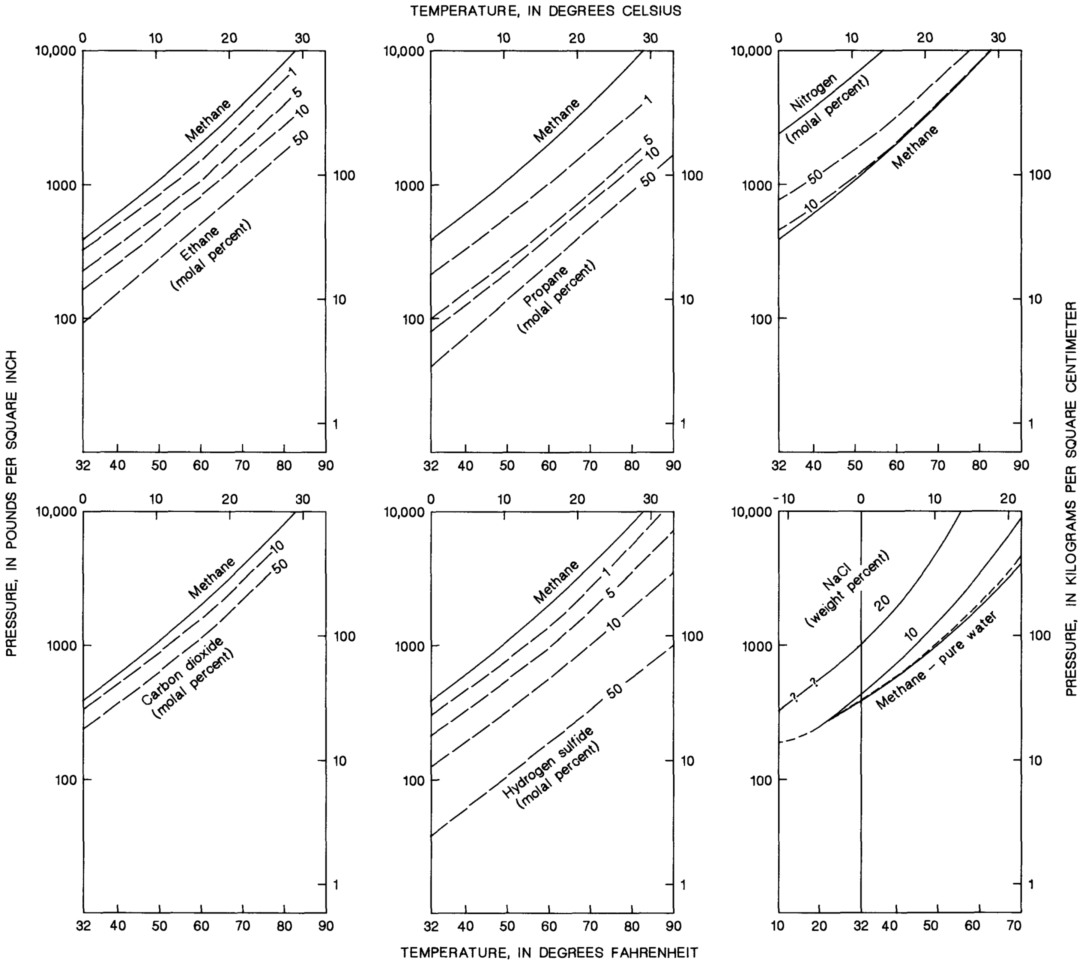

FIGURE 22.5.—Phase diagrams showing relative effects of adding various amounts of different gases and of sodium chloride on the conditions for initial formation of methane hydrate. Dashed line on diagram showing effects of NaCl is for effects of water salinity on formation water from South Barrow. Modified from Hitchon (1974).

Table 22.3.—*Composition of gases from petroleum wells on the North Slope.*

[Figures in mole percent; n.d., not determined]

Sample----	78-AK-51	78-AK-52	78-AK-54	79-AK-8	---	---
Well------	S. Barrow 11	S. Barrow 5	ARCO 13 D.S. #3	Dalton 1	B.P. Put River	B.P. 7-11-13
CH_4--------	94.8	98.9	54.8	97.3	68.5	68.1
C_2H_6-------	1.0	.9	1.28	1.0	15.1	1.19
C_{3+}--------	.1	.1	.01	1.02		.38
CO_2--------	.15	.20	42.9	.01	15.7	29.1
N_2---------	.8	.9	.92	.7	.6	.94
He---------	.03	.03	.03	n.d.	n.d.	.33
H_2---------	.01	.01	.07	n.d.	n.d.	n.d.
Ar---------	.01	.01	.01	n.d.	n.d.	n.d.
O_2---------	.01	.01	.01	n.d.	n.d.	n.d.

dissolved constituents. The combined effects of water salinity and composition of natural gas on clathrate formation on the North Slope are varied. In the Prudhoe Bay area these combined effects increase the temperature for the formation of methane hydrates by at least 10 °C; in the Barrow area the effect is negligible.

Finally, the most significant conclusion of this study is from data on the stable isotopes of the formation water. The isotopes indicate that the water is meteoric in origin, but this original meteoric water had δD and $\delta^{18}O$ values much heavier than those of present-day meteoric water of the area. To explain this difference requires either a location for the North Slope, at the time of recharge, thousands of kilometers to the south of its present location, or, more likely, climatic conditions at high latitudes with mean annual temperatures 15-20 °C higher than at present. Obviously more data will be welcomed, especially information on the stable isotopes of present-day meteoric water from the Brooks Range and coastal areas of the North Slope and on isotopes and chemical composition of formation water from wells in the Colville trough and foothills of the Brooks Range. We hope to fill some of these information gaps.

REFERENCES CITED

Brown, R.M., 1970, Distribution of hydrogen isotopes in Canadian waters: Proceedings International Atomic Energy Agency (IAEA), Vienna, March 1970, paper SM129/1, 11 p.

Burk, R.L., and Stuiver, M., 1981, Oxygen isotope ratios in trees reflect annual temperature and humidity: Science, v. 211, p. 1417-1419.

Carothers, W.W., and Kharaka, Y.K., 1978, Aliphatic acid anions in oil-field waters and their implications for the origin of natural gas: American Association of Petroleum Geologists Bulletin, v. 62, p, 2441-2453.

Childers, J.M., Kernodle, D.R., and Loeffler, R.M., 1979, Hydrologic reconnaissance of western Arctic Alaska, 1976 and 1977: U.S. Geological Survey Open-File Report 79-699, 70 p.

Childers, J.M., Sloan, C.E., Meckel, J.P., and Nauman, J.W., 1977, Hydrologic reconnaissance of the eastern North Slope, Alaska, 1975: U.S. Geological Survey Open-File Report 77-492, 77 p.

Clayton, R.N., Friedman, Irving, Graf, D.L., Mayeda, T.K., Meents, W.F., and Shimp, N.F., 1966, The origin of saline formation waters. I. Isotopic composition: Journal of Geophysical Research, v. 71, no. 16, p. 3869-3882.

Collins, F.R., 1958a, Test wells, Umiat area: U.S. Geological Survey Professional Paper 305-B, p. 71-206.

——— 1958b, Test wells, Topagoruk area, Alaska: U.S. Geological Survey Professional Paper 305-D, p. 265-316.

——— 1958c, Test wells, Meade and Kaolak areas, Alaska: U.S. Geological Survey Professional Paper 305-F, p. 341-376.

Coney, P.J., Jones, D.L., and Monger, J.W.H., 1980, Cordilleran suspect terranes: Nature, v. 288, p. 329-333.

Coplen, T.B., and Hanshaw, B.B., 1973, Ultrafiltration by a compacted clay membrane—I. Oxygen and hydrogen isotopic fractionation: Geochimica et Cosmochimica Acta, v. 37, p. 2295-2310.

Craig, Harmon, 1961, Isotopic variations in meteoric waters: Science, v. 133, p. 1702-1703.

——— 1963, The isotopic geochemistry of water and carbon in geothermal areas, in Tongiorgi, E., ed., Nuclear geology on geothermal areas: Pisa, Italy, Consiglio Nazionale delle Ricerche, p. 17-53.

——— 1966, Superheated steam and mineral-water interactions in geothermal areas [abs.]: American Geophysical Union Transactions, v. 47, p. 204.

Dansgaard, W., 1964, Stable isotopes in precipitation: Tellus, v. 16, p. 436-468.

Ellis, A.J., and Mahon, W.A.J., 1967, Natural hydrothermal systems and experimental hot water/rock interactions: Geochimica et Cosmochimica Acta, v. 31, p. 519-538.

Friedman, Irving, and O'Neil, J.R., 1977, Compilation of stable isotope fractionation factors of geochemical interest: U.S. Geological Survey Professional Paper 440-KK, p. KK1-KK12.

Grantz, Arthur, Eittreim, S.L., and Whitney, O.T., 1979, Geology and physiography of the continental margin north of Alaska and implications for the origin of the Canada basin: U.S. Geological Survey Open-File Report 79-288, 75 p.

Habicht, J.K.A., 1979, Paleoclimate, paleomagnetism, and continental drift: American Association of Petroleum Geologists Studies in Geology, no. 9, 31 p.

Hand, J.H., Katz, D.L., and Verma, V.K, 1974, Review of gas hydrates with implication for ocean sediments: Marine Science, v. 3, p. 179-194.

Hitchon, Brian, 1974, Occurrence of natural gas hydrates in sedimentary basins: Marine Science, v. 3, p. 195-225.

Hitchon, Brian, and Friedman, Irving, 1969, Geochemistry and origin of formation waters in the Western Canada sedimentary basin, I. Stable isotopes of hydrogen and oxygen: Geochimica et Cosmochimica Acta, v. 33, p. 1321-1349.

Hitchon, Brian, and Horn, M.K., 1974, Petroleum indicators in formation waters from Alberta, Canada: American Association of Petroleum Geologists Bulletin, v. 58, p. 464-473.

Hitchon, Brian, and Krouse, H.R., 1972, Hydrogeochemistry of the surface waters of the Mackenzie River drainage basin, Canada—III. Stable isotopes of oxygen, carbon, and sulphur: Geochimica et Cosmochimica Acta, v. 36, p. 1337-1357.

Hopkins, D.M., Matthews, J.V., Wolfe, J.A., and Silberman, M.L., 1971, A Pliocene flora and insect fauna from the Bering Strait region: Paleogeography, Paleoclimatology, Paleoecology, v. 9, p. 211-231.

Irving, E., 1978, Paleopoles and paleolatitudes of North America and speculations about displaced terrains: Canadian Journal of Earth Sciences, v. 16, p. 669-694.

Jones, H.P., and Speers, R.G., 1976, Permo-Triassic reservoirs of Prudhoe Bay field, North Slope, Alaska, *in* Braunstein, Jules, North American oil and gas fields: American Associaton of Petroleum Geologists Memoir 24, p. 23-50.

Katz, D.L., Cornell, D., Kobayashi, R., Poettmann, F.H., Vary, J.A., Elenbass, J.R., and Weinaug, C.F., 1959, Handbook of natural gas engineering: New York, McGraw-Hill, 802 p.

Kharaka, Y.K., and Barnes, Ivan, 1973, SOLMNEQ; solution-mineral equilibrium computations: U.S. Geological Survey Computer Contributions, National Technical Information Service Report PB-215-899, 81 p.

Kharaka, Y.K., Berry, F.A.F., and Friedman, Irving, 1973, Isotopic composition of oil-field brines from Kettleman North Dome, California, and their geologic implications: Geochimica et Cosmochimica Acta, v. 37, p. 1899-1908.

Kharaka, Y.K., Callender, Edward, and Carothers, W.W., 1977, Geochemistry of geopressured geothermal waters from the Texas Gulf Coast: Geopressured-Geothermal Energy Conference, Lafayette, La., 1977, Proceedings, p. GI-121 to GI-165.

Kharaka, Y.K., and Carothers, W.W., 1986, Oxygen and hydrogen isotope geochemistry of deep basin brines, chap. 2 *of* Fritz, Peter, and Fontes, J., eds., Handbook of environmental isotope geochemistry: Amsterdam, Elsevier, v. 2, p. 305-360.

Kharaka, Y.K., Carothers, W.W., and Brown, P.M., 1978, Origins of waters and solutes in the geopressured zones of the northern Gulf of Mexico Basin: Society of Petroleum Engineers of American Institute of Mining and Metallurgical Engineers Annual Conference, 53d, Proceedings, preprint paper SPE 7505, 8 p.

Kharaka, Y.K., Hull, R.W., and Carothers, W.W., 1985, Water-rock interactions in sedimentary basins, chap. 2 *of* Relationship of organic matter and mineral diagenesis: Society of Economic Paleontologists and Mineralogists Short Course 17, p. 79-176.

Kharaka, Y.K., and Mariner, R.H., 1988, Chemical geothermometers and their application to formation waters from sedimentary basins, *in* Naeser, N.D., and McCullough, T.H., eds., Thermal history of sedimentary basins—methods and case histories: New York, Springer Verlag, p. 99-117.

Lico, M.S., Kharaka, Y.K., Carothers, W.W., and Wright, V.A., 1982, Methods for collection and analysis of geopressured geothermal and oil field waters: U.S. Geological Survey Water-Supply Paper 2194, 21 p.

Miller, T.P., Barnes, Ivan, and Patton, W.W., Jr., 1975, Geologic setting and chemical characteristics of hot springs in western-central Alaska: U.S. Geological Survey Journal of Research, v. 3, no. 2, p. 149-162.

O'Neil, J.R., and Kharaka, Y.K., 1976, Hydrogen and oxygen isotope exchange reactions between clay minerals and water: Geochimica et Cosmochimica Acta, v. 40, p. 241-246.

Rickwood, F.K., 1970, The Prudhoe Bay field, *in* Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska: Los Angeles, American Association of Petroleum Geologists, Pacific Section, p. L1-L11.

Robinson, F.M., 1959a, Test wells, Titaluk and Knifeblade areas, Alaska: U.S. Geological Survey Professional Paper 305-G, p. 377-422.

—— 1959b, Test wells, Simpson area, Alaska: U.S. Geological Survey Professional Paper 305-J, p. 523-568.

—— 1964, Core tests, Simpson area, Alaska: U.S. Geological Survey Professional Paper 305-L, p. 645-730.

Smiley, C.J., 1967, Paleoclimatic interpretations of some Mesozoic floral sequences: American Association of Petroleum Geologists Bulletin, v. 51, p. 849-863.

Tailleur, I.L., and Brosgé, W.P., 1970, Tectonic history of northern Alaska, *in* Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska: Los Angeles, American Association of Petroleum Geologists, Pacific Section, p. E1-E20.

Taylor, H.P., Jr., and Magaritz, Mordeckai, 1978, Oxygen and hydrogen isotope studies of the Cordilleran batholiths of western North America: New Zealand Department of Scientific and Industrial Research Bulletin 220, p. 151-173.

Tissot, B.P., and Welte, D.H., 1978, Petroleum formation and occurrence: New York, Springer-Verlag, 538 p.

van de Kamp, P.C., 1979, Stratigraphy and diagenetic alteration of Ellesmerian sequence siliciclastic rocks, North Slope, Alaska: ONPRA Preliminary Report 7995, 56 p. [Available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey].

White, D.E., 1965, Saline waters of sedimentary rocks, *in* Young, Addison, and Galley, J.E., eds., Fluids in subsurface environments: American Association of Petroleum Geologists Memoir 4, p. 342-366.

White, D.E., Barnes, Ivan, and O'Neil, J.R., 1973, Thermal and mineral waters of nonmeteoric origin, California Coast Range: Geological Society of American Bulletin, v. 84, p. 547-560.

Wolfe, J.A., 1980, Tertiary climates and floristic relationships at high latitudes in the northern hemisphere: Paleogeography, Paleoclimatology, Paleoecology, v. 30, p. 313-323.

Yeh, H.W., and Savin, S.M., 1977, Mechanism of burial metamorphism of argillaceous sediments; 3. O-isotope evidence: Geological Society of America Bulletin, v. 88, p. 1321-1330.

23. INORGANIC CHEMICAL ANALYSES OF BLACK SHALE FROM WELLS IN THE NATIONAL PETROLEUM RESERVE IN ALASKA

By WILLIAM P. BROSGÉ and IRVIN L. TAILLEUR

INTRODUCTION

Core samples of Mississippian through Upper Cretaceous black shale, siltstone, and limy mudstone from 24 test wells in the National Petroleum Reserve in Alaska (NPRA) (figs. 23.1, 23.2) have been analyzed for trace elements in order to provide data on regional background concentrations for inorganic geochemical exploration.

This study was made because we had noticed that several of the rock units cored in the subsurface were associated with surface geochemical anomalies or small mineral deposits in the areas where they crop out. In the southwestern part of the NPRA, the heavy-mineral concentrates from sediments of streams that flow over shale and graywacke of the Lower Cretaceous Fortress Mountain and Torok Formations are unusually rich in lead, arsenic, and silver (Churkin and others, 1978). Southeast of the NPRA, in the foothills of the Philip Smith Mountains, stream sediments in areas of Permian to Lower Cretaceous shale locally contain anomalously large amounts of zinc and thorium (Cathrall and others, 1978; Reiser and others, 1983). Barite concretions are common in the shale and chert of the Pennsylvanian to Lower Triassic Siksikpuk Formation (Patton and Tailleur, 1964; Churkin and others, 1978) and locally in shale of the Permian to Lower Triassic Sadlerochit Group (Detterman, 1976; Bundtzen and Henning, 1978). Phosphate rock is present in the Triassic Shublik Formation and in the Mississippian part of the Lisburne Group (Patton and Matzko, 1959). In addition, the high organic-carbon content of the Shublik Formation, Jurassic (part) Kingak Shale, and lowest Cretaceous pebble shale unit in the subsurface in the Prudhoe Bay area (Morgridge and Smith, 1972; Seifert and others, 1979) indicate that they may be rich in trace metals. Outcrops of the Shublik in the Brooks Range locally contain much copper, molybdenum, vanadium, and rare-earth elements (Tourtelot and Tailleur, 1971), and the high gamma-radiation characteristic of the pebble shale unit in the subsurface shows that it is rich in uranium and thorium (Carman and Hardwick, 1983). The shale section with the most important known metallic deposits is the Mississippian shale and chert now assigned to the Kuna Formation (Mull and others, 1982). These rocks contain massive-sulfide zinc deposits in the southern part of the NPRA (Nokleberg and Winkler, 1982) but were penetrated by only one well, Lisburne No. 1.

The distribution of vanadium and nickel may also be of interest in oil exploration. Hughes and others (1983) found higher V/Ni ratios in the Prudhoe-Barrow types of oil than in the Umiat-Simpson types and attributed these higher ratios to sources in the Shublik Formation and Jurassic (part) Kingak Shale.

ROCK UNITS SAMPLED

All but 10 of the core samples are from the 10 major stratigraphic units penetrated by wells in the coastal plain and northern foothills of the NPRA (fig. 23.1). Almost all of the stratigraphic assignments of these samples are based on the formation boundaries for wells in that area listed by Bird (1982); a few are based on his revised stratigraphy for the East Simpson No. 2 well (K.J. Bird, written commun., 1983). Ten of the core samples are from the Lisburne No. 1 well in the southern foothills. This well penetrated a series of thrust plates of allochthonous rocks that are of facies different from those of coeval autochthonous rocks in the northern wells and are best known from their outcrops in the southern foothills and Brooks Range. Formation assignments for the Lisburne No. 1 well are by Tailleur. We differ with Bird on the assignment of only four of the samples from the other wells. Two of these are from the Shublik Formation at depths of 2,308 m (7,572 ft) and about 15 cm (0.5 ft) deeper in the Drew Point No. 1 well, where we differ from Bird's contact by only about 75 cm (2.5 ft). We have assigned the core at 1,850 m (6,070 ft) in Simpson No. 1 to the Kingak Shale rather than to the Sag River Sandstone, and the core at 537 m (1,763 ft) in Square Lake No. 1 to the Colville Group rather than to the Nanushuk Group. Bird (1982) also lists references and notes for most of the sampled units; see also Bird (chapter 15). A brief description of each unit is given below with some remarks about the samples.

The rocks have been divided into two major sequences by Lerand (1973). The Brookian sequence com-

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prises the Upper Jurassic (Mayfield and others, 1983) to Tertiary (Molenaar, 1981, 1983) orogenic and postorogenic deposits that were derived from an ancestral Brooks Range to the south and prograded northward, whereas the Ellesmerian sequence comprises the Mississippian through earliest Cretaceous shelf deposits that were derived from the north. The Brookian and Ellesmerian sequences are partly coeval. During the interval from Late Jurassic through earliest Cretaceous time, Brookian graywacke was being deposited in northward-migrating foredeeps near the Brooks Range while Ellesmerian shale and sandstone were still being deposited on the shelf in the northern part of the NPRA. Some of the rocks in this interval have recently been placed in a third sequence by Carman and Hardwick (1983), who placed the locally derived Lower Cretaceous rocks penetrated in the Kuparuk oil field into a section that they have named the Barrovian sequence.

AUTOCHTHONOUS ROCKS OF THE COASTAL PLAIN AND NORTHERN FOOTHILLS

Colville Group (table 23.1).—Upper Cretaceous (Turonian and younger) deltaic deposits comprising a basal marine shale unit and an upper, partly nonmarine sandy unit. The highest sample is from a coal-bearing nonmarine interval; the others are from the basal marine shale unit.

Nanushuk Group (table 23.1).—Topset, foreset, and alluvial deposits of the Early (Albian) and Late (Cenomanian) Cretaceous deltaic system that preceded the Colville Group delta. The highest sample from each of the two wells is from nonmarine beds; the others are marine (Molenaar, 1981).

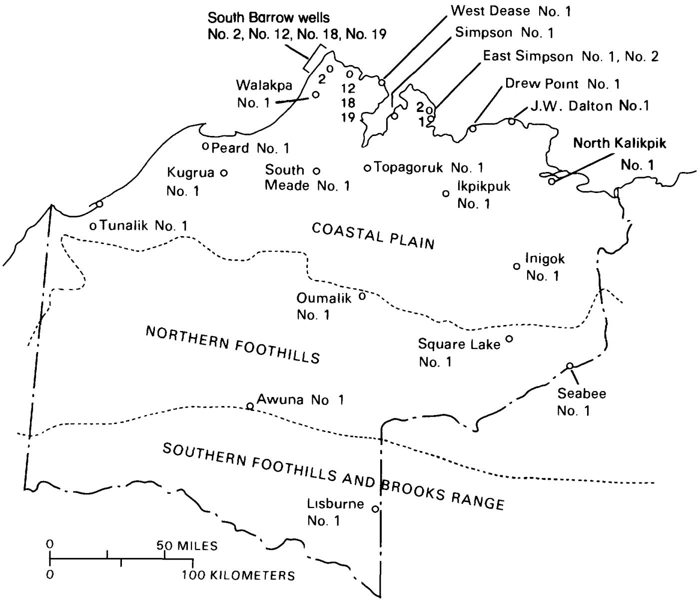

FIGURE 23.1.—Index map of the NPRA showing location of wells sampled.

Torok Formation (table 23.1).—Thick foreset and thin bottomset shale and sandstone deposits at the front of the Early Cretaceous (Albian and Aptian?) deltaic system that are generally considered to be the oldest Brookian deposits in the coastal plain. Correlative rocks in outcrops of the southern foothills are in the Fortress Mountain Formation, which is composed of coarse-grained polymict turbidites and some fluvial beds and was derived from several local sources (Molenaar, 1981). Beneath the northern foothills, in the deeper parts of the Cretaceous basin, the Torok grades downward into shale and sandstone. The lower sample from the Awuna No. 1 well and the lowest three samples from Seabee No. 1 are from this lower unit.

Pebble shale unit (table 23.2).—An informally named unit only a few hundred feet thick that is composed of fissile carbonaceous shale containing floating quartz grains and rests with erosional unconformity on pre-Mississippian to Lower Cretaceous rocks. The pebble shale unit forms the upper part of the unnamed subsurface unit of Robinson (1956) and Collins (1958) and is equivalent to the pebble shale member of the Kongakut Formation in outcrop (Detterman and others, 1975). In the NPRA the pebble shale unit seems to be mostly of Early Cretaceous (Hauterivian to Barremian) age. A highly radioactive zone, 6-45 m (20-150 ft) thick, which usually occurs in the upper part of the unit, is separately identified from wire-line logs as the gamma ray zone (GRZ) and is so marked on table 23.2. The gamma ray zone may actually be bottomset beds of the Torok Formation; if so, it would be the base of the Brookian sequence.

Kingak Shale (table 23.3).—At its type locality, and in the subsurface at Prudhoe Bay and Barrow, this unit is entirely of Jurassic age (Detterman and others, 1975; Carman and Hardwick, 1983). However, in the NPRA south of Barrow, a thick unit of previously unnamed lowest Cretaceous shales, which are similar to the Kingak, lies between the Jurassic Kingak and the unconformity at the base of the pebble shale unit and progrades southward over the Jurassic shales. Molenaar (1981, 1983) and Bird (1982) have stratigraphically extended the Kingak to include these Cretaceous beds as well as the underlying Jurassic ones. In classifying our samples we have distinguished the Cretaceous part of the Kingak from the Jurassic part by using the tops of paleontologic zones listed by Witmer and others (1981). According to them, the upper part of the Kingak is Early Cretaceous in age (Berriasian and Valanginian). It is therefore equivalent in age to the Okpikruak Formation. According to Bird (1981), the entire Kingak and the pebble shale unit are part of the Ellesmerian sequence, which was derived from the north.

Shublik Formation and Sag River Sandstone (table 23.4).—In the coastal plain the black shale, siltstone, and phosphatic limestone of the Middle and Upper Triassic Shublik Formation are overlain by 6-75 m (50 to 250 ft) of glauconitic sandstone and siltstone of the Upper Triassic Sag River Sandstone (Fackler and others, 1970; Jones and Speers, 1976). The core samples from this Triassic interval include two from the Sag River Sandstone (Simpson No. 1, 6240; East Simpson No. 1, 6865).

Sadlerochit Group (table 23.4).—This group comprises the Permian nearshore marine Echooka Formation and the Lower Triassic marine to fluvial Ivishak Formation (Detterman and others, 1975; Jones and Speers, 1976), which was deposited as a southward-prograding delta system. The samples are all from the Triassic rocks: three from the upper siltstone member, four from the middle sandstone member, and two from the lower shale member. All are of marine rocks.

Lisburne Group (table 23.5).—In the coastal plain and northern foothills, this unit consists mostly of carbonate rocks of Mississippian to Permian age (Bird and Jordan, 1977; Bird, 1981). Shale is rare in the cores, and the samples consist of black clay mudstone and very fine grained argillaceous limestone, as noted on table 23.5.

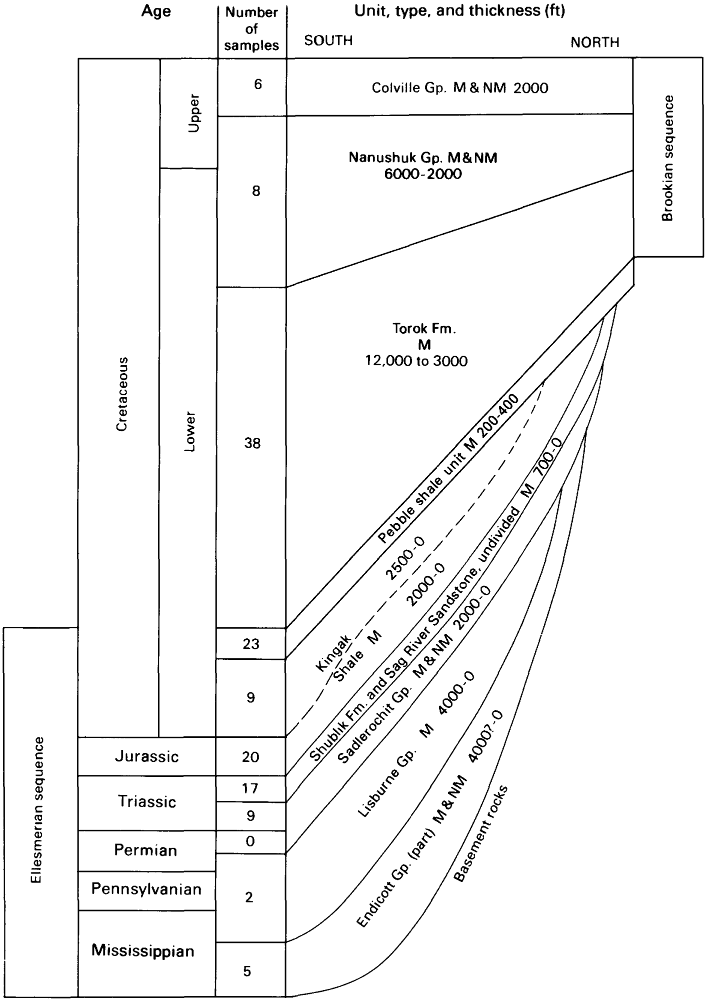

FIGURE 23.2.—Stratigraphic diagram showing rock units sampled from wells in coastal plain and northern foothills in the NPRA, their thickness in feet, and number of samples from each unit. Not shown are stratigraphic units exposed in southern foothills and penetrated only by Lisburne No. 1 well. M, marine; NM, nonmarine.

TABLE 23.1.—*Chemical analyses of core samples from the Colville Group, Nanushuk Group, and Torok Formation in the National Petroleum Reserve in Alaska*

[Sample identification consists of well name and depth, in feet. H, interference; X, no data; G, greater than upper mination given at top of columns

		Major elements (in weight percent)								Minor and trace elements (in parts per million)						
	Sample	Si G40 L10	Al	Na L0.15	K	P G0.45 L0.02	Fe G10 L0.05	Mg	Ca G10	Ti	Mn L200	Ag L1	B L10	Ba G5000	Be L1	Cd L2
								Colville Group								
Square Lake	265	31	7.9	1.2	1.6	0.02	1.6	0.57	0.23	0.16	L	L	38	1700	3	L
	710	28	8.3	1.4	2.1	.11	4.5	1.2	.73	.42	530	L	45	690	3.1	L
	942	28	7.8	1.5	2.3	.09	4.4	1.1	.71	.43	430	L	45	640	2.6	L
	1287	32	8.6	1.5	2.6	.09	4.1	.92	.35	.44	230	L	76	640	2.7	L
	1475	27	8.7	.99	3.0	.08	4.6	1.6	1.2	.49	440	L	93	620	2.5	L
	1763	28	7.1	1.1	2.1	.11	4.6	1.2	1.4	.38	650	L	55	660	2.4	L
								Nanushuk Group								
Square Lake	2051	32	7.9	1.2	2.0	.06	3.8	.87	.24	.46	1400	L	51	680	2.3	L
	2344	31	7.4	1.1	1.9	.05	3.2	.81	.12	.49	L	L	55	650	2.0	L
	2500	29	8.7	1.0	2.0	.06	5.2	1.1	.23	.53	550	L	60	680	2.4	L
	2845	29	8.2	1.3	1.9	.08	4.6	1.2	.25	.54	550	L	66	670	2.0	L
	3200	25	9.2	.97	2.6	.10	6.0	1.3	.49	.50	620	L	110	700	3.2	L
Tunalik	3295	28	9.0	1.1	2.3	.12	4.9	.98	.72	.49	700	L	78	570	2.8	L
	3822	26	9.7	.95	2.7	.12	5.3	.94	.38	.44	570	L	110	640	2.9	L
	5553	26	8.5	1.1	2.6	.10	5.3	1.2	1.1	.42	540	L	88	530	2.7	L
								Torok Formation								
Awuna	2447	28	8.0	1.4	2.0	.10	4.5	1.4	1.9	.44	440	L	77	420	2.7	L
	3668	27	8.4	1.2	2.3	.09	4.8	1.4	1.7	.44	470	L	95	480	2.9	L
Seabee	6548	28	9.5	1.1	2.8	.13	5.4	1.4	.72	.50	390	L	110	720	2.9	L
	10068	27	8.0	.92	2.1	.10	4.5	1.7	2.1	.42	370	L	89	630	2.2	L
	10883	27	8.9	.99	2.5	.08	4.9	1.2	.56	.49	340	L	99	720	2.6	L
	12014	23	8.5	.87	2.9	.09	5.6	1.0	.42	.46	270	L	130	740	3.2	L
Oumalik	8100	28	8.6	1.5	2.2	.12	4.9	1.1	.69	.51	430	L	100	480	2.5	L
	8287	28	9.0	1.3	2.6	.11	5.2	1.1	.72	.52	370	L	110	500	2.7	L
	8498	28	8.9	1.5	2.5	.12	5.3	1.2	.67	.50	500	L	100	510	2.7	L
	8695	28	8.5	1.3	2.3	.12	5.2	1.1	.66	.48	460	L	100	510	2.5	L
	8930	28	8.5	1.4	2.4	.12	5.1	1.1	.82	.48	520	L	110	520	2.8	L
	9546	26	9.2	1.3	2.7	.09	4.7	1.4	1.2	.54	400	L	130	650	3.2	L
	9832	26	9.2	1.3	3.1	.09	4.8	1.1	.63	.61	330	L	150	680	3.3	L
	10018	29	8.4	1.6	2.6	.10	4.5	1.1	.79	.50	400	L	120	580	3.2	L
	10240	26	9.5	1.5	3.2	.10	5.0	1.1	.74	.57	410	L	160	730	4.1	22
	10453	29	7.4	1.5	1.9	.08	3.3	1.2	1.5	.41	380	L	100	570	2.5	L
	10680	27	9.2	1.2	3.5	.11	4.8	.66	.59	.54	520	1.2	190	770	4.7	10
Inigok	4214	28	8.1	1.1	2.3	.10	4.0	1.2	.47	.51	300	L	100	470	2.4	L
	7060	27	9.0	.97	2.8	.11	4.7	1.4	.69	.54	330	L	120	650	2.9	L
	8843	25	8.5	.79	2.9	.11	4.1	1.0	.44	.48	230	2.6	150	840	3.1	70
Ikpikpuk	7133	26	8.8	1.4	2.7	.11	5.1	1.1	.60	.51	440	L	130	660	2.8	L
S. Meade	3018	28	9.3	1.4	2.8	.11	5.5	1.3	.81	.52	550	L	97	500	3.0	L
	4010	28	8.0	1.1	2.0	.12	4.9	1.4	.92	.46	510	L	86	430	2.5	L
	4954	29	8.8	1.2	2.5	.12	5.2	1.2	.57	.52	520	L	100	490	2.9	L
	5994	30	6.4	1.2	1.5	.09	3.4	1.1	1.2	.38	360	L	63	380	1.9	L
Peard	4284	27	8.6	1.1	2.3	.14	4.8	1.3	.81	.47	440	L	97	470	2.8	L
	5411	28	8.4	1.3	2.2	.12	4.7	1.5	1.3	.46	600	L	92	480	3.1	L
	5911	28	9.4	1.3	2.5	.14	4.7	1.2	.72	.53	490	L	120	560	2.8	L
	6122	29	8.2	1.4	2.4	.10	4.7	1.1	.68	.47	570	L	120	550	2.5	L
Tunalik	6504	25	9.4	1.2	2.8	.10	5.4	1.1	.56	.50	750	L	90	580	3.2	L
	7879	28	7.6	1.2	2.0	.12	4.3	.92	.73	.44	480	L	76	400	2.1	L
	8782	30	7.5	1.4	2.0	.12	4.4	.92	.80	.41	470	L	73	410	2.1	L
Dalton	4686	29	6.9	1.3	1.7	.09	4.2	.96	.77	.42	410	L	70	450	2.1	L
	5623	28	8.3	1.3	2.2	.10	4.5	1.0	.54	.48	300	L	90	530	2.5	L
	6586	28	9.0	1.3	2.7	.10	5.2	1.3	.66	.51	360	L	100	540	2.7	L
Drew Pt.	5532.5	28	8.4	1.3	2.0	.12	4.8	1.1	.89	.48	470	L	100	550	2.5	L
	5910	26	8.0	1.2	2.0	.11	4.5	1.4	1.6	.44	370	L	95	500	2.2	L
W. Dease	1909.5	28	7.8	1.4	1.8	.10	4.6	1.1	.79	.45	510	L	82	450	2.4	L

TABLE 23.1.—*Chemical analyses of core samples from the Colville Group, Nanushuk Group, and Torok Formation in the National Petroleum Reserve in Alaska*—Continued

limit of determination; L, detected but below lower limit of determination; upper and lower limits of determination where needed by G and L, respectively, and numerical value]

Minor and trace elements (in parts per million)																		
Co	Cr	Cu	La	Mo	Nb	Ni	Pb	Sc	Sn	Sr	V	Y	Zn	Zr	Ce	Ga	Th	U
											G1000							
			L20	L10	L25		L10	L10	L10				L50		L100	L10		
Colville Group--Continued																		
4.2	46	92	28	L	L	19	23	L	L	140	64	31	59	140	L	20	15.3	6.86
12	75	40	32	L	L	39	24	16	L	150	110	38	82	260	L	24	18.1	4.80
13	83	49	34	L	L	41	26	16	L	150	130	34	72	260	L	20	18.6	5.34
12	110	31	35	L	L	47	20	17	L	140	140	33	68	240	L	23	14.5	4.16
17	120	70	31	L	L	71	26	22	L	120	200	31	98	260	L	21	15.8	3.82
12	86	36	23	L	L	49	24	17	L	130	120	31	89	280	L	15	14.5	3.82
Nanushuk Group--Continued																		
18	140	41	31	L	L	65	20	17	L	89	140	34	110	260	L	20	13.2	3.53
19	130	37	35	L	L	72	20	17	L	91	160	33	100	260	L	20	12.8	4.34
24	180	49	33	L	L	83	22	24	L	91	200	35	93	260	L	22	12.1	3.78
23	180	53	31	L	L	97	21	23	L	100	190	31	94	250	L	21	10.5	3.54
17	120	58	40	L	L	61	34	26	L	120	240	41	90	280	L	24	15.4	3.87
10	110	44	39	L	L	42	25	22	L	140	180	36	78	230	L	25	14.3	3.73
13	110	37	46	L	L	47	26	22	L	160	200	34	120	250	L	31	15.1	3.36
13	97	45	26	L	L	54	24	21	L	120	180	31	140	240	L	21	15.0	4.02
Torok Formation--Continued																		
13	91	37	29	L	L	46	26	17	L	140	150	31	88	270	L	15	13.5	3.77
14	97	36	32	L	L	54	24	21	L	140	170	33	100	260	L	21	13.2	3.74
14	110	44	34	L	L	52	25	22	L	120	210	33	95	240	L	22	15.4	3.60
13	120	46	26	L	L	71	24	21	L	100	180	34	160	240	L	19	14.1	4.14
16	120	49	37	L	L	70	28	33	L	110	230	34	120	250	L	23	13.9	4.07
40	110	58	31	15	L	98	50	19	L	140	200	31	100	240	L	21	16.02	4.65
15	99	39	36	L	L	48	22	18	L	130	170	34	76	260	L	20	13.7	3.21
16	110	39	36	L	L	59	28	20	L	140	220	33	84	230	L	22	15.9	4.36
15	110	42	33	L	L	50	26	19	L	140	190	31	89	230	L	20	15.4	3.30
14	100	40	30	L	L	50	21	19	L	140	170	32	84	250	L	18	13.0	3.51
15	100	39	36	L	L	50	21	19	L	140	180	34	83	260	L	19	14.1	3.27
17	110	50	37	L	L	59	26	20	L	150	210	37	70	270	L	21	16.3	4.82
17	130	48	41	L	L	54	21	20	L	140	240	35	75	260	L	25	18.2	4.03
13	100	38	38	L	L	42	22	17	L	140	180	36	79	270	L	18	15.7	3.71
19	120	48	52	L	L	65	33	22	L	200	370	41	110	300	100	24	22.4	5.80
13	85	43	31	L	L	39	20	14	L	140	140	34	91	270	L	13	13.9	4.15
22	180	140	46	L	L	89	25	21	L	220	900	39	560	300	L	25	23.4	11.3
15	110	45	33	L	L	48	18	18	L	120	180	30	92	270	L	17	15.24	3.85
17	120	51	34	L	L	56	27	19	L	120	230	31	92	230	L	23	16.14	4.14
13	160	250	38	47	L	120	20	24	L	13	G	36	1900	250	L	23	20.82	23.16
16	110	52	39	L	L	52	27	21	L	140	200	36	78	250	L	19	16.5	3.77
16	120	39	42	L	L	56	27	22	L	130	210	34	78	260	L	22	16.3	3.42
15	97	42	27	L	L	50	19	17	L	140	150	29	88	230	L	17	13.76	3.67
17	110	42	32	L	L	52	23	18	L	150	170	31	95	240	L	19	14.62	3.38
11	79	29	20	L	L	38	L	12	L	130	96	24	86	280	L	L	10.61	3.17
16	100	46	30	L	L	51	21	17	L	140	160	32	100	240	L	20	16.32	4.00
15	96	43	28	L	L	46	23	16	L	160	140	31	100	250	L	19	14.26	3.80
18	110	47	32	L	L	51	25	18	L	150	170	32	94	240	L	21	14.52	3.77
16	98	38	29	L	L	50	23	16	L	160	140	27	94	250	L	19	14.78	3.55
17	110	43	41	L	L	50	26	20	L	150	180	35	73	250	L	21	17.0	3.73
16	93	36	22	L	L	48	34	15	L	150	150	29	96	220	L	14	13.80	3.38
18	89	35	23	L	L	49	36	13	L	150	140	28	88	210	L	16	12.58	3.28
14	88	39	23	L	L	49	20	14	L	96	120	29	84	260	L	13	14.1	3.26
14	100	41	32	L	L	48	19	18	L	110	170	33	79	240	L	16	14.5	3.44
15	110	44	36	L	L	53	21	21	L	120	210	34	75	260	L	18	13.8	3.60
13	95	40	33	L	L	46	23	18	L	110	160	35	75	260	L	18	17.2	3.37
14	95	40	28	L	L	50	24	18	L	120	160	31	100	220	L	17	16.3	3.55
14	89	36	30	L	L	44	20	16	L	120	140	33	72	260	L	15	14.3	3.22

TABLE 23.2.—*Chemical analyses of core samples from the pebble shale unit in the National Petroleum Reserve in Alaska*

[Sample identification consists of well name and depth, in feet. H, interference; X, no data; G, greater than upper
mination given at top of columns

		Major elements (in weight percent)								Minor and trace elements (in parts per million)						
	Sample	Si	Al	Na	K	P	Fe	Mg	Ca	Ti	Mn	Ag	B	Ba	Be	Cd
	(R, sample from	G40				G0.45	G10		G10					G5000		
	gamma ray zone)	L10		L0.15		L0.02	L0.05				L200	L1	L10		L1	L2
							Pebble shale unit									
Walakpa 1	1840	29	8.8	0.95	3.0	0.10	4.7	1.1	0.36	0.54	270	L	230	560	3.2	L
	1982	28	9.5	1.1	3.1	.10	6.1	1.3	.53	.55	340	L	240	560	3.4	L
Barrow 2	1951	32	7.7	.89	2.2	.07	3.5	.86	.26	.47	L	L	160	550	2.3	L
	2014	28	7.8	.99	2.3	.11	4.3	.98	.40	.49	250	L	160	560	2.3	L
	2052	28	7.9	.87	2.6	.08	5.2	1.1	.34	.51	310	L	190	580	2.6	L
	2214	31	8.3	.77	2.8	.07	4.3	1.1	.32	.55	260	L	220	740	2.8	L
	2321	33	6.9	.37	1.9	.04	2.3	.55	.09	.39	L	1.4	230	680	2.5	L
Barrow 18	1374.5 (R)	26	9.5	1.4	2.4	.12	5.5	1.4	.65	.51	340	L	200	650	3.2	L
	1388.5 (R)	26	9.9	1.3	2.4	.12	5.7	1.3	.63	.54	320	L	210	610	3.0	L
Barrow 19	1359 (R)	22	7.7	1.1	2.2	.14	8.7	.88	.61	.39	210	L	180	480	2.9	4.1
Tunalik	10671 (R)	25	8.9	.78	2.9	.12	4.3	1.2	.89	.51	290	1.9	200	660	3.1	L
	10701	22	7.7	.50	2.9	.07	G	.98	.76	.39	380	L	H	700	2.8	L
Kugrua	7198	23	6.2	.42	2.1	.08	8.0	.98	.55	.29	370	L	260	520	3.3	L
Peard	6411	25	9.0	.50	2.5	.06	5.5	.86	.38	.46	260	L	240	570	3.0	L
Ikpikpuk	7372	28	9.3	.62	2.9	.07	4.1	.98	.33	.54	260	1.2	230	700	3.0	L
N.Kalikpuk	7032	26	9.4	.67	2.4	.09	3.8	1.0	.34	.46	230	2.6	190	840	3.5	L
	7037.2	6.7	4.8	.46	.53	.04	G	.22	.21	.05	510	H	H	1300	1.9	L
	7062.5	25	9.7	.46	2.2	.08	7.5	1.2	.57	.48	270	L	220	900	3.2	L
	7139	32	6.4	.35	1.6	.07	3.8	.65	.75	.38	290	L	160	580	2.2	L
Oumalik	11000	34	6.0	.46	1.9	.06	3.5	.65	.58	.40	360	L	150	460	1.8	L
W. Dease	2945	31	7.7	.69	2.5	.10	4.0	.98	.32	.51	220	L	160	510	4.1	L
	2976	29	7.0	.60	2.5	.08	4.0	.89	.36	.46	250	L	170	500	2.5	L
Simpson 1	5467	27	7.8	.71	2.5	.07	4.8	1.1	.65	.45	240	L	150	540	2.4	3.6

Endicott Group (table 23.5).—In the coastal plain, this group consists of Mississippian clastic rocks that rest unconformably on the basement rocks. Interbedded shale and limestone in the upper part of the Endicott grade upward into the Lisburne Group. The lower part of the Endicott includes coarse clastic rocks and is partly nonmarine and coal bearing; all of the samples (table 23.5) are from this lower part of the unit.

ALLOCHTHONOUS ROCKS OF THE SOUTHERN FOOTHILLS

Okpikruak Formation (table 23.3).—This oldest Brookian unit crops out only in the Brooks Range and in the southern foothills, where it was penetrated by the Lisburne No. 1 well. It consists of graywacke turbidite as much as 900 m (3,000 ft) thick that underlies the Fortress Mountain Formation. It is of Late Jurassic to Early Cretaceous (Valanginian) age (Bird, chapter 15; Patton and Tailleur, 1964; Mayfield and others, 1983), and most of it is therefore slightly older than the pebble shale unit.

Etivluk Group (table 23.5).—This group consists of the Triassic to Middle Jurassic Otuk Formation and the Siksikpuk Formation, a chert and siltstone unit of Pennsylvanian to Early Triassic age (Mull and others, 1982). It occurs only in the southern foothills and Brooks Range and was penetrated only by the Lisburne No. 1 well. The single core sample of the Etivluk Group from that well is probably from the Siksikpuk Formation (table 23.5). This single sample cannot properly be grouped with samples from any other unit, so it has been omitted from the statistical summaries shown in tables 23.6-23.9 and figures 23.3-23.5.

Otuk Formation (table 23.4).—Mull and others (1982) geographically restricted the Shublik Formation to outcrops in its type locality and in the subsurface. Lower to Upper Triassic rocks in the southern foothills and in most of the Brooks Range that were formerly assigned to the Shublik are now assigned to the Otuk Formation. Unlike the type Shublik, these strata include much bedded chert and siliceous limestone. The Lisburne No. 1 well penetrated the Otuk Formation; the single core sample of black calca-

TABLE 23.2.—*Chemical analyses of core samples from the pebble shale unit in the National Petroleum Reserve in Alaska*—Continued

limit of determination; L, detected but below lower limit of determination; upper and lower limits of deter-
where needed by G and L, respectively, and numerical value]

Minor and trace elements (in parts per million)																		
Co	Cr	Cu	La	Mo	Nb	Ni	Pb	Sc	Sn	Sr	V G1000	Y	Zn	Zr	Ce	Ga	Th	U
			L20	L10	L25		L10	L10	L10				L50		L100	L10		
Pebble shale unit--Continued																		
13	140	53	43	L	L	54	25	21	L	190	300	30	100	260	L	25	15.66	4.20
15	150	63	41	L	L	62	32	23	L	200	330	30	110	260	L	28	14.78	3.96
11	98	36	35	L	L	42	21	15	L	130	180	29	98	290	L	19	13.22	4.27
13	110	35	31	L	L	43	23	16	L	130	190	30	100	270	L	19	13.16	3.53
15	120	42	36	L	L	66	22	19	L	130	240	27	110	280	L	20	12.26	3.35
15	120	51	38	L	L	52	21	20	L	150	250	27	110	290	L	23	15.38	4.35
14	93	30	33	L	L	44	18	13	L	96	170	20	76	250	L	18	13.82	4.44
19	100	52	41	L	L	60	24	21	L	150	230	34	150	190	L	19	X	X
21	93	49	39	L	L	64	25	21	L	140	220	36	130	180	L	19	X	X
42	96	99	39	37	L	130	26	24	L	130	550	40	180	260	L	16	21.3	20.2
13	170	80	56	L	L	64	32	22	L	210	560	38	130	270	120	25	17.00	8.56
19	92	71	54	L	L	100	26	19	L	210	350	29	H	240	H	20	16.76	3.30
19	87	36	34	L	L	46	14	21	L	140	210	33	88	250	L	13	14.9	4.26
16	97	44	48	L	L	56	25	18	L	160	240	30	100	260	L	22	16.24	3.87
12	130	58	47	L	L	52	21	19	L	190	330	26	110	240	110	26	18.48	6.14
14	220	110	32	20	L	85	20	24	L	160	590	37	180	240	L	26	19.6	8.87
16	20	33	21	H	H	18	16	L	H	100	80	32	H	44	H	H	X	X
14	97	61	60	L	L	52	30	17	L	190	210	43	170	210	120	21	X	X
13	98	25	21	L	L	39	11	11	L	110	110	26	88	400	L	14	13.5	3.58
11	80	15	31	L	L	36	16	11	L	190	100	21	59	300	L	10	10.52	2.93
10	120	46	48	L	L	45	20	17	L	170	230	30	80	340	L	21	14.98	4.10
8.8	90	41	39	L	L	35	20	15	L	170	190	27	81	330	L	17	14.16	4.68
18	120	75	34	28	L	100	26	20	L	200	410	27	300	240	L	20	15.76	9.17

reous shale from the Otuk in that well is listed with samples from the Shublik Formation in table 23.4.

Lisburne Group (table 23.5).—In the series of thrust plates penetrated by the Lisburne No. 1 well this unit consists mostly of carbonate rocks of Mississippian age. The single core sample of the dominantly noncarbonate Kuna Formation (Mull and others, 1982) of the Lisburne Group that is listed in table 23.5 has been omitted from the statistical summaries shown in tables 23.6-23.9 and figures 23.3-23.5.

SAMPLES

The sample set consists of 147 samples from conventional drill cores and 16 samples of drill cuttings. Although several samples were taken from some cores, they are grab samples, not composite samples. Each consists of a semicircular chip 1-2.5 cm (0.5-1 in.) thick taken from the longitudinally sliced core. Almost all samples are of black shale or siltstone; exceptions are a few samples of gray shale or argillaceous limestone. The limestone samples are noted on tables 23.4 and 23.5.

The distribution of samples among the various stratigraphic units is unequal. It was determined partly by the availability of suitable material and partly by our assessment of the importance of the units in terms of relative thickness and potential metal content. The Kingak Shale and pebble shale unit were sampled most thoroughly, relative to their thickness.

CONTAMINATION

All of the samples were exposed to possible contamination by barite drilling mud, but most of the cores seemed clean when sampled. We scraped mud from three exceptions: Kugrua No. 1, 7198 (pebble shale unit); Walakpa No. 1, 2112 (Jurassic part of Kingak Shale), and Drew Point No. 1, 6937.5 (Jurassic part of Kingak Shale). In addition, all of the core samples were cleaned in the analytical laboratory.

The amounts of barium reported in the analyses indicate that most of the core samples were free of mud when analyzed. The median concentration of barium reported from the cores differs by only 4 percent from the worldwide median concentration of barium in shales (Rose

TABLE 23.3.—*Chemical analyses of core samples from the Okpikruak Formation and from Jurassic and Cretaceous parts of the Kingak Shale in the National Petroleum Reserve in Alaska*

[Sample identification consists of well name and depth, in feet. H, interference; X, no data; G, greater than upper
mination given at top of columns

		Major elements (in weight percent)								Minor and trace elements (in parts per million)						
	Sample	Si	Al	Na	K	P	Fe	Mg	Ca	Ti	Mn	Ag	B	Ba	Be	Cd
		G40				G0.45	G10		G10					G5000		
		L10		L0.15		L0.02	L0.05				L200	L1	L10		L1	L2
Okpikruak Formation																
Lisburne	1554	31	6.6	1.6	1.7	0.07	4.2	1.6	0.59	0.46	500	L	66	510	1.7	L
	2991.5	27	7.8	1.5	2.6	.10	6.5	2.5	.37	.54	630	L	98	780	2.0	L
	5341	26	7.6	1.2	2.2	.10	3.7	2.8	4.3	.32	1000	L	90	710	2.3	L
	6219	28	7.1	1.1	1.9	.07	5.6	1.5	.29	.40	1200	L	76	1000	1.8	L
Kingak Shale (Cretaceous part)																
Seabee	13220	33	6.9	.59	1.8	.06	3.1	.48	.18	.48	320	L	160	540	1.9	L
	14596	27	7.5	.42	2.1	.09	5.3	1.0	.68	.44	530	L	180	390	2.5	L
Inigok	9348	30	7.4	.46	2.0	.08	2.8	.72	.43	.46	330	L	160	450	2.6	L
	9451	31	6.7	.43	1.9	.07	3.3	.61	.33	.41	390	L	160	380	2.5	L
Tunalik	11685	32	6.7	.44	2.4	.06	2.4	.54	.29	.46	250	1.5	190	430	2.3	L
	12573	36	6.1	.46	1.8	.06	2.9	.50	.31	.44	240	L	170	330	2.0	L
	12593	35	7.2	.45	1.8	.06	2.8	.48	.28	.60	210	L	190	780	1.9	L
Topagoruk	7052	27	9.0	.46	2.9	.10	4.4	1.0	.36	.51	260	L	210	530	2.7	L
Ikpikpuk	7499	28	6.6	.40	2.0	.07	3.7	.71	.50	.45	440	L	150	440	2.2	L
Kingak Shale (Jurassic part)																
Inigok	11005	30	7.3	.42	2.0	.11	3.2	1.0	.99	.49	260	L	160	520	2.6	L
	11704	29	7.8	.43	1.9	.15	3.9	.89	1.2	.48	230	L	170	960	2.8	L
N. Kalikpik	7186	35	5.8	.34	1.4	.07	2.1	.64	.85	.38	L	L	140	560	1.9	L
	7226	29	8.4	.40	2.0	.10	2.4	.77	.68	.48	L	L	190	800	3.0	L
	7394	32	8.0	.42	1.8	.11	2.9	.78	.98	.46	210	L	170	710	2.7	L
Topagoruk	8105	29	8.8	.41	2.8	.12	6.0	.98	.64	.47	240	L	270	460	3.6	L
	8630	34	5.6	.36	1.6	.09	2.4	.59	.54	.38	L	L	150	550	2.3	L
S. Meade	8497	36	5.6	.40	1.7	.11	2.4	.74	.78	.39	L	L	130	450	4.5	L
Walakpa 1	2112	32	7.0	.69	2.6	.07	3.6	1.1	.66	.43	240	1.0	250	460	2.5	L
	2935	30	7.9	.47	2.1	.06	2.8	.81	.30	.47	200	L	240	450	3.0	L
Barrow 12	2170	30	8.3	.42	2.1	.06	3.0	.67	.37	.51	L	L	280	1100	3.1	L
	2197	31	8.1	.41	2.0	.06	2.7	.67	.50	.50	L	L	280	1200	3.3	L
W. Dease	3796	29	7.6	.33	2.2	.07	2.0	.79	.48	.48	L	L	230	700	2.9	L
Simpson 1	5679	32	5.1	.31	1.8	.06	2.0	.62	.60	.35	L	L	160	380	1.7	L
	5866	36	6.8	.40	2.0	.07	2.7	.79	.47	.44	L	L	170	470	2.6	L
	6070	31	6.8	.34	1.9	.06	2.7	.60	.30	.47	L	L	180	550	2.7	L
Drew Point	6906	28	9.2	.38	2.1	.07	2.7	.81	.62	.53	270	L	230	890	2.8	L
	6919	27	9.6	.45	2.6	.08	2.8	.92	.47	.54	270	L	240	920	3.3	L
	6937.5	26	9.8	.43	3.0	.08	2.6	.87	.41	.57	260	L	290	980	3.2	L
	6952	26	9.9	.46	2.8	.07	3.5	.74	.25	.62	L	L	250	880	2.4	L

and others, 1979). However, the 16 samples of cuttings from Lisburne No. 1 well are certainly contaminated either by mud or by cuttings from the barium-rich Siksikpuk Formation, and the 2 core samples of the Kuna Formation and Etivluk Group from that well may also be contaminated. The cuttings of the Lisburne Group limestone from Lisburne No. 1 contain at least 10 times as much barium as do the core samples of the Lisburne Group from the same well. The Etivluk and Kuna core samples are also unusually high in barium, although this may simply reflect the inherently high barium content of the Siksikpuk Formation. Neither the cuttings shown in table 23.5 nor the two Kuna Formation and Etivluk Group cores in table 23.5 are included in the statistical summaries.

Inigok No. 1 well was knowingly contaminated when ZnO was added to the drilling mud at a depth of 5,355 m (17,570 ft) in order to quell a strong blow of H_2S encountered in the Lisburne Group. However, the zinc is not evident in

TABLE 23.3.—*Chemical analyses of core samples from the Okpikruak Formation and from Jurassic and Cretaceous parts of the Kingak Shale in the National Petroleum Reserve in Alaska*—Continued

limit of determination; L, detected but below lower limit of determination; upper and lower limits of deter-
where needed by G and L, respectively, and numerical value]

Minor and trace elements (in parts per million)																		
Co	Cr	Cu	La	Mo	Nb	Ni	Pb	Sc	Sn	Sr	V	Y	Zn	Zr	Ce	Ga	Th	U
											G1000							
			L20	L10	L25		L10	L10	L10				L50		L100	L10		
Okpikruak Formation--Continued																		
16	130	100	20	L	L	53	16	15	L	120	150	23	150	240	L	11	10.15	2.82
20	110	87	21	L	L	60	15	23	L	140	240	27	120	220	L	20	10.92	3.34
12	73	25	35	L	L	33	23	14	L	220	83	28	120	260	L	15	15.18	3.15
16	85	65	L	L	L	61	25	16	L	110	160	25	110	240	L	17	11.46	2.64
Kingak Shale (Cretaceous part)--Continued																		
11	88	20	43	L	L	33	16	11	L	160	110	28	69	390	L	15	12.08	3.07
13	96	28	41	L	L	42	19	16	L	190	150	27	77	300	L	18	14.02	3.17
14	120	22	49	L	L	33	10	14	L	180	130	27	83	330	120	19	17.0	3.34
18	100	26	46	L	L	40	16	13	L	140	120	28	75	390	130	17	14.1	3.19
11	92	22	39	L	L	35	L	11	L	160	160	20	60	310	L	15	13.86	2.88
8.9	84	17	37	L	L	28	L	10	L	140	110	25	52	360	L	12	11.11	2.99
11	110	20	44	L	L	35	21	11	L	150	140	32	67	490	L	14	15.88	3.93
16	110	33	44	L	L	56	18	16	L	190	180	25	93	250	L	24	16.62	3.73
8.6	86	20	48	L	L	25	L	13	L	200	150	25	86	420	110	15	14.26	3.31
Kingak Shale (Jurassic part)--Continued																		
13	120	24	34	L	L	42	L	15	L	130	170	30	120	290	L	18	13.7	3.34
22	120	37	39	L	L	62	37	16	L	150	160	33	110	310	L	18	12.4	3.80
8.9	95	17	23	L	L	30	12	10	L	100	95	27	75	390	L	11	11.1	3.73
14	110	25	28	L	L	43	12	15	L	140	140	26	97	290	L	19	13.2	3.63
12	120	25	28	L	L	40	17	13	L	140	140	29	88	300	L	17	13.4	3.41
23	140	26	32	L	L	60	18	16	L	140	110	33	120	300	L	20	15.1	3.45
7.5	130	21	26	L	L	33	L	12	L	140	120	34	75	350	L	11	12.7	3.82
6.5	150	14	21	L	L	25	L	11	L	120	110	36	89	390	L	13	11.8	3.67
10	84	35	37	L	L	40	19	14	L	170	140	29	95	340	L	16	12.96	3.06
14	140	24	35	L	L	41	13	15	L	150	150	28	99	270	L	19	17.5	3.47
17	150	38	37	L	L	61	20	17	L	110	230	27	110	290	L	21	16.3	4.05
14	160	33	37	L	L	49	18	18	L	120	250	28	110	290	L	20	13.9	3.86
83	140	39	33	L	L	79	50	15	L	150	170	28	94	290	L	17	16.3	4.01
8.9	97	15	24	L	L	30	L	L	L	100	71	25	68	430	L	L	12.9	3.54
11	120	22	29	L	L	36	10	13	L	140	110	32	86	360	L	16	13.7	3.58
8.9	140	27	28	L	L	36	L	14	L	140	150	32	83	320	L	14	13.9	4.02
16	140	39	42	L	L	45	17	18	L	180	190	32	79	300	L	23	18.3	3.27
17	150	44	45	14	L	52	23	19	L	210	200	33	110	260	L	27	18.7	4.17
19	160	53	52	L	L	69	49	17	L	220	220	30	78	260	L	29	25.8	5.39
13	150	37	34	L	L	46	21	19	L	210	190	32	68	290	L	27	17.4	3.87

the sample of the Endicott Group recovered from farther down the same hole. The density of the drilling mud was also increased by 50 percent below 5,355 m (17,570 ft). This might account for the anomalous amount of barium in the Endicott Group core from this well, but even more barium was found in some of the Endicott cores taken at shallower depths with normal mud weight in the East Simpson No. 2 well.

ANALYSES

All of the samples were analyzed by direct-reading emission spectrometer in the U.S. Geological Survey (USGS) laboratory at Menlo Park, Calif. This method determined the concentrations of the 10 major elements and 22 of the trace elements. It is quantitative for all of the silicate rocks, but only semiquantitative for the nonsilicate rocks. For this reason, the samples consisting in part of limestone are separately noted in tables 23.1-23.5. In all of the rocks, zirconium values are subject to errors of more than 10 percent. The analysts were T.L. Fries, J.J. Consul, and R.W. Lerner.

TABLE 23.4.—*Chemical analyses of core samples from the Shublik Formation, Sag River Sandstone, Otuk Formation, and Sadlerochit Group in the National Petroleum Reserve in Alaska*

[Sample identification consists of well name and depth, in feet. H, interference; X, no data; G, greater than upper mination given at top of columns

Sample (C, limestone sample)		Major elements (in weight percent)								Minor and trace elements (in parts per million)						
		Si	Al	Na	K	P	Fe	Mg	Ca	Ti	Mn	Ag	B	Ba	Be	Cd
		G40				G0.45	G10		G10					G5000		
		L10		L0.15		L0.02	L0.05				L200	L1	L10		L1	L2
Shublik and Otuk Formations and Sag River Sandstone																
Lisburne	11164	21	4.1	0.62	1.5	0.06	3.3	1.5	G	0.18	220	H	55	3000	1.6	L
Inigok	12273	27	7.3	.42	3.2	.02	5.6	1.1	4.7	.37	240	L	230	1300	2.6	L
S. Meade	8862	L	3.4	.51	1.2	.15	2.0	.64	.97	.29	L	L	96	510	4.7	L
	9055	33	5.9	.62	2.3	.02	2.7	.80	1.8	.48	L	L	150	650	2.0	L
Ikpikpuk	10280	25	6.4	.60	2.0	.05	3.2	1.5	G	.32	L	H	150	470	2.3	L
	10299 (C)	31	3.2	.53	.98	G	1.1	.86	G	.26	L	H	60	270	2.3	L
Drew Point	7097	26	6.9	.46	1.8	.09	2.9	.73	5.8	.44	L	L	170	830	1.6	L
	7360.5	32	6.4	.50	1.4	.02	2.7	.66	2.0	.45	L	L	150	530	1.6	L
	7559	28	8.5	.40	2.0	.29	2.6	.69	1.1	.57	L	L	270	520	3.0	L
	7572 (C)	28	2.3	L	.55	G	2.5	.71	G	.13	L	L	54	480	1.2	L
	7572.5	30	7.0	.39	2.3	.24	3.5	.66	1.1	.47	L	L	220	440	2.5	L
E. Simpson 1	6865	28	9.4	.47	3.5	.08	4.8	1.1	.41	.60	270	L	300	710	4.9	L
Simpson 1	6240	30	4.2	.27	1.2	.02	L	1.1	.64	.30	230	L	H	190	3.5	L
	6310	30	4.0	.27	.97	.04	2.5	.41	8.1	.31	L	L	100	360	L	L
	6350	31	6.3	.35	1.7	L	2.7	.54	3.5	.42	L	L	170	500	1.3	L
W. Dease	3923	24	8.5	.36	2.7	.04	5.0	.82	.23	.51	L	L	290	880	3.5	L
	3984	31	7.5	.30	2.6	.05	4.9	.86	.30	.54	L	L	220	730	2.1	L
	3997.5	34	5.0	.32	1.4	L	4.5	.61	.80	.42	L	L	140	550	1.9	L
Sadlerochit Group																
Inigok	13508	30	9.4	.52	3.0	.09	3.7	.99	.16	.54	300	L	130	980	3.4	L
Tunalik	14855	33	5.4	.68	2.3	.14	3.5	.87	1.5	.40	L	L	160	610	2.4	L
	15408	33	6.4	.68	2.0	.12	2.4	.75	.56	.45	L	L	130	560	2.5	L
	15425	31	8.5	.71	2.7	.14	3.3	.97	.65	.55	240	L	150	690	3.4	L
	16244	30	8.3	.61	2.7	.09	3.2	1.0	.44	.51	270	L	150	750	3.4	L
Peard	8995	29	8.8	.60	3.0	.15	4.9	1.0	.41	.55	290	L	200	630	3.8	L
Kugrua	10486	23	11	.53	3.8	.10	6.4	1.4	.44	.67	1600	L	210	1000	4.2	L
Drew Point	7613	34	6.6	.20	2.0	.16	1.4	.38	.36	.49	L	1.7	160	930	3.4	L
Dalton	8081	26	8.3	.49	2.2	.07	3.4	.80	.26	.52	L	1.1	150	660	2.6	5.0

All but four of the samples were analyzed for uranium and thorium by delayed neutron-activation method in the USGS laboratory at Lakewood, Colo. Single-run determinations were made for 78 of the core samples. These include all of the samples from the Colville, Nanushuk, and Endicott Groups and the Jurassic part of the Kingak Shale; most of the samples from the Torok Formation and Sadlerochit Group; and a few from the pebble shale unit. The coefficients of variation, expressed as percentages of the reported value, are 5-11 percent for thorium and 1-4 percent for uranium. Robert B. Vaughn made these analyses. High-precision analyses of 5 or 6 runs were made on the 16 samples of cuttings from the Lisburne No. 1 well and on 65 core samples that include all of the samples from the Okpikruak Formation, the Cretaceous part of the Kingak Shale, the Etivluk Group, the Shublik Formation, the Sag River Sandstone, the Otuk Formation, and the Lisburne Group and Kuna Formation, as well as most of the samples from the pebble shale unit and a few from the Torok Formation. The coefficients of variation for thorium in the high-precision analyses range from 2 to 15 percent and are generally less than 8 percent; for uranium they range from 0 to 2 percent. Barbara A. Keaten made these analyses. At the suggestion of David M. McKown, these multiple-run analyses were discontinued in favor of single runs when it became apparent that, for our purposes, multiple runs did not significantly improve the data.

TABLE 23.4.—*Chemical analyses of core samples from the Shublik Formation, Sag River Sandstone, Otuk Formation, and Sadlerochit Group in the National Petroleum Reserve in Alaska*—Continued

limit of determination; L, detected but below lower limit of determination; upper and lower limits of deter-
where needed by G and L, respectively, and numerical value]

Minor and trace elements (in parts per million) and P_2O_5 (in weight percent)																			
Co	Cr	Cu	La	Mo	Nb	Ni	Pb	Sc	Sn	Sr	V	Y	Zn	Zr	Ce	Ga	P_2O_5	Th	U
											G1000								
			L20	L10	L25		L10	L10	L10				L50		L100	L10			
Shublik and Otuk Formations and Sag River Sandstone--Continued																			
12	600	260	H	H	H	170	H	23	L	360	390	49	H	230	L	L	0.15	5.61	10.38
19	140	79	35	52	L	210	21	18	12	280	410	17	95	250	L	20	.03	13.48	5.54
7.2	160	13	34	L	L	25	L	L	L	160	110	22	69	360	L	L	.31	8.79	3.70
9.9	170	34	37	L	L	48	14	14	L	180	210	17	100	330	L	13	.04	12.96	4.78
11	180	86	H	H	H	260	H	16	L	340	670	20	H	240	L	14	.15	11.70	8.40
7.3	130	14	H	L	H	27	L	11	L	360	73	46	H	490	H	L	1.42	12.56	9.62
9.7	130	32	37	L	L	52	14	15	L	370	180	30	120	340	L	11	.19	12.32	4.38
9.4	140	30	27	L	L	42	15	13	L	200	130	28	120	280	L	L	.06	11.64	3.57
9.6	240	54	46	L	L	81	19	16	L	150	190	39	140	420	L	16	.57	19.54	6.16
7.0	51	8.1	H	L	H	40	H	11	L	790	55	43	H	430	120	L	9.97	8.13	5.03
10	130	31	41	L	L	48	21	15	L	160	160	33	120	300	L	16	.66	15.68	4.60
11	150	45	37	L	L	41	41	19	L	180	180	36	96	290	L	27		18.8	4.49
18	450	15	L	L	H	56	39	15	L	60	470	27	H	430	L	L	.05	16.94	2.64
7.5	88	15	27	L	L	25	11	L	L	370	86	28	88	350	L	L	.10	8.16	3.58
8.9	120	30	29	L	L	43	19	12	L	240	160	29	110	350	L	L	.04	12.0	4.47
9.1	130	46	44	L	L	31	29	17	L	140	290	29	88	320	L	20	.05	23.18	5.90
11	120	48	37	L	L	38	23	17	L	150	210	30	95	390	L	16	.08	17.88	5.29
9.2	110	28	28	L	L	47	18	12	L	110	160	30	99	480	L	L	.03	12.60	4.39
Sadlerochit Group--Continued																			
18	160	47	38	L	L	61	L	21	L	180	230	28	100	240	L	27		16.4	4.28
9.8	160	35	44	L	L	61	23	13	L	150	190	15	120	380	L	12	.30	14.94	8.05
9.1	120	23	32	L	L	34	L	14	L	140	110	33	68	340	L	14		15.1	3.78
14	140	30	37	L	L	52	L	18	L	170	140	34	78	280	L	22		16.4	4.02
17	140	32	33	L	L	53	13	18	L	160	160	29	89	250	L	23		18.5	3.92
17	140	38	34	L	L	61	15	20	L	270	200	33	72	330	L	20		18.6	4.30
25	190	53	40	L	L	70	25	25	L	220	280	28	94	320	L	32		23.4	4.83
5.4	110	94	37	L	L	34	13	14	L	220	160	39	72	340	L	18		19.0	4.27
13	150	62	29	21	L	68	20	19	L	150	410	31	360	280	L	23		18.4	8.95

Special analyses for P_2O_5 were made in the USGS laboratory at Menlo Park by M.J. Cremer for 25 core samples and for all 16 of the samples of cuttings from the Lisburne No. 1 well. The core samples are from those units known to contain phosphate rock. They include all of the samples from the Shublik Formation, the Sag River Sandstone, and the Otuk Formation and from the Lisburne Group and Kuna Formation. They also include the single sample from the Etivluk Group and one of the samples from the Sadlerochit Group.

RESULTS

The analytical data for the 8 major elements (Fe, Mg, Ca, Si, Al, Na, K, and P) and 26 trace elements are listed by stratigraphic interval in tables 23.1-23.5 for all of the samples. Cumulative frequency curves showing the number of samples (as a percentage of 145 samples) that contain elemental concentrations less than or equal to each plotted concentration have been drawn for phosphorus and 18 of the trace elements (figures 23.3-23.5). Curves cannot be drawn, nor medians calculated, for silver, cadmium, molybdenum, niobium, tin, and cerium because in most of the samples the concentration of these elements is below the limit of determination. Two Kuna Formation and Etivluk Group cores from the Lisburne No. 1 well have been omitted from the calculations.

To judge the regional background information provided by the ana-

TABLE 23.5.—*Chemical analyses of core samples from the Etivluk Group, Lisburne Group, Endicott Group, and Kuna Formation and of cuttings samples from the Etivluk Group and Lisburne Group in the National Petroleum Reserve in Alaska*

[Sample identification consists of well name and depth, in feet. H, interference; X, no data; G, greater than upper
mination given at top of columns

Sample (C, limestone sample)		Major elements (in weight percent)								Minor and trace elements (in parts per million)						
		Si G40 L10	Al	Na L0.15	K	P G0.45 L0.02	Fe G10 L0.05	Mg	Ca G10	Ti	Mn L200	Ag L1	B L10	Ba G5000	Be L1	Cd L2
Etivluk Group, core																
Lisburne	13605.5	32	6.6	0.30	2.9	0.02	3.3	1.0	0.30	0.33	L	L	110	G	2.2	L
Kuna Formation, core																
Lisburne	15329	25	8.3	.39	2.6	.06	3.2	.95	.63	.46	430	L	130	770	2.5	L
Etivluk Group, cuttings																
Lisburne	7320-30	35	5.8	.59	2.1	.07	4.3	1.0	1.9	.27	2000	L	100	G	2.3	L
	7360-70	38	5.4	.53	2.2	.04	3.7	.96	1.2	.27	1100	L	99	G	2.2	L
	7380-90	37	5.8	.71	2.6	.05	4.1	1.1	1.6	.31	1200	L	110	4600	2.4	L
	7390-7400	35	5.7	.63	2.3	.20	3.8	1.3	6.5	.28	2400	L	96	G	2.1	L
	9610-20	39	4.0	.28	1.5	.04	2.2	.64	.74	.18	1700	L	80	G	1.8	L
	9650-60	33	6.8	.55	2.7	.06	5.9	1.1	1.1	.33	G	L	160	G	3.0	L
	11490-11500	G	4.0	.29	1.6	.03	2.3	.74	1.2	.19	340	L	64	G	1.8	L
Lisburne and Etivluk Groups, mixed cuttings																
Lisburne	9660-70	31	4.6	.38	1.2	G	3.8	1.7	4.5	.23	2500	L	98	G	1.9	L
	11540-60	34	3.7	.26	1.4	.11	1.9	2.6	7.1	.19	1100	L	56	4200	1.3	L
Lisburne Group, cuttings																
Lisburne	7400-10	31	4.2	.47	1.8	.08	2.8	1.3	G	.22	1600	L	54	4200	1.4	L
	7420-30	21	2.1	.30	.73	.40	1.6	1.3	G	.10	640	L	L	3100	L	L
	7450-60	25	2.9	.33	.75	.16	1.8	2.6	G	.13	1000	L	12	3500	L	L
	7500-10	19	1.6	.28	.44	.05	1.3	4.0	G	.07	660	L	L	1600	L	L
	9670-80	16	1.7	.18	.49	.30	2.1	1.7	G	.07	1400	L	L	4500	L	L
	9700-10	19	1.3	L	.29	.05	1.1	4.2	G	.05	1700	L	L	3200	L	L
	9770-80	16	2.9	.25	.86	.08	2.0	1.1	G	.11	3400	L	39	G	L	L
Lisburne Group, cores																
Lisburne	16319.5 (C)	L	.79	L	.59	L	.58	9.0	G	.03	390	H	L	150	L	L
	16861 (C)	31	3.4	.15	1.3	.04	2.2	.92	G	.12	L	L	44	180	L	L
	16984 (C)	24	2.4	L	.85	.02	.87	3.1	G	.09	L	H	L	140	L	L
Inigok	14032 (C)	30	6.6	.63	2.4	.04	2.9	1.5	3.7	.42	220	L	120	540	1.9	L
	15199 (C)	30	6.4	.29	2.2	L	2.1	1.7	3.2	.39	L	L	140	700	1.8	L
Endicott Group cores																
Inigok	20092	27	9.5	.28	2.9	.06	.40	.31	.07	.68	L	1.5	130	1400	3.9	L
E. Simpson 2	7202	30	9.5	.31	1.7	.05	.85	.36	.07	.60	L	L	130	580	2.2	L
	7212	26	10	.38	1.6	.06	.76	.35	.07	.61	L	1.7	150	1600	2.5	L
	7268	31	9.7	.24	2.2	.06	.73	.38	.06	.74	L	1.5	150	1400	3.9	L
	7297	31	9.1	.33	1.9	.05	.68	.37	.07	.60	L	1.4	150	2100	3.4	L

lytical data, we have compared the median concentrations of most of the trace elements with their median or average values in shales in North America or worldwide (table 23.6). In order to discover whether there may be any marked differences in trace-element content between stratigraphic units, we have compared the distribution of high median concentrations among the stratigraphic units and have also compared the distribution of anomalously high values among the stratigraphic units.

TABLE 23.5.—*Chemical analyses of core samples from the Etivluk Group, Lisburne Group, Endicott Group, and Kuna Formation and of cuttings samples from the Etivluk Group and Lisburne Group in the National Petroleum Reserve in Alaska*—Continued

limit of determination; L, detected but below lower limit of determination; upper and lower limits of determination where needed by G and L, respectively, and numerical value]

Minor and trace elements (in parts per million) and P_2O_5 (in weight percent)																			
Co	Cr	Cu	La	Mo	Nb	Ni	Pb	Sc	Sn	Sr	V	Y	Zn	Zr	Ce	Ga	P_2O_5	Th	U
			L20	L10	L25		L10	L10	L10		G1000		L50		L100	L10			
Etivluk Group, core--Continued																			
8.0	130	72	32	L	L	40	18	16	L	200	140	23	140	190	L	12	0.05	10.79	1.95
Kuna Formation, core--Continued																			
15	130	26	38	L	L	61	16	20	L	110	180	26	160	210	L	15	.16	16.74	3.28
Etivluk Group, cuttings--Continued																			
14	88	74	24	L	L	63	22	17	L	250	160	31	210	190	L	11	.21	7.30	3.35
14	76	60	26	L	L	64	32	17	L	220	130	27	130	210	L	11	.12	8.65	2.28
16	83	57	25	L	L	69	26	17	L	200	150	29	150	240	L	12	.17	9.92	3.17
15	8.7	64	31	L	L	60	26	17	L	280	130	40	200	230	L	12	.62	9.13	6.04
15	50	60	L	L	L	62	26	13	L	190	71	22	130	150	L	L	.10	6.04	1.83
51	85	140	43	L	L	230	H	22	L	260	150	36	260	300	L	15	.16	12.02	2.71
15	58	46	17	L	L	46	27	11	L	190	77	22	110	150	L	L	.06	5.73	1.69
Lisburne and Etivluk Groups, mixed cuttings--Continued																			
31	87	69	38	L	L	83	190	14	L	260	100	52	630	240	L	L	1.14	10.32	13.18
19	66	59	33	L	L	50	89	10	L	190	93	33	620	200	L	L	.29	6.92	5.10
Lisburne Group, cuttings--Continued																			
13	72	41	H	L	H	49	H	14	L	210	120	30	H	190	H	L	.31	7.80	4.94
9.7	59	25	H	L	H	37	H	L	L	180	69	42	H	140	L	L	1.07	5.11	8.95
12	49	25	H	L	H	37	H	L	L	140	70	31	H	130	L	L	.44	4.54	4.57
9.6	38	18	H	L	H	30	H	L	L	95	62	22	H	95	H	L	.18	2.88	3.26
22	37	35	H	H	L	59	H	L	L	200	53	50	H	120	H	L	.72	6.76	15.45
13	31	24	H	L	H	55	H	L	L	140	49	25	H	91	H	L	.15	3.53	7.72
19	38	79	H	H	H	74	H	13	L	230	63	35	H	150	H	L	.24	6.24	3.51
Lisburne Group, cores--Continued																			
6.6	29	6.4	H	L	H	35	H	L	L	210	32	18	H	59	H	L	.08	1.29	3.15
7.8	87	25	H	L	H	73	H	L	L	240	84	19	H	81	L	L	.13	4.52	6.17
5.8	68	19	H	L	H	56	L	L	L	520	58	13	H	71	L	L	.08	3.33	5.95
13	93	24	37	L	L	43	18	15	L	190	130	24	130	240	L	10	.09	11.03	3.74
12	99	24	28	L	25	71	16	13	L	580	140	16	110	220	L	10	.05	11.98	5.35
Endicott Group cores--Continued																			
13	180	47	76	L	L	52	L	20	L	130	290	37	L	470	180	45		32.8	9.95
9.2	150	35	51	L	L	38	L	17	L	120	170	22	90	220	100	26		18.4	5.08
9.2	180	74	56	L	L	46	23	22	L	170	320	31	180	260	110	33		22.3	9.72
12	210	42	68	L	L	45	13	20	L	160	260	36	120	360	180	32		21.5	8.56
5.6	160	40	52	L	L	33	13	17	L	150	300	28	96	270	110	23		21.0	5.54

MEDIAN CONCENTRATIONS

Median values were calculated from the frequency distribution histograms drawn for phosphorus and 18 of the trace elements in each of the stratigraphic units and in the whole group of 145 core samples. The medians, rather than average values, are presented because they are less affected by anomalously high values in a few samples.

Median concentration values for trace elements in shales worldwide are available only for Ba, Cu, Pb,

TABLE 23.6.—*Median concentrations of 19 trace elements in each sampled stratigraphic unit in the National Petroleum Reserve in Alaska and their deviation from the world average (or median) concentrations in shale*

[Figures beneath element symbols are average concentrations (those in parentheses are median values) in shale from: for Ga, Weeks (1973); for Sc in North American shale, Norman and Haskin (1968) -- compare with value of 13 ppm in Turekian (1977); for all other elements, Rose and others (1979). Figures for P in weight percent, for all other elements in parts per million. < indicates figure is lower limit of determination; deviations given as percents of average (or median) concentrations; deviations in parentheses are minimum absolute values]

Stratigraphic unit	Number of samples	Cu (42)	Pb (25)	Zn (100)	Co 19	Ni 68	Sc 12	Ga 20	Be 3	V 130	Cr 90	B 100	La 39	Y 35	P 0.07	Th 12	U (3.7)	Ba 550	Sr 300	Zr 160
Colville Group-------	6	45 +7	24 -4	77 -23	12 -37	44 -35	17 +42	21 +5	2.7 -10	125 -4	85 -6	55 -45	32 -18	32 -9	0.09 +29	15.6 +30	4.5 +22	650 +18	140 -53	260 +63
Nanushuk Group-------	8	45 +7	23 -8	97 -3	18 -5	63 -7	22 +83	22 +10	2.6 -13	185 +42	125 +39	72 -28	34 -13	34 -3	.09 +29	13.8 +15	3.8 +3	660 +20	110 -63	255 +59
Torok Formation------	38	42 0	24 -4	89 -11	15 -21	50 -26	19 -58	19 +5	2.7 -10	175 +35	105 +17	110 +10	33 -15	33 -6	.10 +43	14.7 +23	3.7 0	525 -5	140 -53	250 +56
Pebble shale unit----	23	49 +17	22 -12	110 +10	14 -26	52 -24	19 +58	23 +15	2.9 -3	230 +77	98 +9	200 +100	39 0	30 -14	.08 +14	15 +25	4.3 +16	580 +5	160 -47	260 +63
Okpikruak Formation--	4	76 +81	20 -20	120 +20	16 -16	58 -15	16 +33	16 -20	1.9 -37	155 +19	98 +9	83 -17	21 -46	26 -26	.09 +29	11.2 -7	3 -19	745 +35	130 -57	240 +50
Kingak Shale, Cretaceous part.	9	22 -48	16 -36	75 -25	11 -42	35 -49	13 +8	15 -25	2.5 -17	140 +8	96 +7	170 +70	44 +13	27 -23	.07 0	14.1 +18	3.2 -14	440 -20	110 -63	360 +125
Kingak Shale, Jurassic part.	20	27 -36	17 -32	92 -8	13 -32	43 -37	15 +25	18 -10	2.8 -7	150 +15	140 +56	210 +110	34 -13	30 -14	.07 0	13.8 +15	3.7 0	630 +15	140 -53	300 +88
Shublik and Otuk Formations and Sag River Sandstone.	18	32 -24	19 -24	99 -1	9.7 -49	45 -34	15 +25	<10 (-50)	2.2 -27	180 +39	135 +50	150 +50	33 -15	30 -14	.05 -29	12.6 +5	4.7 +27	525 -5	190 -37	345 +116
Sadlerochit Group----	9	38 -10	13 -48	89 -11	13 -32	61 -10	18 +60	20 0	3.4 +13	190 +46	140 +56	150 +50	37 -5	31 -11	.12 +71	18.4 +53	4.3 +16	690 +25	170 -43	320 +100
Lisburne Group-------	5	24 -43	16 -36	120 +20	7.8 -59	56 -18	<10 (-17)	<10 (-50)	<1 (-67)	84 -35	77 -14	44 -56	33 -15	18 -49	.02 -71	4.5 -63	5.4 +46	180 -67	240 -20	80 -50
Endicott Group-------	5	42 0	13 -48	96 -4	9.2 -52	45 -34	20 +67	32 +60	3.4 +13	290 +123	180 +100	150 +50	56 +44	31 -11	.06 -14	21 +75	8.6 +132	1400 +155	150 -50	270 +69
All units------------	145	39 -7	21 -16	94 -6	14 -26	50 -26	17 +42	19 -5	2.6 -13	170 +31	110 +22	150 +50	35 -10	31 -11	.09 +29	14.6 +22	3.8 +3	570 +4	150 -50	260 +63

TABLE 23.7.—*Stratigraphic units in the National Petroleum Reserve in Alaska having the three highest median concentrations for each of 19 trace elements*

[Based on data in table 23.6. Symbol for each element appears opposite the three units with highest median concentrations of that element]

Colville Group------	-	Pb	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nanushuk Group------	-	-	-	Co	Ni	Sc	Ga	-	-	-	-	-	Y	-	-	-	-	-	-
Torok Formation-----	-	Pb	-	-	-	-	-	-	-	-	-	-	Y	P	-	-	-	-	-
Pebble shale unit (gamma-ray zone).	Cu	Pb	Zn	Co	Ni	Sc	-	Be	V	-	B	La	Y	P	Th	U	-	-	-
Pebble shale unit---	Cu	-	-	-	-	-	Ga	-	V	-	B	-	-	-	-	-	-	-	-
Okpikruak Formation-	Cu	-	Zn	Co	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Ba
Kingak Shale, Cretaceous part.	-	-	-	-	-	-	-	-	-	-	-	La	-	-	-	-	-	Zr	-
Kingak Shale, Jurassic part.	-	-	-	-	-	-	-	-	-	Cr	B	-	-	-	-	-	-	-	-
Shublik Formation---	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Sr	Zr	-
Sadlerochit Group---	-	-	-	-	Ni	-	-	Be	-	Cr	-	-	-	P	Th	-	Sr	Zr	Ba
Lisburne Group------	-	-	Zn	-	-	-	-	-	-	-	-	-	-	-	-	U	Sr	-	-
Endicott Group------	-	-	-	-	-	Sc	Ga	Be	V	Cr	-	La	-	-	Th	U	-	-	Ba

Zn, and U. For the other elements only the average value is available. Comparison of median values with average values is not rigorous because the average is greater than the median in positively skewed distributions like those commonly found for trace elements. When the medians for the group are compared with those of an average shale, the group is: richer than average in scandium, vanadium, chromium, boron, phosphorus, thorium, and zirconium; poorer than average in cobalt, nickel, and strontium; and comparable in content of gallium, beryllium, lanthanum, and yttrium.

When the medians for the NPRA group of samples are compared with median values worldwide, the group is poorer in lead and has about the same content of barium, copper, zinc, and uranium.

Inasmuch as the medians for only four of the elements differ from the worldwide medians or averages by more than 33 percent (table 23.6), it is likely that most of the differences are within one or two standard deviations of the worldwide averages. When compared with the average values for 20 sets of black shales in the United States determined by Vine and Tourtelot (1970), the results are somewhat different because the Vine and Tourtelot average values are generally smaller than those used in table 23.6. However, the only prominent differences between the medians for the group of 145 core samples and the Vine and Tourtelot averages are for scandium, beryllium,

TABLE 23.8.—*Anomalous concentrations of trace elements in the 10 samples from the National Petroleum Reserve in Alaska that contain most of the trace element anomalies*

[All concentrations in parts per million; sample identification includes well name and depth in feet; concentrations above the 94th percentile taken as anomalous, except that for Ag, Cd, Mo, and Sn all values above lower limit of determination are considered anomalous; -, concentrations not anomalous; value with >, upper limit of determination; values with <, lower limit of determination and maximum possible values of median concentration]

Stratigraphic unit	Sample	Cu	Zn	Ag	Cd	Co	Mo	Ni	Sn	Ga	V	Cr	La	Ce	Th	U	Ba	Sr	Zr
Torok Formation	Oumalik 1 10680	140	560	1.2	10	-	-	-	-	-	900	-	-	-	-	11.3	-	-	-
Do -----	Inigok 1 8843	250	1900	2.6	70	-	47	120	-	-	>1000	-	-	-	-	23.16	-	-	-
Pebble shale unit (gamma-ray zone)	Barrow 19 1359	-	180	-	4.1	42	37	130	-	-	550	-	-	-	-	20.2	-	-	-
Pebble shale unit	N. Kalikpik 7032	110	180	2.6	-	-	20	-	-	-	590	220	-	-	-	-	-	-	-
Do -----	Simpson 1 5467	-	300	-	3.6	-	28	-	-	-	410	-	-	-	-	-	-	-	-
Otuk Formation	Lisburne 1 11164	260	-	-	-	-	-	170	-	-	-	600	-	-	-	10.38	3000	360	-
Shublik Formation	Inigok 1 12273	-	-	-	-	-	52	210	12	-	410	-	-	-	-	-	-	-	-
Sadlerochit Group	Dalton 1 8081	-	360	1.1	5.0	-	21	-	-	-	410	-	-	-	-	-	-	-	
Endicott Group	Inigok 1 20092	-	-	1.5	-	-	-	-	-	45	-	-	76	180	32.8	-	1400	-	470
Do -----	E. Simpson 2 7268	-	-	1.5	-	-	-	-	-	-	-	210	68	180	-	-	-	-	-
Entire sample set of 145 samples																			
Number of anomalous concentrations		5	7	14	6	3	8	5	1	1	10	5	3	2	2	4	4	8	4
Median concentration		39	94	<1	<2	14	<10	50	<10	19	170	110	35	<100	14.6	3.8	570	150	260

TABLE 23.9.—*Trace elements showing high median concentration or abundant anomalous concentrations in stratigraphic units in the National Petroleum Reserve in Alaska*

[V/Ni, highest values of vanadium/nickel ratio; REE, rare-earth elements La, Ce, and Y; -, elements not having high median or abundant anomalous concentrations]

Sequence	Unit	Elements												
Brookian sequence, derived from southern sources	Colville Group-------	Cu	-	Co	Cd	-	-	-	-	P	-	-	-	-
	Nanushuk Group-------	Cu	-	Co	Cd	-	-	-	-	P	-	-	-	-
	Torok Formation------	Cu	-	Co	Cd	-	-	-	-	P	-	-	-	-
	Okpikruak Formation--	Cu	Zn	Co	Cd	-	-	-	-	P	-	-	-	-
Ellesmerian sequence, derived from northern sources	Pebble shale unit----	Cu	Zn	Co	Cd	V	V/Ni	B	REE	P	-	U	-	-
	Kingak Shale, Cretaceous part.	-	-	-	-	-	V/Ni	-	REE	-	-	-	-	Zr
	Kingak Shale, Jurassic part.	-	-	-	-	-	-	B	-	-	-	-	-	Zr
	Shublik and Otuk Formations and Sag River Sandstone.	-	-	-	-	-	V/Ni	-	-	P	Th	U	-	Zr
	Sadlerochit Group----	-	-	-	-	V	-	-	REE	P	Th	U	-	Zr
	Lisburne Group-------	-	-	-	-	-	-	-	-	-	-	-	-	-
	Endicott Group-------	-	-	-	-	V	V/Ni	-	REE	-	Th	U	Ba	-

boron, barium, and zirconium. For these elements our medians are, respectively, 170, 260, 400, 190, and 370 percent of their averages. Our very high median values for zirconium may partly reflect the rather low precision of the zirconium analyses. Thus, the NPRA sample group as a whole seems to consist of very ordinary shale and might serve as background anywhere.

When the median concentrations of elements in the different stratigraphic units are compared with each other (table 23.7), a few of the units are seen to be richer than the others in a few elements. The median concentrations of copper, lead, zinc, cobalt, and phosphorus are generally higher in all of the postorogenic Brookian deposits, especially in the Okpikruak Formation, than in the Ellesmerian deposits. Conversely, the median concentration of zirconium is generally lower in the Brookian deposits. The two samples analyzed from the gamma-ray zone of the pebble shale unit have a higher median concentration of uranium than samples from any other unit and almost as high a median concentration of thorium as those of the Endicott Group. By contrast, the Lisburne Group is particularly poor in almost all of the trace elements, and the Shublik Formation is poor in cobalt, gallium, beryllium, thorium, and (surprisingly) phosphorus.

ANOMALOUS CONCENTRATIONS

We picked anomalies starting at the 94th percentile in the frequency distribution histograms of each of the elements in the group of 145 core samples and found 102 anomalies distributed among 40 of the samples. These anomalies are not evenly distributed among samples or among the stratigraphic units. Ten of the samples contain 57 of the anomalous concentrations, and these 10 samples come from only 6 stratigraphic units: The Torok Formation, the pebble shale unit, the Shublik and Otuk Formations, the Sadlerochit Group, and the Endicott Group (table 23.8). The other 45 anomalies are distributed among 30 samples, most of which are in the Torok Formation, the pebble shale unit, the Shublik Formation, the Sag River Sandstone, and the Endicott Group. Of the 102 anomalous concentrations of individual elements, 83 are in the Torok Formation, the pebble shale unit, the Shublik and Otuk Formations, the Sag River Sandstone, and the Endicott Group. Thus, both the distribution of samples that are anomalous for one or more elements and the distribution of the actual element anomalies show a high concentration of anomalies in only a few stratigraphic units.

The number of anomalous samples from each stratigraphic unit is at least in part related to the total number of samples collected from that unit. The Torok Formation, the pebble shale unit, and the combined Shublik Formation, Sag River Sandstone, and Otuk Formation, which provide most of the total number of samples (26, 16, and 12 percent, respectively), also provide most of the anomalous samples (13, 18, and 30 percent, respectively) and most of the individual anomalies (19, 22, and 27 percent, respectively). Two-thirds of all of the samples from the combined Shublik Formation, Sag River Sandstone, and Otuk Formation contain anomalies, so it is likely that the abundance of anomalous samples in those units, as well as in the sparsely sampled Endicott Group, is significant.

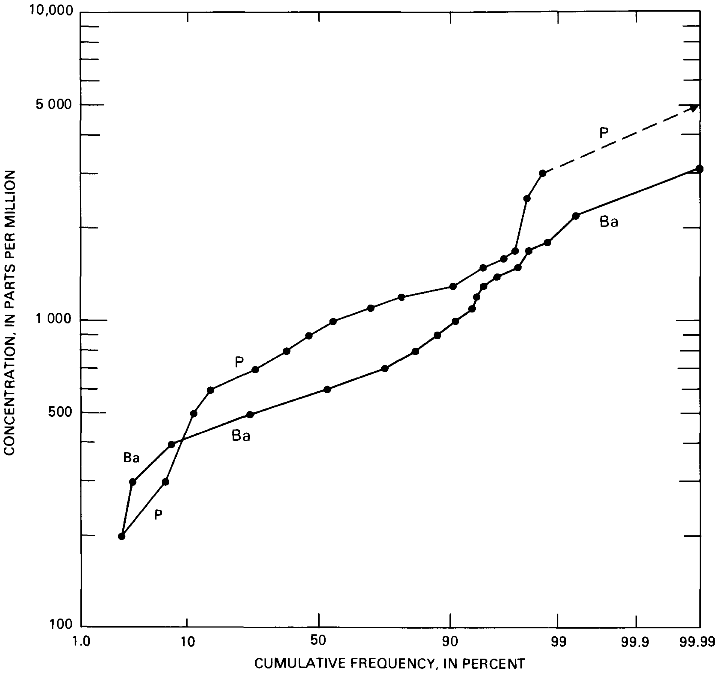

FIGURE 23.3.—Cumulative-frequency-distribution graphs for barium and phosphorus concentrations in 145 core samples from the NPRA. Broken line with arrow indicates that highest concentration is above limit of numerical determination.

Anomalies for each element tend to be concentrated in one or two stratigraphic units. Samples from the Endicott Group contain all the cerium and gallium anomalies, most of the lanthanum anomalies, and half of the barium and thorium anomalies. Samples from the Shublik Formation, Sag River Sandstone, and Otuk Formation contain all of the phosphorus and tin anomalies and most of the chromium, nickel, strontium, and zirconium anomalies. Metal anomalies are mainly in the Torok Formation and pebble shale unit, which contain most of the anomalous concentrations of copper, zinc, cadmium, cobalt, molybdenum, vanadium, uranium, and scandium.

The stratigraphic distribution of anomalies agrees with the distribution of high median values in several respects: The Torok Formation and pebble shale unit are relatively rich in copper and cobalt; the pebble shale unit is also relatively rich in zinc, vanadium, and uranium; the Shublik Formation is relatively rich in chromium, strontium, and zirconium; and the Endicott Group is relatively rich in gallium, lanthanum, barium, and thorium.

However, the anomalies and medians disagree in a few elements: All of the phosphorus anomalies are in the Shublik Formation, but the median concentration of phosphorus in the Shublik is lower than that in almost all other units, suggesting that Shublik phosphate is concentrated in certain beds; most lead anomalies are in the Shublik Formation and Kingak Shale, but all of the higher median concentrations of lead are in the Brookian rocks; and half of the uranium anomalies are in the Torok Formation, whereas all of the higher median concentrations of uranium are in the pebble shale unit and the Triassic and older rocks.

CONCLUSIONS

The rocks sampled and analyzed are not significantly different from the average shale in trace-element content, but certain stratigraphic units seem to be slightly favored as hosts for a few of the elements (table 23.9). When the strongest evidence from anomalies and from high median concentrations is combined, the following conclusions appear justified:

1. The Brookian sequence strata, which were derived from the south, are richer than the other rocks in copper, cobalt, and cadmium.

2. The pebble shale unit and the included gamma-ray zone, which

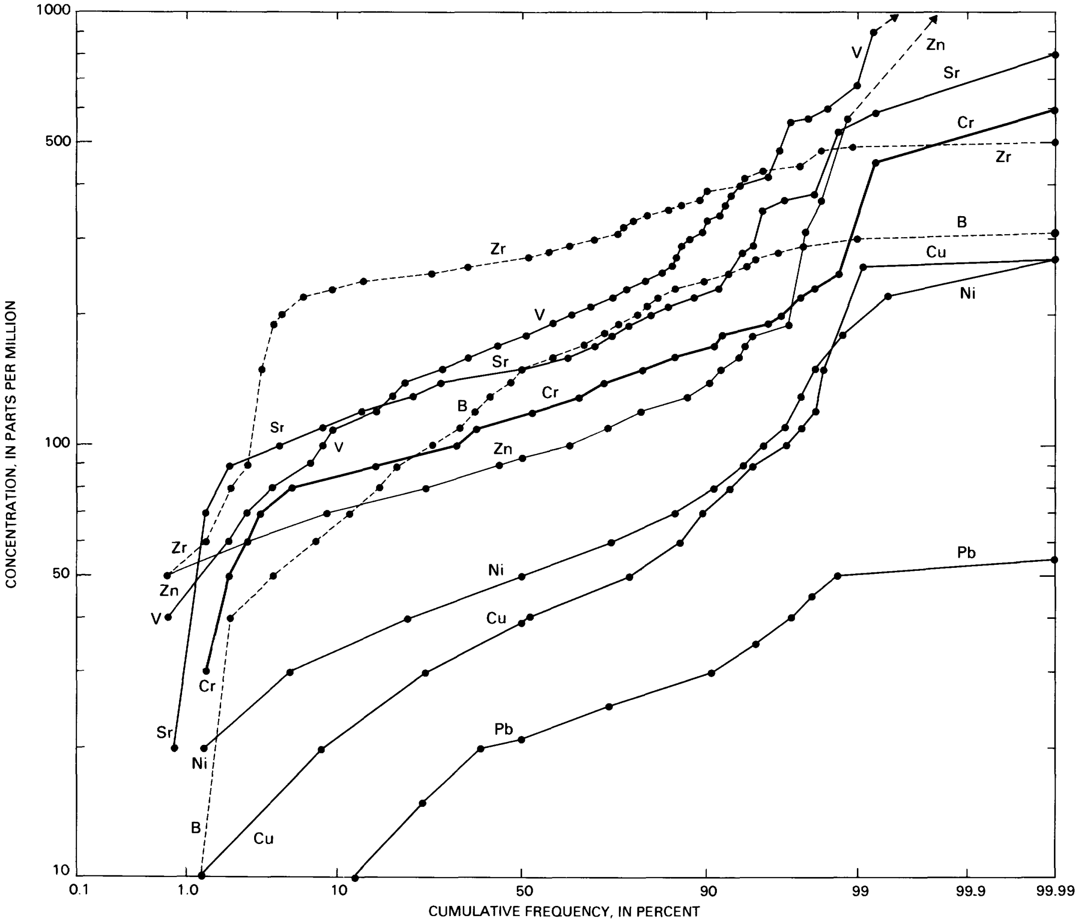

FIGURE 23.4.—Cumulative-frequency-distribution graphs for boron, copper, chromium, lead, nickel, strontium, vanadium, zinc, and zirconium concentrations in 145 core samples from the NPRA. Lines are short dashed or solid for visual separation only. Broken line with arrow indicates that highest concentration is above limit of numerical determination.

are part of the Ellesmerian sequence derived from the north, are moderately rich in uranium, vanadium, and zinc.

3. The Triassic and older Ellesmerian sequence strata, particularly the coaly Endicott Group, are richer than the other rocks in uranium plus thorium.

4. The rocks that are richer than others in uranium are also richer in vanadium, particularly the coaly rocks of the Endicott Group. Except for those coaly Endicott Group rocks, the highest ratios of vanadium to nickel are in the pebble shale unit, and the next highest are in the Shublik Formation and the Cretaceous part of the Kingak Shale.

5. Although a few lead anomalies are present in the Kingak Shale, that unit is not favored as a host for metals.

6. The deepest marine units, the pebble shale unit and the Jurassic part of the Kingak Shale, are richer than the other rocks in boron.

7. The rocks derived from the north, particularly those relatively rich in uranium, are richer than other rocks in rare-earth elements.

8. The rocks of northern derivation beneath the pebble shale unconformity are richer than others in zirconium.

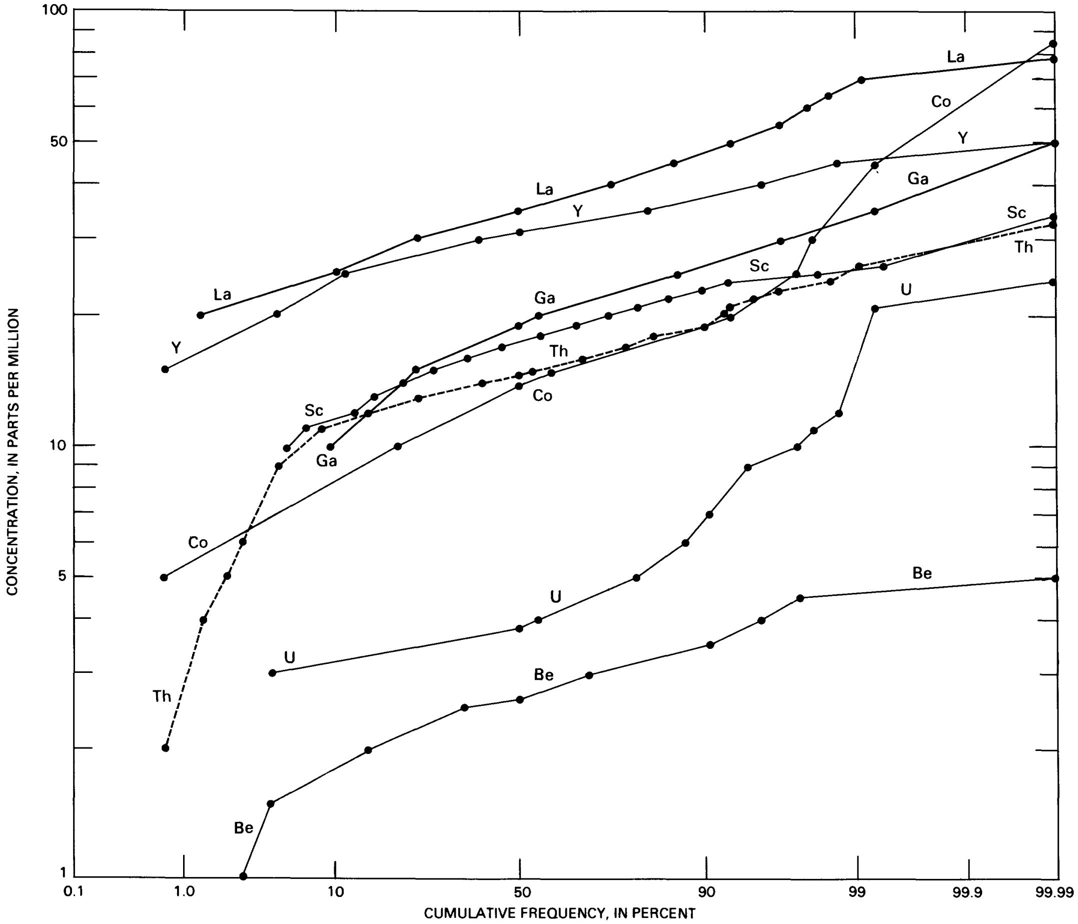

FIGURE 23.5.—Cumulative-frequency-distribution graphs for beryllium, cobalt, gallium, lanthanum, scandium, thorium, uranium, and yttrium concentrations in 145 core samples from the NPRA. One line (Th) is dashed for ease of visual separation from other lines.

9. The coaly rocks of the Endicott Group are richer than other rocks in barium.

10. The Shublik Formation and Sadlerochit Group are richer than other Ellesmerian sequence strata in phosphorus, and the Brookian sequence strata are also generally richer in phosphorus than the rest of the Ellesmerian strata.

These conclusions seem consistent with the regional geology. They indicate that the source of the Brookian sequence in the ancestral Brooks Range was richer in base metals than the unknown northern source of the Ellesmerian sequence and that the Brookian deposits are compositionally less mature than the Ellesmerian (Molenaar, 1983). The suite of elements more abundant in the Ellesmerian strata may reflect either the character of the source or the environment of deposition; most of the elements in this suite are commonly associated with each other in phosphate deposits (P, U, V, rare earths, Zr) (Cathcart and Gulbrandson, 1973; Klemic and others, 1973) or in monazite deposits (Th, rare earths, Zr) (Staats and Olson, 1973).

REFERENCES CITED

Bird, K.J., 1981, Petroleum exploration of the North Slope in Alaska, U.S.A.: U.S. Geological Survey Open-File Report 81-227, 48 p.

—— 1982, Rock-unit reports of 228 wells drilled on the North Slope, Alaska: U.S. Geological Survey Open-File Report 82-278, 106 p.

Bird, K.J., and Jordan, D.F., 1977, Lisburne Group (Mississippian and Pennsylvanian), potential major hydrocarbon objective of Arctic Slope, Alaska: American Association of Petroleum Geologists Bulletin, v. 61, no. 9, p. 1493-1512.

Bundtzen, T.K., and Henning, W.W., 1978, Barite in Alaska: Alaska Division of Geological and Geophysical Surveys Mines and Geology Bulletin, v. 27, no. 4, p. 1-4.

Carman, G.J., and Hardwick, Peter, 1983, Geology and regional setting of Kuparuk oil field, Alaska: American Association of Petroleum Geologists Bulletin, v. 67, no. 6, p. 1014-1031.

Cathcart, J.B., and Gulbrandson, R.A., 1973, Phosphate deposits, *in* Brobst, D.A., and Pratt, W.D., eds., United States mineral resources: U.S. Geological Survey Professional Paper 820, p. 515-525.

Cathrall, J.B., Detra, D.E., and O'Leary, R.M., 1978, Geochemical maps showing the distribution and abundance of zinc in the Philip Smith Mountains quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-879I, scale 1:250,000.

Churkin, Michael, Jr., Mayfield, C.F., Theobald, P.K., Barton, Harlan, Nokleberg, W.J., Winkler, G.R., and Huie, Carl, 1978, Geological and geochemical appraisal of metallic mineral resources, southern National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 78-70A, 85 p.

Collins, F.R., 1958, Test wells, Topagoruk area, Alaska: U.S. Geological Survey Professional Paper 305-D, p. 265-316.

Detterman, R.L., 1976, Lithofacies fence diagram of Sadlerochit Group for Philip Smith Mountains quadrangle and adjacent areas, northeastern Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-744.

Detterman, R.L., Reiser, H.N., Brosgé, W.P., and Dutro, J.T., Jr., 1975, Post-Carboniferous stratigraphy, northeastern Alaska: U.S. Geological Survey Professional Paper 886, 46 p.

Fackler, W.C., Brockway, R.G., Crane, R.C., Harrison, C.R., Hiles, R.M., Jr., Mangus, M.D., Mull, C.G., Nelson, F.E., Penttila, W.C., Pessel, G.H., Stoneley, Robert, Streeton, D.L., and Tailleur, I.L., 1970, The Sag River Sandstone and Kuparuk River sands, two important subsurface units in the Prudhoe Bay field, *in* Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska: Los Angeles, American Association of Petroleum Geologists, Pacific Section, p. P1-P3.

Hughes, W.B., Miller, D.E., and Holba, A.G., 1983, North Slope, Alaska oil-rock correlation study, *in* Magoon, L.B., and Claypool, G.E., eds., Alaska North Slope oil-rock correlation study—a compilation of abstracts: American Association of Petroleum Geologists Short Course, Dallas, Tex., 1983 (Catalogue No. 480).

Jones, H.P., and Speers, R.G., 1976, Permo-Triassic reservoirs of Prudhoe Bay field, North Slope, Alaska, *in* Braunstein, Jules, ed., North American oil and gas fields: American Association of Petroleum Geologists Memoir 24, p. 23-50.

Klemic, Harry, Gottfried, David, Cooper, Margaret, and Marsh, S.P., 1973, Zirconium and hafnium, *in* Brobst, D.A., and Pratt, W.D., eds., United States mineral resources: U.S. Geological Survey Professional Paper 820, p. 713-722.

Lerand, Monti, 1973, Beaufort Sea, *in* McCrossan, R.G., ed., The future petroleum provinces of Canada—their geology and potential: Canadian Society of Petroleum Geologists Memoir 1, p. 315-386.

Mayfield, C.F., Tailleur, I.L., and Ellersieck, Inyo, 1983, Stratigraphy, structure and palinspastic synthesis of the western Brooks Range, northwestern Alaska: U.S. Geological Survey Open-File Report 83-779, 58 p.

Molenaar, C.M., 1981, Depositional history and seismic stratigraphy of lower Cretaceous rocks, National Petroleum Reserve in Alaska and adjacent areas: U.S. Geological Survey Open-File Report 81-1084, 42 p.

—— 1983, Depositional relations of Cretaceous and lower Tertiary rocks, northeastern Alaska: American Association of Petroleum Geologists Bulletin, v. 67, no. 7, p. 1066-1080.

Morgridge, D.L., and Smith, W.B., Jr., 1972, Geology and discovery of Prudhoe Bay field, eastern Arctic Slope, Alaska, *in* Stratigraphic oil and gas fields—classification, exploration methods and case histories: American Association of Petroleum Geologists Memoir 16, p. 489-501.

Mull, C.G., Tailleur, I.L., Mayfield, C.F., Ellersieck, Inyo, and Curtis, S., 1982, New upper Paleozoic and lower Mesozoic stratigraphic units, central and western Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 66, no. 3, p. 348-362.

Nokleberg, W.J., and Winkler, G.R., 1982, Stratiform zinc-lead deposits in the Drenchwater Creek area, Howard Pass quadrangle, northwestern Brooks Range, Alaska: U.S. Geological Survey Professional Paper 1209, 22 p.

Norman, J.C., and Haskin, L.A., 1968, The geochemistry of Sc; A comparison to the rare earths and Fe: Geochimica et Cosmochimica Acta, v. 32, no. 1, p. 93-108.

Patton, W.W., Jr., and Matzko, J.J., 1959, Phosphate deposits in northern Alaska: U.S. Geological Survey Professional Paper 302-A, p. 1-17.

Patton, W.W., Jr., and Tailleur, I.L., 1964, Geology of the Killik-Itkillik region, Alaska: U.S. Geological Survey Professional Paper 303-G, p. 409-500.

Reiser, H.N., Brosgé, W.P., Hamilton, T.D., Singer, D.A., Menzie, W.D., II, Bird, K.J., Cady, J.W., Le Compte, J.R., and Cathrall, J.B., 1983, The Alaska Mineral

Resource Assessment Program; guide to information contained in folio of geologic and mineral resource maps of the Philip Smith Mountains quadrangle, Alaska: U.S. Geological Survey Circular 759, 22 p.

Robinson, F.M., 1956, Core tests and test wells, Oumalik area, Alaska: U.S. Geological Survey Professional Paper 305-A, p. 1-70.

Rose, A.W., Hawkes, H.E., and Webb, J.S., 1979, Geochemistry in mineral exploration (2d ed.): London, Academic Press, 657 p.

Seifert, W.K., Moldowan, J.M., and Jones, R.W., 1979, Application of biological marker chemistry to petroleum exploration: World Petroleum Congress, 10th, Bucharest, 1979, Proceedings, v. 2, p. 425-440.

Staats, M.C., and Olson, J.C., 1973, Thorium, *in* Brobst, D.A., and Pratt, W.D., eds., United States mineral resources: U.S. Geological Survey Professional Paper 820, p. 468-476.

Tourtelot, H.A., and Tailleur, I.L., 1971, The Shublik Formation and adjacent strata in northeastern Alaska: U.S. Geological Survey Open-File Report 71-284, 62 p.

Turekian, K.K., 1977, Geochemical distribution of elements, *in* Encyclopedia of science and technology (4th ed.): New York, McGraw Hill, p. 627-630.

Vine, J.D., and Tourtelot, E.B., 1970, Geochemistry of black shale deposits—a summary report: Economic Geology, v. 65, no. 3, p. 253-272.

Weeks, R.A., 1973, Gallium, germanium and indium, *in* Brobst, D.A., and Pratt, W.D., eds., United States mineral resources: U.S. Geological Suvey Professional Paper 820, p. 237-246.

Witmer, R.J., Haga, Hideyo, and Mickey, M.B., 1981, Biostratigraphic report of thirty-three wells drilled from 1975 to 1981 in National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 81-1166, 47 p.

24. HELIUM SURVEYING, A GEOCHEMICAL EXPLORATION TECHNIQUE FOR PETROLEUM ON THE NORTH SLOPE

By ALAN A. ROBERTS[1] and KIMBERLEY I. CUNNINGHAM

INTRODUCTION

Much work has been done in recent years to determine the utility of direct geochemical detection techniques in prospecting for petroleum. These techniques involve the detection of near-surface manifestations of microseepage of petroleum hydrocarbons and related compounds from petroleum reservoirs. Most of this work has involved determining the concentration of hydrocarbons in the top 3 m of soil. Complications arise, however, because of the biogenic production of hydrocarbons in the soil. Attempts to differentiate between hydrocarbons of fossil origin and of biogenic origin have had varying degrees of success (Smith and Ellis, 1963; Debnam, 1969; Horvitz, 1972; Hunt, 1979, p. 425-433). In order to circumvent these complications, another common component of petroleum—helium—has been studied as a possible direct geochemical indicator of oil and gas reservoirs (Ball and Snowdon, 1973; Roberts and others, 1976; Palacas and Roberts, 1980; Pogorski and Quirt, 1981; Roberts, 1981).

The origin of virtually all nonprimordial helium on Earth is the alpha decay of uranium, thorium, and their radioactive daughters. As a result of the dissemination of uranium and thorium throughout the Earth's crust and of chelation by organic matter in source rocks, there is a continual flux of helium through the crust. This helium can be trapped along with oil and gas in petroleum reservoirs; it can become dissolved in hot brines, in which it is quite soluble; or it can migrate to the surface, where it enters the atmosphere and is eventually lost to outer space. Most oil and gas reservoirs in the United States are observed to contain significant (greater than 100 ppm) concentrations of helium (Dyck, 1976; Moore, 1976). Because the helium molecule is very small and of low mass, some of the helium in these reservoirs can escape from the traps and eventually migrate to the Earth's surface. Because it cannot be biogenically produced and cannot be destroyed in a natural environment, its presence or absence cannot be attributed to reactions in the near-surface environment. Thus, the presence of anomalously high concentrations of helium in soil must be attributed to a deep source, such as a petroleum or geothermal reservoir, or to a highly concentrated uranium deposit.

Surveys have shown anomalously high concentrations of helium gas to be associated with many petroleum reservoirs (Roberts, 1981), with geothermal reservoirs (Roberts, 1975; Roberts and others, 1975), with uranium deposits (Dyck, 1976; Reimer and Otton, 1976; Clarke and others, 1977; Torgerson and Clarke, 1978; Reimer and others, 1979), and with permeable fault zones or fault systems (Plyusnin and others, 1972; Bulashevich and Bashorin, 1973). Because there are many possible sources for anomalous concentrations of helium, such surveys should be conducted in conjunction with geological and geophysical investigations if they are to be of use in petroleum exploration.

ACKNOWLEDGMENTS

We thank L.A. Pogorski and S.G. Quirt of Chemical Projects Ltd. for their assistance in developing the sampling techniques and for their excellent cooperation in analyzing the samples and interpreting the data.

EXPERIMENTAL METHODS

More than 1,600 samples of permafrost were collected on a rough 1.6-km grid in the northern part of the National Petroleum Reserve in Alaska (fig. 24.1). These samples were taken from a depth of about 60 cm by using a power-driven coring auger mounted in the cargo basket of a helicopter. About 150 cm^3 of permafrost was collected at each station and immediately hermetically sealed in an aluminum can. The barometric pressure and atmospheric temperature were then measured. This sampling technique proved to be quite efficient, requiring only about 2-3 min per site. The cans were subsequently shipped back to the contractor's laboratory for analysis.

In the laboratory the cans are kept for at least two weeks at 30 °C. The internal pressure of the gas in the can is measured, and 5 cm^3 of the headspace gas is then removed. This gas is analyzed for helium content with a mass spectrometer having a sensitivity of about 10 ppb.

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The water and air content of the sample are then measured, and the original helium content of the sample is calculated, making corrections for differences between field and laboratory conditions. Helium concentration is reported in terms of volume of helium per volume of water in the sample.

RESULTS AND DISCUSSION

Isopleth maps of the helium concentration in near-surface permafrost were prepared for areas in the northern part of the National Petroleum Reserve in Alaska from data on more than 1,600 samples (figs. 24.2-24.5). The concentration ranged from trace or unmeasurable amounts to almost 3,000 nanoliters (nL) of helium per liter (L) of water. The mean concentration observed was about 500 nL/L, and the samples showed a roughly normal distribution skewed toward the high side. Normal background concentration appears to be about 350-450 nL/L. The values obtained from areas south and southeast of Barrow and on the Simpson Peninsula are significantly higher than those from elsewhere in the area.

When the western quarter of the area near Camp Lonely was surveyed in 1978, the Drew Point No. 1 was the only well that had been drilled there (fig. 24.2). This well bottomed in the basement complex and was dry. The general pattern of helium values in this area was observed to be random, and concentrations were low. This helium survey gives no support for the existence of any petroleum reservoirs within the area. Another well, the J.W. Dalton No. 1, was drilled the following winter near Camp Lonely. The major goal in drilling here was to reach sandstone and conglomerate of the Triassic Ivishak Formation (Sadlerochit Group) and possibly carbonate rocks of the mostly Carboniferous Lisburne Group; the trap was expected to be a combination stratigraphic pinchout and truncation. The helium data, however, did not suggest the presence of a petroleum reservoir. When the well was drilled, only a small quantity of very viscous asphaltic material was found.

A second area of interest is around the structurally complex South Barrow gas fields (fig. 24.3). At least two and probably three gas reservoirs are located within this area. The main South Barrow field produces gas from a sandstone—the Barrow sand of local usage—in the Kingak Shale of Mesozoic age and presumably also from fractures in the argillite basement (Collins, 1961). This gas contains about 0.03 percent helium. The South Barrow East field is located about 10 km to the east and also produces gas from the same sandstone. The two wells on the west side of this field produce gas that has an extremely high helium content, ranging from about 1 to 4 percent. The eastern two wells produce gas having a helium content of about 0.05 to 0.13 percent. This difference in helium content in gases produced from supposedly the same horizon and only a few kilometers apart implies that there are two reservoirs and a permeability barrier between them. The area between the South Barrow East field and the South Barrow field is commonly known as the disturbed zone, so called because it is characterized by numerous faults cutting Jurassic and Cretaceous beds that dip at angles ranging from 20° to nearly vertical. In the seismic records it appears as "a nearly circular area of no seismic

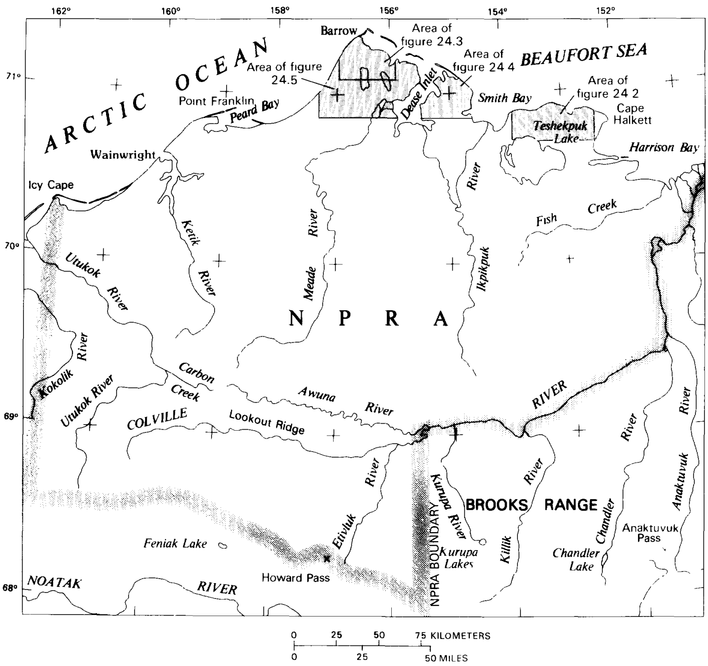

FIGURE 24.1.—Area of helium survey in northern part of National Petroleum Reserve in Alaska (NPRA).

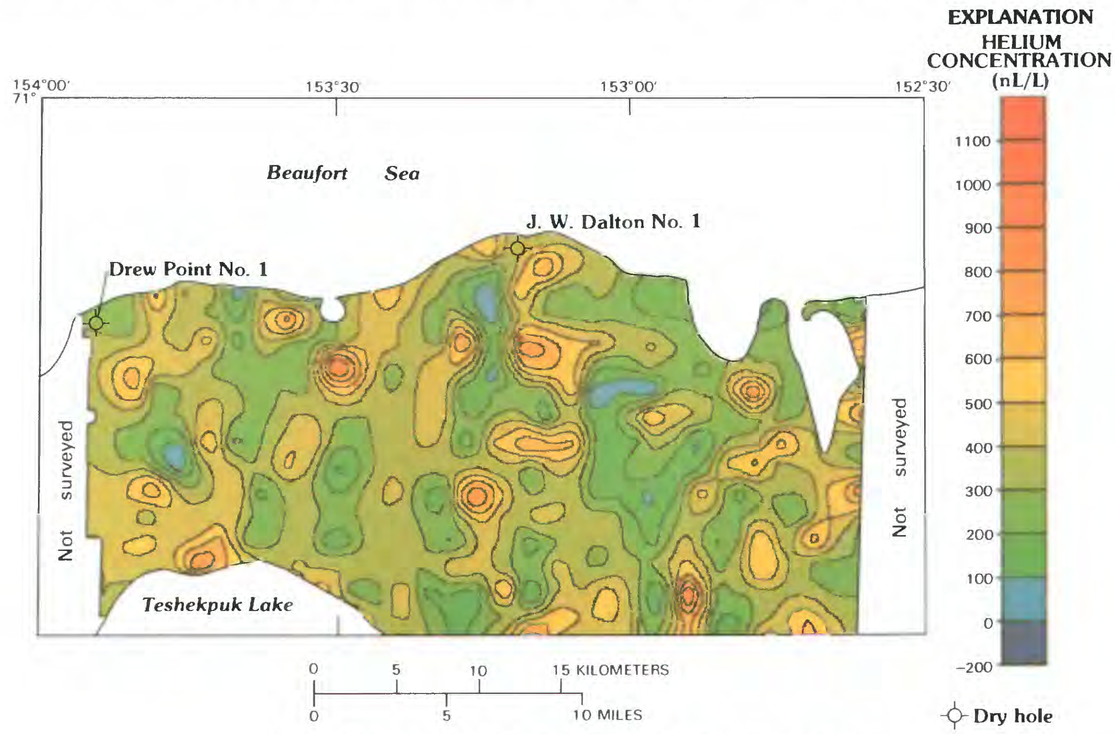

FIGURE 24.2.—Results of helium survey in Camp Lonely area.

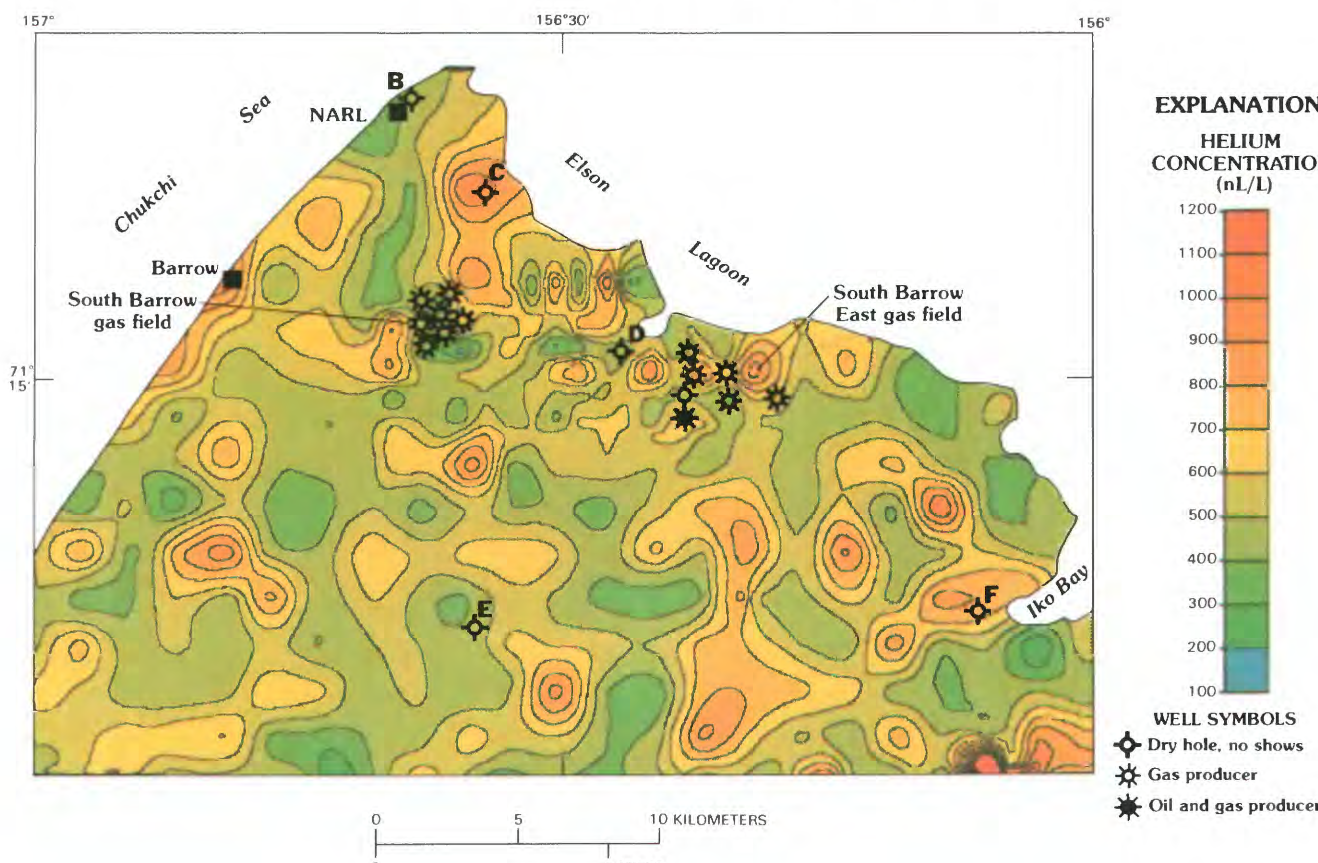

FIGURE 24.3.—Results of helium survey, South Barrow gas field and vicinity. NARL, Naval Arctic Research Laboratory; B, South Barrow No. 1; C, South Barrow No. 16; D, Avak No. 1; E, South Barrow No. 3; F, Iko Bay No. 1.

reflections, from which faults appeared to radiate in several directions'' (Collins, 1961, p. 629). The U.S. Navy Avak No. 1 test well was drilled into this disturbed zone and was dry.

The initial helium survey was run in the Barrow area in 1978, and results were somewhat ambiguous. At the time, it seemed that ''no clear picture emerges from the distribution of these high-helium samples'' (Roberts, 1981, p. 146). In an attempt to clear up these ambiguities, a second survey was run in 1980 on a somewhat closer grid spacing (approx 0.4 km). The results of the combined surveys are shown in figure 24.3. There does not appear to be a good correlation between the pattern of the helium values and the location of the known gas reservoirs. The average helium concentration from the 1978 survey was 450 nL/L, and the average from the 1980 survey was 425 nL/L. Thus there was good consistency between the measurements taken in the two completely independent surveys. Many values were observed to be in the range 700-950 nL/L. These values are higher than what we consider to be

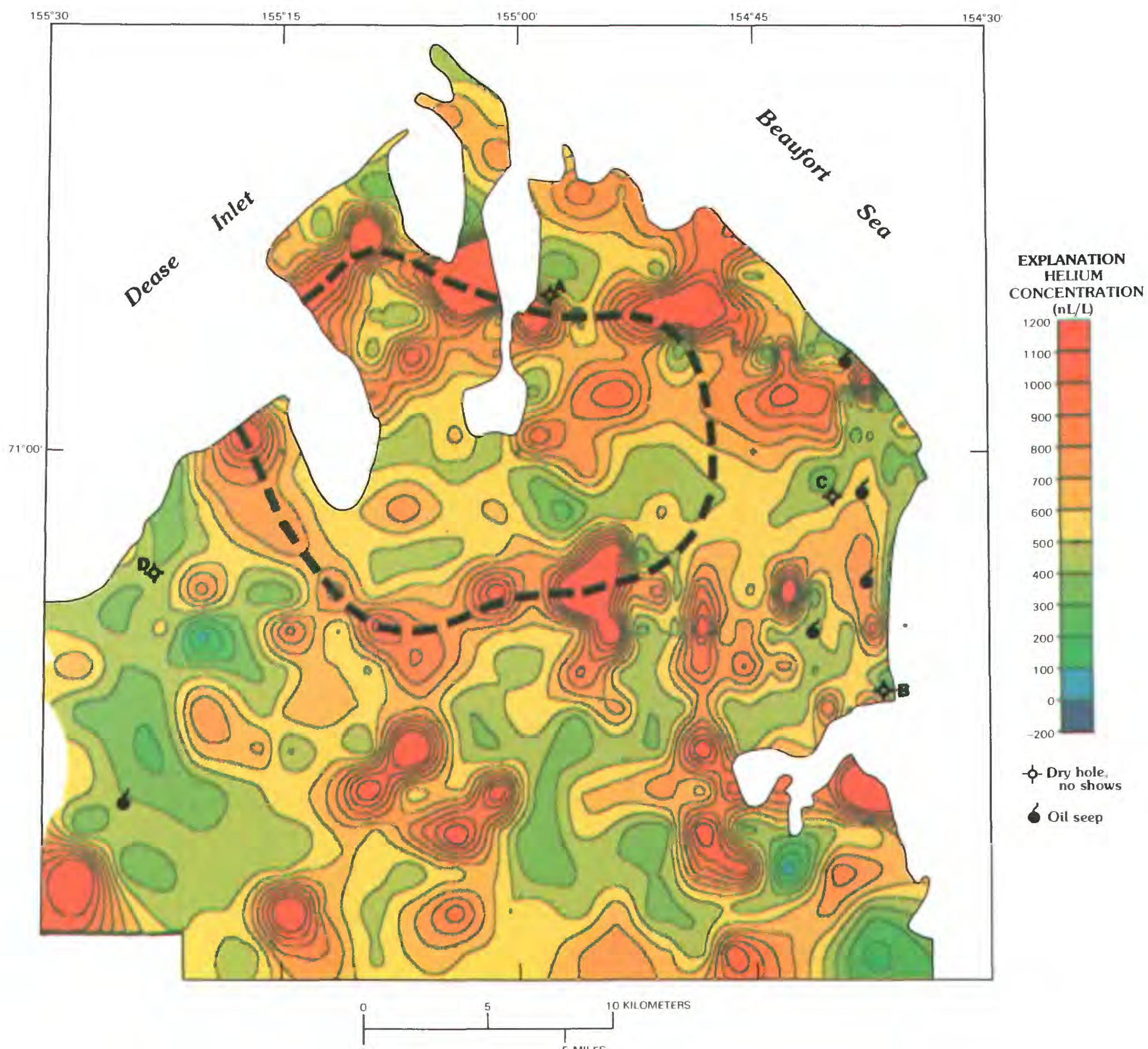

FIGURE 24.4.—Results of helium survey, Simpson Peninsula. Dashed line marks zone of high helium concentration. A, North Simpson No. 1; B, East Simpson No. 1; C, East Simpson No. 2; D, South Simpson No. 1.

the normal background concentration of helium in permafrost. We suggest that these high values are probably related to the proximity here of the argillite basement, which is encountered at a depth of about 750 m in the South Barrow field and drops off rapidly to the south.

An isopleth map of the helium concentration in permafrost on the Simpson Peninsula is shown in figure 24.4. The values observed in this area are much higher (average 640 nL/L) than in other permafrost areas studied and well above what we consider to be a normal background (350-450 nL/L). Five oil seeps have been observed on the Simpson Peninsula and have sparked great interest in its petroleum potential. Numerous shallow wells were drilled in the vicinity of the four seeps on the east side of the peninsula. Subsurface data from these wells, together with seismic data, have identified an unconformity within the Seabee Formation of the Upper Cretaceous Colville Group (Robinson, 1964). West of the area of this unconformity is the deep Simpson paleocanyon, filled with as much as 350 m of Cretaceous (Seabee Formation) clay shale. East of the area of the unconformity are alternating sandstone and claystone of the Seabee. These porous sandstones dip gently to the east and are truncated on the west by the paleocanyon just west of the seeps. Wells drilled near the seeps recovered oil at depths of about 100 m in the basal part of the Seabee and Ninuluk Formations (undivided) or in the upper part of the Lower Cretaceous Grandstand Formation. This oil may be in a small stratigraphic trap (or traps), and the seeps may represent leakage at the truncation zone.

The most obvious feature of the helium survey of the Simpson Peninsula is an arcuate pattern of exceptionally high helium values indicated in figure 24.4 by the heavy dashed line. The northern, eastern, and western portions of this anomaly are generally located over what is believed to be the Simpson paleocanyon. This same area is strikingly delineated in a low-level aeromagnetic survey (Donovan and others, chapter 26) as an area characterized by high-wave-number peaks. These peaks are believed to be related to near-surface diagenetic

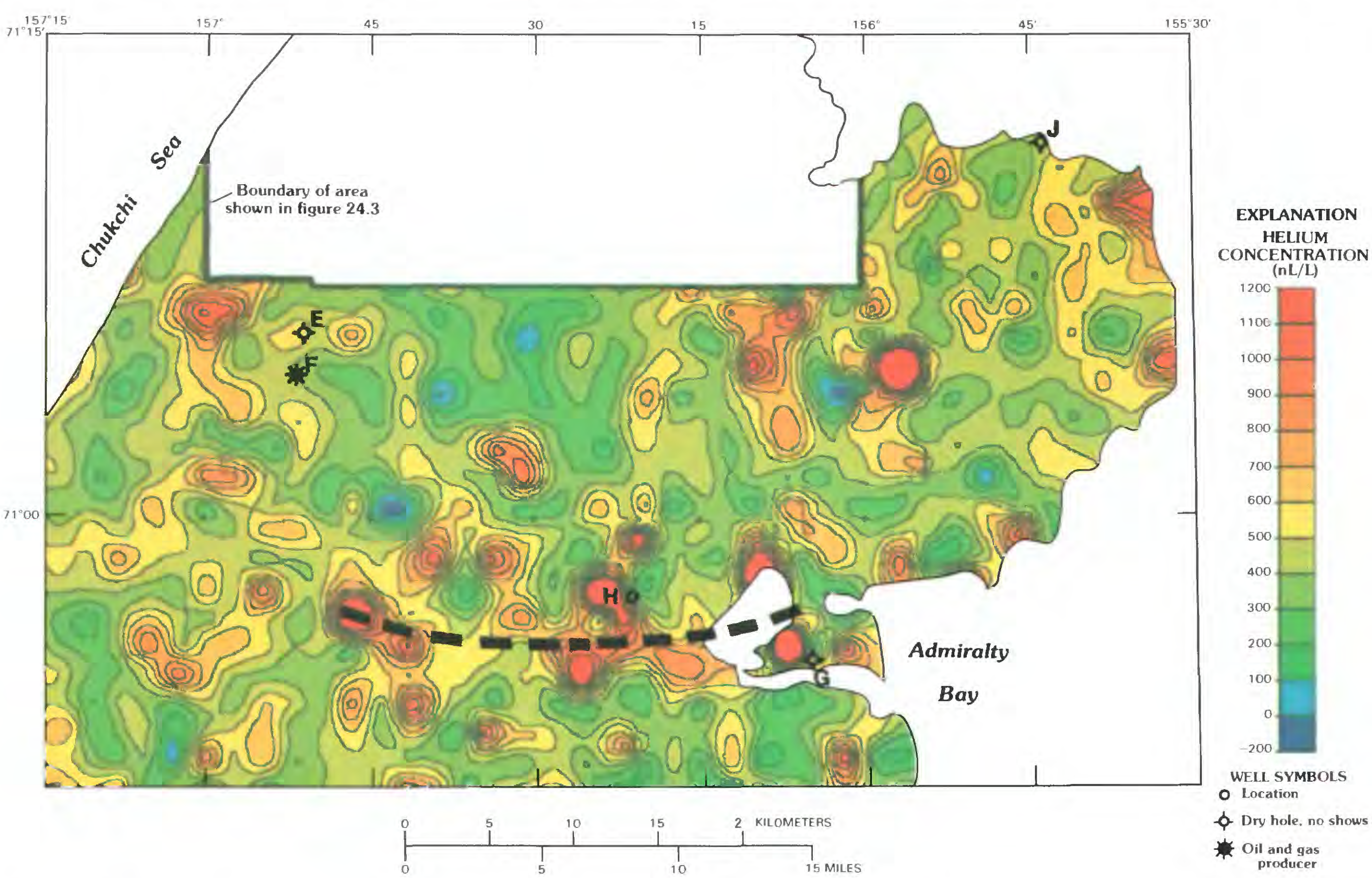

FIGURE 24.5.—Results of helium survey in area south of Barrow, site of possible tests of Jurassic sandstone in upper part of Kingak Shale. Heavy dashed line marks band of high helium concentration. Letters denote older wells: E, Walakpa No. 1; F, Walakpa No. 2; G, Kuyanak No. 1; H, Ekalgruak No. 1; J, Tulageak No. 1.

magnetic minerals, which are formed through reduction of oxidized iron minerals in areas where seepage of hydrocarbons has occurred (Donovan and others, 1979). Possibly these features represent seepage of hydrocarbons and helium from a petroleum source underlying the area within the anomaly indicated by the dashed line in figure 24.4. The petroleum may be in a stratigraphic trap formed where the Simpson paleocanyon truncates the southeastward-dipping strata. The high helium values and the inferred diagenetic magnetic minerals would be the results of microseepage along this truncation zone (Roberts, 1981).

Four deep wells (deeper than 1,000 m) have been drilled within the survey area, but none was within this particular area. None of these wells encountered producible oil or gas.

An isopleth map of the helium concentration in permafrost in an area south of Barrow is shown in figure 24.5. Several possible drill sites have been identified here. These all have the Jurassic sandstone that is seen in the South Simpson No. 1 well at a depth of 1,988 m (6,521 ft) in the upper part of the Kingak Shale as their target. The seismic data have been interpreted to indicate a lithologic change within this sandstone in this area and a shale-out to the west. This interpretation is supported by the fact that this sandstone was absent because of shale-out at the Walakpa No. 1 test well. Truncation by the basal Cretaceous unconformity to the north coupled with this permeability barrier to the west indicate the possibility of a significant structural-stratigraphic trap creating a reservoir in this sandstone (Guldenzopf and others, 1980; Miller and others, 1979). The Ekalgruak and Kuyanak drill sites were proposed to test this hypothesis.

The most striking feature of the map shown in figure 24.5 is a linear band of helium highs indicated by the dashed line. The average helium concentration measured in the 94 samples collected in this area was 630 nL/L, about 50 percent higher than is expected of background samples. Many of the samples contained more than 1,000 nL/L of helium. This zone of high helium values is believed to represent leakage of gas along the truncation zone. The helium data together with the seismic interpretation and the subsurface geology indicate that Ekalgruak would be an excellent place to test this prospect. Kuyanak, on the southern edge of the zone of anomalous helium values, would not provide as good a test of this geochemical prospect. However, a well here may encounter a petroleum reservoir in the Jurassic sandstone. The helium survey gives no support, however, to the belief that petroleum reservoirs exist at either the Walakpa No. 2 or the Tulageak site.

Another zone of anomalously high helium values is shown in the northeastern section of the map in figure 24.5. It does not appear to be associated with any possible petroleum reservoirs identified by seismic investigations. Whether or not these high values are related to a reservoir can be determined only when more is known about the subsurface geology.

CONCLUSIONS

Studies in the conterminous United States have demonstrated that concentrations of helium in near-surface soils may indicate the presence of oil and gas reservoirs. In 8 out of 10 surveys, anomalously high concentrations of helium were found to be associated with reservoirs. Analogous surveys in areas where no source of high helium concentration was thought to exist revealed no helium anomalies. Such surveys must be used in conjunction with geophysical and geologic studies because there are several other possible sources of anomalously high helium concentration. This exploration technique is especially applicable to the remote and fragile Arctic environment because it is relatively inexpensive and environmentally nondestructive.

In this chapter we have presented the results of such helium studies in the National Petroleum Reserve in Alaska. No pattern of high helium values was found around any of the dry holes that have been drilled within the area. The survey around the South Barrow gas fields yielded somewhat ambiguous results, probably because the very shallow basement rocks in the area may in themselves be a source of higher concentrations of helium in the permafrost. Two areas have been identified as good prospective drill sites by using a combination of this geochemical exploration technique and geophysical and geologic information.

REFERENCES CITED

Ball, N.L., and Snowdon, L.R., 1973, A preliminary evaluation of the applicability of the helium survey technique to prospecting for petroleum, *in* Report of activities, part B; November 1972 to March 1973: Geological Survey of Canada Paper 73-1B, p. 199-202.

Bulashevich, Yu.P., and Bashorin, V.N., 1973, On the detection of faults along the Sverdlovsk DSS profile from high concentrations of helium in underground water: Physics of the Solid Earth, Academy of Sciences, USSR-Izvestiya, no. 3, p. 185-189.

Clarke, W.B., Top, Z., Beavan, A.P., and Ghandi, S.S., 1977, Dissolved helium in lakes; Uranium prospecting in the Precambrian terrain of central Labrador: Economic Geology, v. 72, no. 2, p. 233-242.

Collins, F.R., 1961, Core tests and test wells, Barrow area, Alaska: U.S. Geological Survey Professional Paper 305-K, p. 569-644.

Debnam, A.H., 1969, Geochemical prospecting for petroleum and natural gas in Canada: Geological Survey of Canada Bulletin, v. 177, p. 1-26.

Donovan, T.J., Forgey, R.L., and Roberts, A.A., 1979, Aeromagnetic detection of diagenetic magnetite over oil fields: American Association of Petroleum Geologists Bulletin, v. 63, no. 2, p. 245-248.

Dyck, Willy, 1976, The use of helium in mineral exploration: Journal of Geochemical Exploration, v. 5, p. 3-20.

Guldenzopf, E.C., Orlovsky, M.B., Higgs, D.A., Freytag, C.G., and Ovalle, E.R., 1980, National Petroleum Reserve in Alaska; summary geologic report, FY-1980: Tetra Tech, Inc., 149 p. [Available from National Geophysical Data Center, 325 Broadway, E/GC, Dept. CNP, Boulder, CO 80303]

Horvitz, Leo, 1972, Vegetation and geochemical prospecting for petroleum: American Association of Petroleum Geologists Bulletin, v. 56, no. 5, p. 925-940.

Hunt, J.M., 1979, Seeps and surface prospecting, *in* Petroleum Geochemistry and Geology: San Francisco, W.H. Freeman and Co., 615 p.

Miller, C.C., Pickard, J.E., Taber, E.C., and Rogers, R.B., 1979, National Petroleum Reserve in Alaska; Summary geophysical report, FY-1979: Tetra Tech, Inc., 37 p. [Available from National Geophysical Data Center, 325 Broadway, E/GC, Dept. CNP, Boulder, CO 80303]

Moore, B.J., 1976, Analyses of natural gases: U.S. Bureau of Mines Computer Printout 1-76.

Palacas, J.G., and Roberts, A.A., 1980, Helium anomaly in surficial deposits of South Florida; possible indicator of deep subsurface petroleum or shallow uranium-associated phosphate deposits: U.S. Geological Survey Open-File Report 80-91, 16 p.

Plyusnin, G.S., Volkova, N.V., Godumskiy, G.P., Smirnov, V.N., Papolitov, E.I., and Brandt, S.B., 1972, Trends in the distribution of argon and helium in contact regions and fault zones: Geokhimiya, no. 10, p. 1189-1196 [in Russian, with English abstract].

Pogorski, L.A., and Quirt, G.S., 1981, Helium emanometry in exploring for hydrocarbons, pt. 1 *of* Gottlieb, B.M., ed., Unconventional methods in exploration for petroleum and natural gas II: Dallas, Southern Methodist University Press, p. 124-135.

Reimer, G.M., Denton, E.H., Friedman, Irving, and Otton, J.K., 1979, Recent developments in uranium exploration using the U.S. Geological Survey mobile helium detector: Journal of Geochemical Exploration, v. 11, p. 1-12.

Reimer, G.M., and Otton, J.K., 1976, Helium in soil gas and well water in the vicinity of a uranium deposit, Weld County, Colorado: U.S. Geological Survey Open-File Report 76-699, 10 p.

Roberts, A.A., 1975, Helium surveys over known geothermal resource areas in the Imperial Valley, California: U.S. Geological Survey Open-File Report 75-427, 6 p.

—— 1981, Helium emanometry in exploring for hydrocarbons, part II, *in* Gottlieb, B.M., ed., Unconventional Methods in exploration for petroleum and natural gas II: Dallas, Southern Methodist University Press, p. 136-149.

Roberts, A.A., Dalziel, Mary, Pogorski, L.A., and Quirt, S.G., 1976, A possible petroleum related helium anomaly in the soil gas, Boulder and Weld Counties, Colorado: U.S. Geological Survey Open-File Report 76-544, 7 p.

Roberts, A.A., Friedman, Irving, Donovan, T.J., and Denton, E.H., 1975, Helium survey, a possible technique for locating geothermal reservoirs: Geophysical Research Letters, v. 2, p. 209-210.

Robinson, F.M., 1964, Core tests, Simpson area, Alaska: U.S. Geological Survey Professional Paper 305-L, p. 645-730.

Smith, G.H., and Ellis, M.M., 1963, Chromatographic analysis of gases from soils and vegetation, related to geochemical prospecting for petroleum: American Association of Petroleum Geologists Bulletin, v. 47, no. 11, p. 1897-1903.

Torgerson, Thomas, and Clarke, W.B., 1978, Excess helium-4 in Teggan Lake; possibilities for a uranium ore body: Science, v. 199, p. 769-771.

Seismic train parked to form temporary camp.

Drill holes for shot emplacement to create sonic waves.

Inside the seismic recording trailers, where the sonic waves are recorded and plotted.

Drill rigs mounted on tracked vehicle.

Seismic train moving to next work station.

Scenes of seismic crews at work in winter in the NPRA. Photographs by George Gryc and Jeep Johnson.

GEOPHYSICS

A principal requirement for the accumulation of an oil deposit is a trap, commonly a structural feature, that confines and holds the oil and gas. Although mapping of the rocks at the surface provides some clues to the structure at depth, remote-sensing geophysical methods provide the best data for interpretation of the deeper geologic structure.

Modern geophysical techniques for petroleum exploration in Arctic regions, such as seismic reflection and refraction, gravity, and airborne magnetic surveys, were pioneered in the Naval Petroleum Reserve No. 4 (now the NPRA) by the U.S. Navy and the U.S. Geological Survey.

In the NPR-4 exploration program (1945-53) and in the more recent program (1974-81), the seismic surveys and interpretations were made by contractors. In both programs the USGS staff worked with the contractors at several stages during the geophysical surveys. The areas to be surveyed and studied were delineated by the USGS, and the geologic interpretations were reviewed by USGS field geologists in a workshop exchange. Additional geophysical studies by the USGS in the NPRA supplement those completed by the contractors and demonstrate the different interpretations that are possible using the same basic data.

25. DEPOSITIONAL HISTORY AND SEISMIC STRATIGRAPHY OF LOWER CRETACEOUS ROCKS IN THE NATIONAL PETROLEUM RESERVE IN ALASKA AND ADJACENT AREAS

By CORNELIUS M. MOLENAAR

INTRODUCTION

Lower Cretaceous rocks, which are widespread throughout the National Petroleum Reserve in Alaska (NPRA) and adjacent areas north of the Brooks Range, make up the major part of the thick sedimentary fill of the Colville basin. These strata range from deep-water flyschoid deposits to shallow-marine and nonmarine deltaic deposits. Much seismic and well information obtained since 1974 has aided considerably in understanding these rocks. These data include about 20,000 km of seismic lines, covering much of the NPRA with a grid spacing of 10-20 km, and 28 exploratory wells that bring the total to more than 50 wells in and adjacent to the NPRA (fig. 25.1; tables 25.1, 25.2). The purpose of this chapter is to interpret the depositional history of Lower Cretaceous rocks in the NPRA and adjacent areas on the basis of the latest seismic and well data and on information from outcrops in the southern part of the Colville basin.

Many studies have been made of the Cretaceous rocks that crop out in the foothills north of the Brooks Range. Some of this work is included in Gryc and others (1956), Chapman and Sable (1960), Detterman and others (1963), Chapman and others (1964), Patton and Tailleur (1964), and Ahlbrandt and others (1979). The earlier studies established the stratigraphic sequence in a structurally complex area in which many of the outcrops are limited to discontinuous river cuts or ridgetops. Because of structural complications, direct correlations into the subsurface could be made only with the Nanushuk and Colville Groups in the northern foothills, where several test wells were drilled in the late 1940's and early 1950's. Payne and others (1951) synthesized all of the data applying to the NPRA area (formerly known as Naval Petroleum Reserve No. 4 or NPR-4). Later, Collins and Robinson (1967) made a subsurface study using data from the available wells, mostly Nanushuk tests. With the aid of more recent seismic lines and many newer well penetrations, additional subsurface stratigraphic studies were made of the Nanushuk Group and associated strata by Bird and Andrews (1979) and Molenaar (1985). The basin geometry and depositional history described in those reports will be repeated here in the context of the overall Lower Cretaceous depositional history.

Well data (including paleontology) and seismic data are used almost exclusively to interpret relations in the northern foothills and coastal plain areas. Surface data and some well data are used in the southern parts of the northern foothills, and surface data are used exclusively to interpret the depositional history in the southern foothills and Brooks Range.

The quality of seismic data is fair to good in most of the coastal plain, where the structure is simple. In the northern foothills, tracing seismic reflections is more difficult, especially in the shallower part of the section because of structural complications in the thrust-faulted anticlines.

The quality of seismic data across the structurally complex southern foothills area is inadequate to correlate stratigraphic units of the outcrop area of the southern foothills with subsurface units to the north. However, certain consistent depositional patterns evident on north-south seismic lines in the coastal plain and northern foothills can be extrapolated into the areas of poor-quality seismic data in the southern foothills. The stratigraphic relations in that area are nevertheless highly interpretative.

STRATIGRAPHIC ANALYSES AND METHODS

In the discussion of each formation or rock unit in this chapter, the different rock types or subunits are placed in a meaningful stratigraphic sequence in relation to the overall depositional history. The depositional environments of the units are interpreted in the context of their ages, lithologies, and physical relations as shown by seismic data. Specific age data on some of the stratigraphic units are sparse or subject to differing interpretations. The ages used in this chapter are those generally accepted or published, except where new well data

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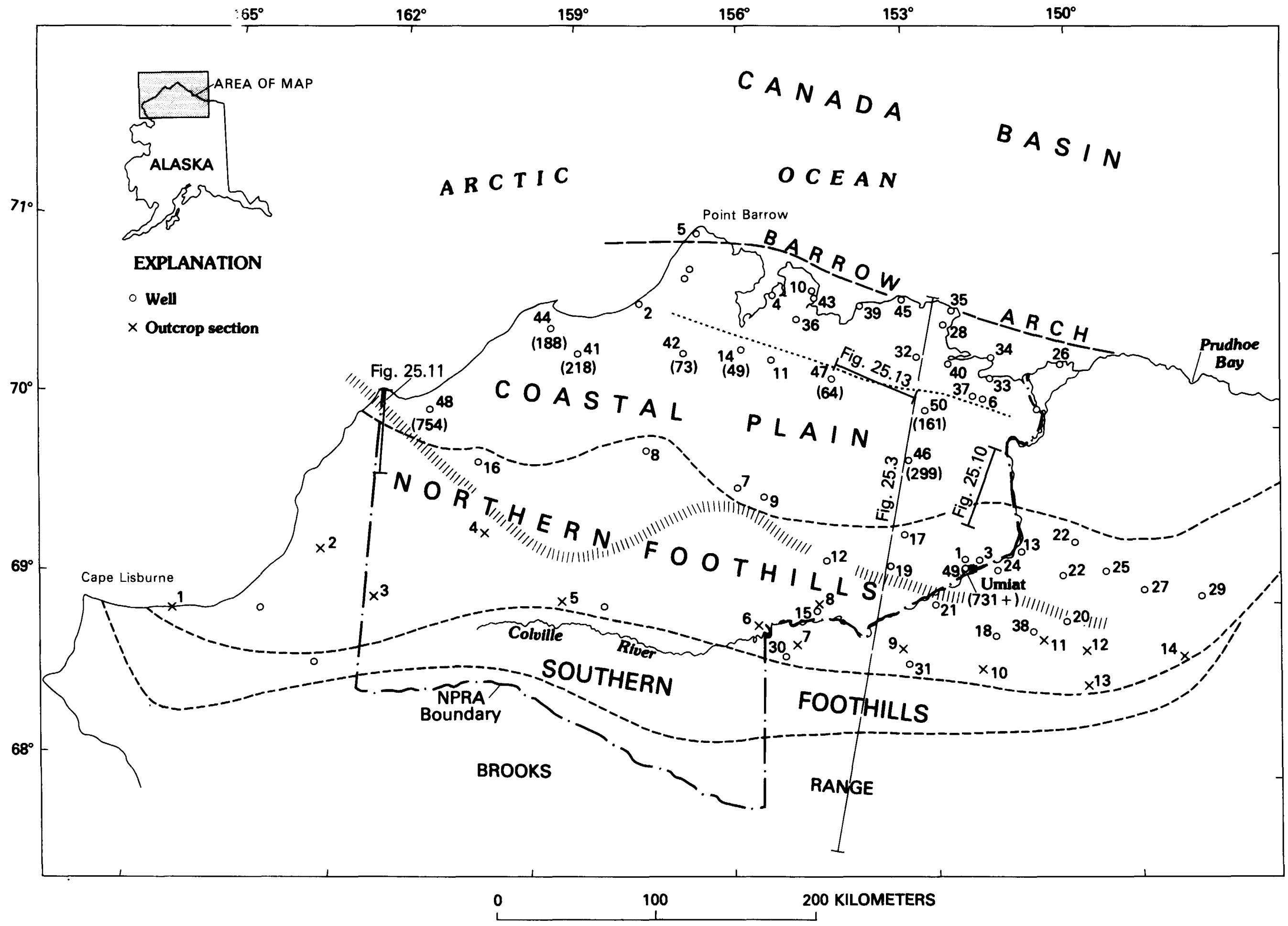

FIGURE 25.1.—Index map of NPRA and adjacent areas showing physiographic subdivisions, wells, outcrop sections, and lines of cross sections of figure 25.3 and seismic sections of figures 25.10, 25.11, and 25.13. Dotted line is approximate subcrop of Jurassic-Cretaceous boundary under mid-Neocomian unconformity. Hachured line is approximate position of shelf break (and southernmost limit of mid-Neocomian unconformity) over which pebble shale unit was deposited. Numbers in parentheses by wells are penetrations in meters of Cretaceous part of Kingak Shale based on paleontology. Identification of wells and outcrop sections given in tables 25.1 and 25.2.

TABLE 25.1.—*Well locations and stratigraphic data on the Nanushuk Group for wells drilled in the NPRA and adjacent areas, North Slope, Alaska*

[?, data not resolved; ±, approximate top of section; +, eroded top of Nanushuk Group, incomplete section]

Locality (fig. 25.1)	Well	Location			Nanushuk Group			
		Sec.	T.	R.	Top (ft)	Base (ft)	Thickness	
							(ft)	(m)
1	USN Umiat-1	34	1 N.	2 W.	915	2,840	[1]1165	[1]355
2	USN Skull Cliff C.T.-1	23	8 N.	22 W.	10	450	440+	134+
3	USN Umiat-2	3	1 S.	1 W.	80	1,060	980	299
4	USN Simpson-1	32	19 N	13 W.	20	980	960	293+
5	USN South Barrow-1	28	23 N	18 W.	70	695	625+	190
6	USN Fish Creek-1	15	11 N.	1 E.	2,890	4,110	1,220	372
7	USN Oumalik-1	30	6 N.	16 W.	20	2,770	2,750+	838+
8	USN Meade-1	19	8 N.	22 W	45	3,450	3,405+	1,038+
9	USN East Oumalik-1	13	5 N.	15 W.	35	2,970	2,935+	895+
10	USN Simpson C.T. 31	36	19 N.	11 W.	220	([2])	([2])	([2])
11	USN East Topagoruk-1	12	14 N.	14 W.	90	2,280	2,190+	667+
12	USN Titaluk-1	23	1 N.	11 W.	40	3,500	3,460	1,055
13	USN Gubik-1	20	1 N.	3 E.	3,350	4,005	655	200
14	USN Topagoruk-1	25	15 N.	6 W.	50	2,150	2,100+	640+
15	USN Knifeblade-2A	2	4 S.	12 W.	0	([2])	1,805+	500+
16	USN Kaolak-1	25	7 N.	34 W.	113	5,205	5,092+	1,552+
17	USN Square Lake-1	2	2 N.	6 W.	1,630	3,940	2,310	704
18	USN Grandstand-1	32	5 S.	1 E.	110	1,070	960+	293+
19	USN Wolf Creek-3	2	1 S.	7 W.	30	3,575	3,545+	1,080+
20	British Petroleum Shale Wall-1	1	5 S.	5 E.	1,080	3,150?	2,070?	631?
21	Sinclair Little Twist-1	34	3 S.	4 W.	0	3,075	3,075+	937+
22	British Petroleum Kuparuk-1	1	2 S.	5 E.	5,365	6,330	965	294
23	British Petroleum Itkillik-1	11	1 N.	6 E.	-----------Not present-----------			
24	McCulloch Colville U-2	15	1 S.	1 E.	1,765	2,820	1,055	322
25	Texaco-Newmont E. Kuparuk-1	10	2 S.	8 E.	6,680	6,860	180	55
26	Gulf Colville Delta-1	19	13 N.	6 E.	-----------Not present-----------			
27	Pan Am. Aufeis-1	30	3 S.	11 E.	2,450	3,474	1,025	312
28	USN Cape Halkett-1	5	16 N.	2 W.	3,118	4,235	1,117	340
29	Forest Lupine-1	13	4 S.	14 E.	?	?	?	?
30	Texaco W. Kurupa-1	33	6 S.	4 W.	0	1,730	1,730+	527+
31	Texaco E. Kurupa-1	9	7 S.	6 W.	0	2,190	2,190+	667+
32	USN East Teshekpuk-1	16	14 N.	4 W.	1,585	3,100	1,515	462
33	USN So. Harrison Bay-1	6	12 N.	2 E.	3,220	4,220	1,000	305
34	USN Atigaru Point-1	19	14 N.	2 E.	3,470	4,400	930	283
35	USN W.T. Foran-1	13	17 N.	2 W.	3,480	4,380	900	274
36	USN South Simpson-1	22	17 N.	12 W.	50±	1,915	1,865+	568+
37	USN West Fish Creek-1	11	11 N.	1 W.	2,550	3,915	1,365	416
38	Texaco Tulugak-1	26	5 S.	3 E.	0	2,665	2,665	812
39	USGS Drew Point-1	26	18 S.	8 W.	1,230	3,200	1,970	600
40	USGS North Kalikpik-1	3	13 N.	2 W.	2,395	3,470	1,075	328
41	USGS Kugrua-1	8	14 N.	26 W.	100	2,330	2,230+	680+
42	USGS South Meade-1	31	15 N.	19 W.	50±	2,490	2,440+	759+
43	USGS East Simpson-1	18	18 N.	10 W.	350	2,690	2,340	713
44	USGS Peard-1	25	16 N.	28 W.	50±	2,470	2,420+	738+
45	USGS J.W. Dalton-1	14	18 N.	5 W.	2,660	4,135	1,475	450
46	USGS Inigok-1	34	8 N.	5 W.	2,250	3,935	1,685	514
47	USGS Ikpikpuk-1	25	13 N.	10 W.	150	2,950	2,800	853
48	USGS Tunalik-1	20	10 N.	36 W.	50	6,250	6,200+	1,890+
49	USGS Seabee-1	5	1 S.	1 W.	280	1,300	1,020	311
50	USGS North Inigok-1	36	11 N.	4 W.	1,920	3,625	1,345	410

[1] Fault repetition of 760 ft (232 m) has been removed.

[2] Base of Nanushuk Group not reached.

required some reinterpretation. The generalized relations of the stratigraphic units discussed in this chapter are shown in figure 25.2.

For purposes of regional synthesis and facies projection, the depositional environments of the various sedimentary units or facies are grouped into three categories—nonmarine, shallow-water marine, and deep-water marine. Each of these three categories is then placed in its proper paleogeographic position in relation to the depositional basin at a particular time. These three major facies usually are coeval in the overall depositional pattern, although in some cases a shallow-marine facies may be bypassed or a nonmarine facies may not be preserved along the basin edge, as for example in the orogenic deposits of the Fortress Mountain Formation (Molenaar and others, chapter 12). Seismic sections in the northern part of the NPRA show the coeval stratigraphic relations clearly. Shallow-marine and nonmarine strata are represented by topset reflectors. Slope deposits are represented by inclined foreset reflectors that dip basinward at angles ranging from less than a 1° to as much as 6° as measured from topset reflectors. Deep-water basinal deposits are represented by bottomset reflectors and the lower part of foreset reflectors. In effect, the profile of correlative topset, foreset, and bottomset reflectors represents the compacted depositional profile of the basin. At the time of deposition, the angle of slope and the topographic relief of the basin were somewhat greater.

In the discussion of the stratigraphic units, the terms topset and shelf, foreset and slope, and bottomset and basinal are used interchangeably. These terms correspond to undaform, clinoform, and fondoform, respectively, of Rich (1951).

Two prominent seismic reflectors that are mappable over most of the coastal plain and northern foothills areas have been helpful in relating underlying and overlying seismic stratigraphic horizons. One such seismic reflector is the pebble shale unit of Neocomian age, and the other is the top of the Triassic Shublik Formation. Both units are considered to be synchronous and to have been deposited on a near-horizontal surface, except for the pebble shale unit in the southern part of its mapped area.

The seismic-stratigraphic terms used in this chapter are from Mitchum (1977, p. 205). Toplap refers to

TABLE 25.2.—*Location and thickness of outcrop sections of Nanushuk Group shown in figure 25.1*

[Numbers of sections keyed to figure 25.1; +, incomplete section]

Outcrop section	Location		Nanushuk Group thickness (m)	Source
	T.	R.		
1. Corwin Bluff	6-7 S.	53-56 W.	4,723+ 3,444+	Chapman and Sable, 1960 Smiley, 1969
2. Barbara syncline	1 N.-2 S.	44-45 W.	3,110+	Chapman and Sable, 1960
3. Kokolik warp syncline	3-4 S.	40-41 W.	2,091+	Huffman and others, 1981a
4. Elusive syncline	1-3 N.	33 W.	1,977	Chapman and Sable, 1960
5. Carbon Creek anticline	2 S.	28 W.	786+	Huffman and others, 1981a
6. Colville River	5 S.	15-17 W.	1,911+	Chapman and others, 1964
7. Kurupa River	6 S.	12-14 W.	1,832+	Huffman and others, 1981b
8. Knifeblade Ridge	3-4 S.	12 W.	1,452+	Brosgé and Whittington, 1966
9. Killik River	5-6 S.	6-7 W.	1,361+	Detterman and others, 1963
10. Mammoth Creek and Chandler River Tuktu Bluff	7-8 S.	1-2 W.	1,430 1,842+	Detterman and others, 1963 Huffman and others, 1981b
11. Type Grandstand	6 S.	4 E.	812+	Huffman and others, 1981b
12. Rooftop	7 S.	6-7 E.	195+	Huffman and others, 1981b
13. Nanushuk River	9 S.	6 E.	1,070+	Detterman and others, 1963
14. Marmot syncline	8 S.	13 E.	853+	Huffman and others, 1981b

the termination of strata against overlying topset beds as a result of nondeposition, that is, sedimentary bypassing with perhaps only minor erosion. Toplap could be caused by a relative stillstand of sea level or, if erosion is involved, by a temporary drop in relative sea level. Downlap refers to a base-discordant relation in which initially inclined (foreset) strata terminate downdip against an initially horizontal or inclined surface. Onlap refers to a base-discordant relation in which initially horizontal strata terminate progressively against an initially inclined surface, or in which initially inclined strata terminate progressively updip against a surface of greater initial inclination.

In the northern part of the NPRA, where the structure is simple, the number of well penetrations and the close spacing of seismic lines provide excellent data for interpreting the overall depositional history, especially of the Torok-Nanushuk section. Interpretations can be made with a fair degree of confidence of (1) stratigraphic correlations, (2) progradational directions, (3) basin slope angle, (4) paleobathymetry of the basin, and (5) width of the basin shelf.

The depositional history of the Lower Cretaceous rocks of the Colville basin is interpreted largely from the cross sections shown in figures 25.3 and 25.5-25.9. Figure 25.3 shows the inferred depositional relations across the Colville basin at three different periods during Early Cretaceous time. Although these cross sections are based on data from the eastern part of the NPRA and adjacent areas, similar depositional patterns occur throughout the area. In addition, because significantly more data are available for the Torok Formation and Nanushuk Group, five more detailed interpretive stratigraphic cross sections for these units and an index map are shown in figures 25.4-25.9.

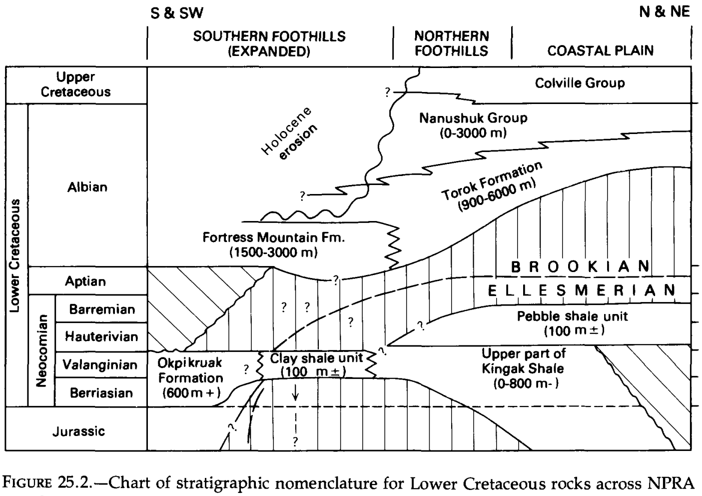

FIGURE 25.2.—Chart of stratigraphic nomenclature for Lower Cretaceous rocks across NPRA and adjacent areas. Diagonally lined pattern represents eroded section; vertically hatched pattern represents nondeposition or condensed section. Time scale not uniform.

LOWER CRETACEOUS ROCKS

The Colville basin is largely filled with a thick section of Lower Cretaceous siliciclastic rocks. The basin is asymmetric; on the south flank it is bounded abruptly by the Brooks Range orogenic belt, whereas the gentle north flank of the basin is bounded by the Barrow arch. In earliest Cretaceous time the Barrow arch was part of a mildly positive area, and through most of Cretaceous time it was a passive submarine ridge that separated the Colville basin on the south from the continental margin and Canada Basin, an oceanic basin, on the north.

The Lower Cretaceous section ranges in thickness from about 1,200 m in the northeastern part of the NPRA to more than 7,000 m in the axial part of the basin in the southern foothills. However, duplication of the thick shale section of the Torok Formation by thrust faults probably accounts for some of this thickness. Two general types of source area for these rocks are recognized. A source area to the

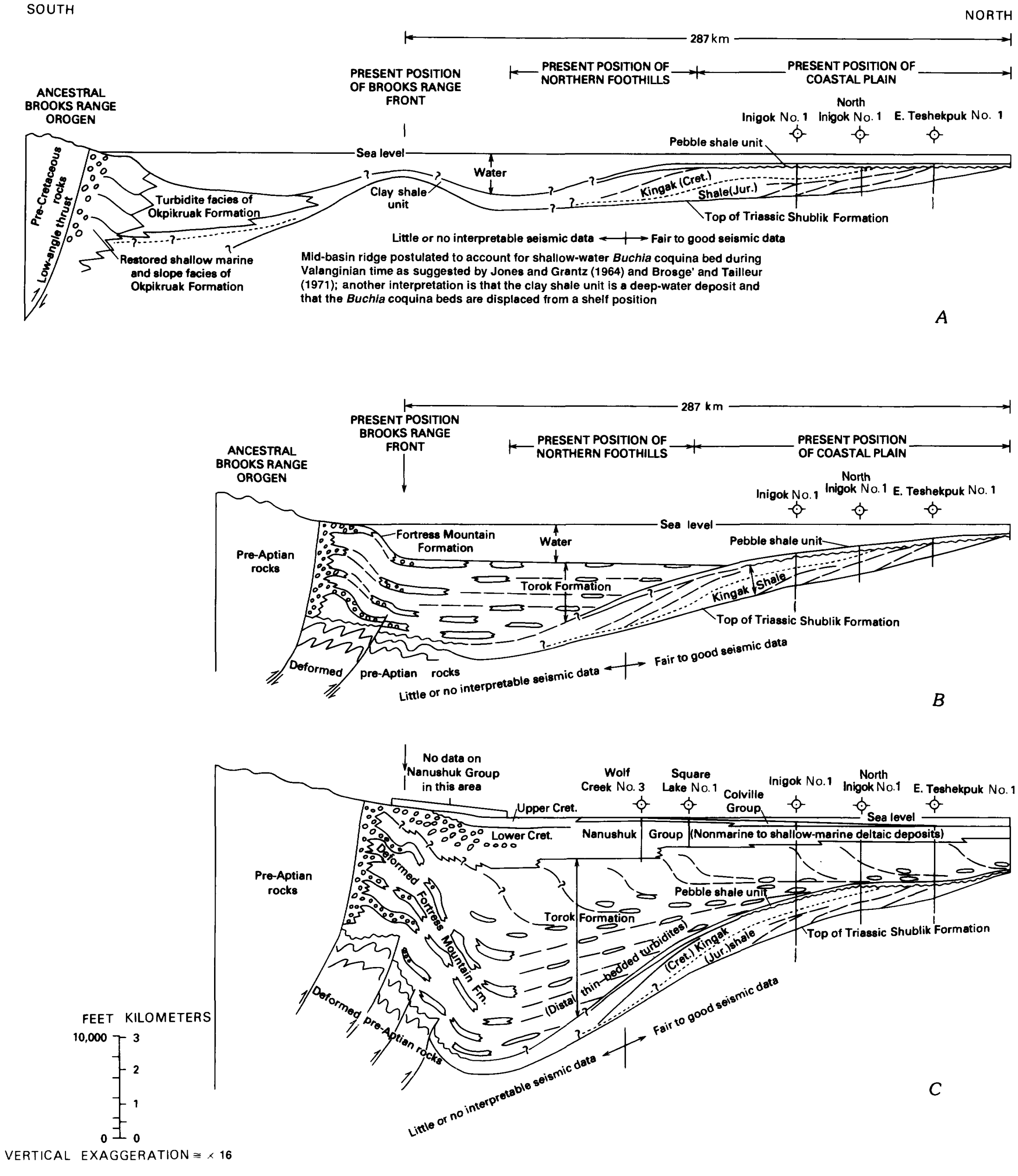

Figure 25.3.—Restored cross sections across the Colville basin showing Lower Cretaceous rocks at three different times in the Cretaceous. Dotted line approximates Jurassic-Cretaceous boundary; dashed lines represent bedding traces as indicated by seismic data. South half of sections is diagrammatic. See figure 25.1 for location of sections. *A*, End of pebble shale (Neocomian) time. Palinspastic restoration not meant to be rigorous. *B*, End of Fortress Mountain-lower Torok (early Albian) time. Horizontal beds in upper left are alluvial and shallow-marine facies, tilted beds are slope-shale and submarine-canyon facies, and lower horizontal beds are basinal-shale and turbidite facies. *C*, End of Nanushuk (Cenomanian) time. Turbidites in lower part of Torok Formation shown diagrammatically to illustrate relations with Fortress Mountain Formation. In addition, Torok Formation probably has been tectonically thickened in south half of section. Line of section oriented oblique to progradation direction of Torok-Nanushuk interval (east-northeastward).

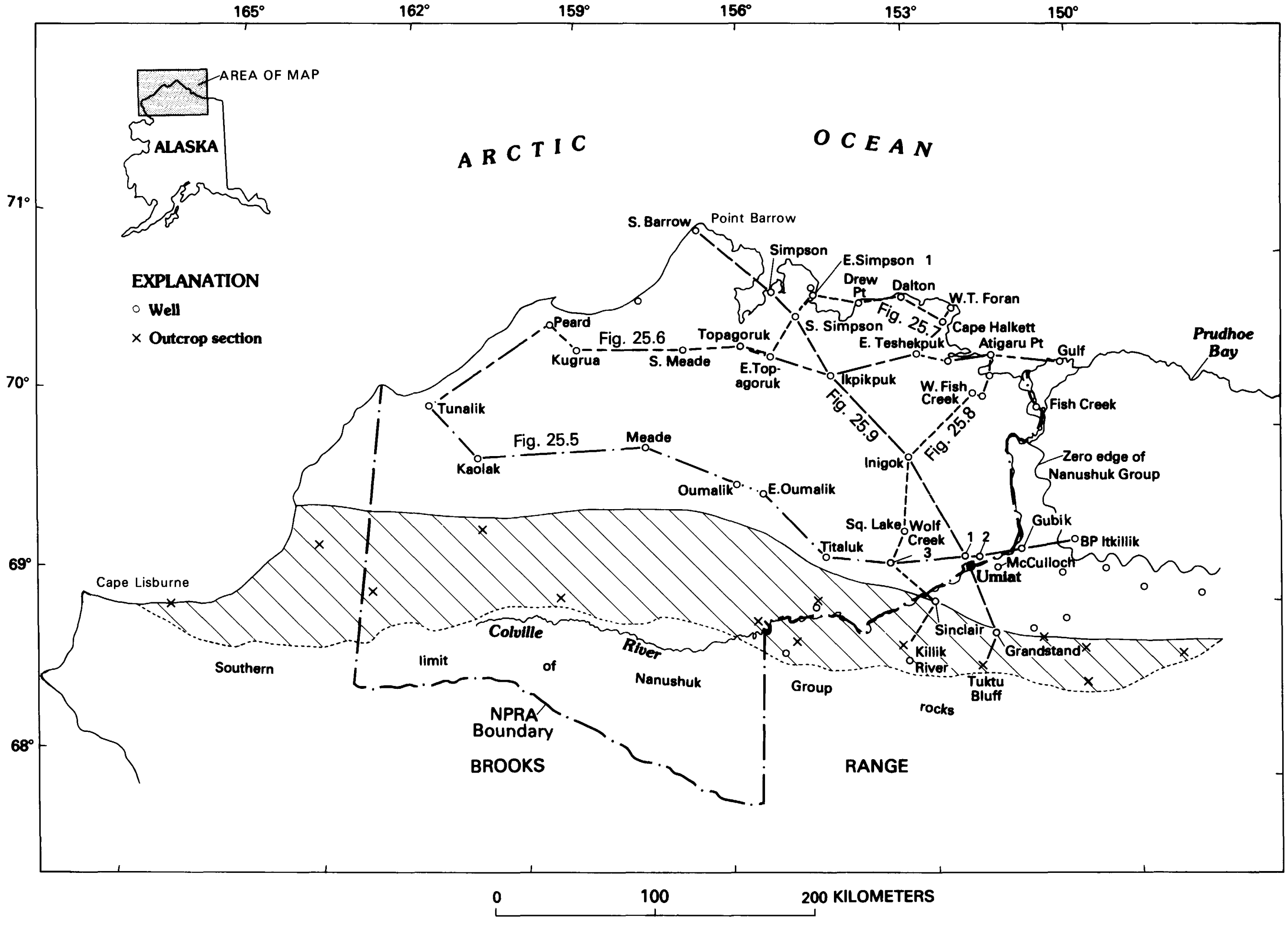

FIGURE 25.4—Index map of NPRA and adjacent areas showing lines of stratigraphic cross sections of Torok-Nanushuk interval (figs. 25.5-25.9), eastern extent of Nanushuk Group, and selected wells and outcrop sections of Nanushuk Group. Diagonally lined area is outcrop belt of Nanushuk Group. Identification of wells and outcrop sections given in figure 25.1 and tables 25.1 and 25.2.

south and west-southwest that contributed lithic-rich clastics dominated sedimentation throughout Early Cretaceous time. These rocks form part of what is known as the Brookian sequence. A northern source area, which was the dominant or only source area before Cretaceous time, contributed primarily finer clastics during earliest Cretaceous time on the north flank of the basin. Rocks derived from this northern provenance are more quartzose and mineralogically mature, and they belong to what is called the Ellesmerian sequence.

Some of the Lower Cretaceous stratigraphic units are not present over the entire basin. Some are areally restricted facies and some units are restricted geographically—coeval strata consist of condensed sections or are replaced by depositional hiatuses. The units involved are, in generally ascending order, a previously unnamed Neocomian shale unit in the northern part of the basin herein assigned to the Kingak Shale, the Okpikruak Formation and an unnamed clay shale unit of the southern foothills, the informally named pebble shale unit, the Fortress Mountain Formation of the southern foothills, the Torok Formation, and the Nanushuk Group (fig. 25.2). The uppermost part of the Nanushuk ranges into the Upper Cretaceous (Cenomanian).

With the exception of part of the Nanushuk Group and part of the Fortress Mountain Formation, all Lower Cretaceous rocks of the Colville basin are considered to be marine in origin.

NEOCOMIAN (EARLY CRETACEOUS) PART OF KINGAK SHALE

In the northern part of the coastal plain of the NPRA, the Kingak Shale, there of Jurassic age, and older rocks underlie a mid-Neocomian unconformity. This sequence is indicated by well and seismic data. The truncation plane of the unconformity cuts progressively older strata from south to north toward the Barrow arch; progressively younger strata are preserved under the unconformity to the south in the coastal plain and northern part of the northern foothills. Foraminiferal and palynological data from wells in those areas indicate that shale of Neocomian age is present below the unconformity (NPRA palynology/micropaleontology reports, 1980; Witmer and others, 1981). The greatest well penetration of the Neocomian section below the pebble shale unit was in the Tunalik No. 1 well on the west, where the section is 754 m (2,475 ft) thick. The thickness penetrated by other wells and the approximate subcrop limit of these Neocomian strata under the pebble shale unconformity are shown in figure 25.1. This Neocomian section below the pebble shale consists mainly of dark-gray to black, micaceous, marine shale containing some floating fine sand grains but includes a small amount of sandstone in the western part of the area. Because this Neocomian section is lithologically similar to, and appears to be part of, the same general depositional cycle as the underlying Kingak Shale of Jurassic age, it is here included in the Kingak Shale.

The Kingak Shale was named by Leffingwell (1919, p. 179) for shale exposures on the southeast side of the Sadlerochit Mountains in northeastern Alaska. At that locality the Kingak is entirely Jurassic in age; however, it underlies the regional mid-Neocomian unconformity in that general area (Detterman and others, 1975, p. 21)—the relations are similar to those noted in the northernmost part of the NPRA. In the Bathtub Ridge area 110 km southeast of the type area, a clay shale unit at least 100 m thick containing Valanginian (Early Cretaceous) fossils, and included in the Kongakut Formation, underlies the Kemik Sandstone Member of the Kongakut Formation and the pebble shale unit (Detterman and others, 1975, p. 22). Also, in the Kemik Creek area 95 km west-southwest of the type area, a Berriasian fossil, *Buchia subokensis*, was collected from shale at least 200 m below the Kemik Sandstone (Molenaar, 1983). Note that in the mountain front and coastal plain areas of northeastern Alaska, the Kemik Sandstone, formerly a member of the Kongakut Formation, has been elevated to formation rank by Molenaar and others (1987); see also Bird (chapter 15, comment 20). In addition, on the east bank of the Shaviovik River a few kilometers farther southwest, a possible *Buchia sublaevis* of Valanginian age was collected a few meters beneath the Kemik. This shale in the Shaviovik River and Kemik Creek areas was mapped as the Kingak Shale by Keller and others (1961) and seems to be continuous with underlying shale of Jurassic age. As in the NPRA, it appears that progressively younger shale is preserved under the unconformity to the south from the type area. Therefore, inclusion of the Neocomian shale underlying the pebble shale unit in the Kingak is logical and will simplify nomenclature problems throughout northern Alaska.

Foraminiferal and palynological data in the northern part of the NPRA indicate that the Neocomian shale overlies shale of Kimmeridgian and Tithonian (Late Jurassic) age in the east and shale of Oxfordian (Late Jurassic) age on the northwest. Whether this break on the west represents an unconformity, a depositional hiatus (that is, a toplap relation), or an as yet inadequately sampled condensed section is unknown. The missing Kimmeridgian-Tithonian section or deposi-

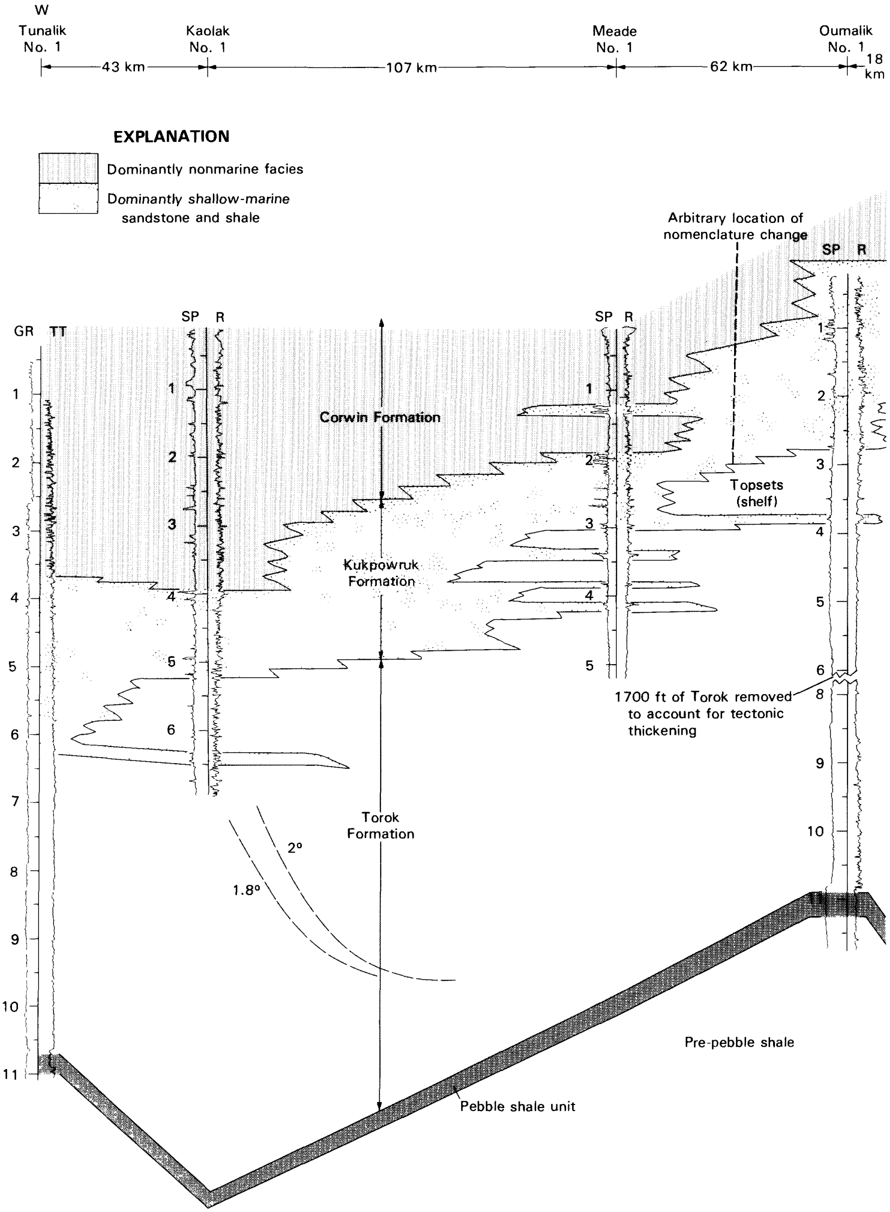

FIGURE 25.5.—Stratigraphic cross section of Nanushuk Group and associated strata across northern foothills area. See figure 25.4 for location of section. Horizontal distance between wells or sections indicated; well depths labeled at 1,000-ft intervals. Vertical exaggeration approximately ×58. SP, spontaneous potential; R, resistivity; GR, gamma ray; TT, transit time. Dashed lines are correlations of miscellaneous reflectors. Dip angle of foreset beds indicated with respect to topset beds. Datum is base of Colville Group (Seabee Formation) where present; otherwise datum generally conforms to topset beds. From Molenaar, 1985.

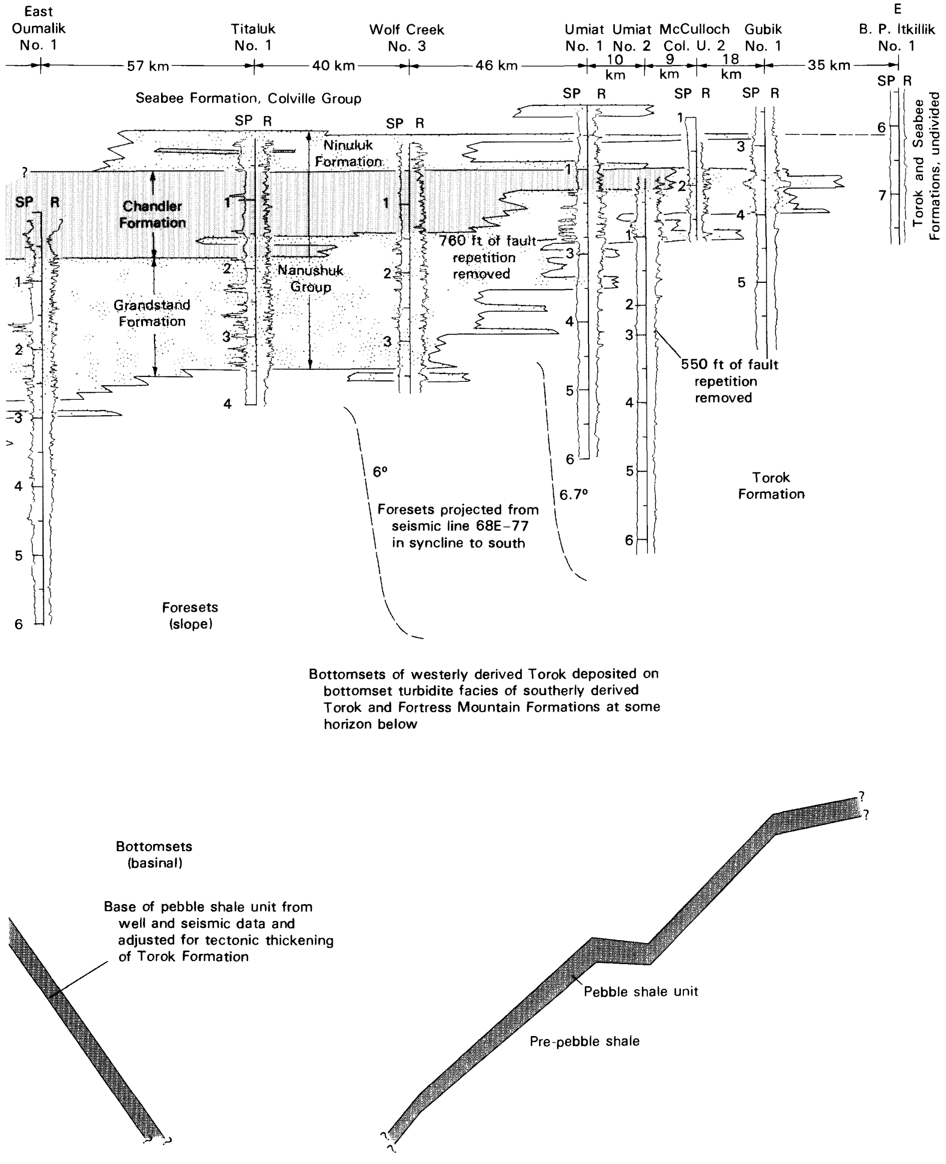

FIGURE 25.5.—Continued

tional hiatus on the west may be similar to apparently missing Jurassic intervals elsewhere within the Kingak (Imlay and Detterman, 1973, p. 12).

A toplap relation within the Upper Jurassic part of the Kingak Shale is indicated on seismic line 7X-75-G-1182 south from the Inigok No. 1 well. This part of the record corresponds to a depth of about 3,400 m (11,000 ft) in the well. A similar relation may exist in the Cretaceous part also, but seismic reflections are not prominent

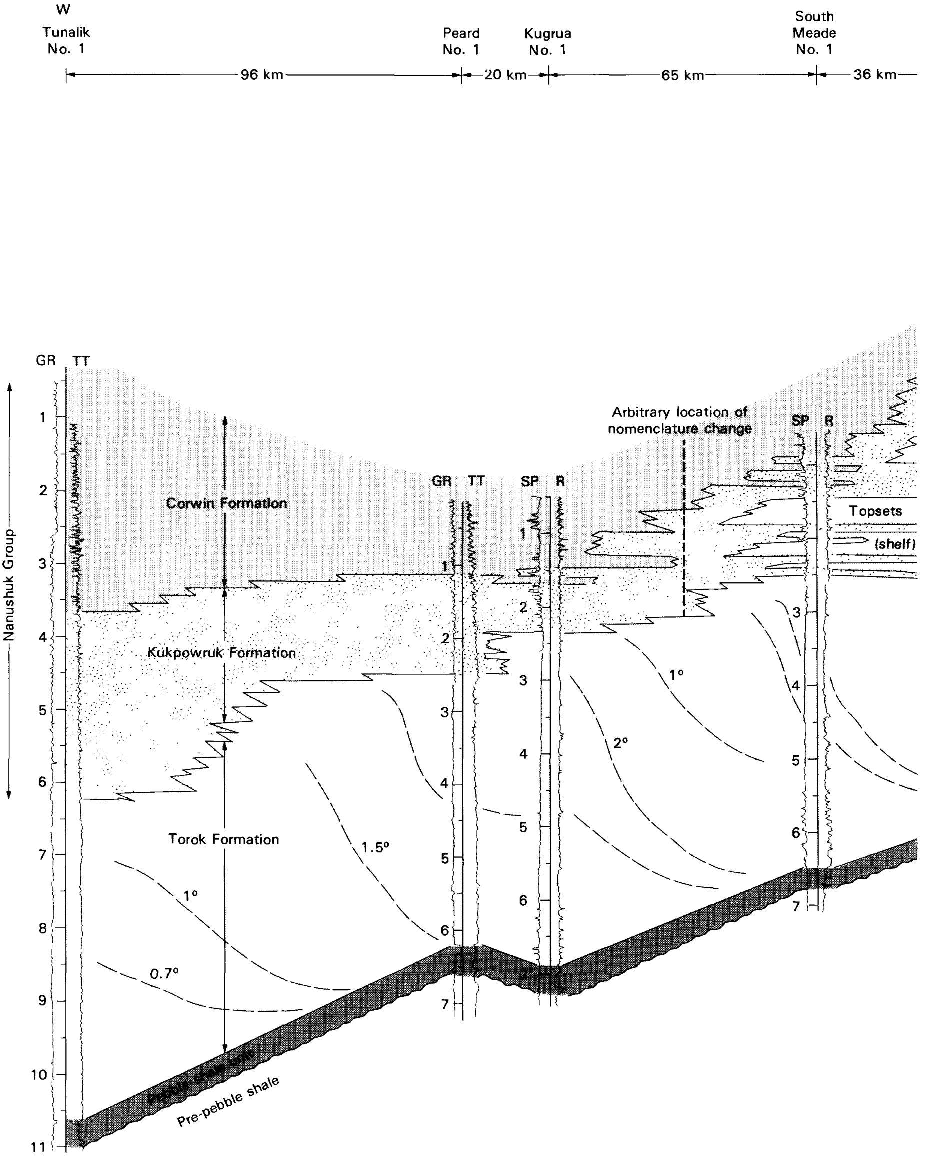

FIGURE 25.6.—Stratigraphic cross section of Nanushuk Group and associated strata across northern coastal plain area. See figure 25.4 for location of section. Horizontal distance between wells or sections indicated; well depths labeled at 1,000-ft intervals. Vertical exaggeration approximately ×58. SP, spontaneous potential; R, resistivity; GR, gamma ray; TT, transit time. Dashed lines are correlations of miscellaneous reflectors. Dip angle of foreset beds indicated with respect to topset beds. Datum is base of Colville Group (Seabee Formation) where present; otherwise datum generally conforms to topset beds. From Molenaar, 1985.

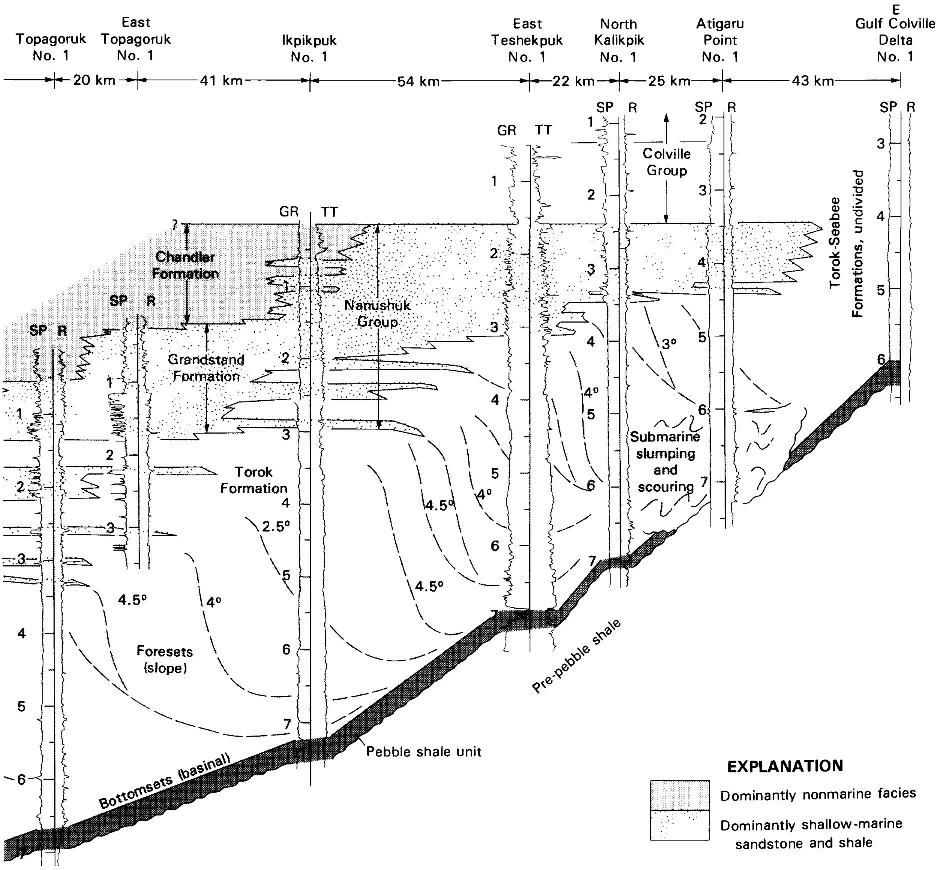

FIGURE 25.6.—Continued

enough to document it. The main sedimentologic inference from the moderate to weak seismic reflections, however, is that the entire Kingak Shale, as defined above, is a southward-prograding shelf-and-slope sequence that grades into basinal facies to the south, as shown in figures 25.3*A* and 25.10. The northern (Ellesmerian) provenance, the clastic source for earlier formations, still existed in early Neocomian time.

Paleontologic data from wells and seismic data indicate that the truncated northern limit of the Cretaceous part of the Kingak Shale trends west-northwest from between the North Inigok No. 1 and East Teshekpuk No. 1 wells (fig. 25.1). To the south of this limit, seismic reflections indicate the Cretaceous portion to be part of a shelf sequence consisting of topset beds that grade into south-dipping slope beds to the south and possibly into southwest-dipping slope beds on the far west. Two zones containing thin sandstone beds, which occur in the lower or middle part of the slope facies according to the seismic data, were penetrated in the Tunalik No. 1 well on the west. One zone at 3,810 to 3,840 m (12,500-12,600 ft) in the well had a significant gas show. In addition, a 160-m-thick sandstone and shale zone that appears, according to the seismic data, to be either at a shelf break or in the upper part of the slope is present immediately below the pebble shale unconformity in this well.

In the northern part of the northern foothills, the Cretaceous part of the Kingak downlaps to within 100 m of the Triassic Shublik reflector. Similarly, the underlying Jurassic part of the Kingak grades from shelf (topset) beds to slope (foreset) beds, but the shelf break is farther north than that indicated for the Cretaceous part. To the south, the Jurassic part is a thin condensed section or is missing because of nondeposition in deep water. The Cretaceous part is correspondingly thicker to the south in the northern part of the northern foothills, even though the interval between the pebble shale and Shublik reflectors remains fairly uniform (fig. 25.3A). However, farther south the Kingak Shale

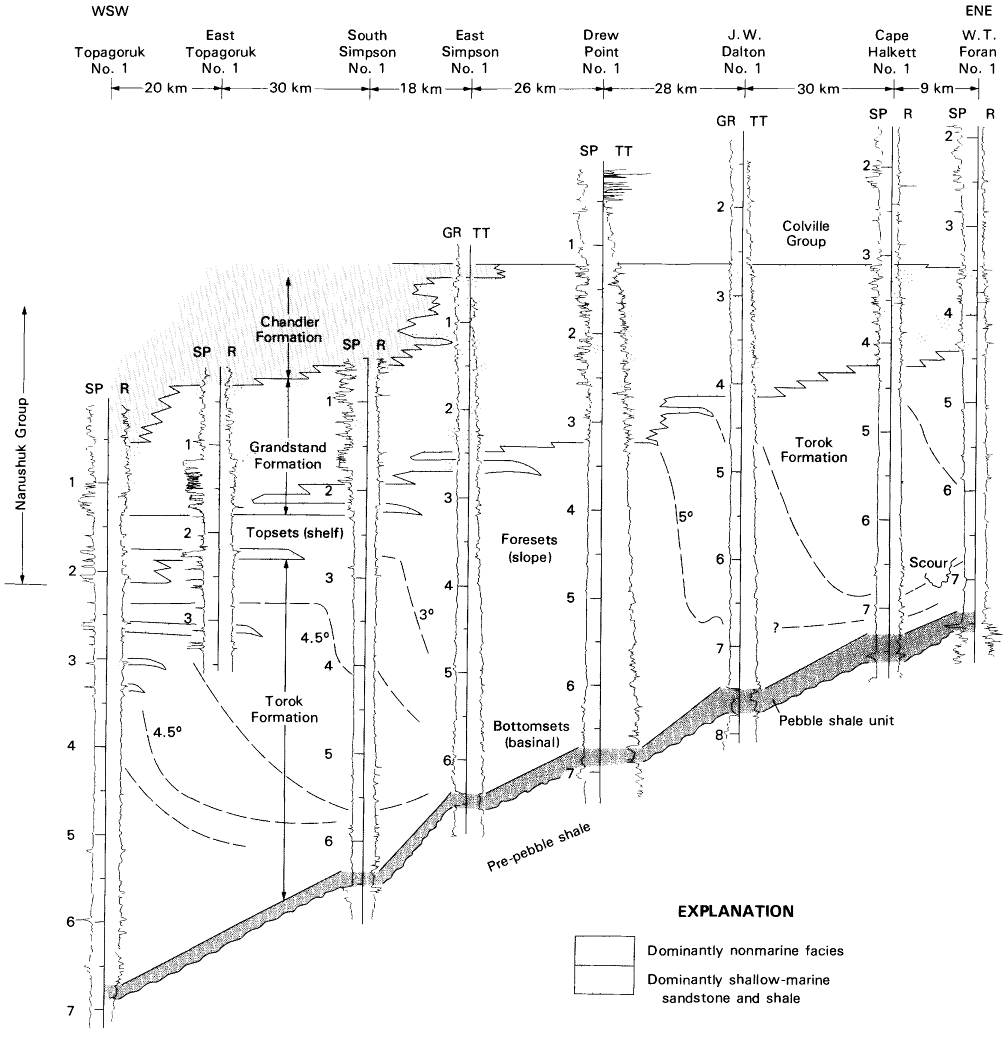

FIGURE 25.7.—Stratigraphic cross section of Nanushuk Group and associated strata across northeastern part of coastal plain area. See figure 25.4 for location of section. Horizontal distance between wells or sections indicated; well depths labeled at 1,000-ft intervals. Vertical exaggeration approximately ×58. SP, spontaneous potential; R, resistivity; GR, gamma ray; TT, transit time. Dashed lines are correlations of miscellaneous reflectors. Dip angle of foreset beds indicated with respect to topset beds. Datum is base of Colville Group (Seabee Formation) where present; otherwise datum generally conforms to topset beds. From Molenaar, 1985.

thins markedly as the overlying pebble shale unit converges toward the underlying Shublik Formation (figs. 25.3*A*, 25.11).

The present slope angle of the foreset beds of the Kingak in relation to topset beds is gentle, ranging from less than 1° to slightly more than 2°. The water depth in which the basinal or condensed Kingak bottomset beds were deposited was somewhat greater than the 400 to 900 m indicated by the present relief on the compacted south-dipping foreset beds.

NEOCOMIAN ROCKS OF THE SOUTHERN FOOTHILLS

There are no control points on the Neocomian section between the northern foothills and outcrops of coeval strata along the southern part of the southern foothills. In the southern foothills, the structural relations are complex, and two separate facies of early Neocomian age are recognized. One is a thin clay shale unit containing thin lenses of coquina limestone. This unit is considered to be a stable-shelf facies (Jones and Grantz, 1964, p. 1472; Brosgé and Tailleur, 1971, p. 82) and is informally referred to in this report as the clay shale unit. The second facies is a thick turbidite sequence known as the Okpikruak Formation. In some areas, the Okpikruak Formation appears to overlie the clay shale unit, but fossils indicate that the Okpikruak is the same age as, or older than, the clay shale unit. Evidently, the Okpikruak Formation was thrust northward from an original position many kilometers to the south relative to the underlying autochthonous rocks (Mull and others, 1976, p. 24).

OKPIKRUAK FORMATION

The Okpikruak Formation, of Neocomian age, consists of a sequence of interbedded graywacke sandstone and shale that occurs in thrust slices along the structurally complex north side of the Brooks Range (Gryc and others, 1951, p. 159). Because of structural complexities, a complete section of the Okpikruak is not exposed at any one locality, and the total thickness of the formation is unknown. The thickest measured section is about 580 m (Patton and Tailleur, 1964, p. 447).

The Okpikruak Formation is a basinal turbidite deposit of Brookian origin; that is, its source was to the south. Although some conglomerate is present, especially in the lower part (Patton and Tailleur, 1964, p. 446), much of the sandstone in the Okpikruak is fine to very fine grained and occurs in thin graded beds. In most outcrops, sandstone makes up only 10 to 25 percent of the section, although a few sections contain as much as 60 percent (Patton and Tailleur, 1964, p. 446). The remaining portions are siltstone and shale. In the submarine-fan facies model as described by Mutti and Ricci Lucchi (1972), most of the Okpikruak Formation outcrop belt would be considered an outer-fan or distal facies.

In addition to the thin-bedded turbidite sequence, Mull and others (1976, p. 25) described an associated sedimentary chaos or olistostrome that occurs in many areas along the front of the Brooks Range. This unit probably was deposited closer to the ancestral Brooks Range front. The juxtaposition of these different facies may be the result of displacement of different thrust sheets.

On the basis of the presence of the fossils *Buchia okensis, B. subokensis, B. crassicollis,* and *B. sublaevis,* the Okpikruak Formation is considered to be of Berriasian and Valanginian age (Jones and Grantz, 1964, p. 1464).

Inasmuch as the Okpikruak Formation exposed in the outcrop belt is largely a distal, deep-water, basinal facies, and partially coeval rocks are a condensed section of possible shallow-marine shale, the basinal facies should not occur anywhere in the subsurface north of the outcrop belt. It is shown in figure 25.3*A* as having originated far south of its present position and been subsequently thrust northward to its present position. The Okpikruak could conceivably underlie Paleozoic rocks in much of the present-day Brooks Range.

CLAY SHALE UNIT

The clay shale unit or coquinoid-limestone-bearing shale unit has been reported from many localities along the Brooks Range front. This unit has been described as resting in many places directly on Triassic rocks and in some places on a thin Jurassic shale section with no intervening Okpikruak turbidites (Jones and Grantz, 1964, p. 1471). Because of the structural complexities and the limited outcrop of the clay shale unit, no accurate measurement of its thickness is available. Most descriptions indicate that it is thin, possibly 100 m thick (Brosgé and Tailleur, 1971, p. 84). The top is usually covered or is overlain by the Fortress Mountain Formation or by overthrust older rocks.

Crane and Wiggins (1976, p. 2177) in an abstract applied the name "Ipewick Formation" to the clay shale unit in the central and western Arctic region. In the western part of the NPRA and farther west, a Valanginian quartz sandstone unit, which they called the "Tingmerkpuk member," was included in the Ipewick unit. The presence of a clean quartz sandstone in an area that far south is anomalous. It is very unlike the typical lithic-rich or graywacke sandstones typical of southern-source or Brookian units and is more typical of Ellesmerian rocks. Perhaps it had a source to the

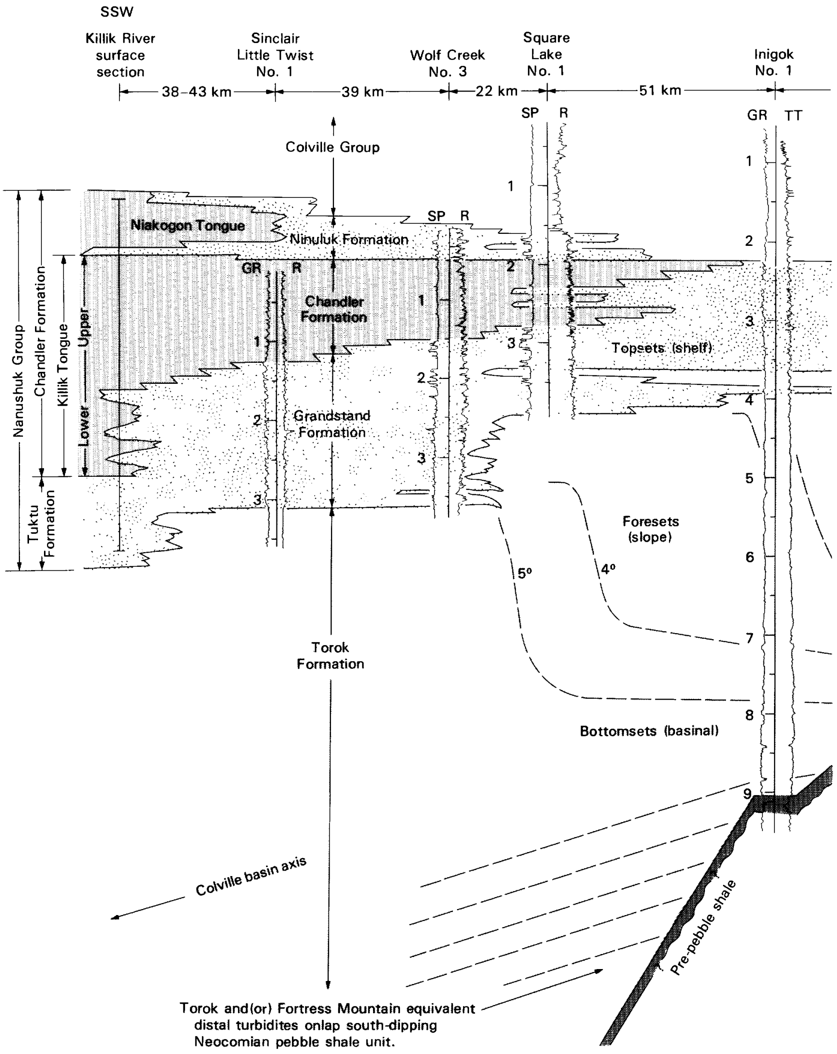

FIGURE 25.8.—South-to-north stratigraphic cross section of Nanushuk Group and associated strata across eastern part of NPRA. See figure 25.4 for location of section. Horizontal distance between wells or sections indicated; well depths labeled at 1,000-ft intervals. Vertical exaggeration approximately ×58. SP, spontaneous potential; R, resistivity; GR, gamma ray; TT, transit time. Dashed lines are correlations of miscellaneous reflectors. Dip angle of foreset beds indicated with respect to topset beds. Datum is base of Colville Group (Seabee Formation) where present; otherwise datum generally conforms to topset beds. From Molenaar, 1985.

northwest. Another possibility is that it was derived from the sandy Utukok Formation of the Lisburne Group, or from older Devonion clastic rocks, which may have been exposed in nearby thrust sheets (C.G. Mull, oral commun., 1981).

The clay shale unit of the central southern foothills area is predominantly black and contains minor lenses of coquinoidal limestone (Brosgé and Tailleur, 1971, p. 84). These lenses are as much as 2 m thick and are composed almost entirely of broken bivalve shells. The

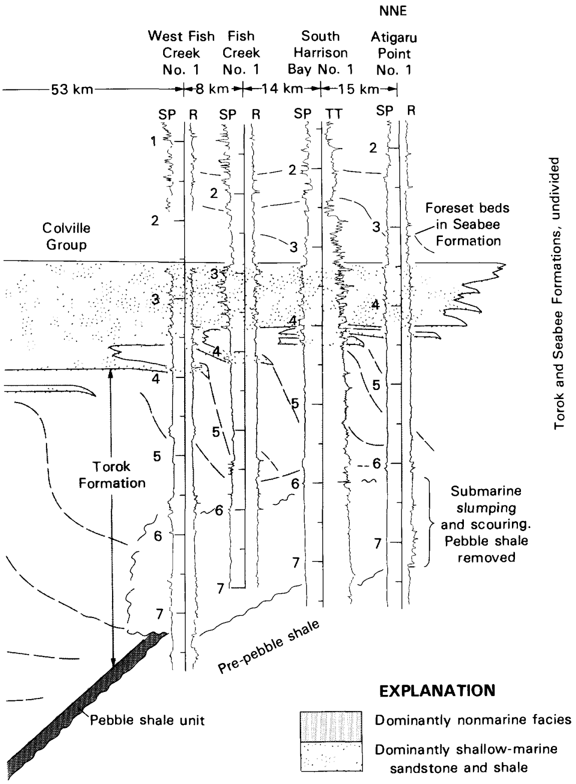

FIGURE 25.8.—Continued

fossils have been identified as *Buchia sublaevis* of Valanginian age (Jones and Grantz, 1964, p. 1464). The occurrence of fragmented specimens of *Buchia* in coquina beds suggests that they were probably deposited in fairly shallow water, that is, in a shelf environment. Jones and Grantz (1964, p. 1474) and Brosgé and Tailleur (1971, p. 82) suggested that an intrabasin medial sill or ridge separated the orogenic foredeep to the south, where turbidites of the Okpikruak were deposited, from the broad shale basin to the north. Figure 25.3*A* shows this interpretation.

An alternate interpretation might be that the clay shale unit is a distal condensed basinal section of the Kingak Shale. This interpretation would eliminate the need to postulate an intrabasin medial sill, but it would mean that *Buchia* flourished in water depths of at least 600 m, which is unlikely (D.L. Jones, oral commun., 1981). Still another interpretation might be that the beds containing fragmented *Buchia* were displaced from a shelf position into deeper water.

PEBBLE SHALE UNIT

The pebble shale unit, an informally named, well-known stratigraphic unit of Neocomian age, is present throughout most of the North Slope. It is an important unit because (1) its base marks a major regional unconformity in northernmost Alaska, (2) it represents the termination of northern-source (Ellesmerian) clastics, and (3) it is a shale of distinctive low seismic velocity that can be mapped seismically over most of the area. Hence, it is a good mappable unit with which to relate depositional units above and below. In the northern part of the NPRA, the pebble shale unit is 70 to 125 m thick and consists predominantly of organic marine shale containing distinctive floating quartz and chert sand grains and a few pebbles scattered throughout. Locally, a basal transgressive sandstone as much as 15 m thick is present. This sandstone is probably equivalent to the Kemik Sandstone that crops out in northeastern Alaska. However, its contemporaneity and continuity have not been proved. Its formation may be related to the underlying lithology; for example, the sandstone of the Ivishak Formation may have been eroded in front of the advancing Neocomian sea.

The rare chert and quartzite pebbles that are scattered throughout the pebble shale unit are an enigma. Rather than being concentrated at the base as is common in transgressive shale units, they are scattered throughout most of the unit. The pebble shale unit undoubtedly represents slow deposition over a broad area for a long period of time. Perhaps the pebbles were rafted by floating shore ice, kelp, or logs; or perhaps they were stomach stones from marine vertebrates such as ichthyosaurs.

The pebble shale unit is easily recognized on gamma-ray and transit-time logs of wells by the abruptly higher transit times and high gamma-ray deflection compared to shales of the overlying Torok Formation and the underlying Kingak Shale. The gamma-ray

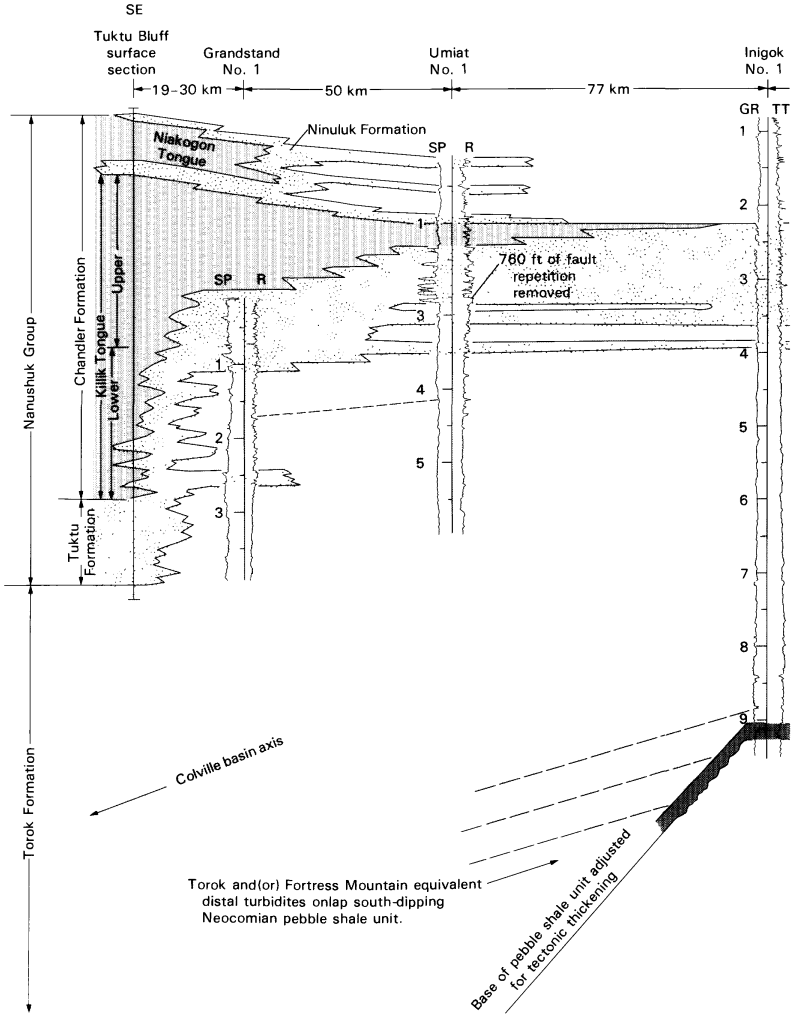

FIGURE 25.9.—Southeast-to-northwest stratigraphic cross section of Nanushuk Group and associated strata across northeastern part of NPRA. See figure 25.4 for location of section. Horizontal distance between wells or sections indicated; well depths labeled at 1,000-ft intervals. Vertical exaggeration approximately ×58. SP, spontaneous potential; R, resistivity; GR, gamma ray; TT, transit time. Dashed lines are correlations of miscellaneous reflectors or beds. Dip angle of foreset beds indicated with respect to topset beds. Datum is base of Colville Group (Seabee Formation) where present; otherwise datum generally conforms to topset beds. From Molenaar, 1985.

deflection is much higher in the upper part of the pebble shale unit, and that part is frequently referred to as the gamma-ray zone. In the eastern North Slope, the gamma-ray zone, which is Aptian(?)-Albian in age in that area, is separated from the pebble shale unit and included in the overlying newly named Hue Shale (Molenaar and others, 1987; see also Bird, chapter 15). Both the high gamma-ray radiation and the high transit time may be due, at least in part, to the high organic content of the shale.

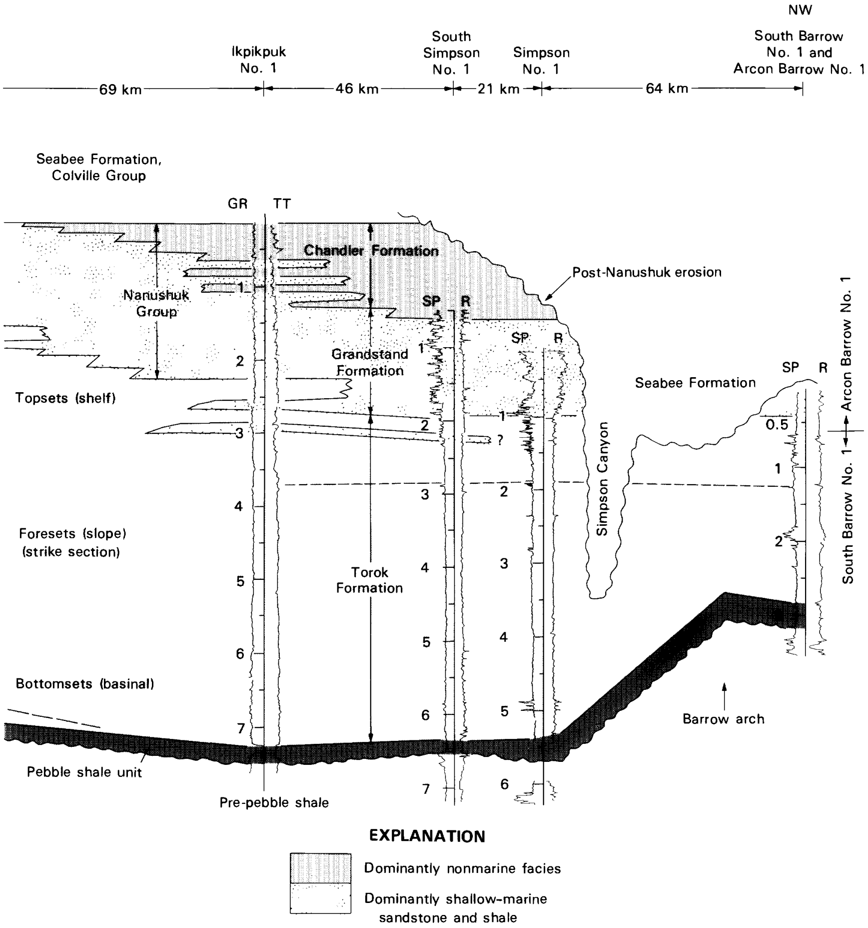

FIGURE 25.9.—Continued

In the northernmost part of the NPRA, the unconformity at the base of the pebble shale unit truncates progressively older rocks from south to north. To the south, however, seismic facies relations indicate that the erosional unconformity merges into a conformable shelf and slope facies. In the north, seismic data show that the pebble shale unit was deposited on a beveled surface; to the south, however, seismic lines show that the pebble shale unit was deposited on a broad shelf break and slope and converges toward the Shublik Formation (Triassic) to the south (fig. 25.11). The Shublik maintains a more constant southward dip. The position of the shelf break over which the pebble shale was deposited is shown in figure 25.1. This shelf break probably represents the southernmost limit of the mid-Neocomian unconformity. South of the shelf break, the pebble shale unit probably represents slow pelagic deposition on the preexisting slope and basinal topography associated with the youngest (Valanginian) deposits of the Kingak Shale.

Micropaleontologic data from wells drilled in the NPRA indicate that the pebble shale unit is Hauterivian and Barremian in age (NPRA palynology/micropaleontology reports, 1980; Witmer and others, 1981). Megafossil data in the NPRA area are absent, but fossils have been reported from the Bathtub Ridge area in northeastern Alaska, 360 km east of the NPRA (Detterman and others, 1975, p. 25). In that area, the Hauterivian ammonite *Simbirskites* sp. occurs in the Kemik Sandstone Member of the Kongakut Formation, which there underlies the pebble shale member. The pebble shale contains only a few poorly preserved pelecypods of possible Aptian to Albian age. In addition, a probable *Simbirskites* sp. was reported from the Kemik along the Echooka River 150 km east of the NPRA (Molenaar, 1983, p. 1072). Inasmuch as the Kemik is considered here to be part of the pebble shale depositional cycle, it seems likely that the pebble shale unit is Hauterivian and Barremian in age, as suggested by the micropaleotologic data. It is likely, however, that the upper part of the pebble shale unit is a condensed section of Aptian and lower Albian strata.

The pebble shale unit is apparently younger than the clay shale unit and Okpikruak Formation of the southern foothills area. In that area, however, the pebble shale unit has not been recognized with certainty in outcrops. The reason may be that it has lost its characteristic floating sand grains and pebbles, or possibly that good outcrops are lacking because it is a soft-weathering shale. Another possibility is that thrusting and subaerial erosion occurred during late Neocomian time, or that strata equivalent to the pebble shale unit were removed by subsequent erosion in the southern part of the southern foothills. Farther north in the southern foothills, however, deep-water facies of the Fortress Mountain Formation overlie or are in close proximity to the clay shale unit in some areas, such as near Brady, about 9 km from the mouth of the Kiligwa River in the south-central part of the NPRA (Tailleur and Kent, 1953, p. 12). In those areas, the pebble shale unit may be represented by a condensed section, or possibly time-equivalent strata are included in the lower part of the Fortress Mountain Formation. Additional data are needed on

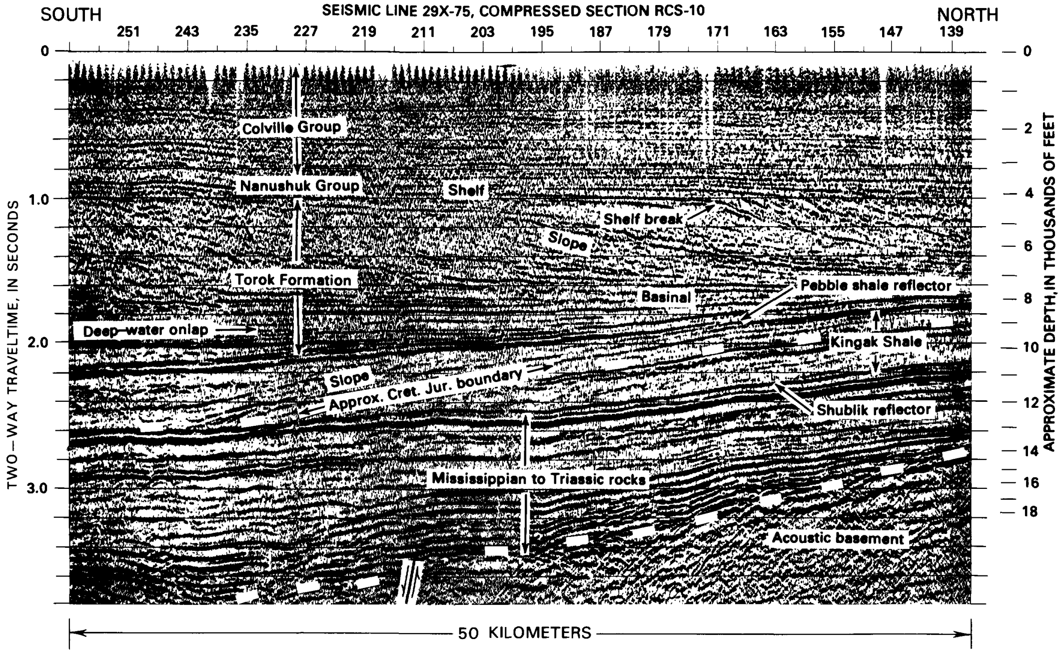

FIGURE 25.10.—Seismic section in eastern part of NPRA showing southward prograding shelf and slope deposits of Kingak Shale; approximate Jurassic-Cretaceous boundary within Kingak Shale; lower part of Torok Formation onlapping south-dipping pebble shale unit; and relation of shelf, slope, and basinal deposits (topset, foreset, and bottomset beds) of Torok-Nanushuk interval. Line of section oriented oblique to progradation direction of Torok-Nanushuk interval. Numbers above section are shot-point numbers. See figure 25.1 for location of section.

the age of the lower part of the Fortress Mountain Formation in those areas in order to clarify these relations.

APTIAN ROCKS

Following Neocomian deposition the Colville trough was downwarped, and little, if any, sedimentation occurred in the coastal plain and northern foothills areas on the north flank of the basin until middle or late Albian time. The downwarping affected the entire north flank of the basin, and the south dip apparently steepened to the south as indicated by both the pebble shale and Triassic reflecting horizons (NPRA summary geophysical report, FY-1978, 1980).

Deep-water bottomset or basinal beds of Albian age onlap the south-dipping pebble shale unit as indicated by seismic reflectors in the northern half of the northern foothills (figs. 25.10, 25.11). In the outcrop belt of the southern foothills, the Fortress Mountain Formation of early Albian age apparently unconformably overlies folded Neocomian and older rocks. Large-scale thrusting and folding evidently occurred during Aptian time. Whether or not rocks of Aptian age were deposited in the Colville basin is not known. Aptian megafossils are unknown in northern Alaska, perhaps because (1) rocks of Aptian age are not exposed in northern Alaska, (2) Aptian megafossils have not been differentiated from Neocomian or Albian forms, or (3) rocks of Aptian age are of deep-water unfossiliferous facies. Aptian strata are probably present as a deep-water facies in the axial part of the Colville basin. It is also possible that some of the Fortress Mountain Formation in the axial part of the basin is Aptian or even older.

Foraminifers tentatively assigned to the Aptian have been reported from wells in the coastal plain area (NPRA palynology/micropaleontology reports, 1980; Witmer and others, 1981), but strata in which these foraminifers occur can be traced seismically into beds of Albian age. The strata thought to be Aptian are probably a deeper water facies of Albian beds higher on the slope or shelf (figs. 25.6-25.8).

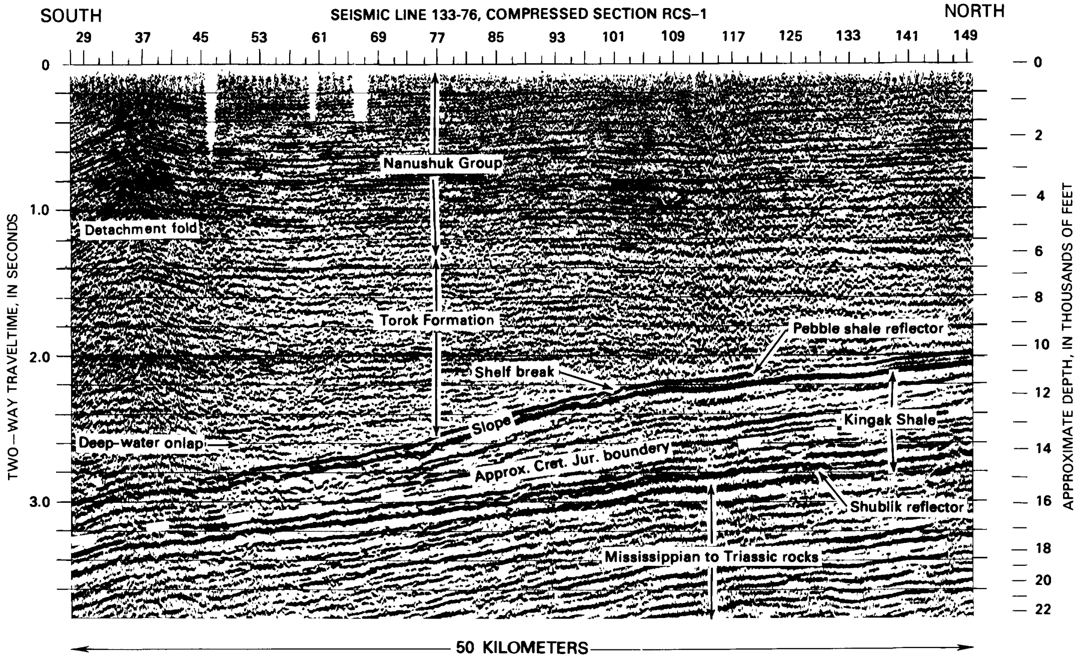

FIGURE 25.11.—Seismic section in western part of NPRA showing gradual shelf break and slope relations of pebble shale unit to Triassic Shublik Formation; southward thinning of Kingak Shale; approximate Jurassic-Cretaceous boundary within Kingak Shale; and lower part of Torok Formation onlapping south-dipping pebble shale unit. Foreset beds in Torok not present or dipping at very low angle in this part of basin. Also, line of section oriented about 60° to dip of foreset beds. Numbers above section are shot-point numbers. See figure 25.1 for location of section.

FORTRESS MOUNTAIN FORMATION

The Fortress Mountain Formation, of early Albian age, consists of a thick section of shale, sandstone, and conglomerate that unconformably overlies folded Neocomian and older rocks in a broad, structurally complex belt along the southern foothills (Patton and Tailleur, 1964, p. 452). The formation is about 3,000 m thick at its type section on and adjacent to Castle Mountain, 85 km south of Umiat. It is doubtful that the formation is that thick in other areas. Thickness variations can be explained by penecontemporaneous folding and local unconformities reported in the southern part of the outcrop belt (Molenaar and others, chapter 12; Chapman and others, 1964; Patton and Tailleur, 1964, p. 456; Tailleur and others, 1966).

The Fortress Mountain Formation is largely a deep-water orogenic deposit, although the rocks in some of the southernmost exposures are nonmarine. The deposits range from fluvial, submarine canyon, and inner-fan channel facies on the south to outer-fan and basin-plain facies to the north within the complexly folded outcrop belt of the southern foothills (fig. 25.3*B*); see Molenaar and others (chapter 12) for a more detailed discussion of the Fortress Mountain Formation. It is apparent that facies changes are rapid and that the coarse clastic rocks of the Fortress Mountain Formation grade into and intertongue with shale of the lower part of the Torok Formation to the north. Also, there is much depositional onlap and thinning between the outcrop belt in the southern foothills and the little-deformed belt in the northern part of the northern foothills, where stratal relations are indicated by seismic data (figs. 25.3C, 25.10, 25.11).

Because the Fortress Mountain Formation becomes thinner bedded and finer grained to the north within the southern foothills, differentiation between the Fortress Mountain and Torok Formations is arbitrary. The placement of the contact in the subsurface in the northern foothills is further complicated by the occurrence of thin-bedded turbidites in the Torok that were derived from Nanushuk deltas to the west or southwest (figs. 25.3C, 25.5). For this reason, Molenaar and others (chapter 12) recommend that the name Fortress Mountain Formation be dropped as a subsurface unit in the northern foothills and areas to the north. The deep-water sandstone bodies are included in the lower part of the Torok Formation.

TOROK FORMATION

As originally defined, the Torok Formation included all strata above the Okpikruak Formation and below the Nanushuk Group (Gryc and others, 1951, p. 160). Later, Patton (1956, p. 219) removed from its lower part the southern facies, which crops out in the southern foothills and contains a large percentage of sandstone and conglomerate, and named that part the Fortress Mountain Formation. Torok Formation was retained as the name for the dominantly shale facies that crops out in the northern half of the southern foothills. At the type section in the vicinity of the Chandler River and Torok Creek, an incomplete section of the Torok about 1,830 m thick was measured (Patton, 1956, p. 222). The lower part of that section may include distal facies of the upper part of the Fortress Mountain Formation. Because of discontinuous scattered outcrops, structural complications, and intimate intertonguing of the two formations or facies, the mapped contact between the two units in the field is rather arbitrary.

Except for small areas in the northern foothills, where the uppermost part of the Torok Formation is exposed, the Torok is a subsurface formation in the northern foothills and coastal plain areas. Seismic and well data in those areas indicate that the Torok Formation ranges in thickness from about 6,000 m on the south near the Colville River to less than 900 m on the Barrow arch (fig. 25.12). The thick section on the south includes strata that are contemporaneous with the Fortress Mountain Formation. In addition, the section probably has been tectonically thickened. In constructing the isopach map (fig. 25.12), I tried to remove at least part of the apparent thickening associated with compressional folding and thrust faulting within the Torok shale in the northern foothills by subtracting the structural relief of the anticlines developed in the overlying Nanushuk Group. The underlying pebble shale reflector beneath the surface anticlines is generally a south-dipping surface (NPRA summary geophysical report, FY-1978, 1980) and is not involved in the folding of the overlying rocks in most of the structures. The folds in the overlying strata apparently are due to folding or shale flowage caused by the surfacing or dying out upwards of thrust faults within the incompetent Torok shale. Even though all the tectonic thickening in the Torok may not have been accounted for in the southern part of the northern foothills, there is no doubt that the total section thickens markedly to the south from the coastal plain area.

NORTHERN FOOTHILLS AREA

Much of the southward thickening of the Torok Formation is due to the presence of older beds within the lower part of the formation (fig. 25.3*B*). Post-pebble shale onlap, apparently from the south, is clearly shown on north-south seismic lines in the southern part of the coastal plain and northern foothills area (figs. 25.10, 25.11). As much as 1,250 m of section wedges out by onlapping the south-dipping pebble shale unit between the area of the Wolf Creek No. 3 well in the anticlinal belt of the northern foothills and the zero edge north of the Inigok No. 1 well, a distance of about 80 km. Similar rates of onlap occur across the entire belt. The average calculated acute angle made by the wedge ranges from 0.9° to 1.2°. Inasmuch as the onlapping wedge was probably almost flat when deposited, the acute angle of the wedge approximates the south dip of this part of the basin during early Torok time (less the effects of compaction). The wedge apparently continues to thicken farther to the south, but structural complications in the anticlinal belt mask seismic reflections.

The Inigok No. 1 well penetrated about 150 m of the onlapping wedge, the Oumalik No. 1 well penetrated about 800 m, and the Seabee well penetrated about 1,100 m. The section in these wells is composed of interbedded shale, siltstone, and fine-grained to very fine grained sandstone and is thought to be basin-plain distal turbidite and shale deposits. The lower part of the wedge was probably derived from the ancestral Brooks Range and is probably equivalent to the Fortress Mountain Formation. However, most if not all of the 800 m penetrated in the Oumalik No. 1 well and all of the 150 m in the Inigok No. 1 well can be traced seismically to the west into eastward-dipping foreset (slope) beds and into topset deltaic deposits of the Nanushuk Group. Therefore, strata equivalent to the Fortress Mountain Formation are probably limited to an area no farther north than the northern foothills.

In addition to the upper part of the apparently northward onlapping wedge being traceable to eastward-dipping prodelta slope beds of the Nanushuk delta, there is evidence that the lower part of the wedge was also deposited by east-northeastward currents. Directional features in distal turbidites of Fortress Mountain outcrops in the

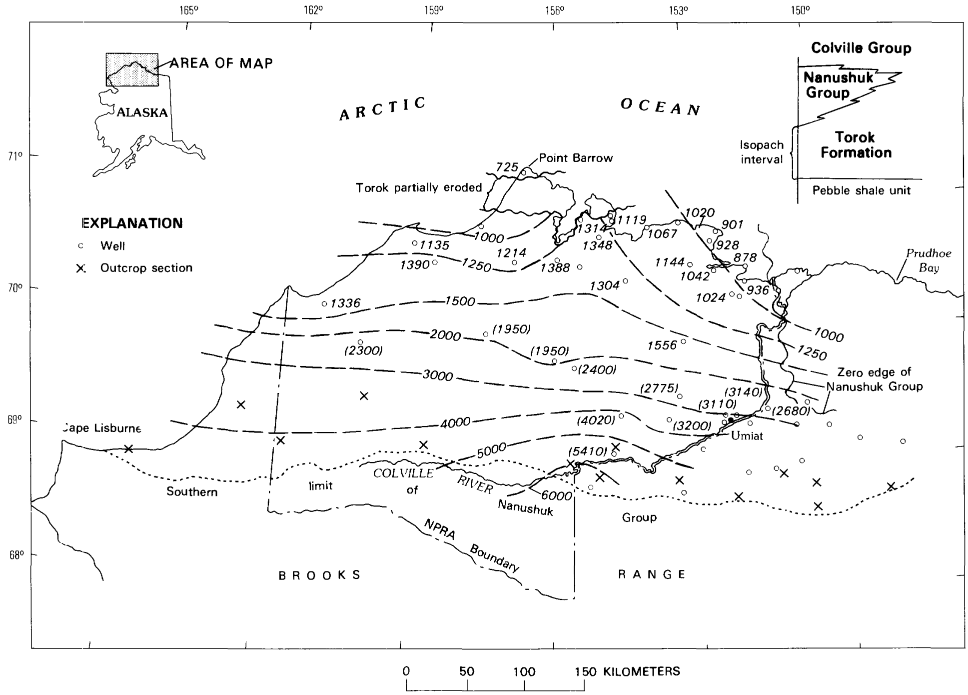

FIGURE 25.12.—Isopach map of Torok Formation (modified from Bird and Andrews, 1979). Numbers beside wells indicate thickness of Torok Formation; thickness values in parenthesis corrected (approximately) for tectonic thickening in thrust-faulted anticlines. Isopach interval 250, 500, and 1000 m. Identification of wells given in table 25.1 and figure 25.1.

northern part of the southern foothills indicate a dominance of east-northeastward turbidity currents (Molenaar and others, chapter 12).

COASTAL PLAIN AREA

The Torok Formation in the northern part of the NPRA is represented on seismic lines by, in ascending order, bottomset (basinal), foreset (slope), and topset (shelf) reflectors. Where traced laterally, these reflectors indicate that the three facies are equivalent in time; basinal beds can be traced into slope, shelf, and indeed, into deltaic deposits of the Nanushuk Group (figs. 25.6, 25.7, 25.8, 25.13). In effect, the profiles of these correlative seismic reflections represent the depositional profile of the basin, less the subsequent compaction of the sediments.

The basinal facies of the Torok Formation ranges in thickness from about 150 to 700 m in the coastal plain area and thickens to the south, where it includes the apparently northward onlapping wedge. The bottomset beds consist of shale, siltstone, and thin beds of fine-grained to very fine grained sandstone. The sandstone beds are thought to be turbidites derived from deltas to the west-southwest, where sediments of the Nanushuk Group were being deposited (Molenaar, 1985). The water depth in which the basinal beds were deposited is indicated by the calculated present 450-m to 1,000-m relief of the slope-foreset beds plus (1) the amount of additional postdepositional compaction of the already deposited and partially compacted sediments below the shelf break and (2) the water depth of the shelf break. The latter depth was probably no more than 50 to 75 m.

The slope facies makes up the major part of the Torok Formation in the coastal-plain area. This part of the Torok ranges in thickness from 450 to 1,000 m and consists mostly of shale, siltstone, and a few thin sandstone beds. The seismic reflectors in this foreset sequence are caused by sandy intervals or low-velocity shale beds (Molenaar, 1985). Foreset bedding is best seen on seismic lines in the eastern and northeastern parts of the NPRA. In the western part, these features are obscure and less numerous, partly because of poor seismic data in the shallow Torok-Nanushuk interval. Some foreset beds can be seen, however, as far west as the Tunalik No. 1 well, where they are at a much lower angle than to the east.

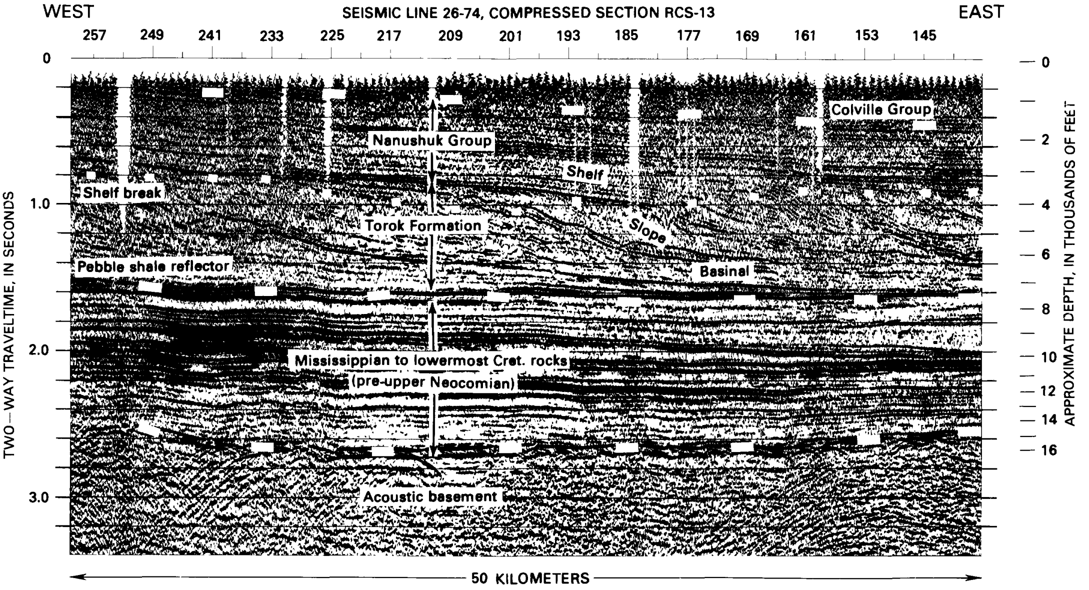

FIGURE 25.13.—Seismic section in northeastern part of NPRA showing stratigraphic relations of shelf, slope, and basinal deposits (topset, foreset, and bottomset beds) of Torok-Nanushuk interval. Dots represent position of shelf break. Note stratigraphic rise of shelf break from west to east. Numbers above section are shot-point numbers. See figure 25.1 for location of section.

The foreset dip angles, which were calculated relative to the topset beds, range from less than 2° on the west to between 4° and 6° in the eastern and northeastern parts of the NPRA (figs. 25.5-25.8). These calculations were made on the steeper upper parts of the beds and were averaged over at least 4 km of horizontal distance. The variation in slope angle is probably related to the rate of deltaic progradation of coeval Nanushuk deposits. The greater the rate of progradation, the steeper the slope angle. The 450-m to 1,000-m relief of the foresets from top to base is the thickness of the slope deposits.

The shelf facies of the Torok Formation consists of shale, siltstone, and occasional thin sandstone beds, and ranges in thickness from a few meters to as much as 335 m. This range is due to the balance or imbalance between the rate of deposition and the rate of subsidence. In addition, because the upper part of the Torok grades into, and intertongues with, shallow-marine sandstones of the Nanushuk Group, the selection of the Torok-Nanushuk contact is arbitrary in many areas.

Robinson and others (1956, p. 223) applied the name Oumalik Formation to the section between 1,481 and 3,316 m (4,860 and 10,880 ft) penetrated in the Oumalik No. 1 well, and they also applied the name Topagoruk Formation to the section between 411 and 1,189 m (1,350 and 3,900 ft) penetrated in the Topagoruk No. 1 well. Because the Oumalik is now recognized as the Torok Formation (fig. 25.5), and the Topagoruk is part of the highly time-transgressive transition zone between the Torok Formation and the Nanushuk Group (fig. 25.6), the names Oumalik Formation and Topagoruk Formation are here abandoned.

In the northeastern part of the NPRA in the area from the Fish Creek wells to beyond the Atigaru Point No. 1 well, seismic data show that the lower part of the Torok is disturbed (fig. 25.8). Inasmuch as this interval is laterally adjacent to bottomset beds and underlies foreset and bottomset beds, the disturbed interval is thought to have been caused by large-scale submarine slumping. In some of this area, the pebble shale unit is missing, at least in part, indicating that scouring was associated with the slumping.

In the northern part of the NPRA, where the data are well displayed, bottomset beds downlap onto or near the pebble shale unit (figs. 25.6-25.8, 25.13). Because these bottomset beds can be correlated seismically with beds of late Albian age, the hiatus or thin interval between these downlapping beds and the pebble shale unit is interpreted as being a deep-water condensed or nondepositional zone representing part of Neocomian, all of Aptian, and much of Albian time. The thickness of this interval is less than the resolution that can be obtained from the seismic data, that is, less than 25 m. Strata representing this time period may indeed be included in the upper part of the pebble shale unit. This starved condition of the depositional system is thought to have occurred because the deeper part of the Colville basin to the south received all the sediment derived from the south and southwest after deposition of at least the lower part of the pebble shale unit. Seismic lines show the progressive northward onlap of older Torok strata, including probable equivalents of the Fortress Mountain Formation (fig. 25.3*B*). It was not until the latest stages of the Torok-Nanushuk depositional cycle that the Colville basin was filled sufficiently so that sediments reached the northern part of the NPRA. A similar depositional pattern can be seen to the northeast of the Nanushuk depositional limit in younger Cretaceous and Tertiary deposits. On seismic lines in the northeastern part of the NPRA, topset, foreset, and bottomset bedding can be seen in the overlying shale of the Colville Group (figs. 25.8, 25.13). In the Prudhoe Bay area, foreset and bottomset beds of Turonian age downlap onto or near the pebble shale unit (Bird and Andrews, 1979, p. 35).

NANUSHUK GROUP

The Nanushuk Group, of Albian and Cenomanian age, is a thick deltaic deposit that crops out in the northern foothills and is present in much of the subsurface in the western and central North Slope. It ranges in thickness from at least 3,444 m in outcrops at Corwin Bluff (Smiley, 1969) along the Chukchi Sea on the west to a pinchout edge in the area of the present Colville delta on the east (fig. 25.14). The thickest subsurface penetration is about 1,900 m (top eroded) in the Tunalik No. 1 well on the west.

The lower part of the Nanushuk consists of a thick sequence of intertonguing shallow-marine sandstone and neritic shale and siltstone that grades seaward into the more shaly Torok Formation. The upper part of the Nanushuk Group consists of a dominantly nonmarine facies of paludal shale, coal, and fluvial sandstone that grades into the marine facies. Conglomerate is present, primarily in the fluvial facies, in the southern part of the outcrop belt, which is closer to the source.

Two delta systems were recognized in outcrop studies by Ahlbrandt and others (1979, p. 17): the Corwin or western delta and the Umiat or southern delta. Both deltas were river dominated, but the Umiat delta to a lesser extent than the Corwin. The Corwin delta was a strongly constructional delta and had low sand and high mud contents in contrast to the Umiat delta. Paleocurrent directions in outcrops (fig. 25.15) indicate that the Corwin delta was probably derived from a source area to the southwest. Because the Corwin delta dominated the depositional patterns of the Nanushuk Group, a source area encompassing a large drainage area probably extended far to the west or southwest in the area of the present Chukchi Sea or beyond (Molenaar, 1985). The Umiat delta had a source to the south in the ancestral Brooks Range. In addition to the Umiat delta, there were probably many small deltas emanating from the ancestral Brooks Range (fig. 25.16).

On seismic sections, the Nanushuk Group is represented by topset reflectors that can be traced northward or eastward (seaward) into offshore or deeper water deposits of the Torok Formation (fig. 25.13). These relations are shown by five cross sections that correlate the Lower Cretaceous rocks in most of the wells throughout the NPRA and adjacent areas (figs. 25.5-25.9). The correlations in these sections are based on lithology and seismic data. The datum used is the base of the overlying Colville Group where it is present. In other areas, assumed near-horizontal time-correlative beds or reflections in the lower part of the Nanushuk Group are used between adjacent wells.

On the cross sections, the Nanushuk Group is divided into a lower part, which is dominantly marine, and an upper, dominantly nonmarine part to show the lateral relations. These major facies are the basis for distinguishing most of the formations of the group. The relations and names of the formational units of the group that were described by Detterman (1956) from outcrops in the Colville River area southeast of the NPRA and by

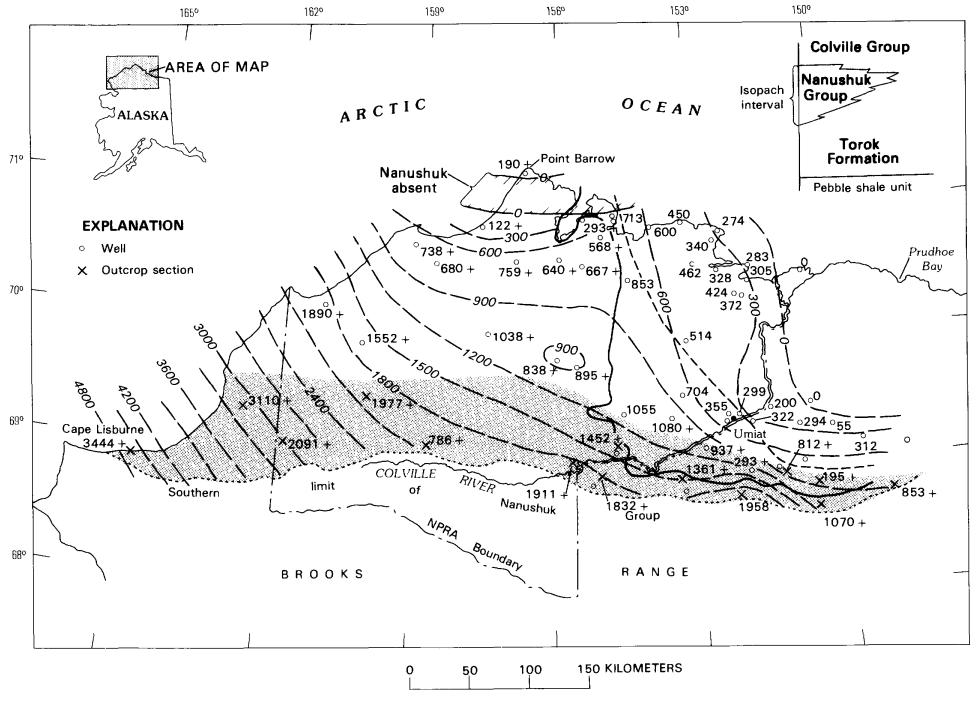

FIGURE 25.14.—Isopach map of Nanushuk Group (modified from Bird and Andrews, 1979). Short-dashed line, northward and eastward extent of subaerial plain deposits; heavy solid line, present western and southern limit of Colville Group. Shaded area is outcrop belt of Nanushuk Group. Numbers beside outcrop-section control points indicate thickness of Nanushuk Group; number followed by plus indicates minimum thickness because top of Nanushuk was eroded (well) or incomplete data section of Nanushuk outcrop. Isopach interval 300 m. Identification of wells and outcrop sections given in figure 25.1 and tables 25.1 and 25.2.

Sable (1956) from outcrops on the west side of the NPRA are portrayed on the cross sections. Two of the cross sections (figs. 25.8, 25.9) are tied to outcrop sections south of Umiat, where some of these units were orignally named. The outcrop sections are very generalized and show only the major facies relations.

The Ninuluk Formation, of Cenomanian age, occurs in the upper part of the Nanushuk Group in the outcrop belt of the Chandler River-Killik River area (Detterman, 1956; Detterman and others, 1963; and Chapman and others, 1964). It is a marine unit that intertongues with the Niakogon Tongue of the nonmarine Chandler Formation, also in the Nanushuk Group, and attains a thickness of as much as 350 m (Detterman and others, 1963, p. 264). As shown on the cross sections (figs. 25.8, 25.9), it is thought to represent deposition by the southern-source Umiat delta during the time of the initial Colville transgression farther north. In other words, the Umiat delta was still actively aggrading after the delta to the north, which had prograded east-northeastward, had become inactive and was being transgressed by the Colville sea.

DEPOSITIONAL PATTERNS

Seismic data indicate that the major part of the Nanushuk delta prograded east-northeastward across the subsiding Colville basin. Such prograding is indicated by foreset dip directions in the underlying prodelta slope deposits

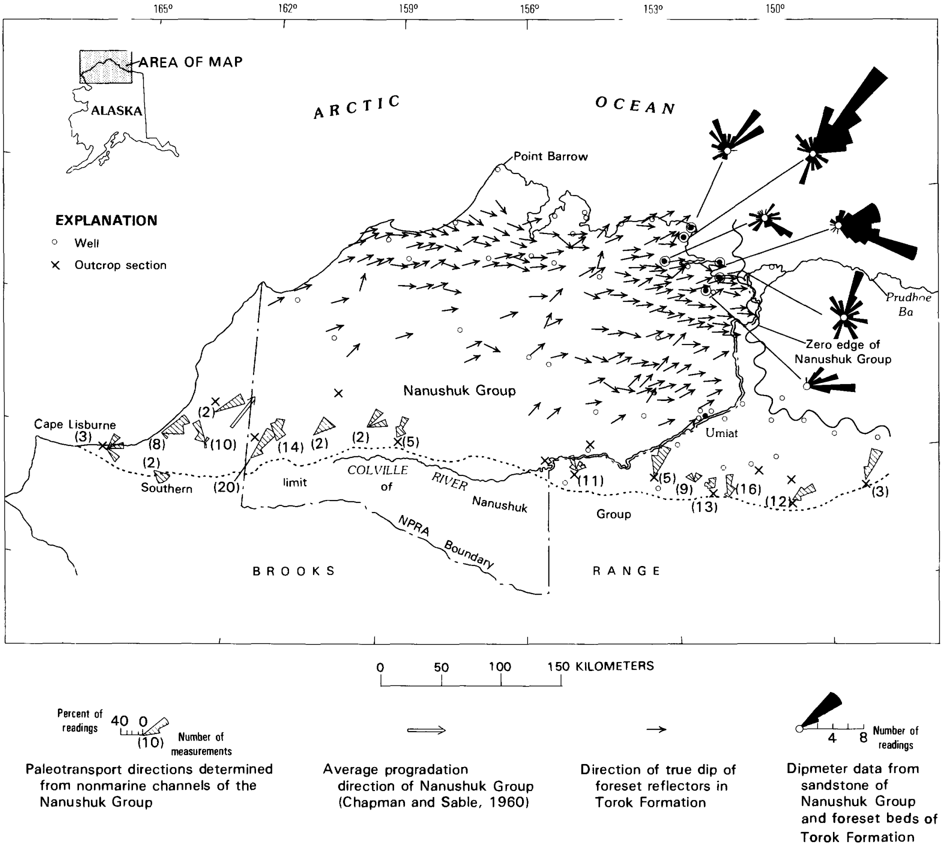

FIGURE 25.15.—Plot of directional data from seismic foreset dips in Torok Formation, dipmeter data from Nanushuk Group sandstone and Torok Formation, direction of Nanushuk progradation from outcrop (Chapman and Sable, 1960), and direction of plunge of symmetrically filled nonmarine channels of Nanushuk Group as measured by Ahlbrandt and others (1979) and Huffman and others (1985). Modified from Bird and Andrews (1979).

of the Torok Formation (fig. 25.15). The overall prograding regressive sequence was interrupted many times by marine transgressions; these resulted in part from delta shifting but mostly from episodic pulses of basin subsidence. Except for the compaction of underlying sediment, basinal subsidence (or rise of relative sea level) is necessary for thick multicyclic shallow-marine sequences to be deposited and to

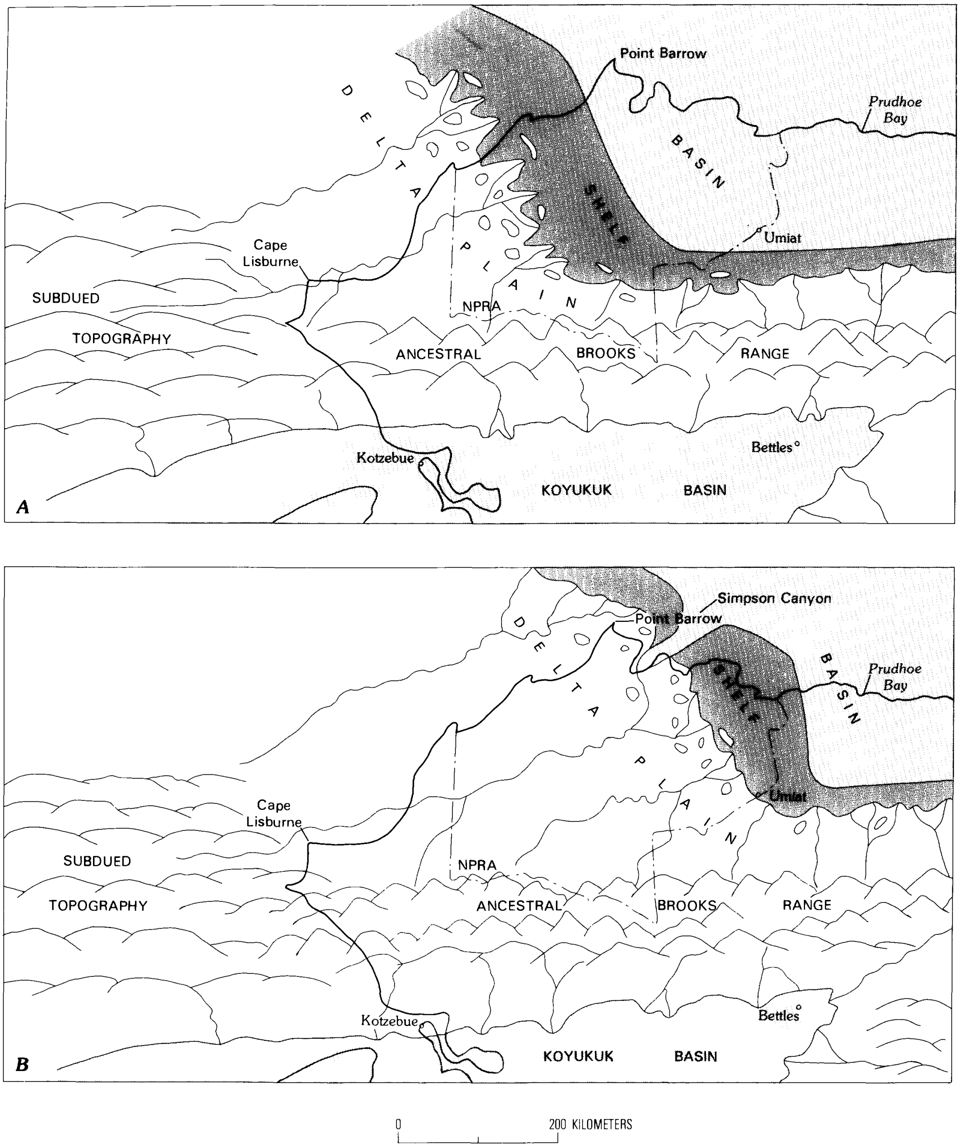

FIGURE 25.16.—Inferred paleogeographic maps of part of northern Alaska and adjacent areas at (*A*) middle Nanushuk time and (*B*) latest Nanushuk time (maximum regression).

account for the upward change in stratigraphic position (stratigraphic rise) of the sequence during progradation. As a result, the Nanushuk is not one simple regressive sequence but a composite of intertonguing shallow-marine shale, shallow-marine sand, and subaerial delta-plain deposits.

The total incremental stratigraphic rise (a measure of the sum of relative sea-level rise and basin subsidence) of the base of the Nanushuk from the Tunalik No. 1 well on the west to the Atigaru Point No. 1 well on the east, a distance of 350 km, is about 2,100 m. However, subsidence was not uniform throughout the basin, as indicated by less and (or) later subsidence of the Barrow arch. This conclusion is based on the following evidence and reasoning: (1) Greater subsidence is required to accomodate the thicker Torok-Nanushuk section in areas to the south and west than in areas of the Barrow arch to the north and northeast. (2) Inasmuch as both the basinal and the shelf beds were probably essentially flat when deposited, differential subsidence during Torok-Nanushuk time is necessary to account for some of the basinal beds of the Torok dipping west or southwest (toward the depositing currents) with respect to the overlying shelf beds. These features are shown in figures 25.6 and 25.7. Indeed, much of the differential subsidence of the basin may have been caused by differential sediment loading.

During most of the Torok-Nanushuk depositional cycle, the Barrow arch was a passive submarine high that separated the Colville basin from the Canada Basin to the north. Thus, the Barrow arch was partly responsible for the eastward progradation of the deltaic system. The Corwin delta, however, is considered to have played the major part in influencing the direction of progradation.

Sedimentary bypassing or even minor beveling of shelf sediment in the Torok-Nanushuk interval is indicated by the apparent toplap relations shown on some seismic lines. The dominant pattern, however, is one of constructional progradation. The width of the prodelta shelf of the Corwin delta ranged between 75 and 150 km as shown on the cross sections. This width is determined by closely correlating seismic data with the marine-nonmarine boundary or transition interpreted in well logs and tracing a seismic reflection to the shelf break.

Because of the relatively greater subsidence on the south side of the basin, the southern-source deltas probably did not extend very far to the north. The growth of the Umiat delta southeast of the NPRA, however, coincided with the presence of the prodelta shelf of the larger eastward-prograding western delta, so that the southern-derived clastics could be distributed along the north-northwestward-trending shoreline and shelf, probably by longshore currents (fig. 25.16). It is postulated that during late Nanushuk time, wave action and longshore currents increased because of the more open marine conditions that prevailed after the Barrow arch subsided enough to lose its silling effect on the Colville basin. It is further postulated that before that time, marine circulation was somewhat restricted in the Colville basin. This restricted circulation may account for the low energy of marine currents and the relative paucity of good marine fauna in much of the Nanushuk in the western part (Molenaar, 1985).

Thus the eastern part of the NPRA along the alignment of the Umiat, Inigok, and Simpson wells has thicker, better sorted, cleaner sandstone units. In addition, the sand from the Umiat delta was relatively richer in quartz (Bartsch-Winkler, 1979, p. 64), especially farther north, where labile constituents probably were removed by winnowing and abrasion. Alternate hypotheses for the thicker sandstone buildups along that trend are that increased wave energy concentrated sand into thicker units or that the influx of a western fluvial system in late Nanushuk time was responsible for the increase in sand. Evidence for such a fluvial system is absent, however, because of erosion of that part of the section to the west.

In the area of Dease Inlet southeast of Point Barrow, a large incised canyon or valley, known as Simpson Canyon, has cut out the Nanushuk Group and much of the Torok Formation in the subsurface (figs. 25.9, 25.16). This canyon, which is filled with shale of the Colville Group, is thought to have been cut by submarine processes during the late stages of the Nanushuk regression (Payne and others, 1951). After the Nanushuk delta had prograded across the Barrow arch, and the depositional pathway was open to the Canada Basin to the north, a canyon-cutting phase was probably initiated. Relative sea-level rise and the Colville transgression terminated the regression and the canyon cutting. This transgression marks the beginning of the Late Cretaceous cycle of deposition. Some of the deltaic clastic deposits of this cycle in the area south of Umiat, however, are included in the Nanushuk Group.

SUMMARY OF DEPOSITIONAL HISTORY

Earliest Cretaceous sedimentation in the northern part of the NPRA was a continuation of the Jurassic cycle of deposition and is represented by the southward-prograding Ellesmerian sequence of shelf and slope deposits of the Kingak Shale. On the south side of the Colville basin, turbidites of the Okpikruak Formation were deposited in front of the ancestral Brooks Range orogen—an orogen that may have been initiated in Jurassic time. Partly coeval or slightly younger rocks in the area of what is now the southern foothills consist of a thin condensed section of black shale containing coquinoidal limestone beds. Because a shallow-marine environment is inferred for the coquina beds, a medial ridge or sill may have separated the Okpikruak turbidite basin to the south from the Ellesmerian shale basin to the north, or, alternatively, the shallow-marine coquina beds may have been transported into deep water.

In middle Neocomian time, relative uplift in northernmost Alaska, subsequent erosion, marine transgression, and deposition of the Hauterivian and Barremian pebble shale unit terminated the Ellesmerian depositional cycle. In the northern half of the NPRA, the pebble shale unit was deposited on a beveled surface. Farther south, the pebble shale was deposited conformably on the slope topography developed in the upper part of the Kingak Shale. Definitive seismic and other subsurface data are absent toward the axis of the Colville basin. On the structurally complex south side of the Colville basin, there are no reported strata of late Neocomian age. Large-scale deformation and thrusting may have been initiated at that time.

After pebble shale deposition in the northern part of the NPRA, the Colville basin was downwarped. Thus the north flank of the basin was isolated from the influx of Brookian clastics until the basin was filled from the south or southwest. This characteristic of Cretaceous sedimentation is known throughout northern Alaska. In the northern part of the NPRA area, significant post-Neocomian deposition did not occur until late Albian time.

Large-scale deformation and thrusting continued during Aptian time in the ancestral Brooks Range orogen on the south. Aptian rocks are not known with certainty in northern Alaska. Undoubtedly, however, there must have been Aptian deposition in the axial part of the Colville basin. Parts of the Fortress Mountain Formation, which is a thick, orogenic, largely deep-water deposit on the south flank of the basin, may be Aptian, although the unit is generally considered to be early Albian. The Fortress Mountain grades into the lower part of the Torok Formation to the north. During Albian time, deep-water basin-plain deposits of the Torok onlapped the south-dipping late Neocomian pebble shale unit on the north flank of the Colville Basin. Deposits representing the intervening time are either absent or form a thin condensed section and may be included in the uppermost part of the pebble shale unit.

Final filling of the Colville basin occurred in middle and late Albian time and is represented by prodelta shale and thin-bedded turbidite deposits of the Torok Formation and overlying deltaic deposits of the Nanushuk Group. Although some of the Nanushuk deltaic deposits prograded to the north on the south side of the basin, the main delta prograded to the east-northeast, almost parallel with the axis of the Colville basin. A large source area is thought to have existed to the south-southwest in the area of the present Chukchi Sea and Hope basin and perhaps even farther to the southwest. The Barrow arch, which was a passive high in Albian time, may have influenced the direction of progradation.

Regional subsidence (or sea-level rise) and subsequent transgression in early or middle Cenomanian time mark the termination of Early Cretaceous deposition and the beginning of a Late Cretaceous cycle of deposition.

REFERENCES CITED

Ahlbrandt, T.S., Huffman, A.C., Fox, J.E., and Pasternack, Ira, 1979, Depositional framework and reservoir-quality studies of selected Nanushuk Group outcrops, North Slope, Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 14-31.

Bartsch-Winkler, Susan, 1979, Textural and mineralogical study of some surface and subsurface sandstones from the Nanushuk Group, western North Slope, Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 61-76.

Bird, K.J., and Andrews, Jack, 1979, Subsurface studies of the Nanushuk Group, North Slope, Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 32-41.

Brosgé, W.P., and Tailleur, I.L., 1971, Northern Alaska petroleum province, *in* Cram, I.H., ed., Future petroleum provinces of the United States; their geology and potential: American Association of Petroleum Geologists Memoir 15, v. 1, p. 68-99.

Brosgé, W.P., and Whittington, C.L., 1966, Geology of the Umiat-Maybe Creek region, Alaska: U.S. Geological Survey Professional Paper 303-H, p. 501-638.

Chapman, R.M., Detterman, R.L., and Mangus, M.D., 1964, Geology of the Killik-Etivluk Rivers region, Alaska: U.S. Geological Survey Professional Paper 303-F, p. 325-407.

Chapman, R.M., and Sable, E.G., 1960, Geology of the Utukok-Corwin region, northwestern Alaska: U.S. Geological Survey Professional Paper 303-C, p. 47-174.

Collins, F.R., and Robinson, R.M., 1967, Subsurface stratigraphic, structural and economic geology, northern Alaska: U.S. Geological Survey open-file report, 259 p.

Crane, R.C., and Wiggins, V.D., 1976, Ipewick Formation, significant Jurassic-Neocomian map unit in northern Brooks Range fold belt [abs.]: American Association of Petroleum Geologists Bulletin, v. 60, no. 12, p. 2177.

Detterman, R.L., 1956, New and redefined nomenclature of Nanushuk Group, *in*

Gryc, George, and others, Mesozoic sequence in Colville River region, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 40, no. 2, p. 233-244.

Detterman, R.L., Bickel, R.S., and Gryc, George, 1963, Geology of the Chandler River region, Alaska: U.S. Geological Survey Professional Paper 303-E, p. 223-324.

Detterman, R.L., Reiser, H.N., Brosgé, W.P., and Dutro, J.T., Jr., 1975, Post-Carboniferous stratigraphy, northeastern Alaska: U.S. Geological Survey Professional Paper 886, 46 p.

Gryc, George, Bergquist, H.R., Detterman, R.L., Patton, W.W., Jr., Robinson, F.M., Rucker, F.P., and Whittington, C.L., 1956, Mesozoic sequence in Colville River region, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 40, no. 2, p. 209-254.

Gryc, George, Patton, W.W., Jr., and Payne, T.G., 1951, Present Cretaceous stratigraphic nomenclature of northern Alaska: Washington Academy of Science Journal, v. 41, no. 5, p. 159-167.

Huffman, A.C., Jr., Ahlbrandt, T.S., Pasternak, Ira, Fox, J.E., Bartsch-Winkler, Susan, May, F.E., Scott, R.A., and Materna, W.L., 1981a, Measured sections of the Cretaceous Nanushuk Group undivided, western North Slope, Alaska: U.S. Geological Open-File Report 81-176, 18 p.

Huffman, A.C., Jr., Ahlbrandt, T.S., Pasternak, Ira, Stricker, G.D., Bartsch-Winkler, Susan, Fox, J.E., May, F.E., Scott, R.A., and Materna, W.L., 1981b, Measured sections of the Cretaceous Nanushuk and Colville Groups undivided, central North Slope, Alaska: U.S. Geological Survey Open-File Report 81-177, 18 p.

Huffman, A.C., Jr., Ahlbrandt, T.S., Pasternack, Ira, Stricker, G.D., and Fox, J.E., 1985, Depositional and sedimentologic factors affecting the reservoir potential of the Cretaceous Nanushuk Group, central North Slope, Alaska, *in* Huffman, A.C., Jr., ed., Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 61-74.

Imlay, R.W., and Detterman, R.L., 1973, Jurassic paleobiogeography of Alaska: U.S. Geological Survey Professional Paper 801, 34 p.

Jones, D.L., and Grantz, Arthur, 1964, Stratigraphic and structural significance of Cretaceous fossils from Tiglukpuk Formation, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 48, no. 9, p. 1462-1474.

Keller, A.S., Morris, R.H., and Detterman, R.L., 1961, Geology of the Shaviovik and Sagavanirktok Rivers region, Alaska: U.S. Geological Survey Professional Paper 303-D, p. 169-222.

Leffingwell, E. de K., 1919, The Canning River region, northern Alaska: U.S. Geological Survey Professional Paper 109, 251 p.

Mitchum, R.M., Jr., 1977, Seismic stratigraphy and global changes of sea level, Part II—Glossary of terms used in seismic stratigraphy, *in* Payton, C.E., ed., Seismic stratigraphy; applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 205-212.

Molenaar, C.M., 1983, Depositional relations of Cretaceous and lower Tertiary rocks, northeastern Alaska: American Association of Petroleum Geologists Bulletin, v. 67, no. 7, p. 1066-1080.

——— 1985, Subsurface correlations and depositional history of the Nanushuk Group and related strata, North Slope, Alaska, *in* Huffman, A.C., Jr., ed., Geology of Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 37-59.

Molenaar, C.M., Bird, K.J., and Kirk, A.R., 1987, Cretaceous and Tertiary stratigraphy of northeastern Alaska, *in* Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Calif., Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 513-528.

Mull, C.G., Tailleur, I.L., Mayfield, C.F., and Pessel, G.H., 1976, New structural and stratigraphic interpretations, central and western Brooks Range and Arctic Slope, *in* Cobb, E.H., ed., The United States Geological Survey in Alaska; accomplishments during 1975: U.S. Geological Survey Circular 733, p. 24-26.

Mutti, Emiliano, and Ricci Lucchi, Franco, 1972, Le torbiditi dell'Appennino settentrionale; introduzione all'analisi de facies: Società Geologica Italiana Memorie, v. 11, p. 161-199 [Translated by T.H. Nilson, 1978, Turbidites of the northern Apennines: Introduction to facies analysis: American Geological Institute Reprint Series 3, reprinted from International Geology Review, v. 20, no. 2, p. 125-166].

NPRA palynology/micropaleontology reports for 17 wells, 1980, data set TGY-0030 [Available from National Geophysical Data Center, 325 Broadway, E/GC, Dept. CNP, Boulder, CO 80303].

NPRA summary geophysical report, FY-1978, 1980, data set TGX-0050 [Available from National Geophysical Data Center, 325 Broadway, E/GC, Dept. CNP, Boulder, CO 80303].

Patton, W.W., Jr., 1956, New and redefined formations of Early Cretaceous age, *in* Gryc, George, and others, Mesozoic sequence in Colville River region, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 40, no. 2, p. 219-223.

Patton, W.W., Jr., and Tailleur, I.L., 1964, Geology of the Killik-Itkillik region, Alaska: U.S. Geological Survey Professional Paper 303-G, p. 409-500.

Payne, T.G., and others, 1951, Geology of the Arctic slope of Alaska: U.S. Geological Survey Oil and Gas Investigations Map OM-126, scale 1:1,000,000, 3 sheets.

Rich, J.L., 1951, Three critical environments of deposition and criteria for recognition of rocks deposited in each of them: Geological Society of America Bulletin, v. 62, p. 1-20.

Robinson, F.M., Rucker, F.P., and Bergquist, H.R., 1956, Two subsurface formations of Early Cretaceous age, *in* Gryc, George, and others, Mesozoic sequence in Colville River region, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 40, no. 2, p. 223-232.

Sable, E.G., 1956, New and redefined Cretaceous formations in western part of northern Alaska: American Association of Petroleum Geologists Bulletin, v. 40, no. 11, p. 2635-2643.

Smiley, C.J., 1969, Floral zones and correlations of Cretaceous Kukpowruk and Corwin Formations, northwestern Alaska: American Association of Petroleum Geologists Bulletin, v. 53, no. 10, p. 2079-2093.

Tailleur, I.L., and Kent, B.H., 1953, Progress report on the Kiligwa anticlinorium: U.S. Geological Survey Geological Investigations, Naval Petroleum Reserve No. 4 and Adjacent Areas, Alaska, Special Report 40, 17 p. [Available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey].

Tailleur, I.L., Kent, B.H., and Reiser, H.N., 1966, Outcrop/geologic maps of the Nuka-Etivluk region, northern Alaska: U.S. Geological Survey open-file report, scale 1:63,360, 5 sheets.

Witmer, R.J., Haga, Hideyo, and Mickey, M.B., 1981, Biostratigraphic report of thirty-three wells drilled from 1975 to 1981 in National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 81-1166, 47 p.

26. LOW-LEVEL AEROMAGNETIC SURVEYING FOR PETROLEUM IN ARCTIC ALASKA

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INTRODUCTION

Magnetic anomalies of high wave number measured over oil fields have been interpreted as reflecting abundant near-surface magnetic minerals formed as a direct result of petroleum seepage (Donovan and others, 1979). The investigation reported here, undertaken during the summer of 1979, demonstrates that these kinds of anomalies are associated with known occurrences of petroleum in northern Alaska. Because routine geological and geophysical information is especially difficult and expensive to acquire in northern Alaska, rapidly gathered and relatively inexpensive aeromagnetic data that might conceivably serve as an indirect indicator of hydrocarbons could have an impact on exploration activities there. Additionally, documentation of microseepage-related phenomena is an important step toward understanding petroleum microseepage in a permafrost environment.

Rocks above and adjacent to the Barrow arch, a buried regional feature along the north coast of Alaska, are a primary habitat for oil and gas, but the geologic framework and the geology of petroleum occurrence are complex. Upper Devonian to lowermost Cretaceous carbonate and clastic rocks derived from northern sources were deposited in a basin that deepened southward. These rocks contain four of the five major reservoirs in the Prudhoe Bay field, which is located on the arch 330 km southeast of Barrow. Formation of the ancestral Brooks Range and the opening of the Arctic Ocean in the Late Jurassic and Early Cretaceous caused southern sediment sources to replace the northern landmass. Subsequent subsidence and tilting of the continental margin toward the opening Arctic Ocean resulted in the formation of the Barrow arch. The Barrow arch was onlapped and overlapped in Late Cretaceous and Tertiary times by a series of clastic wedges that filled northeastward-migrating foredeeps. "It was the fortuitous combination of excellent reservoir rocks located on a major structure; the truncation, overlapping, and sealing of these reservoir rocks by rich source beds; and their subsequent burial that resulted in the Prudhoe Bay field, the largest petroleum accumulation in North America" (Bird and Jordan, 1977, p. 1,496).

THE SURVEY

Total-field aeromagnetic profiles recorded at 90-m altitude over a variety of petroleum seeps, commercial and noncommercial accumulations, and prospects (fig. 26.1) demonstrate abundant high-wave-number magnetic anomalies. Approximately 8,000 km of low-altitude profile line was collected. All areas surveyed except the Meade region were flown in a north-south and east-west grid with 1.5-km line spacing. A Geometrics Inc. G-803 total-field proton-precession magnetometer was used with the sensing head located 2.1 m behind the aircraft in a fiberglass boom. Readings, taken at one-second intervals, yield at an average aircraft speed of 125 knots a magnetic measurement about every 65 m along the flight path.

With a one-second reading rate, the magnetometer system has a sensitivity of approximately 0.3 nT. Variations in the magnetic field resulting from different aircraft headings were electronically compensated to less than 0.5 nT. Other induced noise (for example, electrical noise or eddy currents) was less than 0.25 nT. The error of the magnetic measurements consequently was less than 1 nT, regardless of heading.

A magnetic base station was established at the Naval Arctic Research Laboratory (NARL) at Point Barrow. The base station was operated continuously to provide a record of solar magnetic storms, during which no aerial surveys were conducted. Readings were not corrected for diurnal variation because the magnetic field at high latitudes is so heterogeneous (Westcott, 1960). The flight crew consisted of a pilot, copilot/navigator, and instrument operator. Identifiable ground positions along flight paths were plotted on standard 1:63,360-scale topographic maps by the copilot/navigator. Magnetic

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data and fiducial marks were recorded on a strip chart recorder; magnetic data and radar altimetry, read every second, were also digitally recorded on magnetic tape. Fiducial positions were later verified and located to within 0.1 km with the aid of videotapes continuously recorded through a port in the aircraft floor. Regional and offshore lines were positioned with a very low frequency navigational system (VLF/OMEGA). The maximum position error using this system without the aid of video checks is believed to be less than 1 km.

All data were reduced and stored in a computer to create a file that consists of latitude, longitude, and total-field magnetic value for each one-second reading along flight lines. This file was transformed into gridded format suitable for computer map compilation.

The apparent wavelength of anomalies believed to result from changes in iron minerals induced by hydrocarbon seepage is on the order of 20 to 100 times less than that of anomalies caused by variations in the magnetic basement (fig. 26.2). Anomalies of interest have wavelengths that range from 100 to 1,000 m and amplitudes ranging from the noise level (<1.0 nT) to about 50 nT. In order to construct maps or generate computer images that show the areas and trends of high-wave-number anomalies that are free of the effects of the variable diurnal changes, we computed the horizontal magnetic gradient. The gradient was calculated by comparing every fourth reading along the flight line, thereby eliminating basement-induced long-wavelength anomalies and effects of diurnal changes (the maximum diurnal change observed was less than 1 nT for any 4-s interval).

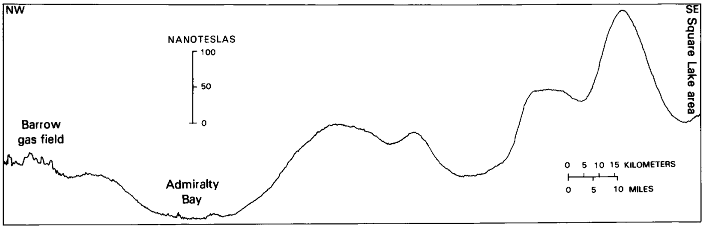

FIGURE 26.2.—Regional low-altitude aeromagnetic profile from Barrow (lat 71°17'N., long 156°37'W.) southeastward to Square Lake (lat 69°35'N., long 153°25'W.), demonstrating general absence of high-wave-number anomalies of significant amplitude in the vicinity of the Barrow gas field.

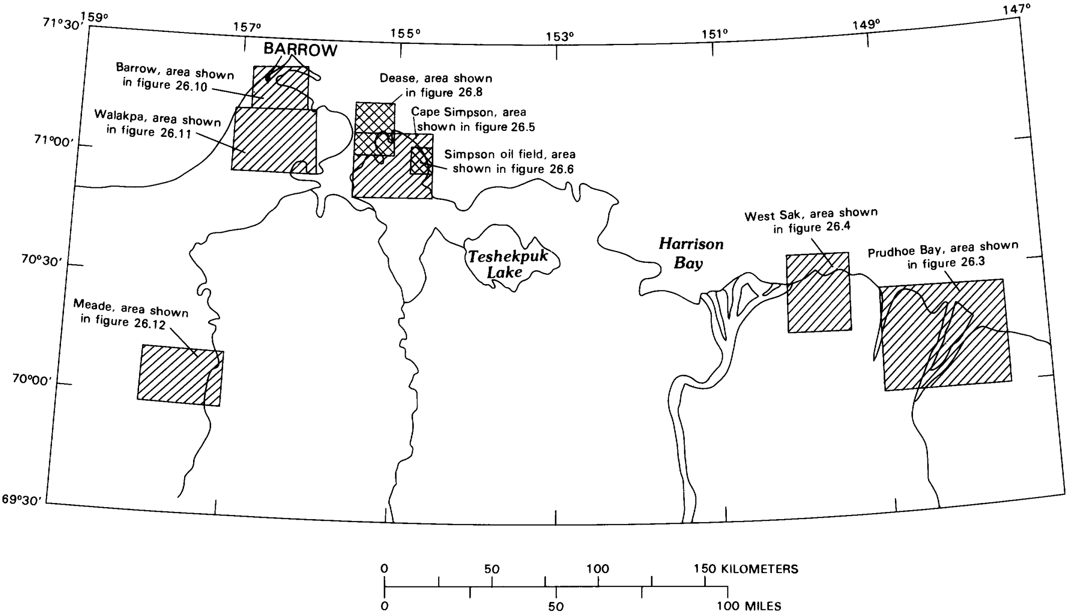

FIGURE 26.1.—Index map of Arctic Alaska showing areas of aeromagnetic coverage.

Spatial-array processing techniques can be applied to the data to correct for improper registration, to smooth the data and areally interpolate, and to display the data as an image (Eliason and others, 1983). In this report the data are presented in several formats, which include profiles, hand-constructed maps of magnetically anomalous areas, and computer-generated images of the aeromagnetic data.

The effects of culture (pipelines, drill sites, buildings, and such) are readily detectable and in densely developed areas tend to mask signals of interest. In sparsely developed areas, however, these signals are too rare to be confused with hydrocarbon induced anomalies.

PRUDHOE BAY

The Prudhoe Bay oil field is on the north coast of Alaska approximately 330 km southeast of Barrow. The structure is a plunging anticlinal nose at the eastern end of the southeast-plunging Barrow arch. It is faulted on the north and west and truncated by an unconformity on the east. The area of production mapped on the primary (Sadlerochit) reservoirs is more than 500 km^2. Mississippian through Jurassic rocks, derived from northern source areas, contain the principal reservoirs. The unconformably overlying Cretaceous clastic rocks were derived from southern source areas. In the western portion of the field, shallow Upper Cretaceous sandstones yield dense, viscous oil. Shallow gas accumulations are trapped under the base (at 600-m depth) of the permafrost in the Sagavanirktok Formation. Detailed descriptions of the structure, stratigraphy, and development history of Prudhoe Bay have been published by Rickwood (1970), Morgridge and Smith (1972), and Jones and Speers (1976).

Areas of high-wave-number anomalies over the Prudhoe Bay region are shown in figure 26.3. These anomalous areas are north of the field and the truncation zone as mapped by Jones and Speers (1976). A few small areas of high-wave-number magnetic anomalies are mapped to the northeast beyond the present known limits of production.

A band of small areas of aeromagnetic anomalies arranged in rough echelon fashion appears to align subparallel to a subsurface truncation line in the Ugnuravik River region, south of Oliktok Point (fig. 26.4). These anomalies lie generally updip from productive wells. Little information has been published about the petroleum geology of the region, so a thorough discussion of the significance of these occurrences in a geologic context must be postponed.

SIMPSON AREA

Mesozoic rocks, unconformably underlying the late Cenozoic Gubik Formation, dip generally east in the Cape Simpson area; Upper Cretaceous rocks were abruptly truncated along and near the present coast, in an arcuate pattern from Dease Inlet to Smith Bay, by the carving of Simpson Canyon and its subsequent infilling with younger Cretaceous rocks. An extensive core-drilling program conducted by the U.S. Navy during 1945-1951 defined the Simpson oil field as a long narrow feature in Upper Cretaceous rocks in the eastern part of the area. In the western part of the area seeps and abundant noncommercial shows of oil in core holes and the Simpson Test Well 1 have been documented (Robinson, 1959, 1964).

A band of high-wave-number anomalies coincides with the southern margin of Simpson Canyon (fig. 26.5). The straightforward interpretation of this correlation is that hydrocarbons issue from truncated east-southeast-dipping older rocks at the canyon edge and seep upward along the unconformity to interact with overlying sediments.

A detailed map of the region immediately surrounding the Simpson oil field is shown in figure 26.6. Isopach lines, drawn from net sandstone thicknesses estimated from published sample descriptions of the oil-producing interval in wells (Robinson, 1964), clearly indicate the channellike nature of the sandstone. Average depth to the oil-bearing interval is only about 100 m. Correspondence between the net oil-productive sandstone pattern and the overlying area of high-wave-number magnetic anomalies is apparent.

Previous work has shown that late diagenetic carbonate cements, diagnostically depleted in ^{13}C, in superincumbent rocks over oil accumulations are an indicator of the strong influence of carbon dioxide derived from oxidized seeping hydrocarbons (Donovan, 1974; Donovan and others, 1974; Donovan and Dalziel, 1977). Supportive empirical evidence that the aeromagnetic anomalies are partly related to seepage-induced phenomena in the Simpson area is tabulated in table 26.1 and plotted in part in figure 26.7. Isotopic data from calcite cement in sandstone cores show an apparent trend from slightly negative $\delta^{13}C$ values at a depth of 44 m toward slightly positive values at 95 m; the trend is sharply disrupted in the interval 72-78 m by an excursion of exceptionally negative values, indicating a hydrocarbon-derived carbon source during a late diagenetic (seepage) event. (Not plotted or tabulated is one possibly spurious $\delta^{13}C$ value of 25.78 permil or parts per thousand from Simpson Core Test 31 at 61.6 m). Simpson area oils have $\delta^{13}C$ values that range from -29.1 to -27.8 permil (Magoon and Claypool, 1979).

Of special interest is an area having anomalies of unusually high wave number superposed on a large, high-amplitude feature centered in upper Dease Inlet near the Plover Islands west of Tangent Point (figs. 26.8, 26.9). This anomalous area approximately coincides with a structurally high region along the northwest flank of Simpson Canyon mapped by Tetratech from seismic data; it is considered highly prospective, particularly if potential reservoir rocks can be expected to lap onto the structural high.

BARROW AREA

A computer-generated image of the magnetic data for the area about the Barrow gas field is shown in figure 26.10. The color-spectrum scale reflects increasing magnetic gradient from dark blue to red. The ring of bright yellow near the center of the image corresponds with the circular Barrow fault complex of Woolson and others (1962, p. 16). Presumably that feature controls a zone of enhanced fluid communication through the overburden, thus dictating the areal pattern of near-surface diagenetic production of magnetic minerals and of diagnostic magnetic anomalies. Mesozoic rocks in the Barrow region range from 610 to 915 m in thickness. Two Navy test wells, Barrow wells 2 and 4, were drilled on the northwest side of the Barrow structure; they produced gas from Jurassic sandstone at a depth of about 760 m. The dry Avak test well was drilled closer to the center of the circular complex; it penetrated argillite basement at 702 m.

WALAKPA AREA

The Walakpa test well 1, drilled in 1979-1980, encountered subcommercial amounts of gas at 631 m in a thin sandstone bed (informally designated the Walakpa sand) unconformably underlying the Lower Cretaceous pebble shale unit. This test was predicated on a potential pinch-out of porous sandstone against older rocks along the flank of the Barrow arch. Walakpa test

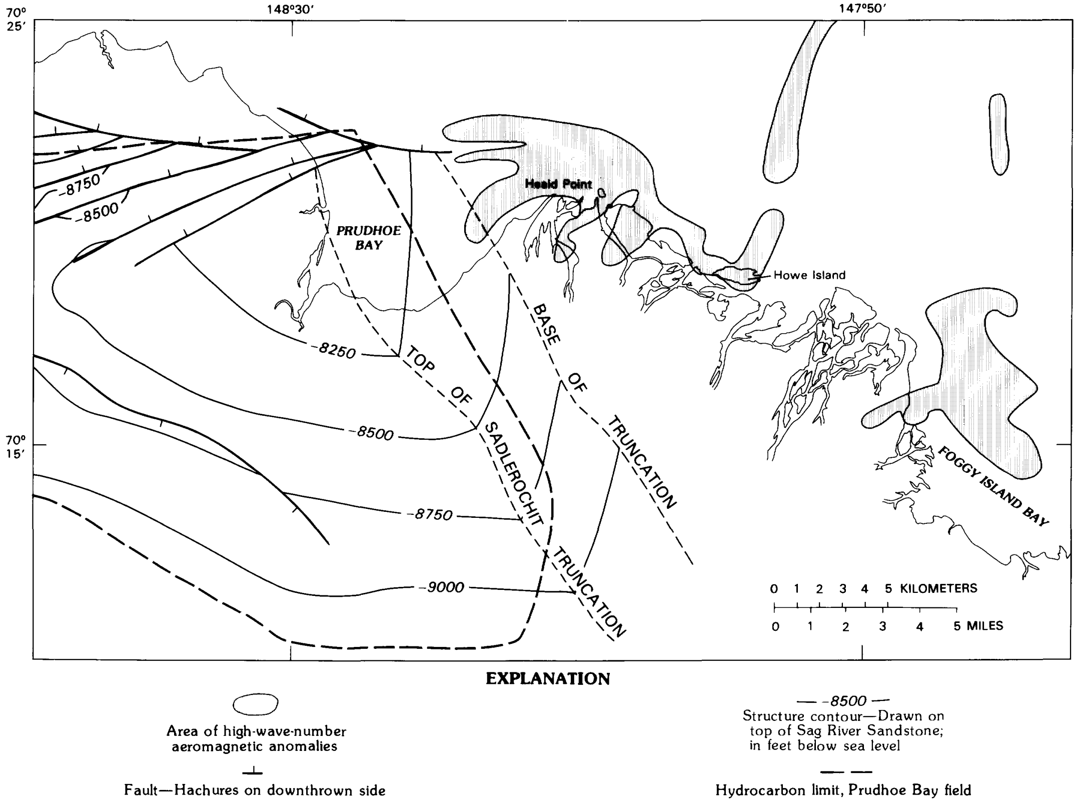

FIGURE 26.3.—Areas of high-wave-number aeromagnetic anomalies, hand picked from analog records, in the Prudhoe Bay region.

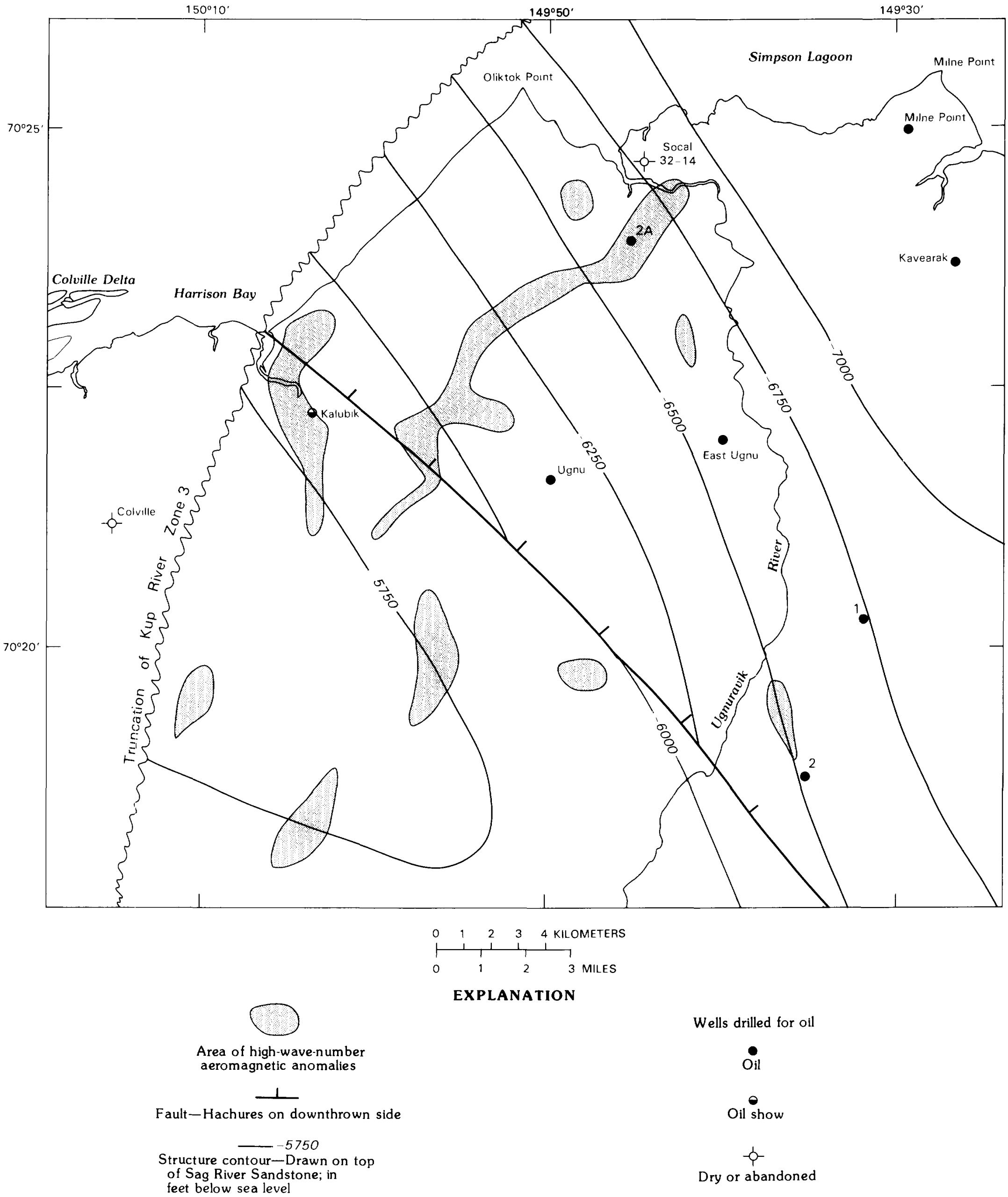

FIGURE 26.4.—Areas of high-wave-number aeromagnetic anomalies, hand picked from analog records, in the Ugnuravik River region, Arctic coast of Alaska. Geologic interpretation from Bushnell (1981). Contours approximately located. Base from Harrison Bay (1955) and Beechey Point (1960) 1:250,000-scale topographic quadrangle maps, both revised 1976.

well 2 was drilled in 1981 to a total depth of 1,329 m and completed as a gas producer from the Walakpa sand. A poorly developed but persistent crescentic band of high-wave-number anomalies arcs just north of and updip from the drill sites (fig. 26.11).

MEADE AREA

A limited survey in the immediate area of the U.S. Navy Meade test well was flown parallel to the strike of the Meade anticline (fig. 26.12). A small area of high-wave-number anomalies was delineated along the north flank of the structure. The Meade well, drilled to 1,617 m, encountered an undetermined amount of gas.

A repeat line in this survey was flown at three different altitudes in order to document how the high-wave-number anomalies attenuate

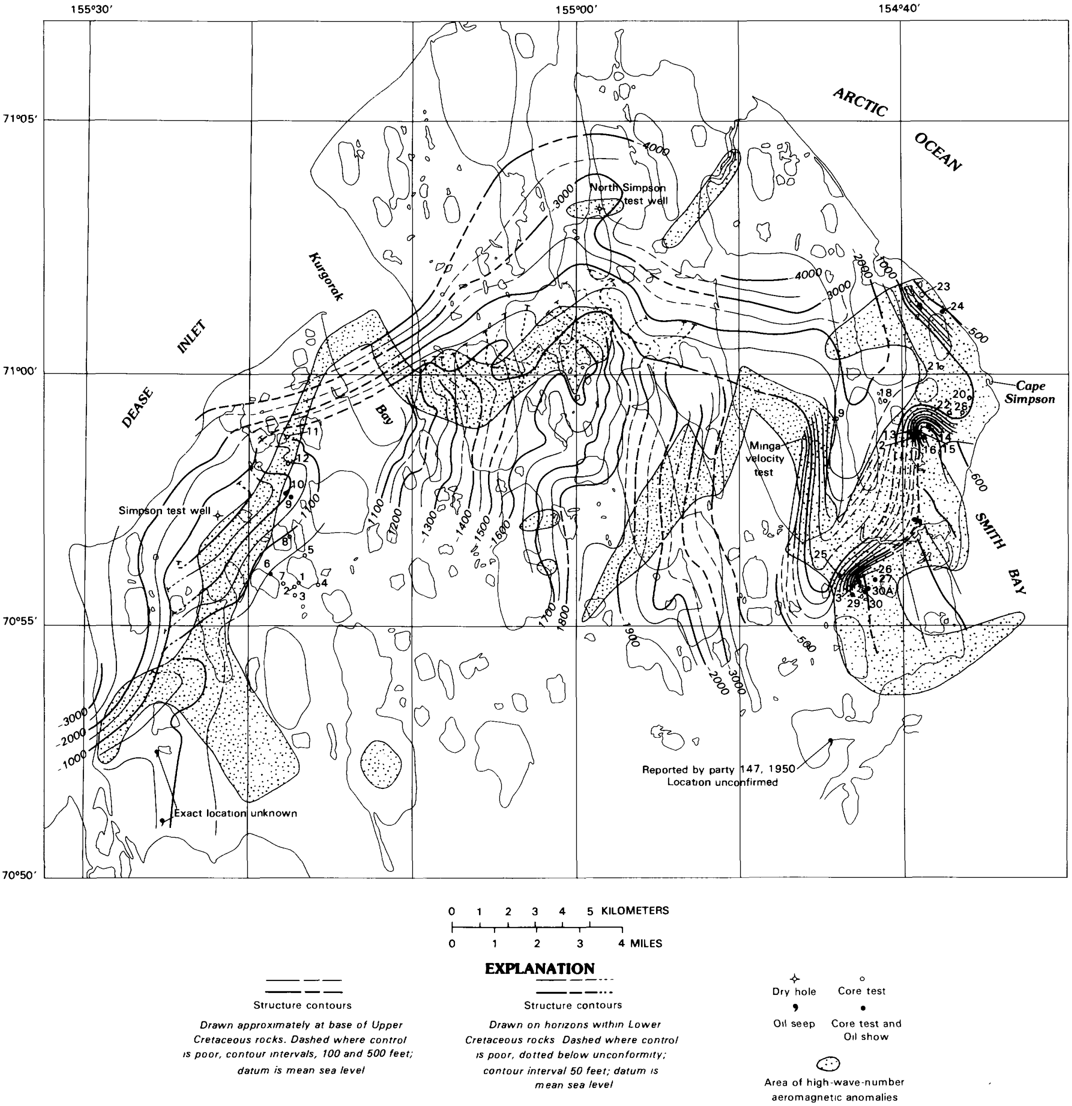

FIGURE 26.5.—Areas of high-wave-number aeromagnetic anomalies, hand picked from analog records, in the Cape Simpson region.

TABLE 26.1.—*Isotopic composition of carbon and oxygen in carbonate cement from sandstone cores, Simpson area, Alaska*

[Delta values derived by subtracting ratio in standard from ratio in sample, dividing by former, and multiplying by 1000. Standard for carbon, Pee Dee Belemnite; standard for oxygen, SMOW (Standard Mean Ocean Water)]

Depth (m)	Depth (ft)	$\delta^{13}C$ (permil)	$\delta^{18}O$ (permil)
Simpson Test Well 1			
43.9	144	-1.67	17.14
46.0	151	-1.62	16.00
49.1	161	-.24	21.30
54.3	178	-1.78	14.05
Simpson Core Test 31			
71.6	235	-5.06	8.21
75.0	246	-22.17	23.47
78.4	257	-20.25	22.45
88.4	290	-1.93	12.76
91.8	301	3.42	31.65
95.1	312	1.08	20.89
98.5	323	1.31	17.23

with altitude and to illustrate the complex nature of the individual anomalies. Results of this experiment are shown as figure 26.13, and calculations by the method described by Vacquier and others (1951) indicate that the maximum depth to the top of the source (or iron accumulations) is less than about 70 m.

SUMMARY

Low-level aeromagnetic surveying may be an effective method of defining oil and gas prospects in remote areas. High-wave-number magnetic anomalies are associated with known occurrences of petroleum or natural gas in northern Alaska and are readily detected by low-altitude (90-m) surveying. The magnetitic signature in these areas is complex and indicates a variable, near-surface (<300-m depth) source. The suggested cause of these anomalies is diagenetic magnetic mineralization caused by reduction of iron

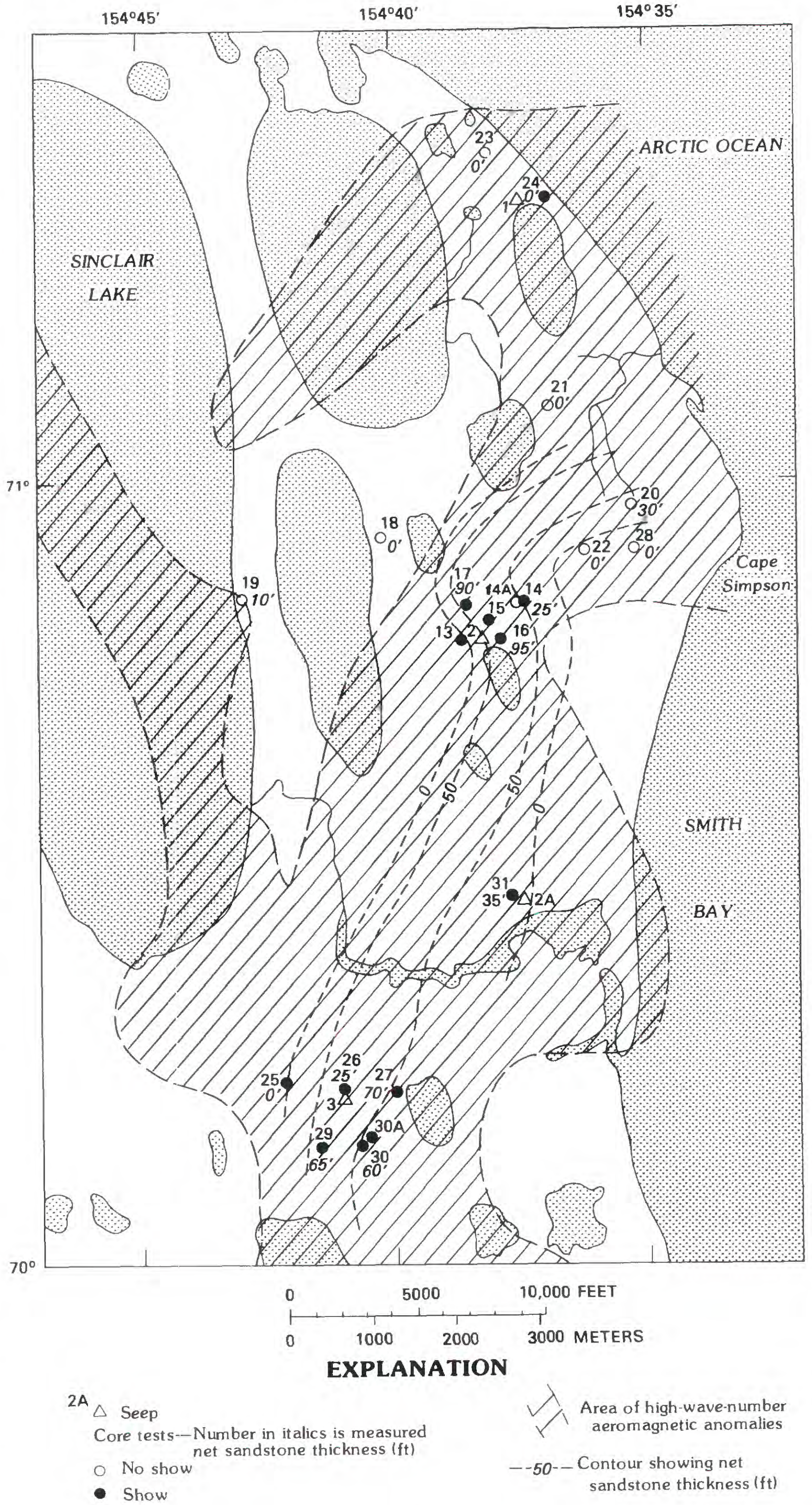

FIGURE 26.6.—Detailed map of Simpson oil field region showing areas of high-wave-number aeromagnetic anomalies, core holes, test wells, seeps, and net sandstone thickness of oil-bearing interval.

oxides in the presence of seeping hydrocarbons. The magnetically anomalous signatures appear to result from hydrocarbons seeping from imperfect traps or along subregional zones of improved subsurface-to-surface fluid communication, such as unconformities, truncation zones, and faults.

REFERENCES CITED

Bird, K.J., and Jordan, C.F., 1977, Lisburne Group (Mississippian and Pennsylvanian), potential major hydrocarbon objective of Arctic Slope, Alaska: American Association of Petroleum Geologists Bulletin, v. 61, no. 9, p. 1493-1512.

Bushnell, Hugh, 1981, Unconformities; key to N. slope oil: Oil and Gas Journal, v. 79, no. 2, (January 12), p. 114-118.

Donovan, T.J., 1974, Petroleum microseepage at Cement, Oklahoma; evidence and mechanism: American Association of Petroleum Geologists Bulletin, v. 58, no. 3, p. 429-446.

Donovan, T.J., and Dalziel, M.C., 1977, Late diagenetic indicators of buried oil and gas: U.S. Geological Survey Open-File Report 77-817, 44 p.

Donovan, T.J., Forgey, R.L., and Roberts, A.A., 1979, Aeromagnetic detection of diagenetic magnetite over oil fields: American Association of Petroleum Geologists Bulletin, v. 63, no. 2, p. 245-248.

Donovan, T.J., Friedman, Irving, and Gleason, J.D., 1974, Recognition of petroleum-bearing traps by unusual isotopic compositions of carbonate-cemented surface rocks: Geology, v. 2, no. 7, p. 351-354.

Eliason, P.T., Donovan, T.J., and Chavez, P.S., Jr., 1983, Integration of geologic, geochemical, and geophysical data of the Cement oil field, Oklahoma, using spatial array processing: Geophysics, v. 48, no. 10, p. 1305-1317.

Jones, H.P., and Speers, R.G., 1976, Permo-Triassic reservoirs of Prudhoe Bay field, North Slope, Alaska, *in* North American oil and gas fields: American Association of Petroleum Geologists Memoir 24, p. 23-50.

Magoon, L.B., and Claypool, G.E., 1979, Two oil types on the North Slope of Alaska; implications for future exploration: U.S. Geological Survey Open-File Report 79-1649, 21 p.

Morgridge, D.L., and Smith, W.B., Jr., 1972, Geology and discovery of Prudhoe Bay field, eastern Arctic Slope, Alaska, *in* King, R.E., ed., Stratigraphic oil and gas fields; classification, exploration methods, and case histories: American Association of Petroleum Geologists Memoir 16, p. 489-501.

Rickwood, F.K., 1970, The Prudhoe Bay field, *in* Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the Geologic seminar on the North Slope of Alaska: Los Angeles, American Association of Petroleum Geologists Pacific Section, p. L1-L11.

Robinson, F.M., 1959, Test wells, Simpson area, Alaska: U.S. Geological Survey Professional Paper 305-J, p. 523-568.

——— 1964, Core tests, Simpson area, Alaska: U.S. Geological Survey Professional Paper 305-L, p. 645-730.

Vacquier, Victor, Steenland, N.C., Henderson, R.G., and Zietz, Isidore, 1951, Interpretation of aeromagnetic maps: Geological Society of America Memoir 47, 151 p.

Wescott, E.M., 1960, Magnetic and telluric current disturbances in Alaska: Geophysics, v. 25, no. 6, p. 1242-1250.

Woolson, J.R., and others, 1962, Seismic and gravity surveys of Naval Petroleum Reserve No. 4 and adjoining areas, Alaska: U.S. Geological Survey Professional Paper 304-A, 25 p.

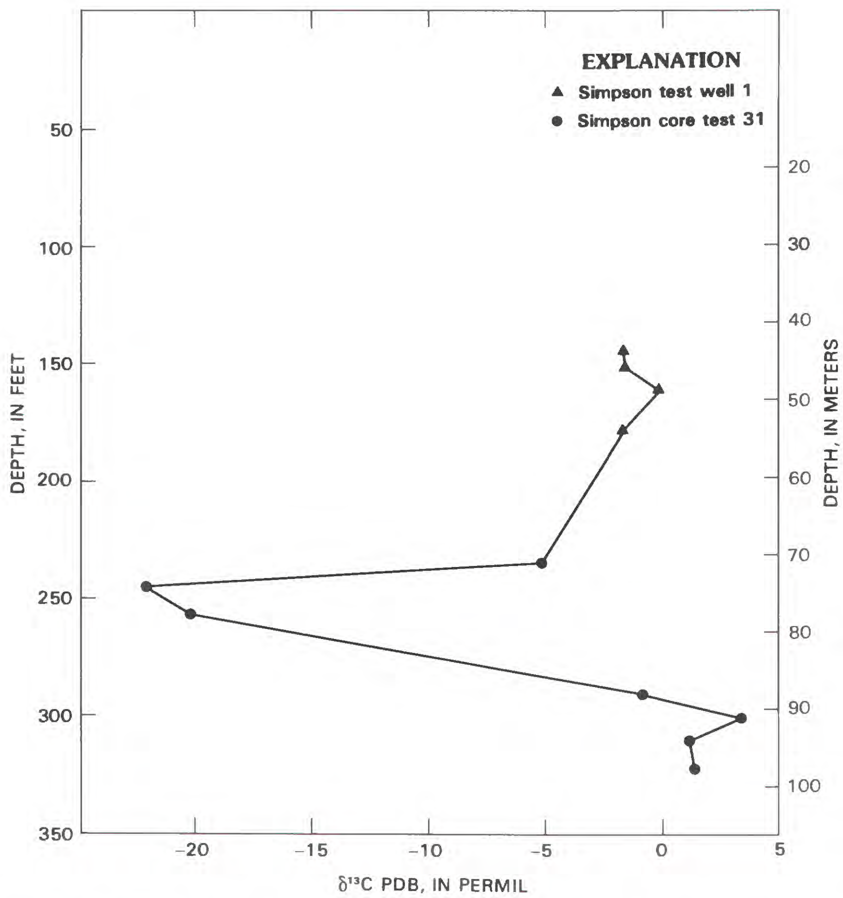

FIGURE 26.7.—Plot of $\delta^{13}C$ versus depth for carbonate cement in sandstone cores from Simpson Test Well 1 and SimpsonCoreTest 31. Data from table 26.1. Isotope values relative to Pee Dee belemnite (PDB) standard.

FIGURE 26.8.—Computer-generated image of aeromagnetic gradient in Upper Dease Inlet. Dark blue represents zero gradient, yellow intermediate, and red maximum gradient (60 nT/km).

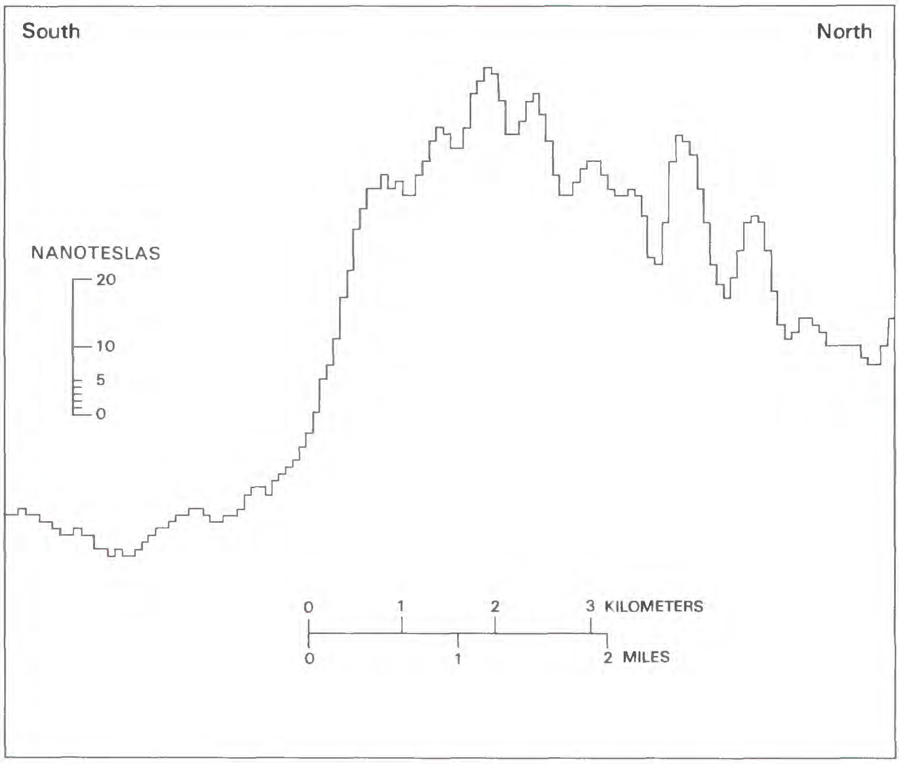

FIGURE 26.9.—Aeromagnetic profile through upper Dease Inlet showing high-wave-number anomalies superposed on regional magnetic high.

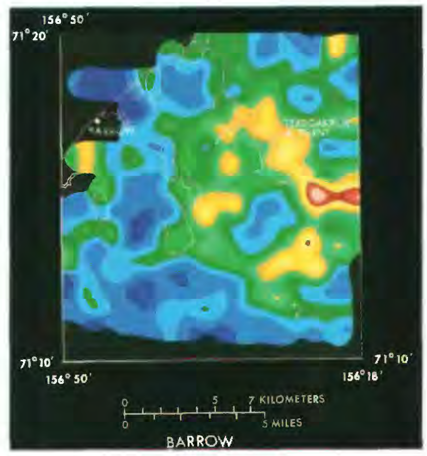

FIGURE 26.10.—Computer-generated image of magnetic gradient in Barrow region. Dark blue represents zero gradient, yellow intermediate, and red maximum gradient. Black, no data.

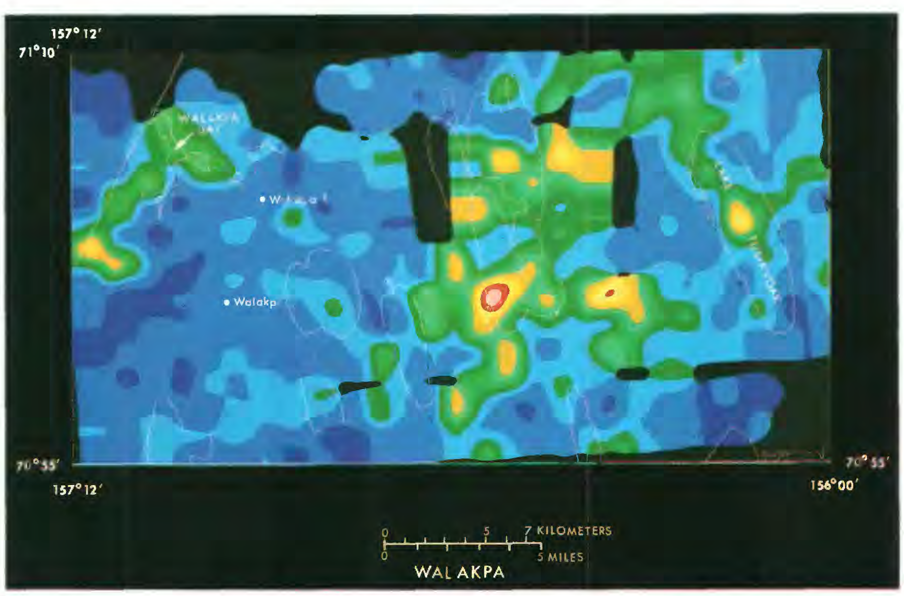

FIGURE 26.11.—Computer-generated image of magnetic gradient in Walakpa region. Dark blue represents zero gradient, yellow intermediate, and red maximum gradient. Black, no data.

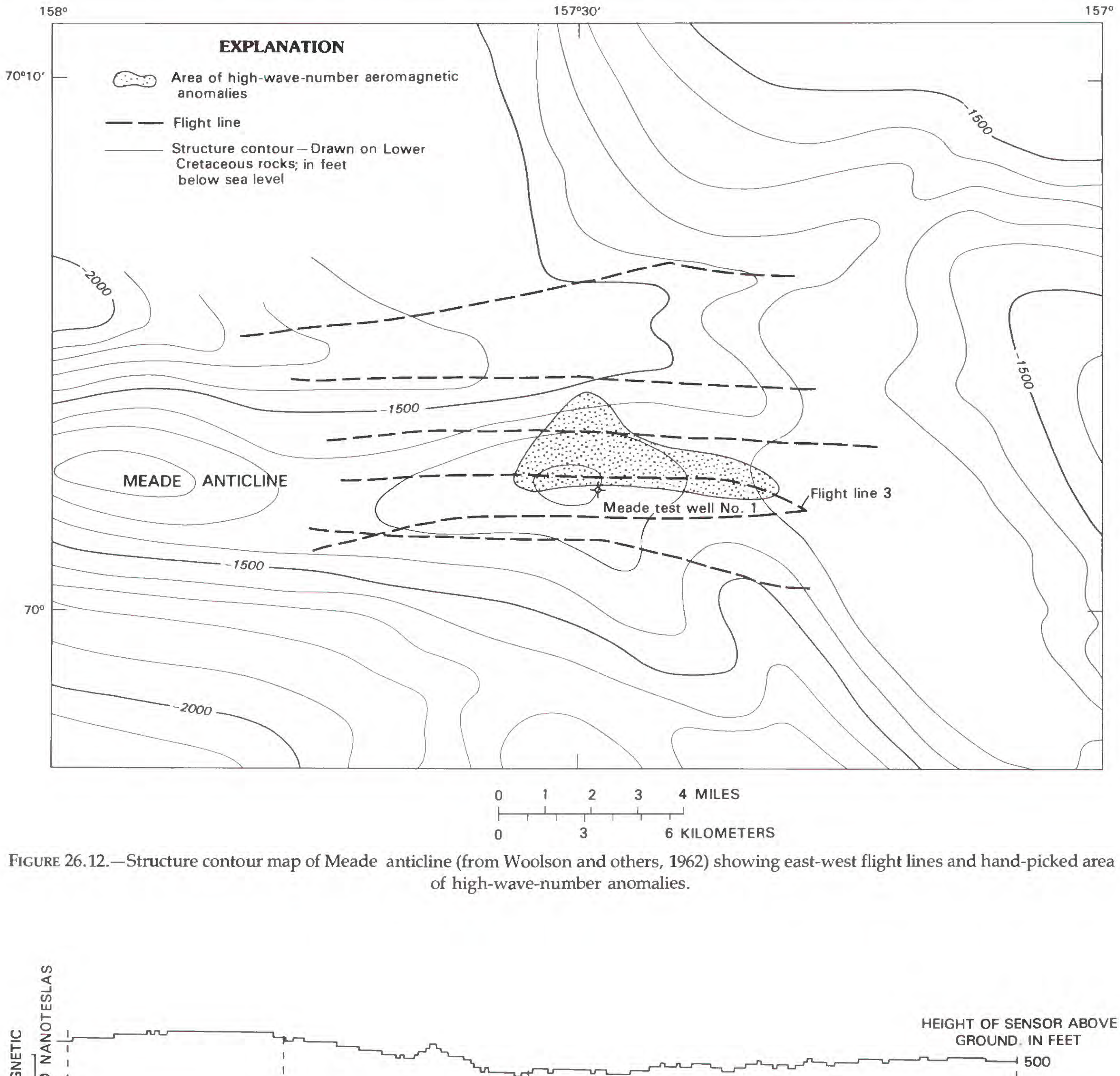

FIGURE 26.12.—Structure contour map of Meade anticline (from Woolson and others, 1962) showing east-west flight lines and hand-picked area of high-wave-number anomalies.

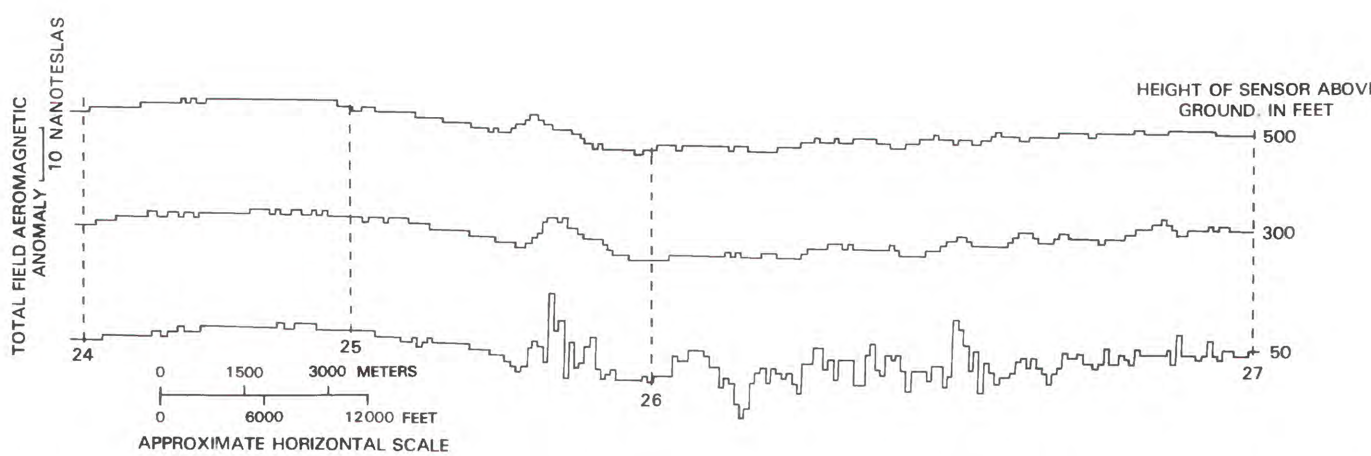

FIGURE 26.13.—Example of repeat aeromagnetic profiles (flight line 3) in Meade area flown at different altitudes. High-wave-number anomaly occurs between fiducials 25 (east) and 26 (west). On the basis of this kind of data, 90 m (300 ft) was selected as optimum altitude for signal response and aircraft safety.

27. CRETACEOUS REMAGNETIZATION OF PALEOZOIC SEDIMENTARY ROCKS IN THE BROOKS RANGE, ALASKA

By JOHN W. HILLHOUSE and SHERMAN GROMMÉ

INTRODUCTION

We have made a paleomagnetic study of sedimentary rocks in the northern Brooks Range in an effort to determine the paleoposition of Arctic Alaska during Devonian and Mississippian time. Although the Brooks Range affords excellent exposures, the Paleozoic strata are mostly within thrust sheets that have been displaced far from their sites of origin. Realizing that some of the thrust sheets may have undergone local rotations, we took paleomagnetic samples hundreds of kilometers apart and from several structural levels in the range. If consistent paleomagnetic poles can be obtained from such a broad region, we believe they should accurately represent the poles recorded in the concealed autochthonous basement of the North Slope.

Ideas concerning the tectonic evolution of the western Arctic Ocean have centered on two topics: the original position of Arctic Alaska and the nature of the crust within the Canada Basin. For example, Eardley (1948) speculated that the basin is a submerged continental platform and, thus, that northern Alaska has remained fixed relative to the North American craton. Others have speculated that rifting beginning in the late Mesozoic caused Arctic Alaska to break away and rotate 70° counterclockwise from its original position adjacent to northernmost Canada, the rotation creating new oceanic crust in the Canada Basin (Carey, 1958; Tailleur, 1973). Conversely, Churkin and Trexler (1980) suggested that Arctic Alaska, as a detached microplate, moved northward and formed the Canada Basin by trapping a segment of old oceanic crust. Paleomagnetic investigation of northern Alaska was undertaken to help resolve these questions.

Newman and others (1979) pioneered paleomagnetic studies in the Brooks Range in an attempt to detect the rotation proposed by Tailleur (1973). If such rotation occurred, middle Paleozoic poles from Northern Alaska should be displaced significantly from North American cratonic poles of the same age. Their sample localities in Devonian, Mississippian, and Permian sedimentary rocks spanned the entire east-west extent of the Brooks Range, a distance of 1,000 km. Preliminary analysis of this large body of data supported the argument for large-scale counterclockwise rotation of Arctic Alaska. However, our examination of their unpublished data left us unconvinced that the magnetization measured was of Paleozoic age.

Our independent study overlaps part of the region that was investigated by Newman and his coworkers but does not extend west of the southern apex of the National Petroleum Reserve in Alaska (NPRA). Our samples are largely from Upper Devonian clastic rocks, though a few are from Mississippian limestone. The study encompasses 15 sites with significantly different bedding attitudes; the diversity of orientation permits us to apply a fold test to the magnetic-pole data. The distribution of Mississippian paleomagnetic poles (before being corrected for tilt of the bedding) clusters about the Cretaceous pole for central North America. The bedding corrections move the Mississippian poles into the equatorial Pacific but increase the overall dispersion of the poles. The increased dispersion suggests that the rocks retain a postdeformational magnetic overprint, despite being treated in alternating fields (AF) to remove unstable magnetizations.

ACKNOWLEDGMENTS

We thank W.P. Brosgé, H.N. Reiser, and J.T. Dutro, Jr., for providing logistic and geologic guidance; T.E. Moore and D.M. Orchard for help with the fieldwork; and Kathy Pagan, Gordon Thrupp, and Eugene Yates for their assistance in the laboratory. We are indebted to C.G. Mull for sharing with us his maps and paleomagnetic data in advance of publication.

GEOLOGY

The Brooks Range is interpreted to be an eroded stack of thrust sheets that structurally overlies the autochthonous terrane of Arctic Alaska (Mull and others, 1976). Although the autochthon is buried by a thick cover of younger sedimentary rocks, its Paleozoic stratigraphy is known from numerous

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drill holes on the North Slope. Thin slices of these Paleozoic rocks are exposed in the thrust sheets of the northern Brooks Range. In particular, our study concerns Upper Devonian and Lower Mississippian(?) clastic rocks of the Endicott Group and Mississippian limestone of the overlying Lisburne Group, which are mapped along the entire length of the Brooks Range. Sedimentology and stratigraphy of the Endicott Group are described by Nilsen and others (1980). The Endicott Group consists of the Upper Devonian marine Hunt Fork Shale, fluvial and shallow-marine deposits of the Upper Devonian and Lower Mississippian(?) Kanayut Conglomerate, and the fluvial Kekiktuk Conglomerate and the marine Kayak Shale, both Mississippian in age. The Kayak is conformably overlain by limestone of the Lisburne Group, of Mississippian and Pennsylvanian age.

PALEOMAGNETIC RESULTS

Oriented cores were drilled from outcrops near Arctic Village (sites 1, 2), Anaktuvuk Pass (sites 3-7), and the Lisburne Test Well (sites 8-15). The sites are distributed in a narrow zone that extends 450 km along the continental divide (fig. 27.1). Our sampling was concentrated in the Kanayut Conglomerate in conjunction with geologic and sedimentologic studies by W.P. Brosgé, H.N. Reiser, J.T. Dutro, Jr., and T.H. Nilsen. In addition, we sampled four sections of limestone in the Lisburne Group near Kurupa Lake.

KANAYUT AND KEKIKTUK(?) CONGLOMERATES

The paleomagnetism of the Upper Devonian and Lower Mississippian(?) rocks was studied in 384 oriented cores from 11 stratigraphic sections (table 27.1). We restricted our sampling to siltstone and sandstone members of the Kanayut Conglomerate, although site 1 may be in the Lower Mississippian Kekiktuk Conglomerate (the stratigraphic correlation of this site remains uncertain, but its strata undoubtedly underlie the Kayak Shale). In general, the sandstone beds form prominent, dark-gray ledges that provide excellent exposures. The resistant sandstone consists largely of quartz and chert grains cemented by overgrowths of silica. Subordinate constituents include lithic fragments of argillite and quartzite. At several sites, resistant sandstone is interbedded with highly fractured red shale; this shale yielded very few cores because of its fissility and poor exposure.

The sedimentary rocks have natural remanent magnetization (NRM) that ranges in intensity from 10^{-5} to 10^{-1} A/m, clustering about

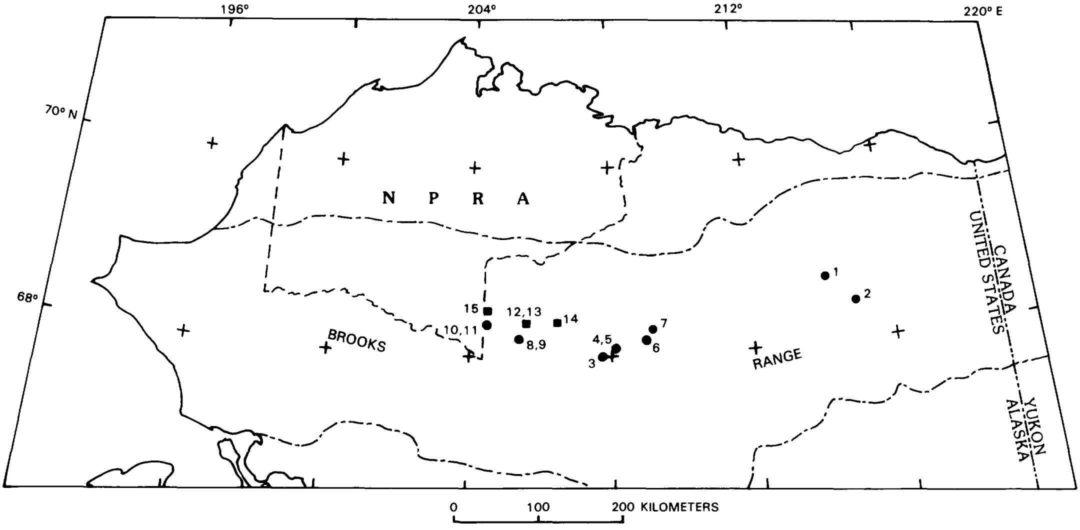

FIGURE 27.1.—Sampling sites for paleomagnetic study of the Kanayut Conglomerate (circles) and limestone of the Lisburne Group (squares), northern Alaska. Site numbers keyed to tables 27.1 and 27.2.

TABLE 27.1.—*Description of paleomagnetic sites in the Brooks Range, Alaska*

Site	Location		Rock section		Bedding attitude (degrees)	
	N. lat	E. long	Thickness (m)	Description	Strike	Dip
Kanayut Conglomerate (Upper Devonian and Lower Mississippian?)						
1[1]	68.68	214.10	100	Interbedded sandstone and siltstone	92	24 N.
2	68.40	214.95	75	Interbedded sandstone and red shale	85	50 S.
3	68.00	207.67	15	Crossbedded sandstone interbedded with siltstone	30	7 W.
4	68.08	208.10	200	Interbedded sandstone, siltstone, and conglomerate	96.5	83 S.
5	68.08	208.13	50	Crossbedded sandstone interbedded with shale and conglomerate	75	25 S.
6	68.19	209.07	40	Crossbedded sandstone interbedded with shale and conglomerate	65	30 S.
7	68.29	209.20	8	Interbedded siltstone and sandstone	96	21.5 S.
8	68.20	205.37	12	Sandstone	76	39 S.
9	68.22	205.37	52	Sandstone and shale interbedded with pebble conglomerate	90.5	43.5 S.
10	68.32	204.47	2	Crossbedded sandstone	69	39 N.
11	68.32	204.47	136	Crossbedded sandstone	80	72 N.
Lisburne Group (part) (Mississippian)						
12	68.36	205.58	5	Limestone with chert beds and nodules	65	47 N.
13	68.36	205.58	87	Limestone with chert beds	95	44 S.
14	68.38	206.38	21	Limestone with chert beds and nodules	161	24 E.
15	68.47	204.50	16	Limestone with chert nodules	165	8 W.

[1] Correlation uncertain; site may be in Lower Mississippian Kekiktuk Conglomerate of Endicott Group.

10^{-3} A/m (fig. 27.2*A*). Within stratigraphic sections, the magnetic directions of the weakly magnetized specimens generally showed large angular dispersion about a steep, downward mean direction. Precision parameters of NRM directions ranged from 1 to 43 (Fisher, 1953).

Approximately 25 percent of the specimens were progressively demagnetized in alternating fields up to 100 mT in a shielded fixed-specimen apparatus. We employed vector diagrams (Zijderveld, 1967) and plots of difference vectors to analyze successive changes in magnetic direction produced by the demagnetization treatments. The results of the AF demagnetization fall into three groups, as shown by representative intensity curves (fig. 27.3). Most specimens (fig. 27.3*A*) lost more than 50 percent of their NRM in alternating fields of less than 10 mT and showed erratic directional changes in fields above 30 mT. The curves in figure 27.3*B* are typical of the second group, which exhibits only minor changes in direction and intensity in fields above 50 mT. The most stable specimens, making up the third group (fig. 27.3C), retain at least 50 percent of their NRM in fields up to 50 mT; all the red shale specimens fall into this category. On the basis of demagnetization results from this group of samples, we identified the AF strength that produced characteristic (stable-endpoint) magnetization of each core and partially demagnetized the remaining cores from each section at that field setting, which ranged from 10 to 30 mT (table 27.2). Magnetic vectors removed by the cleaning treatment were directed along the recent geomagnetic field, as would be expected of an overprint of viscous remanent magnetization. For most samples, AF cleaning decreased the directional dispersion compared to the dispersion of NRM vectors, although angular standard deviations remained rather large (>25°) for half of the sites (table 27.2).

Before applying the cleaning treatment to the entire collection, we thermally demagnetized several specimens at temperature steps up to 660 °C. The samples were heated in air in a shielded furnace with an internal field of less than 10 nT. The specimens chosen for these experiments were untreated specimens taken from the same cores used for the AF demagnetization. Heating to 400 °C typically reduced the intensity of magnetization by 90 percent for specimens that exhibited low resistance to AF demagnetization. We observed sharp increases in intensity and erratic directional changes when the samples were heated above 500 °C. This spurious remanence is probably thermoremanent magnetization (TRM) acquired in the furnace by newly formed magnetite. Since irreversible chemical changes apparently occurred during heating, the thermal properties of the NRM of these specimens could not be investigated fully. On the other hand, the extremely stable specimens of group 3, such as the red shale samples, did not show erratic directional changes until heated above 650 °C. Sharp drops in the intensity of magnetization near 575 and 650 °C, suggest that a mixture of magnetite and hematite is present in the samples of group 3.

Finally, we measured the acquisition of isothermal remanent magnetization (IRM) to test the magnetic mineralogy of the Devonian and Mississippian(?) sedimentary rocks. IRM was produced by a 10-cm electromagnet with a maximum field strength of 0.7 T. Demagnetized specimens used in the AF experiments were selected for the IRM acquisition curves (fig. 27.3). According to Dunlop (1972), IRM curves that reach saturation near 0.1 T indicate the presence of magnetite, whereas curves that reach saturation above 0.3 T indicate fine-grained hematite. Our IRM curves show that proportions of magnetite and hematite vary in the Devonian and Mississippian(?) sedimentary rocks. As expected, the group 3, high-stability specimens give curves characteristic of hematite. Specimens characterized by low resistance to AF demagnetization (group 1) reach 95 percent of their maximum IRM in fields below 0.2 T, implying that the IRM and NRM are carried predominantly by magnetite grains. We also observed hybrid IRM curves corresponding to mixtures of hematite and magnetite (group 2). Each of these curves has a plateau or inflection point near 0.2 T but is not saturated below 0.7 T.

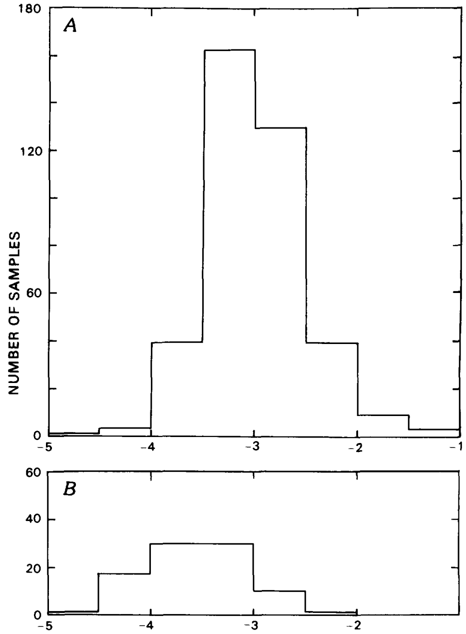

FIGURE 27.2.—Logarithmic distribution of natural remanent magnetization (NRM) intensities for the Kanayut Conglomerate (*A*) and limestone of the Lisburne Group (*B*).

The stepwise demagnetization experiments indicate that fine-grained hematite and magnetite contribute to the NRM of the Devonian and Mississippian(?) rocks. Comparing magnetite-dominated specimens with those dominated by hematite, we found no significant differences in magnetic direction within a given site. We conclude that the two minerals acquired their magnetization simultaneously.

As a first step toward determining the age of magnetization, we tested whether the remanence originated before the Devonian and Mississippian(?) rocks were deformed. The fold test compares the angular dispersion of virtual geomagnetic poles (VGP) before and after the results are corrected for tilt of the bedding. If the magnetization predates deformation, then application of the tilt corrections will decrease the angular dispersion of VGP's, provided that all corrections are not similar. Our 11 stratigraphic sections have sufficiently different structural attitudes to provide a significant fold test. The tilt corrections drastically increase the angular dispersion of the VGP's from these sections (fig. 27.4; table 27.3). We conclude that the characteristic magnetization postdates Cretaceous deformation of the Brooks Range; no trace of primary depositional remanence remains. Averaging the 11 site VGP's that were calculated before tilt corrections were made gives an overall mean paleomagnetic pole at lat 59° N., long 197° E. (α_{95} = 12°), in the southeastern Bering Sea.

LISBURNE GROUP

Mississippian limestone was sampled at four sites (totaling 103 cores) near the southeastern boundary of the NPRA (table 27.1). In that region, the Lisburne Group crops out in a thin thrust sheet that structurally underlies klippen of Upper Devonian sedimentary rocks to the south. The pale-gray limestone is coarsely crystalline and free of silty or sandy detritus. Dissolution surfaces and dark-gray chert beds (0.5-3 m thick) give the formation a banded appearance. Silicified reef-forming corals are abundant at sites 12, 13, and 14. During the coring, we avoided the chert beds and nodules, which were too hard for the drill bit to penetrate.

The limestone has NRM intensities averaging 5×10^{-4} A/m, about 10 times weaker than the mean NRM of the Devonian and Mississippian(?) rocks (fig. 27.2*B*). NRM directions for two sites (13, 14) were tightly clustered about two steeply inclined mean directions in the southwest quadrant; the remaining sites gave widely dispersed directions. One-fourth of the specimens were thermally demagnetized in eight steps to a peak temperature of 550 °C. In general, heating of the limestone to 450 °C removed 95 percent of the initial remanence (fig. 27.5). Heating the specimens beyond 500 °C produced erratic directional changes as the specimens acquired spurious TRM.

By observing the successive changes of magnetic direction during the thermal experiments, we could assess the magnetic stability of each site and could prescribe the appropriate cleaning treatment. Directional changes of samples from sites 12 and 15 were erratic during thermal demagnetization and failed to isolate stable, characteristic magnetizations. Therefore, the internally inconsistent results for these two sites are omitted from further discussion. In contrast, a group of samples from sites 13 and 14 attained stable characteristic magnetizations at temperatures above 200 °C. This group making up 25 percent of the samples, indicated that characteristic magnetizations are obtained between the 200 and 450 °C heatings, so we heated the remaining untreated specimens from sites 13 and 14 to 400 °C and then to 425 °C. Results from the 400 °C treatment, which minimized the directional

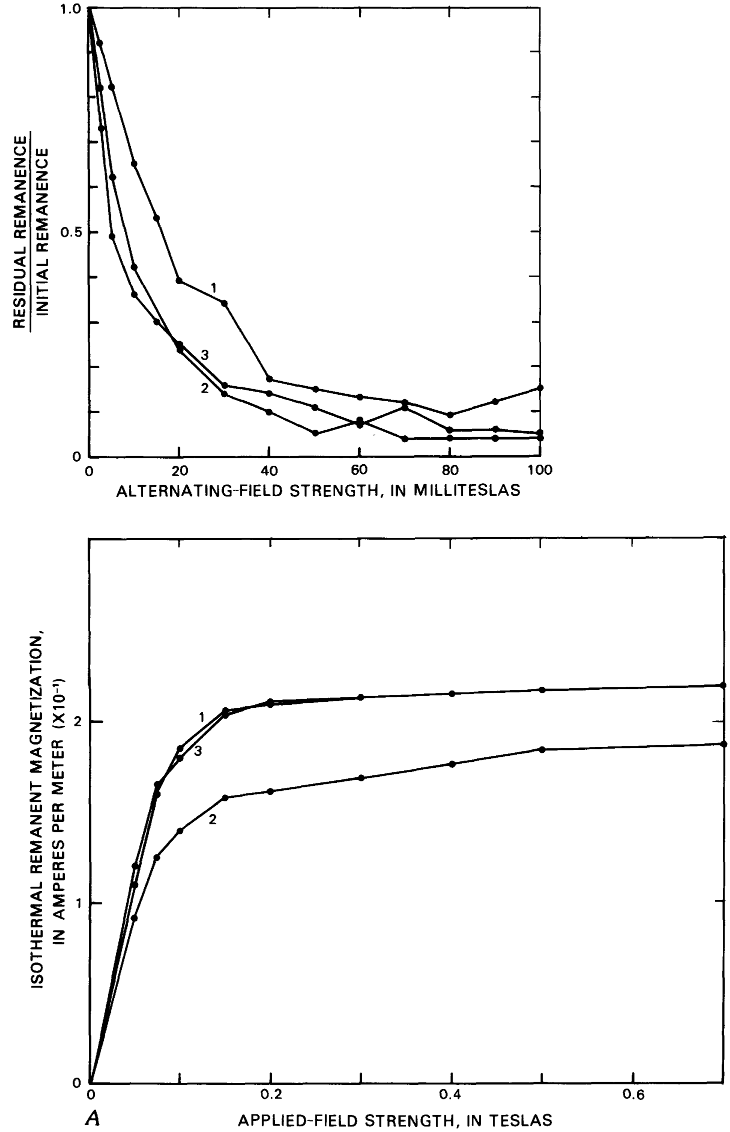

FIGURE 27.3.—Alternating-field demagnetization of NRM (upper diagram) compared with acquisition of isothermal remanent magnetization (IRM) (lower diagram) for representative specimens from the Kanayut Conglomerate, grouped according to common magnetic mineralogy. Shapes of IRM curves indicate dominance of magnetite (*A*), magnetite-hematite mixtures (*B*), and hematite (*C*).

dispersion, are shown in fig. 27.6 and listed in table 27.2. Five representative specimens were demagnetized in alternating fields up to 100 mT. Results of the AF demagnetization generally mimic the pattern of thermal demagnetization.

After thermal cleaning, the two stable sites gave significantly different mean directions, which became more divergent when the bedding corrections were made (fig. 27.6). Two sites do not constitute a statistically significant fold test; however, the large divergence of mean directions suggests that not all of the magnetization was acquired during formation of the limestone. In fact, two magnetic components, presumably acquired at different times, are apparent. Before thermal cleaning, the characteristic magnetization of site 13 is overprinted by a steep, southwestern component similar to the uncorrected magnetic direction of site 14. Applying bedding corrections to the overprint of site 13 and the mean direction of site 14 increased the angular difference between the means. Therefore, the steep component appears to be a post-deformational overprint, similar to the magnetization in the Upper Devonian and Lower Mississippian(?) sedimentary rocks (table 27.2). Whether the characteristic magnetization of site 13 originated during formation of the limestone remains open to debate until supporting evidence is obtained from a definitive fold test.

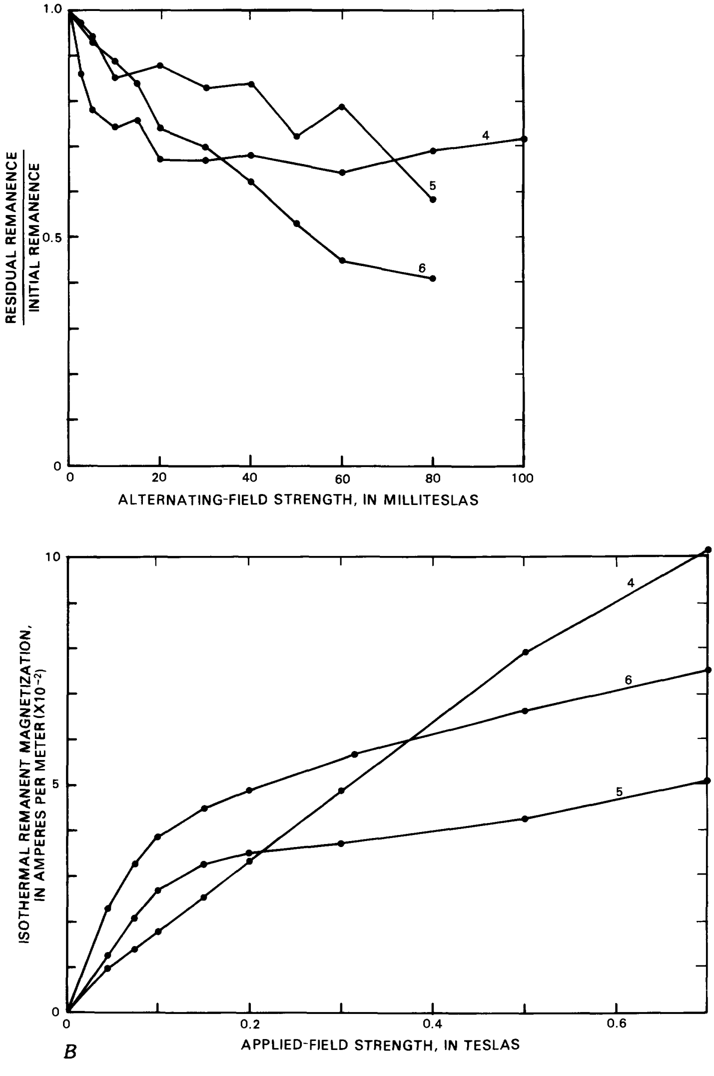

FIGURE 27.3.—Continued

Acquisition of IRM was measured for the five AF-demagnetized limestone specimens (fig. 27.7). The flattening of IRM curves near 0.2 T indicates that magnetite is the dominant magnetic mineral in the limestone (Dunlop, 1972). This result, together with demagnetization curves of low coercivity and blocking temperatures below 450 °C (fig. 27.5), indicates that the NRM is carried by magnetite.

DISCUSSION

In the central Brooks Range (Killik River, Chandler Lake, and Arctic 1:250,000-scale quadrangles), sedimentary rocks have apparently lost their Paleozoic magnetic signatures. The original remanence has been replaced by a normally polarized magnetic overprint that postdates or is contemporaneous with the Cretaceous orogeny of the Brooks Range, the final stages of which occurred in Albian time (Mull, 1979). When compared to the reference curve for North American apparent polar wander (Irving, 1979), the paleomagnetic pole corresponding to the overprint implies a Cretaceous age of remagnetization (fig. 27.8). Of course, assigning ages on the basis of paleomagnetic pole positions is a dubious practice in tectonically active regions such as Alaska. However, isotopic evidence from the southern Brooks Range indicates that a thermal event occurred in the Cretaceous and supports an Early Cretaceous age of remagnetization: Plutonic rocks in the southern Brooks Range generally give K-Ar ages of 130-100 Ma (Turner and others, 1979), but Pb-isotopic ages indicate that the plutons originated much earlier, approximately 375 Ma (Dillon and others, 1980). The resetting of the K-Ar system is attributed to a Cretaceous thermal event, probably related to thrusting in the Brooks Range. In addition, the onset of argon retention overlaps the Cretaceous normal polarity epoch (110-81 Ma; Irving and Pullaiah, 1976); correlation of the two events may account for the normal polarity of the overprint.

If we ascribe the remagnetization of these rocks to a Cretaceous thermal event, it becomes necessary to examine the thermal history of our sampling localities in the northern thrust sheets. These localities are far north of the greenschist metamorphic zone of the southern Brooks Range (Dillon and others, 1980), where the regional heating was most intense. However, petrographic evidence indicates that rocks within the northern thrust sheets were slightly heated. Well-preserved textures and the absence of recrystallized minerals in our samples indicate that the maximum temperatures were no more than approximately 300 °C. In the Survey Pass quadrangle, 50 km south of sites 8-15, the color of conodonts in the Lisburne Group indicates heating to between 200 and 300 °C (Brosgé and others, 1981). Although conodont temperatures are not available from our sample localities, regional trends based on the Survey Pass study suggest that heating did not exceed 200 °C in the sampled area. Reflectance of vitrinite from Paleozoic shales in the Arctic quadrangle

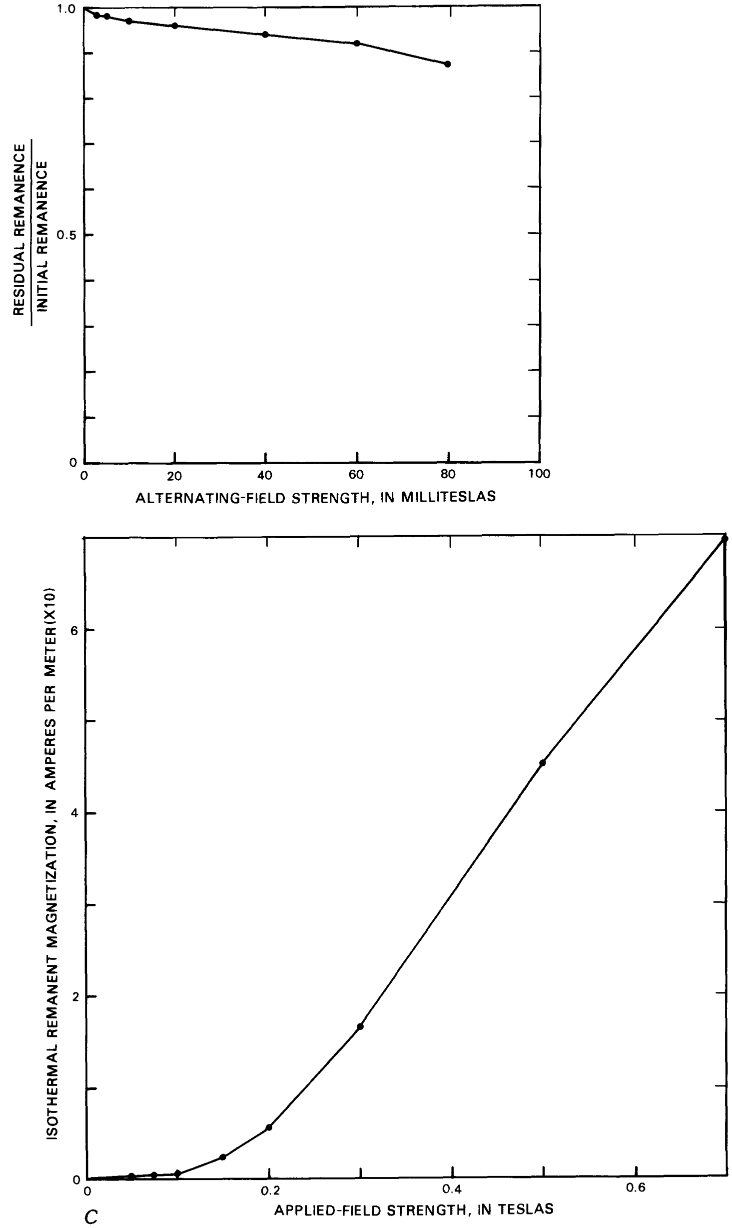

FIGURE 27.3.—Continued

TABLE 27.2.—*Paleomagnetic data from the Brooks Range, Alaska*

[N, number of specimens. Parameters of paleomagnetic directions: I, inclination; D, declination; R, length of resultant vector; k, precision; α_{95}, 95-percent confidence radius, in degrees; I_c and D_c, tilt-corrected values. Parameters of virtual geomagnetic poles: Θ, N. latitude; Ø, E. longitude; Θ_c and $Ø_c$, tilt-corrected values. Treatments: AF, alternating field, in mT; T, thermal, in degrees Celsius]

Site	N	I	D	R	k	α_{95}	Angular standard deviation	Θ	Ø	Treatment	Corrected for dip of bed			
											I_c	D_c	Θ_c	$Ø_c$
						Kanayut Conglomerate of the Endicott Group								
1[1]	93	86.6	335.5	65.8054	3	9.5	44.1	74.6	203.4	AF 10	62.9	358.6	65.6	36.4
2	25	69.1	255.5	20.7915	6	13.3	33.9	43.1	161.4	AF 10	33.8	200.0	-1.9	196.0
3	30	85.8	145.3	23.1992	4	14.5	39.2	60.7	217.5	AF 10	86.3	270.5	66.9	188.8
4	50	79.2	228.0	44.4692	9	7.2	27.2	51.1	183.2	AF 10	-1.1	193.6	-21.8	193.4
5	38	84.0	284.0	33.7503	9	8.4	27.5	67.9	176.0	AF 15	67.3	178.8	28.2	209.0
6	28	82.7	312.4	27.4591	50	3.9	11.5	74.1	167.1	AF 15	66.6	162.1	28.1	222.3
7	27	85.6	166.0	26.5992	65	3.5	10.1	59.8	213.4	AF 15	64.4	182.6	24.5	207.3
8	10	80.2	350.7	9.6888	29	9.1	15.1	85.7	160.5	AF 30	60.7	164.4	20.5	217.8
9	32	77.3	161.0	30.9926	31	4.6	14.6	44.6	216.2	AF 20	34.4	175.4	-2.8	209.7
10	4	74.7	189.4	3.9065	32	16.5	14.3	39.8	198.6	AF 20	63.2	321.7	59.3	84.1
11	47	69.8	160.9	43.8760	15	5.6	21.1	32.8	217.8	AF 20	37.9	354.0	42.8	32.2
						Limestone of the Lisburne Group								
12[2]	9	-	-	-	-	-	-	-	-	-	-	-	-	-
13	58	32.5	188.8	52.6480	11	6.0	24.8	-3.7	197.1	T 400	-11.4	188.3	-27.2	196.3
14	24	72.9	247.4	21.8171	11	9.6	25.0	45.9	162.4	T 400	83.0	79.7	66.7	242.8
15[2]	12	-	-	-	-	-	-	-	-	-	-	-	-	-

[1] Site 1 may be in Kekiktuk Conglomerate of the Endicott Group, but correlation remains uncertain.

[2] Thermal and AF treatment yielded unstable magnetic directions.

gives inferred paleotemperatures of approximately 200 °C near sites 1 and 2.

Such mild heating was capable of remagnetizing the Paleozoic sandstone and limestone, because the thermal stability of the original remanence was inherently low. Theoretically, magnetite domains with laboratory-determined blocking temperatures of 425 °C (as in the Lisburne Group limestones) will be demagnetized in nature if heated to 200 °C for 10 m.y. (Dunlop and Buchan, 1977). Hematite domains with blocking temperatures below 525 °C will be demagnetized under similar conditions in the natural environment. Once unblocked, the magnetic domains will become aligned with the ambient field. In addition, new carriers of magnetic remanence with high thermal stability will develop if chemical conditions favor the growth of authigenic hematite. These processes can account for the loss of original remanence and the growth of a magnetic overprint in these sedimentary rocks. The remagnetization process probably ceased when the formerly buried thrust sheets were uplifted and cooled as the southern allochthons were thrust over the autochthonous North Slope terrane (Mull, 1979).

CONCLUSION

Sandstone within the Upper Devonian and Lower Mississippian(?) Kanayut Conglomerate carries a weak remanent magnetism shared by magnetite and hematite grains. Vector diagrams from AF and thermal-demagnetization experiments indicate that the remanence constitutes a single component of magnetization. After AF cleaning (in fields of 10-30 mT), a fold test of specimens from the Kanayut and Kekiktuk(?) Conglomerates conclusively indicates a postdeformational age for the magnetic overprint. No vestiges of the Paleozoic depositional remanence were detected. The Mississippian limestone of the Lisburne Group has NRM carried by magnetite with blocking temperatures below 450 °C. With one exception, results for thermally cleaned (400 °C) specimens from the Lisburne sites are similar to the overprinted magnetic direction observed in the Kanayut and Kekiktuk(?) Conglomerates.

Inherently low thermal stability of the depositional remanence and heating during the Early Cretaceous orogeny of the Brooks Range are probably responsible for remagnetization of the Paleozoic sedimentary rocks. Our sampling indicates that the remagnetized rocks occur within the northern thrust sheets in a belt extending at least 450 km from Arctic Village westward to the southeast boundary of the NPRA. Although regional heating never exceeded 200 °C, the remagnetization is ubiquitous along the 450-km-long belt. Rapid uplift and cooling of the northern range front concomitant with underthrusting of the North Slope terrane may account for the simultaneous remagnetization of this immense region. An Early Cretaceous age for this event is supported by reset K-Ar ages in the southern Brooks Range and by the paleomagnetic pole position obtained from the magnetic overprint. Our results fail to prove or disprove the hypothetical rotation of Arctic Alaska and the rift origin of the Canada Basin, because the thermal disturbance created by the Brooks Range orogeny has destroyed the Paleozoic magnetic signature that is required to test the rotation hypothesis.

REFERENCES CITED

Brosgé, W.P., Reiser, H.N., Dutro, J.T., Jr., and Detterman, R.L., 1981, Organic geochemical data for Mesozoic and Paleozoic shales, central and eastern Brooks Range, Alaska: U.S. Geological Survey Open-File Report 81-551, 18 p.

Carey, S.W., 1958, The tectonic approach to continental drift, *in* Carey, S.W., ed., Continental drift, a symposium: Hobart, University of Tasmania, p. 177-355.

Churkin, Michael, Jr., and Trexler, J.H., Jr., 1980, Circum-Arctic plate accretion; isolating part of a Pacific plate to form the nucleus of the Arctic Basin: Earth and Planetary Science Letters, v. 48, no. 2, p. 356-362.

Dillon, J.T., Pessel, G.H., Chen, J.H., and Veach, N.C., 1980, Middle Paleozoic magmatism and orogenesis in the Brooks Range, Alaska: Geology, v. 8, p. 338-343.

Dunlop, D.J., 1972, Magnetic mineralogy of unheated and heated red sediments by coercivity spectrum analysis: Geophysical Journal Royal Astronomical Society, v. 27, no. 1, p. 37-55.

Dunlop, D.J., and Buchan, K.L., 1977, Thermal remagnetization and the paleointensity record of metamorphic rocks: Physics of Earth and Planetary Interiors, v. 13, no. 4, p. 325-331.

Eardley, A.J., 1948, Ancient Arctica: Journal of Geology, v. 56, p. 409-436.

Fisher, R.A., 1953, Dispersion on a sphere: Royal Society of London Proceedings, ser. A, v. 217, p. 295-305.

Irving, Edward, 1979, Paleopoles and paleolatitudes of North America and speculations about displaced terrains: Canadian Journal of Earth Sciences, v. 16, p. 669-694.

Irving, Edward, and Pullaiah, G., 1976, Reversals of the geomagnetic field, magnetostratigraphy, and relative magnitude of paleosecular variation in the Phanerozoic: Earth-Science Reviews, v. 12, p. 35-64.

Mull, C.G., 1979, Nanushuk Group deposition and the Late Mesozoic structural evolution of the central and western Brooks Range and Arctic Slope, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 5-13.

Mull, C.G., Tailleur, I.L., Mayfield, C.F., and Pessel, G.H., 1976, New structural and stratigraphic interpretations, central and western Brooks Range and Arctic Slope, *in* Cobb, E.H., ed., The United States Geological Survey in Alaska; accomplishments during 1975: U.S. Geological Survey Circular 733, p. 24-26.

Newman, G.W., Mull, C.G., and Watkins, N.D., 1979, Northern Alaska paleomagnetism, plate rotation, and tectonics, *in* Sisson, Alexander, ed., The relationship of plate tectonics to Alaskan geology and resources: Anchorage, Alaska Geological Society Symposium, 6th, Proceedings, p. 16-19.

Nilsen, T.H., Moore, T.E., Dutro, J.T., Jr., Brosgé, W.P., and Orchard, D.M., 1980, Sedimentology and stratigraphy of the Kanayut Conglomerate and associated units, central and eastern Brooks Range, Alaska; report of 1978 field season: U.S. Geological Survey Open-File Report 80-888, 80 p.

Tailleur, I.L., 1973, Probable rift origin of Canada Basin, Arctic Ocean, *in* Pitcher, M.G., Arctic geology: American Association of Petroleum Geologists Memoir 19, p. 526-535.

Turner, D.L., Forbes, R.B., and Dillon, J.T., 1979, K-Ar geochronology of the southwestern Brooks Range, Alaska: Canadian Journal of Earth Sciences, v. 16, p. 1789-1804.

Zijderveld, J.D.A., 1967, A.C. demagnetization of rocks; analysis of results, *in* Collinson, D.W., Creer, K.M., and Runcorn, S.K., eds., Methods in paleomagnetism: Amsterdam, Elsevier (Developments in Solid Earth Geophysics, v. 3), p. 254-286.

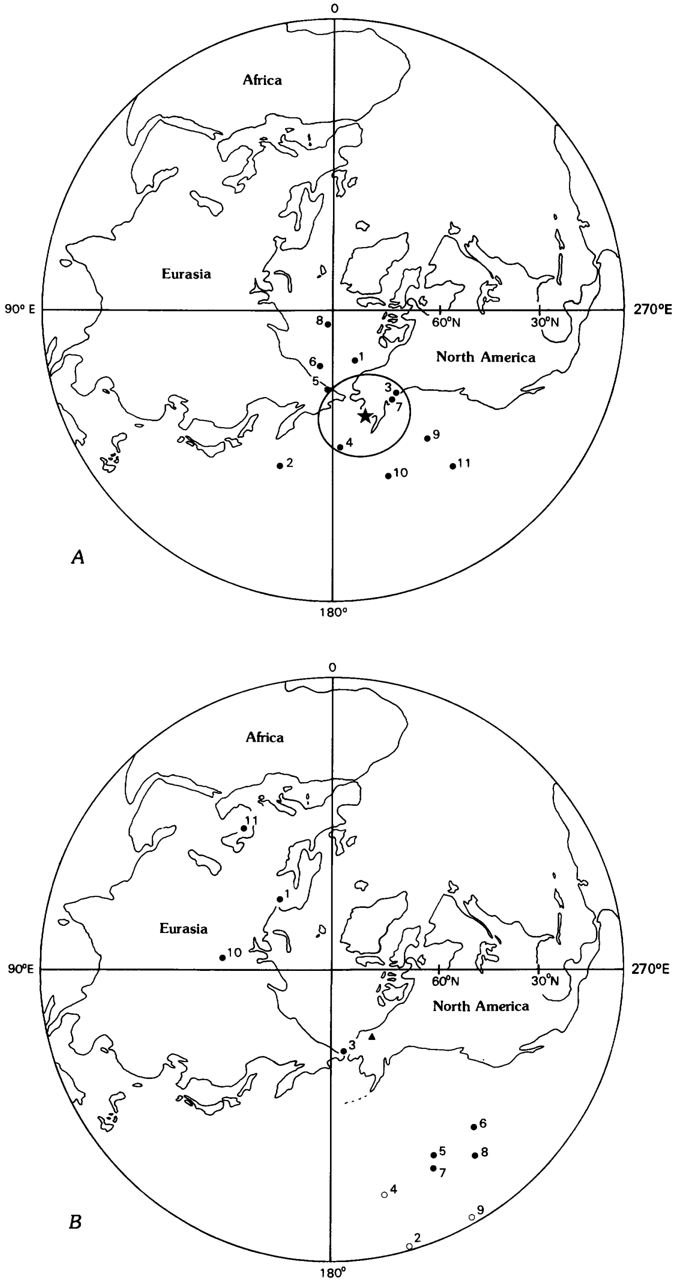

FIGURE 27.4.—Equal-area polar projection of virtual geomagnetic poles (VGP's) from the Kanayut Conglomerate, showing distribution before (*A*) and after (*B*) tilt corrections. Dots, northern hemisphere; circles, southern hemisphere. Mean magnetic pole (star) shown with its 95-percent-confidence limit. Triangle, mean of sample sites.

TABLE 27.3.—*Mean paleomagnetic poles for Kanayut Conglomerate*

[N, number of sites. Parameters of virtual geomagnetic poles: Θ, mean latitude; Ø, mean longitude; A_{95}, 95-percent confidence radius; K, precision]

	N	Θ	Ø	A_{95} (degrees)	K
In place	11	59° N.	197° E.	12	16
Corrected for tilt	11	40° N.	201° E.	36	3

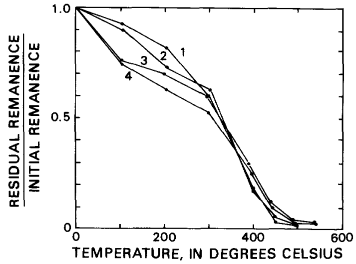

FIGURE 27.5.—Thermal demagnetization of representative specimens from limestone of the Lisburne Group. Example 1, site 12; 2, site 13; 3, site 14; 4, site 15.

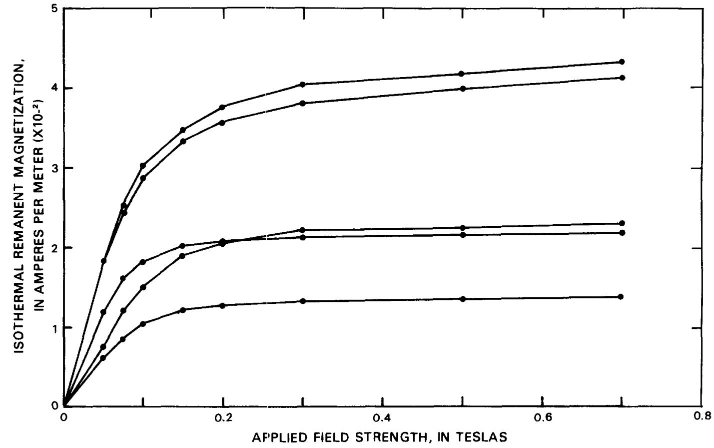

FIGURE 27.7.—IRM acquisition curves for representative specimens from limestone of the Lisburne Group, indicating magnetite (sites 13 and 14; see table 27.2).

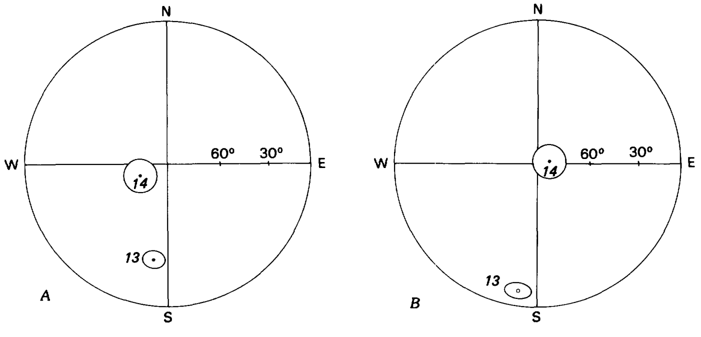

FIGURE 27.6.—Equal-area projection of mean magnetic directions and 95-percent-confidence circles from two sites in the Lisburne Group before (*A*) and after (*B*) application of tilt corrections. Dots, positive inclination; circles, negative inclination.

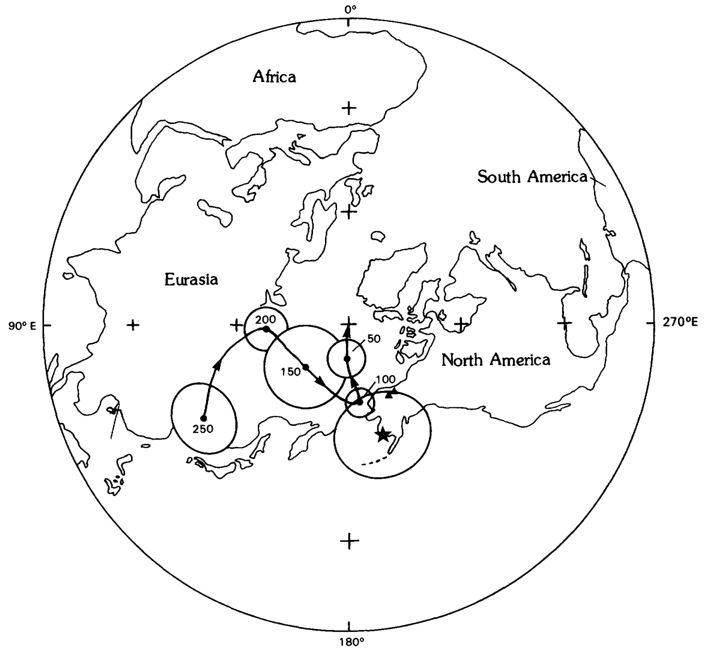

FIGURE 27.8.—Comparison of overprinted virtual geomagnetic pole (star) from the Kanayut Conglomerate with curve of North American apparent polar wander; numbers are ages (in Ma) of points at 50-Ma intervals on the curve (dots). Also shown are 95-percent-confidence circles for paleomagnetic poles. Sample sites in northern Alaska indicated by triangles.

28. TEMPERATURE AND DEPTH OF PERMAFROST ON THE ARCTIC SLOPE OF ALASKA

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INTRODUCTION

The temperature and depth of permafrost in Arctic sedimentary basins are of considerable importance in connection with petroleum exploration and production, but there is much confusion and surprisingly little information about them. They are important because a knowledge of the temperature field is needed for an understanding of the state of the material (water, ice, brine, and gas hydrates) filling pores in the sediment; this understanding, in turn, is important for the interpretation of seismic surveys and for dealing with engineering problems associated with well completions and the production, storage, and transportation of petroleum. Permafrost conditions are a source of confusion largely for semantic reasons. To many investigators, "permafrost" is identified with material containing ice, and this has led to estimates of "permafrost depth" from a variety of surface and downhole geophysical measurements based on inferences of the effect of such ice on the particular property (mechanical or electrical) being measured. Although much of the interest in permafrost depends upon the presence or absence of ice, this casual usage has led to "permafrost" meaning different things to different people, depending on their method of measurement. To avoid this confusion between definition and physical inference, permafrost was initially defined by its (negative centigrade) temperature (Muller, 1947). Consequently, there is only one way to determine the depth of permafrost and that is to measure temperatures in an undisturbed borehole that penetrates it. The reason so little information is available on the temperature and depth of permafrost is that holes drilled by the petroleum industry do not generally remain idle and accessible for precision temperature logging during the long times required for the thermal disturbance caused by drilling to dissipate.

Osterkamp and Payne (1981) estimated the maximum depth of ice-bearing sediments in 150 wells in Arctic Alaska from inspection of well logs; they confirmed their estimation method by comparison with equilibrium temperatures available for some of the wells (Lachenbruch and others, 1982a, b). The product is a useful "tentative map of the thickness of ice-bearing permafrost on the North Slope of Alaska," mostly in the region east of the National Petroleum Reserve in Alaska (NPRA). They were careful to make the distinction between "ice-bearing permafrost" and "permafrost," and they discussed the uncertainties in determining whether or not ice is present from various types of well-log data. Osterkamp and Payne concluded that in coarse-grained ice-rich material of the type characteristic of the Prudhoe Bay area, the base of ice-bearing strata can be detected from (nonthermal) logs without difficulty, but in the finer grained sediments generally found to the west in the NPRA, it cannot. This is consistent with our findings from the two areas. In any case, however, a knowledge of undisturbed temperature is necessary for confirmation of these largely empirical depth estimates and for an understanding of the physical conditions controlling the occurrence of the ice, fluids, and gas hydrates near the base of ice-bearing sediments and elsewhere.

A rare opportunity to obtain undisturbed temperatures in permafrost was provided through the efforts of our colleagues in the USGS' Office of National Petroleum Reserve, Alaska (ONPRA). During the course of exploratory drilling in the NPRA, 21 of the wells were completed according to a special procedure in which the upper 600 m was filled with a nonfreezing fluid (diesel oil) and preserved in a condition that permits subsequent reentry for precision temperature logging. Through the courtesy of the Mobil, Exxon, BP, Sinclair, and

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TABLE 28.1.—*Permafrost data from wells on the Alaskan Arctic Slope*

[Numbered columns referred to in text. For explanations of permafrost terms, see text. Figures for bottom of ice-rich layer are depth below surface. (e), values derived by extrapolation; (u), uncertain estimate; ?, doubtful determination; n.d., none detected. Partial data only for the 5 wells from the previous studies]

Well	Symbol	Location			Well data		Permafrost data					
					Drilling duration (d)	Logs	Last log		Equilibrium condition			Bottom of ice-rich layer (m)
		N. lat (degrees)	W. long (degrees)	Elevation (m)			τ	$\Delta\theta$ (°C)	θ_o(e) (°C)	z^* (m)	Γ^* (°C/km)	
					1	2	3	4	5	6	7	8
Tulageak	TUL	71.19	155.73	3	21	3	49	0.1	-12.5(u)	305	42	n.d.
West Dease	WDS	71.15	155.62	2	36	4	44	.1	-12.0	280	44	260
J.W. Dalton	JWD	70.92	153.14	6	86	4	21	.2	-12.1(u)	410	30	310?
North Inigok	NIN	70.26	152.77	41.5	50	2	31	.2	-10.5(u)	285	37	n.d.
Tunalik	TLK	70.20	161.07	26	423	4	3.9	.8	-10.4(u)	290	36	n.d.
Peard Bay	PEA	70.71	159.00	23	76	5	26	.2	-10.3	310	33	270
Kugrua	KUG	70.59	158.66	20	106	4	21	.3	-10.7	282	38	250?
South Meade	SME	70.61	156.89	12	349	5	5.8	.3	-10.2(u)	200	50	160
Kuyanak	KUY	70.26	156.06	3	41	3	27	.2	-10.9	330	33	n.d.
East Simpson 1	ESN	70.92	154.62	4	50	5	40	.1	-11.0	370	30	280
Ikpikpuk	IKP	70.45	154.33	10	458	4	3.6	.3	-10.6(u)	340	30	280?
Drew Point	DRP	70.87	153.89	4	59	5	40	.1	-11.1	325	34	250
East Teshekpuk	ETK	70.57	152.94	2	60	4	50	.1	-11.5(u)	265	43	n.d.
North Kalikpik	NKP	70.51	152.37	6	46	5	50	.1	-11.3	215	53	n.d.
Fish Creek 1	FCK	70.32	152.06	28	72	6	37	.2	-11.8	260	45	140
South Harrison Bay	SOH	70.42	151.73	7	79	6	35	.2	-11.4	375(e)	30	n.d.
Atigaru Point	ATI	70.55	151.72	2	65	6	42	.1	-10.8	405	27	330
Awuna	AWU	69.15	158.02	336	415	3	2.9	.9	-9.0	295	31	n.d.
Lisburne	LBN	68.48	155.68	556	357	4	4.3	.6	-6.3	290	22	n.d.
Koluktuk	KOL	69.75	154.61	56	23	3	46	.1	-9.3	290(e)	32	n.d.
Seabee	SBE	69.37	152.17	89	289	4	5.7	.5	-8.9(u)	310	29	n.d.
[1] Sinclair/BP Kuparik 1	KK1	69.30	150.81	190	207	1	6.2	.5	-8.8(u)	300	28	n.d.
[1] Forest Oil Lupine 1	LUP	69.10	148.62	524	309	3	7.5	.4	-4.6	240	19	n.d.
[1] Mobile Echooka	EB1	69.40	147.27	200	160	3	20	.2	-6.6	280	24	260
[1] Exxon Canning River	CNR	69.60	146.36	282	107	4	24	.2	-8.3	282	29	n.d.
[2] South Barrow 3	SB3	71.16	156.58	9					-12.2	404(e)	30	n.d.
[3] Cape Thompson D	CTD	68.11	165.74	23					-7.1	356	20	n.d.
[4] Simpson 28	S28	70.99	154.67	3					-12.1(u)	280	43	n.d.
[5] Umiat 9	UM9	69.39	152.77	122					-8.6(u)	356(e)	24	n.d.
[5] Topagoruk 1	TPK	70.62	155.89	9					-10.2(u)	315	32	n.d.

[1] Outside the NPRA.
[2] From Lachenbruch and Brewer (1959).
[3] From Lachenbruch and others (1966)
[4] From Brewer (1958).
[5] M.C. Brewer, unpublished data.

Forest Oil Companies, four other wells on the Alaskan North Slope were preserved for our use in a similar condition. We have relogged these 25 wells several times over a period of years, and most are now close to thermal equilibrium. In this chapter, we present a brief summary of results of these observations, along with similar results obtained previously from a few other North Slope wells. They are compared with results from a study of permafrost conditions near Prudhoe Bay, Alaska (Lachenbruch and others, 1982b). This chapter supersedes an earlier report (Lachenbruch and others, 1982a) based on interim temperature observations.

ACKNOWLEDGMENTS

We are grateful to George Gryc for his efforts in arranging for the special hole completions that made the NPRA measurements possible, and to David Blanchard and Irvin Tailleur for discussions of their unpublished tabulations of temperatures obtained at great depths in some of the NPRA holes. We also thank the late Reuben Kachadoorian for a helpful review of our preliminary manuscript, and Fred Grubb and Greg Eiche for their assistance in obtaining some of the temperature data upon which this work is based.

BASIC THERMAL DATA FROM NORTH SLOPE WELLS

Some basic information from each of the 25 holes observed in this study and 5 from previous studies is summarized in table 28.1. The locations of the sites are shown in figure 28.1; of the new holes, 21 are in the NPRA and 4 are in the

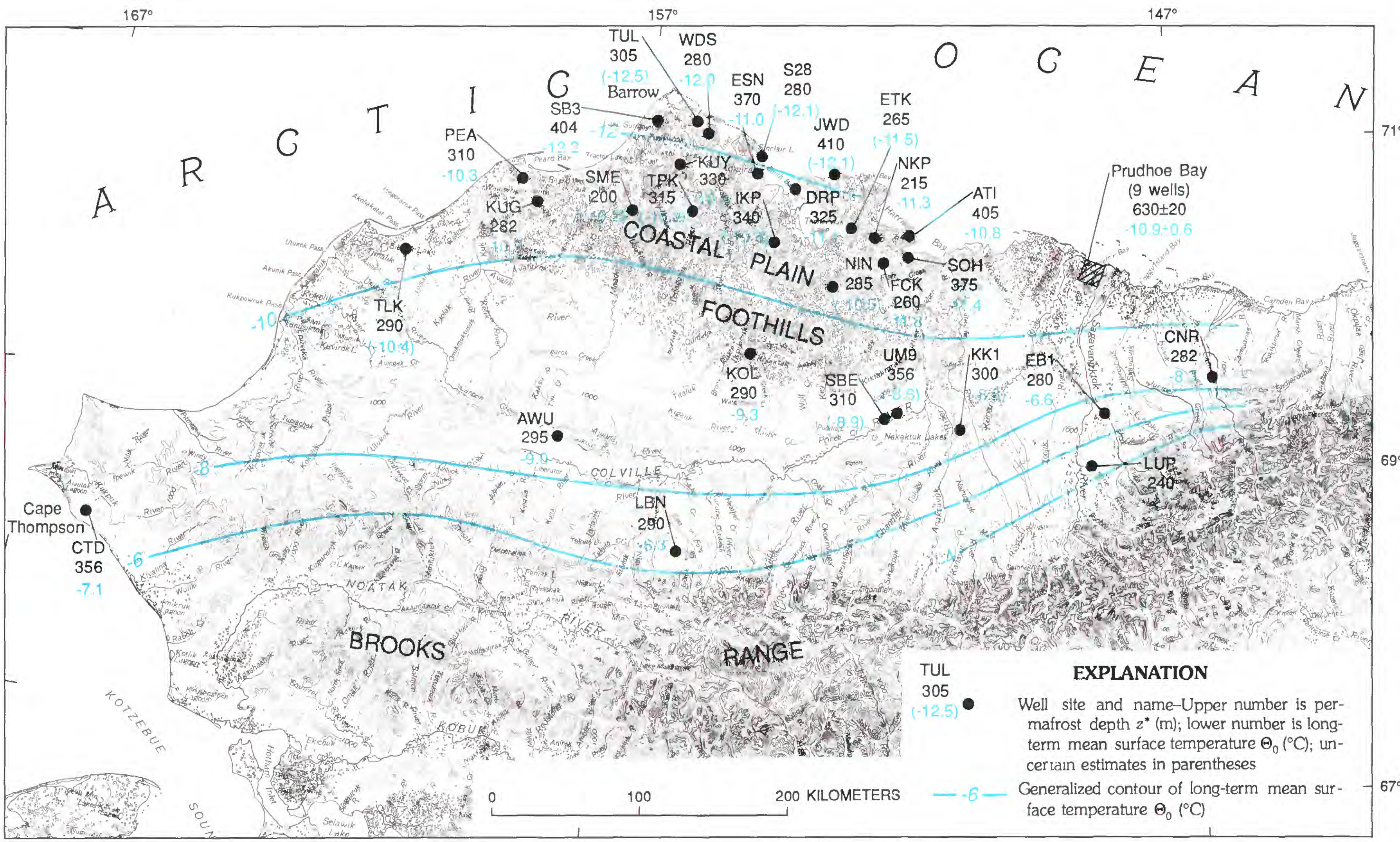


FIGURE 28.1.—Northern Alaska showing well locations, permafrost depth z^* (m) and estimated long-term mean surface temperature θ_0 (°C) for each well, and generalized contours of θ_0. For names of wells and other data see table 28.1.

foothills of the Brooks Range to the east. All of the holes were completed without a surface plug and with the portion of the casing in permafrost filled with diesel oil to prevent refreezing. This made it possible for us to relog them at convenient intervals to trace the dissipation of the drilling disturbance and the reestablishment of natural formation temperatures. Temperature measurements were made at depth intervals of 0.3-3.0 m with a multiconductor cable and thermistor thermometer having a precision better than 0.01 °C (the "portable mode" described by Sass and others, 1971). Owing largely to convective fluid motion in the borehole, the reproducibility is generally considerably worse (±0.05 °C). The number of logs made in each hole to date is shown in column 2 of table 28.1.

A sample of the data is shown in figure 28.2 for the site at Awuna (AWU) in the southern foothills (fig. 28.1). The duration of the drilling disturbance (that is, the period between the start of drilling and the final cessation of circulation) is denoted by s and given in column 1 of table 28.1; for the example in figure 28.2, s was 415 d.

The dissipation of the drilling disturbance depends on the ratio of the time elapsed since completion of the disturbance, t, to the duration of the disturbance, s. This ratio or dimensionless time we denote by τ:

$$\tau = t/s \qquad (1)$$

For the three successive logs illustrated in figure 28.2, τ ranged

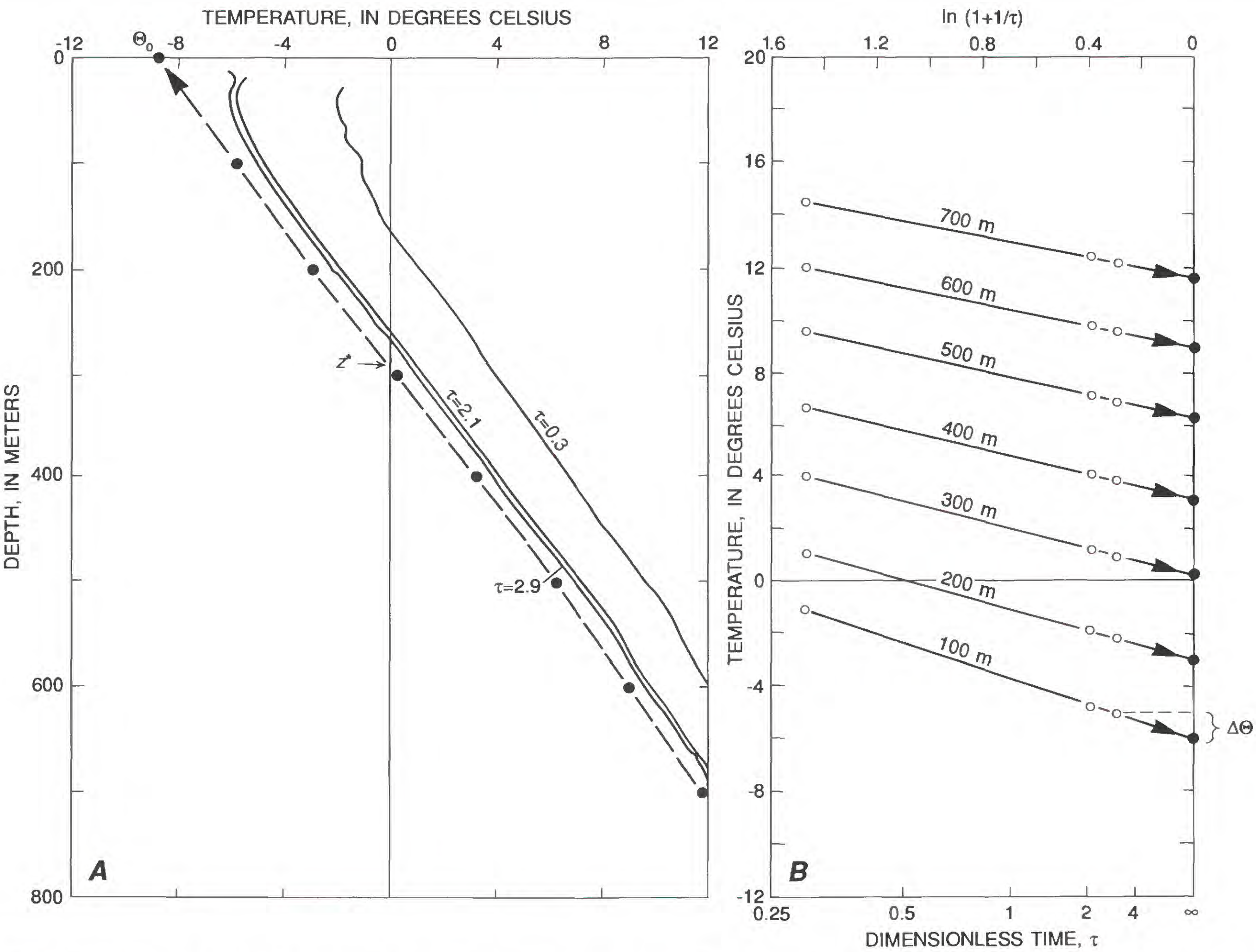


FIGURE 28.2.—Dissipation of temperature disturbance from drilling at Awuna well. *A*, Successive temperature profiles observed 125 days (τ=0.3), 876 days (τ=2.1), and 1,200 days (τ=2.9) after completion of drilling. Dots, estimates of undisturbed temperature, θ_∞, determined from *B*; z^*, estimated permafrost depth; θ_0, long-term mean surface temperature. *B*, Dissipation of drilling disturbance (equation 2) for selected depths indicated. τ, ratio of time elapsed since completion of drilling (t) to drilling period (s, in this case 415 d). Extrapolated intercept at right-hand margin is equilibrium temperature θ_∞. Drilling disturbance remaining at time of last observation is $\Delta\theta$.

from 0.3 to 2.9, representing observations made from 125 to 1,200 d (3.3 yr) after completion of drilling. The value of τ for the last observation in each hole is given in column 3 of table 28.1.

For observations taken not too soon after completion of drilling (that is, for sufficiently large values of τ), the temperature at any depth in a drill hole is usually given to a good approximation by assuming that drilling acted as a constant heat source of duration s. This assumption leads to the expectation that successive temperature measurements at a given depth will be given by (Lachenbruch and Brewer, 1959)

$$\theta(\tau) \cong A \ln\left(1 + \frac{1}{\tau}\right) + \theta_{\infty} \qquad (2)$$

where $\theta(\tau)$ is the temperature observed at dimensionless time τ, θ_{∞} is the undisturbed predrilling temperature, and A is a constant with the dimension of temperature. Thus after an initial period (whose length depends on the departure of the actual drilling process from the constant-source model), a straight line of slope A is expected in a plot of borehole temperature versus $\ln(1+1/\tau)$; extrapolation to $\ln(1+1/\tau)=0$ (that is, to $\tau=\infty$) yields an estimate of θ_{∞}. Such a plot for AWU is shown in figure 28.2*B* for depths in multiples of 100 m. Extrapolation of the empirically determined straight line to the right-hand margin of figure 28.2*B* shows that the observed temperatures were still about 0.9 °C above the undisturbed temperatures θ_{∞} at the time of the last observation. We refer to this disturbance as $\Delta\theta$; an estimate for each of the holes is given in column 4 of table 28.1. The dots plotted in figure 28.2*A* represent the estimated equilibrium temperatures obtained from figure 28.2*B*.

Linear extrapolation of the equilibrium temperature (dots in figure 28.2*A*) to the surface ($z=0$) yields an estimate of the long-term mean annual surface temperature to which the present deep permafrost temperatures have adjusted. We denote this quantity by θ_0; for AWU (fig. 28.2*A*) it is about -9.0 °C. Estimates of θ_0 for the other holes can be found in column 5 of table 28.1. It is seen from the curvature in the upper 100 m of the latest temperature profile at AWU (fig. 28.2*A*) that the complete profile (adjusted by $\Delta\theta=0.9$ °C for disequilibrium) extrapolates to a surface temperature about 2 °C warmer than θ_0. The discrepancy represents a climatic warming of the last century (Lachenbruch and Marshall, 1986; see also Lachenbruch and others, 1982b). We note in passing that this example dispels a common notion, based on fragmentary data, that the recent rapid warming was confined to Arctic coastal locations (see location of AWU, figure 28.1).

By definition, permafrost extends to the depth at which the undisturbed formation temperature is 0 °C. This depth, denoted by z^*, is estimated from figure 28.2 to be 295 m at AWU. Estimates of permafrost depths for the other holes are given in column 6 of table 28.1. The average equilibrium thermal gradient in permafrost is denoted by Γ^* and given by

$$\Gamma^* = -\theta_0/z^*, \qquad (3)$$

where θ_0 is measured in °C. Γ^* is tabulated for each hole in column 7 of table 28.1.

Although all permafrost is below 0 °C, only part of the permafrost can contain ice because the freezing temperature of pore water is generally depressed below 0 °C by the confining pressure, by dissolved salts, and (in fine-grained material) by capillary forces (for example, Dorsey, 1940; National Academy of Science, 1984). However, interstitial icelike structures can be formed by hydrates of natural gas, which may be stable under conditions that extend below the base of permafrost (for example, Katz, 1971). Where appreciable amounts of ice are present in permafrost, its presence can often be detected by the tendency of its latent heat of refreezing to retard the dissipation of the drilling disturbance (for example, Lachenbruch and others, 1982b). Thus at Atigaru Point (ATI, see figures 28.1 and 28.3) the separation of the early temperature profiles (curves for $\tau=4.2$ and 8.4 in figure 28.3) implies that the bottom of an ice-rich layer occurs at a depth of about 330 m. Estimates, by this method, of depths to the bottoms of ice-rich layers for some of the other holes are tabulated in column 8 of table 28.1.

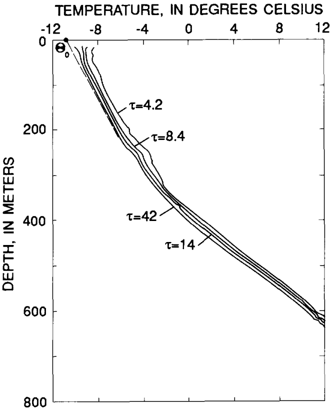


FIGURE 28.3.—Successive temperature profiles measured in Atigaru Point well. τ, ratio of time elapsed since cessation of drilling (t) to drilling time (s, in this case, 65 d). Large temperature separation between first two curves ($\tau=4.2$ and 8.4) inferred to indicate that cooling was retarded initially by latent heat in an ice-rich layer of sediment above 330-m depth. θ_0, long-term mean surface temperature.

EQUILIBRIUM TEMPERATURE PROFILES

Estimates of the complete profile of undisturbed temperatures are given in figure 28.4 for each of the wells studied. We have grouped the wells into those on the coastal plain and those in the foothills, taking the boundary between foothills and coastal plain as the 50-m elevation contour, roughly consistent with the classification of Wahrhaftig (1965). The profiles were obtained by subtracting the drilling disturbance computed by the method of figure 28.2*B* from the most recently measured temperatures, most of which were taken at 0.3-m (1-ft) depth intervals. The curves probably represent natural formation temperatures to within about 0.1 °C, the approximate width of the ink line for the curves in these figures. To keep the individual curves of figure 28.4 from falling on top of one another, they have been offset along the temperature axis. The short vertical lines represent the position of 0 °C (and therefore the base of permafrost) on each curve. Permafrost depths determined from these curves are shown in figure 28.1; they are probably accurate to within a few meters.

It has been shown (Lachenbruch and others, 1982b; Lachenbruch and others, 1987) that a sharp change in thermal gradient just above the base of permafrost in the Prudhoe Bay and Kuparuk oil fields is caused by a thermal conductivity contrast between abundant interstitial ice in the permafrost above the phase boundary and interstitial water below. The general absence of such a gradient contrast in the profiles of figure 28.4 indicates that the ice content of permafrost in the NPRA is generally much less than that at Prudhoe Bay.

The second number shown by each well in figure 28.1 is θ_0 (column 5 of table 28.1), which we have defined as the long-term mean annual temperature of the solid surface. For generalized studies of permafrost, it is the most useful measure of surface temperature, but it is often difficult to determine objectively. For the simple smooth profile (AWU) illustrated in figure 28.2*A*, θ_0 was obtained by extrapolation of the deep linear portion of the profile upward to the surface past the curved portion identified with recent surface warming in the upper 100 m. This procedure is valid if the thermal conductivity does not vary in the depth interval involved in the extrapolation, that is, in the upper 200 m at AWU. In the example, this is probably justified by the uniformity of the gradient. At other sites (for example, TLK, IKP, SBE, and KKI in figure 28.4), changing gradients imply changing conductivities in the upper few hundred meters, and the identification of θ_0 by extrapolation to the surface becomes ambiguous (Lachenbruch and Marshall, 1986). In such cases, we have used our best judgment in selecting the ap-

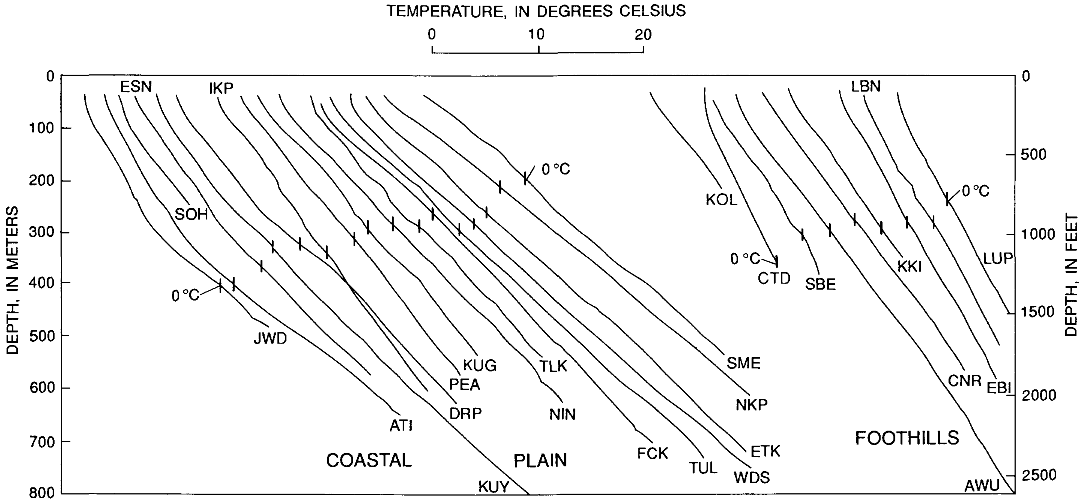


FIGURE 28.4.—Equilibrium temperature profiles (±0.1 °C) for wells on the coastal plain (left group) and in the foothills (right group) in the NPRA. Small vertical bars show position of 0 °C for each curve. For well names and locations, see table 28.1 and figure 28.1. See also figures 28.5 and 28.6.

propriate tangent (generally below 100 m) to project to the surface in determining the value of θ_0 shown. An arbitrary but objective alternative, in which the line joining the temperatures measured at 100 and 200 m (corrected by $\Delta\theta$) is extended to the surface, leads to values of θ_0 that are generally within 0.2 °C of our estimates, but for some irregular profiles they differ by as much as 0.5 °C. These differences give a measure of the uncertainty in the estimates of θ_0 shown. The less certain estimates are followed by (u) in table 28.1 and placed in parentheses on the map (fig. 28.1). The contoured interpretation in figure 28.1 is similar for θ_0 values determined by either method.

PERMAFROST TEMPERATURES AND GAS-HYDRATE STABILITY

The equilibrium temperature profiles (fig. 28.4) for the coastal plain and the foothills are plotted without the temperature offsets in figures 28.5 and 28.6, respectively. Shown also in each of those figures is the envelope of near-equilibrium profiles from nine holes on the coastal plain near Prudhoe Bay (from Lachenbruch and others, 1982b).

The dashed arcuate curve in figures 28.5 and 28.6 represents the phase boundary for stability of methane hydrate in the presence of pure water (from Katz, 1971), assuming that the confining pressure is hydrostatic. To the lower left of that curve, solid icelike methane hydrate can occur; to the upper right, it cannot. Increasing the salinity of the pore water would shift the curve downward; decreasing the molecular weight of the gas would move it upward. If the confining pressure were increased from the assumed hydrostatic values (those caused by an overburden with unit specific gravity) to lithostatic values (those caused by the full overburden weight of the sediments), the curve would be shifted upward to about half the depth shown. At any locality, gas hydrates are possible only where the thermal profile lies below the appropriate phase-boundary curve. According to Kharaka and Carothers (chapter 22), in the Barrow area the assumption of hydrostatic pressure is approximately correct, and the compensating effects of salinity and gas composition lead to a stability curve close to the one shown in figures 28.5 and 28.6. Under these conditions, gas hydrate could occur to depths of ~500 m at the colder sites on the coastal plain (such as JWD, ATI, and ESN; see fig. 28.4) but at the warmer sites there could be none. Similarly, at some of the foothill sites gas hydrate could occur to depths of ~600 m. At the Prudhoe Bay sites, the temperatures are much lower (figs. 28.5 and 28.6), and according to Kharaka and Carothers (chapter 22) the phase-boundary curve is shifted ~10 °C to the right by the gas composition there. Under those circumstances, any gas hydrates occurring at Prudhoe Bay can be stable to great depths. (For a discussion of hydrate stability based on recent temperature measurements west of Prudhoe Bay in the Kuparuk oil field, see Lachenbruch and others, 1987.)

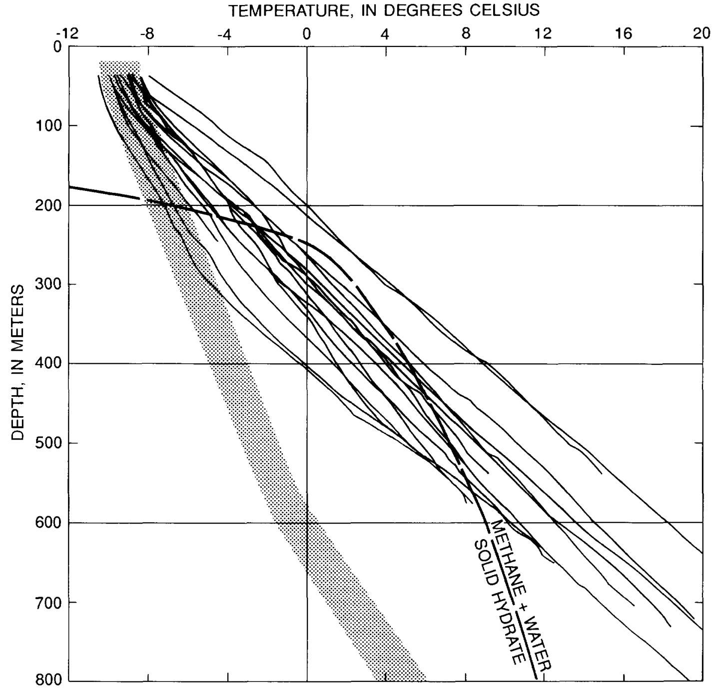


FIGURE 28.5—Equilibrium temperature profiles from wells on coastal plain in NPRA plotted with common temperature origin (see also fig. 28.4). Shaded band is region occupied by similar profiles from nine wells in Prudhoe Bay area (Lachenbruch and others, 1982a, b). Dashed curve is phase boundary for methane hydrate (see text).

REGIONAL VARIATIONS IN PERMAFROST TEMPERATURE AND DEPTH

Rewriting equation 3, we can consider the depth of permafrost (z^*) to be controlled by two factors, the long-term mean surface temperature (θ_0) and the mean thermal gradient (Γ^*):

$$z^* = \frac{\theta_0}{\Gamma^*} \tag{4}$$

Low (that is, large negative) values of θ_0 and small values of Γ^* favor deep permafrost (large z^*). As explained above, our best estimates of θ_0 and z^* are shown for each well in figure 28.1. Means and standard deviations for those quantities for the nine holes studied near Prudhoe Bay are also given in figure 28.1 (Lachenbruch and others, 1982b). The generalized contours in figure 28.1 show that the estimated values of θ_0 vary systematically, increasing from north to south in a pattern modified by the regional topography. This is not surprising, because θ_0 is controlled by climatic factors that probably follow a similar trend. Local relief in the Brooks Range would, of course, be expected to cause local departures from this pattern. From equation 4, we should expect the permafrost depth z^* to follow the same simple regional pattern of θ_0 if the mean thermal gradient in the permafrost (Γ^*) were fairly uniform from place to place.

That this is not the case is best seen from figure 28.7, in which the equilibrium depth to permafrost, z^*, is plotted against long-term mean surface temperature, θ_0. The vertical dashed line at a value of θ_0 near -10 °C separates data obtained in the coastal plain from those obtained in the foothills. Although the foothills generally have higher surface temperatures, the mean permafrost thickness for our (10-well) sample there (300±12 m standard error) is not significantly different from that for the (20-well) sample from the coastal plain (312±14 m standard error), excluding Prudhoe Bay. The diagonal lines in figure 28.7, which represent constant values of mean permafrost gradient, Γ^*, illustrate how lower gradients at the foothill sites generally compensate for higher surface temperatures there to maintain substantial permafrost thicknesses. Even within the thin coastal band north of the contour $\theta_0 = -12$ °C (fig. 28.1), permafrost thickness undergoes extreme local variations (from 280 m at S28 to 420 m at JWD). More generally, it is seen from figures 28.1, 28.6, and 28.7 that permafrost thickness in the NPRA varies by a factor of about two (from 200 m to 400+ m); unlike θ_0, its variation shows no conspicuous regional trends on the scale of our sample (fig. 28.1). The anomalously deep permafrost at Prudhoe Bay is represented by the rectangle in figure 28.7.

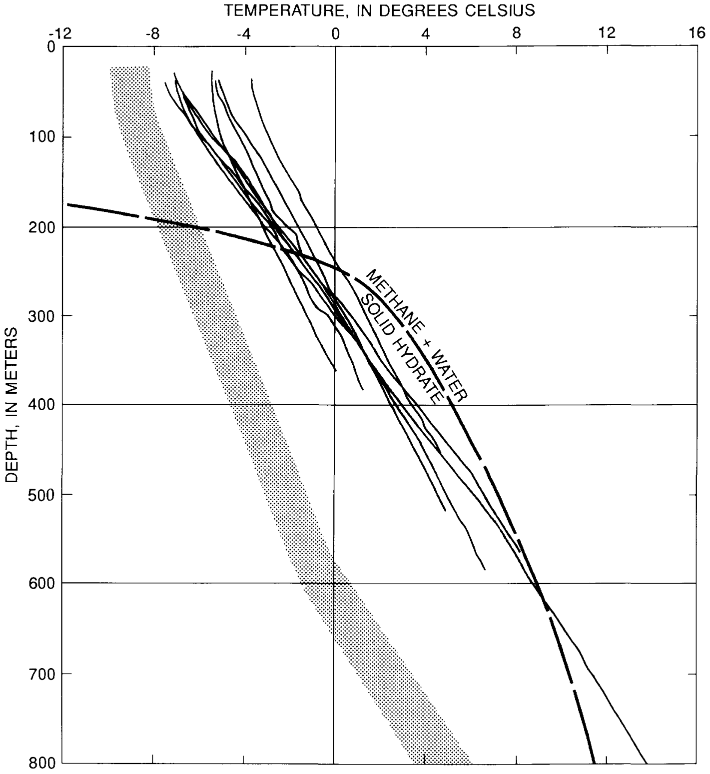


FIGURE 28.6—Equilibrium temperature profiles from wells in foothills of Brooks Range plotted with common temperature origin (see also fig. 28.4). Shaded band is region occupied by similar profiles from nine wells in Prudhoe Bay area (Lachenbruch and others, 1982a, b). Dashed curve is phase boundary for methane hydrate (see text).

REASONS FOR LOCALLY VARYING PERMAFROST DEPTH

The permafrost depth shows local variation unrelated to the regional trend in mean surface temperature. There are three possible reasons for this: (1) local effects of bodies of water on temperatures at the solid Earth surface, (2) lateral variations in heat flow from below the permafrost, and (3) lateral variations in thermal conductivity of the permafrost. It is premature to undertake a detailed discussion of these factors until more information is available on sediment conductivity. We therefore give here only a brief outline of the problem.

EFFECTS OF BODIES OF WATER

The wells in which we measured temperatures are all on dry land, where, as we have seen, the mean surface temperature on the coastal plain is ∿−10 °C. However, some sites are within a few hundred meters of the ocean shoreline and many are close to lakes, which in some parts of the coastal plain cover 30-50 percent of the surface. Those portions of lakes and seas deeper than about 2 m do not freeze to the bottom, and consequently they have mean bottom temperatures close to 0 °C (slightly higher for freshwater, slightly lower for saltwater; see Lachenbruch and others, 1962). Thus, as deep lakes form or drain and coastlines migrate, the solid surface on the coastal plain undergoes local changes in mean temperature from ∿−10 °C to ∿0 °C and back again; we have sampled only emergent sites, and they are presently at the cold end of this range. Although most Arctic lakes freeze to the bottom, some of our sites might have been beneath deep lakes in the past and accordingly might have had surface temperatures ∿10 °C warmer than they have today. It is seen from the coastal-plain profiles in figure 28.5 that the range of temperatures at depths of a few hundred meters is on the order of 10 °C. If we had no information other than that in figure 28.5, we might contrive histories of growth and drainage of lakes that could account for this range of temperatures. For example, the warmer profiles in figure 28.5 require that the 10 °C surface anomaly propagate to depths of ∿500 m; this would require a large, deep lake over the site for many thousands of years; subsequent drainage over the last thousand years or so would have to be postulated to account for the low temperatures observed at shallower depths. From temperature observations made at depths of a few kilometers in these wells, however, we know that the temperature differences among wells persist and, in fact, increase at depth (Blanchard and Tailleur, 1982). To account for these temperature differences at such great depths with surface bodies of water is impossible; the water bodies would have had to persist for millions of years.

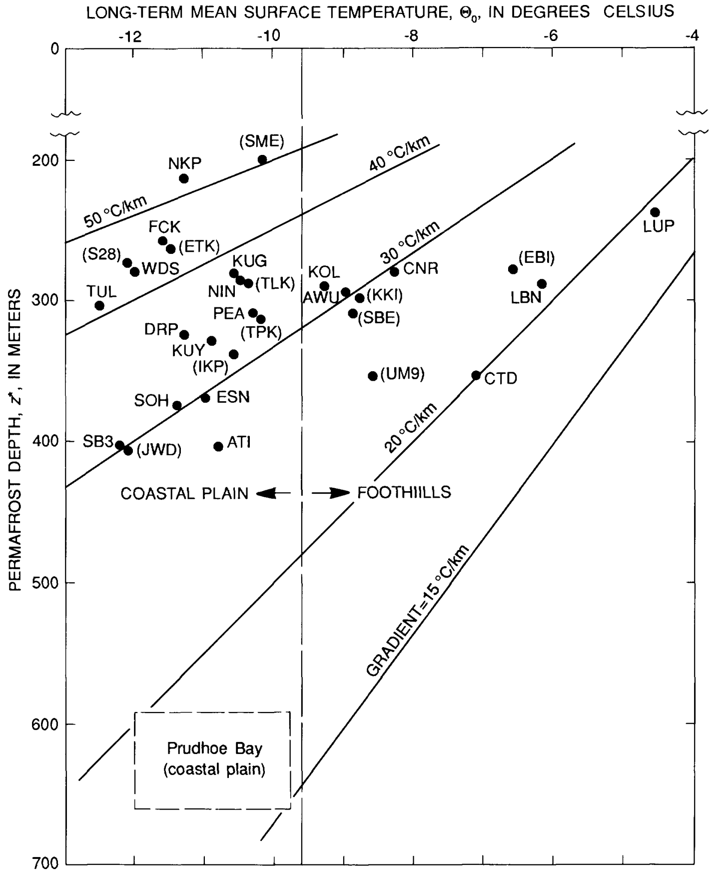


FIGURE 28.7.—Plot of estimated permafrost depth (z^*) versus long-term mean surface temperature (θ_0) for North Slope wells. Dashed rectangle encloses results from nine wells near Prudhoe Bay (Lachenbruch and others, 1982a, b). Designations of wells with less reliable estimates of θ_0 enclosed in parentheses. Vertical dashed line separates wells on coastal plain from those in foothills. Diagonal lines show position of selected mean temperature gradients (Γ^*).

Similar effects are illustrated for the ocean in figure 28.8, which shows the thermal influence of an advancing shoreline on wells near the coast, an application of the theory set forth in Lachenbruch (1957). In figure 28.8C the ocean, assumed to have a mean bottom temperature 10 °C greater than the land surface (fig. 28.8*A*), moved rapidly into its present position (x=0, fig. 28.8*B*) *t* years ago. It is seen that temperature anomalies caused by proximity to a shoreline will be appreciable to depths of a few kilometers only if the shoreline has been in place for very long times (on the order of 10^6 yr). On the other hand, permafrost temperatures in the upper 200 m at sites within 100 m of a shoreline will take on their maximum (steady-state) warming after the shoreline has been in place for about 10^4 yr (compare curves for $t=10^4$ and $t=\infty$ for well at x=100 m, fig. 28.8C). Such nearly steady-state conditions have been observed in shallow nearshore wells in the vicinity of Barrow, Alaska, and this has led to the conclusion that the shoreline has been stable there in recent times (Lachenbruch, 1957; Lachenbruch and others, 1962). The absence of shoreline thermal effects at Cape Simpson to the east of Barrow was interpreted (Lachenbruch, 1957) to indicate that the shoreline there has been transgressing rapidly, and indeed subsequent thermal studies (including this one) elsewhere along the Beaufort Sea coast of Alaska have failed to reveal significant ocean effects. Geomorphic studies along this coast generally indicate shoreline transgression at current rates of about 1 m/yr or more (Hopkins and Hartz, 1978). From figure 28.8*D*, which shows the effect in advance of a shoreline encroaching at constant velocity, it is seen that for such transgression rates, ocean effects would be undetectable even at sites within 100 m of the shoreline (see curve representing 10^0m/yr in second graph from the right in figure 28.8*D*).

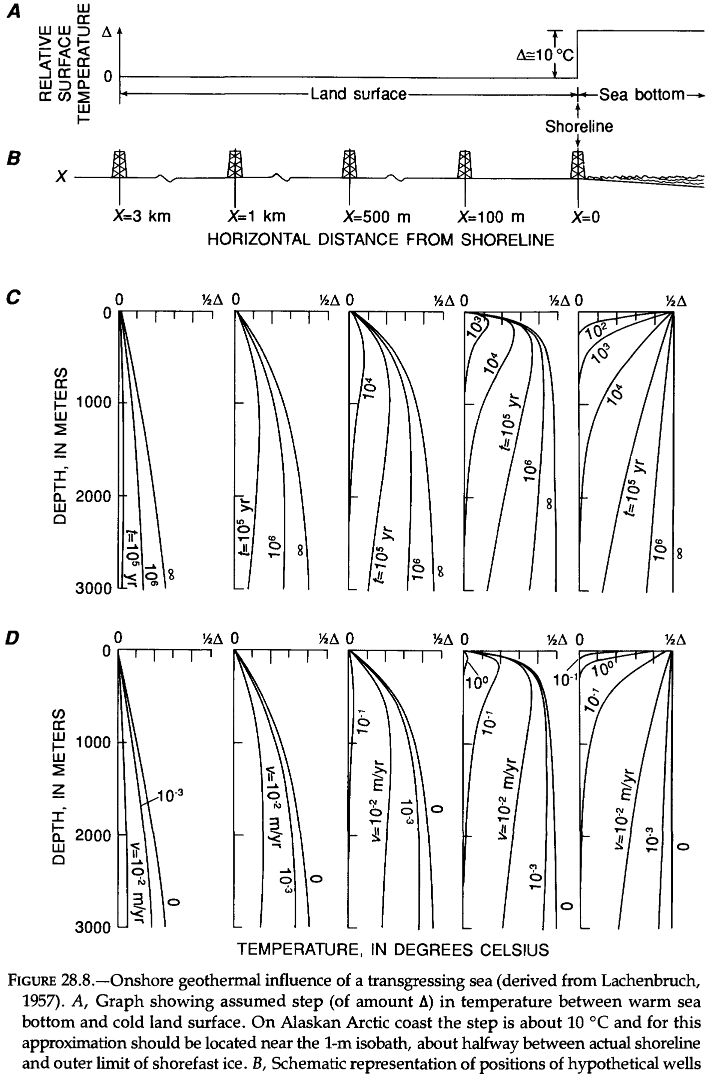


FIGURE 28.8.—Onshore geothermal influence of a transgressing sea (derived from Lachenbruch, 1957). *A*, Graph showing assumed step (of amount Δ) in temperature between warm sea bottom and cold land surface. On Alaskan Arctic coast the step is about 10 °C and for this approximation should be located near the 1-m isobath, about halfway between actual shoreline and outer limit of shorefast ice. *B*, Schematic representation of positions of hypothetical wells for temperature profiles in *C* and *D*; wells are on shoreline (x =0) and at points 0.1, 0.5, 1, and 3 km inland. *C*, Temperature disturbance as a function of depth at selected times (*t*, in years) since shoreline transgressed instantaneously to its present position (x =0). Graphs show conditions at corresponding well sites in *B*. *D*, Temperature disturbance as a function of depth for shoreline that transgresses with constant velocity (*v*, in meters per year). Graphs for selected velocities show effects at corresponding well sites in *B*.

There is little doubt that surface bodies of water can have substantial effect on permafrost temperature (for example, Lachenbruch and others, 1966), that some of the differences among the coastal-plain profiles in figure 28.4 result from this cause, and that detailed studies of such differences might yield useful geomorphic information. However, most of the local variability in permafrost depth that we have observed must be controlled by other factors.

THERMAL CONDUCTIVITY AND HEAT FLOW

It has been shown that local variability of permafrost depth results from local variability in the mean thermal gradient (Γ^*) in permafrost. For the reasonable assumption of one-dimensional steady-state conductive heat flow in permafrost, Γ^* can be expressed as

$$\Gamma^* = q/K, \tag{5}$$

where K is the (harmonic) mean thermal conductivity of the permafrost section and q is the rate at which heat enters its base (per unit area). Local variation in either q or K can cause variation in Γ^*.

How thermal conductivity of a saturated sediment varies with the mean thermal conductivity of its grains (K_g) and with its porosity (ϕ) is shown in figure 28.9 (modified from Lachenbruch and others, 1982b) for the cases where the pores are filled with ice (dashed curves) or water (solid curves). For quartz-rich silicic sediment the grain conductivities are typically in the range of 3-5 W/m·K (upper three solid or dashed curves in figure 28.9), for argillaceous grains they are generally in the range of 1-3 W/m·K, and for coal they are typically <1 W/m·K. We have measured mean grain conductivities that cover this complete range in samples of drill cuttings from wells in northern

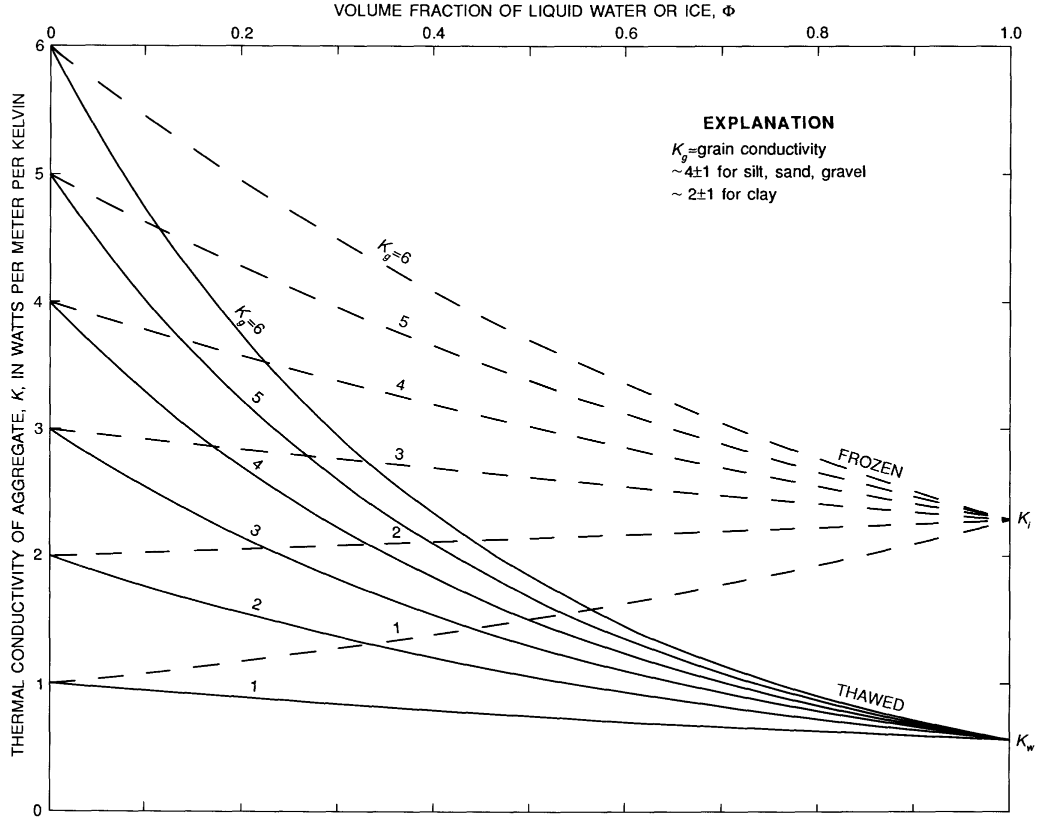


FIGURE 28.9.—Chart for estimating thermal conductivity of saturated sediment with mean grain conductivity K_g and porosity ϕ; dashed curves are for pores containing ice; solid curves are for pores containing liquid water (modified from Lachenbruch and others, 1982b). K_i, thermal conductivity of pure ice; K_w, conductivity of pure water; 1 W/(m·K)=2.39 mcal/(cm·s·°C).

Alaska. The porosities (ϕ, see fig. 28.9) of these sediments typically lie in the range of 20-50 percent (0.2-0.5 volume fraction). Coarse sediment in permafrost often has most of its moisture frozen, whereas fine sediment often does not. Figure 28.7 shows that on the coastal plain Γ^* varies by a factor of about 2; within individual profiles, the gradient varies with depth by as much as a factor of 3. Inspection of figure 28.9 and equation 5 leaves little doubt that these local variations in gradient can easily be accommodated by the expectable ranges of K_g and ϕ without changes in heat flow. We note that the tendency toward lower gradients (Γ^*) in the foothills (figs. 28.7) is consistent with a uniform regional heat flow q (equation 5) and the occurrence of higher conductivities such as would be expected in the more competent rocks of the foothills.

Whether or not heat flow (q, equation 5) varies across northern Alaska cannot be resolved until thermal conductivity studies are completed for some of the wells in which gradients have been measured. If the heat flow from depth is not augmented by advection in vertically moving fluids, its lateral changes would be very gradual and could not explain the local variations in gradient observed. As fluid circulation is likely to be controlled by basin structure, it is worth noting that three anomalously high permafrost gradients (at NKP, ETK, and FCK; see table 28.1) are grouped on the Fish Creek platform, and the high gradient at SME (table 28.1) is on the axis of the Meade arch (see Gutman and others, 1982, fig. 17). It remains to be seen whether such sites with anomalously high local gradients have anomalously high heat flow; if they do, they might indicate upwelling of interstitial fluids in the underlying basin sediments.

REFERENCES CITED

Blanchard, D.C., and Tailleur, I.L., 1982, Temperatures and interval geothermal-gradient determinations from wells in National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 82-391, 79 p.

Brewer, M.C., 1958, Some results of geothermal investigations of permafrost in northern Alaska: American Geophysical Union Transactions, v. 39, p. 19-26.

Dorsey, E.N., 1940, Properties of ordinary water-substance: New York, Reinhold, 673 p.

Gutman, S.I., Goldstein, A., and Guldenzopf, E.C., 1982, Gravity and magnetic investigations of the National Petroleum Reserve in Alaska: NPRA Gravity and Magnetic Investigations Final Report, v. 1, 57 p. [Available from National Geophysical Data Center, 325 Broadway, E/GC1, Dept CNP, Boulder, Colorado 80303]

Hopkins, D.M., and Hartz, R.W., 1978, Coastal morphology, coastal erosion, and barrier islands of the Beaufort Sea, Alaska: U.S. Geological Survey Open-File Report 78-1063, 54 p.

Katz, D.L., 1971, Depths to which frozen gas fields (gas hydrates) may be expected: Journal of Petroleum Technology, v. 23, p. 419-423.

Lachenbruch, A.H., 1957, Thermal effects of the ocean on permafrost: Geological Society of America Bulletin, v. 68, p. 1515-1529.

Lachenbruch, A.H., and Brewer, M.C., 1959, Dissipation of the temperature effect of drilling a well in Arctic Alaska: U.S. Geological Survey Bulletin 1083-C, p. 73-109.

Lachenbruch, A.H., and Marshall, B.V., 1986, Changing climate; geothermal evidence from permafrost in the Alaskan Arctic: Science, v. 234, p. 689-696.

Lachenbruch, A.H., Brewer, M.C., Greene, G.W., and Marshall, B.V., 1962, Temperatures in permafrost, *in* Temperature—its measurement and control in science and industry, v. 3, pt. 1: New York, Reinhold, p. 791-803.

Lachenbruch, A.H., Greene, G.W., and Marshall, B.V., 1966, Permafrost and the geothermal regimes, *in* Wilimovsky, N.J., and Wolfe, J.N., eds., Environment of the Cape Thompson region, Alaska: U.S. Atomic Energy Commission, Division of Technical Information, p. 149-163.

Lachenbruch, A.H., Sass, J.H., Marshall, B.V., and Moses, T.H., Jr., 1982a, Thermal regime of permafrost at Prudhoe Bay, Alaska: U.S. Geological Survey Open-File Report 82-535, 77 p.

——— 1982b, Permafrost, heat flow, and the geothermal regime at Prudhoe Bay, Alaska: Journal of Geophysical Research, v. 87, p. 9301-9316.

Lachenbruch, A.H., Galanis, S.P., Jr., and Moses, T.H., Jr., 1987, A thermal cross section for the permafrost and hydrate stability zones in the Kuparuk and Prudhoe Bay oil fields, *in* Galloway, J.P., and Hamilton, T.D., eds., Geologic studies in Alaska by the U.S. Geological Survey during 1987: U.S. Geological Survey Circular 1016, p. 48-51.

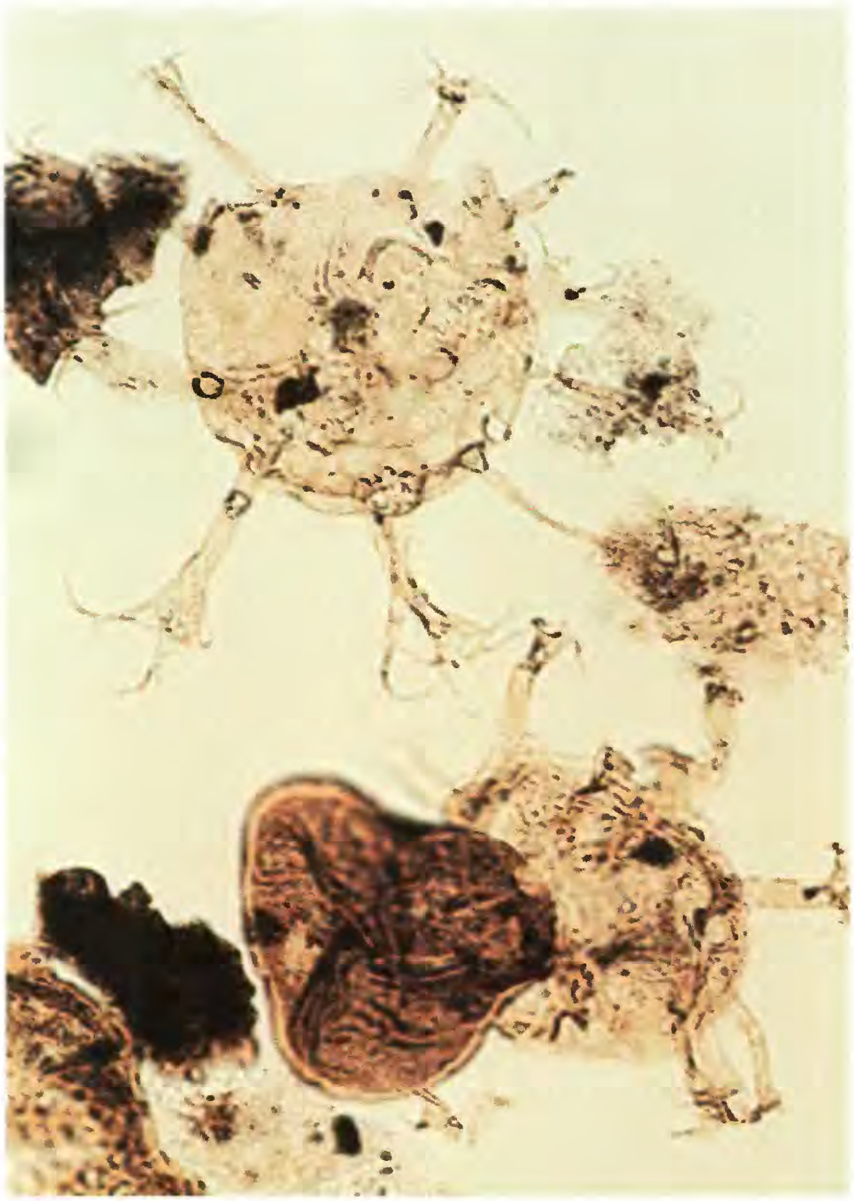
Muller, S.W., 1947, Permafrost, or permanently frozen ground, and related engineering problems: U.S. Engineers Office, Strategic Engineering Study Special Report 62, 136 p.

National Academy of Science, 1984, Ice segregation and frost heaving: Washington, National Academy Press, 72 p.

Osterkamp, T.E., and Payne, M.W., 1981, Estimates of permafrost thickness from well logs in northern Alaska: Cold Regions Science and Technology, v. 5, p. 13-27.

Sass, J.H., Lachenbruch, A.H., Munroe, R.J., Greene, G.W., and Moses, T.H., Jr., 1971, Heat flow in the western United States: Journal of Geophysical Research, v. 76, p. 6376-6413.

Wahrhaftig, Clyde, 1965, Physiographic divisions of Alaska: U.S. Geological Survey Professional Paper 482, 52 p.



Paleontologists determine the age of the rock layers penetrated by the drill by identifying the contained microscopic fossils. Pictured above are ancient marine planktonic forms, dinoflagellates, and plant spores from the pebble shale unit of Early Cretaceous age. Photograph by Roger Witmer.

PALEONTOLOGY

The application of paleontology, particularly micropaleontology, to the exploration for hydrocarbons is especially useful in a large and remote region such as the NPRA. It has proved its value in the correlation of rock layers penetrated by the drill as well as those exposed at the surface. Besides being a major dating tool, it provides another criterion for interpreting the depositional and diagenetic history of the rocks.

Systematic study of microfossils in Arctic North America was pioneered by the USGS in the 1944-51 NPR-4 program and the results published in a professional paper by H.R. Bergquist in 1966. In the more recent program (1974 to 1981), several wells were drilled simultaneously and with improved drilling techniques, and thus samples were accumulated more rapidly. Since drilling was limited in most locations to the winter months, great efforts were made to complete the test well before the spring breakup. The consequent volume of samples and the short turnaround time required exceeded the capacity of the USGS laboratories and staff, and the work of studying these samples had to be contracted out.

A compilation and synthesis by two of the principal contractor paleontologists is included in this section (chapter 29). Other chapters identify fossils from surface samples and microfossils from subsurface cores. These studies complete the record for paleontological work under the NPRA program. Well-by-well details of microfossil occurrences, species distribution, abundance, and related lithology are available through the National Geophysical Data Center, NOAA, Boulder, Colorado 80303.

29. DISTRIBUTION OF LARGE-SCALE DEPOSITIONALLY RELATED BIOSTRATIGRAPHIC UNITS, NATIONAL PETROLEUM RESERVE IN ALASKA

By MICHAEL B. MICKEY[1] and HIDEYO HAGA[1]

INTRODUCTION

The stratigraphic and geographic distribution of 6 biostratigraphic units has been inferred on the basis of data from 18 wells (table 29.1; see also plate 2.1) in the National Petroleum Reserve in Alaska (NPRA). These large-scale biostratigraphic units represent depositionally related packages of sediment. Therefore, the units should correspond to the major recognized seismic sequence intervals.

Seismic stratigraphy is the appropriate approach to refining interpretations of subsurface geology on the North Slope. Properly applied biostratigraphy is essential to this approach. We attempt here to show relations among current results from various disciplines, recognizing that revisions will be needed as work progresses.

ACKNOWLEDGMENTS

We thank McClelland Engineers, Inc., for their assistance in drafting and for permission to publish this chapter. Some of the work on which this chapter is based was completed while we were employed at Anderson, Warren and Associates, Inc.

DEFINITION AND USAGE OF BIOSTRATIGRAPHIC ZONES

In this chapter we are dealing with biostratigraphic units, and these particular units encompass very large time intervals. The Code of Stratigraphic Nomenclature (American Commission on Stratigraphic Nomenclature, 1961, p. 655) states: "A biostratigraphic unit is a body of rock strata characterized by its content of fossils contemporaneous with the deposition of the strata.* * * Commonly, biostratigraphic evidence is the most useful means for determining time-stratigraphic boundaries, but criteria for defining biostratigraphic and time-stratigraphic units differ fundamentally." In short, biostratigraphic zones and zonules can, with use, prove to have time-stratigraphic significance, but they do not have to have such significance.

Some of the potential problems associated with interpreting biostratigraphic data are illustrated in figure 29.1. A change in the thickness of biostratigraphic unit X can be interpreted in several ways; three possible interpretations are shown in the figure. These problems can be overcome by using an interdisciplinary approach involving the geologist, geophysicist, and micropaleontologist in a team effort. Seismic data can help determine which interpretation is most likely. Individual faunal and floral events can then be correlated and a superpositional catalog of these events prepared. This approach should result in a more detailed set of correlations and lead to a clearer understanding of the regional geologic history.

SIX BIOSTRATIGRAPHIC UNITS IN THE NPRA

Six biostratigraphic units can be recognized in the subsurface in the NPRA on the basis of data from 33 wells. The stratigraphic distribution of the six biostratigraphic units is shown on figure 29.2, and the basal interval depth and thickness of each unit in each well are given in table 29.1. The subsurface distribution of the six large-scale biostratigraphic units in the NPRA area is given in figures 29.3 and 29.4. The areal distribution and drilled thicknesses of each of the units are shown in isochore maps, figures 29.5-29.11. The large dots on the individual isochore maps indicate the wells where that particular biostratigraphic unit was encountered. The age, areal distribution, and depositional environments associated with each of the biostratigraphic units are discussed below.

Biostratigraphic unit I.—The drilled thicknesses and areal distribution of biostratigraphic unit I are shown on figure 29.5. This unit represents Tertiary deltaic deposits (mostly alluvial plain to inner delta plain), which are restricted to coastal wells between Smith Bay and Harrison Bay.

Biostratigraphic unit II.—This unit (shown on fig. 29.6) represents Late Cretaceous (Cenomanian to Maestrichtian) deltaic and progradational

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[1] Micropaleo Consultants, Inc., Encinitas, CA 92024.

TABLE 29.1.—*Depths to base and thicknesses of large-scale biostratigraphic units in 18 wells in the National Petroleum Reserve in Alaska*

[Upper figure is depth to base of unit; lower figure is unit thickness; all figures in meters. TD, total depth; Ag, argillite; Dev., Devonian rocks. +, minimum thickness; -, unit absent or not penetrated]

Well	Biostratigraphic unit							
	I	II	III	IV	V	VI-A	VI-B	Basement complex
1. Atigaru No. 1	- -	1059.18 1059.18+	2219.55 1160.37	2621.28 401.73	2895.60 274.32	3307.08 411.48	3416.81 109.73	3511.30 TD 94.49+ Ag
2. Cape Halkett No. 1	326.14 326.14+	949.45 623.31	2231.14 1281.69	2476.50 245.36	2683.76 207.26	2840.74 156.98	2959.61 118.87	3017.52 TD 57.91+ Ag
3. J.W. Dalton No. 1	277.37 277.37+	810.77 533.40	2250.95 1440.18	2401.82 150.87	2531.36 129.54	2791.97 260.61	2819.40 27.43	2854.70 TD 35.30+ Ag
4. Drew Point No. 1	42.67 42.67+	440.44 397.77	2045.21 1604.77	2307.34 262.13	2389.63 82.29	- -	- -	2421.94 TD 32.31+ Ag
5. West Fish Creek No. 1	- -	769.62 769.62+	2217.42 1447.80	2900.17 682.75	3200.40 300.23	3447.29 246.89	3480.82 TD 33.53+	- -
6. W.T. Foran No. 1	338.33 338.33+	1094.23 755.90	2237.25 1143.00	2325.62 88.39	2497.84 172.22	2610.61 112.77	2670.05 59.44	2701.75 TD 31.70+ Ag
7. South Harrison Bay No. 1	- -	981.46 981.46+	2221.99 1240.53	2816.35 594.36	3118.10 301.75	3441.19 TD 323.09+	- -	- -
8. Ikpikpuk No. 1	- -	- -	2206.75 2206.75+	3166.87 960.12	3471.67 304.80	4526.28 1054.61	4718.30 TD 192.02+	- -
9. Inigok No. 1	- -	605.03 605.03+	2755.39 2150.36	3810.00 1054.61	4221.48 411.48	5522.98 1301.50	6124.04 TD 601.06+	- -
10. Kalikpik No. 1	- -	730.00 730.00+	2112.26 1382.26	2254.00 TD 141.74+	- -	- -	- -	- -
11. Kugrua No. 1	- -	- -	2100.07 2100.07+	3038.86 938.79	3403.09 364.23	3838.65 TD 454.76+	- -	- -
12. South Meade No. 1	- -	- -	1973.58 1973.58+	2799.59 826.01	2904.74 105.15	- -	- -	3030.63 TD 125.89+ Dev.
13. Peard Bay No. 1	- -	- -	1888.24 1888.24+	2663.95 775.71	2938.27 274.32	- -	- -	3116.58 TD 178.31+ Ag
14. East Simpson No. 1	- -	160.02 160.02+	1940.05 1780.03	2272.28 332.23	2313.43 41.15	- -	- -	2358.54 TD 45.11+ Ag
15. East Simpson No. 2	- -	320.04 320.04+	1932.43 1612.39	2053.13 120.70	2184.50 131.37	- -	2287.22 TD 102.72+	- -
16. South Simpson No. 1	- -	- -	1930.91 1930.91+	2487.17 556/26	2618.23 131/06	2667.00 48.77	- -	2680.72 TD 13.72+ Ag
17. East Teshekpuk No. 1	- -	591.31 591.31+	2097.02 1505.71	2699.00 601.98	2941.32 242.32	3236.98 295.66	3244.29 TD 7.31+	- -
18. Tunalik No. 1	- -	- -	3241.55 3241.55+	4517.14 1275.59	5212.08 694.94	6196.58 TD 984.50+	- -	- -

shelf deposition. These strata occur in varying thicknesses in wells in the northeastern part of the NPRA, and they appear to thin rapidly to the west.

Biostratigraphic unit III.—This unit (shown on fig. 29.7) consists of northeastward progradational deltaic and shelf-basin sediments of Early Cretaceous (Barremian?) and Late Cretaceous (early Cenomanian) age. This is the thickest of the six units observed, and it occurs in all the wells.

Biostratigraphic unit IV.—These strata of Middle Triassic to (Aptian?) late Early Cretaceous age (shown on fig. 29.8) represent fairly stable shelf-basin deposition, or else deposition associated with a tide-dominated deltaic system. This unit is present, at least in part, in all the wells. Correlation of the biostratigraphic zones recognized indicates much structural complexity within this interval. There appear to be several hiatuses (erosional?, nondepositional?) associated with the Upper Jurassic and Lower Cretaceous (Neocomian) parts of this biostratigraphic unit. In addition, the Lower and Middle Jurassic shale strata become depositionally thinner toward the basin.

Biostratigraphic unit V.—These strata of Permian and Early Triassic age (shown on fig. 29.9) are predominantly nonmarine to marginal marine, but locally include inner-shelf deposits. This unit is fairly thin throughout the area and tends to become even thinner over the structural highs.

Biostratigraphic unit VI.—This unit is divided into a carbonate facies (biostratigraphic unit VI-A) and a clastic facies (biostratigraphic unit VI-B). We include the Lower Permian calcareous shale, packstone, and grainstone strata within biostratigraphic unit VI-A. We recognize that future detailed study of these Lower Permian strata may reveal that they represent a separate depositional interval or are a part of the overlying depositional interval.

Biostratigraphic unit VI-A (the carbonate facies), consists of as much as 1,300 m of Upper Mississippian, Pennsylvanian, and Lower Permian carbonate shelf deposits. These carbonate strata (shown on fig. 29.10) are present in most wells, but they are noticeably missing from the Meade Arch, Peard Bay, and Smith Bay areas. This unit thickens rapidly on the flanks of the structures and appears from the zonal data to lap onto the basement highs.

Biostratigraphic unit VI-B (the clastic facies), shown on figure 29.11, represents the oldest definitely datable strata so far found in these wells. These rocks range in age from Early Mississippian to possibly as young as Early Pennsylvanian (Zone 20), as in the J.W. Dalton No. 1 well. These nonmarine to shallow-marine strata appear to represent a basal clastic sequence lying directly on the basement rocks, which consist of argillite and are generally thought to be Devonian or older in age. The South Meade well, however, bottomed in nonargillite rocks lithologically comparable to the rocks dated as having a questionable Early Devonian age (based on a plant fossil) in the adjacent Topagoruk No. 1 well (Collins, 1958). Biostratigraphic unit VI-B was penetrated by nine wells in this study; several other wells stopped short of its projected depth.

SUMMARY

We have been able to recognize six large-scale biostratigraphic units that we feel correspond to major intervals recognized on seismic records. The current level of biostratigraphic correlation allows us to define some structural and depositional complications within these larger, sedimentologically related units. A more complete picture of the geologic history of this area would be established, however, from a detailed correlation of individual faunal and floral events within the biostratigraphic units. Such detailed correlations can only be attained through an integration of biostratigraphic, seismic, and electric-log interpretations.

REFERENCES CITED

American Commission on Stratigraphic Nomenclature, 1961, Code of Stratigraphic Nomenclature: American Association of Petroleum Geologists Bulletin, v. 45, no. 5, p. 645-665.

Collins, F.R., 1958, Test wells, Topagoruk area, Alaska: U.S. Geological Survey Professional Paper 305-D, p. 265-316.

Witmer, R.J., Haga, Hideyo, and Mickey, M.B., 1981, Biostratigraphic report of thirty-three wells drilled from 1975 to 1981 in National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 81-1166, 50 p.

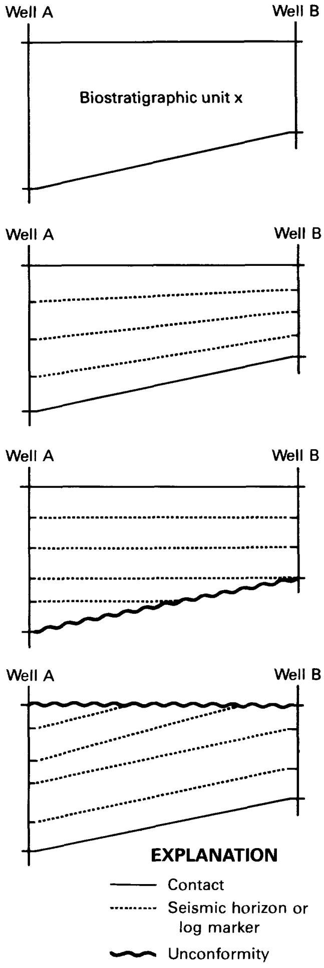

FIGURE 29.1.—Schematic diagrams showing possible interpretations of an observed thinning of a biostratigraphic unit between two wells.

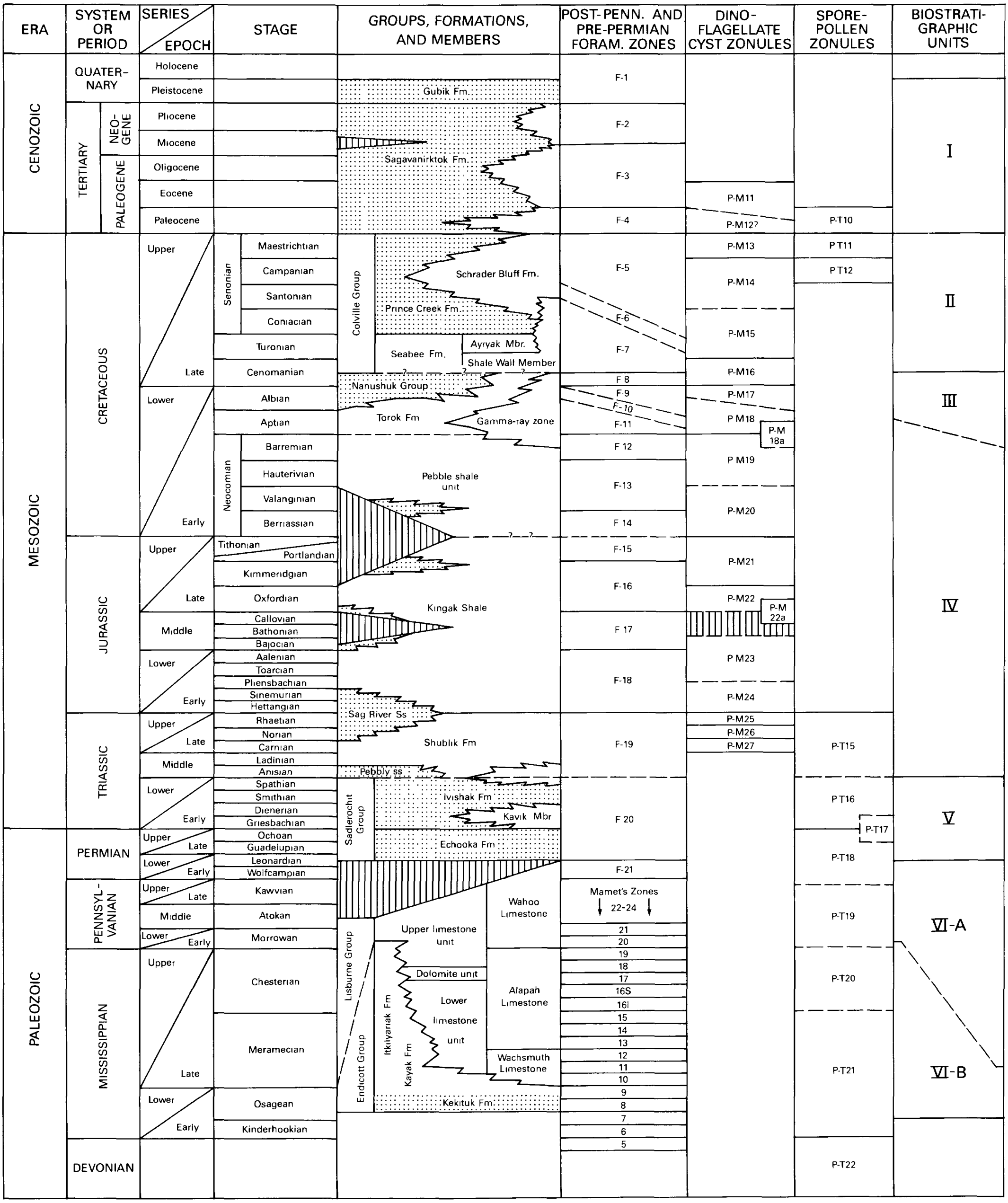

FIGURE 29.2.—Generalized subsurface biostratigraphic chart for the North Slope, prepared by BioStratigraphics, Inc. in 1982. Stratigraphic nomenclature and age assignments do not necessarily conform to U.S. Geological Survey usage. Modified from Witmer and others (1981).

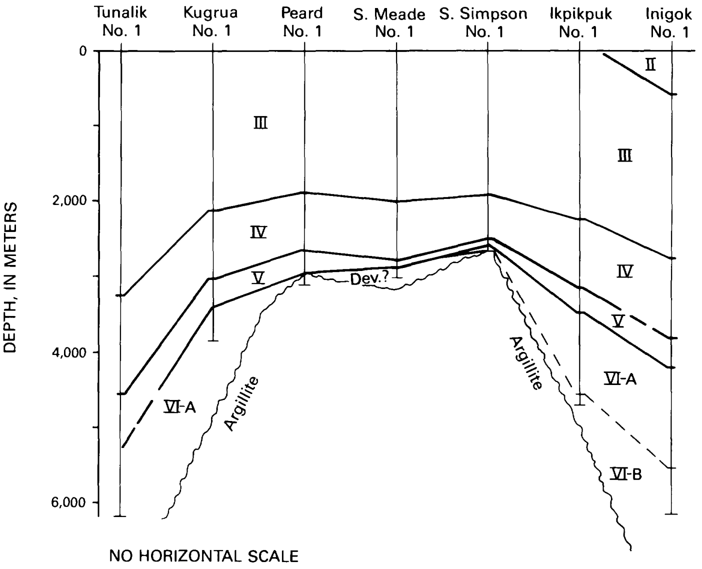

Figure 29.3.—Distribution of biostratigraphic units II through VI-B in wells on the interior coastal plain in NPRA. Boundaries of units dashed where uncertain. Light dashed line separates subdivisions of unit VI. Argillite and possible Devonian rocks are considered parts of basement complex.

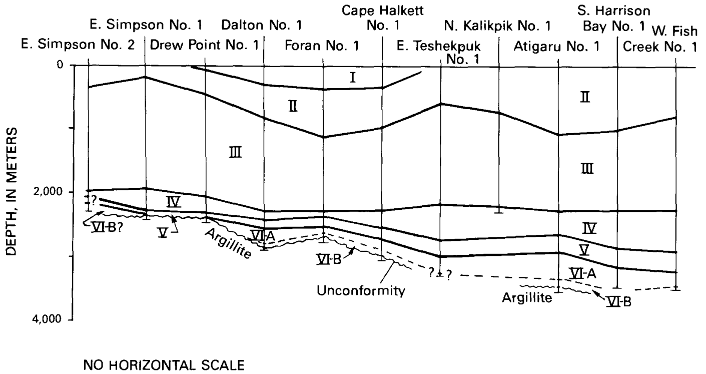

Figure 29.4.—Distribution of biostratigraphic units I through VI-B in coastal wells in NPRA. Light dashed line separates subdivisions of unit VI. Argillite is considered part of basement complex.

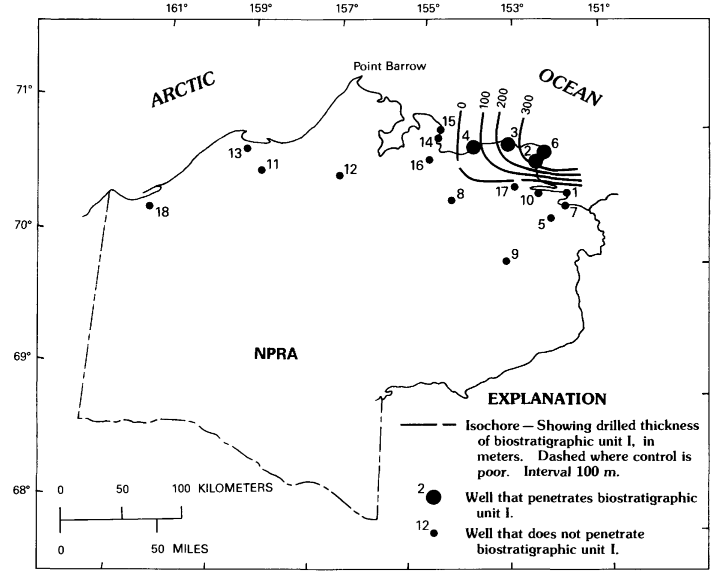

FIGURE 29.5.—Isochore map of biostratigraphic unit I in NPRA. Well numbers refer to table 29.1 and apply also to figures 29.6-29.11.

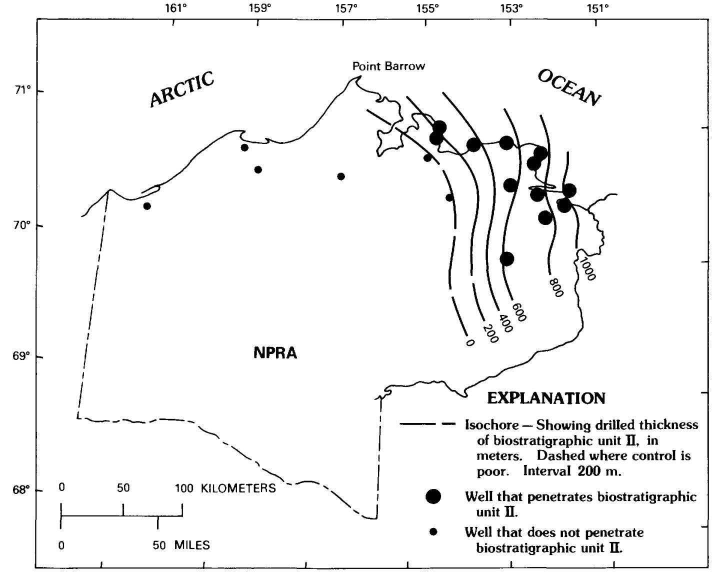

FIGURE 29.6.—Isochore map of biostratigraphic unit II in NPRA. For identification of wells, see figure 29.5 and table 29.1.

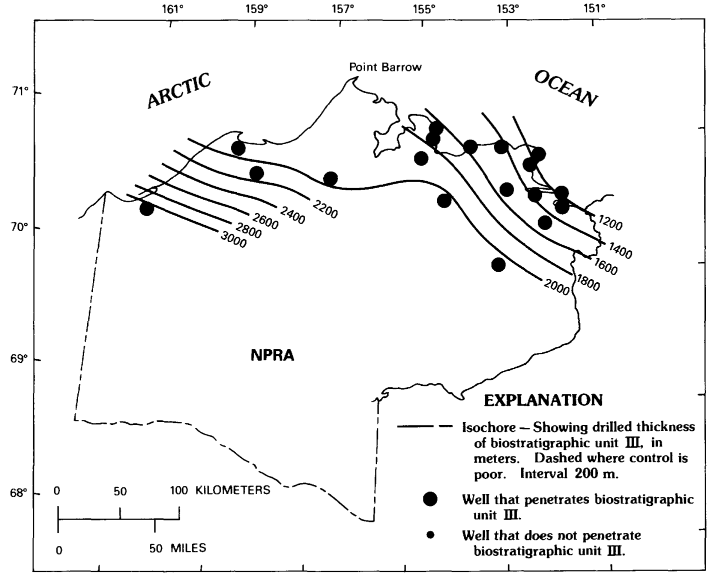

FIGURE 29.7.—Isochore map of biostratigraphic unit III in NPRA. For identification of wells, see figure 29.5 and table 29.1.

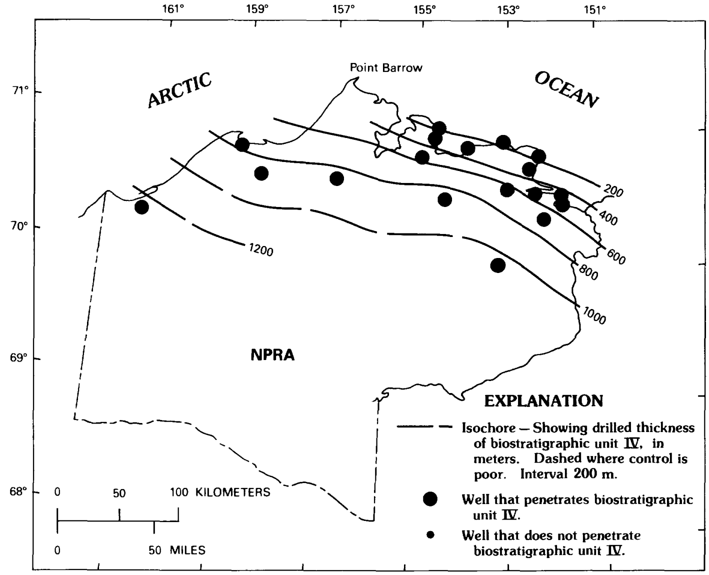

FIGURE 29.8.—Isochore map of biostratigraphic unit IV in NPRA. For identification of wells, see figure 29.5 and table 29.1.

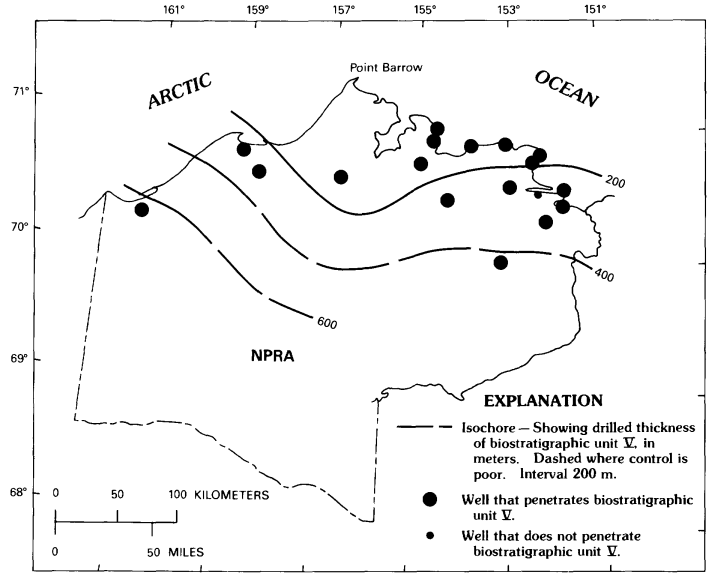

FIGURE 29.9.—Isochore map of biostratigraphic unit V in NPRA. For identification of wells, see figure 29.5 and table 29.1.

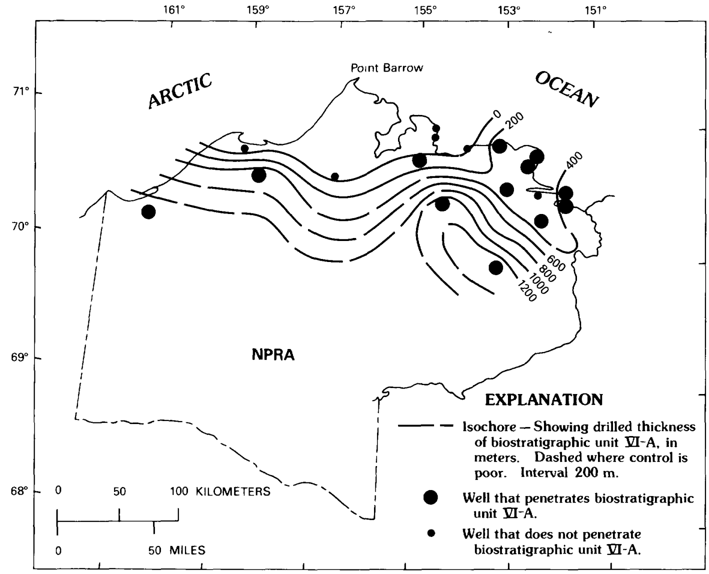

FIGURE 29.10.—Isochore map of biostratigraphic unit VI-A in NPRA. For identification of wells, see figure 29.5 and table 29.1.

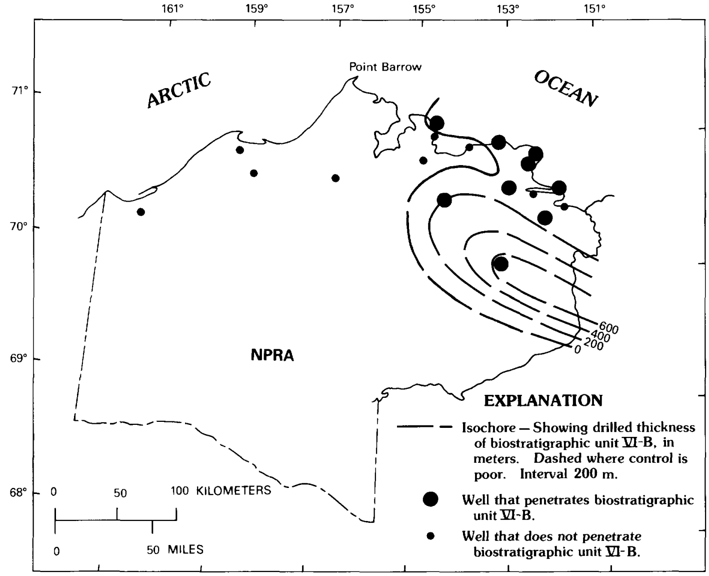

Figure 29.11.—Isochore map of biostratigraphic unit VI-B in NPRA. For identification of wells, see figure 29.5 and table 29.1.

30. MEGAFOSSIL BIOSTRATIGRAPHY OF SOME DEEP TEST WELLS, NATIONAL PETROLEUM RESERVE IN ALASKA

By J. Thomas Dutro, Jr., and Norman J. Silberling

INTRODUCTION

Fourteen of the exploration wells drilled on the National Petroleum Reserve in Alaska (NPRA) since 1975 (table 30.1; see also pl. 2.1) yielded significant megafossils, which provide new biostratigraphic information for the northern Alaskan subsurface. Fourteen stratigraphic intervals ranging from possible Late Devonian to Albian (late Early Cretaceous) age are documented (fig. 30.1).

Eight of the wells are located near the Arctic Coast, where many formations pinch out against the Barrow High, but five others were drilled into basinal sequences to the south, where Paleozoic and lower Mesozoic strata thicken greatly. By far the best documented well is the second deepest one, Inigok No. 1, drilled in the northern part of the Umiat basin. Tunalik No. 1 well, drilled to a depth of 6,198 m (20,335 ft) in the western part of the NPRA about 50 km southwest of Wainwright, apparently penetrated upper Carboniferous strata immediately above the basement. Lisburne No. 1 well, drilled in the structurally complex foothills belt in the southern part of the NPRA, passed through several thrust slices that yielded late Paleozoic and Triassic fossils.

ACKNOWLEDGMENTS

We thank the following paleontologists who identified some of the fossils from these NPRA cores: David L. Jones identified Late Jurassic and Early Cretaceous mollusks, Raymond C. Douglass studied the Early Permian fusulinids from the Inigok well, Olgerts Karklins identified the Permian bryozoans from the Ikpikpuk well, E.L. Yochelson examined Permian gastropods, I.G. Sohn identified Mississippian ostracodes from the Lisburne well, Sergius Mamay examined the possible Devonian plant material from Inigok, A.K. Armstrong identified the Carboniferous corals from both Inigok and Ikpikpuk wells, and Anita Harris processed a huge quantity of material from many of the wells and identified late Paleozoic conodonts from several of them. We also thank Roger Witmer for his careful sampling of the cores for megafossils and for his meticulous documentation of the paleontologic material.

MESOZOIC BIOSTRATIGRAPHY

The most widespread unit sampled during the drilling is the Upper Triassic, represented in eight wells by characteristic Karnian and Norian molluscs. Early Jurassic fossils are recorded from seven wells, but most of the other levels were sampled in only one or two wells. No Mesozoic microfossils are discussed in this chapter; Paleozoic conodonts, ostracodes, and fusulinids are the only microfossils included.

LOWER CRETACEOUS

The youngest biostratigraphic zone documented by fossils in this study is the middle or late Albian *Gastroplites kingi* Zone of Imlay (1961). Fossils referrable to this zone are found only in the J.W. Dalton No. 1 well at depths of 1,070 to 1,076 m (3,510.5-3,530 ft) and at 1,710 m (5,610.5 ft). D.L. Jones (written commun., 1980) identified *Ditrupa cornu* Imlay, *Periplomya* sp. and *Yoldia kissoumi* McLearn from the higher levels and *Paragastroplites* sp. from the lower one. These taxa are widespread in northern Alaska, both in surface exposures and in the subsurface, in the upper part of the Torok Formation and the lower part of the Nanushuk Group and equivalent strata (Imlay, 1961).

UPPER JURASSIC(?)

Late Jurassic megafossils are provisionally reported only from Ikpikpuk No. 1 well, where Buchias of possible late Tithonian age were identified by D.L. Jones (written commun., 1980) from depths of 2,283 to 2,286 m (7,491.4-7,501 ft). Because the specimens are all crushed individuals, as is common in *Buchia* coquinas in many places in northern Alaska, Jones could not identify these forms with certainty. He suggested that they may be *Buchia unschensis* Lahusen. Also identified from 2,286 m (7,501 ft) is the pelecypod *Oxytoma* sp., a long-ranging genus.

Species of *Buchia* are difficult to distinguish, and many different species are known from the Upper Jurassic and Lower Cretaceous in northern Alaska (Imlay, 1959, 1961). *Buchia* coquinas are widespread in surface outcrops in the foothills belt of the Brooks Range, where they

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TABLE 30.1.—*Data on test wells drilled in the NPRA from 1975 to 1981 and discussed in this chapter*
[For locations of wells, see pl. 2.1]

Well	Location	Date spudded (mo/d/yr)	Date completed (mo/d/yr)	Total depth (m)	Total depth (ft)	Oldest unit (age) attained	Remarks
S. Harrison Bay No. 1	50 mi SE. of Barrow	11/21/76	02/08/77	3,441	11,290	Lisburne Group (Pennsylvanian part)	Poor oil shows; plugged and abandoned
W.T.Foran No. 1	23 mi ESE. of Lonely	03/07/77	04/24/77	2,702	8,864	Argillite (Devonian or older)	Oil and gas shows; plugged and abandoned
Drew Point No. 1	14 mi W. of Lonely	01/13/78	03/13/78	2,422	7,946	Argillite (Devonian or older)	Poor oil and gas shows; plugged and abandoned
South Meade No. 1	45 mi S. of Barrow	02/07/78 (reentered 12/04/78)	01/22/79	3,031	9,945	Argillite (Devonian or older)	Poor gas shows; plugged and abandoned
Inigok No. 1	60 mi S. of Lonely	06/07/78	05/22/79	6,127	20,102	Kekiktuk Conglomerate (Mississippian)	Encountered hydrogen sulfide and sulfur at 5,355 m (17,570 ft); poor gas shows; plugged and abandoned
Tunalik No. 1	22 mi SE. of Icy Cape	11/10/78	01/07/80	6,198	20,335	Lisburne Group (Pennsylvanian part)	Gas test; plugged and abandoned
Ikpikpuk No. 1	42 mi SW. of Lonely	11/28/78	02/28/80	4,719	15,481	Kekiktuk Conglomerate (Mississippian)	Gas shows; plugged and abaondoned
Peard No. 1	25 mi NE. of Wainwright	01/26/79	04/13/79	3,117	10,225	Argillite (Devonian or older)	Poor gas shows; plugged and abandoned
East Simpson No. 1	55 mi SE. of Barrow	02/19/79	04/10/79	2,359	7,739	Argillite (Devonian or older)	Oil and gas shows; plugged and abandoned
J.W. Dalton No. 1	3 mi E. of Lonely	05/07/79	08/01/79	2,855	9,367	Argillite (Devonian or older)	Oil and gas shows; some heavy oil recovered during testing; plugged and abandoned
Lisburne No. 1	110 mi SW. of Umiat	06/11/79	06/02/80	5,182	17,000	Lisburne Group (Mississippian part)	Shows of gas; plugged and abandoned
Walakpa No. 1	15 mi S. of Barrow	12/25/79	02/07/80	1,117	3,666	Argillite (Devonian or older)	Shows of gas; plugged and abandoned
East Simpson No. 2	50 mi SE. of Barrow	01/29/80	03/15/80	2,288	7,505	Argillite (Devonian or older)	Oil and gas shows; plugged and abandoned
West Dease No. 1	28 mi SE. of Barrow	02/19/80	03/26/80	1,271	4,170	Argillite (Devonian or older	Oil and gas shows; plugged and abandoned

usually contain Early Cretaceous species. Because both the palynologic and foraminiferal data from this level in the Ikpikpuk well indicate a possible Early Cretaceous age, the Buchias may be related to one or more of the Cretaceous species.

LOWER JURASSIC

Definite and possible Early Jurassic molluscs are identified from seven wells in the NPRA, all of them from the Arctic Coast area; the southernmost of the seven is South Meade well. These occurrences and their relations to underlying Upper Triassic strata are here discussed from east to west. Correlation of the test wells yielding both Triassic and Early Jurassic megafossils is shown in figure 30.2.

Drew Point No. 1 well.—Although no age-diagnostic megafossils occur in the interval 2,130 to 2,136 m (6,987-7,008.4 ft), just above beds that have been assigned to the Triassic Shublik Formation, the rock type and the indeterminate fossils are similar to those found in the Lower Jurassic intervals of nearby test wells. The glauconitic calcareous siltstone and sandstone are like those at depths of 1,882 to 1,902 m (6,174-6,240 ft) in Simpson No. 1 well, where a species of the bivalve *Oxytoma* is considered by Imlay (written commun., 1969) to be Early Jurassic in age. From this interval in the Drew Point well we have identified only possible inoceramid shell fragments, indeterminate thin-shelled smooth bivalves, and a rhynchonelloid brachiopod that could well be Jurassic in age.

East Simpson No. 1 well.—Ammonoids from a depth of 2,079 to 2,081 m (6,820.4-6,828.6 ft) in this well are definitely of Early Jurassic age. The presence of *Psiloceras* sp. and *Caloceras*? sp. indicates a late Hettangian to early Sinemurian age range for this segment of the core. From lower down in the hole, at depths of 2,105 to 2,109 m (6,906.7-6,917.8 ft) the following forms have been identified: *Oxytoma* sp., *Amussium* sp., an isognomonid bivalve, and a terebratuloid brachiopod.

The fossils in the lower part are like those of the Lower Jurassic segments in nearby wells, but by superposition they may be either very latest Triassic or very earliest Jurassic in age. Nondiagnostic Middle or Late Triassic bivalves are found from 2,264 to 2,266 m (7,427.1-7,435.5 ft).

East Simpson No. 2 well.—A few bivalve fragments from a depth of 2,045 to 2,046 m (6,708.6-6,712.9 ft) may be of very latest Triassic or Early Jurassic age. Forms identified are *Entolium* sp. and, possibly, *Oxy-*

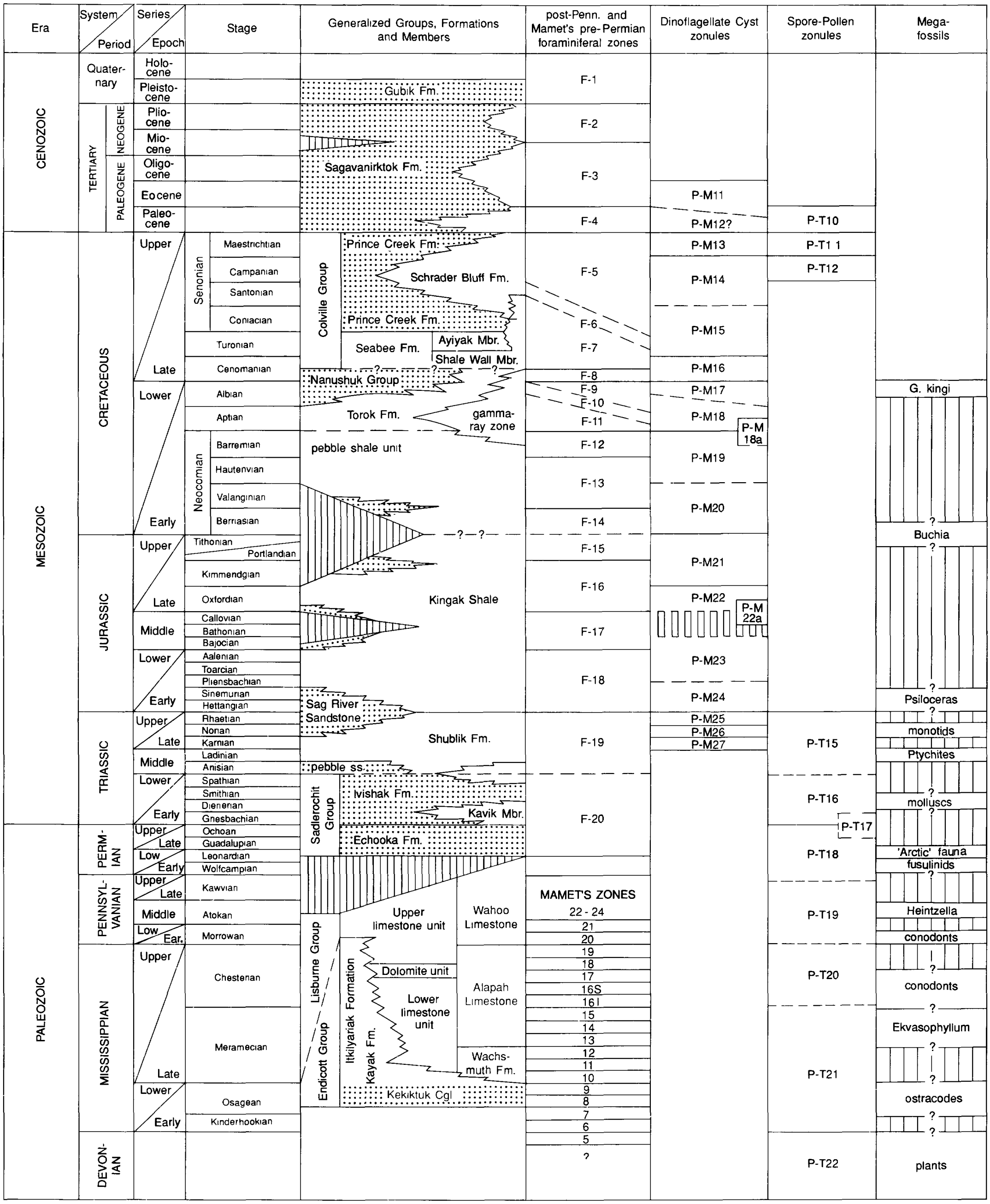


FIGURE 30.1.—Stratigraphic position of the megafossil occurrences in NPRA test wells discussed in this chapter and their relation to foraminiferal zones, dinoflagellate cyst zonules, and spore-pollen zonules. Correlation chart of zones originally prepared by M.B. Mickey and Hideyo Haga of BioStratigraphics in 1982. Unit ages and stratigraphic nomenclature used here may not necessarily conform to current USGS usage.

toma sp. The bivalves are comparable to those from a depth of 1,902 to 1,904 m (6,240-6,246 ft) in the Simpson No. 1 well, an interval about 6 m (20 ft) above the top of the Shublik Formation, as judged from lithology, and about 18 m (60 ft) above the occurrence of middle Norian fossils.

West Dease No. 1 well.—Ammonoids of Hettangian age occur in an interval of about 30 m (100 ft) in this well. Identified taxa and their levels are: *Franziceras* sp. along with pectenacid bivalves from 1,142 to 1,143 m (3,746-3,748.6 ft); psiloceratid and schlotheimiid ammonites from 1,153 to 1,154 m (3,783.9-3,786 ft). Other less diagnostic Early Jurassic fossils occur at both higher and lower levels and include *Otapiria*? sp. from 1,140 m (3,739 ft), *Entolium*? sp. from 1,143 m (3,750 ft), and *Oxytoma* sp. from 1,144, 1,161, and 1,171 m (3,753.5, 3,810, and 3,842.9 ft). The *Oxytoma*-bearing, glauconitic, calcareous sandstone at 1,171 m (3,842.9 ft) could even be latest Triassic in age, but no older than late Norian.

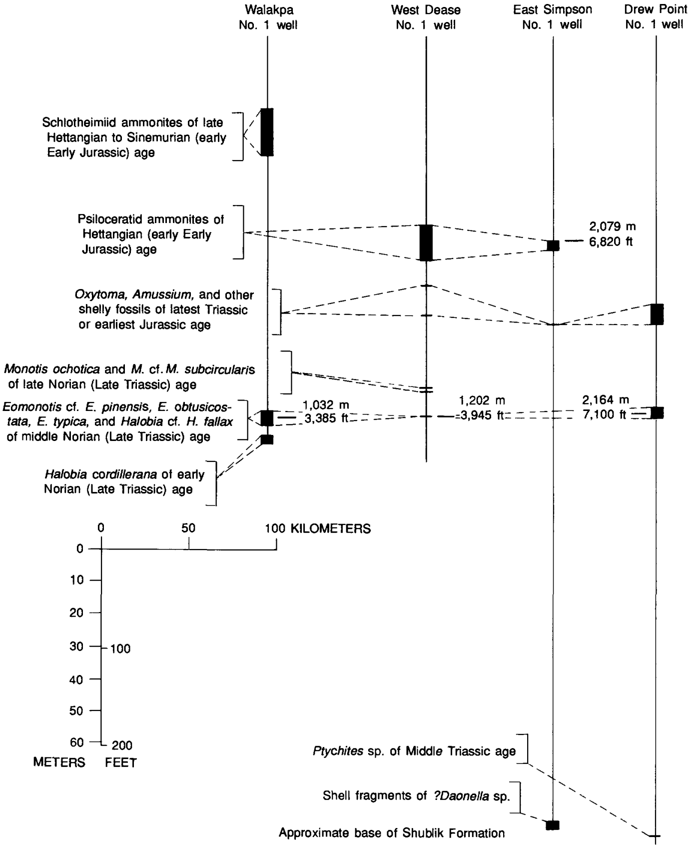


FIGURE 30.2.—Correlation of portions of four post-1975 NPRA test wells from which superposed age-diagnostic Triassic and Early Jurassic megafossils have been obtained (black bars show megafossil source intervals). Age-equivalent parts of these lower Mesozoic strata tend to be laterally similar in thickness because line of section connecting the four wells roughly parallels trend of Barrow Arch. Top of Shublik Formation approximately coincides with upper limit of upper Norian *Monotis*-bearing rocks.

Walakpa No. 1 well.—Core samples from two levels in this well produced megafossils of probable early Sinemurian age. Schlotheimiid ammonites have been identified from 935 and 948 m (3,068.8 and 3,110.8 ft), the former being a possible *Sulciferites*. Underlying beds at 1,025 m (3,362.8 ft) contain middle Norian bivalves.

South Meade No. 1 well.—The bivalves *Amussium* sp. and *Gryphaea*? sp. have been identified from a depth of 2,694 m (8,837.9 ft) and *Avicula* sp. from 2,698 m (8,850.2 ft). This shelly fauna is like the one associated with a species of *Oxytoma* in the East Simpson No. 1 well, regarded as Sinemurian in age by R.W. Imlay (written commun., 1969), and it also resembles faunas from beds of Hettangian or even latest Triassic age in other test wells.

Peard No. 1 well.—The bivalve *Oxytoma* sp., identified from a depth of 2,579 m (8,462.2 ft), and the lithology of the core at that level are like those in the Lower Jurassic interval of East Simpson No. 1 well, within 60 m (200 ft) above the top of the Shublik Formation.

UPPER TRIASSIC

The dominantly Upper Triassic Shublik Formation and its equivalents are the most fossiliferous and distinctive units in the geologic column in northern Alaska. Distinctive and easily recognizable bivalves are found in almost every outcrop or well that has been sampled in the region (fossil pl. 30.1). Eight of the wells examined in this study yielded Late Triassic fossils, and the correlation of four test wells yielding Late Triassic megafossils in sequence with younger and older early Mesozoic faunas is shown in figure 30.2. Two of these wells, Drew Point and Walakpa, produced especially interesting sequences of faunas that document much of the Late Triassic. The Drew Point core is particularly significant because it has yielded ammonites at two different levels, which is unusual in the Triassic of northern Alaska. As with the Lower Jurassic, the Upper Triassic sections of these wells are discussed in a general east-to-west direction through the region, starting with the Inigok well on the southeast and ending with the South Meade well in the west.

Inigok No. 1 well.—Shells of the bivalve *Halobia* are recorded from depths of 3,741 and 3,744 m (12,273.0 and 12,283.0 ft) in the core. At both levels, these are identified as *Halobia* cf. *H. superba* (Mojsisovics), indicating a late Karnian to early Norian age range.

Ikpikpuk No. 1 well.—A 6.9-m (22.6-ft) section of core from 3,131.4 to 3,138.3 m (10,273.5-10,296.1 ft) is crowded with *Halobia* shells. All of them are identified as either *Halobia* cf. *H. superba* (Mojsisovics) or *Halobia* cf. *H. cordillerana* Smith, or as related to those two groups of species. These species indicate a probable age range of late Karnian to early Norian, similar to that of the fossiliferous interval in the Inigok well. The name *Halobia superba* is used here for the morphologic group that also includes *H. zitteli* Lindstrom, a species commonly reported from the Upper Triassic of the Arctic.

Drew Point No. 1 well.—In the core from depths of 2,162 to 2,165 m (7,093.5-7,103 ft), the following molluscs have been determined: *Halobia* cf. *H. fallax* Mojsisovics, *Eomonotis* cf. *E. obtusicostata* (Westermann), and *Neohimavatites* cf. *N. canadensis* (McLearn). The species of flat clams are diagnostic of the middle Norian, but the ammonite compared with *Neohimavatites canadensis* permits a more precise assignment of this level to the uppermost of three subzones recognized by Tozer (1980) within the Columbianus Zone. This zone is at the top of the middle Norian as defined by Silberling and Tozer (1968). Comparable flat clams occur within 15 m (50 ft) of the top of the Shublik as found in the East Simpson No. 1 well, and in the Prudhoe Bay field they occur within 3-4.5 m (10-15 ft) below the Sag River Sandstone. Thus, this interval in the Drew Point well is near the top of the Shublik, the very highest beds of which just reach the upper Norian in most sections.

East Simpson No. 1 well.—Segments of core from depths of 2,264 to 2,266 m (7,427.1-7,435.5 ft) contain probable fragments of the flat clams *Daonella* or *Halobia*, along with abundant indeterminate pteriid and pectenid bivalves. Species having the ribbing characteristics of *Daonella* or *Halobia* are both Middle and Late Triassic in age. A Middle Triassic age, and a position near the base of the Shublik Formation, are implied by the stratigraphic position of these cores with respect to Lower Jurassic levels in this well (fig. 30.2).

West Dease No. 1 well.—This well is significant in the biostratigraphy of the Upper Triassic in that it includes most of the Norian in a span of less than 30 m (100 ft). In the depth interval 1,193 to 1,195 m (3,915-3,919.1 ft), *Monotis ochotica* (Keyserling) sensu stricto, *Monotis* cf. *M. subcircularis* Gabb, and *Oxytoma* sp. indicate an early late Norian age. *Halobia* cf. *H. fallax* Mojsisovics at 1,202 m (3,945 ft) indicates a middle Norian age, and a *Juvavites*-like haloritid ammonite at 1,217 m (3,992.2 ft) indicates a latest Karnian to middle Norian age range.

Walakpa No. 1 well.—The 15-m (50-ft) core from depths of 1,025 to 1,040 m (3,362.8-3,411.9 ft) is significant in that it documents the Karnian-Norian boundary within a few feet. The upper part of the core yields two species of the middle Norian flat clam *Eomonotis*. *Eomonotis* cf. *E. pinensis* (Westermann) occurs at 1,025 m (3,362.8 ft) and *E. typica* (Kiparisova) occurs at 1,029 m (3,376.1 ft). *Halobia* cf. *H. fallax* Mojsisovics and *Meleagrinella* sp., of early or middle Norian age, occur at 1,034 to 1,035 m (3,394-3,395.7 ft). *Halobia* cf. *H. cordillerana* Smith, probably early Norian in age, was recovered at 1,038 m (3,404.3 ft). Probable late Karnian Halobias of the *H. superba-zitteli* group were identified from a depth of 1,039 m (3,408 ft). Thus, the Karnian-Norian boundary falls in the short interval between 1,038 and 1,039 m (3,404.3 and 3,408 ft) in this core.

South Meade No. 1 well.—The depth interval between 2,756 and 2,761 m (9,043.4 and 9,057.9 ft) in this well contains numerous bivalves including: *Halobia* cf. *H. fallax* Mojsisovics, *Halobia* cf. *H. halorica* (Mojsisovics), *Chlamys* sp. indet., *Gryphaea*? sp., and indeterminate brachiopod fragments. The association of flat clam species indicates a middle Norian age.

Lisburne No. 1 well.—Four segments from core 10, at depths of 3,402 to 3,405 m (11,163-11,170 ft), contain flat clams identified as *Halobia* cf. *H. cordillerana* Smith, suggesting an early Norian age for these strata, which are the top beds in a particular thrust slice in this structurally complex core.

MIDDLE AND LOWER TRIASSIC

The only definite Middle Triassic fossil in the material from the NPRA wells occurs at 2,299 m (7,544 ft) in the Drew Point No. 1 well. The ammonite *Ptychites* sp. occurs with scraps of other fossils including bivalves, an orthoconic nautiloid cephalopod, and a rhynchonelloid brachiopod. This *Ptychi-*

tes indicates a late Anisian through Ladinian age and a stratigraphic position within a few meters (tens of feet) above the base of the Shublik Formation. The laminated siltstone or fine-grained sandstone from 3 m (10 ft) lower in the core is lithologically indistinguishable from the Fire Creek Siltstone Member of the Lower Triassic Ivishak Formation as it is exposed in the vicinity of Sag Lake and the Lupine River along the foothills of the Brooks Range in the northeastern Philip Smith Mountains quadrangle. The Fire Creek contains middle Early Triassic (Smithian) ammonites (Brosgé and others, 1979; Detterman and others, 1975). Thus, the base of the Shublik in the Drew Point well may fall within the interval 2,299 to 2,302 m (7,544-7,554 ft). As the top of the Shublik can be interpolated as being at approximately 2,150 m (7,050 ft), the total thickness of the Shublik Formation is apparently about 150 m (500 ft), somewhat greater than that of the type section at Fire Creek in northeastern Alaska.

In addition to the strata below 2,299 m (7,544 ft) in the Drew Point well, which may be Early Triassic in age on the basis of lithology and superposition, only two wells have yielded possible Early Triassic fossils. In the Tunalik No. 1 well, cores from depths of 4,699 to 4,705 m (15,415.8-15,436.1 ft) contain several impressions of a relatively high whorled, involute, smooth ammonite, which could well be of an Early Triassic kind but cannot be definitely identified. Other fossils include a smooth pteriid bivalve and several nondescript bivalves. These forms provide no definitive basis for an age determination. Another core segment, from 4,956 m (16,259.4 ft), also contains indeterminate impressions of bivalves and an ammonite that is different from those higher in the core. Although these may also be Early Triassic in age, the fossils are nondiagnostic.

In the Peard No. 1 well, three samples from a depth of 2,738 to 2,742 m (8,983.1-8,995.3 ft) contain fragments of *Lingula* aff. *L. borealis* Bittner. Specimens very like these occur in the Ledge Sandstone Member of the Ivishak Formation in northeastern Alaska (Detterman and others, 1975) and are reported from the Lower Triassic of northern Greenland and the Western United States. Although no definitive age can be assigned, the occurrence of *Lingula* indicates a very shallow littoral to subtidal depositional environment. *Lingula* is found today primarily in shallow nearshore environments, and modern forms can live in brackish water.

PALEOZOIC BIOSTRATIGRAPHY

In contrast to the fairly widespread distribution of Mesozoic megafossils in the NPRA, Paleozoic megafossils have been found in only four wells. Inigok and Ikpikpuk cores yielded the most complete, and nearly similar, sequences of Carboniferous and Permian megafossils. Permian fossils are also found in the Tunalik well, and possible Devonian plants are reported from near the bottom of the Inigok well.

PERMIAN

Two distinct ages of Permian faunas are found in the Inigok and Ikpikpuk wells. The younger one is similar to the mid-Permian shelly assemblage that is widespread in the lower part of the Ikiakpaurak Member—upper member of the Lower and Upper Permian Echooka Formation—in northeastern Alaska (Detterman and others, 1975). This assemblage occurs at depths of 4,221 to 4,229 m (13,848-13,874.5 ft) in the Inigok well. Fossils identified are: *Arctitreta*? sp., *Chonetina*? cf. *C.*? *superba* Gobbett, *Waagenoconcha* sp., *Liosotella* sp., *Rhynchopora* sp., *Stenocisma*? sp., *Spiriferella*? sp., and *Atomodesma* prisms. The age of this assemblage is probably late Leonardian to Wordian. A fauna of probably similar age is found in the Tunalik well at depths from 5,223 to 5,226 m (17,135-17,145.7 ft). This assemblage includes: fenestrate and rhomboporoid bryozoans, an indeterminate strophomenoid brachiopod, *Dyoros* cf. *D.* (*D.*) *angulatus* Cooper and Grant, *Horridonia*? sp., *Licharewia* sp., *Spiriferella* sp., *Martinia*? sp., *Spiriferellina*? sp., and indeterminate gastropod steinkerns.

The older of the two Permian assemblages occurs at depths of 4,273 to 4,287 m (14,020-14,066 ft) in the Inigok well and at depths of 3,572 to 3,576 m (11,718-11,733 ft) in the Ikpikpuk well. The taxa identified in Inigok are: *Chonetinella* sp., *Paucispinifera* sp., *Waagenoconcha* sp., *Spiriferella*? sp., *Licharewia* sp., *Martinia*? sp., *Attenuatella* sp., an indeterminate punctate spiriferoid, and indeterminate gastropods (fossil pls. 30.2, 30.4). From this core in the Inigok well, Anita Harris identified conodonts including *Neostreptognathodus pequopensis* Behnken and inferred a late Wolfcampian to middle Leonardian correlation (written commun., 1980). Most significant is the identification of fusulinids from a depth of 4,279 m (14,040 ft) by R.C. Douglass (written commun., 1979). These first Permian fusulinids reported from northern Alaska are *Pseudofusulinella* sp. aff. *P. valkenburghae* Petocz, a species reported by Petocz (1970) from his Zone B of the central Alaska Range sequence (fossil pl. 30.2). Petocz correlated Zone B with the Wolfcampian.

The taxa found in the Ikpikpuk well include many of the same forms as those in the Inigok well. The fauna consists of a wide variety of bryozoans, brachiopods, conodonts, and gastropods. The bryozoans were studied by Olgerts Karklins who identified the following forms: *Archimedes* sp., *Dyscritella* sp., *Fenestella* sp., *Penniretepora* sp., *Polypora* sp., *Streblotrypa* sp., and fragments of rhabdomesid, fistuliporoid, and dyscritellid genera that were not identifiable (fossil pl. 30.3). Brachiopods from the Ikpikpuk well include: *Leurosina* sp., *Dyoros*? sp., *Waagenoconcha*? sp., linoproductoids, indet., *Spiriferella* sp., *Attenuatella* sp., *Rhynchopora* sp., and *Spiriferellina*? sp. Gastropods identified by Ellis Yochelson (written commun., 1980) include *Peruvispira* cf. *P. delicatula* J. Chronic and *Straparollus* (*Euomphalus*) sp. Conodonts studied by Anita Harris (written commun., 1980) are like those in the Inigok well, including *Neostreptognathodus* cf. *N. pequopensis* Behnken, and have the same age significance.

This diversified invertebrate assemblage is like those found in the Joe Creek Member of the Echooka Formation in surface outcrops in the northeastern Brooks Range (Detterman and others, 1975) and also contains some of the brachiopods that are common in the Siksikpuk Formation in the western and central Brooks Range.

UPPER CARBONIFEROUS (PENNSYLVANIAN)

Late Carboniferous megafossils are reported from both the Inigok and Ikpikpuk wells. A colonial coral, *Heintzella jagoensis* (Armstrong), was identified by A.K. Armstrong from a depth of 4,635 m (15,205.5 ft) in the Inigok well and from 3,802 to 3,803 m (12,473.4-12,478 ft) in the Ikpikpuk well (fossil pl. 30.3). This coral, originally described by Armstrong (1972) from the Carboniferous Wahoo Limestone of the northeastern Brooks Range, where it occurs in beds that contain Zone 21 foraminifers, is an indicator of Atokan age. A rather diverse invertebrate shelly fauna from depths of 4,628 to 4,638 (15,185-15,215 ft) in the Inigok well includes: fenestrate and rhomboporoid bryozoans, *Platycrinites*? sp., indeterminate horn corals, *Conularia* sp., chonetid and productoid fragments, *Anthracospirifer* sp., *Neospirifer*? sp., *Cleiothyridina* sp., *Crurithyris*? sp., *Hustedia* sp., *Spiriferellina*? sp., fragments of indeterminate pelecypods, and the pygidium of a proetid trilobite—clearly an early Middle Pennsylvanian invertebrate assemblage.

Conodonts found in three of the northern wells in the upper part of the Lisburne Group indicate a Morrowan, Zone 20 age according to Anita Harris (written commun., 1980). In the J.W. Dalton well, taxa of an early to middle Morrowan conodont fauna are found at depths from 2,535 to 2,542 m (8,317-8,341.5 ft). Identified species include *Adetognathus spathus* (Dunn) and *Rachistognathus*? *minutus* (Higgins and Bouckaert). The latter species is also found in the W.T. Foran well at depths from 2,516 to 2,520 m (8,253-8,269 ft) and in the South Harrison Bay well from 3,235 to 3,239 m (10,613-10,626 ft). Harris stated: "Forms identical to specimens identified * * * as *Rachistognathus*? *minutus* have been reported from part of the upper Namurian A in Great Britain and Belgium (Higgins, 1975, as *Idiognathoides minutus*), from the lower middle Morrowan rocks in Nevada (Webster, 1969, as *Streptognathodus lanceolatus*), and occur in rocks of early to middle Morrowan age in northern Alaska (H.R. Lane, oral commun., 1980). *Adetognathus spathus* is known to range from the lowest Morrowan into the early Atokan."

LOWER CARBONIFEROUS (MISSISSIPPIAN)

Mississippian megafossils and conodonts are reported from only two wells. The Inigok well contains Late Mississippian fossils through about 300 m (1,000 ft) of beds below 4,933 m (16,185 ft), and the Lisburne well has Mississippian fossils in at least two of the thrust slices that were penetrated by that deep test.

From the Inigok well, Anita Harris reported (written commun., 1980) late Meramecian to Chesterian conodonts from cores 20 and 21. Taxa identified at depths from 4,933 to 4,937 m (16,185-16,197.7 ft) include *Adetognathus* or *Cavusgnathus*, "*Spathognathodus*" *minutus* (Ellison), and apatognathiform, ligonofiniform, and spathognathodiform elements. Those from 5,198 to 5,203 m (17,053-17,069.6 ft) include *Cavusgnathus unicornis* Youngquist and Miller, *Cavusgnathus* sp., and ligonodontiform elements. From depths of 5,203 to 5,207 (17,069.6-17,083 ft), Harris identified *Gnathodus nodosus* Bischoff. According to Harris: "*Gnathodus nodosus* has not been reported previously from North America. In Europe, it is known to range from the latest Viséan through the early Namurian (goniatite Zones P2 to E2c). These would equate to the latest Meramec through most of the Chester." Also identified from this lower level are fenestrate bryozoans, *Spirifer* aff. *S. leidyi* (Norwood and Pratten), and *Composita* sp. These fossils are compatible with a Late Mississippian, possibly early Chesterian, age.

In the Lisburne well, Mississippian fossils are identified from depths of 4,969 to 4,974 m (16,302-16,319.5 ft). There is some question about the age significance of these fossils, because the three lines of evidence appear contradictory. A single conodont was identified from 4,969 to 4,971 m (16,302-16,309 ft) by Harris as "*Bispathodus*" sp., which she reported as indicating most probably a latest Devonian through Kinderhookian age range. From the same sample, however, I.G. Sohn (written commun., 1980) identified several ostracodes that indicate a Kinderhookian to Osagean age range. This assemblage includes: *Beyrichiopsis* cf. *B. carinata carinata* Green, *B.* aff. *B. glyptopleuroides* Green, *Savagellites* sp., *Glyptopleuroides* spp., *Lichvinella* ex gr. *Glyptopleura plicata* (Jones and Kirkby), *Knoxiella archedensis* (Tsigova, 1958) Robinson, 1978, *Glyptolichvinella* cf. *G. simplex* Gurevich, 1966, *Microcheilinella* spp., *Glyptopleura* spp., *Hollinella* ex gr. *H. longispina* (Jones and Kirkby), *Hollinella* spp., *Shivaella* aff. *S. armstrongiana* (Jones and Kirkby), *Rectobairdia* cf. *R. confragosa* Green, *Geffenina* sp., *Cavellina* sp., and *Sansabella* sp.

From a depth of 4,974 m (16,319.5 ft), A.K. Armstrong identified a coral and a foraminifer that he suggested (written commun., 1980) were of late Meramecian (Mamet Foram Zones 13-15) age. He identified *Ekvasophyllum* aff. *E. proteus* Sutherland and *Endothyra* aff. *E. bowmani* Phillips.

As there is no apparent reason to dispute any of these age designations, the possibility that the thrust slice in which they occur is overturned should be taken into account. The Lisburne test penetrated very complex structures in the foothills belt, where stacked thrust sheets and overturning are commonplace.

UPPER DEVONIAN(?)

The oldest fossil material encountered in any of these wells is from a depth of 5,901 to 5,904 m (19,360-19,370 ft) in the Inigok well. According to S.H. Mamay (written commun., 1980), "This chip of black shale contains abundant fossil plant compressions, but these are all leafless, sterile, and otherwise nondiagnostic axial fragments. Although a positive age determination cannot be ventured on the basis of this sample, the absence of leaf fragments in such a dense concentration of axial material suggests the possibility that the fossils represent rubble from a truly leafless flora. This line of thought introduces the speculation that the plants are Devonian, but I emphasize that this is only a guess with no real substantiation." Because Mamay has examined dozens of plant collections from both the Upper Devonian and Lower Mississippian of northern Alaska, his speculation is probably valid. Consequently, this level is considered as of probable Late Devonian age.

UNRESOLVED ANOMALIES

The significance of several determinations remains unclear for a variety of reasons. The *Buchia* identification of D.L. Jones implies a late Tithonian age in the Ikpikpuk well, whereas the microfossils point to an Early Cretaceous age assignment. The collections attributed to the Lower Jurassic are not all based on equally firm paleontologic grounds. Definitive ammonites are identified from the East Simpson, West Dease, and Walakpa wells, and associated bivalves serve to correlate this level in four other wells. The possibility remains that some very uppermost Triassic strata may be included in some of the intervals here assigned to the Lower Jurassic. The paleontologic basis for assigning an Early Triassic age to beds in the Tunalik well is not at all firm, but the general kinds of fossils and the stratigraphic position make the age assignment a reasonable one. Early Permian brachiopods, conodonts, and fusulinids in the Inigok and Ikpikpuk cores all occur below levels that have been picked, on the basis of various criteria, as the top of the Lisburne Group by other workers. We emphasize that the brachiopods are like those found in the Joe Creek Member of the Echooka Formation in the northeastern Brooks Range, and we feel that assigning these strata to the Lisburne obscures important regional geologic correlations. One piece of core, reported to come from a depth of 4,629 to 4,633 m (15,186.5-15,201 ft) in the Inigok well, contains brachiopods of Permian aspect. Other fossils from this same level (*Heintzella jagoensis* and foraminifers) point to a Pennsylvanian (Atokan) age. At this time, we can offer no clear explanation for this anomaly. Three wells produced Morrowan conodonts at levels that, on the basis of other microfossil data, are assigned a Zone 21 (Atokan) age. The conodonts may have been reworked into younger beds or there may be some difficulty with the foraminiferal zonal assignments in the J.W. Dalton, W.T. Foran, and South Harrison Bay wells. All these problems deserve continued efforts to find their solutions.

REFERENCES CITED

Armstrong, A.K., 1972, Pennsylvanian carbonates, paleoecology, and rugose colonial corals, north flank, eastern Brooks Range, Arctic Alaska: U.S. Geological Survey Professional Paper 747, 21 p., 16 figs., 8 pls.

Brosgé, W.P., Reiser, H.N., Dutro, J.T., Jr., and Detterman, R.L., 1979, Bedrock geologic map of the Philip Smith Mountains quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-879-B, scale 1:250,000.

Detterman, R.L., Reiser, H.N., Brosgé, W.P., and Dutro, J.T., Jr., 1975, Post-Carboniferous stratigraphy, northeastern Alaska: U.S. Geological Survey Professional Paper 886, 46 p., 14 figs., 3 tables.

Higgins, A.C., 1975, Conodont zonation of the late Viséan-early Westphalian strata of the south and central Pennines of northern England: Great Britain Geological Survey Bulletin 53, 90 p., 14 figs., 18 pls., 5 tables.

Imlay, R.W., 1959, Succession and speciation of the pelecypod *Aucella*: U.S. Geological Survey Professional Paper 314-G, p. 155-169, fig. 36, pls. 16-19, 1 table.

——— 1961, Characteristic Lower Cretaceous megafossils from northern Alaska:

U.S. Geological Survey Professional Paper 335, 74 p., 1 fig., 24 pls., 14 tables.

Petocz, R.G., 1970, Biostratigraphy and Lower Permian Fusulinidae of the Upper Delta River area, East-Central Alaska Range: Geological Society of America Special Paper 130, 94 p., 7 figs., 10 pls., 29 tables.

Silberling, N.J., and Tozer, E.T., 1968, Biostratigraphic classification of the marine Triassic in North America: Geological Society of America Special Paper 110, 63 p., 1 fig., 1 pl.

Tozer, E.T., 1980, New genera of Triassic Ammonoidea: Geological Survey of Canada Current Research, pt. A, p. 107-113, 1 pl., 1 table.

Webster, G.D., 1969, Chester through Derry conodonts and stratigraphy of northern Clark and southern Lincoln Counties, Nevada: University of California Publications in Geological Sciences, v. 79, 105 p., 27 figs., 8 pls.

PLATES 30.1–30.4

[Contact photographs of the plates in this report are available, at cost, from the U.S. Geological Survey Photographic Library, Federal Center, Denver, CO 80225]

PLATE 30.1

Early Mesozoic mollusks from test wells in the National Petroleum Reserve in Alaska

[All figures natural size; photography by R.W. Burkholder]

FIGURES 1–3. *Monotis ochotica* (Keyserling). Late Norian (Late Triassic); West Dease No. 1 well, depth 1,195 m (3,919.1 ft). *Monotis* having this morphology are included by some authorities in the subgenus *Entomonotis*.

- 1,2. Left valves (along with fragmentary shells) showing the characteristically inflated shape and coarse ribbing. USNM 316127 and 316128, respectively.
- 3. Right valve showing the relatively flat valve. USNM 316129.

4. Psiloceratid ammonite resembling *Caloceras*. Hettangian (early Early Jurassic); East Simpson No. 1 well, depth 2,080 m (6,825.4 ft). Partial impression of inner whorls and a fragment of an outer whorl, presumably from the same individual. USNM 316130.

5. *Oxytoma* sp. Earliest Jurassic or possibly latest Triassic; East Simpson No. 1 well, depth 2,105 m (6,906.7 ft). USNM 316131.

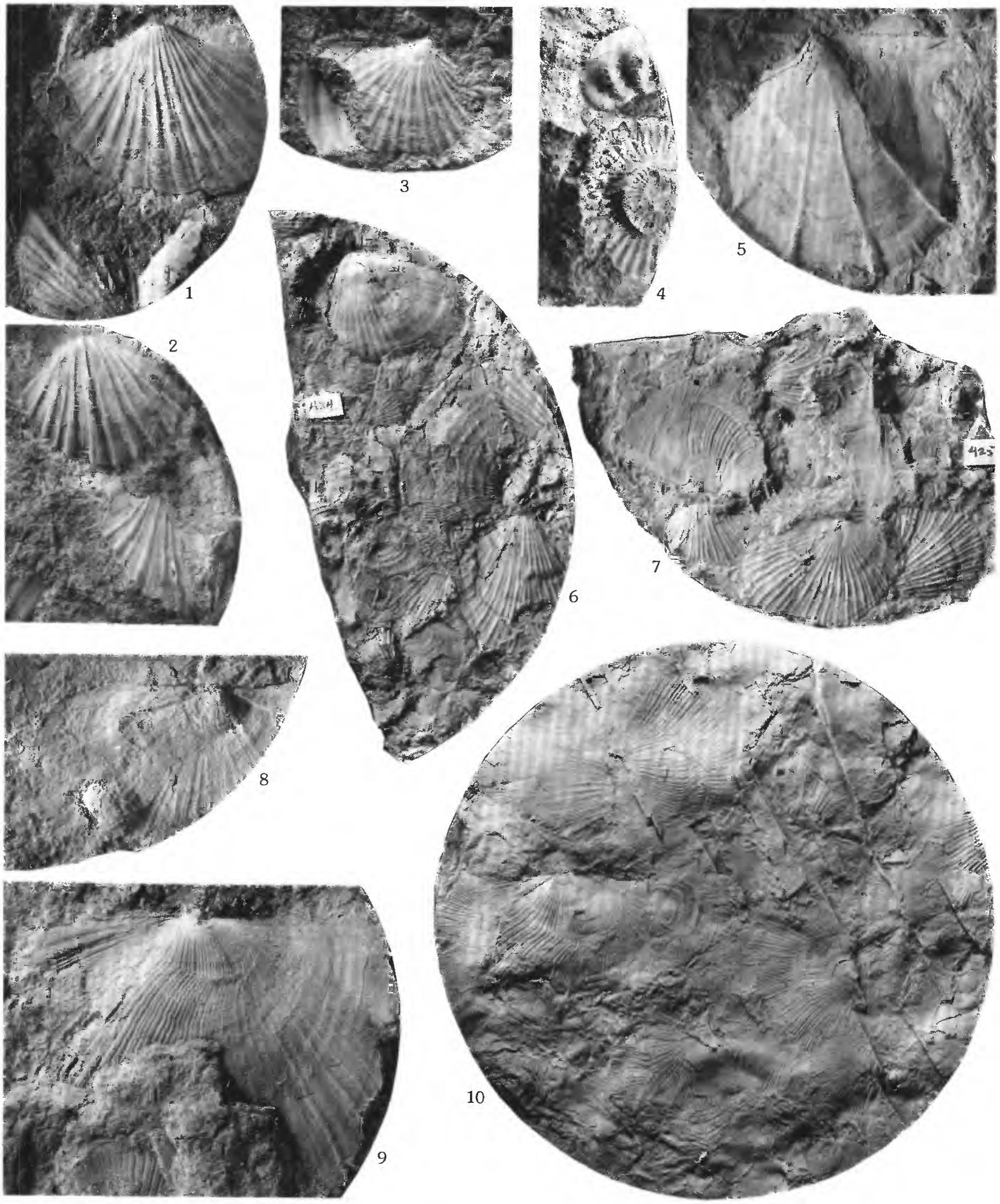
6–7. Associated specimens of *Eomonotis*, *Halobia*, and the ammonite *Neohimavatites*. Middle Norian (Late Triassic); Drew Point No. 1 well, depth 2,164 m (7,101 ft).

- 6. Whorl fragment of *Neohimavatites* cf. *N. canadensis* (McLearn) in center of slab; fairly complete left valves of *Eomonotis* cf. *E. obtusicostata* (Westermann) in upper left and lower right. USNM 316132.
- 7. Right valve of *Eomonotis* cf. *E. obtusicostata* (Westermann) in central lower part of slab showing the costate, poorly differentiated posterior ear characteristic of this subgenus. Other fragmentary bivalves include *Halobia* cf. *H. fallax* Mojsisovics, the most complete specimen of which on the left side of the slab is a negative impression. USNM 316133.

8–9. *Halobia* from Ikpikpuk No. 1 well.

- 8. Right valve of *Halobia* cf. *H. cordillerana* Smith. Early Norian (Early Triassic), depth 3,134 m (10,282.8 ft). USNM 316134.
- 9. Left valve of *Halobia* cf. *H. superba* Mojsisovics. Late Karnian (Late Triassic), depth 3,138 m (10,294.5 ft). This species name is used here in a group sense to include *H. superba*, *H. zitteli* Lindström and similar species. USNM 316135.

10. Characteristic profusion of incomplete shells of *Halobia* cf. *H. superba* Mojsisovics on parting surface of core segment. Late Karnian; Inigok No. 1 well, depth 3,744 m (12,283 ft). USNM 316136.



MONOTIS, CALOCERAS?, OXYTOMA, EOMONOTIS, HALOBIA, NEOHIMAVATITES

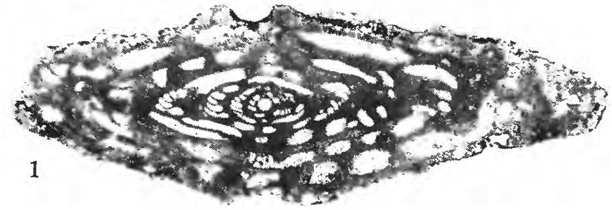
PLATE 30.2

Early Permian fusulinids and brachiopods from test wells in the National Petroleum Reserve in Alaska

FIGURES 1–3. *Pseudofusulinella* sp. aff. *P. valkenburghae* Petocz, 1970. Axial sections of three specimens, X20; Inigok No. 1 well, depth 4,279 m (14,040 ft); probably Wolfcampian Zone B of Petocz, 1970.

1. USGS f14035-2, USNM 316137.
2. USGS f14035-4, USNM 316138.
3. USGS f14035-7, USNM 316139.

4. Surface of piece of core, same depth as figures 1-3, showing several randomly oriented specimens of *Pseudofusulinella* sp. aff. *P. valkenburghae* Petocz, 1970. USGS f14035-3, USNM 316140.
5. *Licharewia* sp. Brachial valve, ×2; USNM 316141; Inigok No. 1 well, depth 4,275 m (14,025.4 ft). Early Permian.
6. *Waagenoconcha* sp. Pedicle valve, ×2; USNM 316142; Inigok No. 1 well, depth 4,282 m (14,047.4 ft). Early Permian.
7. *Paucispinifera* sp. Pedicle valve above, brachial valve below, partly crushed, ×2; USNM 316143; Inigok No. 1 well, depth 4,277 m (14,033.3 ft). Early Permian.



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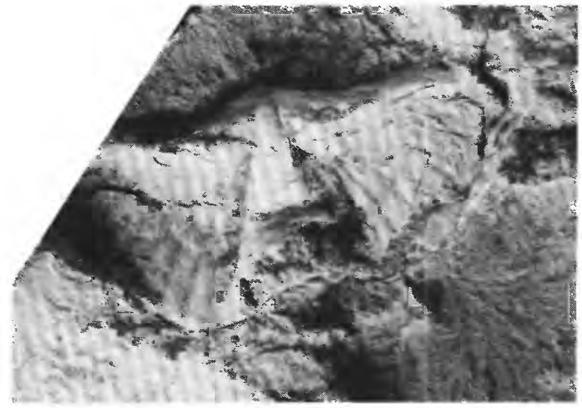

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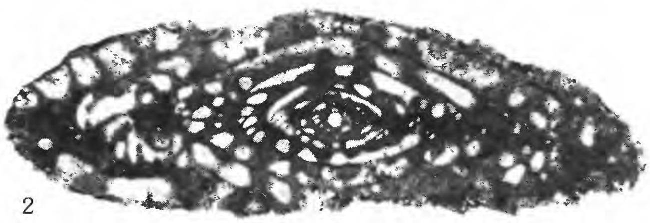

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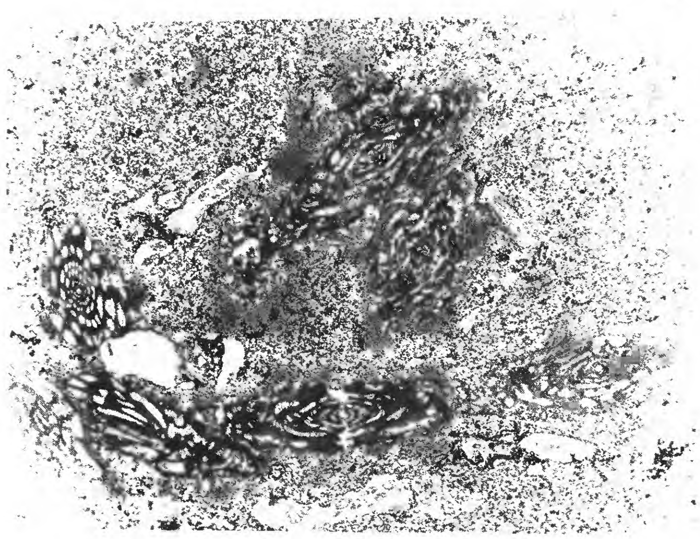


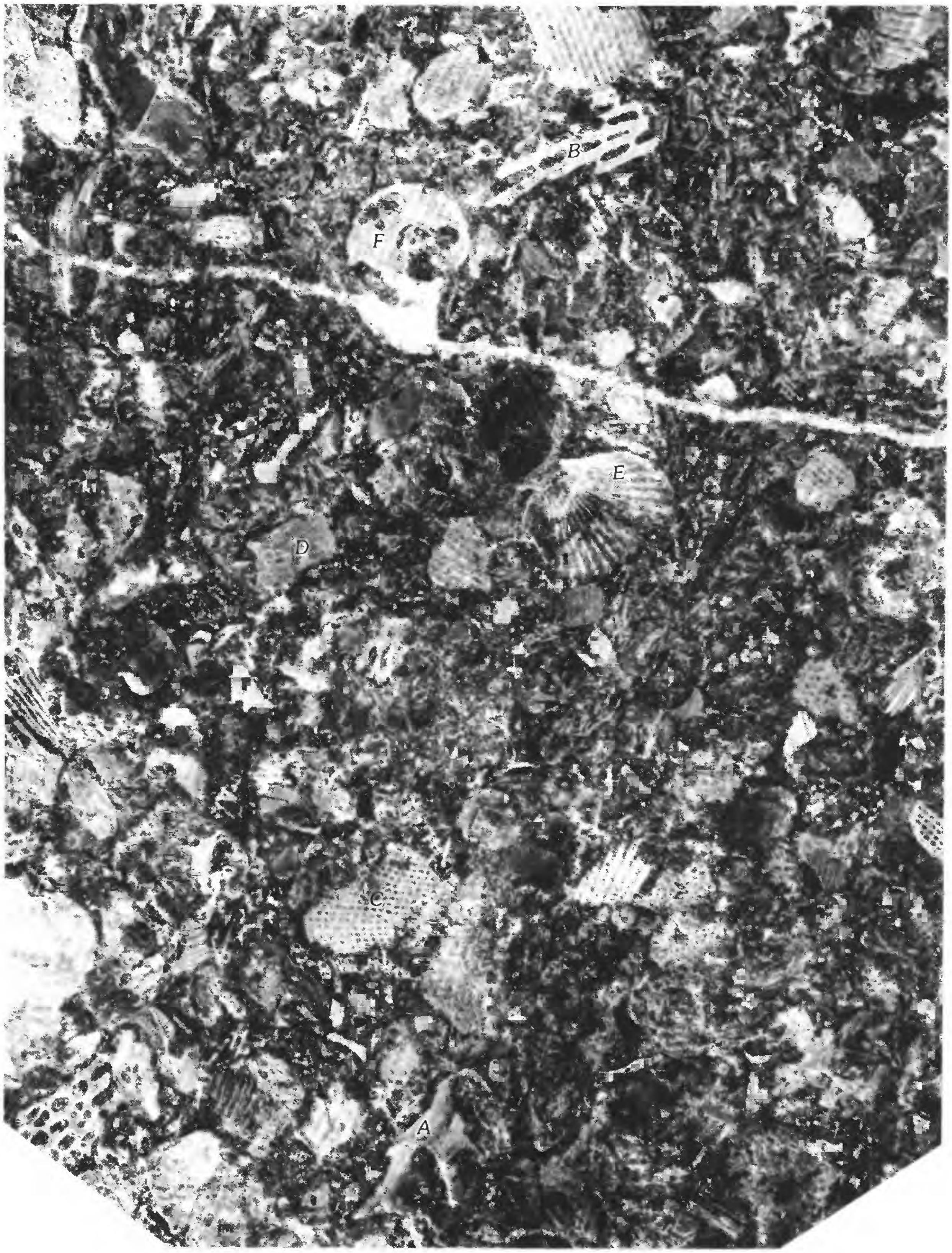
7

PSEUDOFUSULINELLA, LICHAREWIA, WAAGENOCONCHA, PAUCISPINIFERA

PLATE 30.3

Early Permian bryozoans, brachiopod, and gastropod from test wells in the National Petroleum Reserve in Alaska

FIGURE 1. Surface of part of core from Ikpikpuk No. 1 well, depth 3,573 m (11,723.5 ft). ×2; USGS loc. 27664-PC, USNM 316144; A, *Archimedes* sp.; B, *Polypora* sp.; C, *Fenestella* sp.; D, fistuliporoid, indet.; E, *Rhynchopora* sp.; F, possible euomphalacean gastropod, indet.; Early Permian.



ARCHIMEDES, POLYPORA, FENESTELLA, RHYNCHOPORA

PLATE 30.4

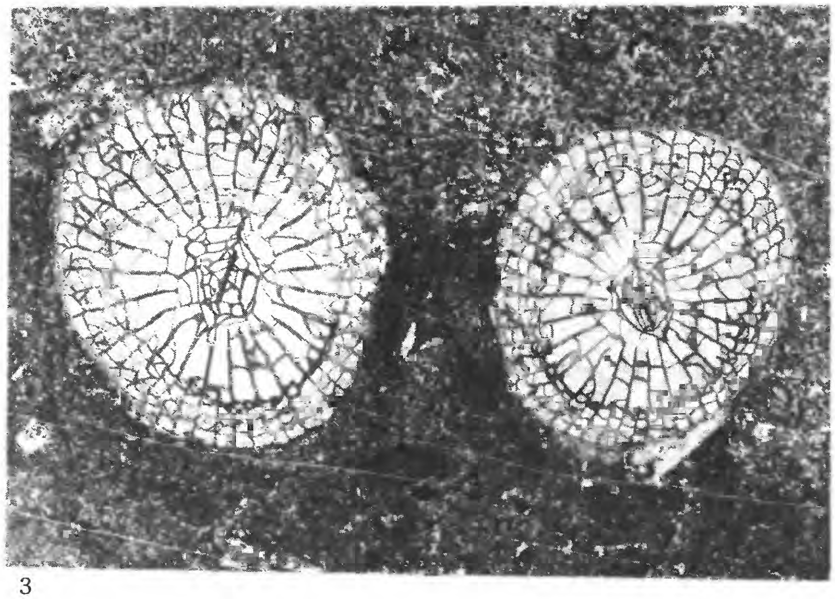
Pennsylvanian coral and Early Permian brachiopods from test wells in the National Petroleum Reserve in Alaska

FIGURE 1–3. *Heintzella jagoensis* (Armstrong); Inigok No. 1 well, depth 4,635 m (15,205.5 ft); Pennsylvanian, Zone 21 of Mamet (Atokan).

1. Oblique transverse section of a corallite, ×3, USNM 316145.
2. Oblique transverse section of another corallite, ×3, USNM 316146.
3. Axial sections of two corallites, ×3, USNM 316147.

4. *Attenuatella* sp. Pedicle valve and several other partly crushed specimens, ×2; USNM 316148; Inigok No. 1 well, depth 4,273 m (14,020.0 ft). Early Permian.

1



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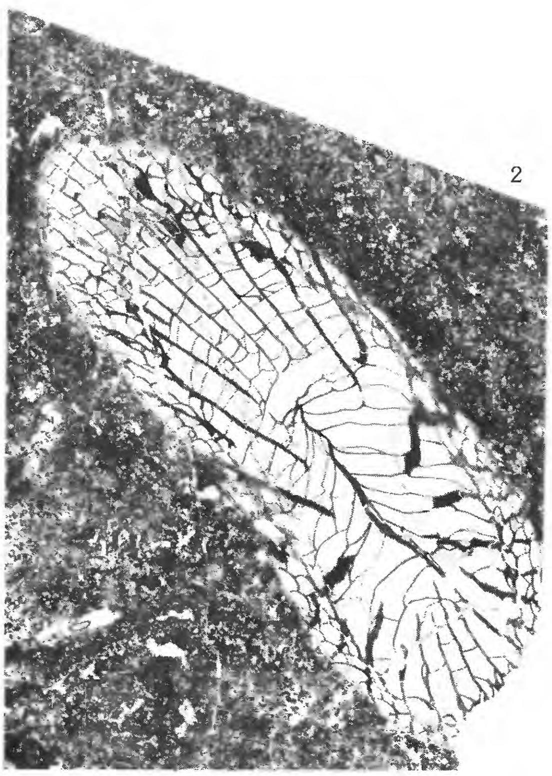

2

HEINTZELLA, ATTENUATELLA

31. EARLY MISSISSIPPIAN (TOURNAISIAN) OSTRACODES FROM THE LISBURNE TEST WELL, NORTHERN ALASKA

By ISRAEL GREGORY SOHN

INTRODUCTION

Anita G. Harris processed limestone sample 27660-PC, core 18, from a depth of 4,968.84 to 4,970.98 m in the Lisburne No. 1 test well, National Petroleum Reserve in Alaska, and recovered poorly preserved silicified ostracodes. The well is located in the disturbed belt, SE¼ sec. 17, T. 11 S., R. 16 W., lat 68°29'0.54381", long 155°41'35.510". A crushed duplicate sample from a depth of 4,968.84 to 4,970.37 m yielded a few unidentifiable fragments and steinkerns and one carapace of *Microcheilinella* Geis, 1933. The crushed limestone was dissolved in acetic acid, from which the fine material was periodically removed, and yielded additional poorly preserved replaced ostracodes, including some that were not represented in the original sample (pl. 31.1, fig. 21; pl. 31.2, fig. 19). The ostracodes indicate a probable Kinderhookian and (or) Osagean age for the rocks. The assemblage differs, on the species level, from congeneric Meramecian ostracodes in the Brooks Range, and there are a few taxa not found in the Meramecian assemblages. In addition to the ostracodes, steinkerns of minute gastropods and pelecypods, brachiopod and echinoderm spines, fish teeth, fragments of bryozoans, and one conodont were recovered. These associated fossils confirm the marine shelf environment indicated by the ostracodes. Because of poor preservation and meager representation of conspecific specimens, the ostracodes are illustrated in open nomenclature. The presently known stratigraphic ranges of the known genera are indicated.

OSTRACODE ASSEMBLAGE

The illustrated specimens are neither listed above the generic level nor classified in a biological system. The assigned USNM numbers are from the Paleobiology collection of the National Museum of Natural History, Washington, D.C.

Genus MICROCHEILINELLA Geis, 1933

Recorded stratigraphic range:—Devonian through Middle Triassic.

Microcheilinella sp.
Plate 31.1, figs. 1-3

Remarks.—The specimens on hand may represent more than one species. The illustrated carapace is approximately 0.52 mm long.

Age.—Nondiagnostic.

Genus BEYRICHIOPSIS Jones and Kirkby, 1886

Recorded stratigraphic range:—Upper Devonian through Lower Pennsylvanian

Beyrichiopsis aff. B. glyptopleuroides Green, 1963
Plate 31.1, figs. 4-6

Remarks.—The illustrated right valve, 1.1 mm long, has an oval surface carina within the variation illustrated by Green (1963, pl. 4, figs. 2, 3, 5-11) in the type series. Specimens in the Alapah Limestone (Meramecian and Chesterian) differ in the shape of the surface carina and in having a deeper subcentral pit. A very poorly silicified right valve having the posterior quarter missing, similar to the illustrated specimen, is present in either the Kayak or the Utukok Formation from lat 68°08'51", long 163°15'14", De Long Mountains quadrangle (field no. 79CX119A); this sample was determined by Anita G. Harris to be Osagean or Meramecian in age (written commun. NPRA-79-4, January 18, 1980). In addition, another valve partly covered by pyrite was recovered from the Kayak Shale, Utukok River quadrangle, Anisak River, lat 68°31'15", long 159°36'30" (field no. 78 EK33L).

Age.—Kinderhookian or Osagean.

Beyrichiopsis cf. B. carinata carinata Green, 1963
Plate 31.1, figs. 20, 21

Remarks.—One left valve approximately 0.75 mm long was recovered. The type series of Green's subspecies ranges in length from 0.73 to 0.91 mm, and the holotype has a better defined anterior node.

Age.—Late Kinderhookian.

New genus and species A
Plate 31.1, figs. 7-12

Remarks.—This is the most abundant taxon; 15 poorly preserved specimens were recovered. A single valve is approximately 0.75 mm long, and the carapace is approximately 0.70 mm long. Polenova (1953, pl. 2, fig. 7) illustrated in lateral and dorsal views a carapace

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of an "instar," which she identified as *Menerella krestovnikovi* Egorov, 1950, from the Upper Devonian of the U.S.S.R., that belongs to this undescribed genus. The Devonian species differs in that the dorsal nodes are rounded and the curved ridge does not extend to the dorsal margin.

Age.—Nondiagnostic.

New genus and species B

Plate 31.1, figs. 13-15

Remarks.—Only the illustrated valve, approximately 0.83 mm long, is available. The thin object on the posterior lobe is a hairlike fiber and not part of the specimen, as is clearly shown on figure 13 where it overhangs the dorsal margin. This specimen differs from the new genus and species A in that the poserior lobe trends down and backwards to well below midheight; it also lacks a large anterior node.

Age.—Nondiagnostic.

Genus GLYPTOPLEUROIDES Croneis and Gale, 1939

Recorded stratigraphic range.—Mississippian.

Glyptopleuroides sp.

Plate 31.1, figs. 16-19

Remarks.—Carapaces belonging to possibly more than one species, including one carapace that might be referred to *Moorites* Coryell and Billings, 1932, were recovered. The carapace illustrated in figures 16 and 17 is approximately 0.6 mm long, and the one shown in figures 18 and 19 is approximately 0.55 mm long.

Age.—Mississippian.

Genus GLYPTOPLEURA Girty, 1910

Recorded stratigraphic range.—Mississippian through Permian.

Glyptopleura sp. 1

Plate 31.1, fig. 22

Remarks.—Valves and fragments belonging to at least three species were recovered. The illustrated specimen, approximately 1.7 mm long, differs from *G. genevievea* Brayer, 1932, from the Salem Limestone (Meramecian) of Missouri in the curvature and junction at the posterior of the costae located second from the dorsal and ventral margins.

Age.—Nondiagnostic, post-Devonian.

Glyptopleura sp. 2

Plate 31.1, fig. 23

Remarks.—This right valve, probably 1.7 mm long, is illustrated to show the variation in the configuration of the costae on the surface of the valve in species of *Glyptopleura.* Blumenstengel (1977) demonstrated that the costae are added during the ontogeny in the Dinantian species *G. ruegensis* Blumestengel, 1977, and *G. varicostata* Blumenstengel, 1977, from a borehole in the Isle of Rügen. Because both illustrated specimens are larger than 1 mm and are therefore mature individuals, the differences in the configuration of the costae suggest different species.

Age.—Nondiagnostic, post-Devonian.

Genus SAVAGELLITES Pribyl, 1953

Recorded stratigraphic range.—Mississippian.

Savagellites sp.

Plate 31.1, figs. 24-27

Remarks.—The specimen illustrated in figures 24-26 is approximately 0.85 mm long and represents a young growth stage; the right valve illustrated in figure 27 is approximately 1.45 mm long and may also be a growth stage. This species resembles an undescribed species from the Gilmore City Limestone (Kinderhookian or lower Osagean) from Iowa that reaches a length of 2.6 mm.

Age.—Kinderhookian or early Osagean.

Genus GEFFENINA Coryell and Sohn, 1938

Recorded stratigraphic range.—Mississippian through Pennsylvanian.

Geffenina sp.

Plate 31.2, figs. 1-3

Remarks.—The illustrated specimen is approximately 0.8 mm long and is the best preserved among four valves. Blaszyk and Natusiewicz (1973, p. 127, pl. 27, figs. 3a-d) described a Namurian species from a borehole in northwestern Poland.

Age.—Nondiagnostic, post-Devonian.

Genus? CAVELLINA Coryell, 1928

Recorded stratigraphic range.—Silurian(?), Devonian through Permian(?).

Cavellina sp.

Plate 31.2, figs. 4, 5

Remarks.—The illustrated specimen is a carapace approximately 0.7 mm long and having part of the left valve missing. It was examined with the scanning electron microscope in the hope that the diagnostic muscle-scar pattern had been preserved; unfortunately, it had not. Consequently, only the dorsal and right views are illustrated.

Age.—Nondiagnostic.

Genus indet.

Genus and species indet.

Plate 31.2, figs. 6-8

Remarks.—The illustrated unique right valve, approximately 1.65 mm long, could belong to *Bythocyproidea* Stewart and Hendrix, 1945, described from the Middle Devonian as having a posterior ridge on the right valve only, or to a healdiid genus that has ridges on both valves. Because the left valve is unknown, a generic assignment is not possible.

Age.—Indeterminate.

Genus KNOXIELLA Egorov, 1950

Remarks.—This genus was considered a synonym of *Hypotetragona*

Morey, 1935 (Sohn *in* Moore, 1961, p. 183). Because Robinson (1978) illustrated a species as *Knoxiella archedensis* (Tschigova [Chizhova], 1958), that generic designation is used.

Recorded stratigraphic range.—Upper Devonian through Carboniferous.

?Knoxiella archedensis
(Tschigova, 1958) sensu Robinson, 1978.
Plate 31.2, figs. 9, 10

Remarks.—The illustrated left valve, approximately 0.8 mm long, is the only specimen available. Robinson (1978, pl. 5, figs. 7a,b) illustrated two carapaces 1.12 and 1.13 mm long from the Courceyan of England in which the left valve is overlapped by the right; consequently, the posterior margin of the smaller valve does not match exactly the posterior outline of the specimen illustrated by Robinson.

Age.—Tournaisian.

Genus GLYPTOLICHVINELLA
Posner *in* Gurevich, 1966

Recorded stratigraphic range.—Tournaisian and Visean(?).

Glyptolichvinella cf. G. simplex
Gurevich, 1966
Plate 31.2, figs. 11-13

Remarks.—The illustrated specimen, approximately 0.8 mm long, differs from the holotype of the nominate species in that the posterior margin of the valve on hand is more convex and bends forward at the level of the subcentral pit, whereas in the Russian specimen that portion of the margin is almost straight. However, a second right valve, approximately 0.85 mm long and not so well preserved, has a broader posterior curve along the dorsal portion.

Age.—Probably Kinderhookian or Osagean.

Genus LICHVINELLA
Posner *in* Gurevich, 1966

Recorded stratigraphic range.—Lower Carboniferous (Tournaisian).

Lichvinella aff. Glyptopleura plicata
(Jones and Kirkby) Chizhova, 1977.
Plate 31.2, figs. 14-17

Remarks.—Only one right valve, approximately 1.6 mm long and having part of the posterior missing, is available. Figure 17 is a posterior oblique view of the posteroventral spine.

Age.—Early Mississippian (Tournaisian).

Genus SHIVAELLA Sohn, 1971

Recorded stratigraphic range.—Mississippian through Pennsylvanian.

Shivaella aff. S. armstrongiana
(Jones and Kirkby, 1886)
Plate 31.2, figs. 18, 19

Remarks.—Only the illustrated specimen, a left valve approximately 1.42 mm long and having the ventral part missing, is available.

Age.—Nondiagnostic.

Genus HOLLINELLA Coryell, 1928

Recorded stratigraphic range.—Middle Silurian through Permian.

Hollinella sp.
Plate 31.2, fig. 20

Remarks.—Fragments of *Hollinella* are present. These neither confirm nor contradict the Kinderhookian or early Osagean age based on some of the other ostracodes in the assemblage.

Age.—Nondiagnostic.

Hollinella n.sp. ex gr. H. longispina
(Jones and Kirkby, 1886)
Plate 31.2, fig. 21

Remarks.—The illustrated specimen, approximately 1.45 mm long, differs from *H. swainia* Brayer, 1952, from the Salem Limestone (Meramecian) of Missouri in that the ventral margin is not as convex, resulting in a narrower outline; it also has an additional spinelet nearer to the contact margin than the other two more robust spines.

Age.—Nondiagnostic.

Genus RECTOBAIRDIA Sohn, 1960

Recorded stratigraphic range.—Middle Devonian through Permian.

Rectobairdia cf. R. confragosa Green, 1963
Plate 31.2, figs. 22-25

Remarks.—The illustrated specimen, approximately 0.9 mm long, is one of the better preserved specimens, even though the anterior is missing. Fragments and steinkerns that belong to other bairdiid genera were also recovered.

Age.—Kinderhookian or early Osagean.

REFERENCES CITED

Blaszyk, Janusz, and Natusiewicz, Danuta, 1973, Carboniferous ostracodes from the borings in northwestern Poland: Acta Palaeontologica Polonica, v. 18, no. 1, p. 117-151, pls. 25-37.

Blumenstengel, Horst, 1977, Zur Gattung *Glyptopleura* Girty (Ostracoda) aus dem Dinant von Rügen [On the genus *Glyptopleura* Girty (Ostracoda) from the Dinantian of Rügen]: Zeitschrift für Geologische Wissenschaften, v. 5, no. 10, p. 1235-1251, 3 pls.

Chizhova, V.A. (Tschigova), 1977, Stratigrafiya i korrelyatsiya neftegazonosnykh otlozhenii Devona i Karbona Evropeiskoi chasti SSSR i zarubezhnykh stran [Stratigraphy and correlation of Devonian and Carboniferous oil- and gas-bearing deposits, European part of the USSR and foreign countries]: Moscow, Izdat "Nedra," 263 p., 47 pls.

Green, Robert, 1963, Lower Mississippian ostracodes from the Banff Formation, Alberta: Research Council of Alberta Bulletin 11, 237 p., 17 pls.

Gurevich, K.Ya., 1966, O priznakakh polovogo dimorfizma rodov *Lichvinella* i *Glyptolichvinella* iz rannego Karbona Volyno-Podolii, p. 34-49, 4 pls., *in* Vyalov, O.S., ed., Iskopaemye ostrakody (Lvov, 1963): Kiev, Akademiya Nauk Ukrainskoy SSR, 191 p. [Manifestation of sexual dimorphism in the genera *Lichvinella* and *Glyptolichvinella* from the Early Carboniferous of Volynia-Podolia, p. 36-55, 4 pls., *in* Vyalov, O.S., ed., Fossil Ostracoda, Papers from the First All-Union Symposium on fossil Ostracoda (Lvov, 1963): Kiev, Akademia Nauk Ukrainian SSR, Israel Program for Scientific Translations, 215 p.]

Moore, R.C., ed., 1961, Treatise on invertebrate paleontology—Part Q, Arthropoda 3, Ostracoda: New York, Geological Society of America, 442 p., 334 figs.

Polenova, E.N., 1953, Ostrakody devonskikh otlozhenii Tsentral'nogo devonskogo polya i Srednego Povolzh'ya: Vsesoyuznogo Neftyanogo Nauchno-Issledovatel'skogo Geologo-Razvedochnogo Instituta (VNIGRI) Trudy, n. ser. 68, 155 p., 14 pls. [Ostracoda of the Devonian deposits in the central Devonian field and the middle Volga region: Leningrad, Gostoptekhizdat (Jerusalem, Israel Program for Scientific Translations)].

Robinson, Eric, 1978, The Carboniferous, p. 121-166 *in* Bate, R.H. and Robinson, Eric, eds., Stratigraphical index of British Ostracoda: Geological Journal Special Issue 8, Liverpool, Seel House Press, 538 p.

PLATES 31.1, 31.2

[Contact photographs of the plates in this report are available, at cost, from the U.S. Geological Survey Photographic Library, Federal Center, Denver, CO 80225]

PLATE 31.1

Early Mississippian ostracodes from the Lisburne test well, Alaska

FIGURES 1–3. *Microcheilinella* sp., carapace, USNM 307512, approx. ×80.
  1. Dorsal view (anterior to left).
  2. Posterior view.
  3. Left view.

4–6. *Beyrichiopsis* aff. *B. glyptopleuroides* Green, 1963, right valve, USNM 307513, approx. ×40.
  4. Dorsal view (anterior to left).
  5. Outside view.
  6. Inside view.

7–9. New genus and species A, right valve, USNM 307514, approx. ×60.
  7. Dorsal view (anterior to left).
  8. Outside view.
  9. Inside view.

10–12. New genus and species A, partly silicified carapace, USNM 307515, approx. ×60.
  10. Dorsal view (anterior to left).
  11. Left view.
  12. Right view.

13–15. New genus and species B, right valve, USNM 307516, approx. ×60.
  13. Inside view.
  14. Dorsal view (anterior to left).
  15. Outside view.

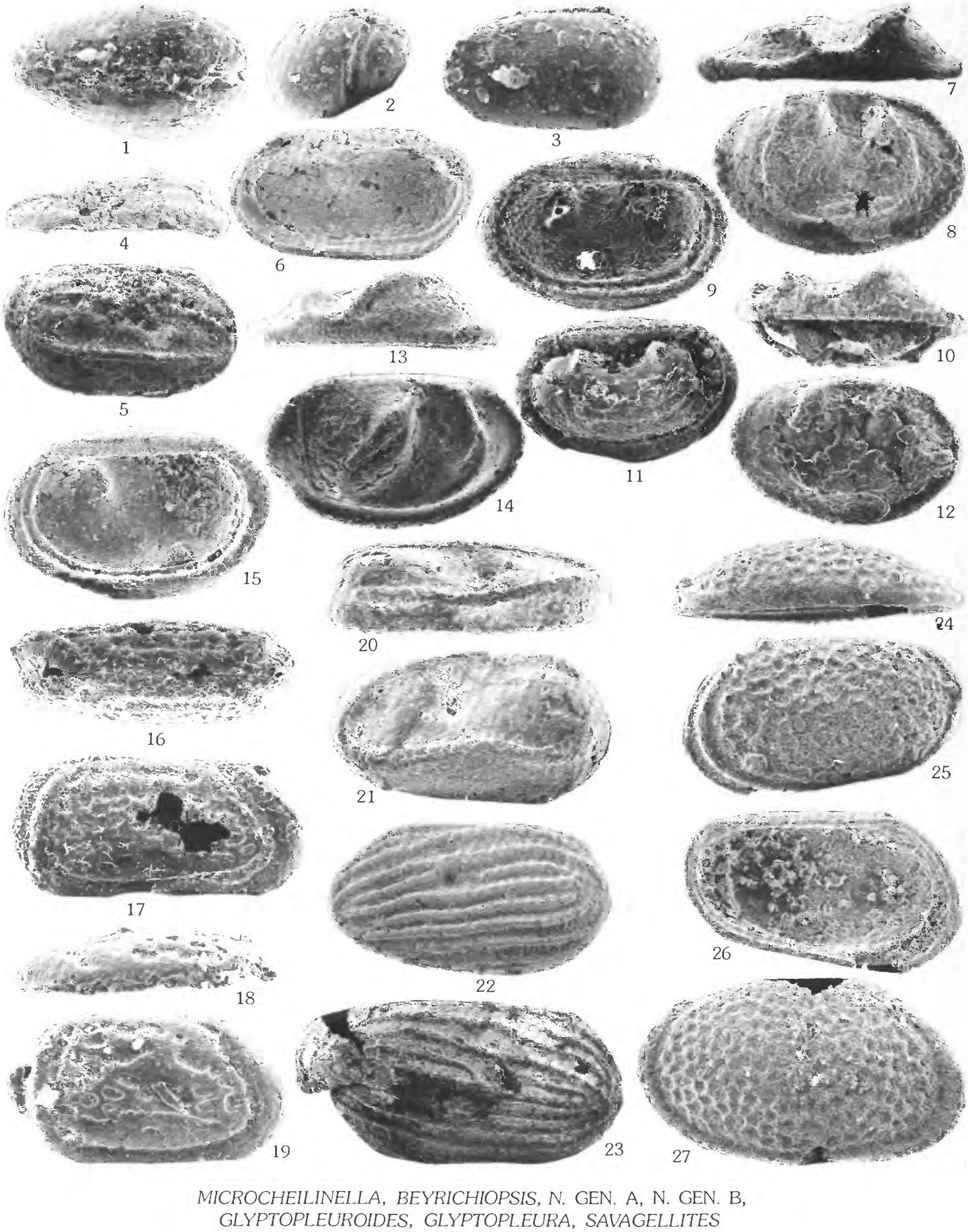
16–19. *Glyptopleuroides* sp.
  16. Dorsal view (anterior to right) of carapace, USNM 307517, approx. ×80.
  17. Right view of carapace, USNM 307517, approx. ×80.
  18. Dorsal view (anterior to left) of right valve, USNM 307518, approx. ×80.
  19. Outside view of right valve, USNM 307518, approx. ×80.

20, 21. *Beyrichiopsis* cf. *B. carinata carinata* Green, 1963, left valve, USNM 307519, approx. ×63.
  20. Dorsal view (anterior to right).
  21. Outside view.

22. *Glyptopleura* sp. 1, outside view of left valve, USNM 307520, approx. ×30.

23. *Glyptopleura* sp. 2, outside view of right valve, USNM 307521, approx. ×33.

24–27. *Savagellites* sp.
  24. Dorsal view (anterior to right) of left valve, USNM 307522, approx. ×60.
  25. Outside view of left valve, USNM 307522, approx. ×60.
  26. Inside view of left valve, USNM 307522, approx. ×60.
  27. Outside view of right valve, USNM 307523, approx. ×40.



MICROCHEILINELLA, *BEYRICHIOPSIS*, *N.* GEN. A, N. GEN. B,
GLYPTOPLEUROIDES, *GLYPTOPLEURA*, *SAVAGELLITES*

PLATE 31.2

Early Mississippian ostracodes from the Lisburne test well, Alaska

FIGURES 1–3. *Geffenina* sp., left valve, USNM 307524, approx. ×60.
- 1. Dorsal view (anterior to right).
- 2. Outside view.
- 3. Ventral view (anterior to left).

4, 5. *Cavellina*? sp., specimen with left valve removed, USNM 307525, approx. ×63.
- 4. Ventral view (anterior to right).
- 5. Right view.

6–8. Genus and species indeterminate, right valve, USNM 307526, approx. ×40.
- 6. Dorsal view (anterior to left).
- 7. Outside view.
- 8. Posterior view.

9, 10. ?*Knoxiella archedensis* (Tschigova, 1958) sensu Robinson, 1978, left valve, USNM 307527, approx. ×60.
- 9. Dorsal view (anterior to right).
- 10. Outside view.

11–13. *Glyptolichvinella* cf. *G. simplex* Gurevich, 1966, right valve, USNM 307528, approx. ×63.
- 11. Dorsal view (anterior to left).
- 12. Outside view.
- 13. Inside view.

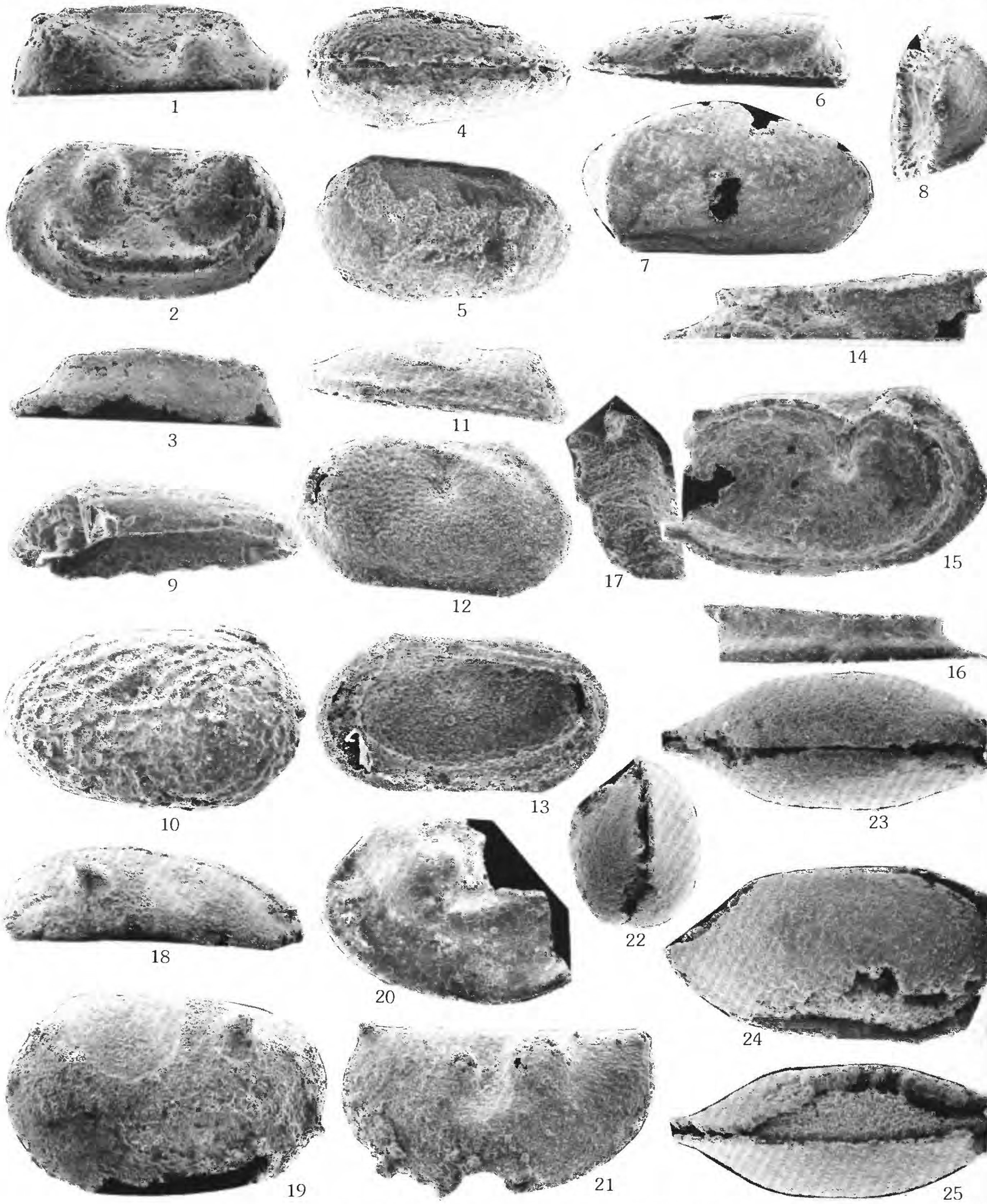
14–17. *Lichvinella* ex gr. *Glyptopleura plicata* (Jones and Kirkby, 1867) Chizhova, 1977, USNM 307529.
- 14. Dorsal view (anterior to left) of right valve, approx. ×80.
- 15. Outside view of right valve, approx. ×80.
- 16. Ventral view (anterior to right) of right valve, approx. ×80
- 17. Posterior oblique detail of posteroventral spine, approx. ×110.

18, 19. *Shivaella* aff. *S. armstrongiana* (Jones and Kirkby, 1886), left valve, USNM 307530, approx. ×40.
- 18. Dorsal view (anterior to right).
- 19. Outside view.

20. *Hollinella* sp., outside view of anterior part of broken left valve, USNM 307531, approx. ×33.

21. *Hollinella* ex gr. *H. longispina* (Jones and Kirkby, 1886), outside view of left valve, USNM 307532, approx. ×40.

22–25. *Rectobairdia* cf. *R. confragosa* Green, 1963, poorly preserved carapace with anterior missing, USNM 307533, approx. ×60.
- 22. Posterior view.
- 23. Dorsal view (anterior to right).
- 24. Right view.
- 25. Ventral view (anterior to right).



GEFFENINA, CAVELLINA? ?KNOXIELLA, GLYPTOLICHVINELLA, LICHVINELLA SHIVAELLA, HOLLINELLA, RECTOBAIRDIA

32. DISTRIBUTION PATTERNS OF FACIES, RADIOLARIANS, AND CONODONTS IN THE MISSISSIPPIAN TO JURASSIC SILICEOUS ROCKS OF THE NORTHERN BROOKS RANGE, ALASKA

By Benita L. Murchey, David L. Jones,[1] Brian K. Holdsworth,[2] and Bruce R. Wardlaw

INTRODUCTION

Mississippian to Jurassic fine-grained siliceous rocks in the northern Brooks Range of Alaska constitute one of the longest known records of continuous deposition of siliceous pelagic and hemipelagic sediments in the world. These rocks include bedded chert, siliceous argillite, siliceous fine-grained limestone, and black carbonaceous shale. They crop out within an east-trending thrust and fold belt more than 1,100 km long. The purpose of this chapter is twofold: (1) to document localities in which siliceous fine-grained facies have been dated by means of radiolarians or conodonts and (2) to examine the temporal and spatial distribution patterns of the microfossil faunas and their associated lithofacies. Because of the large number of samples collected for dating during the mapping of the National Petroleum Reserve in Alaska (NPRA) and adjacent areas, the northern Brooks Range samples constitute the largest data base available in the Cordillera for examining relations between the biofacies and lithofacies of chert and associated rocks.

The siliceous fine-grained facies of the northern Brooks Range are mostly confined to the Etivluk Group and to part of the Lisburne Group (Mull and others, 1982, 1987). Radiolarians are the most commonly used microfossils for dating of these units. The radiolarian faunas range in age from Early Mississippian to Early Jurassic. Siliceous sponge spicules are abundant in many of the rocks examined in this study, but they are not useful for dating. Conodonts, although excellent biostratigraphic fossils, are much less common than either radiolarians or sponge spicules in the siliceous rocks studied. Conodont faunas from the siliceous rocks are Early Pennsylvanian, Permian, and Triassic in age. The distribution of conodont faunas in shallower marine limestone units is not included in this chapter. Benthic foraminifers also constitute a few percent of the microfossils in some samples included in this study. Figure 32.1 shows the localities dated by means of radiolarians or conodonts in the northern Brooks Range siliceous belt. Age data obtained since this manuscript was first submitted for publication are not included herein, but the reader is referred to the theses of Bodnar (1984) and Siok (1985) and to Mull and others (1987) for additional data on siliceous rocks in the Killik River quadrangle.

Microfossil faunas are indicators of past environments. Their distribution patterns provide clues to a basin's history. The two most abundant microfossil groups in this study, radiolarians and sponge spicules, provide different environmental information.

Polycystine radiolarians are planktonic marine protozoans most commonly found in the open oceans. Radiolarian oozes are principally restricted to equatorial ocean basins deeper than the calcite compensation depth (CCD). In sediments deposited above the CCD, radiolarians are commonly subordinate to foraminifers and calcareous nannoplankton. Radiolarians are abundant in siliceous sediment in belts of high productivity, but they are generally subordinant to diatoms. In addition, radiolarians are presently accumulating, along with other microorganisms, in oxygen-poor sediment of starved basins such as the Santa Barbara Basin of California, the Gulf of California, and fjords of western North America and Norway. Typically, in basins of continental-margin borderlands, radiolarians are most abundant in sediment at depths of approximately 500 m. In Paleozoic and early Mesozoic oceans, radiolarians were the only volumetrically important sediment-producing planktonic protozoans. Therefore, radiolarian oozes may then have been widespread beneath oceanic high-productivity zones, regardless of latitude.

Siliceous sponges are relatively unspecialized metazoan filter feeders that live at a wide range of water depths. Spicules from the class Hexactinellida are the most common identifiable spicule group in

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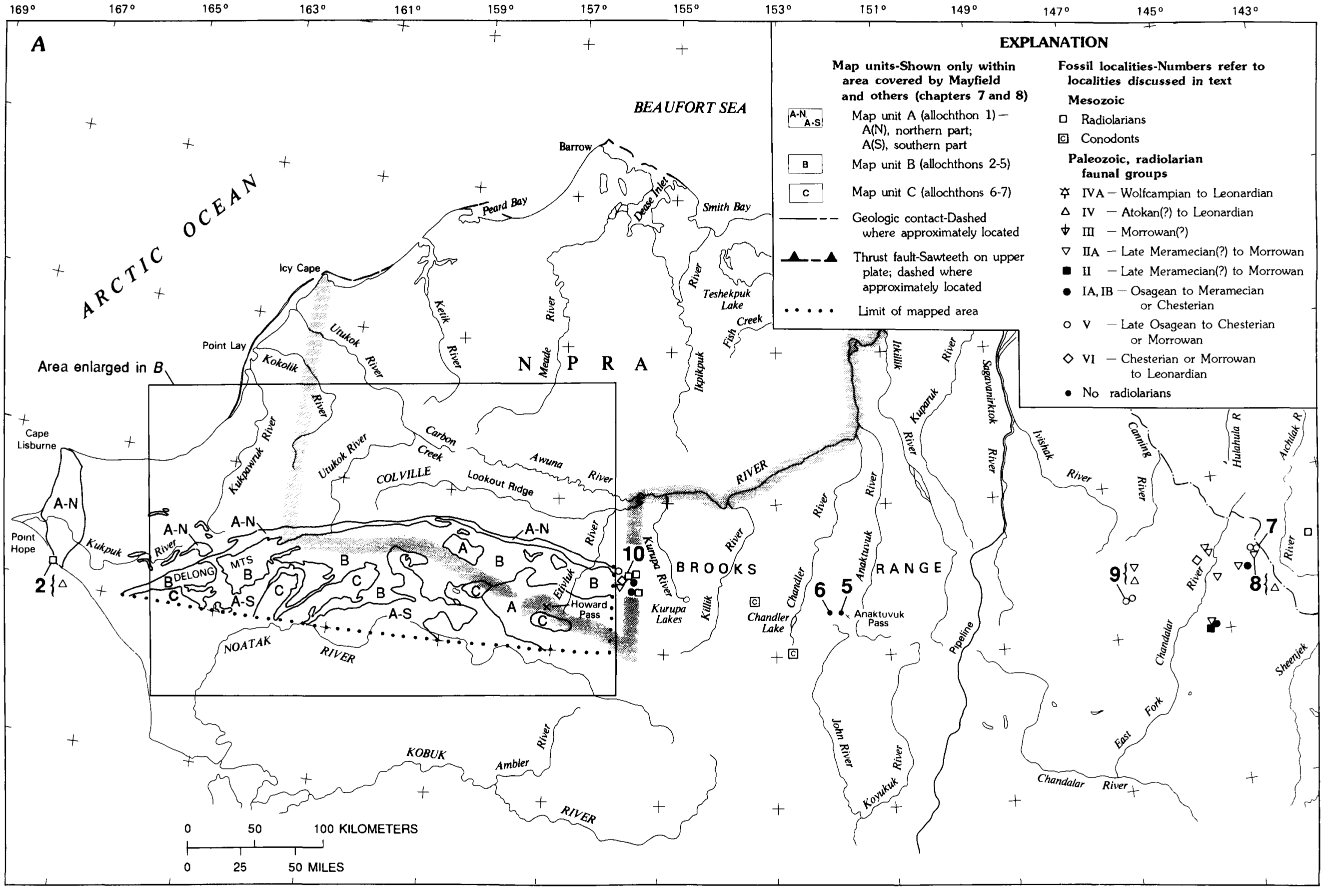

FIGURE 32.1.—Generalized geology of the northern Brooks Range siliceous belt, showing collection localities of dated radiolarians and conodonts used in this study, as well as some barren localities discussed in text. Geology after Mayfield and others, chapters 7 and 8 (see also discussion in text). *A*, Entire east-west extent of Brooks Range. Localities shown only outside area enlarged in *B*. Explanation applies to both *A* and *B*. *B*, Enlargement of western and central Brooks Range area, where localities are concentrated. Thrust faults are shown only in *B*. Unlabeled areas above dotted line in *B* are either autochthonous Cretaceous rocks or Quaternary cover. In both *A* and *B*, site for bracketed symbols is the same as site labeled by bracket's locality number.

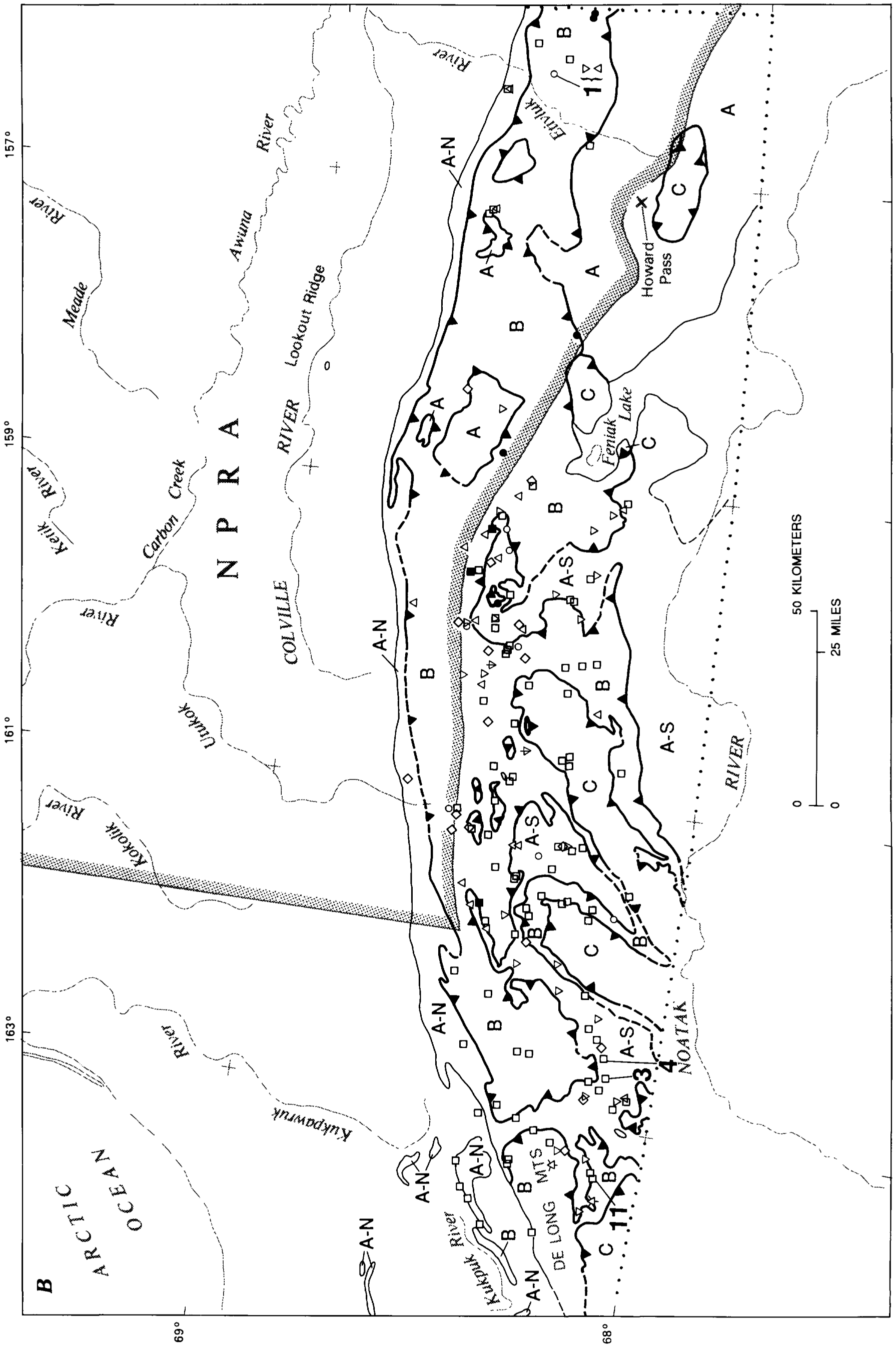

FIGURE 32.1.—Continued

the siliceous rocks of this study. In the northern Brooks Range, hexactinellid spicules are found both in sponge-spicule-dominated biofacies as well as in radiolarian-dominated biofacies. Except in the Antarctic region, where siliceous sponge faunas are anomalously shallow, almost all modern hexactinellid sponges live at depths greater than 90 m, and most live between 200 and 2,000 m (Reid, 1968, after Schulze, 1899, and Ijima, 1927). In the late Paleozoic Delaware basin of Texas, Finks found two specially adapted hexactinellid genera in patch-reef environments and more than ten hexactinellid genera in basinal (as deep as 550 m) facies (Finks, 1960, 1970). Spicules from the class Demospongiae are almost entirely restricted, in the northern Brooks Range, to spicule-dominated biofacies. Modern marine demosponges occupy subtidal to abyssal environments (Rigby, 1983) but are most common in reef or near-reef facies. In the opinion of the senior author, demosponge-bearing spicule-dominated biofacies generally represent a shallower environment than radiolarian-dominated biofacies. Modern siliceous sponges appear to be most abundant in shelf and slope settings in two very different environments: warm water such as the Caribbean and cold nutrient-rich silica-rich water of the polar regions.

The distribution, abundance, diversity, and preservation of the microfossil faunas are correlative with the distribution of lithofacies in space and time. Within the siliceous belt of the northern Brooks Range, at least four facies can be distinguished: (1) dark-gray chert, carbonaceous shale, and fine-grained limestone facies, (2) medium-gray or olive-green chert and argillite facies, (3) maroon and green chert and argillite facies, and (4) associated chert and basalt facies. Lithofacies distribution patterns reflect differences in the depositional environment, such as paleobathymetry, biologic productivity and (or) rate of preservation of organic material, and dilution by fine-grained terrigenous material.

ACKNOWLEDGMENTS

C.F. Mayfield, I.L. Tailleur, D.G. Howell, K.M. Reed, and P.H. Stauffer made helpful suggestions that improved this chapter. Numerous USGS geologists provided samples that were used in this study. The geologists to whom we are indebted are listed in the following section and also in tables 32.2 and 32.3.

METHOD OF STUDY

Most microfossils in this study were recovered from bedded chert; shale, argillite, and siliceous limestone were less extensively sampled. Hundreds of rock samples from the north-central and northwestern Brooks Range were collected during geologic mapping of the NPRA by I.L. Tailleur, C.F. Mayfield, Inyo Ellersieck, and S.M. Curtis (Mayfield and others, chapter 7; Curtis and others, 1982, 1983; Ellersieck and others, 1982, 1983; Mayfield and others, 1982, 1983). Additional samples were collected by B.L. Murchey, R.E. Witmer, W.W. Chamberlain, W.J. Nokleberg, and Michael Churkin. Scattered samples from the eastern Brooks Range were obtained during reconnaissance mapping by W.P. Brosgé and H.N. Reiser. Rocks were collected from measured sections at several of localities. Samples collected from the northern Brooks Range since the initial submission of this chapter for publication are not included herein.

Chert samples were etched two or three times with 5-percent hydrofluoric acid for 24 h, using a modified version of the method of Pessagno and Newport (1972). Siliceous limestone samples were treated with varied concentrations of hydrofluoric and (or) hydrochloric acid for different periods as long as 24 h. Acid-etched residues were collected on screens with opening sizes of 63 and 180 μm. Residues were examined with a binocular microscope in reflected light and with a scanning electron microscope.

In the early stages of this study, all radiolarians were identified by B.K. Holdsworth and D.L. Jones (see Holdsworth and Murchey, chapter 34). B.L. Murchey and P.B. Swain became involved in collecting and identifying radiolarians in 1979 (Murchey and others, 1981; Swain, 1981). C.D. Blome became involved with the dating of Mesozoic radiolarians in 1981 and was later joined by K.M. Reed (Blome and others, chapter 33; Blome and Reed, 1986). During the entire course of the study, B.R. Wardlaw identified conodont samples recovered during processing of samples for radiolarians.

MICROFOSSILS

Radiolarians, sponge spicules, and silicified carbonate fossils recovered by these methods are generally preserved in the form of cryptocrystalline quartz, microcrystalline quartz, or chalcedony. Pyritized individuals are less common. Carbonate and calcitized siliceous microfossils were recovered only from carbonate-rich samples. Radiolarians in the Brooks Range are generally preserved as casts of external molds; many are fragmented. Volume-for-volume replacement is not common. The quality of preservation varies, but it is generally poor. Sponge spicules occur as disaggregated individual spicules. Radiolarians and (or) sponge spicules make up 0-90 percent of the HF-insoluble residues from the Brooks Range, and chert fragments form most of the remainder. Foraminifers form 2-3 percent of some assemblages. Silicified fragments of shallow-marine carbonate fossils such as algae, bryozoans, or echinoderms are generally derived from silicified limestone samples lacking radiolarians but commonly containing sponge spicules.

Conodonts are rare and tend to be associated with Triassic carbonate-rich siliceous rocks. Conodonts extracted by hydrofluoric-acid etching of chert are generally fragmentary. We estimate that fewer than 2-3 percent of the samples processed in this study yielded any conodonts or conodont fragments.

RADIOLARIAN AND CONODONT FAUNAS

The principal reference section for Paleozoic radiolarian biostratigraphy in the Brooks Range is a 77-m-thick chert and argillite unit at the north end of a cutbank in Nigu Bluff on the Nigu River in the Howard Pass quadrangle (fig. 32.1, locality 1). The biostratigraphy of this section is discussed in detail by Holdsworth and Murchey (chapter 34). They have subdivided the Mississippian to Permian radiolarian faunas of the Brooks Range into six faunal groups (I to VI, see table 32.1) and correlated them with the Nigu Bluff biostratigraphic sequence.

Blome and others (chapter 33) discuss the radiolarian biostratigraphy of several Mesozoic sections including the type section of the Otuk Formation (Mull and others, 1982) on Otuk Creek (fig. 32.1, locality 10). (See also, Swain, 1981; Bodnar, 1984).

The ranges and key index fossils of Paleozoic and Mesozoic radiolarian faunal groups or assemblages described by Holdsworth and Murchey (chapter 34) and by Blome and others (chapter 33) are summarized in table 32.1.

TABLE 32.1.—*Paleozoic faunal groups and Mesozoic faunal zones for radiolarian faunas of the Brooks Range*

[For further information, see Blome and others, chapter 33 (Mesozoic zones) and Holdsworth and Murchey, chapter 34 (Paleozoic groups)]

	Mesozoic faunal zones	Age range
	Betraccium deweveri Subzone	Late Norian
	Pantanellium silberlingi Subzone	Early to late Norian
	Capnodoce Zone	Late Karnian to middle Norian
	Pseudostylosphaera Zone	Early Karnian
	Paleozoic faunal groups	**Age range**
VI	*Latentifistula* spp., late forms, ?*Scharfenbergia* spp. late forms, no *Pseudoalbaillella* spp.	Chesterian or Morrowan to Leonardian
V	*Scharfenbergia impella* group	Late Osagean to Chesterian or Morrowan
IVA	*Pseudoalbaillella globosa* group	Wolfcampian to Leonardian
IV	*Pseudoalbaillella* spp., undifferentiated	Atokan(?) to Leonardian
III	*Albaillella furcata* group, *Scharfenbergia tailleurense*	Morrowan(?)
IIA	*Scharfenbergia tailleurense*	Late Meramecian(?) to Morrowan
II	*Albaillella* sp., *S. tailleurense*	Late Meramecian(?) to Morrowan
IB	*Albaillella* sp. cf. *A. cartalla*	Late Osagean to Meramecian or Chesterian
IA	*Albaillella indensis* group	Osagean to early Meramecian

Age-diagnostic conodont faunas recovered by etching chert are very rare in the Brooks Range. Pennsylvanian, Permian, and Triassic conodonts were extracted from chert collected at 11 localities in the eastern and central Brooks Range. These conodonts and their localities are listed in table 32.2. Wardlaw and Jones (1979) documented many of these faunas. Two samples with the conodont *Neogondolella* cf. *N. navicula* (Huckriede), which is considered to be restricted to the Triassic, also contain Paleozoic radiolarians. This may be explained in several ways: (1) The samples are composites collected across a major biostratigraphic boundary, (2) Paleozoic radiolarians have been reworked into Triassic sediments, or (3) species have been misidentified.

Sample numbers, localities, age determinations, and Paleozoic faunal groups for localities with radiolarians or conodont age control are listed in table 32.3. The distribution of faunas is shown on the map of northern Alaska (fig. 32.1). Samples for which no age was determined are not listed.

GEOLOGIC SETTING AND STRUCTURAL UNITS

The siliceous rocks of the Brooks Range form parts of thrust sheets that were emplaced over autochthonous marine deposits of the North Slope in Early Cretaceous time (Mayfield and others, chapters 7 and 8; Martin, 1970; Mayfield and others, 1983). Most of the fine-grained chert-rich rocks in these thrust sheets have been assigned to the Paleozoic Lisburne Group (Mississippian and Pennsylvanian

TABLE 32.2.—*Conodont taxa extracted from siliceous rocks in the northern Brooks Range*

[USGS sample number 0000 indicates samples housed in USGS radiolarian laboratory, Denver. Field number includes abbreviation of collector: Wr, P.B. Swain, B.L. Murchey, and R.E. Witmer; ABe, W.P. Brosgé; ARr, H.N. Reiser; ACn, Michael Churkin, Jr.; MD, C.F. Mayfield]

Sample		Conodont taxa	Age range	Comments
USGS MR No.	Field number			
0000	79Wr-1.39 to 1.60, 1.10 to 1.14	*Neogondolella* sp. cf. *N. navicula* (Huckriede), *Ellisonia* sp.	Late Triassic	Type Otuk Formation, chert and limestone members
0859	ACn-Tiglukpuk	*N. navicula* and *Ellisonia* sp.	Late Triassic	
0521	78ABe-232Fy	*N. navicula* and *Epigondolella* sp. cf. *E. permica* (Hayashi)	Late Triassic, latest Karnian to middle Norian	
0517	78ABe-157	*Neogondolella* sp.	Late Triassic	
0518	78ABe-159A	*N.* sp. cf. *N. navicula*	Triassic, late Anisian to Norian	Sample also yielded Paleozoic Faunal Group IV radiolarians with *Pseudoalbaillella* sp. aff to *P.* sp. at Nigu Bluff
0524	78ARr-19	*N.* sp. cf. *N. navicula*	Triassic	Sample also yielded Paleozoic Faunal Group VI radiolarians with *Latentifistula* spp. (late forms) similar to uppermost Nigu Bluff forms. From black "massive" chert (H.N. Reiser, written commun., 1978)
1804	78ACn-921	*N.* sp. cf. *N. regale* Mosher	Early Triassic, latest Spathian, to Middle Triassic	See Blome and others (chapter 33) for radiolarian faunal description
0375	78Md-98H	*Neogondolella* sp.	Triassic	
0005	60ABe-606	*N.* sp. cf. *N. idahoensis* (Youngquist, Hawley, Miller)	Early Permian, Leonardian	
5301	78Md-147A	*N. idahoensis*	Early Permian, Leonardian	Occurs with Paleozoic radiolarian Faunal Group IV. Maroon and gray chert with shale partings (C.F. Mayfield, written commun., 1979)
0813	78Md-75E	*Declinognathodus noduliferus*	Early Pennsylvanian, earliest Morrowan	Occurs with Paleozoic radiolarian Faunal Group III. See Holdsworth and Murchey (chapter 34) for discussion of possible reworking

Kuna Formation (Mull and others, 1982); Mississippian and Pennsylvanian Akmalik Chert of Mull and others, 1987; and the undivided "black Lisburne" of local usage) or to the overlying Paleozoic and Mesozoic Etivluk Group (Permian Siksikpuk Formation of Mull and others, 1987; Triassic to Middle Jurassic Otuk Formation (Mull and others, 1982); Pennsylvanian to Triassic Imnaitchiak Chert of Mull and others, 1987; Mississippian to Triassic Imnaitchiak(?) Chert discussed herein). Historically, the Siksikpuk Formation, which was named and first described by Patton (1957), has generally been mapped as a widespread unit. Mull and others (1987) restricted the geographic extent of the unit to the area of the type section; this definition is used in this report.[3] The Imnaitchiak Chert of Mull and others (1987) is not differentiated from their Siksikpuk Formation in other chapters of this volume, with the exception of chapter 34 (Holdsworth and Murchey).

In the central and western Brooks Range, structural units have been differentiated primarily by lithologic differences between correlative Mississippian strata (Martin, 1970; Tailleur and Brosgé, 1970; Mull, 1979; Mayfield and others, 1982; Ellersieck and others, 1982;

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[3] The names "(restricted) Siksikpuk Formation," "Imnaitchiak Chert," and "Akmalik Chert" used in this chapter are stratigraphic units defined by Mull and others (1987) and do not appear elsewhere in this volume except in the chapter by Holdsworth and Murchey (chapter 34).

TABLE 32.3.—*Samples with radiolarian or conodont age control in the siliceous facies of the northern Brooks Range*

[Localities numbered on figure 32.1 are listed first; other localities follow, listed from east to west. USGS MR numbers are fossil accession numbers for radiolarian samples in USGS radiolarian laboratory, Menlo Park; number 0000 indicates samples housed in USGS radiolarian laboratory, Denver. Fossil control symbols: R, radiolarian age determination; C, conodont age determination. Reference column indicates samples specifically mentioned in other chapters: B, Blome and others (chapter 33); H, Holdsworth and Murchey (chapter 34). Roman numerals in parentheses after age data refer to Paleozoic faunal groups (see text). Sample field number includes abbreviation of collector: ABe, W.P. Brosgé; ARr, H.N. Reiser; ATr/Tr, I.L. Tailleur; AMd/Md, C.F. Mayfield; AEk/Ek, Inyo Ellersieck; ACn, Michael Churkin, Jr.; RD, W.J. Nokleberg; AMy, B.L. Murchey; AWr, R.E.Witmer; ACx/Cx, S.M. Curtis; W, Houston Oil and Minerals; CM, W.W. Chamberlain; AHe, J.M. Hoare.]

Sample		Locality		Fossil control	Age and faunal data	Reference
USGS MR No.	Field number	Latitude (° ′ ″)	Longitude (° ′ ″)			
Map locality 1, Nigu Bluff—collected by Murchey, Swain, and Curtis						
6527	79AMy-18	68 29	156 27	R	Late Osagean to Meramecian (V)	H
6528	79AMy-19	—do.—	—do.—	R	Late Osagean to Meramecian (V)	H
6529	79AMy-20	—do.—	—do.—	R	Late Osagean to Meramecian (IB)	H
6530	79AMy-21	—do.—	—do.—	R	Late Osagean to Meramecian (IB)	H
6531	79AMy-22	—do.—	—do.—	R	Latest Meramecian to Morrowan (IIA)	H
6532	79AMy-23	—do.—	—do.—	R	Latest Meramecian to Morrowan (IIA)	H
6533	79AMy-24	—do.—	—do.—	R	Latest Meramecian to Morrowan(IIA)	H
6534	79AMy-25	—do.—	—do.—	R	Atokan to Wolfcampian (VI)	H
6535	79AMy-26	—do.—	—do.—	R	Atokan to Wolfcampian (VI)	H
6536	79AMy-27	—do.—	—do.—	R	Atokan to Wolfcampian (VI)	H
6537	79AMy-28	—do.—	—do.—	R	Atokan to Wolfcampian (IV)	H
6538	79AMy-29	—do.—	—do.—	R	Atokan to Wolfcampian (IV)	H
Map locality 2, Agate Rock—collected by Murchey and Tailleur						
5709	80AMy-12.12	68 08.5	165 56	R	Late Pennsylvanian or Early Permian (IV)	
5711	80AMy-12.14	—do.—	—do.—	R	Late Pennsylvanian or Early Permian	
Map locality 3						
7590	79Md-164-51m	68 08 36	162 29 18	R	Late Meramecian(?) to Morrowan (IIA)	
7591	79Md-164-91m	—do.—	—do.—	-	Ammodiscus sp.	
7592	79Md-164-121m	—do.—	—do.—	R	Triassic	
Map locality 4						
5447A	79Ek-107B1	68 15 33	162 13 23	R	Late Meramecian(?) to Morrowan (IIA)	
5447B	79Ek-107B2	—do.—	—do.—	R	Late Meramecian(?) to Morrowan (IIA)	
Map locality 7						
0526	78ARr-33DEF	68 29	144 20	R	Osagean to early Meramecian (IA)	
0590	78ARr-33C	—do.—	—do.—	R	Late Osagean to Chesterian or Morrowan (V)	
0589	78ARr-33B	—do.—	—do.—	R	Late Osagean to Chesterian or Morrowan (V)	
0588	78ARr-33A	—do.—	—do.—	R	Late Osagean to Chesterian or Morrowan (V)	
Map locality 8						
0527	78ARr-34B	68 28	144 23	R	Late Meramecian(?) to Morrowan (IIA)	
0528	78ARr-34C	—do.—	—do.—	R	Late Meramecian(?) to Morrowan (IIA)	

TABLE 32.3.—*Samples with radiolarian or conodont age control in the siliceous facies of the northern Brooks Range*—Continued

Sample		Locality		Fossil control	Age and faunal data	Reference
USGS MR No.	Field number	Latitude (° ′ ″)	Longitude (° ′ ″)			
			Map locality 8—*Continued*			
0529	78ARr-34D	—do.—	—do.—	R	Late Meramecian(?) to Morrowan (IIA)	
0535	78ARr-34E	—do.—	—do.—	R	Late Meramecian(?) to Morrowan (IIA)	
0534	78ARr-34H	—do.—	—do.—	R	Late Meramecian(?) to Morrowan (II)	
0530	78ARr-34I-O	—do.—	—do.—	R	Late Meramecian(?) to Morrowan (IIA)	
0533	78ARr-34Q	—do.—	—do.—	R	Chesterian(?) or Morrowan to Wolfcampian(?) (VI)	
0531	78ARr-34R	—do.—	—do.—	R	Atokan(?) to Wolfcampian(?) (VI), similar to 6535-6538	
0532	78ARr-34S	—do.—	—do.—	R	Atokan(?) to Wolfcampian(?) (VI), similar to 6535-6538	
			Map locality 9			
1094	79ARr-1D	68 16 30	146 45 15	R	Late Osagean to Chesterian or Morrowan (V)	
1092	79ARr-1B	—do.—	—do.—	R	Late Meramecian(?) to Morrowan (IIA)	
1093	79ARr-1A	—do.—	—do.—	R	Wolfcampian(?) to Leonardian (IVA)	
			Map locality 10—collected by Swain, Murchey, and Witmer			
0000	79Wr-1.39 to 1.60 and 79Wr-1.10 to 1.14	68 35	155 46	CR	Late Triassic	B
			Map locality 11			
0000	79CM-0	68 06	163 21	R	Early Jurassic	B
0000	79CM-1	—do.—	—do.—	R	Early Jurassic	B
0000	79CM-2	—do.—	—do.—	R	Early Jurassic	B
0000	79CM-3	—do.—	—do.—	R	Late Triassic or Early Jurassic	B
0000	79CM-4	—do.—	—do.—	R	Late Triassic or Early Jurassic	B
0000	79CM-5	—do.—	—do.—	R	Late Triassic	B
0000	79CM-6	—do.—	—do.—	R	Late Triassic	B
0000	79CM-8	—do.—	—do.—	R	Late Triassic	B
0000	79CM-9	—do.—	—do.—	R	Late Triassic	B
0000	79CM-10	—do.—	—do.—	R	Late Triassic	B
0000	79CM-11	—do.—	—do.—	R	Late Triassic	B
0000	79CM-12	—do.—	—do.—	R	Late Triassic	B
0000	79CM-13	—do.—	—do.—	R	Middle or Late Triassic	B
			Other localities			
1086	79ABe-273	68 32 50	143 25 30	R	Late Triassic	
0004	60ABe-591	68 01 37	145 19 30	R	Late Meramecian(?) to Morrowan (II)	H
0112	60ARr-663	67 43	145 24	R	Not on map. Osagean to early Meramecian (IA)	H

TABLE 32.3.—*Samples with radiolarian or conodont age control in the siliceous facies of the northern Brooks Range*—Continued

Sample		Locality				
USGS MR No.	Field number	Latitude (° ′ ″)	Longitude (° ′ ″)	Fossil control	Age and faunal data	Reference
		Other localities—*Continued*				
0524	78ARr-19	68 29	145 30	CR	Conodont: Triassic. Radiolarians: Chesterian(?) or Morrowan to Leonardian (VI)	
1084	79ABe-257	67 57 10	145 41 40	R	Not on map. Mesozoic	
0005	60ABe-606	67 58	145 43.5	C	Not on map. Leonardian	
7580	78ACn-911	68 50 13	151 12 08	R	Triassic: early(?), middle Norian	B
7581	78ACn-851	68 53 00	151 12 30	R	Triassic: late Karnian(?); early to late middle Norian	B
7582	78ACn-852	68 53 00	151 20 55	R	Triassic: late Ladinian to early Karnian	B
0000	80AMy-05	68 20	151 21	R	Triassic (series of samples)	B
0859	ACn-Tiglukpuk	Not known		C	Triassic. Tiglukpuk Creek locality	
1804	78ACn-921	68 20	151 50	CR	Early or Middle Triassic	B
0521	78ABe-232Fy	68 02.3	152 43.5	C	Latest Karnian to middle Norian	
0517	78ABe-157	68 22 17	153 26 51	CR	Late Triassic	B
0518	78ABe-159A	68 21.7	153 27	CR	Conodont: Triassic, late Anisian to Norian. Radiolarians: Atokan(?) to Leonardian (IV)	
5432	79Md-204D	68 25 00	155 34	R	Late Triassic	B
5353	78Tr-236D	68 28.28	155 34.70	R	Mesozoic: Triassic(?)	B
5519	79Tr-179B	68 25 00	155 36 30	R	Late Osagean to Meramecian or Chesterian (IB)	
5521	79Tr-179D	68 25 12	155 37 48	R	Late Osagean to Meramecian or Chesterian (IB)	
5431	79Md-200E	68 31 24	155 38 30	R	Mesozoic	B
7586	78Tr-241A	68 27 92	155 40.8	R	Mesozoic: Triassic(?)	B
5478	79Ek-300D	68 30 05	155 49 05	R	Early Permian (IV)	
5354	78Tr-238.A2	68 28.95	155 50.8	R	Late Meramecian(?) to Morrowan (IIA)	
5477	79Ek-299B	68 32 50	155 55 00	R	Late Osagean to Chesterian or Morrowan (V)	
0000	80AMy-03	68 22.5	152 56	R	Triassic: series of samples	B
5560	79Cx-279B	68 25 00	156 00 18	R	Late Osagean to Meramecian or Chesterian (IB)	
5433	79Md-206C	68 25 00	156 02 30	R	Late Osagean to Chesterian or Morrowan (V)	
5427	79Md-187B	68 32 08	156 14 25	R	Triassic: Norian	B
5435	79Md-213A	68 28 00	156 19 35	R	Mesozoic	
5349	78Tr-235BcBs	68 36.4	156- 3.4	R	Atokan(?) to Leonardian (IV)	
5355	78Tr-240D2	68 36 03	156 34 02	R	Late Osagean to Meramecian or Chesterian (IB)	
5350	78Tr-235D	68 36.3	156 34.2	R	Triassic: Ladinian	B
5351	78Tr-235I1-3	68 36.3	156 34.2	R	Triassic or Jurassic	B
5352	78Tr-235I4	68 36.4	156 34.9	R	Jurassic	B
5474	79Ek-291C	68 24 50	156 52 10	R	Mesozoic	
5346	78Tr-232A	68 36.5	157 20.0	R	Late Triassic	B
5347	78Tr-232B	68 35.6	157 20.3	R	Mesozoic	
0035	77AHe-56	68 23.92	158 05	R	Early(?) Mississippian	H
0386	78Ek-55B	68 28 30	159 03 12	R	Atokan(?) to Leonardian (IV)	
0384	78Ek-054	68 29	159 03.5	R	Mesozoic	
5277	78Md-33B	68 14 53	159 06 00	R	Triassic: Ladinian	B
0798	78Md-37	68 15 33	159 07 15	R	Atokan(?) to Leonardian (IV)	
5293	78Md-109A	68 16 30	159 10	R	Late Meramecian(?) to Morrowan (IIA)	
0366	78Md-29D	68 32.6	159 15.0	R	Chesterian(?) or Morrowan to Leonardian (VI)	

TABLE 32.3.—*Samples with radiolarian or conodont age control in the siliceous facies of the northern Brooks Range*—Continued

Sample		Locality				
USGS MR No.	Field number	Latitude (° ′ ″)	Longitude (° ′ ″)	Fossil control	Age and faunal data	Reference
			Other localities—*Continued*			
0367	78Md-29E	68 32.6	159 15.0	R	Late Meramecian(?) to Morrowan (IIA)	
0371	78Md-73B	68 29 25	159 15 45	R	Late Triassic	B
5240	78Ek-56D	68 15 45	159 16 10	R	Chesterian(?) or Morrowan to Leonardian (VI)	
5274	78Md-30D	68 31 54	159 17	R	Late Triassic: Karnian	B
5312	78Cx-17C	68 18 46	159 17 58	R	Late Meramecian(?) to Morrowan (IIA)	
0816	78Ek-19C	68 30 15	159 18 30	R	Atokan(?) to Leonardian (IV)	
5275	78Md-31C	68 31.2	159 21.2	R	Late Osagean to Chesterian or Morrowan (V)	
5271	77Md-84	68 32 47	159 24 20	R	Late Meramecian(?) to Morrowan (II)	
5272	77Md-85B	68 33 20	159 25 30	R	Atokan(?) to Leonardian (IV)	
5330	78Tr-68B	68 31 18	159 27 24	R	Late Meramecian(?) to Morrowan (IIA)	
5331	78Tr-68 B.1	68 31 18	159 27 24	R	Triassic or Jurassic	
0419	78Tr-68 B.2	68 31 18	159 27 24	R	Mesozoic	
5288	78Md-84B	68 36 24	159 30	R	Atokan(?) to Leonardian (IV)	
7589	78Ek-29A.1	68 29 00	159 32 20	R	Late Osagean to Meramecian or Chesterian (IB)	
5276	78Md-32C	68 31 30	159 32 24	R	Atokan(?) to Leonardian (IV)	
1941	78Md-43A	68 33 30	159 34	R	Chesterian(?) or Morrowan to Leonardian (VI)	
5281	78Md-61B	68 17 36	159 36	R	Triassic: Ladinian	B
5282	78Md-61C	68 17 36	159 36	R	Late Meramecian(?) to Morrowan (IIA)	
0372	78Md-80C	68 34 30	159 36 25	R	Late Meramecian(?) to Morrowan (II)	
0373	78Md-80D	68 34 28	159 36 30	R	Late Meramecian(?) to Morrowan (II)	
5328	78Tr-35A	68 34 30	159 37 24	R	Triassic: Karnian or Norian	B
5235	78Ek-44B	68 21 48	159 38 30	R	Late Meramecian(?) to Morrowan (IIA)	
5283	78Md-64B	68 23	159 44	R	Late Meramecian(?) to Morrowan (IIA)	
5337	78Tr-107A	68 21 27	159 45 18	R	Triassic	
5338	78Tr-107C	68 20 42	159 46	R	Triassic	
0369	78Md-68C	68 29.1	159 46	R	Mesozoic	
5234	78Ek-34D	68 31 00	159 47 10	R	Late Meramecian(?) to Morrowan (IIA)	
5268	77Md-50A	68 43 40	159 48	R	Atokan(?) to Leonardian (IV)	
5279	78Md-54D	68 30 23	159 48	R	Late Osagean to Meramecian or Chesterian (IB)	
5246	78Ek-101d.1	68 19 10	159 50 45	R	Late Meramecian(?) to Morrowan (IIA)	
5314	78Cx-21A	68 33 42	159 53 30	R	Atokan(?) to Leonardian (IV)	
5289	78Md-88	68 35 10	159 54 50	R	Chesterian(?) or Morrowan to Leonardian (VI)	
0387	78Ek-059	68 35 10	159 54 50	R	Mesozoic	
0380	78Ek-50E.2	68 34 15	159 55	R	Mesozoic	
5284	78Md-72	68 27 48	159 56 30	R	Chesterian(?) or Morrowan to Leonardian (VI)	
5329	78Tr-66A	68 31.6	159 58.5	R	Mesozoic: Triassic?	B
0799	78Md-95d	68 27 12	159 59	R	Atokan(?) to Leonardian (IV)	
5237	78Ek-050A.2	68 34 10	159 59 30	R	Triassic: late Karnian?; early to late middle Norian	B
5315	78Cx-24D	68 33 00	160 03 15	R	Chesterian(?) or Morrowan to Leonardian (VI)	
5334x	78Tr-90B	68 26 00	160 04 45	R	Triassic: Ladinian	B
5292	78Md-93A	68 27 36	160 05	R	Late Osagean to Chesterian or Morrowan (V)	
5290	78Md-90A	68 29	160 05	R	Triassic: late Karnian to early late Norian	B
5324	78Cx-185B	68 28 12	160 05 24	R	Triassic: Ladinian	B
5333	78Tr-82B	68 29 35	160 07 45	R	Triassic: late Ladinian to early Karnian	B

TABLE 32.3.—*Samples with radiolarian or conodont age control in the siliceous facies of the northern Brooks Range*—Continued

Sample		Locality		Fossil control	Age and faunal data	Reference
USGS MR No.	Field number	Latitude (° ′ ″)	Longitude (° ′ ″)			
					Other localities—*Continued*	
5319	78Cx-89B	68 16 27	160 08 30	R	Triassic: Karnian or Norian	B
5320	78Cx-170	68 21 27	160 08 30	R	Mesozoic	
5320	78Cx-170	68 21 27	160 08 30	R	Mesozoic	
0813	78Md-75E	68 31 22	160 08 50	CR	Morrowan(?) (III)	H
5245	78Ek-92	68 21 03	160 11 54	R	Triassic: late Karnian(?); early to late middle Norian	B
5244	78Ek-79A	68 26 30	160 14	R	Chesterian(?) or Morrowan to Leonardian (VI)	
5336	78Tr-100	68 23 45	160 14 20	R	Triassic (late Norian) to Early Jurassic	B
5316	78Cx-29C	68 32 06	160 15 00	R	Late Meramecian(?) to Morrowan (IIA)	
5242	78Ek-60A	68 34 30	160 17 12	R	Late Meramecian(?) to Morrowan (IIA)	
5294	78Md-113B	68 09 45	160 18 30	R	Triassic or Jurassic	
0817	78Ek-62	68 30 15	160 19	R	Atokan(?) to Leonardian (IV)	
5318	78Cx-38D	68 26 12	160 19 18	R	Mesozoic	
5259	78Ek-135A.2	68 20 00	160 19 42	R	Triassic	
5317	78Cx-37G	68 27 45	160 22 42	R	Triassic: Ladinian	B
5345	78Tr-228C	68 15 00	160 26 30	R	Atokan(?) to Leonardian (IV)	
5270	77Md-64A	68 31.6	160 27	R	Mesozoic	
5344	78Tr-228	68 15.0	160 28	R	Mississippian(?) (I)?	
0371	78Md-73B	68 28	160 31	R	Mesozoic	B
5334	78Tr-90B.2	68 26 21	160 34 36	R	Triassic	
5243	78Ek-67A	68 30 25	160 34 45	R	Chesterian(?) or Morrowan to Leonardian (VI)	
5257	78Ek-129	68 24 06	160 42 12	R	Morrowan(?) (III)?	
5241	78Ek-58	68 19.9	160 45.8	R	Mesozoic	
5295	78Md-114D	68 10 45	160 47 30	R	Mesozoic	
5261	78Ek-136A.3	68 18 36	160 49 24	R	Triassic: late Karnian to early late Norian	B
5260	78Ek-136A	68 19 12	160 49 30	R	Mesozoic	
5342	78Tr-172C.2	68 28 30	160 51 25	R	Triassic	
5343	78Tr-172C.4	—do.—	—do.—	R	Triassic	
5267	77Md-44A	68 39 30	160 53 30	R	Chesterian(?) or Morrowan to Leonardian (VI)	
5341	78Tr-171B	68 25 18	160 55 00	R	Mesozoic	
5340	78Tr-171A	68 26 00	160 55 12	R	Late Triassic	
5305	78Md-160B	68 26 15	160 57 20	R	Mesozoic	
5306	78Md-160C	68 26 15	160 57 20	R	Mesozoic	
5307	78Md-160D	68 26 15	160 57 20	R	Triassic: early(?), middle Norian. Norian	B
5324	78Cx-185B	68 28 12	161 05 24	R	Mesozoic: Triassic(?)	
0011	77ACn-362	68 33 25	161 09 30	R	Triassic	
5308	78Md-169C	68 31 30	161 15 03	R	Triassic	
1966	78Md-169D	68 31 30	161 15 03	R	Chesterian(?) or Morrowan to Leonardian (VI)	
7587	78Md-164	68 16 50	161 16 30	R	Triassic: late Ladinian to early Karnian	B
5325	78Cx-186D	68 17 30	161 17 34	R	Chesterian(?) or Morrowan to Leonardian (VI)	
5304	78Md-152A	68 28 53	161 18	R	Mesozoic	
5305	78Md-152B	68 28 50	161 18	R	Triassic or Jurassic	
5310	78Md-191B	68 18 18	161 18	R	Triassic: late Karnian to early late Norian	B
5309	78Md-178B	68 14 28	161 19 30	R	Mesozoic	
5264	78Ek-140F	68 16 06	161 19 42	R	Mesozoic	

TABLE 32.3.—*Samples with radiolarian or conodont age control in the siliceous facies of the northern Brooks Range*—Continued

Sample		Locality				
USGS MR No.	Field number	Latitude (° ′ ″)	Longitude (° ′ ″)	Fossil control	Age and faunal data	Reference
					Other localities—*Continued*	
5256	78Ek-126A	68 25 21	161 21 24	R	Wolfcampian(?) to Leonardian (IVA)	
5301	78Md-147A	68 23 15	161 22 30	CR	Leonardian (IV)	
5303	78Md-148A	68 21 15	161 23 00	R	Mississippian(?) (V)?	
5262	78Ek-136B.3	68 10 12	161 26 12	R	Triassic	
5258	78Ek-133D	68 24 42	161 29 18	R	Mesozoic	B
5254	78Ek-124C	68 23 54	161 32 18	CR	Conodont: Triassic—Anisian or Ladinian Radiolarians: Late Triassic(?)	B
5255	78Ek-125C	68 24 12	161 33 30	R	Triassic	
5300	78Md-146F	68 07 45	161 34 30	R	Mesozoic	
5322	78Cx-172E	68 19 09	161 36 54	R	Mesozoic	
5297	78Md-136B	68 20	161 38	R	Mesozoic	
5299	78Md-141B	68 15 30	161 38 20	R	Mesozoic	
5298	78Md-140	68 16 30	161 40	R	Mesozoic	
5250	78Ek-118B.1	68 12 00	161 41 24	R	Mesozoic	
5231	77Ek-2	68 28 40	161 44 05	R	Late Meramecian(?) to Morrowan (IIA)	
7585	78ACn-453	68 28 39	161 44 40	R	Triassic: Ladinian	B
5248	78Ek-112L	68 12 18	161 44 42	R	Mesozoic: Triassic(?)	
5339	78Tr-139a	68 09 03	161 45 24	R	Late Osagean to Leonardian (V or VI)	
5265	77Md-5	68 34 58	161 45 50	R	Late Osagean to Chesterian or Morrowan (V)	
5266	77Md-14D	68 28 58	161 45 50	R	Atokan(?) to Leonardian (IV)	
5296	78Md-126D	68 21 14	161 46	R	Mesozoic	
5249	78Ek-113d.1	68 20 18	161 46 30	R	Late Triassic	B
0800	78Md-101c	68 24 20	161 47 10	R	Late Meramecian(?) to Morrowan (IIA)	
7583	78ACn-723	68 27 04	161 47 12	R	Late Triassic	B
7584	78ACn-722	68 27 06	161 47 20	R	Late Triassic	B
0375	78Md-098H	68 27	161 49.5	C	Triassic	
7588	78ACn-664	68 28 12	161 50 42	R	Late(?) Triassic	B
5302	78Md-147C	68 22 42	161 53	R	Triassic: Ladinian	B
0410	78ACn-431	68 12 16	161 55 40	R	Triassic: Ladinian	B
5382.a	79Md-42E	68 16	162 03 15	R	Late Meramecian(?) to Morrowan (IIA)	
5273	78Md-9	67 41 25	162 03 20	R	Not on map. Early(?) Mississippian	H
5382.b	79Md-44A	68 21 52	162 04 28	R	Late Meramecian(?) to Morrowan (IIA)	
5233	78Ek-004F	67 60 05	162 06 10	R	Late(?) Triassic	B
5505	79Tr-088C1	68 11 17	162 12 18	R	Mesozoic	
5506	79Tr-088C2	68 11 17	162 12 18	R	Triassic or Jurassic	
5549	79Cx-203C	68 30 30	162 12 36	R	Late Triassic	
5383	79Md-57A	68 25 18	162 18	R	Triassic	
5384	79Md-57B	68 25 18	162 18	R	Mesozoic	
5385	79Md-57C	68 25 18	162 18	R	Mesozoic	
5485	79Tr-001D	68 09 34	162 20 33	R	Late Meramecian(?) to Morrowan (IIA)	
5539	79Cx-073G1	68 23 33	162 28 06	R	Triassic	
5422	79Md-164B	68 08 45	162 29	R	Mesozoic	
5469	79Ek-274B	68 08 22	162 30 48	R	Chesterian(?) or Morrowan to Leonardian (VI)	
5449	79Ek-173D	68 07 28	162 33 46	R	Late Meramecian(?) to Morrowan (IIA)	
5367	79Md-08B	68 07 33	162 35 48	R	Mesozoic	

TABLE 32.3.—*Samples with radiolarian or conodont age control in the siliceous facies of the northern Brooks Range*—Continued

Sample		Locality		Fossil control	Age and faunal data	Reference
USGS MR No.	Field number	Latitude (° ′ ″)	Longitude (° ′ ″)			
			Other localities—*Continued*			
5388	79Md-61E	68 18 06	162 37	R	Mesozoic: Triassic(?)	
5553	79Cx-209G3	68 28 09	162 37 20	R	Mesozoic: Jurassic(?)	
5542	79Cx-077C	68 19 57	162 38 18	R	Mesozoic: Triassic(?)	
5368	79Md-09C	68 06 45	162 42	R	Mesozoic: Triassic(?)	
5530	79Cx-006C	68 09 06	162 45 36	R	Mesozoic	
5438	79Ek-07B	68 07 24	162 47 18	R	Mesozoic	
5371	79Md-11B	68 03 27	162 47 20	R	Mesozoic	
5374	79Md-11E	68 03 24	162 47 24	R	Atokan(?) to Leonardian (IV)	
5375	79Md-11F	68 03 24	162 47 25	R	Mesozoic: Triassic(?)	
5441	79Ek-12K	68 04 38	162 49 50	R	Late Meramecian(?) to Morrowan (IIA)	
2299	78RD-227	68 03.47	162 50.07	R	Triassic: late Karnian to early late Norian	B
5533	79Cx-011B	68 05 42	162 54 12	R	Mesozoic: Triassic(?)	
5251	78Ek-119B	68 22 00	162 57 40	R	Triassic: Ladinian	B
5252	78Ek-119C	68 22 00	162 58 00	R	Late Osagean to Leonardian (V or VI)	
5363	78W-38775	68 09 03	162 58 36	R	Mesozoic: Triassic(?)	B
5362	78W-38774	68 09 14	162 58 54	R	Late(?) Triassic	B
5253	78Ek-119E	68 22 15	162 59 10	R	Triassic: late Karnian(?); early to late middle Norian	B
5456	79Ek-193C	68 24 22	163 03 24	R	Mesozoic	
5457	79Ek-193D	68 24 30	163 03 24	R	Mesozoic	
5365	78W-38780	68 04 42	163 04 12	R	Triassic (late Norian) to Early Jurassic	B
5356	78W-3	68 10 34	163 11 00	R	Mesozoic	
5545	79CX-194G	68 13 50	163 11 20	R	Chesterian(?) or Morrowan to Leonardian (VI)	
5357	78W-6	68 10 19	163 11 30	R	Triassic: Ladinian	B
5546	79Cx-194H	68 13 45	163 11 42	R	Mesozoic: Late Triassic	
5380	79Md-37D1	68 07 08	163 14	R	Late Meramecian(?) to Morrowan (IIA)	
5508	79Tr-102B	68 07 10	163 14 54	R	Late Meramecian(?) to Morrowan (IIA)	
5414	79Md-148C	68 18 00	163 15 00	R	Triassic	
5466	79Ek-262E	68 15 48	163 16 00	R	Mesozoic: Triassic(?)	
5376	79Md-33A	68 06 45	163 18 25	R	Triassic	
5413	79Md-146B	68 18 54	163 19 33	R	Mesozoic	
5406	79Md-122B	68 13 36	163 20 12	R	Atokan(?) to Leonardian (IV)	
5401	79Md-106D	68 25 15	163 21 33	R	Late Triassic or Early Jurassic	
5402	79Md-106E	68 25 10	163 21 45	R	Mesozoic	
5378	79Md-36B	68 05 50	163 27 45	R	Wolfcampian(?) to Leonardian (IVA)	
5458	79Ek-194D	68 25 22	163 31 00	R	Mesozoic: Triassic(?)	
5404	79Md-109A	68 24 00	163 34 33	R	Mesozoic	
5405	79Md-109B	68 23 54	163 35	R	Late Triassic	
5544	79Cx-191E	68 24 45	163 35	R	Mesozoic	
5421	79Md-162C	68 12 58	163 43 48	R	Mesozoic: Triassic(?)	
5415	79Md-156A	68 21 28	163 44 50	R	Mesozoic	
5417	79Md-156C	68 21 28	163 44 50	R	Triassic	

Curtis and others, 1982). Mayfield and others (chapter 7) distinguish seven major allochthons to which we will refer in this chapter. The schematic diagram in figure 33.2 shows the structural relations inferred to exist between the seven allochthons. On the basis of the distribution patterns of siliceous lithofacies and biofacies in the seven allochthons, we have combined them into three map units (A, allochthon 1; B, allochthons 2, 3, 4, and 5; C, allochthons 6 and 7) in order to facilitate discussion of

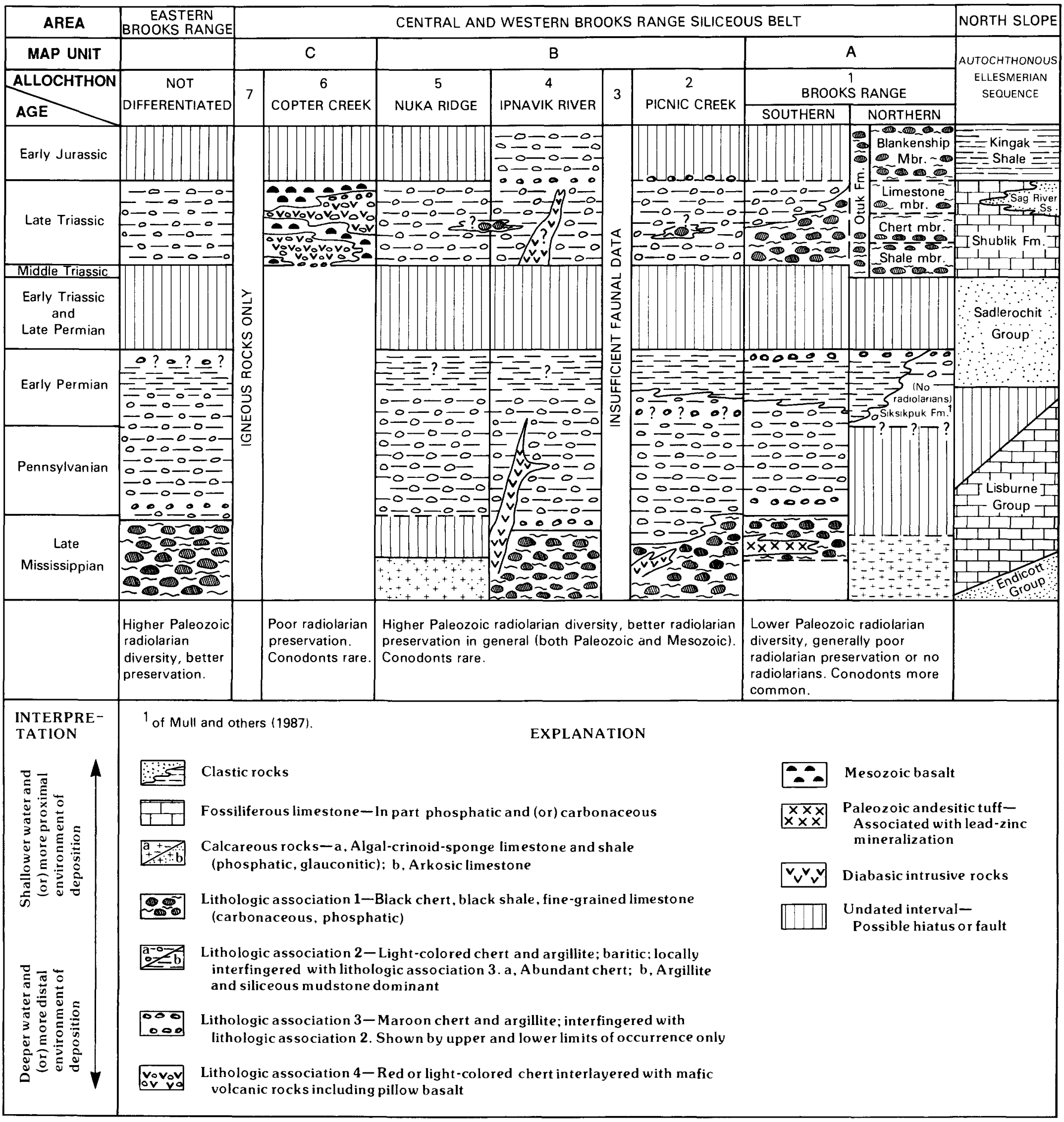

FIGURE 32.2.—Schematic interpretation of facies-distribution patterns in siliceous rocks of the northern Brooks Range, Alaska.

biofacies and lithofacies patterns. The structural boundaries between these map units are shown on figure 33.1. We have not extended these structural boundaries eastward into quadrangles that were mapped only in reconnaissance fashion when this chapter was originally submitted for publication.

MAP UNIT A: ALLOCHTHON 1

Allochthon 1 is the lowest structural unit in the belt of siliceous rocks. It is equivalent to the Brooks Range allochthon (Mayfield and others, chapter 7) and to the Endicott allochthon (Mull and others, 1987) and contains the type sections of the Kuna Formation, the (restricted) Siksikpuk Formation, and the Otuk Formation. The siliceous rocks in this structural unit also partly correspond, at least in the De Long quadrangle, to the Kagvik sequence of Churkin and others (1979). Mayfield and others (chapter 7) give a more complete account of the nomenclature that has been used to designate various structural units within the Brooks Range. In order to prevent confusion, we will use only the designation "allochthon 1" when referring to this structural level. For simplicity's sake, we have also considered the allochthonous units of the Lisburne Peninsula as part of allochthon 1, although these rocks may be structurally lower (Grantz and others, 1983). In general, the siliceous rocks in the northern part of allochthon 1 are more argillaceous and (or) calcareous than the siliceous rocks in the southwestern part of allochthon 1 in the De Long Mountains. The latter are also associated locally with Mississippian andesitic, rhyolitic, and keratophyric tuffs and lava flows and with lead, zinc, and barite mineralization. In their mapping, Mayfield and others (chapters 7 and 8) have treated the lithologic variations between the northern and southern parts of allochthon 1 as gradational facies changes. In addition, they consider that the Upper Mississippian to Lower or Middle Jurassic pelagic and hemipelagic sequence in allochthon 1 depositionally overlies Upper Devonian and Mississippian fluvial and shallow-marine deposits of the Endicott and Lisburne Groups. Churkin and others (1979), however, dispute the depositional relation between the siliceous sequence and the older clastic and carbonate sequence in the De Long Mountains (southwestern part of allochthon 1). The two different interpretations have engendered heated debate (Dutro, 1980; Mayfield, 1980; Metz, 1980).

The distribution of microfossils in allochthon 1 is geographically restricted. Paleozoic radiolarian assemblages with age-diagnostic genera are generally confined to the southwestern part of allochthon 1, which contains the black shale and chert of the Kuna Formation or its correlatives and the green chert and argillite of the Imnaitchiak Chert. In the northwestern part of allochthon 1, Paleozoic radiolarian assemblages, apparently in sponge-spicule-rich facies of the Imnaitchiak Chert, are low in diversity and contain only rare age-diagnostic genera. Paleozoic radiolarian and sponge-spicule assemblages are absent in the northeastern part of map unit A, that is, in the type section of the (restricted) Siksikpuk Formation in the north-central Brooks Range. In contrast to the Paleozoic radiolarian assemblages, Mesozoic radiolarian assemblages are widely distributed throughout allochthon 1 in the Otuk Formation. Conodonts may be somewhat more abundant in the northern part of map unit A than in the southwestern area near the Red Dog lead-zinc deposits.

Several siliceous stratigraphic sections within allochthon 1 have been sampled for microfossils. Five are described below, and three additional sections are described by Blome and others (chapter 33).

1. The (restricted) Siksikpuk Formation at the type section (fig. 32.1, map localities 5, 6, northern part of allochthon 1, central Brooks Range) was collected by B.L. Murchey and I.L. Tailleur in 1980 (see Patton, 1957, and Siok, 1985, for additional data).

Until recently, all maroon, green, and light-gray chert and argillite had been generally mapped as the Siksikpuk Formation. Mull and others (1987) differentiated their (restricted) Siksikpuk Formation from the more siliceous radiolarian-bearing Imnaitchiak Chert. The type section of the (restricted) Siksikpuk Formation lies in the north-central Brooks Range in the northern part of map unit A. At the type section, the (restricted) Siksikpuk is approximately 85 m thick. It consists of maroon and green argillite, calcareous olive-drab argillite, thick-bedded (5-20 cm) dark-gray argillaceous chert associated with some orange staining, red baritic limestone, and barite lenses.

The type section of the (restricted) Siksikpuk overlies black limy shale and shaly limestone of the Kuna Formation and underlies dark shale, gray chert, and cream-colored limestone of the Otuk Formation. Two samples collected by Murchey and Tailleur in 1980 from the Kuna Formation in the vicinity of the type section of the (restricted) Siksikpuk contain Late Mississippian conodonts (A.G. Harris, written commun., 1982). A siliceous mudstone or chert sample collected by Michael Churkin from the basal part of the overlying Otuk Formation on Tiglukpuk Creek (USGS fossil No. MR 1804) contains the conodont *Neogondolella* sp. cf. *N. regale* Mosher (Early Triassic, latest Spathian, to Middle Triassic). Only Permian fossils have been found within the type section of the (restricted) Siksikpuk. Previously reported Pennsylvanian and Triassic radiolarians (Mull and others, 1982) were not from the type section of the (restricted) Siksikpuk Formation. The Guadalupian (Late Permian) cool-water conodont *Neogondolella phosphoriensis* is abundant in limestone nodules and limy shales in the uppermost part of the (restricted) Siksikpuk Formation at Tiglukpuk Creek (samples collected by J.P. Siok). Baritized brachiopod fragments of Permian(?) age have been found on the tributary to Skimo Creek (Patton, 1957), and Permian corals are also reported from this area (Rowett, 1975). The age of the basal part of the (restricted) Siksikpuk does not appear to be well delimited. Chert and argillite samples yielded no siliceous microfossils; one baritized limestone fragment has coarsely crystalline spheroids that may be radiolarian ghosts.

The presence of replaced carbonate megafossils and the limestone and limy argillite in the type section of the (restricted) Siksikpuk indicate that its depositional environment lay above the calcite compensation depth (CCD). This does not necessarily give a reliable indication of paleobathymetry. The Paleozoic CCD may have been quite shallow compared to the present CCD, and, in addition, the CCD can be substantially shallower in small basins and upwelling zones than it is in the open ocean. Relative to the more siliceous, partly correlative Imnaitchiak Chert, the type section of the (restricted) Siksikpuk Formation may have been deposited in shallower water below wave base. The abundant argillite in this section probably represents distal deposits of sediment shed from an emergent landmass. The type section of the (restricted) Siksikpuk Formation is essentially a hemipelagic rather than a pelagic sequence.

2. The Agate Rock section (Campbell, 1967) of the Imnaitchiak(?) Chert (fig. 32.1, locality 2, northwestern part of map unit A, Lisburne Peninsula) was collected by B.L. Murchey and I.L. Tailleur in 1980 (see Blome and others, chapter 33, for discussion of the Otuk Formation at this locality).

At Agate Rock on the Lisburne Peninsula, the Imnaitchiak(?) Chert is partly exposed in an anticline along a seacliff. Gray siliceous argillite 22 m thick is overlain by 26 m of gray and gray-green bedded chert containing finely disseminated pyrite. This section of the Imnaitchiak(?) Chert is overlain by black carbonaceous shale of the basal part of the Otuk Formation. The contact between the two formations is sharp but appears to be conformable, although a hiatus between the two units is possible. In the Imnaitchiak(?) Chert, barite occurs as lenses within argillite and as spheroidal (''cannonball'') concretions in bedded chert.

Nine samples from the lower (argillite) interval yielded no microfossils when processed with hydrofluoric acid; five sequentially collected composite samples from the upper (bedded chert) interval yielded abundant microfossils (USGS fossil Nos. MR 5707 to MR 5711). Radiolarians and siliceous sponge spicules are the most common fossils in these samples and occur in approximately equal proportions. Moderately well preserved spheroidal radiolarians including *Entactinia* sp. dominate the radiolarian populations. The only age-diagnostic radiolarians found were rare *Pseudoalbaillella* sp. aff. *P. lomentaria* Ishiga and Imoto (Ishiga and others, 1982), ?*Scharfenbergia* spp. (late species) fragments from sample MR 5709 (station 80 AMy 12.12), and one poorly preserved ?*Tormentum* sp. from sample MR 5711 (station 80 AMy 12.14) from the uppermost part of the Imnaitchiak(?) Chert. On this sparse evidence, the middle part of the bedded chert interval (sample MR 5709) is Late Pennsylvanian or Early Permian in age, and the age of the uppermost few meters of the bedded chert interval in the Imnaitchiak(?) Chert is probably Permian.

Because the radiolarians in these samples are moderately well preserved and delicate, the extremely low radiolarian diversity of these populations may be a result of original low diversity rather than selective dissolution of delicate specimens. The worldwide distribution patterns of Permian radiolarian assemblages strongly suggest that many taxa are sensitive to environmental conditions (Murchey and Jones, 1983; Murchey and others, 1983). Therefore, environmental factors are likely to be the parameters that control the low diversity of the faunas.

The high sponge-spicule content of these faunas indicates probable proximity to an oxygenated environment conducive to the growth of abundant sponges, probably less than 300 m deep. Upon the death of the sponge, individual siliceous spicules were redeposited down or along a slope.

The lithologic change from an argillite to an argillaceous chert within the Imnaitchiak(?) Chert may indicate a decrease in the rate of dilution of pelagic sediments by clay from a terrigenous source during Late Pennsylvanian or Early Permian time and (or) an increase in biologic productivity.

Samples MR 5707, MR 5710, and MR 5711 each contain 3-10 silicified specimens of the foraminifer *Ammodiscus*. Sample MR 5711 yielded one silicified echinoderm fragment. Although the Imnaitchiak(?) Chert at this locality is not calcareous, the presence of silicified carbonate microfossils implies that deposition occurred near the CCD. Deposition well above the calcite lysocline should have resulted in the preservation of trapped micritic calcite and more abundant calcareous microfossils. An example of deposition above the calcium carbonate lysocline at the same locality is the overlying Otuk Formation, which is black carbonaceous shale, black sooty chert, and cream-colored fine-grained limestone. If the contact between the Imnaitchiak(?) Chert and the Otuk Formation at this locality is indeed depositional, it may mark a hiatus. The basal part of the Otuk at this locality is undated. The oldest radiolarians identified to date are not older than Late Triassic (Blome and others, chapter 33). The Otuk Formation at Agate Rock is very similar to the type Otuk Formation in the central Brooks Range, but the Imnaitchiak(?) Chert at this locality is more siliceous than the type section of the (restricted) Siksikpuk Formation in the central Brooks Range.

3. The Otuk Formation at the type section (fig. 32.1, locality 10, northern part of map unit A, central Brooks Range) was sampled by P.B. Swain, B.L. Murchey, R.E. Witmer, and W.W. Chamberlain in 1979 (see Blome and others, chapter 33; Swain, 1981; Mull and others, 1982; Bodnar, 1984).

The type section of the Otuk Formation is characteristic of Mesozoic siliceous facies in the northern part of map unit A, allochthon 1. Black carbonaceous shale (shale member) grades upward into thin-bedded chert (chert member) that, in turn, grades upward into fine-grained, thick-bedded, buff-weathering limestone (limestone member). The light-weathering limestone is stratigraphically overlain by carbonaceous paper shale, dark chert, and thinly bedded limestone of the Blankenship Member of the Otuk. Swain (1981) and Blome and others (chapter 33) describe the radiolarian biostratigraphy of this formation in detail. Radiolarians from this locality are poorly preserved and have undergone a complex diagenetic history. Associated fossils found in the sequence include conodonts (table 32.2), foraminifers, and the flat clams *Halobia* and *Monotis*. Chert beds in the Otuk Formation are commonly calcareous, and individual beds in the chert member at the type section grade laterally into limestone. As previously mentioned, deposition of these sediments occurred above the CCD.

4. The Key Creek section (fig. 32.1, locality 3, southern part of map unit A) was sampled by C.F. Mayfield, S.M. Curtis, Inyo Ellersieck, and I.L. Tailleur in 1979.

At the Key Creek locality, an interval 124 m thick of siliceous chert, argillite, black shale, and limestone was sampled in a section that consists of the Kayak Shale, Kuna Formation, Imnaitchiak(?) Chert, and Otuk Formation.

The Kuna Formation at this locality grades upward from a black shale with interbedded black limestone into black bedded chert. Residues from cherty samples collected in the shale interval are barren or nearly barren of fossils; several have abundant pyrite. A sample of gray, bedded chert collected at 51 m above the base of the measured section contains latest Meramecian to Morrowan radiolarians (Paleozoic Faunal Group IIA: *Scharfenbergia tailleurense* Holdsworth and Murchey, see chapter 34). This sample is from a 1- to 2-m gradational zone in the uppermost part of the Kuna Formation and the basal part of the Imnaitchiak(?) Chert. Chert beds in this interval are 2-10 cm thick. Most beds in this gradational interval are gray on top and black on the bottom (sedimentary grading?) (C.F. Mayfield, written commun., 1979).

None of the many samples from the overlying Imnaitchiak(?) Chert yielded age-diagnostic radiolarian faunas, although many samples contain poorly preserved spherical radiolarians. At Key Creek the Imnaitchiak(?) Chert contains gray, olive, and maroon chert and gray, gray-green, and maroon argillite and is approximately 50 m thick. Samples from the upper 10 m of the formation contain silicified *Ammodiscus* sp. These foraminifers occur at the same lithostratigraphic horizon as *Ammodiscus* sp. in the Imnaitchiak(?) Chert at Agate Rock (fig. 32.1, locality 2). Overlying Mesozoic rocks containing Late Triassic radiolarians consist of basal black carbonaceous shale and gray, bedded chert overlain by gray-green chert containing minor barite. The Triassic part of the Key Creek section is herein referred to the Otuk Formation but has some similarities with the Imnaitchiak Chert. Unlike the Otuk at localities 2 and 11, the section here includes no bedded limestone. Whether any limestone beds are hidden beneath covered intervals is not known, but such beds do crop out nearby (I.L. Tailleur, written commun., 1988). Both the Imnaitchiak(?) Chert and Otuk Formation in this section are more siliceous than the type sections of the (restricted) Siksikpuk and Otuk.

5. An outcrop of Paleozoic rocks in the Key Creek sequence (fig. 32.1, locality 4, southern part of map unit A) was collected by Inyo Ellersieck in 1979.

Two samples collected on either side of the boundary between black chert of the Kuna Formation (USGS fossil locality MR 5447A) and gray chert of the Imnaitchiak(?) Chert (USGS fossil locality MR 5447B) in the southwestern part of map unit A yielded late Meramecian to Morrowan radiolarians of Faunal Group IIA (see Holdsworth and Murchey, chapter 34). Both samples are dominated by sponge spicules, but the ratio of sponge spicules to radiolarians is lower in the Imnaitchiak(?) Chert sample. This locality, like locality 3, is part of the Key Creek sequence (Mayfield and others, chapter 7). The contact between the Kuna Formation and the Imnaitchiak(?) Chert occurs at the same biostratigraphic horizon at both these localities.

MAP UNIT B: ALLOCHTHONS 2–5

Map unit B is an amalgamation of allochthons 2-5 of Mayfield and others (chapter 7). The Lisburne Group and the Etivluk Group are mapped in all four allochthons. Both Paleozoic and Mesozoic radiolarian assemblages have been recovered from all four.

In allochthon 2 (Picnic Creek allochthon), the Etivluk Group overlies the Akmalik Chert of Mull and others (1987), a Mississippian and Pennsylvanian sequence of black chert or black chert and limestone lithologically similar to, but more siliceous than, the Kuna Formation. Mayfield and others (chapter 7) consider this entire siliceous sequence as depositionally overlying the Endicott Group (shale, siltstone, sandstone, and conglomerate stratigraphically correlative with the undivided Kayak Shale, Noatak Sandstone, and Kanayut Conglomerate).

In allochthon 3 (the Kelly River allochthon), the Etivluk Group overlies Mississippian fossiliferous carbonate rocks of the Lisburne Group. Mayfield and others (chapter 7) report a possible disconformity at the base of the Etivluk Group. They show the Lisburne Group as depositionally overlying the Baird Group, which, in this allochthon, is a fossiliferous sequence of Devonian limestone and dolomite.

Allochthon 4 (the Ipnavik River allochthon) is distinguished by diabase dikes and sills intruded into Mississippian black chert and micritic limestone and Mississippian to Jurassic(?) gray, green, and red chert. The Lisburne and Etivluk Groups in allochthon 4 are mapped as depositionally overlying the Mississippian Kayak Shale (black shale and siltstone containing corals and conodonts) and the Devonian Baird Group (part) (fossiliferous light-gray limestone). Allochthon 5 (the Nuka Ridge allochthon) contains well-bedded gray and red chert of the Etivluk Group that overlies Carboniferous arkose and arkosic limestone of the Nuka Formation. In the interpretation of Mayfield and others (chapter 7), the contact between the two units is depositional. This stratigraphic sequence is mapped as depositionally overlying the Mississippian Kayak Shale and the Devonian Baird Group (part).

Two chert and argillite sequences in map unit B have been sampled extensively:

1. The Nigu Bluff reference section (fig. 32.1, locality 1, allochthon 2 in map unit B, central Brooks Range) was sampled by B.L. Murchey, P.B. Swain, and S.M. Curtis in 1979 (Holdsworth and Murchey, chapter 34; Murchey and others, 1981).

The most complete sequence of Paleozoic radiolarian faunas known in the Brooks Range is in the Nigu Bluff section on the Nigu River in Howard Pass quadrangle. The section lies within allochthon 2 (the Picnic Creek allochthon) in map unit B. At this locality a thickness of 192 m of chert, shale, limestone, and argillite is overturned and dips steeply to the south. At the south end of the cutbank, a diabase sill intrudes the basal part of the sequence. The sill is overlain by an 85-m-thick sequence of dark-gray and black shale, thinly bedded siliceous mudstone, and a minor amount of thinly bedded limestone. A limestone bed 29 m above the sill yielded Devonian(?) ?*Tentaculites* sp. (M.B. Mickey, written commun., 1983) as well as very poorly preserved radiolarians(?) and fragmented conodonts. The interval from 85 to 100 m above the sill is siliceous dolomitic limestone containing siliceous sponge spicules (Demospongiae and Hexactinellida), sponge casts, and barite rosettes. The sponge-rich limestone (Kuna(?) Formation or Akmalik(?) Chert) grades upward into gray-green bedded radiolarian chert (Imnaitchiak(?) Chert; 100 to 160 m stratigraphically above the sill). The 10-m-thick transition zone between these two rock types (100 to 110 m above the sill) is a sponge-rich bedded chert showing diagenetic pinch-and-swell structures. The uppermost interval at Nigu Bluff (Imnaitchiak(?) Chert; 160 to 192 m above the sill) is maroon and green argillaceous chert and shale. Holdsworth and Murchey (chapter 34) have used the interval from 115 to 192 m above the sill in this sequence as the Paleozoic radiolarian reference section for the Brooks Range. They discuss this section and its faunas in detail. In addition, Paleozoic faunal groups recognized by Holdsworth and Murchey throughout the Brooks Range are correlated with the Nigu Bluff reference section (table 32.1; Holdsworth and Murchey, chapter 34, fig. 34.3).

The transition from sponge-rich limestone of the Lisburne Group to more siliceous radiolarian-rich rocks in the basal part of the Etivluk Group does not predate the late Osagean at Nigu Bluff. The basal part of the radiolarian reference interval is late Osagean or Meramecian in age, and the youngest part of the exposed Etivluk Group is Atokan to Wolfcampian in age. Within the reference interval, radiolarian preservation, diversity, and abundance generally increase upward in the stratigraphic section.

In comparison to those at localities 2 (Agate Rock, Lisburne Peninsula, northwestern part of map unit A) and 3 (Key Creek section, western Brooks Range, southern part of map unit A), the radiolarian faunas at Nigu Bluff are more diverse at the specific and generic levels. At Nigu Bluff, radiolarians also tend to be more abundant relative to sponge spicules than in correlative strata in map unit A. As at localities 3 (Key Creek) and 4 in map unit A, the basal part of the Etivluk Group at Nigu Bluff contains faunas in which sponge spicules form more than 50 percent of the siliceous microfossils (280-mesh sieve residue). However, the basal part of the Etivluk Group at Nigu Bluff is older (late Osagean or Meramecian in age, correlative with Faunal Groups 1B and V of Holdsworth and Murchey, chapter 34) than the basal part of the Etivluk Group at localities 3 and 4 (late Chesterian and (or) Morrowan Faunal Group IIA of Holdsworth and Murchey, chapter 34). In the upper part of the Imnaitchiak(?) Chert at Nigu Bluff (uppermost limit not exposed), radiolarians are more abundant than sponge spicules. The radiolarian-rich interval at Nigu Bluff includes strata correlative with the sponge-spicule-dominated upper part of the Kuna Formation and basal part of the Imnaitchiak(?) Chert at localities 3 (Key Creek) and 4 (Ellersieck locality). The radiolarian-rich interval at Nigu Bluff also includes strata possibly correlative with the sponge-spicule-dominated upper part of the Imnaitchiak(?) Chert at localities 2 (Agate Rock) and 3.

The earlier transition from a sponge spiculite to a radiolarite and the persistence of deposition of radiolarian-dominated strata in the Imnaitchiak(?) Chert at Nigu Bluff (allochthon 2) indicate deposition in consistently deeper or more platform-distal environments than for coeval rocks at localities 2, 3, and 4 (allochthon 1). The upward transition from black, carbonaceous shale with minor limestone and thin chert beds (Kuna(?) Formation or Akmalik(?) Chert) into a more siliceous sequence with abundant radiolarians (Imnaitchiak(?) Chert) reflects subsidence or marine transgression within the basin.

2. The Punupkahkroak Mountain section (fig. 32.1, locality 11, map unit B, allochthon 4, western Brooks Range) was sampled by W.W. Chamberlain.

The best-preserved sequence of Mesozoic radiolarian faunas known in the Brooks Range is in an Upper Triassic (Norian) to Lower Jurassic section near Punupkahkroak Mountain in the De Long Mountains. Blome and others (chapter 33) describe the radiolarian biostratigraphy of the sequence. This section of rocks, which lies in allochthon 4 (the Ipnavik River allochthon) contains Norian *Monotis*-bearing chert beds. Mesozoic chert from this locality is both light and dark gray; the *Monotis*-bearing chert weathers to a light-cream color. Although the Punupkahkroak Mountain section is biostratigraphically correlative with the Otuk Formation type section (locality 10, allochthon 1), it is predominantly a bedded-chert sequence lacking limestone beds and carbonaceous shale. The presence of *Monotis* sp. implies that the strata were originally somewhat limy. Etched residues from the 14 samples collected here are medium gray, light gray, and white. In addition to rather well-preserved and abundant radiolarians, these residues contain sponge spicules, condont fragments, a few poorly preserved silicified foraminifers, and minor pyrite but very little carbonaceous material. Compared to the Otuk Formation type section, the Punupkahkroak Mountain sequence may have been deposited in a somewhat deeper or more offshore environment, above but perhaps near the CCD.

MAP UNIT C: ALLOCHTHONS 6 AND 7

Map unit C is composed of allochthons 6 (the Copter Peak allochthon) and 7 (the Misheguk Mountain allochthon) of Mayfield and others (chapter 7). Pillow basalt with minor local radiolarian chert and shale characterize allochthon 6. Allochthon 7 is characterized by gabbro and peridotite and lacks sedimentary rocks. These two allochthons have been treated as one unit because they are both predominantly igneous. Map unit C has been included in the western part of the Angayucham tectonostratigraphic terrane of Jones and others (1981), the outcrop area of which is mostly on the south side of the Brooks Range. Poorly preserved Triassic radiolarians have been found in allochthon 6 in the northern Brooks Range (fig. 32.1; table 32.1). In the southern Brooks Range, the Angayucham terrane contains Late Devonian, Mississippian, Pennsylvanian(?), Permian, Triassic, and Early Jurassic(?) radiolarians. In the northern Brooks Range, the sedimentary rocks in map unit C are entirely siliceous and lack the abundant argillite, carbonaceous shale, and fine-grained limestone characteristic of the Etivluk Group. In addition, the chert in map unit C is commonly red and nonbaritic and may be slightly manganiferous. Megafossils, carbonate microfossils, conodonts, and siliceous sponge spicules have not been found in these rocks in the northern Brooks Range, although some are known from the southern Brooks Range. The fossils and petrography of the chert in this map unit show little evidence for deposition above the CCD or in a platform-proximal environment.

Mayfield and others (chapter 7) have interpreted the rocks in map unit C as being more oceanic in character than correlative rocks in the underlying structural units. In their interpretation, the rocks of map unit C formed as the result of intracratonic extension and rifting beginning in the Mississippian and Pennsylvanian. The sedimentary rocks of allochthons 1, 2, 3, 4, and 5 and the structurally underlying rocks of the North Slope formed the northern margin of the rift basin. Devonian radiolarians in the Angayucham terrane, however, would require earlier rifting and (or) basin formation if this model is generally correct. Whereas I.L. Tailleur contends that pre-Triassic sedimentary rocks in the Angayucham terrane are tectonic inclusions within basalt (written commun. 1988), Jones and others (1981) have suggested that the igneous and sedimentary rocks of the Angayucham terrane represent Paleozoic and Mesozoic seamounts or pieces of oceanic plateaus.

EASTERN BROOKS RANGE

Scattered occurrences of radiolarian chert are found in the Arctic and Christian quadrangles and elsewhere in the eastern Brooks Range. Most of these occurrences have been sampled only in a reconnaissance fashion. Consequently their age, lithologic character, and stratigraphic relations remain poorly known. Both Paleozoic and Mesozoic radiolarian faunas and Triassic conodont faunas have been identified (fig. 32.1; tables 32.2, 32.3). No sequential samples were collected through Mesozoic sections, and we have little information regarding their lithology. Paleozoic radiolarians were recovered from sequential sample collections at map localities 7, 8, and 9 (fig. 32.1; collected by H.N. Reiser in 1978 and 1979). At locality 7, strata with Osagean to Meramecian Faunal Group I radiolarians (Holdsworth and Murchey, chapter 34) are overlain by strata with late Osagean to Chesterian or Morrowan Faunal Group V radiolarians (USGS fossil Nos. MR 0588 to MR 0590). At locality 8 (USGS fossil Nos. MR 0526 to MR 0587) an interval estimated to be 40 to 45 m thick yielding latest Meramecian to Morrowan Faunal Groups II and IIA radiolarians is overlain by one approximately 9 m thick with Faunal Group VI radiolarians similar to post-Morrowan radiolarians at the stratigraphic top of Nigu Bluff (Faunal Group IV) but lacking *Pseudoalbaillella* sp. At locality 9 (USGS fossil Nos. MR 1092 to MR 1094), black chert containing late Osagean to Chesterian or Morrowan Faunal Group V radiolarians is overlain by red and green argillite with latest Meramecian to Morrowan Faunal Group IIA radiolarians, which is in turn overlain by red and green argillite interbedded with red, green, and white chert containing Early Permian, probably Leonardian, Faunal Group IVA radiolarians and *Ammodiscus* foraminifers. The three samples from locality 9 are poor in sponge spicules and yielded no conodonts. The eastern Brooks Range Paleozoic faunas show a faunal range and diversity similar to the collections at Nigu Bluff (fig. 32.1, locality 1, map unit B).

FAUNAL DISTRIBUTION PATTERNS

In the northern Brooks Range, siliceous fine-grained rocks having age-diagnostic radiolarian faunas range in age from Early Mississippian (Osagean) to Early Jurassic. These rocks include the uppermost part of the Lisburne Group, the Imnaitchiak Chert, the Otuk Formation, and their lateral equivalents. In the central and western parts of the Brooks Range, Paleozoic radiolarian faunas are absent or very low in diversity in the northern region of map unit A (allochthon 1) and parts of the southern region of map unit A. More diverse Paleozoic faunas are confined to parts of the southern region of map unit A (allochthon 1) and to map unit B (allochthons 2 to 5). Late Triassic radiolarian faunas are widespread and occur in all three map units, primarily in cherty rocks. Only a few Jurassic radiolarian faunas are known. Conodonts from the siliceous rocks range from Early Pennsylvanian (Morrowan) to Late Triassic (Norian) in age. They are most common in calcareous chert and in chert closely associated with limestone.

PALEOZOIC RADIOLARIAN DISTRIBUTION

So far as known, Mississippian radiolarian faunas older than latest Chesterian (Faunal Group I and part or all of Faunal Group V; see table 32.1) are confined to a narrow belt within map unit B in the central Brooks Range (allochthons 2, including the Nigu Bluff reference section, and 4) and to the easternmost Brooks Range. Possible exceptions are two localities having Faunal Group V (late Osagean to Chesterian or Morrowan) radiolarians in the southwestern part of allochthon 1 near the Red Dog prospect. Probable age-equivalent rocks, in part, include shallow-marine carbonate rocks (Kogruk(?) Formation), deeper marine sponge-rich carbonate rocks (Kuna Formation, Akmalik Chert, Tupik(?) Formation), and arkosic carbonate rocks (Nuka Formation). Chert nodules in these Mississippian and Pennsylvanian carbonate rocks typically contain silicified carbonate fossil fragments, sponge spicules, or silt. The presence of Faunal Groups I and V in both the central (map unit B) and easternmost Brooks Range suggests a structural relation. At the least, radiolarian faunas in both areas indicate relatively deep basins during Late Mississippian time.

By latest Meramecian to Morrowan time (Faunal Groups II, IIA, and III—the faunal groups with *Scharfenbergia tailleurense*), widespread radiolarian deposition is recorded in the strata of all allochthons in map units A and B. Typically, sponge-rich pelagic limestone grades upward into radiolarian-rich bedded chert of the Etivluk Group. This lithologic succession transgresses biostratigraphic boundaries. For instance, this facies change at Nigu Bluff (locality 1) predates an equivalent facies change in the Key Creek section (locality 3). The lithologic sequence just described may be directly underlain by other deep-water facies (as appears to be the case at Nigu Bluff, locality 1, allochthon 2) or by shallow-water facies (as reported in allochthons 3 and 5; Mayfield and others, chapter 7).

Faunal Group IIA (*S. tailleurense*, latest Meramecian to Morrowan) is the most widely distributed Paleozoic faunal group in the Brooks Range. It occurs in the southwestern part of map unit A and throughout map unit B. In the eastern Brooks Range known occurrences lie between long 144° and 147° W. The widespread geographic distribution of this faunal group is controlled by three factors:

1. Because *S. tailleurense* is very robust and is distinctive in shape, even poorly preserved specimens are easily recognizable. Many other species are more likely to be dissolved or to be unrecognizable when poorly preserved. Therefore, the selective preservation and recognition of *S. tailleurense* may be an important factor in the widespread distribution of known occurrences of the species.

2. A time-transgressive lithologic transition from radiolarian-poor, carbonate-rich rocks (Lisburne Group) to radiolarian-rich (commonly) bedded chert (lower part of the Etivluk Group) predates or is contemporaneous with Faunal Group IIA on all thrust sheets in map units A and B so far as known. In other words, by Faunal Group IIA time, siliceous fine-grained sediment, often with abundant radiolarians, was being deposited on all allochthons in map units A and B.

3. *S. tailleurense* is a cosmopolitan species; it is known in Mexico, Nevada, California, and elsewhere in Alaska. Its wide distribution suggests it was able to thrive in a variety of environments.

Latest Meramecian to Morrowan Faunal Group II (*S. tailleurense* and *Albaillella* sp.) is present at eight sample localities within map unit B in the central Brooks Range. At least five and perhaps more of these localities are from allochthon 5 (Nuka Ridge allochthon), even though the outcrop area of this allochthon is relatively small. The close association of Faunal Group II with a single allochthon suggests an environmental or (less likely) diagenetic control over the distribution of the *Albaillella* species associated with *S. tailleurense*. The environmental or diagenetic parameters controlling the presence or absence of *Albaillella* sp. in assemblages with *S. tailleurense* (Faunal Group II versus IIA, respectively) are not understood. Some Permian Albaillellaria seem to favor deep water and low latitudes (Murchey and Jones, 1983; Murchey and others, 1983). Comparable biogeographic studies of Mississippian and Pennsylvanian radiolarian faunas have not been made. Faunal Group II may be the oldest radiolarian fauna on allochthon 5, although structurally underlying allochthons contain older Faunal Groups I and (or) VI.

Late Morrowan to Leonardian radiolarian faunas with *Pseudoalbaillella* sp., ?*Scharfenbergia* sp. (late species), or late *Latentifistula* spp. (Faunal Groups IV, IVA, VI) have approximately the same combined distribution pattern as Faunal Group IIA. They are known in the northwestern part of map unit A (rare), in the southern part of map unit A, and throughout map unit B. Their widespread occurrence is largely controlled by the widespread distribution of Pennsylvanian and Permian gray-green or variegated chert and argillite.

Low-diversity entactinid faunas (no faunal-group designation) are very common within the Pennsylvanian and Permian interval. At present, we believe these low-diversity faunas lacking *Pseudoalbaillella* spp., *Scharfenbergia*, or Latentifistulidea are most characteristic of map unit A (for example, localities 2 and 3). They commonly occur together with abundant sponge spicules (>50 percent of microfossil residue) and with foraminifers. Their distribution appears to be facies controlled and probably reflects a shallower environment than coeval rocks in many parts of map unit B. These assemblages are not shown on the distribution map (fig. 32.1) or in table 32.3 because their ages cannot be determined except when they occur within a stratigraphic sequence with dated samples both above and below.

During the course of this study, no Paleozoic radiolarian faunas were recovered between long 147° and 154° W., even though, Tailleur and Murchey sampled the type section of the (restricted) Siksikpuk Formation extensively. To date, no Paleozoic radiolarian faunas are known from map unit C on the northern side of the Brooks Range, although Murchey and Jones have recovered Paleozoic radiolarian faunas from the Angayucham terrane (interpreted to be structurally equivalent to map unit C) on the southern side of the Brooks Range.

The absence of diagnostic Late Permian and Early Triassic radiolarians is characteristic of all Alaskan chert-bearing terranes north of the Denali fault, including the allochthons of the northern Brooks Range. Only a few samples have

Albaillellaria (undescribed *Pseudoalbaillella* spp.) or Latentifistulidea that may be as young as Leonardian in age. In the northern Brooks Range, this stratigraphic interval is represented, at least in part, by argillaceous rocks. Hiatuses within this time interval are possible and are locally indicated (for example, at Agate Rock). Therefore, nondeposition of radiolarian-rich sediment during this time may be the reason such faunas are missing. Alternatively, the distribution patterns of Permian circum-Pacific radiolarian faunas may indicate that Albaillellaria, Latentifistulidea, and many Entactinacea became increasingly restricted to low latitudes during Permian time (Murchey and Jones, 1983)

MESOZOIC RADIOLARIAN DISTRIBUTION

Mesozoic radiolarian faunas are distributed throughout allochthons 1 to 6 (map units A, B, and C) and also occur in the eastern Brooks Range. The great majority of Mesozoic faunas with diagnostic radiolarians are Late Triassic in age. A few older (Early to Middle Triassic) and younger (Early Jurassic) faunas have been recognized.

The oldest independently dated Triassic radiolarian assemblage in the Brooks Range (USGS sample MR 1804) contains only spherical spumellarians with simple nonbladed primary spines. This sample was dated by the conodont *Neogondolella* sp. cf. *N. regale* Mosher (Wardlaw and Jones, 1979), whose age range is Early Triassic (latest Spathian) to Middle Triassic. The sample was collected from chert above the (restricted) Siksikpuk Formation, presumably in the lower part of the Otuk Formation (Michael Churkin, oral commun., 1979). Similar radiolarian faunas have been extracted from siliceous argillite in the black shale member of the Otuk Formation at a few localities. However, because the faunas are low in diversity and lack independent age control, they cannot be dated with certainty and are not included in the map and tables.

The Mesozoic radiolarian biostratigraphy of measured sections and selected samples in the Brooks Range is discussed by Blome and others (chapter 33) and by Swain (1981). Some of the samples discussed by Blome and others (chapter 33) as well as other miscellaneous samples that have been dated on the basis of a very few poorly preserved nassellarians or fragments of robust spumellarians such as *Capnuchosphaera* spp. are included on figure 32.1 and table 32.3. A precise age for some of the latter poorly preserved Mesozoic faunas cannot be determined.

Coeval radiolarian-bearing Mesozoic rocks range from dark-gray calcareous chert and shale and buff-weathering limestone to red, green, or gray noncalcareous chert. The calcareous facies is most common in map unit A; less calcareous chert is most common in map units B and C. Mesozoic faunas from more siliceous rocks (for example, locality 11 at Punupkahkroak Mountain) are generally better preserved than faunas from limy chert or cherty limestone (for example, locality 10, the type Otuk Formation). Swain (1981) noted that the complex diagenetic history of the radiolarians in the type Otuk Formation has resulted in the preservation of only robust forms or fragments of some genera. Selective preservation of some species and concurrent selective dissolution of others can result in significantly reduced apparent faunal diversity.

CONODONT DISTRIBUTION

Conodont distribution in the siliceous rocks is facies controlled. Condonts were generally recovered only from chert closely associated with limestone. Many of these chert samples are probably silicified limestone. Either the conodonts preferred a somewhat limy (shallower?) environment, or carbonate-enriched host sediments favor their preservation.

FACIES AND BIOSTRATIGRAPHIC BOUNDARIES

Several distinct lithologic packages or facies characterize the siliceous rocks of the northern Brooks Range. These facies transgress biostratigraphic boundaries and also recur in the stratigraphic section. The following discussion is a summary of the spatial and temporal distribution of four lithologic associations characteristic of the siliceous rocks:

1. Black bedded chert, pelagic fine-grained limestone, and carbonaceous shale,
2. Medium-gray, light-gray, or olive-drab chert with or without associated argillite,
3. Maroon chert interbedded with maroon and green argillite, and
4. Chert associated with mafic extrusive volcanic rocks including pillow lava.

An interpretive summary of the distribution of siliceous facies in the northern Brooks Range in space and time is given in figure 32.2. Where possible, the sequential collections described herein were used as the principal data base for this interpretation. In addition, isolated samples of known age and lithology were incorporated into fig. 32.2 where biostratigraphic control was otherwise lacking.

LITHOLOGIC ASSOCIATION 1

Black or dark-gray bedded chert associated with pelagic limestone and carbonaceous shale is a common facies in the northern Brooks

Range. This association occurs in both Paleozoic (Mississippian and Pennsylvanian) and Mesozoic (Triassic and Jurassic) strata.

PALEOZOIC

Mississippian and Pennsylvanian association 1 facies have been mapped as the upper part of the Kuna Formation, the Akmalik Chert, and as informally designated rock units termed ''black chert'' or ''black chert and limestone'' (Mayfield and others, chapter 7). The chert is commonly somewhat laminated, but evidence of bioturbation including burrows is also common. Many samples appear to be silicified sponge- and radiolarian-bearing limestone. The chert contains diagenetic carbonate rhombs or their siliceous pseudomorphs and (or) trapped micritic calcium carbonate. Silicified algal-crinoidal limestones of shallower water origin are not considered to be part of this facies, although they have also been included in ''black chert and limestone'' rock units by Mayfield and others (chapter 7). Residues from hydrofluoric-acid etching of chert from this facies contain black carbonaceous material, finely disseminated or cubic pyrite, abundant sponge spicules, a few radiolarians, rare conodont fragments, and brown spongy matrix fragments (silicified limestone?).

The oldest radiolarian faunas in map units A and B and in the eastern Brooks Range were extracted from this type of siliceous assemblage. The faunas range in age from Mississippian (pre-Chesterian) to latest Mississippian or earliest Pennsylvanian. All Faunal Group IA and IB samples, most Faunal Group V samples, and an estimated 30 percent of Faunal Group II and IIA samples belong to association 1 facies (see table 32.1 for faunal group ranges).

In the northern part of map unit A, the Kuna Formation is characterized by limestone and carbonaceous shale and lacks well-developed bedded black chert. Some sponge spicules but no radiolarians have been extracted from the Kuna in this region. In the southern part of map unit A, the association 1 facies is more siliceous and radiolarians are common to abundant. Lead-zinc mineralization, thick-bedded barite, and andesitic, rhyolitic, and keratophyric tuff and lava flows are intimately associated with this sedimentary package in the southern part of map unit A. In map unit B, Mississippian association 1 facies are well developed on allochthons 2 and 4. The biostratigraphic ranges of association 1 in map units A (southern part) and B (allochthons 2 and 4) overlap, but the base and top of the ranges of association 1 in map unit B appear to be somewhat older than those in map unit A. In addition, the ratio of radiolarians to sponge spicules is generally higher in allochthons 2 and 4 of map unit B than in the southern part of map unit A.

The transition from Mississippian and Pennsylvanian association 1 facies (black chert-fine grained limestone-carbonaceous shale association) into younger medium-gray or olive-drab bedded chert and argillite (association 2) transgresses biostratigraphic boundaries. At localities 1 (Nigu Bluff, allochthon 2, map unit B) and 9 (eastern Brooks Range) the transition is overlain by strata containing late Osagean to Meramecian Faunal Group IB, but at localities 3 and 4 (Key Creek, southwestern part of allochthon 1, map unit A) the facies change is bracketed by the younger latest Meramecian to Morrowan Faunal Group IIA. In these sections, this facies change is accompanied by an upward decrease in the ratio of sponge spicules to radiolarians. At localities 5 and 6 in the central Brooks Range (northern part of map unit A), conodonts indicate that the top of the black limy shale and shaly limestone of the Kuna Formation (not cherty in this area) that underlies limy argillite of the type section of the (restricted) Siksikpuk Formation (somewhat siliceous but lacking radiolarians and sponge spicules) is Chesterian in age (A.G. Harris, written commun., 1982). The only fossils found thus far in the type section of the (restricted) Siksikpuk are Permian in age.

Association 1 facies mark the beginning of siliceous deposition in the study area. The association forms a transitional facies between underlying shallower marine shales and carbonate rocks and overlying deeper (inferred) association 2 facies. Rocks of the Paleozoic black chert and shale facies are commonly somewhat bioturbated. In addition, they commonly contain sponge spicules (including demosponge forms) and locally whole sponges. The marine environment of deposition was, therefore, at least periodically oxygenated. However, organic material was generally buried at a rate faster than bacteria could consume it, resulting in sediments rich in organic matter.

Siliceous basins formed first during the late Early and Late Mississippian (Faunal Groups IA, IB, and V) in parts of map unit B (allochthons 2 and 5) and in the eastern Brooks Range sequence. The apparent absence of association 1 facies containing radiolarian faunas older than Faunal Groups II or IIA in allochthons 1 (southwestern part), 3, and 5 indirectly supports the map interpretations of Mayfield and others (chapter 7) that bedded chert in the allochthons depositionally overlies Mississippian shallow-water carbonate rocks and that initial basin formation was local. The Paleozoic association 1 facies in the northern part of map unit A does not contain radiolarians, so far as known, and may never have had as deep water as association 1 facies in the southern part of map unit A and in map unit B. The transition from association 1 to association 2 is similarly asynchronous, occurring first (late Osagean to Meramecian or Chesterian) in the older and deeper basins in allochthons 2 and 4 and later (latest Meramecian to Morrowan) in allochthons 1, 3, and 5.

MESOZOIC

The Mesozoic association 1 facies is similar to the Paleozoic association 1 facies in many respects. The previously described type Otuk Formation on Otuk Creek (locality 10, map unit A) is a good example of this lithologic package. Acid-etched residues from chert and limestone beds in the Otuk Formation contain black carbonaceous material, pyrite, radiolarians, silicified foraminifers, and conodonts. The chert beds are somewhat limy, laminated, and slightly burrowed.

Mesozoic association 1 is widely distributed in map unit A, especially in the northern region. The lower part of the Otuk Formation at Agate Rock on the Lisburne Peninsula (locality 2, northwesternmost part of map unit A) and the Otuk Formation on Monotis Creek and Tiglukpuk Creek (northeastern part of map unit A) also belong to this lithologic association. The oldest rocks in association 1 sequences containing Mesozoic radiolarians have not been shown to predate the Triassic. The total biostratigraphic range of the Mesozoic association 1 is greatest in the northern part of map unit A, where it ranges from Early(?) Triassic to Jurassic in age. The stratigraphic range of this facies appear to be more restricted in the southwestern part of map unit A. In the Key Creek section (locality 3), Upper Triassic carbonaceous chert and shale (association 1) are overlain by light-colored Upper Triassic bedded chert with barite (association 2). In structurally higher allochthons (map unit B), Upper Triassic and Lower Jurassic rocks correlative with the type Otuk Formation are generally more siliceous, less limy, and less carbonaceous than the type Otuk. Such strata are more consistent with the definition of association 2 than with that of association 1. In parts of map unit B, Upper Triassic rocks partially correlative with the type Otuk Formation also include red or green radiolarian chert and argillite (associations 2 and 3).

As previously stated, black chert, fine-grained limestone, and carbonaceous shale of the Otuk Formation are largely restricted to map unit A and are best developed along the northern part of that map unit. This distribution pattern indicates that during the early Mesozoic, the northern part of allochthon 1 lay approximately parallel to a shelf margin and probably in shallower water than the other allochthons. The black carbonaceous shale may have been deposited where poorly oxygenated water (commonly found at intermediate depths in modern ocean basins) impinged on the sediment-water interface, possibly in a coastal upwelling zone. The deposition of the Otuk Formation was followed locally by deposition of relatively shallow-water coquinoid limestone.

LITHOLOGIC ASSOCIATION 2

Medium-gray, light-gray, or olive-drab chert with or without associated argillite is a very common sedimentary association in all five allochthons in map units A and B. The light-colored chert and siliceous argillite in this association is more homogeneous than black or dark-gray chert in the lithologic association previously described. This homogeneity may be evidence that these beds were well bioturbated. Near transition zones with underlying black chert or limestone, these chert beds commonly exhibit pinch-and-swell diagenetic features. Hemispherical mammillate mounds are very common in association 2 facies. Barite in lenses, beds, or spheroidal masses (''cannonballs'') is a characteristic feature. Green pyritic chert commonly has an orange-weathering surface. Chert beds are generally 5 to 20 cm thick. Residues from hydrofluoric-acid solution are white or light gray and contain sponge spicules (Hexactinellida), radiolarians, a few silicified foraminifers, rare conodont fragments, and cubic pyrite.

Association 2 is more argillaceous in the northern part of map unit A (for example, parts of the type section of the (restricted) Siksikpuk Formation at localities 5 and 6 and the Imnaitchiak(?) Chert at Agate Rock, locality 2). Association 2 is most siliceous, radiolarian-rich, and stratigraphically long ranging in map unit B, particularly in allochthons 2 and 4 (for example, the Imnaitchiak(?) Chert interval at Nigu Bluff, locality 1; the Mesozoic Otuk(?) Formation at Punupkahkroak Mountain, locality 11).

In the northern part of map unit A where association 2 is most argillaceous, it appears to be limited to Paleozoic strata and is everywhere overlain by association 1 facies of the Otuk Formation. In the type section of the previously described (restricted) Siksikpuk Formation (localities 5 and 6, central Brooks Range, map unit A), the association interfingers with a maroon argillite facies (association 3). The entire outcrop of the Imnaitchiak(?) Chert at Agate Rock (locality 2, Lisburne Peninsula, map unit A) consists of argillaceous association 2 rocks.

In the southern part of map unit A, the association 2 facies are more siliceous and occur in both Paleozoic and Mesozoic strata. At localities 3 (Key Creek) and 4 (Ellersieck locality), the basal part of the light-colored chert and argillite facies (association 2) is Late Mississippian or Early Pennsylvanian in age (Faunal Group IIA). Overlying Paleozoic(?) rocks are dominantly gray or green-gray chert and argillite (association 2) with only minor amounts of interbedded maroon argillite and chert (association 3). At locality 3 (Key Creek, see previous discussions), association 2 facies are overlain by Mesozoic chert and shale of association 1 facies, which in turn are overlain by Triassic association 2 facies.

In map unit B, Association 2 facies are as old as Mississippian and as young as Early Jurassic in age. At locality 1 (Nigu Bluff), association 2 facies of Mississippian and Pennsylvanian(?) age are stratigraphically underlain by Mississippian association 1 facies and overlain by Pennsylvanian and (or) Permian association 3 facies. The Triassic and Jurassic Punupkahkroak Mountain section (locality 11) is primarily a gray chert sequence that is more siliceous than the type Otuk Formation. The section is poor in organic matter, and no limestone beds are exposed.

The gray-green chert and argillite facies represents a depositional environment in which bacterial consumption of carbonaceous organic material generally kept pace with the rate of burial. Neither black carbonaceous sediment nor maroon well-oxidized sediment was deposited. The relatively homogeneous bedding in this facies probably indicates good bioturbation, which in turn indicates a fairly well oxygenated environment or very slow rates of deposition. In the northern part of map unit A, the siliceous sediment was apparently diluted with clay. A possible source area for this argillaceous material is the North Slope. However, at least some of the argillaceous facies predate the Lower Permian (Leonardian) to Lower Triassic clastic Sadlerochit Group and must be coeval with part of the underlying Lisburne Group in the North Slope Ellesmerian sequence. Therefore, no one-to-one relation exists between clastic deposition on the North Slope and in the siliceous strata of the northern Brooks Range. The association 2 assemblage (mostly found in the Imnaitchiak Chert and (restricted) Siksikpuk Formation) is commonly poor in carbonate, although the type section of the (restricted) Siksikpuk Formation is somewhat calcareous. A few silicified foraminifers have been recovered from some samples, but radiolarians are the dominant microfossils. From this evidence we infer that most deposition occurred below or near the CCD. As previously discussed, the depth of the CCD in pre-Cretaceous time is not known. In addition, the CCD is commonly elevated in small basins, especially in upwelling zones, and its depth is variable with time. We infer that this facies represents deeper water than the underlying Paleozoic association 1 facies (black chert–limestone–shale facies) because we see a general upsection decrease in the abundance of sponge-spicule faunas and an inversely correlative increase in the abundance of radiolarians. The widespread Paleozoic distribution of the gray-green chert and argillite facies records Late Mississippian and Pennsylvanian subsidence throughout the depositional history of map units A and B. The more restricted Triassic (and Jurassic?) distribution of association 2 facies in map unit B and the southwestern part of map unit A, coupled with the contrasting distribution pattern of Mesozoic association 1 facies in map unit A, mostly in the northern part, are evidence for a Mesozoic regression or general uplift of the northern basin margin.

LITHOLOGIC ASSOCIATION 3

Maroon chert interbedded with maroon and green argillite is fairly widespread in the region studied, but maroon chert with age-diagnostic radiolarian faunas is most common in map unit B. Acid-etched residues appear red because of the presence of hematitic clay. In nonbarren samples, radiolarians are the dominant microfossils; sponge spicules and foraminifers are rare. Residues generally contain no conodont fragments, pyrite, pyrite pseudomorphs, carbonaceous material, carbonate, or carbonate pseudomorphs. Red residues from nine localities in the central and western Brooks Range have age-diagnostic Paleozoic radiolarian faunas. Five contain *Pseudoalbaillella* faunas (Faunal Groups IV or IVA, Atokan to Leonardian), including samples from the top few meters of the Nigu Bluff reference section (locality 1). Three contain Faunal Group VI faunas (Pennsylvanian or Early Permian). Only one red Paleozoic residue from the central Brooks Range (USGS fossil No. MR 5312 from lat 68°18′46″ N., long 159°17′58″ W.) contains Faunal Group IIA radiolarians, although this faunal group is the most common and widespread of all the Paleozoic assemblages. This particular sample also contains elements of Faunal Group VI and is probably Morrowan in age. Only one of the nine Paleozoic maroon chert localities with age-diagnostic radiolarians (USGS fossil No. MR 5257 from lat 68°39′30′ N., long 160°53′30″ W., Faunal Group VI) is in map unit A; the remainder are in map unit B.

At least 10 samples with age-diagnostic Mesozoic radiolarians came from sequences of maroon and gray or green chert in map unit

B. Three of these samples contain definite Late Triassic, Karnian or Norian, radiolarians and are correlative with the chert member or limestone member of the type Otuk Formation:

USGS sample MR 5307 (lat 68°26′15″ N., long 161°57′20″ W.).—This red-stained sample with Norian radiolarians was collected from the middle part of a section of maroon and gray chert and argillite that C.F. Mayfield (written commun., 1979) correlated by lithology with the Siksikpuk Formation (as defined by workers prior to Mull and others, 1987). These maroon and gray siliceous rocks are underlain by 20 m of talus, below which is dark-gray chert of presumed Carboniferous age, and overlain by gray chert with poorly preserved Mesozoic nassellarians. The section is part of the Ipnavik sequence in allochthon 4, map unit B (C.F. Mayfield, written commun., 1979; Ellersieck and others, 1982).

USGS sample MR 5427 (lat 68°32′18″ N., long 156°14′25″ W.).—This red chert sample contains Late Triassic (late Karnian or Norian) radiolarians. Although poor outcrops do not permit definitive determination of the its structural level, this sample appears to be from allochthon 2 or 4 in map unit B.

USGS sample MR 5261 (lat 68°18′36″ N., long 160°49′24″ W.).—This sample, collected from allochthon 4 just below an inferred fault contact with allochthon 6, is late Karnian or early Norian in age.

The maroon chert and argillite facies is better developed and more siliceous and has a longer age-range in map unit B and in the eastern Brooks Range than in map unit A. In map unit A, the radiolarian faunas in association 3 are low in diversity and are not age diagnostic. In general, the maroon chert and argillite facies in map unit A is poor in radiolarians. It may be restricted to the Paleozoic even in the southwestern part of map unit A. In map unit B, this facies has yielded age-diagnostic Pennsylvanian, Permian, and Triassic radiolarian faunas. The stratigraphic range of association 3 in the eastern Brooks Range is unknown, but Faunal Group IIA (latest Meramecian to Morrowan) and IVA (Early Permian) radiolarians have been recovered from this facies at locality 9.

Association 3 may represent an environment with the lowest depositional rate, the lowest biologic productivity rate, and (or) the lowest rate of preservation of organic material of all three siliceous facies in map units A and B. This facies commonly interfingers with the gray-green chert and argillite facies (association 2). The differences between the two facies may represent nothing more than subtle changes in the rates of productivity or burial through time.

LITHOLOGIC ASSOCIATION 4

Red or light-colored chert intimately associated with mafic igneous extrusive rocks including pillow basalt is limited to map unit C. In the northern Brooks Range, known radiolarian faunas in this facies are Mesozoic in age. The characteristics of the chert itself have not been described in detail. However, the radiolarian chert does not appear to be associated with argillite(?), pelagic limestone, carbonaceous shale, bedded barite, or lead-zinc mineralization. We infer that the radiolarian-rich sediment was deposited on basalt in a fairly deep, oxygenated depositional environment at a slow sedimentation rate.

DEPOSITIONAL RATES

Swain (1981) calculated the average depositional rate of the type Otuk Formation (association 1) as 3 cm/1,000 yr (discounting compaction). The maximum possible depositional rate for gray-green chert and maroon argillite (associations 2 and 3) at Nigu Bluff is approximately 0.4 cm/1,000 yr. Assuming no long cryptic hiatuses are present, this maximum possible sedimentary rate of deposition for Nigu Bluff cherts is comparable to sedimentary rates calculated for Mesozoic ribbon cherts such as the red and green cherts of the Franciscan assemblage of California and also to accumulation rates for some high-latitude Cenozoic diatom oozes (Jenkyns and Winterer, 1982). It is an order of magnitude greater than accumulation rates for Cenozoic radiolarian oozes in low-fertility areas in the North Pacific and an order of magnitude less than several Cenozoic diatom oozes in areas of coastal upwelling (Jenkyns and Winterer, 1982). The rate of accumulation of the Otuk Formation, on the other hand, is within the lower range of rates of accumulation of Cenozoic diatom oozes in coastal upwelling areas, such as the Miocene Monterey Formation of California and the Quaternary sediments in the Gulf of California (Jenkyns and Winterer, 1982).

SUMMARY AND INTERPRETATION

In the northern Brooks Range, radiolarian faunas are best preserved and most diverse in deeper-water siliceous facies having low concentrations of carbonate and carbonaceous material (most siliceous parts of association 2 and 3 facies). Conversely, conodont distribution patterns favor carbonate-rich, carbonaceous chert and limestone units (association 1). These microfossil distribution patterns are functions of both depositional environment and diagenetic history.

In the Brooks Range allochthons, deposition of siliceous fine-grained sediment containing radiolarians began in local basins of map unit B, the southwestern part of map unit A, and the eastern Brooks Range during Mississippian time. This event coincided with subsidence that was probably related to rifting (Mayfield and others, chapter 7; Dutro, 1980; Mayfield, 1980; Metz, 1980; Mull and others, 1982).

In map units A and B, the oldest radiolarian faunas (Faunal Groups I and V) are generally found in black chert, commonly in association with abundant sponge spicules. In map unit B (allochthons 2 to 5), the Upper Mississippian rocks record a wide variety of environments from fairly deep marine radiolarian chert to shallow-platform fossiliferous limestone. The northern part of map unit A lay above the Mississippian CCD, and radiolarites were not deposited although sponge-rich lime muds were locally common. The original lateral relations among all the Mississippian facies are not known with certainty. Thrusting has condensed and distorted distances and geometry.

By Late Mississippian or Early Pennsylvanian time (Faunal Groups II, IIA), the basins of allochthons 1 to 5 had subsided sufficiently that fine-grained gray-green chert and argillite (association 2) blanketed most of the study area. Radiolarians were the dominant microfossil in the southwestern part of allochthon 1 and in the structurally higher allochthons 2 to 5.

During Middle Pennsylvanian to Permian time, deposition was more uniform throughout allochthons 1 to 5. Sediments deposited during this period include associations 2 (gray and green chert and argillite) and 3 (maroon chert and argillite). These rocks are most argillaceous in the northern part of map unit A, especially in the central Brooks Range. Radiolarians are most common in the more siliceous parts of the allochthons.

In Triassic and Early Jurassic time, the spatial distribution of facies became less uniform, although pelagic and hemipelagic deposition continued on all allochthons. Black carbonaceous shale, black chert, and fine-grained limestone (association 1) characterize the Triassic and Lower Jurassic rocks of the northern part of allochthon 1 (map unit A). To the south and in structurally higher allochthons (2 to 5), these facies grade into and interfinger with coeval associations 2 (green and gray chert and argillite) and 3 (maroon chert and argillite). The Mesozoic reappearance of association 1 facies in the allochthons may have been the result of regression and (or) uplift to the north. The youngest radiolarians in the siliceous sequences are Early Jurassic in age. Locally the association 1 facies are disconformably overlain by shale of Jurassic age or coquinoid limestone of Cretaceous age (Mull and others, 1982).

The faunas and facies of the Mesozoic rocks in allochthon 6 (map unit C) have not been studied in sufficient detail to adequately compare them to faunas and facies in allochthons 1 to 5.

Mayfield and others (chapter 7) propose a history in which rifting of the Paleozoic platform began during Mississippian time, ultimately resulting in the foundering of the rifted margin (map units A and B) and in the creation of oceanic crust (map unit C). If map unit C and the Angayucham terrane to the south truly represent the rocks of an ocean basin created by rifting of the Paleozoic platform, then rifting must have been well under way by Late Devonian time, because the Angayucham terrane includes chert with Late Devonian radiolarian faunas associated with mafic extrusive rocks. Therefore, we leave open the possibility that the history of allochthons 6 and 7 and the Angayucham terrane may not be directly related to the history of allochthons 1 to 5. In contrast to the rifted platform model, an opposing interpretation was presented by Churkin and others (1979), who contended that most or all of the siliceous sequences in the northern Brooks Range were deposited on oceanic crust adjacent to the continental margin.

Possible analogs for the basin settings in which the siliceous strata of the Brooks Range were deposited are the Mesozoic Tethyan basins. The Tethyan basins have sequences of pelagic chert and limestone overlying shelf carbonate rocks and carbonate turbidites (possible analogs for allochthons 1 to 5) and similar pelagic sequences overlying basalts (possible analogs for allochthon 6). Like the Brooks Range siliceous sequences, many of the Tethyan pelagic sequences contain very little clastic detritus. The pelagic sediments of the Tethys ocean were deposited during and following a complex history of rifting, transform faulting, foundering of a carbonate platform, and creation of oceanic crust (Winterer and Bosellini, 1981). The Tethyan pelagic sequences have been interpreted as having formed in small basins adjacent to the continental margin (Jenkyns and Winterer, 1982).

REFERENCES CITED

Blome, C.D., and Reed, K.M., 1986, Triassic and Early Jurassic radiolarian faunas, Brooks Range, Alaska: U.S. Geological Survey Open-File Report 86-120, 25 p.

Bodnar, D.A., 1984, Stratigraphy, age, depositional environments and hydrocarbon source rock evaluation of the Otuk Formation, north-central Brooks Range, Alaska: Fairbanks, University of Alaska, M.S. thesis, 232 p.

Campbell, R.H., 1967, Areal geology in the vicinity of the Chariot site, Lisburne Peninsula, northwestern Alaska: U.S. Geological Survey Professional Paper 395, 67 p.

Churkin, Michael, Jr., Nokleberg, W.J., and Huie, Carl, 1979, Collision-deformed Paleozoic continental margin, western

Brooks Range, Alaska: Geology, v. 7, no. 8, p. 379-383.

Curtis, S.M., Ellersieck, Inyo, Mayfield, C.F., and Tailleur, I.L., 1982, Reconnaissance geologic map of southwestern Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Open-File Report 82-611, 43 p. 2 sheets, scale 1:63,360.

——— 1983, Reconnaissance geologic map of the De Long Mountains A1, B1, and part of C1 quadrangles, Alaska: U.S. Geological Survey Open-File Report 83-185, 53 p., 2 sheets, scale 1:63,360.

Dutro, J.T., Jr., 1980, Comment on "Collision-deformed Paleozoic continental margin, Western Brooks Range, Alaska": Geology, v. 8, no. 8, p. 355-356.

Ellersieck, Inyo, Curtis, S.M., Mayfield, C.F., and Tailleur, I.L., 1982, Reconnaissance geologic map of south-central Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Open-File Report 82-612, 38 p., 2 sheets, scale 1:63,360.

——— 1983, Reconnaissance geologic map of the De Long Mountains A2, B2, and part of C2 quadrangles, Alaska: U.S. Geological Survey Open-File Report 83-184, 53 p., 2 sheets, scale 1:63,360.

Finks, R.M., 1960. Late Paleozoic sponge faunas of the Texas region; the siliceous sponges: American Museum of Natural History Bulletin, v. 120: 1-160.

——— 1970, The evolution and ecologic history of sponges during Palaeozoic times, *in* Fry, W.G. ed., The biology of Porifera: Zoological Society of London Symposia, no. 25, p. 3-22.

Grantz, Arthur, Tailleur, I.L., and Carter, Claire, 1983, Tectonic significance of Silurian and Ordovician graptolites, Lisburne Hills, northwest Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 274.

Ijima, I., 1927. The Hexactinellida of the Siboga Expedition: Siboga-Expeditie, v. 6, 383 p.

Ishiga, Hiroaki, Kito, Takeo, and Imoto, Nobuhiro, 1982, Permian radiolarian biostratigraphy: News of Osaka Micropaleontologists, Special Volume, v. 5, p. 17-26.

Jenkyns, H. C., and Winterer, E.L., 1982, Palaeoceanography of Mesozoic ribbon radiolarites: Earth and Planetary Science Letters, v. 60, p. 351-375.

Jones, D.L., Silberling, N.J., Berg, H.C. and Plafker, George, 1981, Map showing tectonostratigraphic terranes of Alaska, columnar sections, and summary description of terranes: U.S. Geological Survey Open-File Report 81-792, 21 p., 2 sheets, scale 1:2,500,000.

Martin, A.J., 1970, Structure and tectonic history of the western Brooks Range, De Long Mountains and Lisburne Hills, northern Alaska: Geological Society of America Bulletin, v. 81, no. 12, p. 3605-3621.

Mayfield, C.F., 1980, Comment on "Collision-deformed Paleozoic continental margin, western Brooks Range, Alaska": Geology, v. 8, no. 8, p. 357-359.

Mayfield, C.F., Curtis, S.M., Ellersieck, Inyo, and Tailleur, I.L., 1982, Reconnaissance geologic map of the southeastern Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Open-File Report 82-613, 40 p. 2 sheets, scale 1:63,360.

——— 1983, Reconnaissance geologic map of the De Long Mountains A3, B3, and parts of A4, B4 quadrangles, Alaska: U.S. Geological Survey Open-File Report 83-183, 59 p., 2 sheets, scale 1:63,360.

Metz, P.A., 1980, Comment on "Collision-deformed Paleozoic continental margin, western Brooks Range, Alaska": Geology, v. 8, no. 8, p. 360.

Mull, C.G., 1979, Nanushuk Group deposition and the late Mesozoic structural evolution of the central and western Brooks Range and Arctic Slope, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 5-13.

Mull, C.G., Tailleur, I.L., Mayfield, C.F., Ellersieck, Inyo, and Curtis, S.M., 1982, New upper Paleozoic and lower Mesozoic stratigraphic units, central and western Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 66, no. 3, p. 348-362.

Mull, C.G., Crowder, R.K., Adams, K.E., Siok, J.P., Bodnar, D.A., Harris, E.E., Alexander, R.A., and Solie, D.N., 1987, Stratigraphy and structural setting of the Picnic Creek allochthon, Killik River quadrangle, central Brooks Range, Alaska; a summary, *in* Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Calif., Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 649-662.

Murchey, B.L., and Jones, D.L, 1983, Tectonic and paleobiologic significance of Permian radiolarian distribution in circum-Pacific region [abs.]: American Association Petroleum Geologists Bulletin, v. 67, no. 3, p. 522.

Murchey, B.L., Swain, P.B., and Curtis, Steven, 1981, Late Mississippian to Pennsylvanian radiolarian assemblages in the Siksikpuk(?) Formation at Nigu Bluff, Howard Pass quadrangle, Alaska, *in* Albert, N.R.D., and Hudson, Travis, eds., The United States Geological Survey in Alaska; accomplishments during 1979: U.S. Geological Survey Circular 823-B, p. B17-B19.

Murchey, B.L., Jones, D.L., and Blome, C.D., 1983, Comparison of Permian and lower Mesozoic radiolarian chert in western accreted terranes: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 371.

Patton, W.W., Jr., 1957, A new upper Paleozoic formation, central Brooks Range, Alaska: U.S. Geological Survey Professional Paper 303-B, p. 41-45.

Pessagno, E.A., Jr. and Newport, R.L., 1972, A technique for extracting Radiolaria from radiolarian cherts: Micropaleontology, v. 18, p. 231-234.

Reid, R.E.H., 1968, Bathymetric distributions of Calcarea and Hexactinellida in the present and the past: Geological Magazine, v. 105,no. 6, p. 546-559.

Rigby, J.K., 1983, Introduction to the Porifera, *in* Broadhead, T.W., ed., Sponges and spongiomorphs, notes for a short course: Knoxville, University of Tennessee, Department of Geological Sciences Studies in Geology, v. 7, p. 12-39.

Rowett, C.L., 1975, Stratigraphic distribution of Permian corals in Alaska: U.S. Geological Survey Professional Paper 823-D, p. 59-75.

Siok, J.P., 1985, Geologic history of the Siksikpuk Formation on the Endicott Mountains and Picnic Creek allochthons, north-central Brooks Range, Alaska: Fairbanks, University of Alaska, M.S. thesis, 253 p.

Schulze, F.E., 1899, Amerikanische Hexactinelliden nach dem Materiale der Albatross-Expedition: Jena, Gustav Fischer.

Swain, P.B., 1981, Upper Triassic radiolarians from the Brooks Range, Alaska: Los Angeles, University of California, Los Angeles, M.S. thesis, 174 p.

Tailleur, I.L., and Brosgé, W.P., 1970, Tectonic history of northern Alaska, *in* Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the north slope of Alaska: Los Angeles, American Association of Petroleum Geologists, Pacific Section, p. E1-E19.

Wardlaw, B.R., and Jones, D.L., 1979, Triassic conodonts from eugeoclinal rocks of western North America and their tectonic significance: Rivista Italiana di Paleontologia e Stratigrafia, v. 85, no. 3-4, p. 895-908.

Winterer, E.L., and Bosellini, Alfonso, 1981. Subsidence and sedimentation on Jurassic passive continental margin, southern Alps, Italy: American Association of Petroleum Geologists Bulletin, v. 65, no. 3, p. 394-421.

33. RADIOLARIAN BIOSTRATIGRAPHY OF THE OTUK FORMATION IN AND NEAR THE NATIONAL PETROLEUM RESERVE IN ALASKA

By CHARLES D. BLOME, KATHERINE M. REED,[1] and IRVIN L. TAILLEUR

INTRODUCTION

Bedded chert is a common rock type in the Brooks Range orogen of northern Alaska and is locally abundant in all parts of the orogen except the northeast Brooks Range. Pennsylvanian to Jurassic radiolarian chert is especially widespread in the west, in and adjacent to the De Long Mountains.

The Cretaceous Brookian orogeny superposed and disordered the bedded chert sequences. Initial foreshortening and subsequent Laramide-style deformation created a complex of Carboniferous to Jurassic sedimentary deposits that has been rearranged into a stack of thrust sheets, each distinguished by its own physical, paleontologic, and tectonic characteristics (Mayfield and others, chapter 7, 1983b).

Biostratigraphic control in our study was inadequate to refine many of the earlier paleontologic syntheses (Tailleur and others, 1966; Brosgé and Tailleur, 1970). Verification of the ages for radiolarian cherts was particularly difficult because the only age-diagnostic megafossils were found in the younger horizons. The older parts of the Otuk Formation (Mull and others, 1982) have yielded few useful megafossils.

Renewed investigations of the National Petroleum Reserve in Alaska (NPRA) in the middle and late 1970's corresponded closely with development of a land-based Mesozoic radiolarian zonal scheme pioneered by Pessagno (1976, 1977a, b). Nearly a thousand chert samples from various field projects and from one well were processed for radiolarians during an 8-yr period in the hope that the radiolarian biostratigraphy might refine the ages of the various chert sequences. Investigations of resources other than hydrocarbons in 1977 and 1978 by Michael Churkin, Jr., Inyo Ellersieck, Carl Huie, D.L. Jones, C.F. Mayfield, W.J. Nokleberg, I.L. Tailleur, D.L. Vickery, and G.R. Winkler produced a set of mostly uncontrolled samples from the southern part of the NPRA and the foothills belt eastward to Tiglukpuk Creek (fig. 33.1*A*). During large-scale mapping in 1978, 1979, and 1981 by D.C. Blanchard, S.M. Curtis, Ellersieck, Mayfield, and Tailleur, a large set of chert samples was collected from the De Long Mountains, Misheguk Mountain, and Noatak 1:250,000-scale quadrangles in the western Brooks Range. In 1978, R.J. Witmer and Tailleur collected samples from sections near the Lisburne well in the southern part of the NPRA. W.W. Chamberlain, B.L. Murchey, P.B. Swain, and Witmer systematically sampled several locations in the same area during the 1979 field season (Murchey and others, 1981). During the 1980 field season, Murchey and Tailleur collected samples from reference sections in the lowest allochthon, on the Kiruktagiak River (lat 68°44′15″ N., long 152°20′00″ W.); on Tiglukpuk Creek, 150 km east of the NPRA; and from Agate Rock on the Lisburne Peninsula, 175 km west of the NPRA. J.S. Kelley sampled several sections in the lowest thrust sheet between the NPRA and Tiglukpuk Creek in 1982. Some of Tailleur's 1982 samples were collected at sections near Mount Annette (100 km east of Chandler Lake quadrangle). K.M. Reed and Tailleur collected radiolarian chert on the Lisburne Peninsula in 1982. Projects headed by C.G. Mull (Alaska Division of Geological and Geophysical Surveys) and Kelley continued to supply Brooks Range cherts for age analysis (see also Bodnar, 1984). The success of radiolarian biostratigraphy, together with endothyroid and molluscan dating, has greatly aided recent geological mapping (Mayfield and others, chapter 8; Curtis and others, 1982, 1983, 1984; Ellersieck and others, 1982, 1983, 1984; Mayfield and others, 1982, 1983a, b, 1984a, b, 1987).

This study includes radiolarian faunas from lithostratigraphic sections through the Otuk Formation (fig. 33.2) that include shale, chert, and limestone of Triassic through Early Jurassic age. Our biostratigraphic scheme for the Otuk Formation is based on radiolarian and molluscan faunal assemblages from measured sections, as well as correlation with radiolarian faunas described in recent reports (through 1987) concerning Triassic faunas from Baja California, Oregon, British Columbia, and Japan.

Previous and present work has also enabled us to date isolated

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samples collected from numerous localities along the north side of the Brooks Range; most of these samples contained no megafossils (see table 33.2 and Murchey and others, chapter 32, table 32.3). However, these miscellaneous samples do reflect the generally low abundance and diversity of Triassic Brooks Range radiolarian faunas.

ACKNOWLEDGMENTS

We thank N.J. Silberling for extensive help with pecten age ranges. C.G. Mull (Alaska Division of Geological and Geophysical Surveys) and J.S. Kelley reviewed some of our usage of radiolarian biostratigraphy in 1985, and B.L. Murchey shared samples and information as the paper developed. We are grateful to D.A. Bodnar for his detailed stratigraphic descriptions.

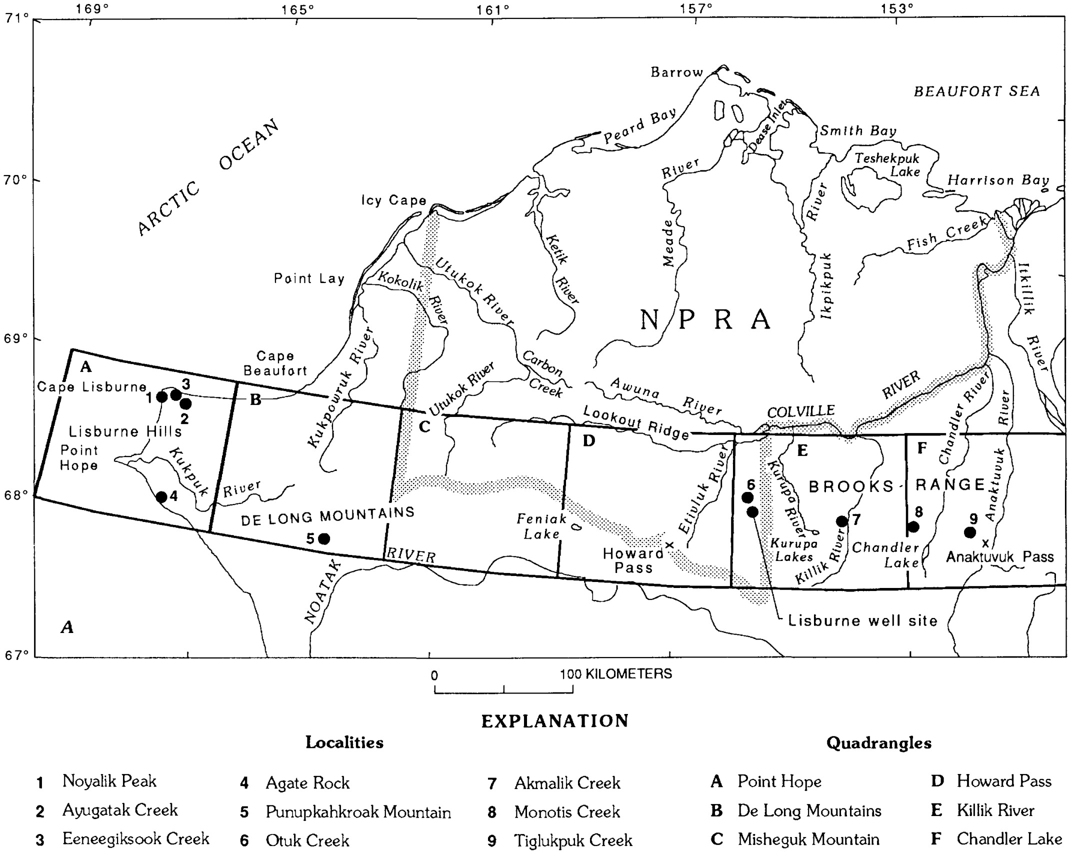


FIGURE 33.1.—Locations and outcrop views of sample localities of the Otuk Formation. *A*, Northern Alaska, showing locations of measured sections and other sampling sites discussed in this chapter. Also shown are boundary of the National Petroleum Reserve in Alaska (NPRA) and outlines and names of the 1:250,000-scale topographic quadrangles covering areas of interest. *B-G*, Outcrop views of some measured and sampled sections of the Otuk Formation. Dotted lines indicate those parts of the sections (and their thicknesses, in meters) from which samples relevant to this study were collected; sampling traverses encompassed virtually the total extent of these exposures. Light lines, stratigraphic contacts (dashed where approximate); heavy lines, faults (arrows indicate inferred sense of displacement). *B*, Noyalik Peak section; view north-northeastward. *C*, Ayugatak Creek section; view north-northeastward. *D*, Agate Rock section; view northeastward. *E*, Otuk Creek section (overturned; type section of the Otuk Formation, Mull and others, 1982); view east-northeastward. *F*, Monotis Creek section; view northward. *G*, Tiglukpuk Creek section; view westward.

N.R.D. Albert picked many samples, particularly those from the Punupkahkroak section. B.L. Reed provided invaluable help with data collection on the Lisburne Peninsula in 1982. Diedra Bohn assisted in the field during examinations of Otuk sections in 1984.

GEOLOGIC SETTING

Mull and others (1982) revised the stratigraphy of the upper Paleozoic and Mesozoic formations in northern Alaska (fig. 33.3). They assigned all the Triassic strata in the western Brooks Range to the Etivluk Group, which contains the Siksikpuk and Otuk Formations. Both these formations include siliceous units that are exposed in the allochthons of the western half of the Brooks Range (Mayfield and others, chapter 7). Few localities expose complete sections of the Etivluk Group because in most places it is structurally deformed and cut by faults.

The Siksikpuk Formation is composed of cherty siltstone, shale, and bedded chert. The formation is characterized in many places by maroon, red, and green siliceous siltstone and by beds that weather orange yellow. This unit is more siliceous in its western exposures and has not been mapped along the mountain front east of the Itkillik River. In some places the Siksikpuk grades downward into the black cherts of the Kuna Formation (Mull and others, 1982; see also Mull and

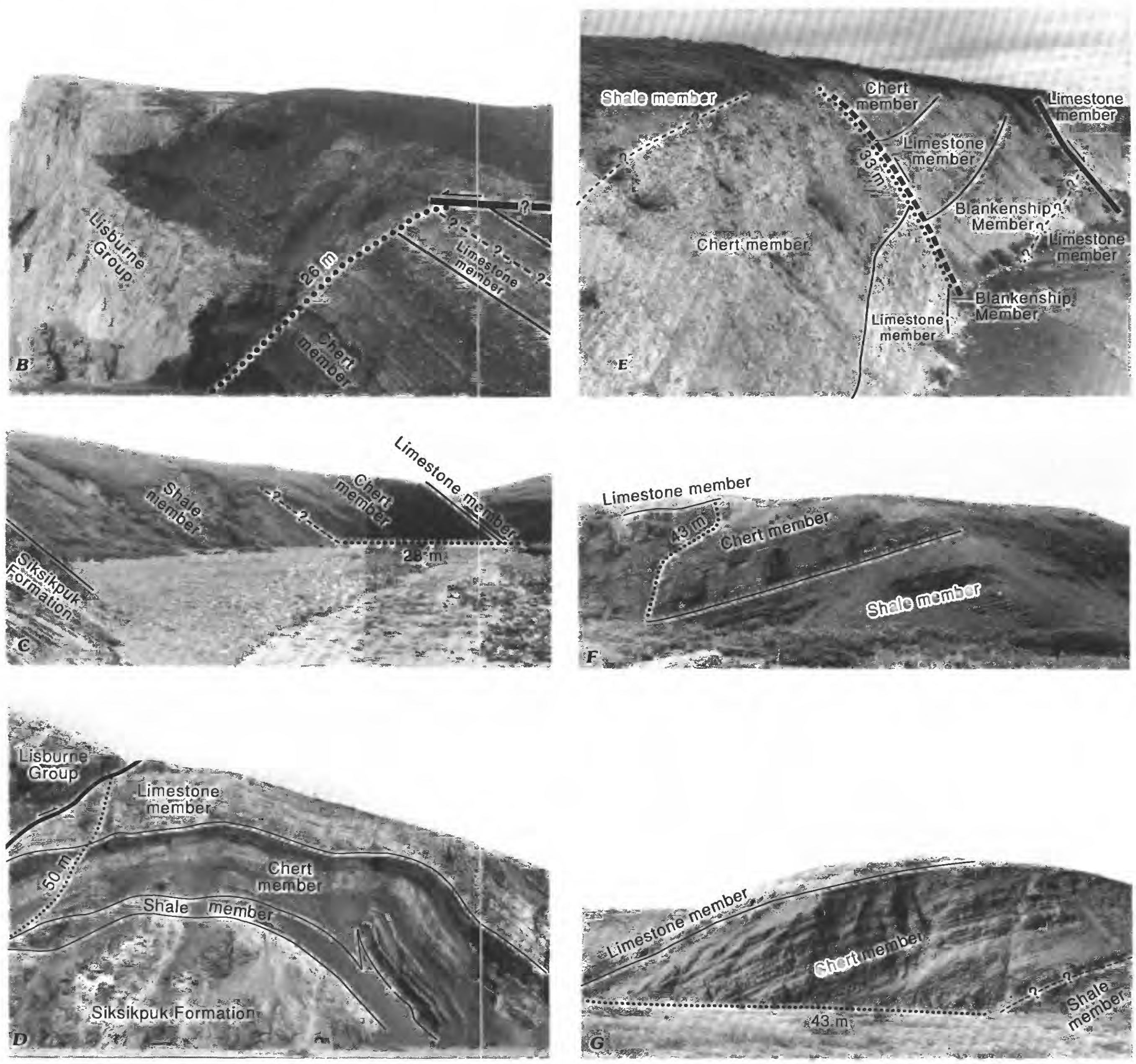


FIGURE 33.1.—Continued

others, 1987), the Siksikpuk being distinguished by its orange-weathering beds. Elsewhere, its contact with older units may be disconformable.

Paleontologic studies have shown that radiolarians from strata questionably assigned to the Siksikpuk Formation may be as old as Late Mississippian (Murchey and others, 1981). Mull and others (1982) extended the age of the Siksikpuk Formation into the Early Triassic. However, the sample on which this Triassic age was based is now

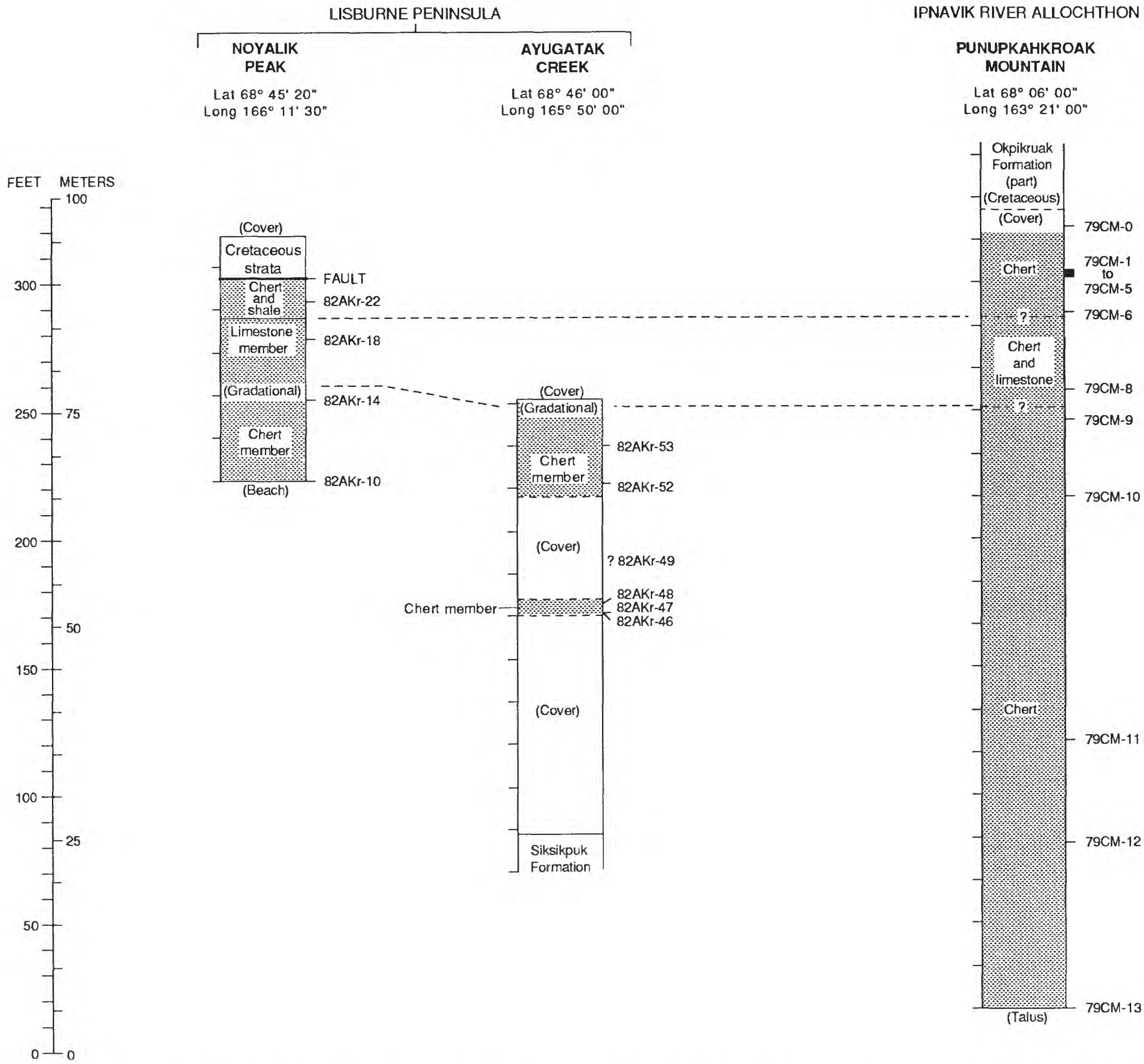


FIGURE 33.2.—Generalized lithologic correlation of members of the Otuk Formation (shaded) in the sections studied. The Blankenship Member and its unnamed equivalent(s) are predominantly shale. Positions of radiolarian samples are indicated by numbers and letters to right of each column; both megafossil and radiolarian sample numbers are shown on Bodnar's sections. See table 33.1 for lists of radiolarians and megafossils at each section. Contacts of members in Noyalik Peak, Ayugatak Creek, Akmalik Creek, and Monotis Creek sections are not shown because they are gradational. Members are not distinguishable at Punupkahkroak Mountain section, because that section contains more siliceous rock and less shale than other sections discussed. Thicknesses of Otuk members recorded by various workers at Otuk Creek and Tiglukpuk Creek sections differ; therefore, two sections are shown for each for comparison. Note also positions of member contacts at these sections. Bodnar's Tiglukpuk Creek section is a composite of exposures on east and west sides of the creek, which may account for his not indicating the fault shown by Murchey.

known to have come from the Otuk Formation.

The Siksikpuk was sampled at the Ayugatak Creek section, at exposures southeast of Agate Rock, and at Akmalik Creek (fig. 33.1), but all radiolarians recovered were preserved as undatable casts. The Siksikpuk is not exposed in the Noyalik Peak, Monotis Creek, or Otuk Creek measured sections (fig. 33.1), nor is it discernable in the Punupkahkroak Mountain section. However, at Agate Rock (fig. 33.1), a sample from a low stratigraphic position in Campbell's (1967) unit 3 contained *Pseudoalbaillella* sp. cf. *P. bulbosa* Ishiga of Late Pennsylvanian (Missourian) through Early Permian age (Ishiga, 1982). Murchey and others (chapter 32) note the presence of *P.* sp. aff. *P. lomentaria* (Early Permian) in beds near the top of the formation at Agate Rock.

The Otuk Formation (Mull and others, 1982) consists of shale, chert, and limestone members that are exposed on imbrications of the Brooks Range/Endicott allochthon in the central and western Brooks Range. These are in turn overlain by its Blankenship Member (or its time equivalents), exposures of which are somewhat more widespread. Light-colored calcilutite beds, rubble fragments of the limestone member, and dark ribbon chert and papery, sooty calcareous shale of the older chert and shale members (Patton and Tailleur, 1964) distinguish the Otuk Formation from the gray, maroon, and

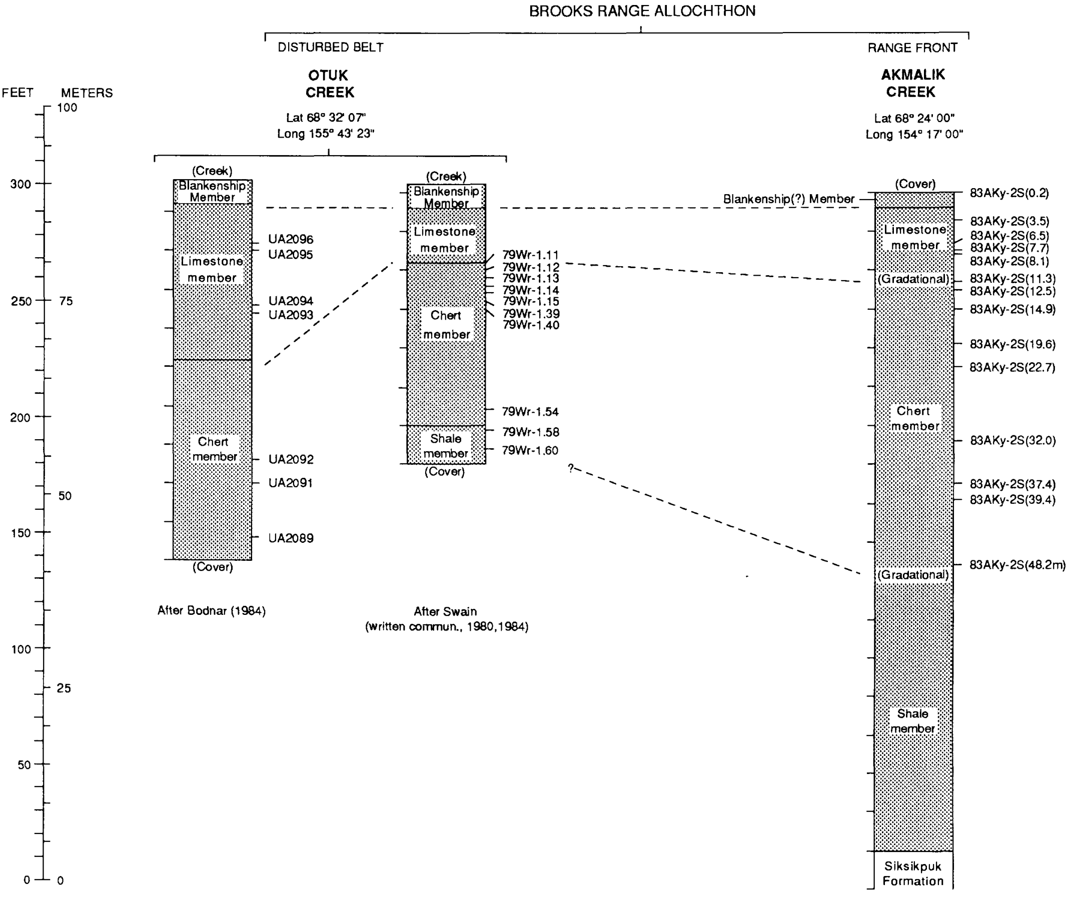


FIGURE 33.2.—Generalized lithologic correlation of members of the Otuk Formation—Continued

green siliceous mudstone and dark chert of the underlying Siksikpuk Formation.

The shale member of the Otuk typically consists of dark-gray to black organic shale that weathers yellow gray and of thinly bedded limestone with dolomitic limestone interbeds. The Lower(?) and Middle Triassic shale member (Patton and Tailleur, 1964, p. 431) occurs at only a few places on the lowest (Brooks Range) allochthon and at even fewer places at the higher structural levels.

The overlying chert member weathers predominantly greenish brown to dark gray and black and contains varying proportions of limestone and shale, both commonly silicified. In many places, black shale interbedded with the chert contains compressed shells of the pecten *Halobia*. Imprints of *Halobia* on weathered surfaces of light-colored chert fragments in the upper part of the member are common

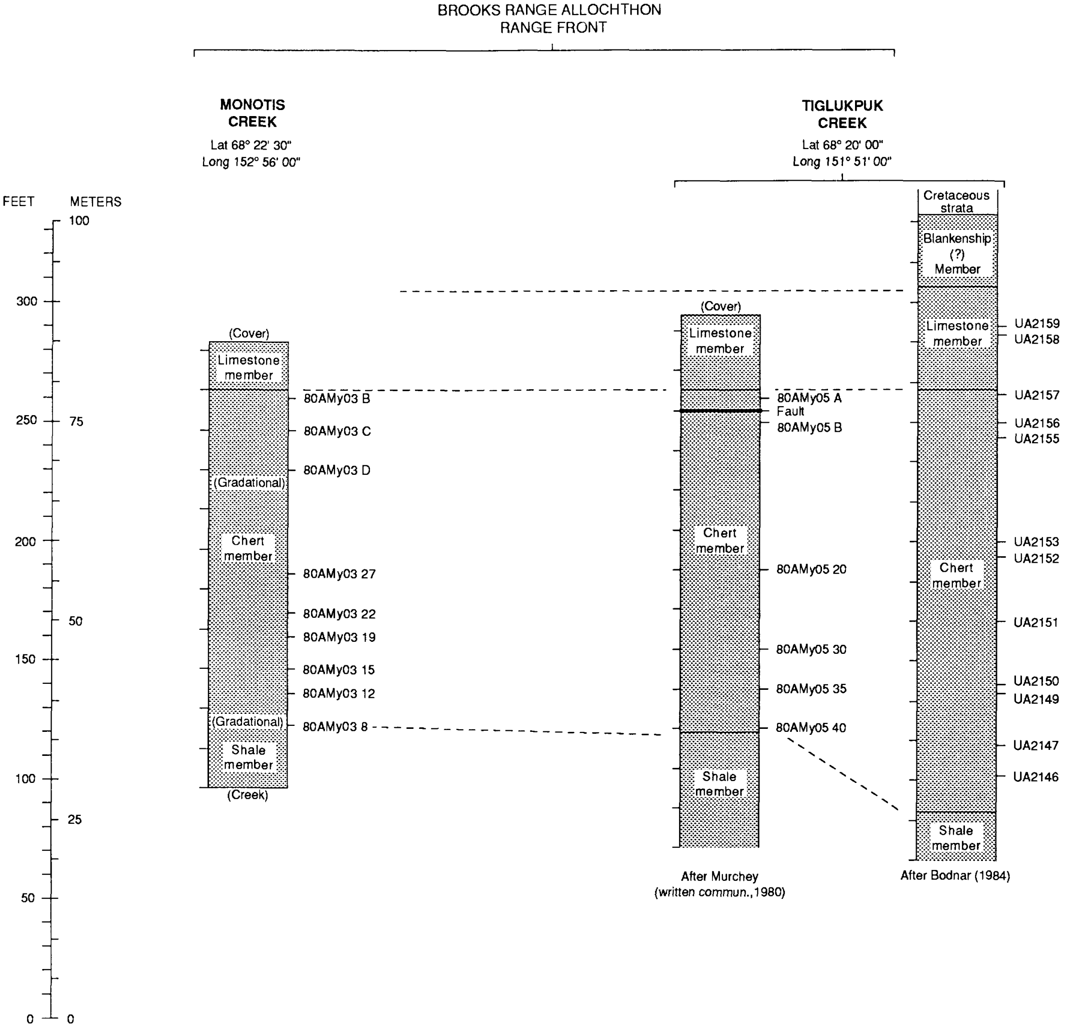


FIGURE 33.2.—Generalized lithologic correlation of members of the Otuk Formation—Continued

in float on the lower allochthon but are rare or absent elsewhere.

The limestone member typically weathers tan and yellowish brown and consists of silicified limestone with many shale interbeds and minor amounts of chert. It also commonly contains *Monotis* in coquinalike beds. The pectens are not as common nor is the limestone as abundant in the structurally higher allochthons.

Examination of any one section from east to west along the Brooks Range front shows little or no sharp demarcation between members. However, there is an upward gradation from shale-rich to siliceous to limestone-rich lithologies. Mull and others (1982) noted that the limestone member contains both chert and siliceous shale and that the shale member contains chert and limestone. Others have noted (for example, Bodnar, 1984) silicified mudstone in the chert member, significant silicification in the limestone member, and the presence of siliceous nodules in the shale member.

We feel that silicification is more significant in the Otuk Formation than is generally acknowledged and that the variations in the ages of shale and chert members may reflect varying local depositional conditions (Bodnar, 1984; Reed and Blome, 1986). These variations could also indicate diagenetic alterations that influenced the ratio of shale and chert. Despite the widespread silicification, the eastern sections do contain more shale and are less silicified than the western or southern sections.

Various workers have inferred different thicknesses both for individual Otuk members and for overall sections (see figs. 33.2 and 33.7). For example, Mull and others (1982) reported the chert member at Otuk Creek as 17 m thick (total section thickness of at least 45 m), whereas Bodnar (1984) indicated at least 26 m for the chert member (80 m of total section). We attempted to construct a composite section for the Otuk and Tiglukpuk Creek sections, but we found the discrepancies too large; we therefore chose to display two versions of each.

The Blankenship Member is composed of thin-bedded, organic paper or oil shale and some thin-bedded chert and limestone interbeds, particularly in the lower part of the unit. Small, silvery-gray-weathered chips of shale and chert are common in Blankenship float at several sites in the lower (Brooks Range) allochthon. The Blankenship Member occurs at localities from the Atigun River west to Kagvik Creek. Time-equivalent units at both Punupkahkroak Mountain and Akmalik Creek are more siliceous than those at the Otuk Creek type section.

We have compared lithostratigraphic and biostratigraphic data from seven areas (fig. 33.2; table 33.1) as the basis for our discussion of the Otuk Formation. In addition, data from four other stratigraphic sections on the Lisburne Peninsula are included in table 33.2. The Blankenship Member was sampled only at the type section at Otuk Creek, but strata believed to belong to this unit are also present at the Akmalik Creek section. Following are brief descriptions of the lithology at the seven measured sections.

NOYALIK PEAK SECTION

A thickness of about 30 m (100 ft) of the Otuk Formation and overlying strata is exposed at a seacliff at

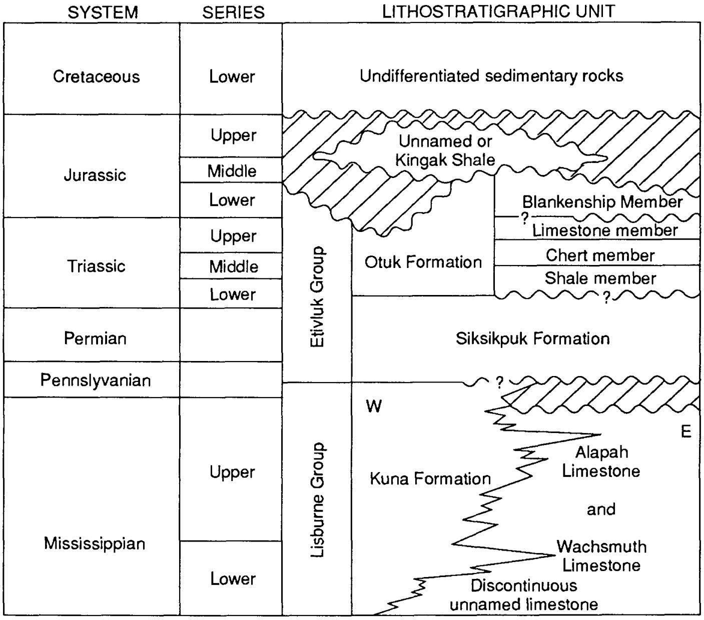


FIGURE 33.3.—Stratigraphic relations and the nomenclature used for formations that occur in and adjacent to the NPRA (slightly modified from Mull and others, 1982). Diagonal lines indicate time gaps at unconformities.

Noyalik Peak (figs. 33.1*B*, 33.2). The section is right side up, and the beds dip gently to the south (B.L. Reed, written commun., 1982). The lowest exposed beds, assigned to the chert member, are dark-gray to black cherts that constitute about 60 percent of the unit. The chert beds are about 5 to 10 cm (2-5 in.) thick and contain shale interbeds that range in thickness from 2 to 15 cm (1-6 in.). At about 10 m (30 ft) stratigraphically above the beach, the first limy beds occur. Above this level, the relative proportion of chert to shale increases, and limestone becomes more abundant. At about 14 m (46 ft), limestone predominates. The limestone is partially silicified, and sedimentary structures, such as wispy bedding, can be observed in hand specimens. Coquinalike beds of *Monotis* and layers with fewer fossil pectens occur from about 18 to 19 m (60-63 ft). A distinctive silver-colored shale overlies the pecten-rich beds and is, in turn, overlain by about 5 m (15 ft) of an unnamed chert and shale unit. Shale is more abundant in the upper beds of this unit, which is richer in chert than is the typical Blankenship Member exposed to the east. A fault is present about 25 m (80 ft) above the base of the section. Beds above the fault contain siltstone and shale, but no radiolarians or megafossils were found.

AYUGATAK CREEK SECTION

A well-exposed section on the east side of the Lisburne Hills on the Lisburne Peninsula includes strata from the Lisburne Group upward through the part of the Otuk Formation that lies beneath the *Monotis*-rich layers (figs. 33.1C, 33.2). The section is on the south fork of Ayugatak Creek, is right side up, wraps around the nose of a plunging anticline, and dips gently to the south and southeast (B.L. Reed, written commun., 1982). The top beds of the Siksikpuk Formation here contain about 7 m (22 ft) of resistant, pinch-and-swell, greenish-brown-weathering chert beds that average 7.5 cm (3 in.) in thickness and have thin shale partings. The shale member of the Otuk Formation conformably overlies the chert. The lower part of the shale member is composed of soft, black, sooty and calcareous shale and is partly covered for about 25 m (80 ft). The pecten *Daonella* sp. was collected in float just below the first prominent cherty shale beds. Chert beds occur about 27 m (90 ft) above the Siksikpuk-Otuk contact, make up about 80 percent of the member, average 5 cm (2 in.) in thickness, and occur with shale partings (about 20 percent of the unit) about 1 cm (0.5 in.) thick. Both the chert and shale beds weather reddish brown. The overlying 10 m (35 ft) of section is covered, but the float consists of black, sooty limestone, shale, and minor chert. Black concretions of shaly material and thin limy shale beds occur above the covered interval. The shale beds become predominantly cherty from this level to about 45 m (145 ft) above the Siksikpuk contact. The chert member is approximately 5 m (15 ft) thick, and individual beds range in thickness from 2 to 20 cm (1-8 in.). Shale partings are less than 1 cm (0.5 in.) thick and make up about 35 percent of the unit. The first limestone beds, interpreted as the base of the limestone member, appear about 49 m (160 ft) above the Siksikpuk-Otuk contact. The section is cut off by erosion above the richly fossiliferous *Monotis* beds that occur at about 52 m (170 ft).

CAPE LISBURNE AREA

Four other sections of the Otuk Formation were measured on the Lisburne Peninsula: at Eeneegiksook Creek, Agate Rock, and two localities southeast of Agate Rock (fig. 33.1). The Eeneegiksook Creek section, near the north coast of the Lisburne Peninsula, was first measured by G.S. Anderson in 1964, and the megafossils collected were identified by N.J. Silberling (written commun., 1965). Tailleur provisionally assigned about 10 m (35 ft) of chert occurring below beds containing *Daonella frami* Kittl to the Siksikpuk Formation. Above the *Daonella* horizon are Karnian *Halobia* cf. *H. zitteli* Lindstrom and *H.* cf. *H. ornatissima* Smith. The chert unit is about 15 m (50 ft) thick and is overlain by about 5 m (15 ft) of limestone, the upper part of which contains *Monotis* cf. *M. subcircularis* Gabb and *M.* cf. *M. ochotica* (Keyserling). The Ogotoruk Formation overlies the Otuk strata at this locality, but a fault may be present at the contact.

At the Agate Rock section (fig. 33.1*D*; Campbell, 1967), the shale member of the Otuk Formation is about 9 m (30 ft) thick, the chert member is about 20 m (70 ft) thick, and the limestone member, which is cut by a shear zone, is about 13 m (45 ft) thick and includes *Monotis* marker beds. Above the *Monotis* beds are chert-rich strata that may be part of the unnamed post-*Monotis* unit exposed at Noyalik Peak. Two additional exposures of Triassic beds, measured and sampled in 1982 by Tailleur, are at the mouth of Imikrak Creek and just to the north (Campbell, 1967). The more northerly section, just southeast of Agate Rock, includes about 4 m (13 ft) of the limestone member overlain by 13 m (45 ft) of cherty shale, possibly the unnamed upper unit of the Otuk Formation. The other Imikrak section exposes approximately 6 m (20 ft) of chert of the Siksikpuk Formation and a few feet of the shale member of the Otuk Formation.

PUNUPKAHKROAK MOUNTAIN SECTION

Field notes made by W.W. Chamberlain in 1979 on the "Permo-

Triassic chert'' section at Punupkahkroak Mountain in the De Long Mountains indicate that the stratigraphically lowest beds are thin-bedded, dark-gray to olive-gray ''limey [sic] chert.'' (Chamberlain noted that he did not chemically test for lime content.) Overlying this unit are ''sandy limestones and chert,'' ''limey [sic] chert,'' and ''sandy to silty'' cherty beds. The various members of the Otuk Formation are not distinguishable in the notes. A sketch in the notes indicates that the Okpikruak Formation (base of very fine grained clay shale) overlies the Permian to Triassic chert. The strata in this section are evidently more siliceous than are Otuk beds in the other sections studied. According to Inyo Ellersieck (written commun., 1985), the rather nondescript gray bedded chert from the Punupkahkroak section is unlike the organic and clam-rich uppermost part of the Etivluk Group in some of the lower allochthons. Although some radiolarian ages from the top of the Punupkahkroak Mountain section are about the same as those from the Blankenship Member of the Otuk Formation, typical Otuk lithologies have not been recognized at most places in the Ipnavik River allochthon. Therefore, the gray chert of the Punupkahkroak Mountain section has generally been termed ''undifferentiated Etivluk Group.'' A reconstruction by Tailleur of the section from Chamberlain's field notes is given in figure 33.2.

OTUK CREEK SECTION

The type section of the Otuk Formation is on Otuk Creek—a stream in the central Brooks Range that drains into the Etivluk River. The base of the section at Otuk Creek is covered, and the section is upside down (fig. 33.1*E*). The shale member here consists of ''rhythmically interbedded organic shale and thin dolomitic limestone'' (Mull and others, 1982, p. 359). Swain (1981) described a gradational contact between the shale and chert members at the top of the cutbank; Bodnar (1984), however, included the shale beds in his chert member. The chert member consists of about 28 m of dark-gray radiolarian-rich chert in beds 2-5 cm thick, with thin interbeds of limestone and shale. Shale interbeds are less common in the upper part of this member. Several species of *Halobia* were recovered both from the uppermost part of the shale member and throughout the chert member. (See the related section in this chapter on megafossil biostratigraphy; the taxonomy in Mull and others, 1982, has been revised by J.A. Grant-Mackie and N.J. Silberling, written commun., 1988.) The limestone member consists of about 10 m of silicified, tan to cream-colored limestone beds that range in thickness from about 5 to 20 cm and are generally thicker near the top of the section. A few thinner limestone, shale, and chert beds occur as interbeds. Many of the limestone beds have a banded appearance; the top and bottom of each bed are calcareous, whereas the middle part is more silicified. Specimens of *Monotis* were recovered from the upper half of the limestone member.

Mull and others (1982) described the Blankenship Member as black shale with minor dolomitic limestone and chert. Its age is defined by *Otapiria* cf. *O. tailleuri* and *Inoceramus lucifer* Eichwald (early Middle Jurassic). Radiolarians have not been studied from this member at the Otuk Creek section.

AKMALIK CREEK SECTION

The Akmalik Creek section (fig. 33.2) is in a gully east of a north-flowing tributary to Akmalik Creek south of Kikiktak Mountain on the north front of the central Brooks Range. This section is about 105 m thick, is upside down, and dips steeply to the south (J.S. Kelley, written commun., 1983). The youngest beds are silicified, medium- to dark-gray shale with some thin calcareous beds. These beds are exposed for 2 m, are structurally overlain by silicified limestone beds that make up a unit nearly 7 m thick, and contain pectens (not identified, but probably *Monotis*). Above this unit on the hillside, silicified limestone with mudstone interbeds occurs for nearly 13 m of section. Dark-gray chert that weathers yellowish gray and silicified limestone that we interpret to be the chert member of the Otuk Formation crop out in the overlying 30 m. Poorly exposed, light- to medium-gray argillite that structurally overlies the cherty beds grades into greenish-gray, green, and maroon argillite that may be part of the Siksikpuk Formation; radiolarian-bearing chert beds were not observed in outcrop. The position of the apparently conformable Siksikpuk-Otuk contact is tentatively placed about 61 m stratigraphically below the dark-gray shale beds in this upside-down section.

MONOTIS CREEK SECTION

The section on Monotis Creek is 65 km farther east along the mountain front than the Akmalik Creek section. It is upright and dips gently north (fig. 33.1*F*; see Patton and Tailleur, 1964, for detailed stratigraphic information). About 27 m (90 ft) of the shale member of the Otuk Formation is overlain by about 40 m (130 ft) of the chert member, represented by thinly interbedded calcareous chert, gray-black shale, and dark-gray limestone. The limestone member caps the section with 10 m (33 ft) of locally cherty, medium- to dark-gray limestone and many thin interbeds of dark-gray shale and cherty shale. Abundant remains of late Norian *Monotis subcircularis* have been collected at the top of this section. The "*Eomonotis subcircularis*" specimens from low in the Otuk section of Patton and Tailleur (1964, p. 436-437) were reidentified as *Daonella frami* and *D.* cf. *D. degeeri* (N.J. Silberling, in Patton and Tailleur, 1964, p. 437).

TIGLUKPUK CREEK SECTION

The Tiglukpuk Creek section near Anaktuvuk Pass, nearly 50 km east of Monotis Creek, is a composite of two sections with an aggregate thickness of about 150 m (500 ft) of the shale member, 49 m (160 ft) of the chert member, and about 25 m (80 ft) of the limestone member (fig. 33.1G; Patton and Tailleur, 1964, p. 432-434). The northern section, on the south flank of the Tiglukpuk anticline, has been cited by Mull and others (1982) as a reference section for the Otuk Formation. Murchey and Tailleur sampled these cutbank exposures of the chert member in 1980; Bodnar (1984) subsequently studied this section in detail and recorded thicknesses for the shale, chert, and limestone members of 50 m, 52 m, and 12 m, respectively.

The shale member consists of grayish-black shale with interbeds of limestone in the lower part and chert interbeds near the top. The chert member is composed of chert, cherty limestone, and shale. The limestone member contains a few gray-black shale interbeds. In cutbanks on the opposite (east) side of the creek, the limestone member is overlain by poorly exposed, thinly interbedded shale and siliceous limestone of the Blankenship Member. Bodnar (1984) collected Middle Triassic conodonts and Ladinian *Daonella frami* Kittl from the lower half of the chert member, in contrast to the Late Triassic fossils found in the lower part of the chert member in other sections. He also uncovered the Otuk-Siksikpuk contact and interpreted it to be "an erosional disconformity" (Bodnar, 1984, p. 58).

STRUCTURAL SETTING

Rocks of the Etivluk Group occur in multiple thrust sheets throughout the western and southeastern Brooks Range orogen. Mayfield and others (chapter 7, 1983b) have synthesized this complex of dislocated and deformed strata into broad allochthons comprising at least seven contrasting sequences. The lower five sequences include the Etivluk Group in stratigraphic successions of continental affinity, whereas the upper two consist of igneous rocks of oceanic affinity; all were successively stacked onto the edge of the tectonic foreland during early stages of the Brookian orogeny. Palinspastically, deposition of the Etivluk Group and Mississippian and older deposits occurred in an intracratonic basin (Mayfield and others, 1983b); this basin was far more extensive than the area occupied by the present Brooks Range.

The Etivluk Group contains more shale and limestone and less chert in the lowest allochthon (Brooks Range allochthon) than in the higher allochthons. We interpret all the discussed lithostratigraphic sections, with the exception of that at Punupkahkroak Mountain, to be part of the Brooks Range allochthon. The chert-rich Punupkahkroak Mountain section occurs in the fourth highest allochthon (Ipnavik River allochthon) of Mayfield and others (1983a). Their reconstructions indicate that the Pennsylvanian to Jurassic rocks (Etivluk Group) in the Ipnavik River allochthon were deposited as siliceous pelagic sediments several hundred kilometers from a shore to the north and at least 100 km from a probable platform edge to the south. From the few data available, it appears that the western sections of the Otuk Formation are more condensed than those to the east.

BIOSTRATIGRAPHY

MEGAFOSSILS

The megafauna of the Otuk Formation provides a useful framework for correlating the early Mesozoic biostratigraphy. Late Triassic megafossil ranges for northern Alaska and the fossil occurrences in the sections studied are summarized in figures 33.4 and 33.5. Radiolarians recovered from the chert and limestone members and the Blankenship Member of the Otuk Formation along the north front of the range and Lisburne Hills can be directly correlated with megafossils having fairly short ranges.

Megafossil control is poorer in the shale member than in the overlying members. Several occurrences of *Posidonia* indicate a pre-Late Triassic age for the shale member as a whole, while the less common *Daonella frami* restricts the age of at least part of the member to early and middle Ladinian (fig. 33.4). Cephalopods collected at the Monotis Creek section (Patton and Tailleur, 1964, p. 436-437) indicate that Anisian time is represented. Another cephalopod and scattered conodonts reported by Mull and others (1982) and Bodnar (1984), and vertebrates mentioned by Patton and Tailleur (1964, p. 437), indicate that the lower part of the shale member may be as old as Early Triassic. We tentatively date the shale member as a whole as post-Permian to Late Triassic in age. The sections in figure 33.5 show the differences in age of the member.

Specimens of *Halobia* collected from the middle and upper parts of the chert member indicate either a late Karnian or an early Norian age. *Halobia superba* (late Karnian) occurs in the chert member at Noyalik

Peak and at other localities. Megafossils from the lower part of the chert member in other sections are generally diagnostic only to the Karnian stage, although the chert member may be older at Tiglukpuk Creek. Bodnar (1984) reported *Neospathodus timorensis* (late Spathian conodont) below *Daonella* and from near the base of his chert member (see also Reed and Blome, 1986).

The topmost beds of the limestone member generally contain early late Norian *Monotis ochotica*. The early late Norian *Monotis subcircularis* also occurs near the top of the section. In the lower part of the member, the overlap of late Karnian to middle Norian halobiids by late middle Norian monotids indicates a late middle Norian age for the interval.

The Blankenship Member contains pelecypods of middle Early Jurassic to early Middle Jurassic ages. *Otapiria* and *Inoceramus* remains are common in the upper part of the member in the type Blankenship Creek section; Imlay (1967, p. B6) described *Otapiria tailleuri* Imlay from about 12 m below *Inoceramus lucifer* Eichwald of Middle Jurassic (Bajocian) age there. Imprints and prisms of *Inoceramus* also occur farther down in the cherty part of the member. Ammonites from the lower part include *Uptonia* cf. *U. jamesoni* Sowerby of Early Jurassic (Sinemurian) age (Imlay, 1981, p. 19).

RADIOLARIAN FAUNAS IN THE LITHOSTRATIGRAPHIC SECTIONS

This discussion is a summary of the age range of each measured section and is based on table 33.1 and comparisons with known ranges of the included taxa.

Radiolarians in the Noyalik Peak section range in age from possibly late Karnian to late Norian. The stratigraphically lowest beds, exposed at beach level, contain both *Capnuchosphaera* De Wever and *Sarla* Pessagno. The uppermost beds in the chert and shale unit above the *Monotis* (early late Norian) marker beds contain the late Norian genera *Laxtorum* Blome and *Ferresium* Blome.

The Otuk Formation cropping out along Ayugatak Creek ranges in age from Ladinian (or older) to late middle Norian (or younger; see table 33.1). The lowest 26 m (85 ft) of the section contains very little chert or other rock types suitable for radiolarian extraction. Our lowest chert sample comes from beds just above *Daonella*-bearing float and contains *Pseudostylosphaera* Kozur and Mostler. The beds just below the *Monotis* marker bed in the limestone member at the top of the exposed section contain both *Pseudoheliodiscus* Kozur and Mostler and *Syringocapsa* Foreman.

The Eeneegiksook Creek section ranges in age from Ladinian (or older) to at least late Norian. Radiolarians such as *Pseudostylosphaera* (table 33.2) were extracted from a sample taken about 9 m (30 ft) below *Halobia*-bearing strata and indicate an early Karnian (late? Ladinian) age. However, *Eptingium manfredi* Dumitricà and ?*Staurocontium* Haeckel found in a chert-rich bed overlying *Halobia*-bearing strata indicate an older, probably Ladinian age. These radiolarian ages imply either a fault in the section near this level or possible reworking. Samples from the upper part of the section were processed for radiola-

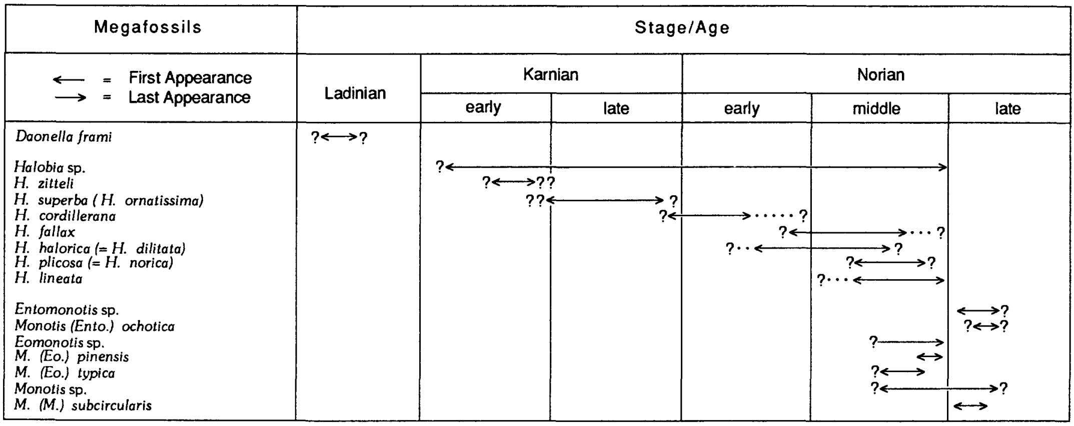


FIGURE 33.4.—Age ranges of pelecypods (halobiids and monotids) for Middle and Upper Triassic rocks of northern Alaska (from Silberling and Tozer, 1968; I.L. Tailleur, unpublished data, 1983; Silberling, 1963; N.J. Silberling, oral commun., 1985, 1988; J.A. Grant-Mackie and N.J. Silberling, written commun., 1988; references in the literature to *Monotis "scutiformis"* refer to various species of *Eomonotis*).

rians but yielded only poorly preserved, unidentifiable taxa. The upper part of the section is late Norian in age, dated by various megafossils.

Radiolarians from the lower part of the Otuk Formation at Agate Rock (table 33.2) have not been age diagnostic. A sample from the chert and shale beds in the limestone member about 4 m (12 ft) above the shear zone (see section above entitled "Geologic Setting"; Campbell, 1967) yielded *Acanthocircus* Squinabol, a genus that ranges in age from Late Triassic to Late Cretaceous.

Sixteen chert samples from Triassic beds exposed southeast of Agate Rock and at the mouth of Imikrak Creek were processed for radiolarians and contained poorly preserved skeletal fragments. The ages of the sections had previously been established by megafossils and lithologic correlations.

At Punupkahkroak Mountain, the radiolarians range in age from late Ladinian or early Karnian to Pliensbachian or Toarcian(?) (late

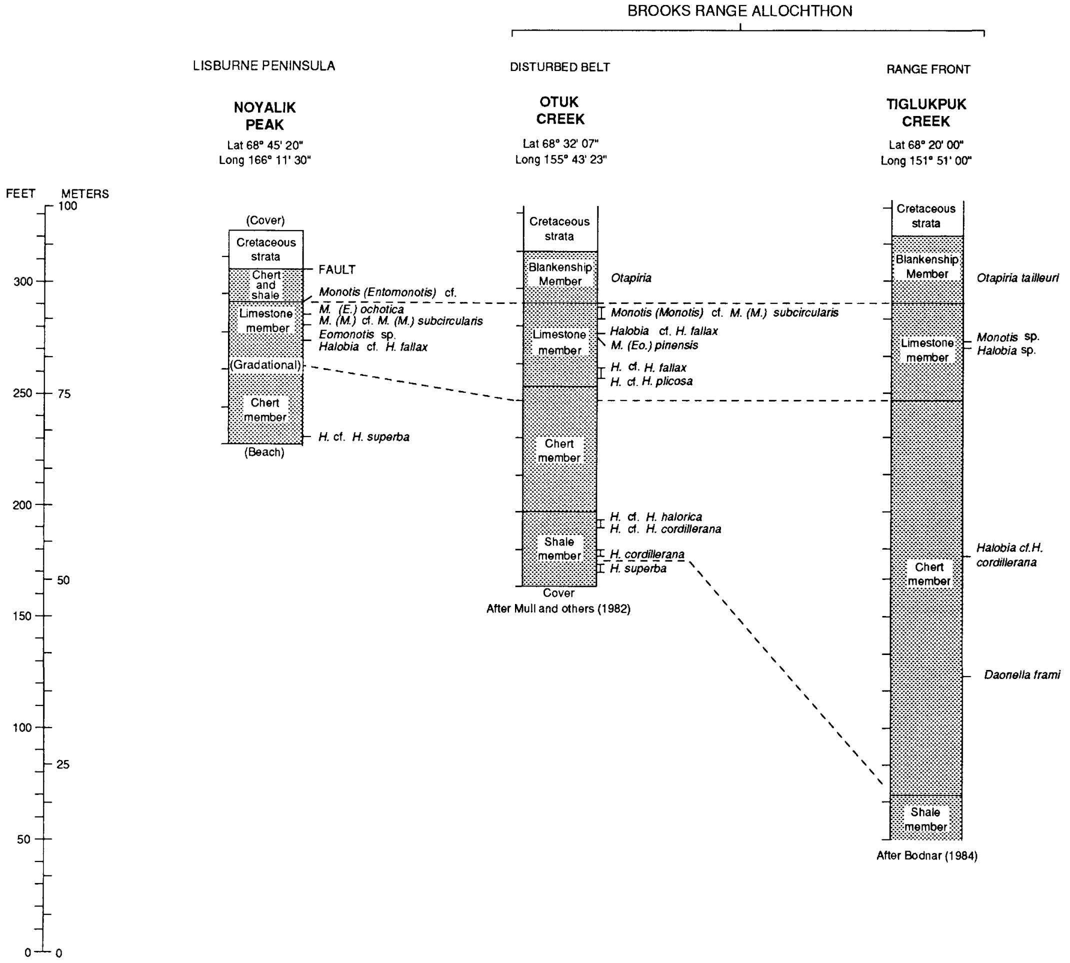


FIGURE 33.5.—Occurrence of pelecypods at three of the measured sections of the Otuk Formation. Taxonomy in this generalized figure has been updated by N.J. Silberling (oral commun., 1988). See figure 33.4 for age ranges of the genera and species noted here. Compare individual pelecypod occurrences with radiolarian faunal occurrences (fig. 33.2); see also table 33.1.

Early Jurassic). These samples span the greatest age range of all the sections studied. The oldest fauna contains *Pseudostylosphaera japonica* (Nakaseko and Nishimura) 1979, *Eptingium manfredi* Dumitricà, 1977, *Triassocampe* spp., and ?*Tripocyclia* sp., all of which occur in late Ladinian or early Karnian assemblages elsewhere. Taxa belonging to *Pseudostylosphaera* are generally more abundant in Karnian assemblages. A sample taken from the highest stratigraphic level in the traverse contains *Bagotum* spp. and *Canutus izeensis* Pessagno and Whalen, 1982. *Bagotum* is not known from strata older than Sinemurian in Alaska.

Radiolarians from the Otuk Creek section only delimit an age range of Karnian to early late Norian. The base of the section is in the upper part of the shale member, according to Mull and others (1982); the presence of *Pseudostylosphaera nazarovi*? (Nakaseko and Nishimura) 1979, as well as taxa belonging to *Yeharaia* Nakaseko and Nishimura, and *Triassocampe* Dumitricà, Kozur, and Mostler indicates an upper age limit of late Karnian (Swain, 1981). One sample collected by Swain (1.54, fig. 33.2) is unique to North American faunas in that it contains both *Capnodoce* De Wever and *Pseudostylosphaera*. However, Bodnar (1984) placed the base of the Otuk Creek section in the chert member and reported that it includes an early Karnian assemblage containing ?*Pachus* with *Pseudostylosphaera helicatum*? and *Triassocampe*. In contrast, the lower part of the chert member is of late Ladinian (or older) age at Tiglukpuk Creek and could be Ladinian at Monotis Creek according to Bodnar's data. At Otuk Creek, the co-occurrence of *Capnuchosphaera lenticulata* Pessagno, 1979, and *C.* sp. cf. *C. mexicana* Pessagno, 1979, in the uppermost beds of the chert member indicates that these strata are as young as early late Norian (table 33.1). The limestone member and Blankenship Member yielded no useful radiolarians.

The Akmalik Creek section ranges in age from Ladinian (early? Karnian) to late Sinemurian (Early Jurassic) (table 33.1). Characteristic Ladinian species such as *Tripocyclia*(?) *japonica* (Nakaseko and Nishimura) 1979 and *Triassocampe scalaris*? Dumitricà, Kozur, and Mostler, 1980, are present at a low stratigraphic position in the chert member. The youngest beds contain typical Early Jurassic (late Sinemurian) taxa such as *Canutus rockfishensis* Pessagno and Whalen, 1982, and *Droltus laseekensis* Pessagno and Whalen, 1982.

Radiolarians from the Monotis Creek section range in age from probable Ladinian to early late Norian (table 33.1). In the chert member, typical Karnian species such as *Pseudostylosphaera japonica* (Nakaseko and Nishimura) 1979 and *Staurocontium*(?) *minoense* Nakaseko and Nishimura, 1979 are overlain by typically Ladinian *Eptingium manfredi* Dumitricà, 1977. This succession seems to imply structural complications, reworking, or range disparities. Precise placement of Murchey's samples in relation to the *Daonella*-bearing beds in this section might explain the possible repetition of faunas. Radiolarians collected from the top of the chert member include *Pseudoheliodiscus sandspitensis* Blome, 1984, *Capnodoce crystallina* Pessagno, 1979, and *Capnuchosphaera triassica* De Wever, 1979, all of which indicate a latest middle to early late Norian age. Some of these same taxa have been found in upper middle Norian strata in eastern Oregon (Blome, 1984).

Radiolarians from samples at the Tiglukpuk Creek section range in age from probably Ladinian to early late Norian. The lowest Bodnar sample from the chert member contains *Pseudostylosphaera japonica*? (Nakaseko and Nishimura) 1979 and *Triassocampe deweveri* (Nakaseko and Nishimura) 1979 and lies below a *Daonella*-bearing horizon of early or middle Ladinian age. The identification of late Norian *Pseudoheliodiscus* sp. in a sample below early Norian *Halobia cordillerana* could be in error and the result of poor preservation; we have not reexamined this sample. We cannot confidently correlate the positions of Murchey's samples relative to those of Bodnar's in their measured sections. A sample from rubble(?) near the top of the chert member contains *Capnuchosphaera lenticulata* Pessagno, 1979, and *C. mexicana* Pessagno, 1979; these are forms known only from the late middle to early late Norian of western North America.

CORRELATION OF LATE TRIASSIC RADIOLARIAN ZONATIONS

Since the early 1970's, the biostratigraphic utility of radiolarians has increased tremendously. Early radiolarian zonations based on samples collected on the Deep Sea Drilling Project were established for parts of the Mesozoic and Cenozoic by Foreman (1973, 1975, 1977) and Riedel and Sanfilippo (1974). Studies by Pessagno (1976, 1977a, b) and Pessagno and others (1984) resulted in the formulation of a system of radiolarian zonations for Upper Jurassic (upper Kimmeridgian and lower Tithonian) to Upper Cretaceous (Maastrichtian) strata of the California Coast Ranges. A zonation for the entire Jurassic of western North America has recently been proposed by Pessagno and others (1987). This zonal scheme is incomplete for parts of the Jurassic because of the absence of ammonites in radiolarian-bearing strata or because some radiolarian assemblages are too poorly preserved to be useful in the zonation scheme. The Early Jurassic time intervals are well integrated with megafossil data (see radiolarian zonation in Carter and others, 1988). Preliminary radiolarian zonations for Triassic strata have been proposed, first by Pessagno (1979) for the Late Triassic of Baja California and later by Blome (1984) for the Late Triassic of western North America (fig. 33.6). Both of these studies integrated radiolarian, pectenacid bivalve, and ammonite data.

NORTH AMERICA

Pessagno's (1979) radiolarian zonal scheme for Upper Triassic strata was based on the radiolarian-bearing chert member of the San Hipolito Formation, Baja California. This member was formally divided into two Oppel zones (International Trust for Zoological Nomenclature, 1964): a lower *Capnodoce* Zone and an upper *Pantanellium silberlingi* Zone. The bottom part of Pessagno's *Capnodoce* Zone was poorly dated because of the absence of megafossils in the lower part of the chert member and was interpreted to be either late Karnian or early Norian in age. According to Pessagno (1979, p. 164), specimens of middle Norian *Halobia lineata* (Muenster) were collected from locality V5F8 and assigned to the top of the *Capnodoce* Zone. Other localities assigned by Pessagno to the lower part of the *Pantanellium silberlingi* Zone were also found to be at or near the same stratigraphic horizon as locality V5F8. The top of the *Capnodoce* Zone, as well as the base of the *Pantanellium silberlingi* Zone, was interpreted by Pessagno (1979, p. 163) to be late middle Norian in age. The early late Norian *Monotis* sp. cf. *M. subcircularis* was collected from the upper part of the overlying limestone member. Radiolarian-bearing samples from the limestone member contained faunal elements in common with the *Pantanellium silberlingi* Zone. The poor preservation of the radiolarians prevented the assignment of these samples to this upper zonal unit, and the top of the *Pantanellium silberlingi* Zone was tentatively interpreted by Pessagno to be late Norian in age.

Upper Triassic (Norian) strata from eastern Oregon, Baja California, and the Queen Charlotte Islands (British Columbia) are represented in the Late Triassic radiolarian zonal scheme proposed by

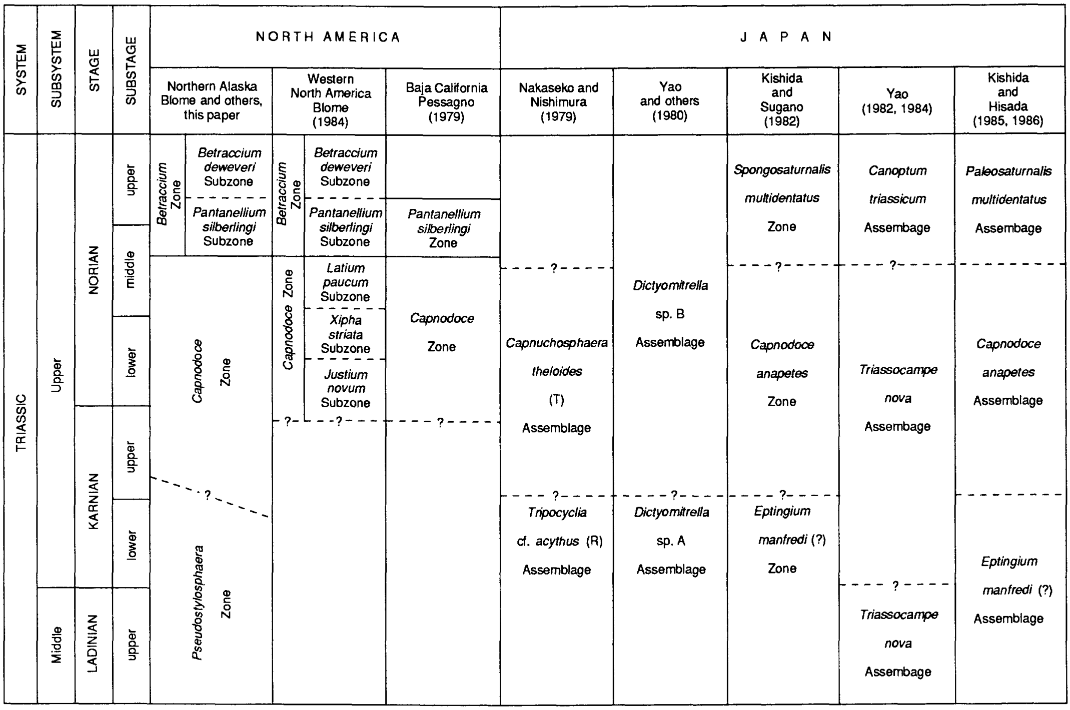


FIGURE 33.6.—Radiolarian zonations for the Upper Triassic of northern Alaska, other areas of western North America, and Japan.

Blome (1984) (fig. 33.6). This preliminary zonal system, which is divided into two zones and five subzones, is based on biostratigraphic data concerning ammonites and the pectens *Halobia* and *Monotis*.

The *Capnodoce* Zone was divided by Blome (1984) into three subzones: the *Justium novum, Latium paucum,* and *Xipha striata* Subzones (fig. 33.6.). The base of the *Capnodoce* Zone (as well as the base of the *Justium novum* Subzone) is simply defined by the first occurrence of *Capnodoce* De Wever. Other genera that make their first appearance at or near the base of this zone are *Renzium* Blome, *Xenorum* Blome, *Corum* Blome, *Canesium* Blome, *Castrum* Blome, *Latium* Blome, and *Quasipetasus* Blome (see section below entitled ''Systematic Paleontology''). The base of the *Capnodoce* Zone is questionably placed in the upper Karnian because of the absence of datable megafossils in the lower part of the Rail Cabin Mudstone Member (Blome and others, 1986; called the ''Rail Cabin Argillite'' by Dickinson and Vigrass, 1965) of the Vester Formation and the upper part of the Brisbois Member of the Vester (Dickinson and Thayer, 1978). Until middle and late Karnian radiolarian assemblages from North America are better dated and understood, the precise age of this base remains unknown.

The top of the *Capnodoce* Zone (and top of the *Latium paucum* Subzone) was defined by Blome (1984) as being the final occurrence of *Capnodoce*. Other genera that make their final appearance at or near the top of the zone are *Catoma* Blome, *Icrioma* De Wever, *Renzium* Blome, *Xenorum* Blome, *Corum* Blome, *Pachus* Blome, *Canesium* Blome, *Castrum* Blome, *Latium* Blome, *Quasipetasus* Blome, and *Xipha* Blome (see section below entitled ''Systematic Paleontology'').

Although megafossils have been collected from the Rail Cabin Mudstone Member at its type locality, the only ones recovered in place were situated somewhat above the middle of the unit. N.J. Silberling (written commun., 1977) collected a fauna from float approximately 60 m (200 ft) below the contact with the overlying Graylock Formation. The megafossils from both the type locality and Silberling's float collection are assignable to the *Himavatites columbianus* Zone (Tozer, 1967) of late middle Norian age.

The upper *Betraccium* Zone of Blome (1984) was divided into a lower *Pantanellium silberlingi* Subzone and an upper *Betraccium deweveri* Subzone. The base of the *Betraccium* Zone and thus the base of the *Pantanellium silberlingi* Subzone were defined by the first occurrence of *Betraccium* Pessagno, as well as of *Betraccium smithi* Pessagno, 1979, *Pantanellium silberlingi* Pessagno, 1979, and *Pseudoheliodiscus finchi* Pessagno, 1979. Blome (1984) defined the base of this zone as above the horizon defined by the final occurrence of *Capnodoce*. However, the base of this zone is missing in the eastern Oregon sections but is represented in Baja California and Alaska. The top of this subzone was assigned to the upper Norian on the basis of the presence of *Monotis* sp. cf. *M. subcircularis* collected from the uppermost part of the limestone member of the San Hipolito Formation (Pessagno, 1979). For a listing of radiolarian species that make their first appearance at or near the base of this zone, see Pessagno (1979). Megafossils used to date the lower part of the *Pantanellium silberlingi* Subzone include *Halobia lineata* of middle Norian age.

The top of Blome's (1984) *Betraccium* Zone is defined by the final occurrence of the genus *Betraccium*. For a listing of the species that also make their apparent final appearance at or near the top of this zone, see Blome (1984, p. 16). The important radiolarian biostratigraphic markers in western North America are generally present in Japanese assemblages but are uncommon in the North Slope Alaskan material examined thus far.

The middle black limestone member of the Kunga Formation on Queen Charlotte Islands (British Columbia) contains common pectenacid bivalves together with rare ammonites. Pectenacids collected by Blome from the middle part of this member (*Monotis subcircularis*, of late Norian age) were used as the megafossil control for the *Betraccium deweveri* Subzone.

JAPAN

Several zonal schemes have been proposed for the Late Triassic of Japan (fig. 33.6), including those of Nakaseko and Nishimura (1979), Yao and others (1980), Kishida and Sugano (1982), Yao (1982, 1984), and Kishida and Hisada (1986). Nakaseko and Nishimura (1979, p. 64) stated that the stratigraphic position of their three radiolarian assemblages cannot be precisely determined and that all the assemblages range in age from late Karnian through Norian, on the basis of conodonts recovered from chert and limestone samples. Yao and others (1980) proposed two long-ranging radiolarian assemblages (middle Karnian and older and middle Karnian through Rhaetian), but poor preservation and their use of transmitted-light photomicroscopy make correlation with North American forms very difficult. Although these zonal schemes are preliminary and contain taxa and even genera missing in coeval western North American radiolarian zones, they still provide useful data for comparative taxonomic and biostratigraphic studies.

Kishida and Sugano (1982) established three assemblage zones for Ladinian through Norian strata from the Chichibu Belt in the Kuchi and Oita Prefectures, Japan. Their lower *Eptingium manfredi* Zone is mainly characterized by the following taxa described by Nakaseko and Nishimura (1979): *Eptingium manfredi*(?) Dumitricà, 1977, *Triassocampe deweveri, Tripocyclia* cf. *T. acythus, Pseudostylosphaera compacta, P. japonica, P. spinulosa, P. tenue, Staurodoras variabilis,* and *Yeharaia* spp. Although the majority of forms in this assemblage represent the Ladinian Stage, the upper part of the assemblage extends into the lower Karnian, although exact placement within the lower Karnian is not known (labeled "?" in fig. 33.6). The *Eptingium manfredi*(?) Assemblage later proposed by Kishida and Hisada (1986) is nearly identical to Kishida and Sugano's original zone and is as broadly defined. The *Triassocampe deweveri* Assemblage proposed by Yao (1982, 1984) is dominated by *Triassocampe deweveri* and other taxa belonging to that genus, as well as by *Yeharaia elegans* Nakaseko and Nishimura, *Eptingium* cf. *E. manfredi* Dumitricà, *Pseudostylosphaera japonica* (Nakaseko and Nishimura), and *P. tenue* (Nakaseko and Nishimura). Associated conodonts indicate that this radiolarian assemblage is confined to the late Ladinian, although it may extend into the Karnian.

Overlying Kishida and Sugano's (1982) *Eptingium manfredi* Zone is their *Capnodoce anapetes* Zone (fig. 33.6). This zone's base and top are defined by the first and final occurrences of species belonging to the genus *Capnodoce* De Wever, 1979, which is the same criterion used to define the *Capnodoce* Zone proposed by Blome (1984) and used in this report. Kishida and Sugano (1982) tentatively placed the base of this zone in the middle Karnian and the top somewhere in the middle Norian. The *Triassocampe nova* Assemblage of Yao (1982, 1984) contains taxa belonging to *Capnodoce* De Wever and *Capnuchosphaera* De Wever, and its range is approximately that of the *Capnodoce anapetes* Zone of Kishida and Sugano (1982). Kishida and Hisada (1986) further divided the *Capnodoce anapetes* Assemblage into two subassemblages (not shown in fig. 33.6).

Kishida and Sugano's (1982) *Spongosaturnalis multidentatus* Zone is typified by species of the genera *Spongosaturnalis* Campbell and Clark, 1944 (= *Acanthocircus* Squinabol, 1903, in this report) and *Paleosaturnalis* Donofrio and Mostler, 1978 (some forms of the latter genus = *Pseudoheliodiscus* Kozur and Mostler, 1972, in this report). Also included are *Sarla natividadensis* Pessagno, 1979, and *S. vizcainoensis* Pessagno, 1979. Kishida and Sugano (1982) defined the base of the zone by the first occurrence of *Paleosaturnalis* and the top of the zone as being the final occurrence of most species belonging to both *Spongosaturnalis* and *Paleosaturnalis*. Their age range for this assemblage zone is middle Norian to early(?) Rhaetian. Kishida and Hisada (1985) redefined this zone as their *Paleosaturnalis multidentatus* Assemblage and subdivided it into the *Canoptum* aff. *C. triassicum* and *Canoptum lubricum* Subassemblages. They also pointed out that taxa belonging to *Betraccium* Pessagno, a genus common to many late Norian North American radiolarian assemblages, were absent in their study material. The *Canoptum triassicum* Assemblage of Yao (1982, 1984) includes taxa belonging to *Paleosaturnalis* that are similar to forms described from the upper Norian in Austria (Kozur and Mostler, 1972; Donofrio and Mostler, 1978). This assemblage also contains taxa that persist from the underlying *Triassocampe nova* Assemblage.

Yao (1982) stated that some taxa belonging to the *Canoptum triassicum* Assemblage range through the Rhaetian. The very top of the Triassic (Rhaetian) is also represented by Kishida and Sugano's (1982) *Pantanellium* sp. B-*Gorgansium* sp. A Zone (not shown in fig. 33.6) of supposed Rhaetian (wholly or in part) age. However, in North America, the Rhaetian stage can be documented only in the Gabbs Valley of Nevada and the Tyaughton Creek area of British Columbia (Silberling and Tozer, 1968). The biostratigraphic evidence from North America and elsewhere indicates that the Rhaetian, as recognized using ammonoids, accounts for only a small part of latest Triassic time, and many paleontologists (such as Tozer, 1979) suggest that the Rhaetian should be eliminated from the Late Triassic chronostratigraphic time scale. Therefore, the uppermost Triassic Japanese zones may not be directly correlated with western North America radiolarian zones.

RADIOLARIAN ZONATION USED HEREIN

The Otuk faunas contain taxa common to both Japanese and other western North American radiolarian assemblages but are sufficiently dissimilar that previous zonal schemes do not precisely apply. According to Blome (1987), the Otuk faunas are typified by different and less abundant species for several generic groups (for example, *Pseudostylosphaera, Capnodoce,* and *Pantanellium* and related genera) in comparison with generic abundances for coeval Cordilleran faunas. The radiolarian zonal scheme we use for the radiolarian faunas collected from the Brooks Range and the NPRA is, primarily, a modified version of that proposed by Blome (1984). Plates 33.1 and

33.2 illustrate typical radiolarians from the Otuk Formation.

The base of the *Pseudostylosphaera* Zone cannot be distinguished at this time because of the absence of radiolarian-bearing rocks containing well-documented Ladinian megafossils. According to Kishida and Sugano (1982), *Pseudostylosphaera*(?) *japonica* (Nakaseko and Nishimura) 1979, as well as other species belonging to the genus *Pseudostylosphaera* Kozur and Mostler, 1981 (= *Stylosphaera* in Kishida and Sugano, 1982; = *Archaeospongoprunum* in Nakaseko and Nishimura, 1979, and other papers), range from the Anisian to the lower Karnian stage. At the Otuk Creek section, near the base of the chert member, Bodnar (1984) found *Pseudostylosphaera* below *Halobia cordillerana* and *H. superba*, strongly implying a pre-late Karnian age for the radiolarians. The top of the *Pseudostylosphaera* Zone is defined as lying slightly above the first occurrence of the genus *Capnodoce*. Kishida and Sugano (1982) also noted that *Capnodoce* may range farther down into the Karnian in Japan than it does in North America. Swain (1981) reported a co-occurrence of these genera in one sample. However, the first appearance of *Capnodoce* in both Japanese and North American faunas appears to broadly coincide with the final appearance of *Pseudostylosphaera*. Other species that make their final appearance within the body of this zone are *Eptingium manfredi* Dumitricà, 1977, *Staurocontium minoense* Nakaseko and Nishimura, 1979, *Triassocampe deweveri* (Nakaseko and Nishimura) 1979, and *Tripocyclia japonica* Nakaseko and Nishimura, 1979.

The base of our revised *Capnodoce* Zone is defined as lying slightly below the final occurrence of the genus *Pseudostylosphaera*. The age of the base of the zone is provisionally placed near the beginning of the late Karnian. Dating this horizon is complicated by the absence of datable megafossils in the lower part of the chert member of the Otuk Formation. The three subzones in the *Capnodoce* Zone of Blome (1984) cannot be recognized, mainly because of the low diversity and scarcity of specimens in the Brooks Range radiolarian faunas. The top of the *Capnodoce* Zone, as used in this report, conforms to that of Blome (1984) and is defined by the final occurrence of the genus *Capnodoce* in late middle Norian time.

The base of the *Betraccium* Zone is defined by the first occurrence of that genus, as well as the first occurrence of *Capnuchosphaera lenticulata* Pessagno, 1979, and *C. mexicana* Pessagno, 1979. Both Blome's (1984) *Pantanellium silberlingi* and *Betraccium deweveri* Subzones within the *Betraccium* Zone are retained. The top of the *Pantanellium silberlingi* Subzone is defined by the last occurrence of the genus *Capnuchosphaera*, and the base of the *Betraccium deweveri* Subzone is arbitrarily defined as lying above this biohorizon. The youngest Triassic strata discussed in this report are represented by the *Betraccium deweveri* Subzone at the Punupkahkroak Mountain and Noyalik Peak sections; the subzone is considered to be of late Norian age on the basis of the presence of *Monotis subcircularis* and *M. ochotica*.

RADIOLARIAN ZONATION AND MEMBERS OF THE OTUK FORMATION

The extensive dating of radiolarian samples, particularly in western North America, has allowed us to assign the radiolarian zones (*Pseudostylosphaera*, *Capnodoce*, and *Betraccium* Zones) to the chert and limestone members of the Otuk Formation, as well as to part of the Blankenship Member (fig. 33.7). However, the poor radiolarian preservation and the absence of co-occurring megafossils make it impossible to link much of the shale member and the upper part of the Blankenship Member to formal radiolarian zones.

The data presented in table 33.1 and figure 33.2 are the basis for figure 33.7, which shows the minimum amounts of section in which each radiolarian zone has been recognized. A comparison of figures 33.2 and 33.7 indicates that the zones and thus the faunal assemblages are not limited to particular lithologic packages. For example, late Norian radiolarians are found in chert beds at Noyalik Peak but also occur in the limestone member in the Ayugatak Creek section. Our work suggests that the age of the basal part of the chert member varies widely from place to place. The variation in the age of the contact between the two lower members of the Otuk may, as noted, reflect local depositional conditions (Bodnar, 1984). On the other hand, this variation could indicate differences in diagenetic alteration that may have influenced the shale/chert ratio (Reed and Blome, 1986). In addition, some of the variation may be due to the gradational contacts separating members and to the placement of the contacts by those who measured the sections. In general, however, radiolarians of the *Pseudostylosphaera* Zone are present in the lower part of the chert member and for an undetermined distance down into the shale member. Forms indicative of the *Capnodoce* Zone occur primarily in the chert member. The variations that we have observed in lithology indicate that the chert member does not consistently range in age from late Karnian to late middle Norian.

Faunas firmly assignable to the various subzones of the *Betraccium* Zone are absent in most sections. Generally, the older *Pantanellium silberlingi* Subzone correlates with the middle and upper parts of the limestone member, and the younger *Betraccium deweveri* Subzone correlates with the upper part of the limestone member and, in places, the lower part of the Blankenship Member.

As noted, the ages of the radiolarian biostratigraphic zones are closely tied to megafossil control in western North America. Conodont collections from the Otuk Formation (Bodnar, 1984) strengthen the zonal dating: the shale member has yielded Spathian and older conodonts (p. 82); the chert member contains late Early Triassic through Norian forms.

It is not possible to relate the Punupkahkroak Mountain section to the other sections studied because the strata at Punupkahkroak Mountain are more siliceous throughout. However, the radiolarian faunas and thus the zones occur in the same succession as at the other sections. The ap-

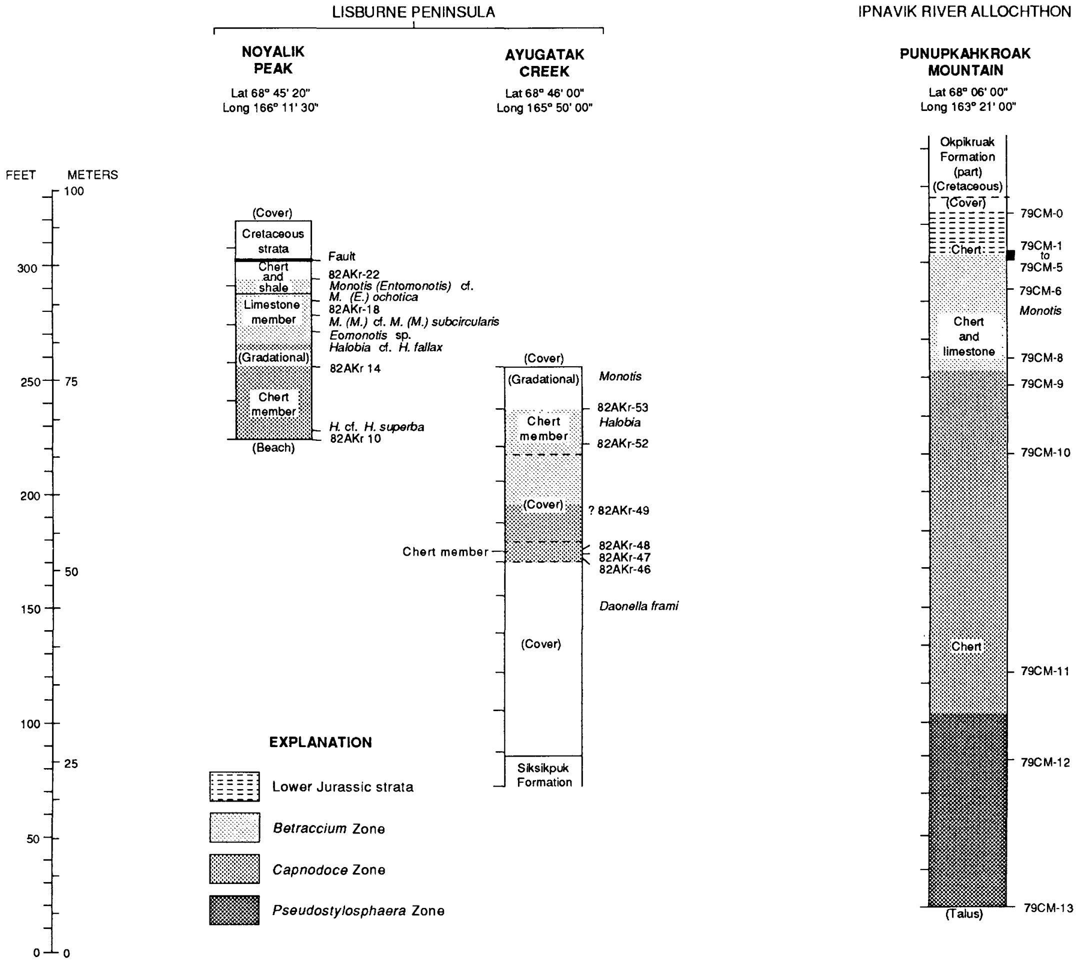


FIGURE 33.7.—Distribution of radiolarian zones for measured sections of the Otuk Formation. Boundary positions are only inferred; paucity of samples precludes precise placement. Contrasting measurements by various workers for their Otuk Creek and Tiglukpuk Creek sections prevent correlation of samples on a composite section; therefore, two columns are shown for each section. "?" indicates that faunas are too sparse for confident assignment or contain taxa whose ranges span the zonal boundary. Sample 79Wr-1.54 (Otuk Creek section) contains both *Pseudostylosphaera* and *Capnodoce*. The *Pseudoheliodiscus* in Bodnar's Tiglukpuk Creek sample UA2151 may be *Acanthocircus*, and the position of the zone boundary could be close to the level of sample UA2153. Compare the zone assignments with the lithostratigraphy of the Otuk Formation shown in figure 33.2.

parent richness of the Punupkahkroak fauna may be the result of the preponderance of pelagic sedimentary rocks. Differences between the Punupkahkroak Mountain and Brooks Range allochthon faunas and among the faunas in the Brooks Range allochthon sections may also be due to differential preservation of the more robust forms, to diagenesis, and (or) to the varying amount of silica. The large amount of the Punupkahkroak Mountain section assigned to the *Capnodoce* Zone may be the result of continuous deposition, structural thickening, or imprecise measurements.

We have used this zonal scheme to determine the ages of miscellaneous samples (table 33.2). Field geologists have used these radiolarian ages to distinguish widely distributed rocks of similar lithology in strongly disturbed and dislocated geologic settings. Such scattered samples have been useful primarily in expanding our information about the Otuk radiolarian faunal components.

SYSTEMATIC PALEONTOLOGY

We include a short section on systematics here to help students who are beginning in radiolarian taxonomy and to aid geologists who may want references to other reports about Triassic and Jurassic radiolarians. For brevity, only genera are discussed here; for species descriptions and ranges, the reader should refer to the authors cited with the generic comparisons (under "Remarks").

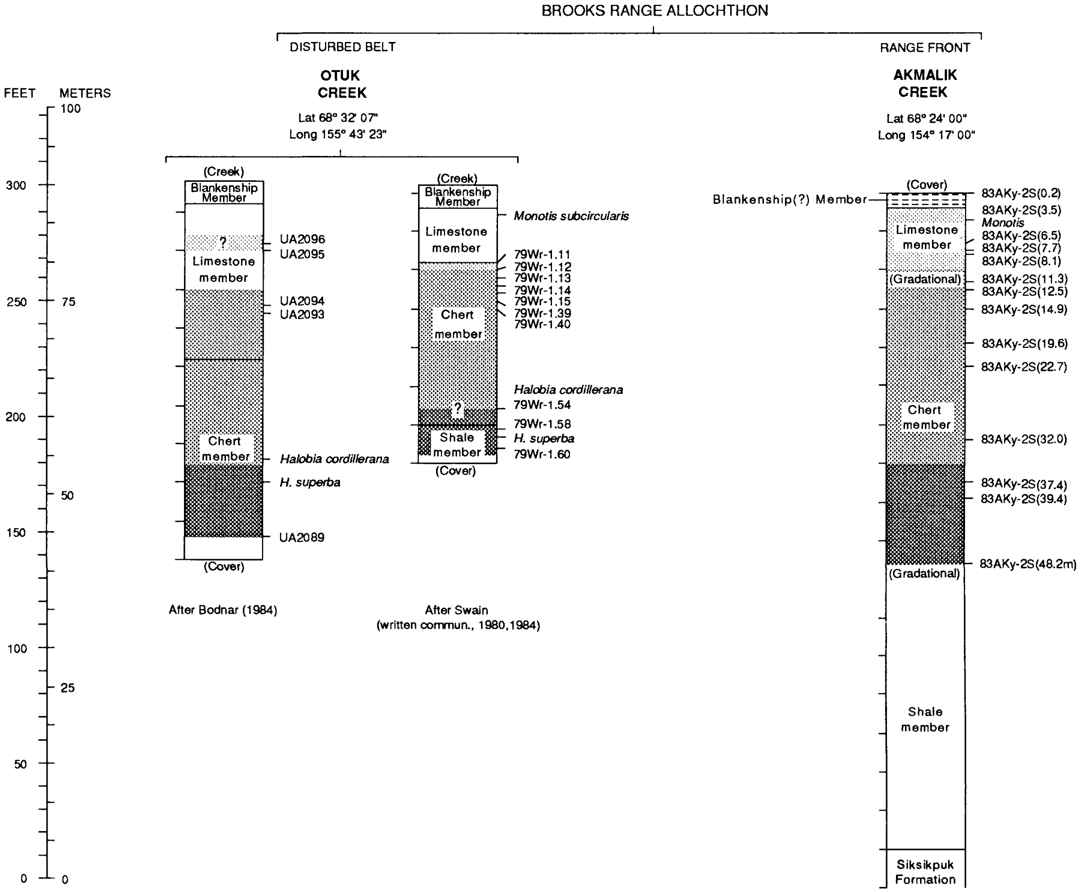


FIGURE 33.7.—Distribution of radiolarian zones for measured sections of the Otuk Formation—Continued

Phylum PROTOZOA
Subphylum SARCODINA
Class RETICULARIA
Subclass RADIOLARIA
Order POLYCYSTIDA
Suborder SPUMELLARIINA Ehrenberg, 1875

Genus *Acanthocircus* Squinabol, 1903 (emend. Pessagno, 1979; De Wever, 1984)

Type species—Acanthocircus irregularis Squinabol, 1903; subsequent designation by Campbell (1954, p. D106)

Remarks—Spongosaturnalis Campbell and Clark, 1944, and *Spongosaturninus* Campbell and Clark, 1944, are regarded as junior synonyms of *Acanthocircus* Squinabol. *Acanthocircus* differs from *Pseudoheliodiscus* Kozur and Mostler, 1972, by having two polar spines.

Range—Upper Triassic (Karnian) to Upper Cretaceous (Maastrichtian).

Occurrence—Worldwide, Tethyan and Boreal Realms.

Genus *Betraccium* Pessagno, 1979

Type species—Betraccium smithi Pessagno, 1979

Remarks—Betraccium differs from *Capnodoce* De Wever by possessing solid, bladed primary spines (triradiate in axial section); from *Gorgansium* Pessagno and Blome, 1980, by having symmetrically arranged, more or less equidistant primary spines of equal length; and from *Cantalum* Pessagno, 1979, by possessing three (versus four) bladed, triradiate primary spines.

Range—Upper Triassic (middle to uppermost Norian).

Occurrence—Oregon, California, Baja California, Alaska, British Columbia, and New Zealand.

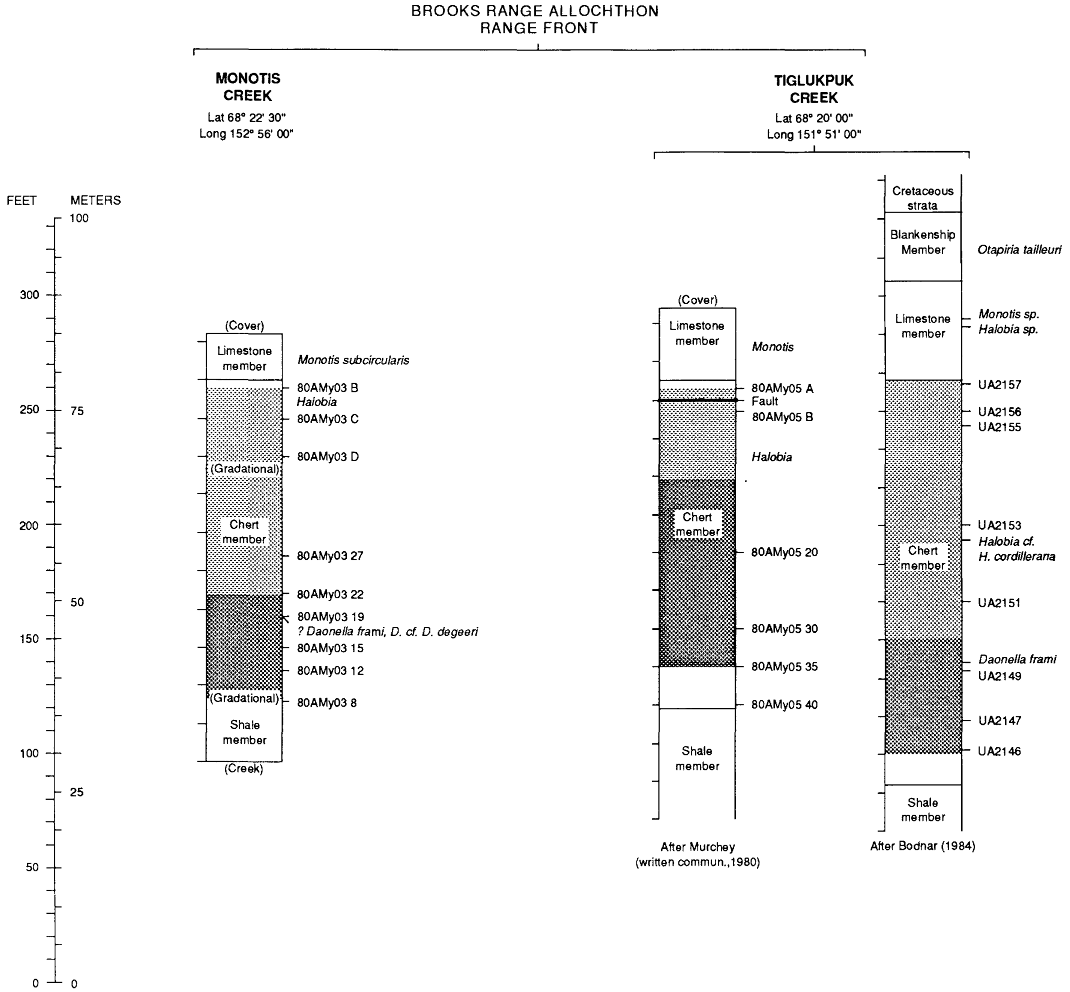


FIGURE 33.7.—Distribution of radiolarian zones for measured sections of the Otuk Formation—Continued

Genus *Cantalum* Pessagno, 1979

Type species—Cantalum holdsworthi Pessagno, 1979

Remarks—Cantalum differs from *Betraccium* Pessagno, 1979, by having a cortical shell that is subpyramidal in shape, and by having four radially arranged, bladed primary spines that lie in more than a single plane.

Range—Upper Triassic (middle to uppermost Norian).

Occurrence—Alaska, Baja California, British Columbia, and Japan.

Genus *Capnodoce* De Wever, 1979 (emend. Pessagno, 1979; emend. Blome, 1983)

Type species—Capnodoce anapetes De Wever, 1979

Remarks—Capnodoce differs from *Loffa* Pessagno, 1979, and *Renzium* Blome, 1983, by possessing three radially arranged tubular primary spines that lie in the same plane.

Range—Upper Triassic (upper Karnian to upper middle Norian).

Occurrence—Oregon, California, Baja California, Washington, British Columbia, Alaska, Europe, Middle East, and Japan.

Genus *Capnuchosphaera* De Wever, 1979 (emend. Pessagno, 1979; emend. Blome, 1983)

Type species—Capnuchosphaera triassica De Wever, 1979

Remarks—Capnuchosphaera differs from *Sarla* Pessagno, 1979, by possessing tumidaspinae (medial part of spine swollen with alternating ridges and grooves). *Capnuchosphaera* also differs from *Icrioma* De Wever, 1979, by possessing three (versus four) primary spines.

Range—Upper Triassic (upper Karnian to basal upper Norian).

Occurrence—Oregon, California, Baja California, Alaska, British Columbia, Europe, Middle East, and Japan.

Genus *Catoma* Blome, 1983

Type species—Catoma geometrica Blome, 1983

Remarks—Catoma differs from *Icrioma* De Wever, 1979, by having primary spines that lack tumidaspinae. *Catoma* also differs from *Hagiastrum* Haeckel, 1881 (emend. Baumgartner, 1980) and any other genera belonging to the family Hagiastridae Riedel, 1971 (emend. Baumgartner, 1980), by having a two-layered cortical shell.

Range—Upper Triassic (upper Karnian to upper middle Norian).

Occurrence—Oregon, California, Baja California, Alaska, Europe, and Japan.

Genus *Emiluvia* Foreman, 1973 (emend. Pessagno, 1977a)

Type species—Emiluvia chica Foreman, 1973

Remarks—We question the generic assignment by Nakaseko and Nishimura (1979) and others, of various forms to *Emiluvia* because of the difficulty in ascertaining the presence of a double layered cortical shell, a distinct medullary shell, and numerous radial beams.

Range—Triassic(?); Middle Jurassic (Bathonian) to Lower Cretaceous (Valanginian; Hauterivian?).

Occurrence—Worldwide, Tethyan and Boreal Realms.

Genus *Ferresium* Blome, 1984

Type species—Ferresium laseekense Blome, 1984

Remarks—Ferresium differs from *Xenorum* Blome, 1984, by having a multilayered test consisting of three layers of polygonal pore frames and by having thin, fragile bars connecting nodes at the pore frame vertices.

Range—Upper Triassic (upper Norian).

Occurrence—California, Alaska, British Columbia, New Zealand, and Japan.

Genus *Gorgansium* Pessagno and Blome, 1980

Type species—Gorgansium silviesense Pessagno and Blome, 1980

Remarks—Gorgansium differs from *Betraccium* Pessagno, 1979, by having primary spines that are asymmetrically arranged and of unequal length (with two shorter spines situated close together).

Range—Upper Triassic (lower Karnian) to Upper Jurassic (Tithonian).

Occurrence—Oregon, California, Baja California, Alaska, British Columbia, New Zealand, Middle East, and Japan.

Genus *Icrioma* De Wever, 1979

Type species—Icrioma tetrancistrum De Wever, 1979

Remarks—Icrioma differs from *Catoma* Blome, 1983, by possessing tumidaspinae. *Icrioma* also differs from *Capnuchosphaera* De Wever, 1979, and *Hexaporobrachia* Kozur and Mostler, 1979, by having a four-sided cortical shell with four radially arranged tumidaspinae and by having an outer layer of meshwork consisting of variably sized, raised polygonal pore frames with massive nodes at the pore frame vertices.

Range—Upper Triassic (upper Karnian to upper middle Norian).

Occurrence—Oregon, California, Alaska, Europe, Middle East, and Japan.

Genus *Khalerosphaera* Kozur and Mostler, 1979

Type species—Khalerosphaera parvispinosa Kozur and Mostler, 1979

Remarks—Khalerosphaera differs from other three-spined Triassic spumellarians by possessing primary spines (triradiate in axial section) that possess four secondary spines in more than one plane.

Range—Upper Triassic (Karnian and Norian).

Occurrence—Alaska, Europe, and Japan.

Genus *Livarella* Kozur and Mostler, 1981

Type species—Livarella densiporata Kozur and Mostler, 1981

Remarks—Livarella differs from other Triassic and Jurassic spumellarians listed in this report by having a cortical shell that possesses a thick (macrogranular silica?) outer layer with randomly arranged, abundant small pores.

Range—Upper Triassic (upper Norian; Rhaetian of Europe) to Lower Jurassic (Hettangian).

Occurrence—California, Alaska, British Columbia, Europe, and Japan.

Genus *Oertlispongus* Dumitricà, Kozur, and Mostler, 1980

Type species—Oertlispongus inaequispinosa Dumitricà, Kozur, and Mostler, 1980

Remarks—Oertlispongus differs from other lower Mesozoic radiolarian genera by possessing a spongy cortical shell in combination with cylindrical bipolar spines, one spine thin and narrow and the other thicker and curved.

Range—Middle Triassic (Ladinian).

Occurrence—Alaska and Europe.

Genus *Orbiculiforma* Pessagno, 1973

Type species—Orbiculiforma quadrata Pessagno, 1973

Remarks—Orbiculiforma differs from other Mesozoic spumellarian genera by having a disc-shaped spongy test with concentric arrangement throughout and central cavities on opposing sides of the test.

Range—Upper(?) Triassic; Lower Jurassic (Hettangian) to Cretaceous (upper Maastrichtian); Tertiary(?).

Occurrence—Worldwide, Tethyan and Boreal Realms.

Genus *Pantanellium* Pessagno, 1977a

Type species—Pantanellium riedeli Pessagno, 1977a

Remarks—Pantanellium differs from *Protoxiphotractus* Pessagno, 1973, by possessing bipolar spines with longitudinally arranged, alternating grooves and ridges.

Range—Upper Triassic (upper Karnian) to Lower Cretaceous (upper Aptian; Albian?).

Occurrence—Worldwide; southern and northern Tethyan Provinces of the Tethyan Realm, southern Boreal Province of the Boreal Realm.

Genus *Paronaella* Pessagno, 1971

Type species—Paronaella solanoensis Pessagno, 1971

Remarks—Paronaella differs from *Patulibracchium* Pessagno, 1971, by lacking a bracchiopyle and expanded ray tips and by always possessing rays that are nearly equal in length.

Range—Permian?; Upper Triassic (Karnian, Norian) to Cretaceous (Maastrichtian).

Occurrence—Worldwide, Tethyan and Boreal Realms.

Genus *Plafkerium* Pessagno, 1979

Type species—Plafkerium abbotti Pessagno, 1979

Remarks—Plafkerium differs from *Emiluvia* Foreman, 1975, by having a cortical shell that is two layered on all surfaces and in having slightly convex (versus planiform) surfaces.

Range—Upper Triassic (Norian).

Occurrence—Oregon, California, Baja California, Alaska, and Japan.

Genus *Pseudohagiastrum* Pessagno, 1979

Type species—Pseudohagiastrum monstruosum Pessagno, 1979

Remarks—Pseudohagiastrum differs from *Hagiastrum* Haeckel, 1881 (emend. Pessagno, 1971, 1977a; emend. Baumgartner, 1980) in having rays that are not oriented in the same plane and that are not rodlike and circular in axial section.

Range—Upper Triassic (Norian).

Occurrence—Oregon, California, Baja California, and Alaska.

Genus *Pseudoheliodiscus* Kozur and Mostler, 1972 (emend. Pessagno, 1979; emend. De Wever, 1984)

Type species—Pseudoheliodiscus riedeli Kozur and Mostler, 1972

Remarks—Pseudoheliodiscus differs from *Heliosaturnalis* Kozur and Mostler (1972) in having a single (versus double) ring. *Pseudoheliodiscus* also differs from *Acanthocircus* Squinabol, 1903, in having auxiliary spines and in having a spongy cortical shell that occupies most of the interior of the ring.

Range—Upper Triassic (upper middle Norian) to Lower Jurassic (Pliensbachian; Toarcian?).

Occurrence—Worldwide, Tethyan and Boreal Realms.

Genus *Pseudostylosphaera* Kozur and Mostler, 1981

Type species—Pseudostylosphaera gracilis Kozur and Mostler, 1981

Remarks—Pseudostylosphaera differs from *Archaeospongoprunum* Pessagno, 1973, by having a nonspongy (latticed) cortical shell possessing an internal spicule. *Pseudostylosphaera* also differs from *Pantanellium* Pessagno, 1977a, by possessing smaller, nonuniform polygonal pore frames and corresponding nodes at pore frame vertices and by possessing an internal spicule.

Range—Middle Triassic (upper Ladinian) to Upper Triassic (upper Karnian).

Occurrence—Oregon, California, Alaska, British Columbia, Europe, Middle East, and Japan.

Genus *Renzium* Blome, 1983

Type species—Renzium webergorum Blome, 1983

Remarks—Renzium differs from *Capnodoce* De Wever, 1979, by having two (versus three) radially arranged primary spines.

Range—Upper Triassic (upper Karnian to upper middle Norian).

Occurrence—Oregon, California, British Columbia, and Alaska.

Genus *Sarla* Pessagno, 1979

Type species—Sarla prietoensis Pessagno, 1979

Remarks—Sarla differs from *Capnuchosphaera* De Wever, 1979, by having primary spines that lack tumidaspinae. *Sarla* also differs from *Tripocyclia* Haeckel, 1881, by possessing a double-layered cortical shell. This form commonly possesses twisting primary spines and may, where preservation is poor, be misidentified as belonging to the genus *Eptingium* Dumitricà, 1977.

Range—Upper Triassic (lower Karnian to lowermost upper Norian).

Occurrence—Western North America, Europe, Middle East, and Japan.

Genus *Staurocontium* Haeckel, 1881

Type species—Staurocontium cruciferum Haeckel, 1887

Remarks—Staurocontium differs from *Emiluvia* Foreman, 1973, by having more regularly arranged meshwork lacking nodes and by having two (versus three) medullary shells. We question the assignment of forms to the genus *Staurocontium* by Nakaseko and Nishimura (1979) and others.

Range—Upper Triassic to Neogene.

Occurrence—Worldwide.

Genus *Staurodoras* Haeckel, 1881

Type species—Staurodoras mojsisovicsii Dunikowski, 1882

Remarks—Staurodoras is a catch-all generic term for four-spined forms possessing a spongy cortical shell that lacks any differentiated medullary shell(s).

Range—Upper Triassic to Neogene.

Occurrence—Worldwide.

Genus *Tripocyclia* Haeckel, 1881

Type species—Tripocyclia trigonum Rüst, 1885

Remarks—Tripocyclia differs from *Acaeniotyle* Foreman, 1973, by having a relatively smooth surfaced test lacking mammae. We question the assignment of *Tripocyclia* by some radiolarian workers to forms occurring in Late Triassic rocks. To our knowledge, *Tripocyclia* has not been recovered from rocks of Early Jurassic age or older, although Yeh (1987) reports a lower age limit of Early Jurassic.

Range—Middle Jurassic (Bajocian) to Lower Cretaceous (Barremian).

Occurrence—Worldwide, Tethyan and Boreal Realms.

Genus *Xenorum* Blome, 1984

Type species—Xenorum largum Blome, 1984

Remarks—Xenorum differs from *Ferresium* Blome, 1984, by having a cortical shell possessing two (versus three) layers of polygonal pore frames, by having more massive nodes at the pore frame vertices, and by having wider, more massive bars connecting the nodes. *Xenorum* also differs from *Eptingium* Dumitricà, 1977, by possessing massive nodes at the pore frame vertices and by having less massive, twisted primary spines.

Range—Upper Triassic (upper Karnian to upper middle Norian).

Occurrence—Oregon, California, Alaska, British Columbia, and Japan.

Genus *Veghicyclia* Kozur and Mostler, 1972

Type species—Veghicyclia pulchra Kozur and Mostler, 1972

Remarks—There seems to be little difference between *Veghicyclia* and *Carinacyclia* Kozur and Mostler, 1972, with the exception that the latter possesses a narrower ring with only rudimentary development of meshwork and a rather planiform spongy cortical shell (after Pessagno, 1979).

Range—Upper Triassic (Karnian and Norian).

Occurrence—Baja California, Alaska, and Europe.

Suborder NASSELLARIINA Ehrenberg, 1875

Genus *Bagotum* Pessagno and Whalen, 1982

Type species—*Bagotum maudense* Pessagno and Whalen, 1982

Remarks—*Bagotum* differs from *Stichocapsa* Rüst, 1885, by displaying a thick, double-layered test typically with more irregular pore frames and by possessing a bluntly rounded or dome-shaped proximal part of the test. *Bagotum* also differs from *Droltus* Pessagno and Whalen, 1982, by lacking a horn, by being ellipsoidal (versus conical), and by having a latticed, dome-shaped cap.

Range—Lower Jurassic (Sinemurian to Toarcian).

Occurrence—Oregon, California, Alaska, British Columbia, Middle East, and Japan.

Genus *Canesium* Blome, 1984

Type species—*Canesium lentum* Blome, 1984

Remarks—*Canesium* differs from *Syringocapsa* Neviani, 1900, by lacking a tapering first post-abdominal chamber and by having chambers that increase rapidly both in height and width. *Canesium* also differs from *Sethocapsa* Haeckel, 1881, by having the first three segments covered by an outer layer of microgranular silica and possessing a less globose, open terminal segment.

Range—Upper Triassic (upper Karnian to upper middle Norian).

Occurrence—Oregon, California, Alaska, British Columbia, and Japan.

Genus *Canoptum* Pessagno, 1979

Type species—*Canoptum poissoni* Pessagno, 1979

Remarks—*Canoptum* differs from *Spongocapsulum* Pessagno, 1977b, in having a two-layered test wall lacking spongy meshwork and differs from *Parvicingula* Pessagno, 1977a, in possessing a two-layered test with a microgranular outer layer lacking discrete pore frames. *Canoptum* also differs from *Wrangellium* Pessagno and Whalen, 1982, by lacking large primary pores on its circumferential ridges and by having asymmetrical rows of pore frames in the constrictions between ridges.

Range—Upper Triassic (upper Karnian) to Middle Jurassic (lower Bajocian).

Occurrence—Oregon, California, Baja California, Washington, Alaska, British Columbia, Europe, Middle East, and Japan.

Genus *Canutus* Pessagno and Whalen, 1982

Type species—*Canutus tipperi* Pessagno and Whalen, 1982

Remarks—*Canutus* differs from *Archaeodictyomitra* Pessagno, 1977a, by having a test with several latticed layers or pore frames possessing pillarlike nodes and by lacking costae.

Range—Lower Jurassic (upper Sinemurian to upper Pliensbachian; Toarcian?).

Occurrence—Western North America, Japan, and the Middle East.

Genus *Castrum* Blome, 1984

Type species—*Castrum perornatum* Blome, 1984

Remarks—*Castrum* differs from other Triassic radiolarian genera by having a test with chambers characterized by two different-sized sets of polygonal pore frames separated by nodose circumferential ridges.

Range—Upper Triassic (lower Karnian to middle Norian).

Occurrence—Oregon, California, Alaska, British Columbia, and Europe.

Genus *Corum* Blome, 1984

Type species—*Corum speciosum* Blome, 1984

Remarks—*Corum* differs from *Pseudodictyomitra* Pessagno, 1977b, by having only one row of primary pores situated between chambers, and by lacking rows of large relict pores between costae. *Corum* also differs from *Dictyomitra* Zittel, 1876, s.s. by having discontinuous costae.

Range—Upper Triassic (lower Karnian to upper middle Norian).

Occurrence—Western North America, Middle East, and Japan.

Genus *Droltus* Pessagno and Whalen, 1982

Type species—*Droltus lyellensis* Pessagno and Whalen, 1982

Remarks—*Droltus* differs from *Bagotum* Pessagno and Whalen, 1982, by possessing a horn, by being conical rather than ellipsoidal, and by having an open final postabdominal chamber.

Range—Lower Jurassic (Sinemurian) to Middle Jurassic (upper Bajocian).

Occurrence—Oregon, California, British Columbia, and Alaska.

Genus *Eptingium* Dumitricà, 1977

Type species—*Eptingium manfredi* Dumitricà, 1977

Remarks—*Eptingium* is distinguished from other genera of the family *Eptingiidae* Dumitricà, 1977, by having the whole basal skeleton included within the cephalic cavity and by possessing a prominent aperture.

Range—Middle Triassic (lower Ladinian) to Upper Triassic (lower Karnian).

Occurrence—Oregon, California, Alaska, Europe, and Japan.

Genus *Latium* Blome, 1984

Type species—*Latium longulum* Blome, 1984

Remarks—*Latium* differs from *Corum* Blome, 1984, and other Triassic nassellarians by having one row of rectangular pore frames situated at the base of each circumferential ridge.

Range—Upper Triassic (upper Karnian to upper middle Norian).

Occurrence—Oregon, California, Alaska, and Japan.

Genus *Laxtorum* Blome, 1984

Type species—*Laxtorum hindei* Blome, 1984

Remarks—*Laxtorum* differs from *Canoptum* Pessagno, 1979, by possessing a test in which the pores are not buried by an outer layer of accreted microgranular silica.

Range—Upper Triassic (upper Norian); Lower(?) Jurassic (Hettangian).

Occurrence—California, Alaska, British Columbia, New Zealand, and Japan.

Genus *Lupherium* Pessagno and Whalen, 1982

Type species—*Lupherium snowshoense* Pessagno and Whalen, 1982

Remarks—*Lupherium* differs from *Dictyomitra* Zittel, 1876 (emend. Pessagno, 1976) and other archaeodictyomitrids in forming its test like members of the Hsuidae (inner latticed layer of linearly arranged square pore frames followed by the superposition of costal ridges between each row of pore frames) and by having the costal elements visible externally.

Range—Lower Jurassic (upper Pliensbachian) to Middle Jurassic (Bajocian).

Occurrence—Oregon, California, Baja California, British Columbia, and Alaska.

Genus *Napora* Pessagno, 1977a

Type species—*Napora bukryi* Pessagno, 1977a

Remarks—*Napora* differs from *Jacus* Pessagno, Whalen, and Yeh, 1986, by lacking a thoracic velum and by possessing more regular thoracic pore frames.

Range—Lower Jurassic (upper Sinemurian; lower(?) Pliensbachian) to Upper Cretaceous.

Occurrence—Worldwide, Tethyan and Boreal Realms.

Genus *Pachus* Blome, 1984

Type species—*Pachus firmus* Blome, 1984

Remarks—*Pachus* differs from *Canoptum* Pessagno, 1979, by possessing a horn. It differs from both *Canoptum* Pessagno and *Relanus* Pessagno and Whalen, 1982, by having a test with broad, highly nodose circumferential ridges.

Range—Upper Triassic (upper Karnian to upper middle Norian).

Occurrence—Oregon, California, Alaska, and British Columbia.

Genus *Parvicingula* Pessagno, 1977a, s.l.

Type species—*Parvicingula santabarbarensis* Pessagno, 1977a

Remarks—*Parvicingula* differs from *Ristola* Pessagno and Whalen, 1982, by possessing a horn. *Parvicingula* differs from *Pseudodictyomitra* Pessagno, 1977b, by lacking costae and by possessing circumferential ridges at chamber joints. *Parvicingula* s.l. includes those forms without a tabular projection or terminal tube on the final postabdominal chamber.

Range—Middle Jurassic (Aalenian) to Lower Cretaceous (lower Hauterivian).

Occurrence—Worldwide, Northern Tethyan Province of the Tethyan Realm, Boreal Realm.

Genus *Poulpus* De Wever, 1979 (emend. De Wever, 1981)

Type species—*Poulpus piabyx* De Wever, 1979

Remarks—*Poulpus* differs from *Saitoum* Pessagno, 1977a, in the position of the fifth cephalic spine.

Range—Upper Triassic (lower Karnian) to Lower Jurassic (Pliensbachian).

Occurrence—Oregon, California, Baja California, Alaska, Europe, Middle East, and Japan.

Genus *Quasipetasus* Blome, 1984

Type species—*Quasipetasus insolitus* Blome, 1984

Remarks—*Quasipetasus* differs from other Triassic nassellarian genera by having a hat-shaped test possessing an imperforate skirt.

Range—Upper Triassic (upper Karnian to upper middle Norian).

Occurrence—Oregon, California, Alaska, and Japan.

Genus *Relanus* Pessagno and Whalen, 1982

Type species—*Relanus reefensis* Pessagno and Whalen, 1982

Remarks—*Relanus* differs from *Canoptum* Pessagno, 1979, by possessing a horn and by having a less extensive veneer of microgranular silica.

Range—Lower Jurassic (Hettangian) as far as is known.

Occurrence—Alaska and British Columbia.

Genus *Ristola* Pessagno and Whalen, 1982

Type species—*Ristola procera* (Pessagno), 1977a

Remarks—*Ristola* differs from *Parvicingula* Pessagno, 1977a, by lacking a horn.

Range—Middle Jurassic (upper Bathonian) to Lower Cretaceous (Hauterivian).

Occurrence—Worldwide; Tethyan and Boreal Realms.

Genus *Syringocapsa* (Neviani), 1900

Type species—*Theosyringium robustum* Vinassa de Regny, 1900

Remarks—*Syringocapsa* differs from *Podobursa* Wisniowski, 1889, *Podocapsa* Rüst, 1885, and *Dibolachras* Foreman, 1973, by lacking radially arranged spines situated on the abdomen and first postabdominal chamber.

Range—Upper Triassic (Karnian?; Norian) to Lower Cretaceous (Barremian).

Occurrence—Worldwide, Tethyan and Boreal Realms.

Genus *Triassistephanidium* Dumitricà, 1977

Type species—*Triassistephanidium laticornis* Dumitricà, 1977

Remarks—*Triassistephanidium* is closely related to *Cryptostephanidium* Dumitricà, 1977, and differs only by the insertion of the element "aj" within the shell.

Range—Middle Triassic (Ladinian).

Occurrence—Alaska, Europe.

Genus *Triassocampe* Dumitricà, Kozur, and Mostler, 1980

Type species—*Triassocampe scalaris* Dumitricà, Kozur, and Mostler, 1980

Remarks—*Triassocampe* differs from *Yeharaia* Nakaseko and Nishimura, 1979, by lacking the gourdlike first two segments and by lacking a large well-developed apical horn.

Range—Middle Triassic [Ladinian for North America; Anisian for Japan, (Ishida, 1984)] to Upper Triassic (middle Norian).

Occurrence—Worldwide.

Genus *Xipha* Blome, 1984

Type species—*Xipha pessagnoi* (Nakaseko and Nishimura), 1979

Remarks—*Xipha* differs from *Eucyrtidium* Ehrenberg, 1847, by lacking an apical horn, by consistently having four or more chambers, and by having subcircular pores situated at the strictures separating chambers. *Xipha* also differs from *Dictyomitra* Zittel (1876, emend. Pessagno, 1976; type species = *D. multicostata* Zittel, 1876; see Nakaseko and Nishimura, 1979, p. 77) by being broadly conical in outline (versus spindle-shaped), by lacking large pores with accessory flaps situated between the costae, and by possessing a much smaller number of postabdominal chambers.

Range—Upper Triassic (upper Karnian to upper middle Norian).

Occurrence—Oregon, California, Baja California, British Columbia, Alaska, Middle East, and Japan.

Genus *Yeharaia* Nakaseko and Nishimura, 1979

Type species—*Yeharaia elegans* Nakaseko and Nishimura, 1979

Remarks—*Yeharaia* differs from *Triassocampe* Dumitricà, Kozur, and Mostler, 1980, by possessing the gourdlike first two segments, by possessing a stout apical horn, and by having prominent ridges at the juncture with subsequent segments.

Range—Upper Triassic [lower Karnian for North America; Anisian for Japan (Ishida, 1984) to middle Norian].

Occurrence—Oregon, California, Alaska, and Japan.

REFERENCES CITED

Baumgartner, P.O., 1980, Late Jurassic Hagiastridae and Patulibracchiidae (Radiolaria) from the Argolis Peninsula (Peleponnesus, Greece): Micropaleontology, v. 26, no. 3, p. 274-322, 12 pls.

Blome, C.D., 1983, Upper Triassic Capnuchosphaeridae and Capnodocinae from eastern Oregon: Micropaleontology, v. 29, no. 1, p. 11-49, 11 pls.

——— 1984, Upper Triassic radiolarians and radiolarian zonation for western North America: Bulletins of American Paleontology, v. 85, no. 318, 88 p.

——— 1987, Paleogeographic significance of Lower Mesozoic radiolarians from the Brooks Range, Alaska, *in* Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope Geology, v. 1: Bakersfield, Calif., Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 371-380.

Blome, C.D., Jones, D.L., Murchey, B.L., and Liniecki, Margaret, 1986, Geologic implications of radiolarian-bearing Paleozoic and Mesozoic rocks from the Blue Mountains province, eastern Oregon, *in* Vallier, T.L., and Brooks, H.C., eds., Geology of the Blue Mountains region of Oregon, Idaho, and Washington—Geologic implications of Paleozoic and Mesozoic paleontology and biostratigraphy, Blue Mountains Province, Oregon and Idaho: U.S. Geological Survey Professional Paper 1435, p. 79-93, 3 pls.

Blome, C.D., and Reed, K.M., 1986, Triassic and Early Jurassic radiolarian faunas, Brooks Range, Alaska: U.S. Geological Survey Open-File Report 86-120, 25 p.

Bodnar, D.A., 1984, Stratigraphy, age, depositional environments and hydrocarbon source rock evaluation of the Otuk Formation, north-central Brooks Range, Alaska: Fairbanks, University of Alaska, M.S. thesis, 232 p.

Brosgé, W.P., and Tailleur, I.L., 1970, Depositional history of northern Alaska, *in* Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska: Los Angeles, American Association of Petroleum Geologists, Pacific Section, p. D1-D17.

Campbell, A.S., 1954, Radiolaria, *in* Moore, R.C., (ed.), Treatise on Invertebrate Paleontology, Part D, Protista no. 3: Geological Society of America, p. D1-D163.

Campbell, A.S., and Clark, B.L., 1944, Radiolaria from Upper Cretaceous of middle California: Geological Society of America Special Paper 57, 61 p., 8 pls.

Campbell, R.H., 1967, Areal geology in the vicinity of the Chariot site, Lisburne Peninsula, northwestern Alaska: U.S. Geological Survey Professional Paper 395, 71 p.

Carter, E.S., Cameron, B.E.B., and Smith, P.L., 1988, Lower and Middle Jurassic radiolarian biostratigraphy and systematic paleontology, Queen Charlotte Islands, British Columbia: Geological Survey of Canada Bulletin 386, 72 p., 18 pls.

Curtis, S.M., Ellersieck, Inyo, Mayfield, C.F., and Tailleur, I.L., 1982, Reconnaissance geologic map of southwestern Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Open-File Report 82-611, 43 p., 1 sheet, scale 1:63,360.

——— 1983, Reconnaissance geologic map of the De Long Mountains A1, B1, and part of C1 quadrangles, Alaska: U.S. Geological Survey Open-File Report 83-185, 53 p., 1 sheet at scale 1:63,360, 1 sheet of sections.

——— 1984, Reconnaissance geologic map of the southwestern part of the Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1502, scale 1:63,360.

De Wever, Patrick, 1979, Systematic section, *in* De Wever, Patrick, Sanfilippo, Annika, Riedel, W.R., and Gruber, Bernhard, Triassic radiolarians from Greece, Sicily, and Turkey: Micropaleontology, v. 25, no. 1, p. 75-110.

——— 1981, Une nouvelle sous-famille, les Poulpinae, et quatre nouvelles espèces de *Saitoum*: Radiolaires mésozoiques téthysiens: Geobios, v. 4, no. 1, p. 5-15.

——— 1984, Révision des Radiolaires Mésozoiques de type Saturnalide, proposition d'une nouvelle classification: Revue de Micropaléontologie, v. 27, no. 1, p. 10-19.

Dickinson, W.R., and Thayer, T.P., 1978, Paleogeographic and paleotectonic implications of Mesozoic stratigraphy and structure in the John Day Inlier of central Oregon, *in* Howell, D.G., and McDougall, K.A., eds., Mesozoic paleogeography of the Western United States: Pacific Section, Society of Economic Paleontologists and Mineralogists, Pacific Coast Paleogeography Symposium 2, p. 147-161.

Dickinson, W.R., and Vigrass, L.W., 1965, Geology of the Suplee-Izee area, Crook, Grant, and Harney Counties, Oregon: Oregon Department of Geology and Mineral Industries Bulletin 58, 109 p.

Donofrio, D.A. von, and Mostler, Helfried, 1978, Zur Verbreitung der Saturnalidae (Radiolaria) im Mesozoikum der Nordlichen Kalkalpen und Südalpen: Geologisch-Paläontologische Mitteilungen Innsbruck, v. 7, no. 5, p. 1-55.

Dumitricà, Paulian, 1977, The new Family Eptingiidae, extinct Nassellariina: Paleontologie, v. 3, p. 27-38.

Dumitricà, Paulian, Kozur, Heinz, and Mostler, Helfried, 1980, Contribution to the radiolarian fauna of the Middle Triassic of the southern Alps: Geologisch-Paläontologische Mitteilungen Innsbruck, v. 10, p. 1-46.

Dunikowski, Emil von, 1882, Die Spongien, Radiolarien, und Foraminiferien der unterliassischen Schichten vom Schafberg bei Salzburg: Akademie der Wissenschaften, Wien, Mathematisch-Naturwissenschaftliche Klasse, Denkschriften, v. 45, p. 163-194.

Ehrenberg, C.G., 1847, Über die mikroscopischen kieselschaligen Polysystinen als machtige Gebirgsmasse von Barbados und über das Verhaltnis der aus mehr als 300 neuen Arten bestehenden ganz eigenthümlichen formengruppe jener Felsmasse zu den lebenden Thieren und zur Kriedebildung—Eine neue Anregnung zur Erforschung des Erdlebens: Monatschrift Königliche Akademie Preussischen Wissenschaft Berlin, 1847, p. 40-60.

——— 1875, Fortsetzung der mikrogeologischen Studien als Gesammt-Übersicht der mikroskopischen Palaeontologie gleichartig analysirter Gebirgsarten der Erde, mit spezieller Rücksicht auf den Polycystinen-Meergel von Barbados: Abhandlungen Königliche Preussischen Akademie Wissenschaft Berlin, 1875, 226 p.

Ellersieck, Inyo, Curtis, S.M., Mayfield, C.F., and Tailleur, I.L., 1982, Reconnaissance geologic map of the south-central Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Open-File Report 82-612, 37 p., 2 sheets, scale 1:63,360.

——— 1983, Reconnaissance geologic map of the De Long Mountains A2, B2, and part of C3 quadrangles, Alaska: U.S. Geological Survey Open-File Report 83-184, 52 p., 1 sheet at scale 1:63,360, 1 sheet of sections.

——— 1984, Reconnaissance geologic map of the south-central part of the Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1504, scale 1:63,360.

Foreman, H.P., 1973, Radiolaria from the Deep Sea Drilling Project Leg 20, p. 205-249, *in* Heezen, B.C., and others, eds., Initial Reports of the Deep Sea Drilling Project, v. 20: Washington, U.S. Government Printing Office, 958 p.

——— 1975, Radiolaria from the Deep Sea Drilling Project Leg 32, p. 579-676, *in* Larsen, R.L., and others, eds., Initial Reports of the Deep Sea Drilling Project, v. 32: Washington, U.S. Government Printing Office, 980 p.

——— 1977, Mesozoic Radiolaria in the Atlantic Ocean off the northwest coast of Africa, Deep Sea Drilling Project, leg 41, p. 739-761, *in* Lancelot, Y., ed., Initial Report of the Deep Sea Drilling Project, v. 41: Washington, U.S. Government Printing Office, 1,259 p.

Haeckel, Ernst, 1881, Entwurf eines Radiolarian-Systems auf Grund von Studien der Challenger—Radiolarien: Jenaische Zeitschrift für Naturwissenschaft, v. 18, no. 3 (new series, v. 8), p. 418-472.

——— 1887, Report on the Radiolaria collected on H.M.S. *Challenger* during the years 1873-1876: Reports of the voyage of the *Challenger*: Zoology, v. 18, 1,803 p., 140 pls.

Imlay, R.W., 1967, The Mesozoic pelecypods *Otapiria* Marwick and *Lupherella* Imlay, new genus in the United States: U.S. Geological Survey Professional Paper 573-B, 11 p., 2 pls.

——— 1981, Early Jurassic ammonites from Alaska: U.S. Geological Survey Professional Paper 1148, 49 p., 12 pls.

International Trust for Zoological Nomenclature, 1964, International Code of Zoological Nomenclature: London, 176 p. (reprint of 1961 ed.)

Ishida, Keisuke, 1984, The order of appearance of some radiolarians in Anisian bedded-chert bodies in the south zone of the Chichibu Belt, eastern Shikoku: Journal of Science, College of General

Education, University of Tokushima, v. 17, p. 15-29.

Ishiga, Hiroaki, 1982, Late Carboniferous and Early Permian radiolarians from the Tamba Belt, southwest Japan: Earth Science, Journal of the Association for Geological Collaboration in Japan, v. 36, no. 6, p. 333-339.

Kishida, Yojiro, and Hisada, Ken-ichiro, 1985, Late Triassic and Early Jurassic radiolarian assemblages from the Uenomura area, Kanto Mountains, central Japan: Memoirs of Osaka Kyoiku University, ser. 3, v. 34, no. 2, p. 103-121, 4 pls.

——— 1986, Radiolarian assemblages of the Sambosan Belt in the western part of the Kanto Mountains, central Japan: News of Osaka Micropaleontologists, Special Volume 7, p. 25-34.

Kishida, Yojiro, and Sugano, Kozo, 1982, Radiolarian zonation of Triassic and Jurassic in outer side of southwest Japan, p. 271-300, *in* Proceedings of the First Japanese Radiolarian Symposium: News of Osaka Micropaleontologists, Special Volume 5, 485 p.

Kozur, Heinz, and Mostler, Helfried, 1972, Beitrage zur Erforschung der mesozoischen Radiolarien. Teil I: Revision der Oberfamilie Coccodiscacea Haeckel 1862 emend. und Beschreibung ihrer triassichen Vertreter: Geologisch-Paläontologische Mitteilungen Innsbruck, v. 2, p. 1-60.

——— 1979, Beiträge zur Erforschung der mesozoichen Radiolarien. Teil III: Die Oberfamilien Actinommacea Haeckel 1862 emend., Artiscacea Haeckel 1882, Multiarcusellacea nov. der Spumellaria und triassische Nassellaria: Geologisch-Paläontologische Mitteilungen Innsbruck, v. 9, p. 1-132.

——— 1981, Beiträge zur Erforschung der mesozoischen Radiolarien. Teil IV, Thalassosphaeracea Haeckel 1862, Hexastylacea Haeckel, 1882 emend. Petrusevskaja, 1979, Sponguracea Haeckel, 1862 emend. und weitere triassische Lithocycliacea, Trematodiscacea, Actinommacea, und Nassellaria: Geologisch-Paläontologische Mitteilungen Innsbruck, Sonderband, p. 1-208.

Mayfield, C.F., Curtis, S.M., Ellersieck, Inyo, and Tailleur, I.L., 1982, Reconnaissance geologic map of the southeastern Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Open-File Report 82-613, 39 p., 1 sheet at scale 1:63,360, 1 sheet of sections.

——— 1983a, Reconnaissance geologic map of the De Long Mountains A3, B3, and parts of A4, B4 quadrangles, Alaska: U.S. Geological Survey Open-File Report 83-183, 59 p., 1 sheet at scale 1:63,360, 1 sheet of sections.

——— 1984a, Reconnaissance geologic map of the southeast part of the Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1503, scale 1: 63,360.

Mayfield, C.F., Ellersieck, Inyo, and Tailleur, I.L., 1984b, Reconnaissance geologic map of the Noatak C5, D5, D6, and D7 quadrangles, Alaska: U.S. Geological Survey Open-File Report 84-396, 27 p., 1 sheet, scale 1:63,360.

——— 1987, Reconnaissance geologic map of the Noatak C5, D5, D6, and D7 quadrangles, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1814, 1 sheet, scale 1:63,360.

Mayfield, C.F., Tailleur, I.L., and Ellersieck, Inyo, 1983b, Stratigraphy, structure, and palinspastic synthesis of the western Brooks Range, Alaska: U.S. Geological Survey Open-File Report 83-789, 58 p.

Mull, C.G., Tailleur, I.L., Mayfield, C.F., Ellersieck, Inyo, and Curtis, S.M., 1982, New upper Paleozoic and lower Mesozoic stratigraphic units, central and western Brooks Range: American Association of Petroleum Geologists Bulletin, v. 66, no. 3, p. 348-362.

Mull, C.G., Crowder, Keith, Adams, K.E., Siok, J.P., Bodnar, D.A., Harris, E.E., Alexander, R.A., and Solie, D.N., 1987, Stratigraphy and structural setting of the Picnic Creek allochthon, Killik River quadrangle, central Brooks Range, Alaska: A summary, *in* Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology, v. 2: Bakersfield, Calif., Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 649-662.

Murchey, B.L., Swain, P.B., and Curtis, S.M., 1981, Late Mississippian to Pennsylvanian radiolarian assemblages in the Siksikpuk(?) Formation at Nigu Bluff, Howard Pass quadrangle, Alaska, *in* Albert, N.R., and Hudson, Travis, eds., The United States Geological Survey in Alaska; accomplishments during 1979: U.S. Geological Survey Circular 823-B, p. B17-B19.

Nakaseko, Kojiro, and Nishimura, Akiko, 1979, Upper Triassic Radiolaria from southwest Japan: Science Reports, College of General Education, Osaka University, v. 28, no. 2, p. 61-109.

Neviani, Antonio, 1900, Supplemente alla fauna a Radiolari delle rocce mesozoiche del Bolognese: Bolletino della Società Geologica Italiana, v. 19, p. 645-671.

Patton, W.W., Jr., and Tailleur, I.L., 1964, Geology of the Killik-Itkillik region, Alaska: U.S. Geological Survey Professional Paper 303-G, p. 409-499.

Pessagno, E.A., Jr., 1971, Jurassic and Cretaceous Hagiastridae from the Blake Bahama Basin (Site 5A, JOIDES Leg 1) and the Great Valley sequence, California Coast Ranges: Bulletins of American Paleontology, v. 60, no. 264, p. 1-83, 19 pls.

——— 1973, Upper Cretaceous Spumellariina from the Great Valley sequence, California Coast Ranges: Bulletins of American Paleontology, v. 63, no. 276, p. 49-102, 13 pls.

——— 1976, Radiolarian zonation and stratigraphy of the Upper Cretaceous portion of the Great Valley sequence, California Coast Ranges: Micropaleontology, Special Paper 2, 95 p.

——— 1977a, Upper Jurassic Radiolaria and radiolarian biostratigraphy of the Californian Coast Ranges: Micropaleontology, v. 23, no. 1, p. 56-113.

——— 1977b, Lower Cretaceous radiolarian biostratigraphy of the Great Valley sequence and Franciscan Complex, California Coast Ranges: Cushman Foundation for Foraminiferal Research Special Publication 15, 87 p.

——— 1979, Systematic paleontology, p. 160-197, *in* Pessagno, E.A., Jr., Finch, J.W., and Abbott, P.L., Upper Triassic Radiolaria from the San Hipolito Formation, Baja California: Micropaleontology, v. 25, no. 2, p. 160-197.

Pessagno, E.A., Jr., and Blome, C.D., 1980, Upper Triassic and Jurassic Pantanellinae from California, Oregon, and British Columbia: Micropaleontology, v. 26, no. 3, p. 225-273.

Pessagno, E.A., Jr., Blome, C.D., Carter, E.S., Macleod, Norman, Whalen, P.A., and Yeh, K.-Y., 1987, Studies of North American Jurassic Radiolaria; Part II. Preliminary radiolarian zonation for the Jurassic of North America: Cushman Foundation for Foraminiferal Research, Special Volume 23, 44 p.

Pessagno, E.A., Jr., Blome, C.D., and Longoria, J.F., 1984, A revised radiolarian zonation for the Upper Jurassic of western North America: Bulletins of American Paleontology, v. 87, no. 320, 51 p.

Pessagno, E. A., Jr., and Poisson, A., 1981, Lower Jurassic Radiolaria from the Gümüslü Allochthon of southwestern Turkey (Taurides Occidentales): Mineral Research and Exploration Institute of Turkey Bulletin 92, p. 47-69, 15 pls. [reprint of 1979 issue]

Pessagno, E.A., Jr., and Whalen, P.A., 1982, Lower and Middle Jurassic Radiolaria (multicyrtid Nassellariina) from California, east-central Oregon, and the Queen

Charlotte Islands, British Columbia: Micropaleontology, v. 28, no. 2, p. 111-169, 13 pls.

Pessagno, E.A., Jr., Whalen, P.A., and Yeh, K.-Y., 1986, Jurassic Nassellariina (Radiolaria) from North American geologic terranes: Bulletins of American Paleontology, v. 91, no. 326, 75 p., 11 pls.

Reed, K.M., and Blome, C.D., 1986, Use of radiolarian biostratigraphy in stratigraphic problems in the Otuk Formation, *in* Bartsch-Winkler, Susan, and Reed, K.M., eds., Geologic studies in Alaska by the U.S. Geological Survey during 1985: U.S. Geological Survey Circular 978, p. 16-19.

Riedel, W.R., 1971, Systematic classification of polycystine Radiolaria, *in* Funnell, B.M., and Riedel, W.R., eds., The micropaleontology of the oceans: Cambridge University Press, p. 649-661.

Riedel, W.R., and Sanfilippo, Annika, 1974, Radiolaria from the southern Indian Ocean, *in* Davies, T.A., and others, eds., Initial reports of the Deep Sea Drilling Project, v. 26: Washington, U.S. Government Printing Office, p. 771-813.

Rüst, H., 1885, Beiträge zur Kenntniss der fossilen Radiolarien aus Gesteinen des Jura: Palaeontographica, v. 31, (ser. 3, v. 7), p. 269-322, 20 pls.

Silberling, N.J., 1963, Field guide to halobiid and monotid pelecypods of the Alaskan Triassic: U.S. Geological Survey open-file report, 9 p., 6 pls.

Silberling, N.J., and Tozer, E.T., 1968, Biostratigraphic classification of the marine Triassic in North America: Geological Society of America Special Paper 110, 57 p.

Squinabol, Senofonte, 1903, Le Radiolarie dei noduli seliciose nella Scaglia degli Euganei; Contribuzione 1: Rivista Italiani di Paleontologia, v. 9, no. 4, p. 105-150.

Swain, P.B., 1981, Upper Triassic Radiolarians from the Brooks Range, Alaska: Los Angeles, University of California, M.S. thesis, 174 p.

Tailleur, I.L., Kent, B.H., and Reiser, H.N., 1966, Outcrop/geologic maps of the Nuka-Etivluk region, northern Alaska: U.S. Geological Survey open-file report, 7 sheets, scale 1:63,360.

Tozer, E.T., 1967, A standard for Triassic time: Geological Survey of Canada Bulletin 56, 103 p.

——— 1979, Latest Triassic ammonoid faunas and biochronology, western Canada: Geological Survey of Canada Paper 79-1B, p. 127-135.

Vinassa de Regny, P.E., 1900, Rocce e fossili dei dintorni de Grizzaria e di Lagaro nel Bolognese: Bolletino della Società Geologica Italiana, v. 19, no. 2, p. 321-348.

Wisniowksi, Thaddaus, 1889, Beiträge zur Kenntniss der Mikrofauna aus den oberjurassischen Feuersteinknollen der Umgegend von Krakau: Jahrbuch Kaiserliche-Königliche Geologische Reichsanstalt Wien, v. 38 (1888), no. 3, p. 657-702, 2 pls.

Yao, Akira, 1982, Middle Triassic to Early Jurassic radiolarians from the Inuyama area, central Japan: Journal of Geosciences, Osaka City University, v. 25, p. 53-70.

——— 1984, Subdivision of the Mesozoic complex in Kii-Yura area, southwest Japan and its bearing on the Mesozoic basin development in the southern Chichibu terrane: Journal of Geosciences, Osaka City University, v. 27, p. 41-103.

Yao, Akira, Matsuda, Tetsuo, and Isozaki, Yukio, 1980, Triassic and Jurassic radiolarians from the Inuyama area, central Japan: Journal of Geosciences, Osaka City University, v. 23, p. 135-164.

Yeh, K.-Y., 1987, Taxonomic studies of Lower Jurassic Radiolaria from east-central Oregon: Taiwan Republic of China, National Museum of Natural Science, Special Publication 2, 108 p., 30 pls.

Zittel, V.A., 1876, Über einige fossile Radiolarien aus der norddeutschen Kreide: Zeitschrift des Deutsche Geologische Gesellschaft, v. 28, p. 75-86.

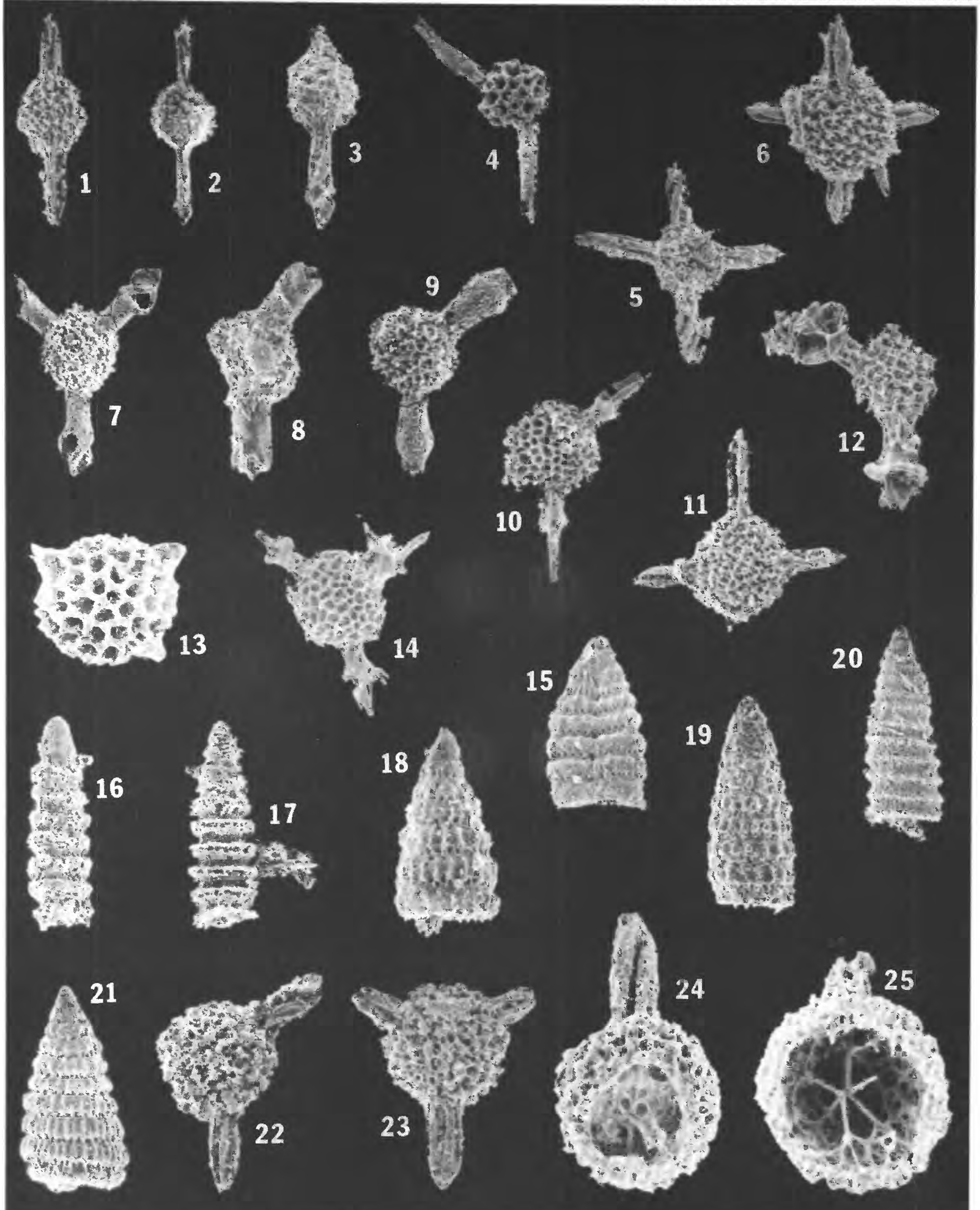
PLATES 33.1, 33.2; TABLES 33.1, 33.2

[Contact photographs of the plates in this report are available, at cost, from the U.S. Geological Survey Photographic Library, Federal Center, Denver, Colorado 80225]

PLATE 33.1

Scanning electron photomicrographs of Middle (Ladinian) to Late Triassic (late middle Norian) radiolarians from the Otuk Formation, northern Alaska. All magnifications are approximate. For data on samples, see table 33.1.

FIGURE 1. *Pseudostylosphaera compacta* (Nakaseko and Nishimura), 1979. 79CM-12, × 62.
2. *Pseudostylosphaera hellenica* (De Wever), 1979. 79CM-13, × 50.
3. *Pseudostylosphaera* cf. *P. hellenica* (De Wever), 1979. 79CM-12, × 112.
4. *Capnodoce primaria* Pessagno, 1979. 79CM-10, × 120.
5. *Emiluvia*(?) *cochleata* (Nakaseko and Nishimura), 1979. 79CM-13, × 85.
6. *Staurodoras*(?) *variabilis* Nakaseko and Nishimura, 1979. 79CM-13, × 112.
7. *Capnuchosphaera triassica* De Wever, 1979. 79CM-11, × 100.
8. *Capnuchosphaera lea* De Wever, 1979. 79CM-11, × 112.
9. *Capnodoce* sp. cf. *C. anapetes* De Wever, 1979. 79CM-11, × 100.
10. *Capnuchosphaera smithorum* Blome, 1983. 79CM-8, × 62.
11. *Staurodoras* sp. aff. *S. variabilis* Nakaseko and Nishimura, 1979. 79CM-13, × 100.
12. Undescribed *Capnuchosphaera* sp. 79CM-8, × 87.
13. *Betraccium*(?) *incohatum* Blome, 1984. 79CM-10, × 187.
14. *Capnuchosphaera mexicana* Pessagno, 1979. 79CM-8, × 62.
15. Undescribed *Corum* sp. 79CM-9, × 175.
16. *Triassocampe scalaris* Dumitricà, Kozur and Mostler, 1980. 79CM-12, × 150.
17. Undescribed *Triassocampe* sp. 79CM-12, × 137.
18. *Latium mundum* Blome, 1984. 79CM-8, × 130.
19. *Corum speciosum* Blome, 1984. 79CM-9, × 125.
20. *Canoptum farawayense* Blome, 1984. 79CM-9, × 112.
21. *Corum perfectum* Blome, 1984. 79CM-9, × 120.
22. Undescribed *Eptingium* sp. 79CM-13, × 137.
23. *Eptingium* sp. cf. *E. manfredi* Dumitricà, 1977. 79CM-13, × 125.
24. Internal view of *Eptingium* sp. 80AMy-19, × 165.
25. Internal view of an entactinid illustrating internal spicule. 80AMy-19, × 180.

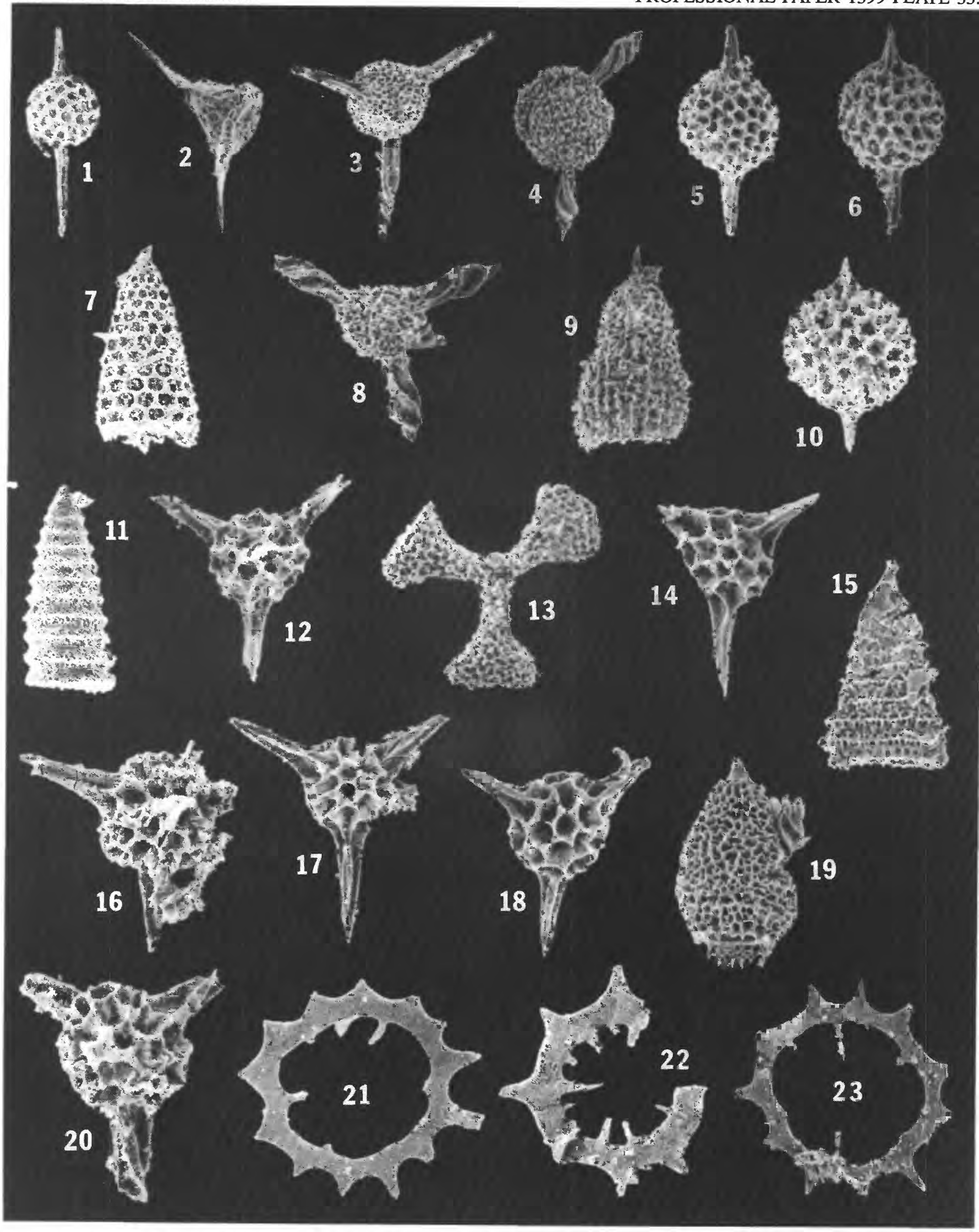


PSEUDOSTYLOSPHAERA, CAPNODOCE, EMILUVIA(?), STAURODORAS(?), CAPNUCHOSPHAERA, STAURODORAS, BETRACCIUM(?), CORUM, TRIASSOCAMPE, LATIUM , CANOPTUM, EPTINGIUM

PLATE 33.2

Scanning electron photomicrographs of Late Triassic (late Norian) to Early Jurassic (Pliensbachian) radiolarians from the Otuk Formation, northern Alaska. All magnifications are approximate. For data on samples, see table 33.1.

FIGURE 1. *Pantanellium talunkwanense* Pessagno and Blome, 1980. 79CM-1, × 100.
2. Undescribed nassellarian. 79CM-5, × 90. Although undescribed, this form is common in the upper Norian of western North America and Japan.
3. ?*Tripocyclia* sp. 79CM-1, × 82.
4. *Ferresium laseekense* Blome, 1984. 79CM-5, × 62.
5, 6. *Pantanellium kluense* Pessagno and Blome, 1980. 79CM-4, × 130 and × 150, respectively.
7. Undescribed nassellarian 79CM-1, × 110.
8. Undescribed *Ferresium* sp. 79CM-6, × 175.
9. *Droltus* sp. aff. *D. hecatensis* Pessagno and Whalen, 1982. 79CM-4, × 162.
10. *Pantanellium tanuense* Pessagno and Blome, 1980. 79CM-1, × 165.
11. *Canoptum dixoni* Pessagno and Whalen, 1982. 79CM-1, × 112.
12. *Cantalum* sp. cf. *C. alium* Blome, 1984. 79CM-6, × 200.
13. ?*Paronaella* sp. 79CM-4, × 120.
14. *Betraccium inornatum* Blome, 1984. 79CM-5, × 200.
15. *Laxtorum hindei* Blome, 1984. 79CM-6, × 125.
16. *Cantalum globosum* Blome, 1984. 79CM-5, × 250.
17, 18. Undescribed *Betraccium* sp. 79CM-5 and 79CM-6, × 180 and × 125, respectively.
19. *Droltus laseekensis* Pessagno and Whalen, 1982. 79CM-2, × 120.
20. *Cantalum* sp. 79CM-6, × 212.
21. *Pseudoheliodiscus sandspitensis* Blome, 1984. 79CM-6, × 137.
22. *Pseudoheliodiscus* sp. aff. *P. yaoi* Pessagno and Poisson, 1979 [1981]. 79CM-3, × 100.
23. Undescribed *Pseudoheliodiscus* sp. 79CM-6, × 112.



PANTANELLIUM, ?TRIPOCYCLIA, FERRESIUM, DROLTUS, CANOPTUM, CANTALUM, ?PARONAELLA, BETRACCIUM, LAXTORUM, PSEUDOHELIODISCUS

TABLE 33.1.—*Radiolarians and megafossils from seven measured sections of the Otuk Formation, northern Alaska*

[Faunas for each section are listed from oldest to youngest regardless of the order of the field numbers. Collectors: AKr, K. Reed; Aky, J. Kelley; AMy, B. Murchey; CM, W. Chamberlain; D, Mull and others; UA, D. Bodnar; Wr, R. Witmer and P. Swain. PPR, radiolarian fauna too poorly preserved for even generic assignment. See figure 33.4 for updated megafossil taxonomy and ranges. Refer to table 3 in Blome and Reed (1986) for the stratigraphic position of taxa in the various members of the Otuk Formation]

Sample	Radiolarian fauna	Megafossils	Age based on radiolarians (* megafossil age only)
Noyalik Peak, lat 68°45'20" N., long 166°11'30" W. (Megafossil data from N.J. Silberling, written commun., 1964, 1968)			
---		*Halobia superba*	*Late Karnian
82AKr-10	*Capnuchosphaera contorta*? Kozur and Mostler, 1979 *Capnuchosphaera* sp. *Pachus* sp. *Sarla plena* Blome, 1983 *Sarla* sp.		Late Karnian to middle Norian
82AKr-14	*Capnuchosphaera* sp.		Late Karnian to early late Norian
---		*Halobia* cf. *H. fallax* *Monotis scutiformis*	*Middle Norian
---		*Monotis* cf. *M. subcircularis* *M.* cf. *M. ochotica*	*Early late Norian
82AKr-18	?*Laxtorum* sp. *Pseudoheliodiscus* sp.		*Late middle to late Norian
---		*Monotis* cf. *M. ochotica*	*Early late Norian
82AKr-22	*Ferresium* sp. *Laxtorum atliense* Blome, 1984 *Laxtorum*(?) *kulense* Blome, 1984 *Livarella densiporata* Kozur and Mostler, 1981 *Pseudoheliodiscus* sp.		Late Norian
(Eleven additional samples yielded nothing useful.)			
Ayugatak Creek, lat 68°46' N., long 165°48' W. (Megafossil data from I.L. Tailleur, written commun. 1982)			
---		*Daonella*	*Early to mid-Ladinian

TABLE 33.1.—*Radiolarians and megafossils from seven measured sections of the Otuk Formation, northern Alaska*—Continued

Sample	Radiolarian fauna	Megafossils	Age based on radiolarians (* megafossil age only)
	Ayugatak Creek (continued)		
82AKr-46	*Pseudostylosphaera japonica* (Nakaseko and Nishimura) 1979		Pre-late Karnian
82AKr-47	PPR		
82AKr-48	PPR		
82AKr-49	?*Eptingium* sp. ?*Pseudostylosphaera* sp. Heavily ribbed primary spines		Karnian
82AKr-52	*Betraccium*(?) *incohatum* Blome, 1984 ?*Capnodoce* sp. *Sarla* sp.		Late Karnian to early Norian
82AKr-53	*Pseudoheliodiscus sandspitensis* Blome, 1984 *Syringocapsa* sp.		Late middle to late Norian
(Two additional Otuk samples and 18 from the Siksikpuk Formation yielded nothing useful.)			
	Punupkahkroak Mountain, lat 68°06' N., long 163°21' W.		
79CM-13	*Emiluvia*(?) *cochleata* (Nakaseko and Nishimura) 1979 *Eptingium manfredi* Dumitricà, 1977 *E.* cf. *E. manfredi* *Eptingium* sp. *Pseudostylosphaera japonica* (Nakaseko and Nishimura) 1979 *Staurodoras*(?) *variabilis* (Nakaseko and Nishimura) 1979 *S.* sp. aff. *S. variabilis* *Triassocampe scalaris* Dumitrricà, Kozur, and Mostler, 1980 *T.* sp. aff. *T. scalaris* *Triassocampe* sp. (undescribed)		Ladinian to early Karnian
79CM-12	*Pachus* sp. *Pseudostylosphaera compacta* (Nakaseko and Nishimura) 1979 *P. helicata* (Nakaseko and Nishimura) 1979 *P. hellenica*? De Wever, 1979		Late Karnian

TABLE 33.1.—*Radiolarians and megafossils from seven measured sections of the Otuk Formation, northern Alaska*—Continued

Sample	Radiolarian fauna	Megafossils	Age based on radiolarians (* megafossil age only)
	Punupkahkroak Mountain (continued)		
	Triassocampe sp. *Yeharaia japonica* Nakaseko and Nishimura, 1979		
79CM-11	*Capnodoce anapetes* De Wever, 1979 *C.* cf. *C. anapetes* *Capnuchosphaera lea* De Wever, 1979 *C. triassica* De Wever, 1979 *Sarla* sp. *Xipha pessagnoi* (Nakaseko and Nishimura) 1979		Late Karnian to early Norian
79CM-10	*Acanthocircus harrisonensis* Blome, 1984 *Acanthocircus* sp. *Betraccium*(?) *incohatum* Blome, 1984 *Canoptum laxum* Blome, 1984 *Capnodoce primaria* Pessagno, 1979 *Capnuchosphaera lenticulata* Pessagno, 1979		Early Norian
79CM-9	*Canoptum*(?) *browni* Blome, 1984 *C. farawayense* Blome, 1984 *Capnodoce anapetes* De Wever, 1979 *C. traversi* Pessagno, 1979 *Capnuchosphaera colemani* Blome, 1983 *C. mexicana* Pessagno, 1979 *C. smithorum* Blome, 1983 *Corum perfectum* Blome, 1984 *C. regium* Blome, 1984 *C. speciosum* Blome 1984 *Corum* sp.		Early Norian to late middle Norian
79CM-8	*Acanthocircus* spp. *Capnuchosphaera lenticulata* Pessagno, 1979 *C. mexicana* Pessagno, 1979 *C. smithorum* Blome, 1984 *C.* sp. aff. *C. lenticulata* Pessagno, 1979 *C. triassica* De Wever, 1979 *Capnuchosphaera* sp. *Latium mundum* Blome, 1984 *Sarla plena* Blome, 1983		Late middle Norian

TABLE 33.1.—*Radiolarians and megafossils from seven measured sections of the Otuk Formation, northern Alaska*—Continued

Sample	Radiolarian fauna	Megafossils	Age based on radiolarians (* megafossil age only)
	Punupkahkroak Mountain (continued)		
79CM-7	Barren	*Monotis* noted at level of 79CM-6 and 79CM-7	*Late Norian
79CM-6	*Betraccium deweveri* Pessagno and Blome, 1980 *B*. sp. aff. *B. deweveri* Pessagno and Blome, 1980 *B. yakounense* Pessagno and Blome, 1980 *Betraccium* sp. *Cantalum* sp. cf. *C. alium* Blome, 1984 *Cantalum* sp. *Ferresium laseekense* Blome, 1984 *Ferresium* sp. *Laxtorum hindei* Blome, 1984 *Pseudoheliodiscus sandspitensis* Blome, 1984 *Pseudoheliodiscus* sp.		Late Norian
79CM-5	*Betraccium deweveri* Pessagno and Blome, 1980 *B. inornatum* Blome, 1984 *B. yakounense* Pessagno and Blome, 1980 *Betraccium* sp. *Cantalum alium* Blome, 1984 *C. globosum* Blome, 1984 *Canoptum* sp. *Ferresium laseekense* Blome, 1984 *Pantanellium fosteri* Pessagno and Blome, 1980		Late Norian
79CM-4	*Canoptum* sp. aff. *C. poissoni* Pessagno, 1979 *Droltus hecatensis* Pessagno and Whalen, 1982 *D*. sp. aff. *D. hecatensis* Pessagno and Whalen, 1982 *Pantanellium kluense* Pessagno and Blome, 1980 *P. tanuense* Pessagno and Blome, 1980 *Paronaella* sp. *Pseudoheliodiscus* sp. (undescribed)		Hettangian (Early Jurassic)
79CM-3	*Canoptum* sp. *Pseudoheliodiscus* sp. (undescribed) *P*. sp. aff. *P. yaoi* Pessagno and Poisson, 1979 [1981] *Veghicyclia* sp.		Late Norian to Early Jurassic

TABLE 33.1.—*Radiolarians and megafossils from seven measured sections of the Otuk Formation, northern Alaska*—Continued

Sample	Radiolarian fauna	Megafossils	Age based on radiolarians (* megafossil age only)
Punupkahkroak Mountain (continued)			
79CM-2	*Canoptum* sp. aff. *C. merum* Pessagno and Whalen, 1982 *Droltus hecatensis* Pessagno and Whalen, 1982 *D. laseekensis* Pessagno and Whalen, 1982 *Pantanellium browni* Pessagno and Blome, 1980 *Relanus reefensis* Pessagno and Whalen, 1982		Hettangian (Early Jurassic)
79CM-1	*Canoptum dixoni* Pessagno and Whalen, 1982 *Pantanellium browni* Pessagno and Blome, 1980 *P. talunkwanense* Pessagno and Blome, 1980 *P. tanuense* Pessagno and Blome, 1980 *Pseudoheliodiscus* sp. aff. *P. yaoi* Pessagno and Poisson, 1979 [1981] *Relanus reefensis* Pessagno and Whalen, 1982 ?*Tripocyclia* sp.		Hettangian to Sinemurian
79CM-0	*Bagotum* sp. aff. *B. maudense* Pessagno and Whalen, 1982 *Bagotum* sp. *Canutus izeensis* Pessagno and Whalen, 1982 *C. rockfishensis* Pessagno and Whalen, 1982 ?*Parvicingula* sp.		Late Pleinsbachian to Toarcian
Otuk Creek, lat 68°32'07" N., long 155°43'23" W. Radiolarian data from P.B. Swain, 1981; megafossil data from Mull and others, 1982)			
79Wr-1.60	*Canesium lentum*? Blome, 1984 *Capnuchosphaera* sp. aff. *C. theloides* De Wever, 1979 *Corum* sp. cf. *C. regium* Blome, 1984 *Paronaella* sp. *Pseudostylosphaera nazarovi* (Kozur and Mostler) 1979 *Triassocampe deweveri* (Nakaseko and Nishimura) 1979 *Xenorum* sp. cf. *X. largum* Blome, 1984		Late Karnian to early Norian

TABLE 33.1.—*Radiolarians and megafossils from seven measured sections of the Otuk Formation, northern Alaska*—Continued

Sample	Radiolarian fauna	Megafossils	Age based on radiolarians (* megafossil age only)
Otuk Creek (data from Swain, continued)			
	?*Xipha* sp. *Yeharaia* sp. cf. *Y. annulata* Nakaseko and Nishimura, 1979		
D11105-D11106		*Halobia superba*	*Late Karnian
79Wr-1.58	*Canesium lentum*? Blome, 1984 *Orbiculiforma* sp. *Paronaella* sp. *Pseudostylosphaera nazarovi* (Kozur and Mostler) 1979 *Pseudostylosphaera* sp. *Triassocampe deweveri* (Nakaseko and Nishimura) 1979 *Yeharaia* sp. cf. *Y. annulata* Nakaseko and Nishimura, 1979		Late Karnian to early Norian
79Wr-1.54	*Capnodoce anapetes* De Wever, 1979 *C. traversi* Pessagno, 1979 *C. vetusta*? Pessagno, 1979 *Pseudostylosphaera nazarovi* (Kozur an Mostler) 1979 *Syringocapsa* sp. *Triassocampe deweveri* (Nakaseko and Nishimura) 1979 ?*Xipha* sp. *Yeharaia* sp. cf. *Y. annulata* Nakaseko and Nishimura, 1979		Late Karnian to late middle Norian
D11103-D11093		*Halobia* cf. *H. cordillerana* *H.* cf. *H. dilitata* ?*Halobia* cf. *H. halorica* *Halobia* cf. *H. lineata*	*Early to middle Norian *Early to middle Norian *Middle Norian
79Wr-1.40	*Canesium lentum* Blome, 1984 *Capnodoce anapetes* De Wever, 1979 *C. traversi* Pessagno, 1979 *C. vetusta* Pessagno, 1979 *Corum* sp. cf. *C. regium* Blome, 1984 ?*Corum* sp.		Late Karnian late middle Norian

TABLE 33.1.—*Radiolarians and megafossils from seven measured sections of the Otuk Formation, northern Alaska*—Continued

Sample	Radiolarian fauna	Megafossils	Age based on radiolarians (* megafossil age only)
Otuk Creek (data from Swain, continued)			
	Latium sp. cf. *L. paucum* Blome, 1984 *Triassocampe deweveri* (Nakaseko and Nishimura) 1979 *Yeharaia* sp. cf. *Y. annulata* Nakaseko and Nishimura, 1979		
79WR-1.39	*Acanthocircus elegans* (Kozur and Mostler) 1972 *Canesium lentum*? Blome, 1984 *Capnodoce traversi* Pessagno, 1979 *Capnuchosphaera* sp. *Corum perfectum*? Blome, 1984 *Corum* sp. cf. *C. regium* Blome, 1984		Early to middle Norian
79Wr-1.14	*Acanthocircus elegans* (Kozur and Mostler) 1972 *Canesium lentum* Blome, 1984 *Capnodoce traversi* Pessagno, 1979 *Capnuchosphaera* sp. cf. *C. schenki* Blome, 1983 *C.* sp aff. *C. triassica* De Wever, 1979 *Corum perfectum*? Blome, 1984 *Corum* sp. cf. *C. regium* Blome, 1984 ?*Corum* sp. *Latium* sp. cf. *L. paucum* Blome, 1984 *Syringocapsa* sp. *Triassocampe deweveri* (Nakaseko and Nishimura) 1979		Early to middle Norian
79Wr-1.13	*Acanthocircus elegans* (Kozur and Mostler) 1972 *Capnuchosphaera* sp. cf. *C. schenki* Blome, 1983 *C.* sp. cf. *C. silviesensis* Blome, 1983 *C. triassica* De Wever, 1979 *C.* sp. cf. *triassica* De Wever, 1979 *C. tricornis* De Wever, 1979 *Corum perfectum* Blome, 1984 *C.* sp. cf. *C. regium* Blome, 1984		Early to middle Norian

TABLE 33.1.—*Radiolarians and megafossils from seven measured sections of the Otuk Formation, northern Alaska*—Continued

Sample	Radiolarian fauna	Megafossils	Age based on radiolarians (* megafossil age only)
	Otuk Creek (data from Swain, continued)		
	?*Corum* sp. *Latium* sp. cf. *L. paucum* Blome, 1984 *Paronaella* sp.		
79Wr-1.12	*Acanthocircus* sp. *Capnodoce* sp. *Capnuchosphaera lenticulata* Pessagno, 1979 *C. mexicana* Pessagno, 1979 *C.* sp. aff. *C. mexicana* Pessagno, 1979 *C.* sp. cf. *C. schenki* Blome, 1983 *C.* sp. cf. *C. silviesensis* Blome, 1983 *C.* sp. cf. *C. sockensis* Blome, 1983 *Corum perfectum* Blome,1984 *C.* sp. cf. *C. regium* Blome, 1984 ?*Corum* sp. *Latium* sp. cf. *L. paucum* Blome, 1984 *Pantanellium tozeri* Pessagno, 1979 *Plafkerium hindei* Pessagno, 1979 *Sarla natividensis* Pessagno, 1979 *Sarla* sp. *Syringocapsa* sp.		Late middle Norian
79Wr-1.11	*Acanthocircus* sp. *Capnuchosphaera lenticulata* Pessagno, 1979 *C. mexicana* Pessagno, 1979 *C.* sp. aff. *C. mexicana* Pessagno, 1979 *C.* sp. cf. *C. schenki* Blome, 1983 *C.* sp. cf. *C.* sockensis Blome, 1983 *Pantanellium tozeri* Pessagno, 1979 *Plafkerium hindei* Pessagno, 1979 *Sarla nativididadensis* Pessagno, 1979 *Sarla* sp. *Syringocapsa* sp.		Late middle to early late Norian
79Wr-1.10	*Capnodoce traversi,* Pessagno, 1979 *C. vetusta* Pessagno, 1979		Late middle to early late Norian

TABLE 33.1.—*Radiolarians and megafossils from seven measured sections of the Otuk Formation, northern Alaska*—Continued

Sample	Radiolarian fauna	Megafossils	Age based on radiolarians (* megafossil age only)
Otuk Creek (data from Swain, continued)			
	Capnuchosphaera lenticulata Pessagno, 1979 *C.* sp. aff. *C. mexicana* Pessagno, 1979 *C.* sp. cf. *C. silviesensis* Blome, 1983 *C.* sp. cf. *C. sockensis* Blome, 1983 *Capnuchosphaera* sp. *Corum* sp. ?*Pachus* sp. *Pantanellium tozeri* Pessagno, 1979 *Plafkerium hindei* Pessagno, 1979 *Sarla natividadensis* Pessagno, 1979 *Sarla* sp.		
D11071-D11091		*Halobia* cf. *H. plicosa* *H.* cf. *H. fallax* Mojsisovics *Monotis* (*Eomonotis*) sp. indet. *H. fallax* Mojsisovics *M.* (*E.*) *pinensis* *H. fallax* Mojsisovics *H.* cf. *H. fallax* Mojsisovics	*Middle Norian and younger
		Otapiria sp. (in Blankenship Member)	*Jurassic
(Twenty-five additional Swain samples apparently yielded nothing useful)			
Otuk Creek, lat 68°32'07" N., long 155°43'23" W. (All data from D.A. Bodnar, 1983-84)			
UA2089	?*Pachus* *Psuedostylosphaera helicata*? (Nakaseko and Nishimura) 1979 *Triassocampe* sp.		Early? Karnian
UA2091		*Halobia superba*	*Late Karnian
UA2092		*H. cordillerana*	*Late Karnian to early Norian

TABLE 33.1.—*Radiolarians and megafossils from seven measured sections of the Otuk Formation, northern Alaska*—Continued

Sample	Radiolarian fauna	Megafossils	Age based on radiolarians (* megafossil age only)
	Otuk Creek (data from Bodnar, continued)		
UA2093	*Corum* sp.		Late Karnian to middle Norian
UA2094	*Acanthocircus* sp. *Capnodoce* sp. *Capnuchosphaera* sp. cf. *C. triassica* *Corum perfectum* Blome, 1984 *Pseudoheliodiscus* sp. *Sarla* sp. cf. *S. vetusta* *Syringocapsa* sp. *Veghicyclia austriacae* Kozur and Mostler, 1972 *Xipha* sp.		Late middle Norian
UA2095	*Capnodoce* sp. *Corum perfectum* Blome, 1984		Late middle Norian [*Neogondolella momberg-ensis* and *N. navicula navicula* (conodonts)]
UA2096	*Psuedoheliodiscus sandspitensis* Blome, 1984		Late Norian
		Otapiria sp. in Blankenship Member	*Jurassic
	Akmalik Creek, lat 68°24' N., long 154°17' W. (Numbers in parentheses give stratigraphic height, in meters, above the youngest beds in this upside-down section; megafossil data from J.S. Kelley, written commun., 1983)		
83AKy-2S (48.2)	*Tripocyclia*(?) *japonica* Nakaseko and Nishimura, 1979 *Triassocampe*(?) *scalaris* Dumitricà, Kozur, and Mostler, 1980 *Triassocampe* sp.		Ladinian (early? Karnian)
83Aky-2S (39.4)	*Emiluvia*(?) *cochleata* Nakaseko and Nishimura, 1979 *Pseudostylosphaera compacta* (Nakaseko and Nishimura) 1979 *Triassocampe* sp.		Karnian
83Aky-2S (37.4)	*Pseudostylosphaera hellenica* (De Wever) 1979 *P. helicata* Nakaseko and Nishimura, 1979 *P. nazarovi* Kozur and Mostler, 1979		Karnian

TABLE 33.1.—*Radiolarians and megafossils from seven measured sections of the Otuk Formation, northern Alaska*—Continued

Sample	Radiolarian fauna	Megafossils	Age based on radiolarians (* megafossil age only)
Akmalik Creek (continued)			
83Aky-2S (32.0)	*Xenorum largum*? Blome, 1984		Late Karnian to early middle Norian
83Aky-2S (22.7)	*Capnodoce* sp. *Triassocampe immaturum* Blome, 1984		Late Karnian to early middle Norian
83Aky-2S (19.6)	*Capnodoce anapetes* De Wever, 1979 *Capnuchosphaera colemani*? Blome, 1984 *Renzium webergorum* Blome, 1983		Late Karnian to early middle Norian
83Aky-2S (14.9)	*Capnuchosphaera* sp. *Corum* sp. *Xipha striata*? Blome, 1984		Late Karnian early late Norian
83Aky-2S (12.5)	*Capnuchosphaera smithorum*? Blome, 1983 *Capnuchosphaera* sp.		Late Karnian to early middle Norian
83Aky-2S (11.3)	PPR		
83Aky-2S (8.1)	PPR	probable *Monotis*	*Late middle to late Norian
83Aky-2S (7.7)	PPR		
83Aky-2S (6.5)	?*Pseudoheliodiscus* sp.	probable *Monotis*	Late Triassic *Late middle to late Norian
83Aky-2S (3.5)	*Livarella densiporata* Kozur and Mostler, 1981 *Pseudoheolidiscus* sp.		Late Norian to Hettangian (Early Jurassic)
83Aky-2S (0.2)	*Canoptum dixoni* Pessagno and Whalen, 1982 *Canutus rockfishensis* Pessagno and Whalen, 1982 *Droltus laseekensis* Pessagno and Whalen, 1982 *Livarella densiporata* Kozur and Mostler, 1981		Hettangian to Sinemurian
Monotis Creek, lat 68°22.5' N., long 152°56' W. (Megafossil data from Patton and Tailleur, 1964)			
80AMy 03 8	PPR		
80AMy 03 12	?*Eptingium* sp. *Triassocampe deweveri* (Nakaseko and Nishimura) 1979 *Tripocyclia*(?) *japonica* Nakaseko and Nishimura 1979		Ladinian to early Karnian

TABLE 33.1.—*Radiolarians and megafossils from seven measured sections of the Otuk Formation, northern Alaska*—Continued

Sample	Radiolarian fauna	Megafossils	Age based on radiolarians (* megafossil age only)
		Monotis Creek (continued)	
---		*Daonella frami,* cf. *D. degeeri*	*Early to middle Ladinian
80AMy 03 15	*Pseudostylosphaera japonica* (Nakaseko and Nishimura) 1979 *Pseudostylosphaera* sp. *Staurocontium minoense* Nakaseko and Nishimura, 1979 *Yeharaia japonica*? Nakaseko and Nishimura, 1979		Karnian
80AMy 03 19	Broken entactinids and *Eptingium*-related forms (mounted SEM s-72)		Triassic
80AMy 03 22	Numerous twisted spines *Eptingium manfredi* Dumitricà, 1977 *Pseudostylosphaera tenue* (Nakaseko and Nishimura) 1979 ?*Triassocampe* sp.		Middle Ladinian to early Karnian
80AMy 03 27	twisted spine ?*Triassocampe* sp.		Karnian
---		*Halobia*	*Karnian to middle Norian
80AMy 03 D	*Capnuchosphaera tricornis* De Wever, 1979		Late Karnian to middle Norian
---		*Halobia*	*Karnian to middle Norian
80AMy 03 C	*Capnodoce miniscula* Blome, 1983		Late Karnian to middle Norian
80AMy 03 B	*Capnodoce crystallina* Pessagno, 1979 *C. vetusta*? Pessagno, 1979 *Capnuchosphaera triassica* De Wever, 1979 *C. colemani*? Blome, 1983 *Pseudoheliodiscus sandspitensis* Blome, 1984 *Pseudoheliodiscus* sp.		Late middle to early late Norian (probably the younger part of this range)
---		*Monotis subcircularis, Monotis*	*Early late Norian

(Four additional samples yielded nothing useful)

TABLE 33.1.—*Radiolarians and megafossils from seven measured sections of the Otuk Formation, northern Alaska*—Continued

Sample	Radiolarian fauna	Megafossils	Age based on radiolarians (* megafossil age only)
	Tiglukpuk Creek, lat 68°21'12" N., long 151°52'24" W. (All data from B.L. Murchey, written commun., 1980)		
80AMy 05 40	PPR		
80AMy 05 35	?*Gorgansium* sp. *Pseudostylosphaera japonica*? (Nakaseko and Nishimura) 1979 *Triassocampe* sp.		Ladinian to middle Karnian
80AMy 05 30	PPR		
80AMy 05 20	*Emiluvia*(?) *cochleata* Nakaseko and Nishimura, 1979 *Triassocampe deweveri* (Nakaseko and Nishimura) 1979		Ladinian?, Karnian?
80AMy 05 B	Twisted spine ?*Canoptum* sp.	*Halobia*	Karnian or Norian
80AMy 05 A	*Canesium lentum* Blome, 1984 *Capnuchosphaera deweveri* Kozur and Mostler, 1979 *C. mexicana* Pessagno, 1979 *C. lenticulata* Pessagno, 1979 *C. schenki* Blome, 1984 *Corum perfectum* Blome, 1984 *Syringocapsa turgida* Blome, 1984		Late middle Norian
---		*Monotis subcircularis* about 15 m above a normal fault	*Early late Norian
(Two additional Murchey samples yielded nothing useful)			
	Tiglukpuk Creek, lat 68°21'12" N., long 151°52'24" W. (All data from D.A. Bodnar, 1984)		
UA2146	?*Tripocyclia*		Ladinian to Karnian
UA2147	*Pseudostylosphaera japonica*? (Nakaseko and Nishimura) 1979 *Triassocampe deweveri* (Nakaseko and Nishimura) 1979		Ladinian to Karnian
UA2149	*Poulpus* sp. cf. *P. piabyx* De Wever, 1979		Ladinian to Karnian
UA2150		*Daonella frami*	*Early to middle Ladinian

TABLE 33.1.—*Radiolarians and megafossils from seven measured sections of the Otuk Formation, northern Alaska*—Continued

Sample	Radiolarian fauna	Megafossils	Age based on radiolarians (* megafossil age only)
	Tiglukpuk Creek (data from Bodnar, continued)		
UA2151	*Pseudoheliodiscus* sp.		Early middle to late Norian
UA2152		*Halobia cordillerana*	*Early Norian
UA2153	*Capnodoce* sp. *Pseudoheliodiscus* sp. *Sarla*(?) sp. cf. *S. externa* Blome, 1984 ?*Xenorum* sp.		Late middle Norian
UA2155	*Capnodoce* sp. *Syringocapsa* sp.		Late Karnian to middle Norian
UA2156	*Capnodoce* sp. *Capnuchosphaera* sp. *Corum perfectum* Blome, 1984 *Pseudoheliodiscus* sp. *Veghicyclia austriacae* Kozur and Mostler, 1972		Late middle Norian
UA2157	*Capnodoce* sp. *Capnuchosphaera* sp. *Corum* sp. *Paronaella* sp. *Quasipetasus* sp.		Late Karnian to late middle Norian
UA2158		*Monotis subcircularis*	*Early late Norian

TABLE 33.2.—*Miscellaneous Mesozoic radiolarian samples from localities in and near the National Petroleum Reserve in Alaska*

[Collectors: ABe = W. Brosgé(?); ACn = M. Churkin, Jr.; Cx = S. Curtis; Ek, EK = I. Ellersieck; AHe = K. Huie; Md = C. Mayfield; AMy = B. Murchey; ANK = W. Nokleberg; AKr = K. Reed; Tr = I. Tailleur; Avy = D. Vickery; W = WGM, Inc. (RD = Red Dog); Wr = R. Witmer, also P. Swain, 1981. In "Unit" column, I–[number] or OFR–[number] identifies published or open-filed map (OFR 83-185, Curtis and others, 1983; I-1502, Curtis and others, 1984; OFR 83-185, Ellersieck and others, 1983, I-1504, Ellersieck and others, 1984; OFR 83-184, Ellersieck and others, 1983; OFR 83-183, Mayfield and others, 1983a; I-1503, Mayfield and others, 1984a) on which sample is located with respect to surrounding rocks; the allochthon name identifies the tectonostratigraphic unit (Mayfield and others, 1983) to which the sample has been assigned. Boxed faunas indicate those taxa are present in some or all of the samples. Dashed leaders (---) indicate insufficient information to identify unit.]

Sample	Latitude (°N)	Longitude (°W)	Radiolarians	Unit
			Latest Spathian to Anisian (Early to Middle Triassic)	
78ACn-921	68°20'00"	151°50'00"	Both the spumellarians and Triassic nassellarians are nondistinct and exhibit very few features. The radiolarians have been independently dated using conodonts. Many of the spumellarians have 2 to 5 or more simple rodlike primary spines and nodose cortical shells. Sample also contains conodonts: *Neogondolella* sp. cf. *N. regale* Mosher (B. Wardlaw, written commun., 1980).	Etivluk Group, Brooks Range allochthon (Tiglukpuk Creek)\
			Ladinian (Middle Triassic)	
78ACn-431	68°12'16"	161°55'40"	Nearly all forms in these samples are undescribed. Gen. et sp. nov. and (or): *Eptingium manfredi* Dumitricà; *Triassocampe* sp.; *Oertlispongus* sp.; *Poulpus curvispinus* Dumitricà, Kozur, and Mostler; *Triassistephandium laticornis* Dumitricà	---
78ACn-453	68°28'39"	161°44'40"		---
78Cx-37D	68°27'45"	160°22'42"		---
78Cx-185B	68°28'12"	160°05'24"		---
78EK-119B	68°22'00"	162°57'40"		Etivluk Group, Picnic Creek allochthon (OFR 83-184)
78Md-33B	68°14'53"	159°06'		Siksikpuk Fm., Brooks Range allochthon
78Md-61B	68°17'36"	159°36"		Otuk Fm., Etivluk Group
78Md-147C	68°22'42"	161°53'00"		Siksikpuk Fm., Brooks Range allochthon (I-1502)
78Tr-90B	68°26'42"	160°34'36"		Etivluk Group, Ipnavik River allochthon (I-1503)
78Tr-235D	68°36'18"	156°34'12"		Chert or shale member, Otuk Fm., Brooks Range allochthon (Blankenship Creek)
78W-6	68°10'19"	163°11'30"		Chert or shale member, Otuk Fm., Brooks Range allochthon (Lik prospect)
			Late Ladinian	
82AKr-75	68°50'	166°06'	*Eptingium manfredi* Dumitricà; *Poulpus* sp.; *Staurocontium granulosum* Dumitricà, Kozur, and Mostler, 1980	Otuk section, Eeneegiksook Creek, about 56 ft from top (Lisburne Peninsula)
82AKr-70	68°08'	166°56'	Undescribed spongy form	Otuk Fm., Agate Rock, in "3" of Campbell (1967, p. 50)
			Late Ladinian or early Karnian	
79Ek-262e	68°15'48"	163°16'00"	*Eptingium* sp.; *Pseudostylosphaera* sp.	Otuk Fm., Picnic Creek allochthon (OFR 83-184)
			Late Ladinian to Karnian	
78Ek-54	68°29'12"	159°03'20"	?*Pseudostylosphaera* sp.; ?*Triassocampe* sp.	Etivluk Group, Ipnavik River allochthon (I-1504)
78Md-30d	68°31'54"	159°17'06"	?*Pseudostylosphaera* sp.; *Triassocampe* sp.	Etivluk Group (I-1504)
			Ladinian to Karnian	
82Tr-04A	68°37'06"	159°12'50"	*Eptingium* sp.; ?*Pseudostylosphaera* sp.	Etivluk Group, Nuka Ridge allochthon (I-1504)
			Karnian	
78Md-178B	68°14'28"	161°19'54"	*Pseudostylosphaera* sp.; *Gorgansium* sp.; ?*Staurodoras* sp.	Etivluk Group, Brooks Range allochthon (I-1502)
79Md-61E	68°18'06"	162°37'00"	*Gorgansium* sp.; *Pseudostylosphaera tenue* (Nakaseko and Nishimura); *Triassocampe* sp.	Etivluk Group (OFR 83-184)

TABLE 33.2.—*Miscellaneous Mesozoic radiolarian samples from localities in and near the National Petroleum Reserve in Alaska*—Continued

Sample	Latitude (°N)	Longitude (°W)	Radiolarians	Unit
			Karnian—*Continued*	
79Ek-194d	68°25"22"	163°31'00"	*Eptingium* sp.; *Pseudostylosphaera hellenica* De Wever; *Staurodoras variabilis* Nakaseko and Nishimura; *Triassocampe* sp.	Otuk Formation, Brooks Range allochthon (OFR 83-183)
			Middle to late Karnian	
82AKr-72	68°08'	165°56'	*Gorgansium* sp.; *Pseudostylosphaera japonica* (Nakaseko and Nishimura)	Eeneegiksook Creek section, about 100 ft from top (Lisburne Peninsula)
			?Karnian	
78Ek-193C	68°24'22"	163°03'48"	*Pseudostylosphaera compacta* (Nakaseko and Nishimura)	Otuk Fm., Brooks Range allochthon (OFR 83-184)
79Md-156C	68°21'28"	163°44'50"	?*Corum* sp.; ?*Pseudostylosphaera* sp.	Etivluk Group, Brooks Range allochthon
			Karnian to early(?) Norian	
78ACn-852	68°20'55"	151°53'	*Castrum perornatum* Blome; *Gorgansium* sp.; *Sarla* sp.	Etivluk Group, Brooks Range allochthon (Tiglukpuk Creek)
78Md-164	68°16'50"	161°16'30"		Etivluk Group, Brooks Range allochthon
78Tr-82B	68°29'35"	160°07'45"		---
			Late Karnian to middle Norian	
79ABe-273	68°32'50"	143°25'30"	*Acanthocircus* sp. aff. *A. usitatus* Blome; *Capnuchosphaera* sp.; *C. deweveri* Kozur and Mostler	Etivluk Group (Table Mountains quadrangle)
79Cx-203C	68°30'30"	162°12'36"	*Acanthocircus* sp.; *Capnuchosphaera* sp.; *Pachus firmus* Blome	Etivluk Group, Brooks Range allochthon
78Md-68C	68°29"10"	159°46'24"	*Capnuchosphaera* sp.	Etivluk Group, Picnic Creek allochthon (I-1504)
79Tr-163D	68°30'52"	156°16'06"	*Canoptum* sp. aff. *C. laxum* Blome; *Capnodoce* sp.; *Capnuchosphaera* sp.; *Castrum perornatum* Blome	Etivluk Group, indeterminate higher allochthon (Nigu Bluff area)
79Md-100B	68°21'30"	163°01'30"	*Canesium lentum* Blome; *Capnodoce anapetes* De Wever; *Capnochosphaera* sp.	Etivluk Group, Brooks Range(?) allochthon (OFR 83-184)
79Md-187B	68°32'08"	156°14'25"	*Capnuchosphaera deweveri* Kozur and Mostler; *Capnuchosphaera* sp.; ?*Pseudostylosphaera* sp.	Etivluk Group, undetermined allochthon (Ivotuk Ridge area)
79Md-11F	68°03'24"	162°47'25"	*Capnuchosphaera* sp.	Etivluk Group, Brooks Range allochthon (OFR 83-184)
79Md-204D	68°25'00"	155°34'00"	*Capnodoce* sp.; *Capnuchosphaera deweveri* Kozur and Mostler; *C. schenki* Blome; *Corum perfectum* Blome; *Latium longulum* Blome; *Sarla prietoensis* Pessagno	Etivluk Group, Nuka Ridge(?) allochthon (Ivotuk Ridge area)
			Late(?) Karnian to middle Norian	
78ACn-851	68°20'00"	151°50'30"	*Acanthocircus* sp.; *Canoptum* sp; *Capnodoce* sp. aff. *C. baldiensis* Blome; *Capnodoce* sp.; *Capnuchosphaera colemani* Blome; *C. contorta* Blome; *C.* sp. aff. *C. schenki* Blome; *C. triassica* De Wever; *Capnochosphaera* sp.; *Corum perfectum* Blome; *C.* sp. aff. *C. perfectum* Blome; *Corum* sp.; *Pseudohagiastrum* sp.; *Sarla* sp.; *Syrigocapsa turgida* Blome; *Xipha turgida* Blome	Etivluk Group, Brooks Range allochthon (Tiglukpuk Creek)
78EK-50A_2	68°34'10"	159°59'30"		---
78EK-92	68°21'03"	160°11'54"		---
78EK-119E	68°22'05"	162°59'10"		Etivluk Group, Brooks Range allochthon (OFR 83-184)
78EK-133D	68°24'42"	161°28'18"		---
78ANK-095A	No data			---
78Tr-232A	68°36'30"	157°20'00"		Etivluk Group, Ipnavik River allochthon (Howard Pass quadrangle)
79Avy-190	No data			---
78Wr-1.20	68°28'53"	155°42'47"		Chert or shale member, Otuk Fm., Brooks Range allochthon (Ivotuk Ridge area)

TABLE 33.2.—*Miscellaneous Mesozoic radiolarian samples from localities in and near the National Petroleum Reserve in Alaska*—Continued

Sample	Latitude (°N)	Longitude (°W)	Radiolarians	Unit
			Late(?) Karnian to middle Norian—*Continued*	
Lisburne test well (cuttings from depth intervals, in feet): 7,425-7,440 11,095-11,100 11,100-11,105 11,105-11,100	68°29'05.44"	155°41'33.51"	*Canesium lentum* Blome; *Capnuchosphaera* sp.; *Capnodoce* sp. aff. *C. anapetes* De Wever; *Capnuchosphaera* sp.; ?*Capnotum* sp.; *Capnuchosphaera mexicana* Pessagno; *Sarla* sp.; ?*Triassocampe* sp.; *Xipha* sp.	Etivluk Group, Brooks Range allochthon (Ivotuk Ridge area); 41 samples from other intervals were barren
79Ek-291C	68°24'50"	156°52'10"	*Capnuchosphaera* sp.; *Latium longulum* Blome	Etivluk Group
			Late Karnian to late middle Norian	
79Cx-11B	68°05'42"	162°54'12"	*Acanthocircus* sp.; *Capnodoce* sp.; *Capnuchosphaera* sp.; ?*Corum* sp.; ?*Populus; Sarla*(?) *externa* Blome	Etivluk Group, Brooks Range allochthon (OFR 83-184)
79Md-106D	68°25'15"	163°21'33"	*Catoma* sp.; *Icrioma* sp. cf. *I. geometrica* Blome; *I.* cf. *I. praecipua* Blome; *Pseudoheliodiscus* sp.	---
79Md-200E	68°31'24"	155°38'30"	*Canesium* sp. cf. *C. lentum* Blome; *Canoptum* sp.; *Capnodoce* sp.; *Capnuchosphaera lenticulata* Blome; *Corum perfectum* Blome	Etivluk Group, undetermined allochthon (Ivotuk Ridge area)
			Late Karnian to early late Norian	
77EK-39	68°19'22"	160°46'12"	Poor preservation precludes exact identification	Copter Peak allochthon (I-1503)
78EK-136A$_3$	68°18'36"	160°49'24"		---
78Md-90A	68°29'00"	160°05'00"		Otuk Fm., Ipnavik River allochthon (I-1503)
78Md-191B	68°18'18"	161°18'00"		Etivluk Group, Brooks Range allochthon
78W-28	68°06'46"	163°34'42"		Etivluk Group, Brooks Range allochthon (Red Dog district)
RD-227	68°03'47"	162°50'07"		Etivluk Group, Brooks Range allochthon (Red Dog)
			Middle Norian	
78ACn-911	68°50'15"	151°12'08"	*Capnuchosphaera contorta* Blome; *C. lenticulata* Pessagno; *C. mexicana* Pessagno; *C. sockensis* Blome; *C. triassica* De Wever; *Capnuchosphaera* sp.; *Corum perfectum* Blome; *C. speciosum* Blome; *Latium* sp.; *Syringocapsa* sp. aff. *S. turgida* Blome	Otuk Fm., Brooks Range allochthon (Tiglukpuk Creek)
78Md-160D	68°26'15"	160°57'20"		Etivluk Group, Nuka Ridge allochthon
78ABe-157	68°22'17"	153°26'51"		Etivluk Group
			Late Norian	
79Md-93	68°14'45"	162°58'00"	*Betraccium* sp. aff. *B. deweveri* Pessagno and Blome; *Pseudoheliodiscus* cf. *P. sandspitensis* Blome	---
79Md-109B	68°23'54"	163°35'00"	*Betraccium* sp.; *Ferresium* sp.; *Pseudoheliodiscus* sp.; *Sarla* sp.	---
			Karnian or Norian (poor preservation precludes more precise age determination)	
78ACn-722	68°27'06"	161°47'20"	?*Capnodoce* sp.; ?*Capnuchosphaera* sp.; *Eptingium* sp.; ?*Plafkerium* sp.; *Triassocampe* sp.	---
78ACn-723	68°27'04"	161°47'12"		---
78Cx-89B	68°16'27"	160°08'30"		---
78EK-113d	68°20'18"	161°46'30"		---
78Md-73B	68°29'25"	159°16'07"		Etivluk Group, Ipnavik River allochthon (I-1504)
78Tr-35A	68°34'30"	159°37'24"		Etivluk Group

TABLE 33.2.—*Miscellaneous Mesozoic radiolarian samples from localities in and near the National Petroleum Reserve in Alaska*—Continued

Sample	Latitude (°N)	Longitude (°W)	Radiolarians	Unit
			Late Triassic	
79Md-65C	68°13'45"	162°49'55"	?*Capnuchosphaera* sp.; ?*Canoptum* sp.	Etivluk Group, Brooks Range allochthon
79Cx-73G.1	68°23'33"	162°28'06"	*Capnodoce* sp. aff. *C. anapetes* De Wever; Foraminifera	---
			Late(?) Triassic	
77ACn-611	No data		?*Pseudoheliodiscus* sp.; ?*Sarla* sp.	---
79Md-148C	68°18'00"	163°15'00"	?*Capnuchosphaera* sp.; ?*Eptingium* sp.	---
79ABe-257	67°57'10"	145°41'40"	?*Capnuchosphaera* sp. fragment	Etivluk Group (Christian quadrangle)
			Late(?) Triassic (poor preservation precludes more precise determination)	
78ACn-664	68°28'12"	161°50'42"	*Canesium* sp; ?*Capnodoce* sp.; ?*Capnuchosphaera* sp.; *Plafkerium* sp.; ?*Sarla* sp.; *Triassocampe*	---
78EK-4F	67°40'05"	162°06'10"		---
78EK-124C	68°23'54"	161°32'18"		Etivluk Group (Red Dog district)
78W-38774	68°09'14"	162°58'54"		---
Lisburne test well (foundation core)	68°29'05.44"	155°41'33.51"		Etivluk Group, Picnic Creek or higher allochthon (Ivotuk Ridge area)
			Triassic	
79Ek204h	68°10'55"	163°19'10"	?*Triassocampe* sp.; conodont fragment	Etivluk Group, Kelley River allochthon
78Cx-179d	68°24'15"	161°30'42"	?*Khalerosphaera* sp.	Etivluk Group
78Tr-235I$_2$	68°36'25"	156°34'55"	Poorly preserved nassellarians; foraminifers; conodonts	Blankenship Member, Otuk Fm., Brooks Range allochthon (Blankenship Creek)
			Triassic(?)	
78Tr-66A	68°31'35"	159°58'30"	Poor preservation precludes exact identification	---
78Tr-236D	68°28'16"	155°34'40"		Blankenship Member, Otuk Fm., Brooks Range allochthon (Ivotuk Ridge area)
78Tr-241A	68°27'55"	155°40'50"		Chert or shale member, Otuk Fm., Brooks Range allochthon (Ivotuk Ridge area)
78W-38775	68°09'03"	162°58'36"		Etivluk Group (Red Dog district)
79Cx-210D	68°15'30"	163°20'00"	?*Pseudostylosphaera* sp.; ?*Sarla* sp.	---
			Late Norian or younger	
82AKr-69	68°08'	165°56'	*Acanthocircus* sp.; twisted spine	Otuk Fm., Agate Rock; in "4" of Campbell (1967, p. 50) (Lisburne Peninsula)
			Norian to earliest(?) Jurassic	
77ACn-362	68°33'25"	161°09'30"	*Canoptum* spp.; ?*Capnodoce* sp.; *Livarella* sp.	---
			Late Norian to Early Jurassic	
78ACn-872C	68°52'50"	151°20'50"	*Canoptum* sp.; ?*Cantalum* sp.; *Capnuchosphaera* sp.; *Ferresium* sp.; *Laxtorum* sp.; *Pantanellium* sp. aff. *P. dawsoni* Pessagno and Blome; ?*Plafkerium* sp.; *Pseudoheliodiscus* sp.; *Sarla* sp.	Etivluk Group, Brooks Range allochthon (Tiglukpuk Creek)
76(78)Tr100	68°23'45"	160°14'20"		Copter Peak allochthon (Siniktanneyak Mountain)
78W-7	68°07'54"	163°12'03"		Etivluk Group, Brooks Range allochthon (Lik prospect)
78W-38780	68°04'42"	163°04'12"		Etivluk Group, Brooks Range allochthon (Red Dog district)
			Triassic or Jurassic	
78Md-113B	68°09'45"	160°18'30"	Poor preservation precludes exact identification	Etivluk Group, Brooks Range allochthon
78Md-152B	68°28'50"	161°18'00"		Etivluk Group, Nuka Ridge allochthon
78Tr-68B	68°31'18"	159°27'24"		Etivluk Group, Brooks Range allochthon
78Tr-235I$_3$	68°36'25"	156°34'55"		Blankenship Member, Otuk Fm., Brooks Range allochthon (Blankenship Creek)

TABLE 33.2.—*Miscellaneous Mesozoic radiolarian samples from localities in and near the National Petroleum Reserve in Alaska*—Continued

Sample	Latitude (°N)	Longitude (°W)	Radiolarians	Unit
			Sinemurian to Pliensbachian (Early Jurassic)	
79Md-15A	68°21'28"	163°44'50"	*Canoptum dixoni* Pessagno and Whalen; *Canutus* sp. aff. *C. izeensis* Pessagno and Whalen; *Pantanellium* sp.	---
			Sinemurian(?)	
79Md-11B	68°03'27"	162°47'20"	*Canutus rockfishensis* Pessagno and Whalen; *Droltus* sp. aff. *D. lyellensis* Pessagno and Whalen; ?*Emiluvia* sp.	Etivluk Group, Brooks Range allochthon (OFR 83-184)
			Early Jurassic	
79Cx-73G	68°23'33"	162°28'06"	*Canoptum* sp.; *Canutus* sp. aff. *C. hecatensis* Pessagno and Whalen; *Livarella* sp.; *Lupherium* sp.	Etivluk Group
			Early(?) Jurassic	
79Md-146B	68°18'54"	163°19'33"	?*Canutus* sp. or ?*Droltus* sp.	Etivluk Group, Picnic Creek allochthon
79Ek-193d	68°24'30"	163°03'24"	?*Canoptum* sp.; ?*Canutus* sp.; *Napora* sp.; *Paronaella* sp.; *Pseudoheliodiscus* spp.	Otuk Fm., Brooks Range allochthon (OFR 83-184)
79Ek-182C	68°18'15"	163°03'06"	?*Canutus* sp.	Etivluk Group, Brooks Range allochthon (OFR 83-184)
79Tr-88C.1	68°11'17"	162°12'18"	?*Droltus* sp.; *Canutus* sp.	Etivluk(?) Group, Brooks Range allochthon (OFR 83-185)
			Early or Middle Jurassic	
82Tr-04E	68°37'06"	159°12'50"	*Canutus* sp.; ?*Emiluvia* sp.; *Paronaella* sp.	Etivluk Group, Nuka Ridge allochthon (I-1504)
			Middle(?) Jurassic	
79Cx-191E	68°24'45"	163°35'00"	?*Hsuum* sp.; ?*Parvicingula* sp.	---
			Jurassic	
78Tr-235I$_4$	68°36'25"	156°34'55"	*Parvicingula* sp.; *Ristola hsui* (Pessagno)	Blankenship Member, Otuk Fm., Brooks Range allochthon (Blankenship Creek)
			Mesozoic	
8Acn-631	No data		Samples contain unidentifiable nassellarians	---
78ACn-731	68°27'03"	161°47'06"		---
78Md-140	68°15'30"	161°40'00"		Ipnavik River allochthon
78Tr-235B	68°36'25"	156°33'25"		Lisburne(?) Group (uppermost part), Brooks Range sequence (Ivotuk Ridge area)
78W-3	68°10'34"	163°11'00"		Etivluk Group, Brooks Range allochton (Lik prospect)
78W-31	68°01'12"	164°37'24"		Etivluk Group (Red Dog district)
78W-38783	68°09'40"	163°22'12"		Etivluk Group (Red Dog district)
77ACn-1421	No data			---
78Md-160C	68°26'18"	160°50'20"		Etivluk Group, Ipnavik River allochthon (I-1503)
79Tr-75C	68°22'40"	162°04'48"		Etivluk Group, Brooks Range allochthon
79Md-164B	68°08'45"	162°29'00"		Etivluk Group, Brooks Range allochthon (OFR 83-185)
79Cx-209G$_3$	68°28'09"	162°37'20"		

34. PALEOZOIC RADIOLARIAN BIOSTRATIGRAPHY OF THE NORTHERN BROOKS RANGE, ALASKA

By BRIAN K. HOLDSWORTH[1] and BENITA L. MURCHEY

INTRODUCTION

Mississippian, Pennsylvanian, and Permian radiolarians are the most abundant fossils in many of the allochthonous siliceous rocks—Lisburne Group (part) and Etivluk Group (see Mull and others, 1982, 1987)—found in the foothills of the northern Brooks Range, Alaska. The upper Paleozoic and lower Mesozoic Lisburne (part) and Etivluk Groups lie in a 1,100-km east-trending belt that has been thrust northward over coeval platform rocks of the North Slope. In recent years, many Paleozoic radiolarian chert samples were collected for microfossil analysis in conjunction with the mapping of the National Petroleum Reserve in Alaska (NPRA) and related adjacent areas (see Murchey and others, chapter 32).

In 1978 the senior author devised a scheme whereby Paleozoic radiolarians collected over a wide area could be allocated to biostratigraphic "radiolarian faunal groups" and by which approximate ages could be assigned. Age assignments based upon this scheme have been published already (Curtis and others, 1982, 1983, 1984; Ellersieck and others, 1982, 1983, 1984; Mayfield and others, 1982, 1983a, b, 1984, 1987). In 1979 the exploration program for the NPRA sponsored field work in the Brooks Range that permitted the junior author to measure and collect radiolarian reference sections (Murchey and others, chapter 32; Murchey and others, 1981). In this chapter we describe the Paleozoic radiolarian zonation scheme and show that the deduced succession of faunas is largely contained in an inverted succession at one locality, Nigu Bluff, which provides a reference section for the greater part of the Paleozoic radiolarian-bearing succession of the northern Brooks Range.

Much work on Paleozoic radiolarians since the chapter was first drafted in 1980 has necessitated considerable revision of taxonomy and somewhat lengthy discussion. No significant alteration of the 1980 age assignments has been necessary.

NIGU BLUFF SEQUENCE

An apparently continuous stratigraphic sequence of radiolarian-bearing siliceous rocks is exposed at Nigu Bluff on the east bank of the Nigu River, 4 mi south of the confluence of the Etivluk and Nigu Rivers in the Howard Pass quadrangle (lat 68°29′ N., long 156°27′ W.; fig. 34.1).

The Nigu Bluff cutbank exposes a thickness of 192 m of chert, shale, limestone, and argillite dipping steeply to the south (fig. 34.2). The rock sequence is part of the Picnic Creek allochthon (see Mayfield and others, chapter 7, 1983b). Chapman and others (1964) assigned the entire sedimentary sequence at Nigu Bluff to the Siksikpuk Formation (Patton, 1957). During NPRA-sponsored mapping (I.L. Tailleur, oral and written communs., 1979), the Nigu Bluff section was assigned to the Etivluk Group of Mull and others (formalized in 1982), which included the Siksikpuk Formation of Patton (1957) and the Otuk Formation of Mull and others (1982). Mull and others (1987) recently proposed several new formations for rocks of the Picnic Creek allochthon in the adjacent Killik River quadrangle. Two of the proposed formations, the Akmalik Chert (Lisburne Group) and the Imnaitchiak Chert (Etivluk Group), are biostratigraphically correlative (in part) with the northern portion of the Nigu Bluff sequence. Chapman and others (1964) considered the Nigu Bluff section to be structurally upright. However, application of the scheme of radiolarian faunal groups suggested in 1979 that the sequence in the northern half of the outcrop is overturned (Murchey and others, 1981), and this has now been proved beyond doubt.

At the south end of the cutbank, the sedimentary sequence is intruded by a mafic igneous sill. The sill marks the base of the section measured and sampled in 1979 by B.L. Murchey, P.B. Swain, and Steve Curtis. The basal 85 m (units 5 and 4 of Chapman and others, 1964) of the stratigraphic sequence is predominantly dark-gray or black thinly bedded chert and shale containing a few thin (5-7 cm) limestone beds (fig. 34.2). The impure chert contains carbonaceous material, clay, pyrite, and carbonate

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rhombs. The chert weathers to a dark-brownish-red or gray rock having limonite-colored surface stains. Fresh surfaces show wispy sedimentary laminae. This chert has the appearance of silicified limestone. The basal 25 m possibly contains some altered volcaniclastic material. The overlying interval from 25 m to 85 m is black carbonaceous shale. Five samples collected in the interval from 13 m to 29 m yielded very poorly preserved spheroidal radiolarians for which no age determination is possible. One limestone bed at 29 m (Nigu-5) yielded *Tentaculites*(?) of Devonian(?) age (M.B. Mickey, written commun., 1983), poorly preserved radiolarians, very simple long-ranging foraminifers, and conodont fragments. None of these microfossils was well enough preserved to give a definitive age determination. Samples at 34 m (Nigu-6) and 55 m (Nigu-7) yielded no microfossils when etched with hydrofluoric acid. The basal 85 m of the Nigu Bluff sequence is quite different from the type Siksikpuk Formation or the Imnaitchiak Chert. However, both the Kuna and Otuk Formations (Mull and others, 1982) and the Akmalik Chert (Mull and others, 1987) consist of similar lithofacies. We tentatively consider the basal 85 m at Nigu Bluff to belong to the Paleozoic Kuna Formation or Akmalik Chert of the Lisburne Group because it underlies the Etivluk Group. The Kuna Formation as described by Mull and others (1982) is dominantly "black bedded chert, shale, limestone, and dolomite." The Akmalik Chert "consists almost entirely of bedded black chert," whereas "the Kuna Formation is predominantly sooty black shale interbedded with black chert" (Mull and others, 1987, p. 658).

The interval from 85 m to 100 m is thick-bedded (to 30 cm) siliceous dolomitic limestone. The buff-weathering limestone contains abundant sponge spicules in a fine-grained matrix. Some limestone beds contain whole sponges approximately 1 cm in diameter. One horizon, at 97 m, contains diagenetic barite spheres. Thinner chert and shale beds are interbedded with the limestone. Noncarbonaceous shale beds within the limestone unit are as much as 4 cm thick. Gray chert occurs as replacement stringers within limestone beds and as dolomitic, pyritic, iron-stained interbeds. The ratio of chert to limestone increases upsection, and bedding surfaces become increasingly irregular and undulating.

Samples collected from this 85- to 100-m interval (samples 8 to 11) yielded abundant sponge spicules, including protriaene forms, and a few very poorly preserved radiolarians. This lithologic unit is part of unit 3 of Chapman and others (1964, p. 348). The type Siksikpuk contains a few limestone beds but no thick limestone sequence. Therefore, we do not consider this unit to be part of the Siksikpuk. Both the Lisburne Group and the Otuk Formation contain significant carbonate sequences. In general, we found sponge-bearing limestone to be common in some facies of the Paleozoic Lisburne Group but rare in the Otuk Formation. Mesozoic foraminifers, pelecypods, and conodonts are common in Otuk limestone but have not been found in the Nigu Bluff limestone unit. In addition, the Nigu Bluff limestone clearly grades into an overturned Paleozoic chert sequence similar to the Imnaitchiak Chert. Therefore, this Nigu Bluff limestone unit is here considered to be part of the Lisburne Group, probably part of the Kuna Formation or the Akmalik Chert.

The limestone grades upwards into gray and gray-green bedded chert. The basal 10 m of this chert unit (100-110 m above the sill) contains many diagenetic features, such as lumpy irregular bedding surfaces, pinch-and-swell bedding, and hemispherical mammillate mounds as large as 18 cm in diameter and projecting as much as 7.5 cm above the bedding surface. From 110 m to 160 m, the chert is evenly bedded and bedding surfaces are fairly flat except in zones having some folding and boudinage. The typical thickness of the beds is 5-8 cm; the maximum thickness of beds within 1-m intervals averages 25 cm. Some chert

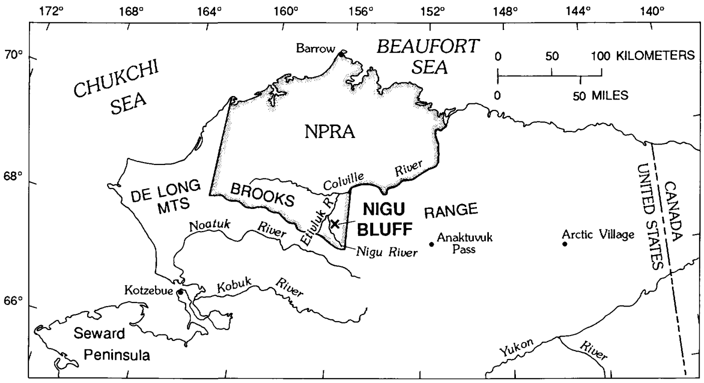
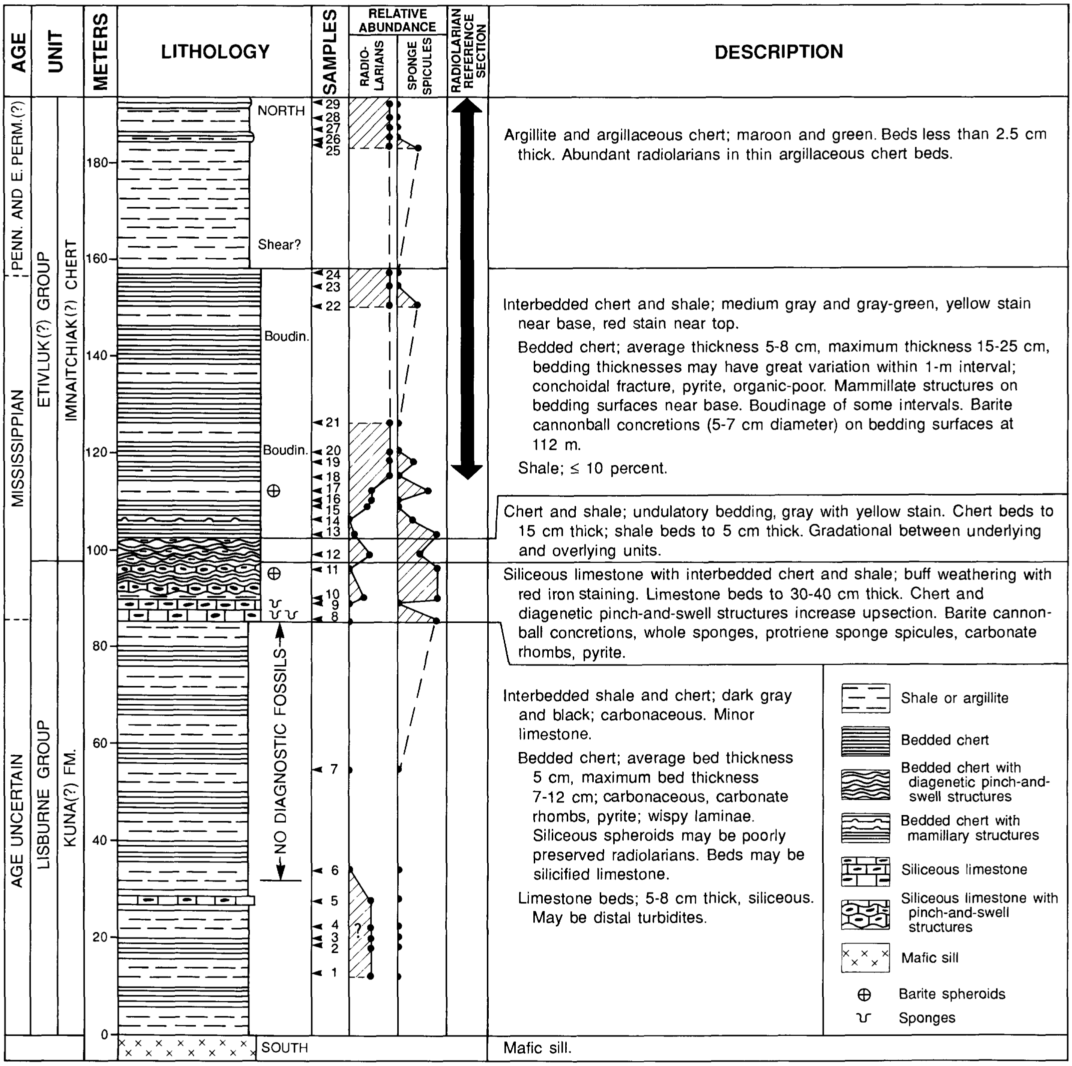


FIGURE 34.1.—Generalized map of northern Alaska showing locality of Paleozoic radiolarian reference section at Nigu Bluff in Howard Pass quadrangle.

beds are slightly laminated. The chert weathers to gray green and frequently has a ferruginous yellow, green, or red surface stain. Chert beds are interbedded with noncarbonaceous gray and gray-green shale beds 0.1-2 cm thick. Numerous diagenetic barite "cannonballs" (5-18 cm in diameter) occur on the bedding surfaces at 112 m. Radiating barite crystals in these balls crosscut radiolarian tests. Within the basal chert zone (100-110 m), the ratio of radiolarians to sponge spicules increases significantly upsection (fig. 34.2).

From 110 m to 160 m, the chert consists of abundant radiolarians



Argillite and argillaceous chert; maroon and green. Beds less than 2.5 cm thick. Abundant radiolarians in thin argillaceous chert beds.

Interbedded chert and shale; medium gray and gray-green, yellow stain near base, red stain near top.

Bedded chert; average thickness 5-8 cm, maximum thickness 15-25 cm, bedding thicknesses may have great variation within 1-m interval; conchoidal fracture, pyrite, organic-poor. Mammillate structures on bedding surfaces near base. Boudinage of some intervals. Barite cannonball concretions (5-7 cm diameter) on bedding surfaces at 112 m.

Shale; ≤ 10 percent.

Chert and shale; undulatory bedding, gray with yellow stain. Chert beds to 15 cm thick; shale beds to 5 cm thick. Gradational between underlying and overlying units.

Siliceous limestone with interbedded chert and shale; buff weathering with red iron staining. Limestone beds to 30-40 cm thick. Chert and diagenetic pinch-and-swell structures increase upsection. Barite cannonball concretions, whole sponges, protriene sponge spicules, carbonate rhombs, pyrite.

Interbedded shale and chert; dark gray and black; carbonaceous. Minor limestone.

Bedded chert; average bed thickness 5 cm, maximum bed thickness 7-12 cm; carbonaceous, carbonate rhombs, pyrite; wispy laminae. Siliceous spheroids may be poorly preserved radiolarians. Beds may be silicified limestone.

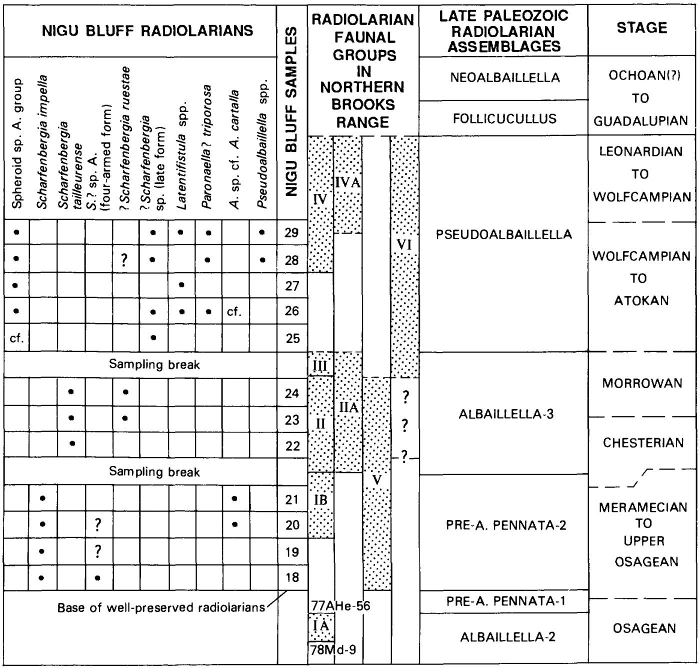
Limestone beds; 5-8 cm thick, siliceous. May be distal turbidites.

Mafic sill.

FIGURE 34.2.—Measured section of Nigu Bluff outcrop, Howard Pass quadrangle, Alaska (lat 68°29′ N., long 156°27′ W.). Measured by B.L. Murchey, P.B. Swain, and S.M. Curtis, 1980. Section is overturned and dips steeply to south.

and fewer sponge spicules in a fine-grained matrix of chert and clay. Sample 18 (115 m) marks the base of the radiolarian biostratigraphic reference section at Nigu Bluff. From 115 m to 192 m, preservation improves and radiolarian diversity increases northward (upsection). This gray and gray-green chert unit is lithologic unit 2 of Chapman and others (1964, p. 348). Although this chert unit is more siliceous than the type locality of the Siksikpuk Formation at Tiglukpuk Creek, which lacks radiolarian-bearing chert, it conforms to the concept of the Siksikpuk Formation used by Mull and others (1982). Their description includes "thick sections of ferruginous-weathering siliceous shale and bedded chert." The chert unit between 110 m and 160 m best fits the description of the recently proposed Imnaitchiak Chert (Mull and others, 1987), which is "dominantly gray and green chert and maroon silicified shale and siltstone" and which is distinguished from the Siksikpuk (restricted sense) by having a greater proportion of chert. The radiolarian faunas in the interval from 110 m to 160 m at Nigu Bluff extend the age range of Imnaitchiak(?) Chert lithofacies into the Mississippian.

At 160 m the rocks become more argillaceous. The interval between 160 m and 180 m is partly covered variegated argillite and chert. The interval from 180 m to 190 m consists of maroon and green interbedded argillaceous chert and shale. The northern end of the Nigu Bluff cutbank (190-192 m) is dominantly maroon and green argillite having a few very thin (2-cm) beds of siliceous argillite containing the best-preserved and most diverse radiolarian faunas in the entire sequence. On the basis of lithology, we also consider this chert and argillite unit to be part of the Imnaitchiak(?) Chert.



NIGU BLUFF RADIOLARIANS: *Spheroid* sp. A. group	*Scharfenbergia impella*	*Scharfenbergia tailleurense*	*S.*? sp. A. (four-armed form)	?*Scharfenbergia ruestae*	?*Scharfenbergia* sp. (late form)	*Latentifistula* spp.	*Paronaella*? *triporosa*	*A.* sp. cf. *A. cartalla*	*Pseudoalbaillella* spp.	NIGU BLUFF SAMPLES
•					•	•	•		•	29
•				?	•		•		•	28
•						•				27
•					•	•	•	cf.		26
cf.					•					25
Sampling break										
		•		•						24
		•		•						23
		•								22
Sampling break										
	•							•		21
	•		?					•		20
	•		?							19
	•		•							18
Base of well-preserved radiolarians										

FIGURE 34.3.—Correlation of common Paleozoic radiolarian faunal groups of northern Brooks Range with Nigu Bluff reference section. Nigu Bluff sample numbers refer to sample sites in Nigu Bluff reference section shown in figure 34.2. Radiolarian assemblages are those of Holdsworth and Jones (1980a, b), with the addition of *Neoalbaillella* assemblage of Ishiga and others (1982b).

RADIOLARIAN FAUNAS AT NIGU BLUFF

The radiolarian biostratigraphic reference section at Nigu Bluff is defined as the stratigraphic interval from 115 m to 192 m stratigraphically above the igneous sill (samples 18 to 29, fig. 34.2). Stratigraphically important species within this sequence are illustrated on plates 34.1 and 34.2. Their occurrences in the reference section are shown in figure 34.3. This stratigraphic interval lies within the Imnaitchiak(?) Chert. Underlying radiolarian faunas are too poorly preserved to be stratigraphically useful. The transition from poorly preserved radiolarians to moderately well preserved radiolarians coincides with a transition from a calcareous, sponge-dominated lithology to a more siliceous, radiolarian-dominated lithology (fig. 34.2).

The Nigu Bluff section from the level of sample 18 to that of sample 21 is Mississippian in age on the basis of the radiolarian fauna present. Samples 18 to 21 contain a fauna that includes *Scharfenbergia impella* (Ormiston and Lane) (fig. 34.3). Samples 18 and, possibly, 19 and 20 contain a previously unfigured species, *Scharfenbergia*? sp. A (four-armed form). Samples 20 and 21 contain *Albaillella* cf. *A. cartalla* Ormiston and Lane. The *Albaillella* cf. *A. cartalla* fauna of samples 20 and 21 appears to be pre-Chesterian in age because it contains no individuals comparable with the *Albaillella pennata* Holdsworth group or other lanceolate, segmented forms. A form similar to *Scharfenbergia*? sp. A (four-armed form) is known from latest Tournaisian (middle Osagean) age rocks of Poland, but in Poland and Germany (Miller and others, 1984) *A. cartalla* occurs no earlier than Viséan "V2" (latest Osagean to Meramecian). None of the first 21 samples at Nigu Bluff has yielded any elements of the Early Mississippian *Albaillella*-1 and -2 Assemblages (Holdsworth and Jones, 1980a) or pre-*A. pennata*-1 association, now known to be in part Early Mississippian in age (Miller and others, 1984). At present, samples 18 to 21 are considered latest Osagean to Meramecian in age. A sampling break separates sample 21 (126 m above the sill) from samples 22 to 24 (150 m to 157 m). These three samples contain *Scharfenbergia tailleurense* n. sp. and ?*Scharfenbergia ruestae* (Ormiston and Lane) group. Based on correlations with *S. tailleurense* faunas in Nevada and Europe, we consider these samples to be latest late Meramecian to Morrowan in age. In Poland (Mariusz Paszkowski, oral commun., 1987), *S. tailleurense* occurs no earlier than Viséan "V3c" (latest Meramecian and early Chesterian). In Nevada, *S. tailleurense* occurs with Morrowan conodonts (Stewart and others, 1986, referring to "*Tetratormentum* sp. A"). Elsewhere in the Brooks Range, *S. tailleurense* and *Paronaella*? *triporosa* n. sp. occur with the Morrowan conodont *Declinognathodus noduliferous* (Bruce Wardlaw, written commun., 1980) in a fauna that may postdate samples 22 to 24 at Nigu Bluff (see discussion in following section of Faunal Groups II and III).

Samples 25 to 29 (183 m to 192 m above the the sill) are separated from samples 22 to 24 by a sampling break. Samples in the 25 to 29 interval contain abundant "?*Scharfenbergia* spp. (late species)", *Latentifistula* spp., *Paronaella*? *triporosa* n. sp. and spheroid sp. A group. Sample 26 contains a poorly preserved lanceolate *Albaillella* sp., whereas samples 28 and 29 contain fragments of *Pseudoalbaillella*. We consider the faunas in 28 and 29 to be correlative with the *Pseudoalbaillella* Assemblage of Holdsworth and Jones (1980a). The *Pseudoalbaillella* specimens in samples 28 and 29 are too fragmentary to correlate them with the *Pseudoalbaillella* assemblages of Ishiga (1982) and Ishiga and others (1982a). The *P.*? *triporosa*, *Latentifistula* spp., and "?*Scharfenbergia* spp. (late species)" are similar to forms occurring with conodonts ranging from late Morrowan to Wolfcampian in age (for example, Stewart and others, 1986). Because samples 25 to 29 lack *S. tailleurense*, their most probable age range is Middle to Late Pennsylvanian and (or) Early Permian (Wolfcampian).

CORRELATION BETWEEN NIGU BLUFF FAUNAS AND PALEOZOIC RADIOLARIAN FAUNAS ELSEWHERE IN THE NORTHERN BROOKS RANGE

Paleozoic radiolarian faunas in the northern Brooks Range had been classified into six groups, I to VI, before work on the Nigu Bluff section. Figure 34.3 shows the estimated positions of these groups relative to the Nigu Bluff section and their estimated age ranges. Index species in the faunal groups are shown on plates 34.1 and 34.2. All figured index species are discussed in the "Systematic Paleontology" section of this chapter. The geographic distribution of the faunal groups is discussed in a companion chapter (Murchey and others, chapter 32).

EARLY MISSISSIPPIAN FAUNAS INCLUDING FAUNAL GROUP IA

All but a very few northern Brooks Range samples appear to be correlative with samples 18 to 29 at Nigu Bluff or to be younger. There are a few exceptions: Samples with *Albaillella indensis* Won group constitute Faunal Group IA and are correlative with the pre-*Albaillella pennata*-1 association of Holdsworth and Jones (1980a, b). Faunal Group IA probably predates Nigu Bluff samples 18 to 21. In Nevada, *A. indensis* group is the index of Schoonover Group 3 of Miller and others (1984), and in the Schoonover sequence it occurs at least as early as middle Osagean time. In Germany, *A. indensis* group ranges from at least latest Tournaisian "Tn3c" (middle Osagean) through some part of Viséan "V2a" (latest Osagean to earliest Meramecian) and may range lower into earliest late Tournaisian "Tn3ab" (early Osagean) (unpublished data of senior author). Two samples not assigned to a particular faunal group may also be older than the basal part of the Nigu Bluff biostratigraphic reference section. Sample 78 Md-9 (USGS MR 5223, lat 67°41′25″ N., long 162°03′20″ W.) yielded a single specimen of *Cyrtisphaeractenium* sp. Deflandre *sensu lato*, which is most frequently encountered in the Lower Mississippian and not definitely known to range higher. Sample 77 AHe-56 (USGS MR 0035, lat 68°23.92′ N., long 158°05′ W.) contains very poorly preserved *Albaillella* specimens somewhat similar to *Albaillella undulata* Deflandre. Specimens of this type are known to occur with elements of the *Albaillella*-2 Assemblage and to range into the early Viséan (late Osagean to early Meramecian). Therefore, these samples may be Early Mississippian in age and may be older than samples 18 to 21 at Nigu Bluff.

FAUNAL GROUP IB

Faunal Group IB is characterized by *Albaillella* sp. cf. *A. cartalla* Ormiston and Lane and *Scharfenbergia* *impella* (Ormiston and Lane). The faunal group is correlative with samples 20 and 21 at Nigu Bluff. The probable age range of this faunal group is late Osagean to Meramecian at Nigu Bluff, but some samples from other localities that have been allocated to Faunal Group IB could be Chesterian.

FAUNAL GROUP II

Faunal Group II samples contain *Scharfenbergia tailleurense* n. sp. and poorly preserved *Albaillella* specimens but lack *Pseudoalbaillella* spp. and *Paronaella*? *triporosa*. Samples 22, 23, and 24 at Nigu Bluff contain Faunal Group II radiolarians. Two samples of the group that were collected elsewhere in the northern Brooks Range, samples 60 ABe-591 (USGS MR 0004, lat 68°01′37″ N., long 145°19′30″ W.) and 78 Md-81C (USGS MR 6539, lat 68°35′14″ N., long 159°55′42″ W.), have *Albaillella* specimens sufficiently well preserved to suggest an identification as the late Meramecian to early Morrowan *A. pennata* group. Similar faunas in the Havallah sequence in Nevada occur with Morrowan conodonts (Stewart and others, 1986). On this basis, Faunal Group II is no older than latest late Meramecian but may include samples as young as Morrowan.

FAUNAL GROUP III

A single sample, 78 Md-75E (USGS MR 0813, lat 68°31′22″ N., long 160°08′50″ W.), constitutes Group III. This sample is characterized by the association of *Scharfenbergia tailleurense* and poorly preserved yet distinctive *Albaillella* specimens (*A. furcata* Won group) similar to both *Albaillella furcata* Won and *Albaillella rockensis* Cheng (a possible junior synonym of *A. furcata*). Sample 78 Md-75E contains the Morrowan conodont *Declinognathodus noduliferous* group (Bruce Wardlaw, written commun., 1980). It also contains *Paronaella*? *triporosa*. In the Nigu Bluff samples, *S. tailleurense* and *P.*? *triporosa* do not occur together. The two species are separated by a 24-m sampling break. We consider Faunal Group III to be correlative with the unsampled interval between samples 24 and 25.

The known combined age range of *A. furcata* and *A. rockensis* is from late Viséan (Meramecian) in Europe to early Morrowan in Oklahoma. The conodont evidence suggests that Group III is at the youngest end of this range. Therefore, the Mississippian-Pennsylvanian boundary at Nigu Bluff may lie in the unsampled interval between samples 24 and 25. Because 78 Md-75E (USGS MR 0813) represents the only known occurrence together of *S. tailleurense* and *P.*? *triporosa* and *P.*? *triporosa* occurs elsewhere with Desmoinesian conodonts, it might seem that overlap in age range of the two species is confined to a short interval of the late Morrowan. Alternatively, 78 Md-75E could record reworking of Morrowan conodonts and radiolarians into a Desmoinesian or younger horizon. In the Havallah sequence in Nevada, *S. tailleurense* occurs with Morrowan conodonts, whereas *P.*? *triporosa* occurs with Desmoinesian and reworked Morrowan conodonts (Stewart and others, 1986). Neither species is known from the English Namurian radiolarian biofacies of equivalent (Chesterian and early Morrowan) age.

FAUNAL GROUP IIA

Group IIA faunas are characterized solely by *S. tailleurense*. The low diversity and poor preservation of these samples prevents discrimination between Groups II and III.

FAUNAL GROUPS IV AND IVA

Group IV and IVA faunas lack *S. tailleurense* but contain specimens, usually very scarce and fragmentary, of *Pseudoalbaillella* spp. Both faunal groups are considered to postdate Group III. Faunal Group IV and IVA faunas are correlative with, or younger than, Nigu Bluff samples 25 to 29. In Faunal Group IV samples, *Pseudoalbaillella* specimens are too poorly preserved to justify discrimination between Pennsylvanian and Early Permian ages. Faunal Group IV could contain both Pennsylvanian and Permian faunas or consist entirely of faunas of one of these ages. Group IVA contains the few faunas in which the *Pseudoalbaillella* specimens can fairly confidently be compared with species of known Early Permian age. The *Pseudoalbaillella* species in Nigu Bluff samples 28 and 29 have some affinity with the strongly inflated forms of the Early Permian *Pseudoalbaillella globosa* Ishiga and Imoto, but the age of the uppermost Nigu Bluff samples remains uncertain.

FAUNAL GROUPS V AND VI

Group V samples, in which *Scharfenbergia impella* (Ormiston and Lane) group is the only diagnostic taxon, are most likely to be correlative with samples 18 to 21 (possibly also 22 to 24) at Nigu Bluff and with Faunal Groups IB and II(?). Faunal Group V may range in age from late Osagean to Chesterian or Morrowan. Group VI samples contain no age-diagnostic radiolarians other than "?*Scharfenbergia* spp. (late species)" and (or) late *Latentifistula* spp. They are most probably correlative with Groups III to IV and samples 25 to 29 at Nigu Bluff. Faunal Group VI has a minimum possible range of early Morrowan to Leonardian. Because "?*Scharfenbergia* spp. (late species)" may occur first in the Chesterian, a slightly greater age range for some of these sparse samples cannot be ruled out.

CONCLUSIONS

Although most Paleozoic radiolarian faunas in the Brooks Range are poorly preserved, many of them can be classified into a series of faunal groups. Faunal Groups IA, IB, II, III, IV, and IVA are essentially time successive and range in age from Early(?) Mississippian (IA, IB) to Early Permian (IVA). Allocations to Faunal Groups IIA, V, and VI provide less precise age estimates. Faunal Groups IB, II, IV, and V can be recognized in the biostratigraphic sequence at the north end of Nigu Bluff on the Nigu River in the Howard Pass quadrangle. The assigned age ranges of the faunal groups are based on conodont age determinations for a few Brooks Range samples and correlations with independently dated radiolarian assemblages from other regions.

SYSTEMATIC PALEONTOLOGY

Subclass RADIOLARIA Muller 1858
Order POLYCYSTINA Ehrenberg 1838, emend. Riedel 1967
Suborder SPUMELLARIA Ehrenberg 1875
SPUMELLARIA INCERTAE SEDIS
Genus uncertain

Spheroid sp. A group

Plate 34.1, figures 21-24

Remarks.—Spheroid with six(?) blunt grooved primary spines set in slight depression in the spheroidal test. Pores of external test are hexagonal and equant.

Occurrence.—Samples 25 to 29 at Nigu Bluff. Part of Faunal Group IV throughout northern Brooks Range.

Range.—Pennsylvanian; possibly Early Permian, Wolfcampian.

"STAURAXON RADIOLARIA" (informal grouping; Spumellaria at least in part)

At the time of final revision of this chapter (September 1987) the stauraxons remain the least well understood of those radiolarians that are important to the biostratigraphy of the Brooks Range. A taxonomy has been constructed to reflect one model of phylogeny where two models at least are possible. Recent publications have confused rather than clarified the biostratigraphic significance of early stauraxon taxa. In revising this section of our 1980 manuscript we take the opportunity to address both these areas.

Apparent Paleozoic stauraxons were first described and figured by Rüst (1892) and Hinde and Fox (1895) from chert thin sections. The modern phase of Paleozoic radiolarian research on matrix-free material, which began in the 1950's and 1960's, provided no confirmation of the Paleozoic existence of Rüst's and Hinde's forms (Holdsworth, 1977). However, in the mid-1960's, a twiglike, four-rayed genus was observed in the latest Viséan to early middle Namurian (Chesterian to earliest Morrowan) age rocks of the British Isles and referred to as "scalariform Incertae Sedis" (Holdsworth, 1977). Ormiston and Lane (1976) published a description of a fauna from the Mississippian Sycamore Limestone in Oklahoma (Fay, 1969) that was radically different in composition from any described in previous modern work. Two new robust spongy stauraxon species were assigned to *Paronaella* Pessagno, a genus founded on Mesozoic material. A third robust stauraxon form was assigned to *Spongotripus* Haeckel, a genus with a Cenozoic type species. The wholly different "scalariform Incertae Sedis" (Holdsworth, 1977) was absent in the Sycamore Limestone fauna.

In the 1970's, work on Cordilleran chert faunas by D.L. Jones and the present authors and independent work on Ural Mountains limestones by B.B. Nazarov revealed a wholly unexpected diversity of stauraxons in Pennsylvanian and Permian rocks. Many stauraxons had clear affinities with the delicate "scalariform Incertae Sedis" (which remained undescribed and unfigured); others possessed apparent affinity with the robust stauraxons from the Sycamore Limestone. It thus appeared to us in 1980 when this chapter was first drafted that the Pennsylvanian and Permian stauraxon radiolarians possessed two quite distinct Mississippian phyletic origins, and we were aware of one stauraxon species group that we believed (and still believe, see below) may have evolved via a third lineage.

Kozur (1980) published the first valid modern names for young (Permian) stauraxons. He erected the Family Ruzhencevispongidae for two new genera, *Ruzhencevispongus* and *Nazarovispongus*, based on southern Urals material. The Urals fauna had been more comprehensively, if informally, reviewed by Nazarov earlier in the same year (Eurorad News, no. 3, 1980). In 1980, neither Kozur nor Nazarov saw the Mississippian Sycamore Limestone taxa as relevant to their treatment of the Permian material. The nature of "scalariform Incertae Sedis" was known to neither author.

In 1983, an importantly different view of the Paleozoic stauraxons was formulated by Nazarov and Ormiston. Kozur's Ruzhencevispongidae was included in a new superfamily, Latentifistulidea, with a newly created nominative family, Latentifistulidae. A second new family, Tormentidae, was erected. The Mississippian "*Paronaella*" of Ormiston and Lane (1976) was assigned to *Latentifistula* and the

Mississippian "*Spongotripus*" to the nominative genus of the Tormentidae, *Tormentum*. We could now recognize that the long-known but unfigured Mississippian "scalariform Incertae Sedis" was close to or identical with the latentifistulid "n.g. Latentifistulidarum" (*nomen nudum*) figured by Nazarov and Ormiston (1983, p. 368, figs. 4-6) (refigured as *Quadriremis* sp., 1985, fig. 5C) . Thus all Paleozoic stauraxon organizations known to us had now come to be included in a single superfamily, the Latentifistulidea, with the implication of a common phyletic origin. A common origin for stauraxons was not our own view in 1980, and we still have serious reservations regarding the 1983 concept of Nazarov and Ormiston.

Relations between stauraxon forms

Two considerations must be addressed to reconstruct the relations between stauraxon forms: (1) the comparative morphology of skeletons, particularly the interior structure of the central area and (2) the timing of the appearance of different skeletal types in the fossil record.

Comparative morphology

The superfamily Latentifistulidea Nazarov and Ormiston 1983 was diagnosed as possessing "an internal framework in the form of a hollow sphere with three to five, rarely more, rays arising from it." The nominative family was diagnosed as possessing "an internal framework in the form of a hollow sphere with three to five, rarely more *hollow* rays" (our italics). Because the Mississippian "*Paronaella*" spp. of Ormiston and Lane (1976) possess internally "a hollow sphere from which three rays radiate", Nazarov and Ormiston (1983) felt justified in viewing them as "the earliest presently known representatives of *Latentifistula*"—and hence the earliest known Latentifistulidae and Latentifistulidea.

The "rays" of the Mississippian forms can more properly and less ambiguously be described as rectilinear axial filaments. An axial filament radiates outward from the central sphere through the center of each spongy skeletal arm. No evidence has been shown that the axial filaments are hollow. In 1980 we were convinced that they were not. Won (1983), who reinvestigated examples of the species from both Germany and the type horizon in the Sycamore Limestone, made no mention of a hollow filament but confirmed the presence of a hollow central shell. On this ground alone, neither of the Mississippian species "*Paronaella*" *impella* Ormiston and Lane 1976 or "*Paronaella*" *turgida* Ormiston and Lane 1976 belongs to *Latentifistula* as diagnosed. We are presently not prepared to consider as homologous the apparently solid axial filament that runs the length of the Mississippian "*Paronaella*" spongy arm and the "thin rods" arising from "*hollow* short rays" (our italics) in the type species of *Latentifistula—L. crux* Nazarov and Ormiston. In addition, Nazarov and Ormiston (1985) specified a "nonporous" sphere in *Latentifistula*, while later (1986, p. 45) confirming "an inner sphere penetrated by pores" in at least one of the supposed *Latentifistula* spp. of Mississippian age.

Won (1983) also demonstrated that the innermost shell of "*Spongotripus*" *ruestae* Ormiston and Lane is similar to that in "*Paronaella*" *impella* and likewise is attached to solid filaments that extend through the length of the spongy lattice. Because Nazarov and Ormiston (1983) diagnosed the Tormentidae as possessing "hollow rays," we cannot accept Nazarov and Ormiston's (1983) assignment of the Mississippian "*Spongotripus*" species to Tormentum.

We find it difficult, therefore, to relate all the robust Mississippian stauraxons to the latentifistulid organization as it is exemplified by the Early Permian type species of *Latentifistula* and by all Latentifistulidea in which the innermost axial element of the arm is wholly or partly hollow. In contrast, the Late Mississippian "scalariform Incertae Sedis" (Holdsworth, 1977) appears to be closely similar structurally to Pennsylvanian and Permian stauraxons with hollow or partly hollow innermost axial elements.

Won (1983) grouped all three robust Mississippian taxa of Ormiston and Lane (1976) into a single new genus *Scharfenbergia*. Certainly *Scharfenbergia impella* and *Scharfenbergia ruestae* are closely connected, as we recognized in 1980. *S. turgida* differs in that the core of the spongy arm is differentiated as a coarsely porous tube in which elongation of pore bars in the direction of arm extension produce a girderlike effect. If, however, it is true that this "tube"—wholly different from the imperforate, hollow, radial elements of described Pennsylvanian and Permian *Latentifistula* and *Tormentum* spp.—encloses a solid axial filament (Nazarov and Ormiston, 1985, fig. 6*B*; 1986, fig. 6*B*), then we accept that *S. turgida*, *S. impella*, and *S. ruestae* are closely connected. Nonetheless, we cannot accept even a likely connection between *Scharfenbergia sensu* Won 1983 and what we think of as the "true latentifistulids" possessing hollow innermost axial elements.

Time of appearance

Until 1986 the earliest occurrence known to the authors of an unquestionable latentifistulid ("scalariform Incertae Sedis") was at an Irish goniatite horizon of P2b, "V3c," late Brigantian (early Chesterian) age. In that year, Mariusz Paszkowski showed the senior author photographs of well-preserved radiolarians from Poland. One form from the lower part of the Polish *Scaliognathus anchoralis* conodont zone section Tn3c (middle Osagean) has the essential features of ''scalariform Incertae Sedis'' *sensu* Holdsworth 1977, and the imperforate central area and hollow nature of the proximal parts of the four rays arising from it clearly identify it as a true latentifistulid in our sense (see below). From a higher part of the *S. anchoralis* zone section, Paszkowski had recovered a robust, spongy four-armed form, closely comparable with the *Scharfenbergia*? sp. A (four-armed form). A broken specimen of the Polish four-armed form from a higher level demonstrably possesses a perforate innermost shell similar to that of *Scharfenbergia sensu* Won, from which arise delicate axial filaments, apparently solid.

Thus the duality in stauraxon architecture already discussed very probably was in existence as early as the middle Osagean. Any common ancestor to these strikingly different structures is likely to have been considerably older. Until such common ancestry is demonstrated, we believe that *Scharfenbergia sensu* Won should be separated taxonomically from the hollow-rayed stauraxons.

With the Polish discoveries, the disputed age of the Sycamore Limestone, Oklahoma, becomes irrelevant in dating the first appearance of stauraxons. The Sycamore fauna, nevertheless, remains important to considerations of stauraxon biostratigraphy, and recent publications by Nazarov and Ormiston (1985, 1986) make it necessary for us to review this area.

The type material of *S. impella*, *S. turgida*, and *S. ruestae* and that of *Albaillella cartalla* derive from a level 10.7 to 11.0 m (35-36 ft) from the base of the Sycamore Limestone as developed on the north limb of the Arbuckle anticline, Oklahoma. According to Ormiston and Lane (1976, p. 160), ''The same radiolarian fauna (lacking only *Eostylodictya eccentrica* n. sp.) is less abundantly represented in the basal bed of the Sycamore which is Unit 28 of Fay * * *.'' Conodonts were reported from Unit 28 (Ormiston and Lane, 1976, p. 163). Ormiston and Lane suggested assignment of the conodonts to ''the *Gnathodus punctatus* Zone of Hass.'' From this it was concluded that ''the lowest limestone in the Sycamore * * * is earliest Osagean'' (Ormiston and Lane, 1976, p. 164). The European equivalent is ''Tn3a-b,'' early Ivorian and middle Courceyan.

Holdsworth and Jones (1980a, b) questioned whether an assemblage such as that of the Sycamore Limestone could occur at an early late Tournaisian level. They believed that the Sycamore Limestone fauna was considerably younger. At least until 1983 the early Osagean age of the basal part of the Sycamore Limestone was maintained by both authors of the Ormiston and Lane (1976) paper (in written comments reviewing a manuscript by B.K. Holdsworth, Y.-N. Cheng, J. Schwartzapfel, and E. A. Pessagno, Jr.).

In 1986 Nazarov and Ormiston (1986) amended this view. In the light of work in Utah by Sandberg and Gutschick (1984), Nazarov and Ormiston concluded that the ''earliest stauraxon Radiolaria'' first occur in the Delle Phosphatic Member (Sandberg and Gutschick, 1984) of the Woodman Formation in the ''Lower *Gnathodus texanus*'' (conodont) ''Zone'' (Nazarov and Ormiston, 1986, p. 35). They stated (p. 35) that ''we have the appearance of the earliest stauraxon radiolaria [sic] in three widely separated geographic areas''—Oklahoma, Utah, and Germany—''at stratigraphic horizons which, within the limits of available biostratigraphic data, could be exactly correlative.'' And more precisely they asserted that the ''entry'' of the stauraxons ''in the Sycamore Limestone and in the Woodman Formation is clearly in strata of Osagean age according to associated conodonts, *apparently in the lower Gnathodus texanus Zone* in each area'' (our italics).

Neither of the last two statements can be justified, as is shown by the following reasons:

(1) In the German Rheinische Schiefegebirge succession, the lowest closely dated occurrence presently known of *Scharfenbergia* spp. is demonstrably younger than in Utah. The lowest *Scharfenbergia* level was found by the senior author and collaborators above the base of beds containing redeposited ''V2a'' foraminifers (B.K. Holdsworth, P. Jackson, and G.D. Sevastopolu, unpub. data). The top of the Utah radiolarian succession (Delle Phosphatic Member) is no younger than ''V1'' equivalent according to Sandberg and Gutschick (1984, p. 140). In the closely dated German successions presently known, faunas approaching that of the Sycamore Limestone and the very similar assemblage described by Won (1983) from a different German area occur only above this level of first *Scharfenbergia* entry, at a horizon judged to be ''within or little below the *Paragnathodus bilineatus* Zone'' (Miller and others, 1984, p. 1025)—that is, higher than any part of the *Gnathodus texanus* Zone.

(2) There is no justification for assigning any Sycamore conodont assemblage associated with radiolarians to the ''Lower *Gnathodus texanus* Zone.'' The first appearance of virtually the full Sycamore Limestone radiolarian fauna is in Bed 28 of the Sycamore Limestone (see previous discussion). No *Gnathodus texanus* was identified at this level (or at any other Sycamore Limestone level) in 1976 (Ormiston and Lane, 1976). Such an occurrence would have precluded the 1976 assignment of the basal bed fauna to the *Gnathodus punctatus* Zone

and the "earliest Osagean." The 1986 implied assignment of the *Siphonodella*-bearing basal-bed fauna to any part of the *Gnathodus texanus* Zone is no more satisfactory than was the 1976 assignment to the *G. punctatus* Zone, *G. punctatus* being unrecorded in the fauna and the species of *Siphonodella* being undeterminable.

Once it is admitted that Bed 28 is unlikely to be "earliest Osagean" and that Ormiston and Lane (1976) were in error, the Sycamore Limestone conodont faunas become biostratigraphically worthless. It becomes obvious that at least the *Siphonodella* and *Elictognathus bialatus* (Branson and Mehl) of Bed 28 are reworked. This being so, and the Sycamore Limestone being largely if not wholly deposited by turbidity flows, there can be no assurance that any conodont assemblage truly reflects depositional age below a probable latest Meramecian (P1) goniatite horizon high in the Sycamore Limestone (J. Schwartzapfel, unpub. data). Given the geological context of the conodont occurrences, Sandberg and Gutschick's (1984) "suggestion" that the illustrated Sycamore conodont fauna "is permissive of an assignment to either the late Osagean Lower *texanus* or early Meramecian Upper *texanus* Zone" is empty of meaning. The Sycamore Limestone radiolarians cannot be safely dated by the conodonts associated with them.

(3) The stauraxon-bearing radiolarian faunas of Utah proven to occur at *G. texanus* Zone levels do not possess those overall characteristics of the Sycamore fauna that led the senior author to query an "earliest Osagean" age in 1980 (Holdsworth and Jones, 1980a, b). The mere presence of stauraxons was never important in dating the Sycamore fauna. Holdsworth and Jones (1980a) clearly stated (p. 283) that the "first appearance of *Paronaella* Pessagno"—that is, of *Scharfenbergia*—probably occurred in their "'Late' *Albaillella*-2 Association," which at that time, because of an erroneous calibration of the earlier *Albaillella*-2 Assemblage corrected by Miller and others (1984, pp. 1074-1077), was believed to be more probably "earlier Meramecian" than late Osagean (see Holdsworth and Jones, 1980a, fig. 1). The Sycamore Limestone fauna was viewed as being significantly younger because it "lacks all Pylentonemidae and all earlier tubular *Albaillellas* and contains the 'advanced' *Albaillella cartalla* Ormiston and Lane and apparently the oldest known examples of '*Spongotripus*' Haeckel. The *total fauna* suggests a level younger than that of earliest Osage * * *" (Holdsworth and Jones, 1980a, p. 283) (our italics).

The Utah faunas manifestly fail to match this diagnosis of the "Pre-*Albaillella pennata* Association 2." According to Sandberg and Gutschick (1984), Pylentonemidae occur in both Lower and Upper *G. texanus* Zone faunas. The tubular *Albaillella paradoxa* Deflandre group is stated to range through both conodont zones. *A. cartalla* Ormiston and Lane is neither figured nor mentioned. It is improbable that any specimens figured by Sandberg and Gutschick are of *Scharfenbergia ruestae*, the "oldest known examples of 'Spongotripus'" alluded to by Holdsworth and Jones (1980a, b). *Scharfenbergia turgida* appears to be absent. If so, this is significant, for the structure of *S. turgida* may be ancestral to that of much younger stauraxons (see following discussions). The first appearance of this structure in stauraxon-containing radiolarian communities may mark a valuable biohorizon.

Genus SCHARFENBERGIA Won 1983

Discussion.—We use "*Scharfenbergia*" in Won's original (1983) sense, except that we include four-armed and tetrahedral forms, which occurred in Won's material only as rare aberrations. Cheng (1986) has claimed that "*Scharfenbergia*" is an invalid genus, believing that the cited type species, the *Spongotripus concentricus* of Rüst (1892), was mistakenly identified with a form in Won's own material. Won's form possesses the characteristics that she and we recognize as being those of "*Scharfenbergia*"; *Spongotripus concentricus* Rüst, described from thin sections only, may not possess them. Nevertheless, at present there is no other Paleozoic genus in which the "scharfenbergids" *sensu* both Won and ourselves can safely be included. For reasons already explained, we disagree with Nazarov and Ormiston's (1986) opinion that "*impella, turgida,* and *plenospongiosa* * * * are clearly representatives of *Latentifistula.*" Nor do we accept that "*Scharfenbergia*" should be restricted to the *Spongotripus concentricus* of Rüst and the *Spongotripus ruestae* of Ormiston and Lane and included in the Tormentidae (Nazarov and Ormiston, 1986, p. 41). It has yet to be shown that any of Won's scharfenbergids possess the "labyrinthine meshwork with hollow bars" that characterizes Cheng's (1986) Archaeopyramisacea, and so no archaeopyramisaceid genus can safely be employed. Should some or all of Won's scharfenbergids be subsequently shown not to be Archaeopyramisacea (which we suspect to be the case), the concept "*Scharfenbergia*" should be consolidated by designating a new type species under the rules of the International Code of Zoological Nomenclature.

Scharfenbergia impella (Ormiston and Lane) 1976

Plate 34.2, figure 24

1976\.
Paronaella impella Ormiston and Lane, p. 169, pl. 3, figs. 1-5.
1983\.

Latentifistula impella n. comb. Nazarov and Ormiston, p. 373, pl. 7, figs. 10-11.

1983.

Scharfenbergia impella Won, p. 160, pl. 9, fig. 9, pl. 10, figs. 1-4.

1986.

Latentifistula impella Nazarov and Ormiston, pl. 1, fig. 9.

Remarks.—The only diagnostic taxon in Faunal Group V in the Brooks Range. Known in the pre-*Albaillella pennata*-2 associations, *Albaillella*-3 Assemblage, and possibly basal *Pseudoalbaillella* Assemblage of Holdsworth and Jones (1980a, b).

Occurrence.—Samples 18, 19, 20, and 21 at Nigu Bluff. Probable fragments of this species also occur in samples 10, 12, and 15 at Nigu Bluff.

Range.—late Osagean to Morrowan(?).

Scharfenbergia tailleurense n. sp.

Plate 34.2, figures 13, 15, 19-21

1986.

Tetratormentum sp. A Stewart and others, p. 1131, appendix fig. 1-U,V.

Diagnosis.—Test of perfect tetrahedral symmetry with sides flat or slightly convex, corners developed as more or less elongate conelike rays, spine terminated. Test internally coarsely and homogeneously spongy with external finely spongy layer, lacking well-defined pores. Terminal rodlike spines possibly continuous with rods of comparable strength and unknown interior extent incorporated axially or subaxially in rays.

Discussion.—This species is equivalent to "Spongodiscaceid gen. nov. (tetrahedral)" of Holdsworth and Jones (1980b, p. 23).

Type specimens.—From sample 78 Md-75E. Holotype USNM 391838, plate 34.2, figure 20. Paratypes USNM 391831, plate 34.2, figure 13; USNM 391833, plate 34.2, figure 15; USNM 391837, plate 34.2, figure 19; USNM 391839, plate 34.2, figure 21.

Measurements from 10 specimens including types.—Length of ray from center to terminal spine: 200 to 290 μm. Distance from tip of one ray to tip of adjacent ray: 260 to 370 μm. Size of "pores" in spongy test: less than 15 μm.

Occurrence.—Type specimens from sample 78 Md-75E (USGS MR 0813) in the Kuna Formation (Mull and others, 1982), northern Brooks Range, Alaska. Samples 22, 23, and 24 from Nigu Bluff. Faunal Groups II, IIA, and III.

Range.—Sample 78 Md-75E associated with early Morrowan conodont *Declinognathodus noduliferous* group (Bruce Wardlaw, written commun., 1980). Also occurs with late Morrowan or early Atokan conodonts in Nevada (Stewart and others, 1986). Total age range may be late Meramecian to Morrowan or early Atokan.

Scharfenbergia? sp. A (four-armed form)

Plate 34.2, figures 25-27

Remarks.—Characterized by four spongy arms, virtually parallel-sided, not always equally developed (fig. 27) and terminating in a solid spine. Internal structure unknown, but likely to compare with that of the recently discovered middle Osagean Polish stauraxon species (see discussion of stauraxons), the structure of which we suspect to be scharfenbergid. Somewhat similar forms ("Latentifistulidea sp., variant of *Tetratormentum* sp. A") in the Havallah assemblage of Nevada differ in having more conical arms (Stewart and others, 1986, appendix fig. 1-Q, R,T).

Occurrence.—In association with *S. impella* in the Group V sample, MR 0798, and also sample 18 (MR 6527) at the base of the Nigu Bluff radiolarian reference section. A similar, possibly identical form (*"Pseudohagiastrum(?) simplex" nomen nudum*) occurs in the Schoonover sequence in Nevada in assocation with probable pre-Chesterian conodonts (Miller and others, 1984).

Range.—Probably middle Osagean to Meramecian. Believed to be Meramecian at Nigu Bluff.

?Scharfenbergia ruestae (Ormiston and Lane) group

Plate 34.2, figures 16, 17, 22, 23

Remarks.—Included are usually poorly preserved specimens of triangular outline, sometimes with a suggestion of trilobation of the flattened test.

Occurrence.—Samples 23, 24, and 29 at Nigu Bluff.

Range.—Mississippian to Permian(?).

?Scharfenbergia spp. (late species)

Plate 34.2, figures 6, 9-12

Remarks.—Samples belonging to Groups III, IV, IVA, and VI contain frequent fragmentary, narrow-armed stauraxons of which examples are figured in plate 34.2. Their total structure remains unknown, but the architecture of the arms is similar to that of the coarsely perforate tube that encloses the axial filament of *Scharfenbergia turgida*, discussed previously. A perforate central sphere, sometimes present, slightly wider than the arms, closely resembles the sphere developed at the center of *S. turgida* (Won, 1983, pl. 9, fig. 8) and which in this species enclose the primary and primitive, delicate latticed capsule known in *S. impella* and *S. ruestae*. We believe that ?*Scharfenbergia* spp. (late species) arose from *S. turgida* or a similar form by elongation of the arms and reduction of the outer spongy layer to a loose patagium, remnants of which are usually apparent. This view has been stated earlier with respect to comparable forms characterizing the Schoonover sequence Group 5 samples of

Miller and others (1984, p. 1075). However, until the primary axial filament can be demonstrated within the tubular arm and the primitive capsule demonstrated within the globular central area, doubt will remain. Both primitive structures may have been secondarily lost in these inferentially late species. Members of this group are the only age-diagnostic fossils found in Group VI Brooks Range samples.

Occurrence.—Samples 25 to 29 at Nigu Bluff. Faunal Groups II, IIA, III, IV, IVA, VI.

Range.—Late Mississippian(?), Pennsylvanian, and Permian.

Family PATULIBRACCHIDAE
Pessagno 1971, emend.
Baumgartner 1980

Genus PARONAELLA Pessagno
1971, emend. Baumgartner 1980

Genus ?PARONAELLA Pessagno
1971, emend. Baumgartner 1980

Discussion.—The apparently truly spongy Pennsylvanian stauraxon that we tentatively include in this otherwise Mesozoic genus might be viewed as constituting a new, essentially monospecific genus of a new Paleozoic family. We are not prepared to erect such new taxa for a form whose structure is not completely known and at a time when the taxonomy of the Paleozoic stauraxons needs restructuring.

Paronaella? triporosa n. sp.

Plate 34.2, figures 1-5, 18

1986.
?*Tormentum* sp. Stewart and others, p. 1131, appendix fig. 1-W, X, Z.

Diagnosis.—*Paronaella triporosa* has very short arms that rapidly expand into arrow-shaped triangular terminations—the inner angles of the terminations linked by porous patagium that forms a subtriangular to subcircular test. Equiangular interarm spaces appear as subcircular to ovoid perforations, sometimes reduced by patagial infill. Test surface covered by large subrounded subequal pores with deep pore frames, the pores showing no marked alignment on rays or terminations. Inner structure is unclear, but cores of rays are apparently more densely spongy than the surficial layers and the material forming ray expansions. Short blunt terminal spines, one per ray, are not connected inwardly with any recognizable differentiated axial structure.

Remarks.—This species is equivalent, in part, to the unfigured "Complex *Paronaella* s.l. spp." of Holdsworth and Jones (1980b, p. 24).

Type specimens.—From sample 28 at Nigu Bluff. Holotype: USNM 391821, plate 34.2, figure 3. Paratype: USNM 391823, plate 34.2, figure 5.

Measurements from type specimens.—Length of arms: 260-300 μm (holotype); 260-300 μm (paratype). Distance between terminal spines: 460-500 μm (holotype); 480 to 530 μm (paratype). Average pore diameter: approximately 20 μm for holotype and paratype.

Occurrence.—Samples 26, 28, and 29 at Nigu Bluff. Faunal Groups III and part of IV in the northern Brooks Range. Also occurs in the Havallah sequence, Nevada (Hoffman Canyon, Tobin Range; see Stewart and others, 1986).

Range.—In Brooks Range sample 78 Md-75E, *P.? triporosa* occurs with the early Morrowan conodont *Declinognathodus noduliferous* group (Bruce Wardlaw, written commun., 1980). In sample USGS MR 0208 from the Havallah sequence of Nevada, *P.? triporosa* occurs with the conodonts *Idiognathoides delicatus* Gunnell, *Idiognathoides sinuatus* Harris and Hollingsworth, and *Neogondolella clarki* (Koike) of late Morrowan age (Bruce Wardlaw, written commun., 1980). Similar material collected nearby contains *P.? triporosa* and both Desmoinesian and reworked Morrowan conodonts (Bruce Wardlaw, written commun., 1982).

Subclass ?RADIOLARIA Muller
Order ?POLYCYSTINA Ehrenberg
1838, emend. Riedel 1967

Superfamily LATENTIFISTULIDEA
Nazarov and Ormiston 1983,
emended herein

Type species.—Latentifistula
crux Nazarov and Ormiston 1983

Emended diagnosis.—Paleozoic siliceous skeletons of stauraxon radiolarian aspect with a hollow central structure from which hollow, empty, radial elements arise.

Remarks.—We believe that the nature of the innermost axial structures (hollow versus solid) is the feature most important in establishing phyletic affinity amongst the Paleozoic stauraxons. We suspect from presently available evidence of earliest (Mississippian) forms, which seem to be Latentifistulidea in our restricted sense, that primitive forms may have possessed an imperforate, only slightly globular central area with the hollow axial elements imperforate for a considerable distance from the origin. *Latentifistula crux* Nazarov and Ormiston, type species of the nominative genus of the Latentifistulidae, appears to exhibit extreme modification of the primitive organization. Striking homeomorphy with some early (Mississippian) *Scharfenbergia* spp. (see previous discussions) has resulted.

Range.—late Tournaisian (middle Osagean) to Late Permian, so far as known.

Genus LATENTIFISTULA
Nazarov and Ormiston 1983

Latentifistula spp.

Plate 34.2, figures 7(?), 8, 14

Remarks.—Latentifistulids in our restricted sense have played little part in Brooks Range biostratigraphy. Imperforate hollow central spheres and hollow rays were noted rarely in samples assigned to Faunal Groups III, IV, IVA, and VI. Note the absence in the figured specimens of traces of an external, fibrous patagium such as are present in fragments of ?late *Scharfenbergia* spp. figured in the same plate.

Suborder ALBAILLELLARIA Deflandre 1953, emend. Holdsworth 1969

Family ALBAILLELLIDAE Deflandre 1952, emend. Holdsworth 1977

Genus ALBAILLELLA Deflandre 1952

Albaillella cartalla Ormiston and Lane 1976

1976.
Albaillella cartalla Ormiston and Lane, p. 171, pl. 5, figs. 9-15.
1983.
Albaillella cartalla Won, p. 125, pl. 12, figs. 1,2; pl. 14, fig. 3; text fig. 3a, b.

Albaillella sp. cf. A. cartalla Ormiston and Lane

Plate 34.1, figures 11-15

Remarks.—Included here are specimens, invariably found poorly preserved in chert residues, having strong segmentation that is variably oblique but commonly nearly transverse and small pointed wings that arise at or close to the same level on both sides of the shell and apparently possess little or no internal lacunae and no well-developed wing spine. Identical suites of specimens occur in chert of the Schoonover and Havallah sequences in Nevada, rarely with the characteristic H-frame of *A. cartalla* preserved (Miller and others, 1984; Stewart and others, 1986).

Occurrence.—Samples 20 and 21 at Nigu Bluff; Faunal Group IB.

Range.—Mississippian. Where, as in Nigu 20 and 21, it is found unassociated with other pennate *Albaillella* morphotypes, *A.* sp. cf. *A. cartalla* is likely to be pre-Chesterian in age.

Albaillella sp. ?cf. A. cartalla Ormiston and Lane

Plate 34.1, figure 6

Remarks.—This rather large form occurs with *Albaillella furcata* Won group in Faunal Group III. It is more similar to *A. cartalla* group specimens from upper Viséan (Meramecian to Chesterian) levels in Europe than to other lanceolate, pennate species.

Albaillella indensis Won 1983

1983.
Albaillella indensis Won, p. 127; pl. 1, figs. 19, 20; text figure 3g.

Albaillella indensis Won group

Plate 34.1, figures 16-20

Remarks.—Specimens have very well developed, strongly oblique segments sloping toward the aperture from the dorsal side of a shell, which is asymmetrically pear shaped in outline. The dorsal side curves continuously from apex to aperture, but commonly the curve of the ventral side changes rather sharply at about the level of the fifth of probably nine segments. Specimens lack true wings. Typically, a small, probably solid, sometimes flangelike spine is present dorsally in the region of the first four to five segments. An H-frame is never seen in the specimens from the Brooks Range.

Occurrence.—Faunal Group IA in the northern Brooks Range. Specimens in plate 34.1 are from sample USGS MR 0112 (lat 67°39′05″ N., long 145°18′30″ W.).

Range and discussion.—Members of *A. indensis* group were observed in 1978 in chert of the Innoko terrane, Alaska (Holdsworth and Jones, 1980b). Holdsworth and Jones (1980a, b) recognized that these earliest "lanceolate, well-segmented *Albaillellas*" probably characterized a specific segment of the Paleozoic record, but erroneously believed the *A. indensis* group to be no older than Meramecian. The discovery of *A. indensis* group (*A. pirum* group *nomen nudum*, not figured, Miller and others, 1984) with the conodont *Scaliognathus anchoralis europensis* in the Schoonover sequence pushed back the earliest known occurrence to the middle Osagean. By 1983, correlative occurrences were known to the senior author at least as early as the late Tournaisian (Tn3c) in Germany. The authors had not observed German or American specimens with preserved H-frames. In 1983 Won described *A. indensis* with a robust H-frame from a pebble of undated chert from Germany. The senior author realized that *A. indensis* was clearly related to his unfigured "*A. pirum*" group (*nomen nudum*); he was convinced beyond reasonable doubt that "*A. pirum*" (*nomen nudum*) group is *A. indensis* Won group in 1986 when Mariusz Paszkowski showed him Polish specimens of the taxa with intact H-frames from the *S. anchoralis* conodont zone of Poland.

The total age range of *A. indensis* group is at least middle Osagean to earliest Meramecian, and it may be longer.

Albaillella furcata Won 1983

1983.
Albaillella furcata Won, p. 126-127; pl. 12, figs. 3,4,5,7; text fig. 3f.

Albaillella rockensis Cheng 1986

1986.
Albaillella rockensis Cheng, p. 61-62, pl. 11, figs. 2,3,11,12,13,18,21.

Albaillella furcata Won group

Plate 34.1, figures 8-10

Remarks.—Members of the group are characterized by inflation of the segmented shell and constriction of the shell at the girdle containing the anterior wing termination. The H-frame in complete specimens proves that these are true forms of *Albaillella* in spite of the superficial resemblance of the incomplete Alaskan specimens to inflated forms of *Pseudoalbaillella* Holdsworth and Jones. The shell features are clearly apparent even in the poor sample 78 Md-75E (USGS MR 0813) specimens. Holdsworth and Jones (1980a, b) were almost certainly wrong in viewing these specimens as very early *Pseudoalbaillella* sp. Nevertheless, *A. furcata* group demonstrates how the *Pseudoalbaillella* organization may have arisen.

Range.—*A. furcata* group occurs with the early Morrowan conodont *Declinognathodus noduliferous* (conodont identified by Bruce Wardlaw, USGS) in sample 78 MD-75E (USGS MR 0813). The total age range of *A. furcata* group is Meramecian to Morrowan, so far as known.

Family ALBAILLELLIDAE
Deflandre 1952,
emend. Holdsworth 1976 or
FOLLICUCULLIDAE
Ormiston and Babcock 1979
Genus PSEUDOALBAILLELLA
Holdsworth and Jones 1980a
HAPLODIACANTHUS
Nazarov and Rudenko 1981
(junior synonym)

Remarks.—We follow herein the suggestions of Ishiga and others (1982b, p. 44-45) regarding the nomenclature for designating many of the Pennsylvanian and Permian Albaillellaria (with the exception of the genus *Parafollicucullus*, which we have not considered synonymous with *Pseudoalbaillella*). In their discussion, Ishiga and others (1982b) describe the problem of assigning family-level designations to these forms. In addition, they delineate the problems of precedence and synonymies.

Pseudoalbaillella globosa
Ishiga and Imoto 1982

1982a.
Pseudoalbaillella sp. B Ishiga and others, pl. 2, figs. 3,4.
1982b.
Pseudoalbaillella globosa: Ishiga and others, p. 275, pl. 1, figs. 1-8
?1985.
Parafollicucullus globosus: Cornell and Simpson, p. 277, pl. 1, figs. 4,8

Pseudoalbaillella globosa
Ishiga and Imoto group

Plate 34.1, figures 1, 3-5

Remarks.—Included here are *Pseudoalbaillella* specimens with a short pseudoabdomen and subglobular pseudothorax separated into two lobes by shallow longitudinal dorsal and ventral grooves that lie in the plane of symmetry and contain the bases of the wings.

Occurrence.—Faunal Group IVA in the northern Brooks Range. Specimens figures in plate 34.1 are from sample USGS MR 0798 (lat 68°15′33″ N., long 159°07′15″ W.).

Range.—This apparently advanced group of *Pseudoalbaillella* sp. occurs with *Parafollicucullus fusiformis* Holdsworth and Jones, which is not known to predate the late Early Permian, in Oregon and Japan. In western Texas, the group occurs in Leonardian strata (Cornell and Simpson, 1985).

REFERENCES CITED

Baumgartner, P.O., 1980, Late Jurassic Hagiastridae and Patulibracchiidae (Radiolaria) from the Argolis Peninsula (Peloponnesus, Greece): Micropaleontology, v. 26, no. 3, p. 274-322.

Chapman, R.M., Detterman, R.L., and Mangus, M.D., 1964, Geology of the Killik-Etivluk Rivers region, Alaska: U.S. Geological Survey Professional Paper 303-F, p. 325-407.

Cheng, Y.-N., 1986, Taxonomic studies on Upper Paleozoic Radiolaria: National Museum of Natural Science (Taiwan, Republic of China), Special Publication 1, 311 p.

Cornell, W.C., and Simpson, R.D., 1985, New Permian albaillellid radiolarians from West Texas: Micropaleontology, v. 31, no. 3, p. 271-279.

Curtis, S.M., Ellersieck, Inyo, Mayfield, C.F., and Tailleur, I.L., 1982, Reconnaissance geologic map of southwestern Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Open-File Report 82-611, 43 p., 2 sheets, scale 1:63,360.

—— 1983, Reconnaissance geologic map of the De Long Mountains A1, B1, and part of C1 quadrangles, Alaska: U.S. Geological Survey Open-File Report 83-185, 54 p. 2 sheets, scale 1:63,360.

—— 1984, Reconnaissance geologic map of the southwestern Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1502, 2 sheets, scale 1:63,360.

Deflandre, Georges, 1952, *Albaillella* gen. nov., Radiolaire fossile du carbonifere inferieur, type d'une lignee aberrante éteinte [*Albaillella* gen. nov., fossil radiolarian of Upper Carboniferous, type of an extinct aberrant lineage]: Academie des Sciences Comptes Rendus, v. 234, p. 872-874.

—— 1953, Radiolaires fossiles [Fossil Radiolaria], *in* Grassé, P.P., ed., Traite de Zoologie: Masson, v. 1, pt. 2, p. 389-436.

Ehrenberg, C.G., 1838, Über die Bildung der Kreidefelsen und des Kreidemergels durch unsichtbare Organismen [On the formation of chalk cliffs and chalk marl by invisible organisms]: Abhandlungen der Königliche Akademie der Wissenschaften zu Berlin, Jahrgang 1838, p. 59-147, pl. 1-4.

—— 1875, Fortsetzung der mikrogeologischen Studien als Gesammt-Uebersicht der mikroskopischen Paläontologie gleichartig analysirter Gebirgsarten der Erde, mit specieller Rücksicht auf den Polycystinen-Mergel von Barbados [The pursuit of microgeological studies as a general overview of the microscopic paleontology of similarly analyzed rock types of the Earth, with special reference to the Polycystine-marl of Barbados]: Abhandlungen der Königliche Akademie der Wissenschaften zu Berlin, Jahrgang 1875, p. 1-226, pl. 1-30.

Ellersieck, Inyo, Curtis, S.M., Mayfield, C.F., and Tailleur, I.L., 1982, Reconnaissance geologic map of south-central

Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Open-File Report 82-612, 38 p., 2 sheets, scale 1:63,360.

—— 1983, Reconnaissance geologic map of the De Long Mountains A2, B2, and part of C2 quadrangles, Alaska: U.S. Geological Survey Open-File Report 83-184, 54 p., 2 sheets, scale 1:63,360.

—— 1984, Reconnaissance geologic map of south-central Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1504, 2 sheets, scale 1:63,360.

Fay, R.O., 1969, Geology of the Arbuckle Mountains along Interstate 35, Carter and Murray Counties, Oklahoma: Ardmore, Okla., Ardmore Geological Society Guidebook.

Hinde, G.J., and Fox, H., 1895, On a well-marked horizon of radiolarian rocks in the Lower Culm Measures of Devon, Cornwall and West Somerset: Quarterly Journal of the Geological Society of London, v. 51, p. 609-688.

Holdsworth, B.K., 1969, The relationship between the genus *Albaillella* Deflandre and the ceratoikiscid Radiolaria: Micropaleontology, v. 15, no. 2, p. 230-236.

—— 1977, Paleozoic Radiolaria; stratigraphic distribution in Atlantic borderlands, *in* Swain, F.M., ed., Stratigraphic micropaleontology of Atlantic Basin and borderlands: Amsterdam, Elsevier, Developments in Paleontology and Stratigraphy, v. 6, p. 167-184.

Holdsworth, B.K., and Jones, D.L., 1980a, Preliminary radiolarian zonation for Late Devonian through Permian time: Geology, v. 8, p. 281-285.

—— 1980b, A provisional Radiolaria biostratigraphy, Late Devonian through Late Permian: U.S. Geological Survey Open-File Report 80-876, 32 p, 2 oversize sheets.

Ishiga, Hiroaki, 1982, Late Carboniferous and Early Permian radiolarians from the Tamba Belt, Southwest Japan: Earth Science (Chikyu Kagaku), v. 36, p. 333-339.

Ishiga, Hiroaki, Kito, Takeo, and Imoto, Nobuhiro, 1982a, Permian radiolarian biostratigraphy: News of Osaka Micropaleontologists, Special Volume 5, p. 17-26.

—— 1982b, Middle Permian radiolarian assemblages in the Tamba District and an adjacent area, southwest Japan: Earth Science (Chikyu Kagaku), v. 36, no. 5, p. 272-281.

Kozur, Heinz, 1980, Ruzhencevispongidae, eine neue Spumellaria-Familie aus dem oberen Kungurian (Leonardian) und Sakmarian des Vorurals [Ruzhencevispongidae, a new spumellarian family from the upper Kungurian (Leonardian) and Sakmarian of the Preurals]: Geologisch-Palaontologische Mitteilungen Innsbruck, v. 10, p. 235-242.

Mayfield, C.F., Curtis, S.M., Ellersieck, Inyo, and Tailleur, I.L., 1982, Reconnaissance geologic map of southeastern Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Open-File Report 82-613, 40 p., 2 sheets, scale 1:63,360.

—— 1983a, Reconnaissance geologic map of the De Long Mountains A3, B3, and parts of A4, B4 quadrangles, Alaska: U.S. Geological Survey Open-File Report 83-183, 60 p., 2 sheets, scale 1:63,360.

—— 1984, Reconnaissance geologic map of southeastern Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1503, 2 sheets, scale 1:63,360.

Mayfield, C.F., Ellersieck, Inyo, and Tailleur, I.L., 1987, Reconnaissance geologic map of the Noatak C5, D5, D6, and D7 quadrangles, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1814, 1 sheet, scale 1:63,360.

Mayfield, C.F., Tailleur, I.L., and Ellersieck, Inyo, 1983b, Stratigraphy, structure, and palinspastic synthesis of the western Brooks Range, northwestern Alaska: U.S. Geological Survey Open-File Report 83-779, 61 p., 5 oversize sheets.

Miller, E.L., Holdsworth, B.K., Whiteford, W.B., and Rodgers, D., 1984, Stratigraphy and structure of the Schoonover sequence, northeastern Nevada; implications for Paleozoic plate-margin tectonics: Geological Society of America Bulletin, v. 95, p. 1063-1076.

Mull, C.G., Crowder, R.K., Adams, K.E., Siok, J.P., Bodnar, D.A., Harris, E.E., Alexander, R.A., and Solie, D.N., 1987, Stratigraphy and structural setting of the Picnic Creek allochthon, Killik River quadrangle, central Brooks Range, Alaska; a summary: *in* Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, California, Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 649-662.

Mull, C.G., Tailleur, I.L., Mayfield, C.F., Ellersieck, Inyo, and Curtis, S.M., 1982, New upper Paleozoic and lower Mesozoic stratigraphic units, central and western Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 66, no. 3, p. 348-362.

Müller, Johannes, 1858, Über die Thalassicollen, Polycistinen und Acanthometren des Mittelmeeres [On the Thalassicolida, Polycystina, and Acanthometrea of the Mediterranean]: Abhandlungen der Königliche Akademie der Wissenschaften zu Berlin, Jahrgang 1858: p. 1-62, pls. 1-11.

Murchey, B.L., Swain, P.B., and Curtis, S.M., 1981, Late Mississippian to Pennsylvanian radiolarian assemblages in the Siksikpuk(?) Formation at Nigu Bluff, Howard Pass quadrangle, Alaska, *in* Albert, N.R., and Hudson, Travis, eds., The United States Geological Survey in Alaska; accomplishments during 1979: U.S. Geological Survey Circular 823-B, p. B17-B19.

Nazarov, B.B., and Ormiston, A.R., 1983, A new superfamily of stauraxon polycystine Radiolaria from the late Paleozoic of the Soviet Union and North America: Senckenbergiana lethaea, v. 64, p. 363-379.

—— 1985, Radiolaria from the late Paleozoic of the Southern Urals, USSR, and West Texas, USA: Micropaleontology, v. 31, p. 1-54.

—— 1986, Origin and biostratigraphic potential of the stauraxon polycystine Radiolaria: Marine Micropaleontology, v. 11, p. 33-54.

Nazarov, B.B., and Rudenko, V.S., 1981, Some bilaterally symmetrical late Paleozoic radiolarians of the South Urals [in Russian]: Voprosy Mikropaleontologii, v. 24, p. 129-139.

Ormiston, A.R., and Babcock, Laurel, 1979, *Follicucullus*, new radiolarian genus from the Guadalupian (Permian) Lamar Limestone of the Delaware Basin: Journal of Paleontology, v. 53, no. 2, p. 328-334.

Ormiston, A.R., and Lane, H.R., 1976, A unique radiolarian fauna from the Sycamore Limestone (Mississippian) and its biostratigraphic significance: Paleontographica, pt. A, v. 154, no. 4-6, p. 158-180.

Patton, W.W., Jr., 1957, A new upper Paleozoic formation, central Brooks Range, Alaska: U.S. Geological Survey Professional Paper 303-B, p. 41-45.

Pessagno, E.A., Jr., 1971, Jurassic and Cretaceous Hagiastridae from the Blake-Bahama Basin (Site 5A Joides Leg 1) and Great Valley Sequence, California Coast Range: Bulletin of American Paleontology, v. 60, p. 1-83.

Riedel, W.R., 1967, Some new families of Radiolaria: Geological Society of London Proceedings, no. 1640, p. 148-149.

Rüst, D., 1892, Beiträge zur Kenntnis der fossilen Radiolarien aus Gesteinen der Trias und der Palaeozoischen Schichten [Contributions to the knowledge of fossil Radiolaria from Triassic and Paleozoic strata]: Palaeontographica, v. 38, p. 107-192.

Sandberg, C.A., and Gutschick, R.C., 1984, Distribution, microfauna, and source-rock potential of Mississippian Delle Phosphatic Member of Woodman Formation and equivalents, Utah and adjacent states, *in* Woodward, Jane, Messner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the greater Rocky Mountain region: Denver, Colorado, Rocky Mountain Association of Geologists, p. 135-178.

Stewart, J.H., Murchey, B.L., Jones, D.L., and Wardlaw, B.R., 1986, Paleontologic evidence for complex tectonic interlayering of Mississippian to Permian deep-water rocks of the Golconda allochthon in Tobin Range, north-central Nevada: Geological Society of America Bulletin, v. 97, p. 1122-1132.

Won, Moon-zoo, 1983, Radiolarien aus dem Unterkarbon des Rheinischen Schiefergebirges (Deutschland) [Radiolaria from the Lower Carboniferous of the Rhenish Schiefergebirge (Germany)]: Palaeontographica, pt. A, v. 182, p. 116-175.

PLATES 34.1, 34.2

[Contact photographs of the plates in this report are available, at cost, from the U.S. Geological Survey Photographic Library, Federal Center, Denver, Colorado 80225]

PLATE 34.1

[Paleozoic radiolarians from the northern Brooks Range, Alaska]

FIGURES 1, 3-5. *Pseudoalbaillella globosa* group. All specimens from USGS sample MR 0798 (78 MD-37); bar, 170 µm.
  1. Specimen USNM 391795.
  3. Specimen USNM 391797.
  4. Specimen USNM 391798.

2. *Pseudoalbaillella* sp. Specimen USNM 391796 from USGS sample MR 6537 (Nigu-28). Bar, 150 µm.

6. *Albaillella* sp. ?cf. *A. cartalla*. Specimen USNM 391800 from USGS sample MR 0813 (78 MD-75E). Bar, 160 µm.

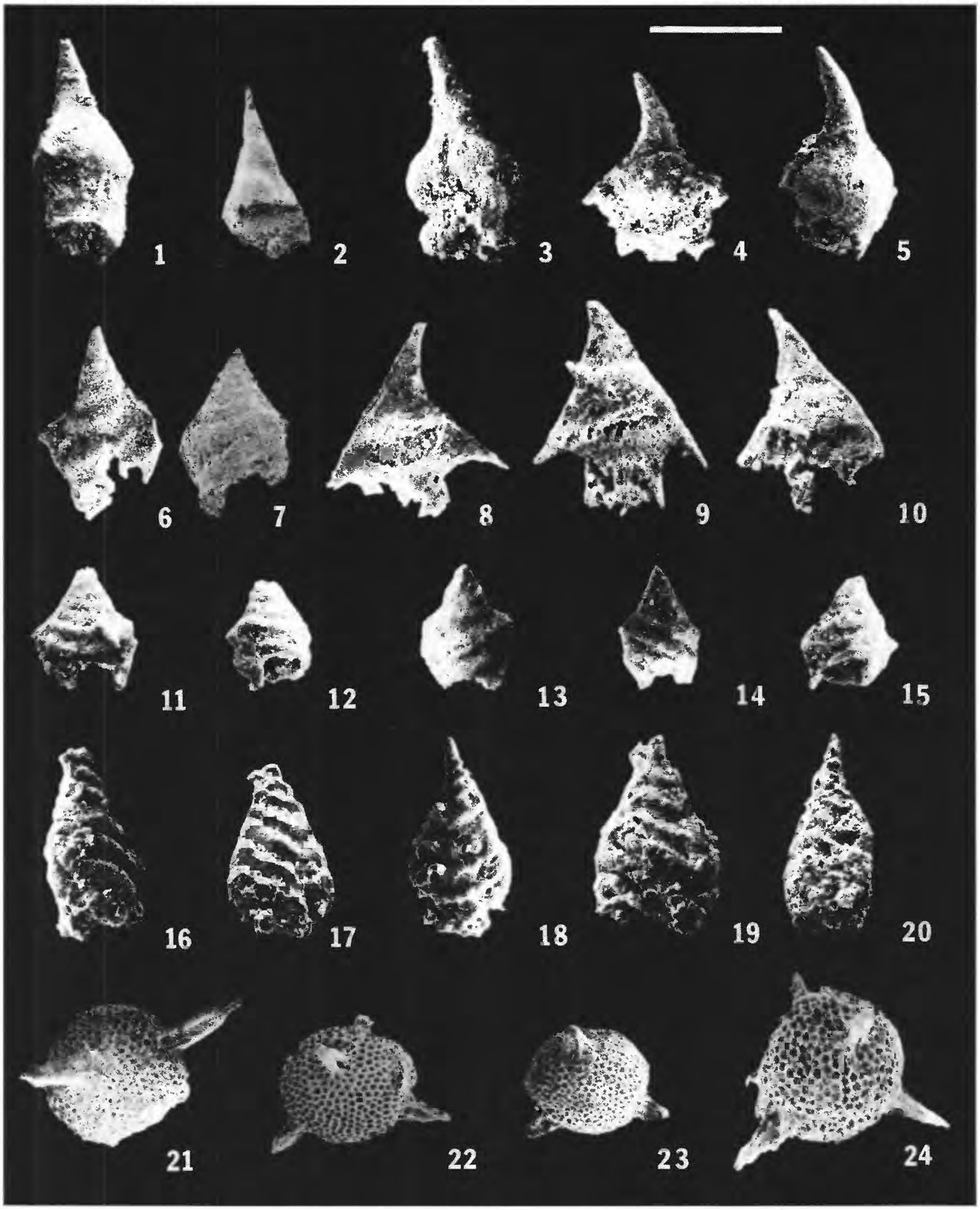
7. *Albaillella* sp. Specimen USNM 391801 from USGS sample MR 6535 (Nigu-26). Bar, 130 µm.

8-10. *Albaillella furcata* group. All speciments from USGS sample MR 0813 (78 MD-75E); bar, 160 µm.
  8. Specimen USNM 391802.
  9. Specimen USNM 391803.
  10. Specimen USNM 391804.

11-15. *Albaillella* sp. cf. *A. cartalla*. All specimens from USGS sample 6530 (Nigu-21); bar, 160 µm.
  11. Specimen USNM 391805.
  12. Specimen USNM 391806.
  13. Specimen USNM 391807.
  14. Specimen USNM 391808.
  15. Specimen USNM 391809.

16-20. *Albaillella indensis* Won group. All specimens from USGS sample MR 0112 (60 ARR 663); bar, 160 µm.
  16. Specimen USNM 391810.
  17. Specimen USNM 391811.
  18. Specimen USNM 391812.
  19. Specimen USNM 391813.
  20. Specimen USNM 391814.

21-24. Spheroid sp. A group.
  21. Specimen USNM 391815 from USGS sample MR 5272 (77 MD-85B). Bar, 170 µm.
  22. Specimen USNM 391816 from USGS sample MR 6535 (Nigu-26). Bar, 220 µm.
  23. Specimen USNM 391817 from USGS sample MR 6538 (Nigu-29). Bar, 250 µm.
  24. Specimen USNM 391818 from USGS sample MR 0813 (78 MD-75E). Bar, 170 µm.



PSEUDOALBAILLELLA, ALBAILLELLA, SPHEROIDS

PLATE 34.2

[Paleozoic radiolarians from the northern Brooks Range, Alaska]

FIGURES 1-5, 18. *Paronaella triporosa* n.sp.

1. Specimen USNM 391819 from USGS sample MR 6535 (Nigu-26). Bar, 390 μm.
2. Specimen USNM 391819 from USGS sample MR 6538 (Nigu-29). Bar, 290 μm.
3. Holotype. Specimen USNM 391821 from USGS sample MR 6537 (Nigu-28). Bar, 330 μm.
4. Specimen USNM 391822 from USGS sample MR 6538 (Nigu-29). Bar, 280 μm.
5. Paratype. Specimen USNM 391823 from USGS sample MR 6537 (Nigu-28). Bar, 330 μm.
18. Specimen USNM 391836 from USGS sample MR 0813 (78 MD-75E). Bar, 230 μm.

6, 9-12. ?*Scharfenbergia* sp. (late species).

6. Specimen USNM 391824 from USGS sample MR 0813 (78 MD-75E). Bar, 330 μm.
9. Specimen USNM 391827 from USGS sample MR 6538 (Nigu-29). Bar, 360 μm.
10. Specimen USNM 391828 from USGS sample MR 6538 (Nigu-29). Bar, 570 μm.
11. Specimen USNM 391829 from USGS sample MR 6536 (Nigu-26). Bar, 210 μm.
12. Specimen USNM 391830 from USGS sample MR 6538 (Nigu-29). Bar, 150 μm.

7. *Latentifistula*? sp. Specimen USNM 391825 from USGS sample MR 6538 (Nigu-29). Bar, 570 μm.

8, 14. *Latentifistula* sp.

8. Specimen USNM 391826 from USGS sample MR 6535 (Nigu-26). Bar, 210 μm.
14. Specimen USNM 391825 from USGS sample MR 6538 (Nigu-29). Bar, 570 μm.

13, 15, 19-21. *Scharfenbergia tailleurense* n.sp. All specimens from USGS sample MR 0813 (78 MD-75E); bar, 290 μm for all specimens except figure 20 where bar is 250 μm.

13. Paratype. Specimen USNM 391831.
15. Paratype. Specimen USNM 391833.
19. Paratype. Specimen USNM 391837.
20. Holotype. Specimen USNM 391838.
21. Paratype. Specimen USNM 391839.

16, 17. ?*Scharfenbergia ruestae*. Specimens from USGS sample 0813 (78 MD-75E); bar, 290 μm.

16. Specimen USNM 391834.
17. Specimen USNM 391835.

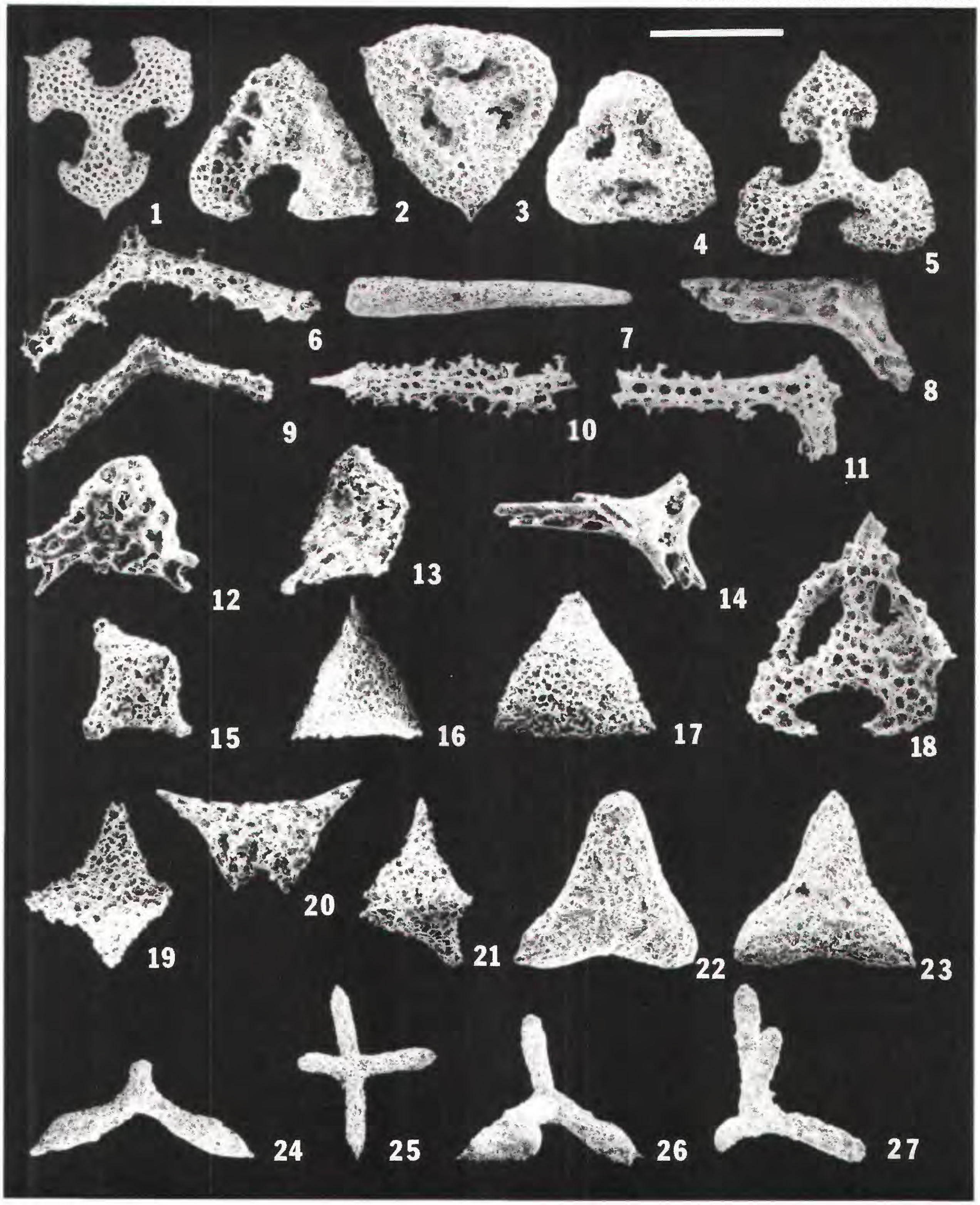
22, 23. ?*Scharfenbergia ruestae*. Specimens from USGS sample MR 6533 (Nigu-24): bar, 290 μm.

22. Specimen USNM 391840. Note slightly concave outline between corners.
23. Specimen USNM 391841. Note slightly concave outline between corners.

24. *Scharfenbergia impella*. Specimen USNM 391842 from USGS sample MR 6527 (Nigu-18). Bar, 500 μm.

25-27. *Scharfenbergia*? sp. A (four-armed form). All specimens from USGS sample MR 6527 (Nigu-18); bar, 500 μm.

25. Specimen USNM 391843.
26. Specimen USNM 391844.
27. Specimen USNM 391845.



PARONAELLA, SCHARFENBERGIA, LATENTIFISTULA

Typical cores of potential reservoir rocks from the Ikpikpuk No. 1 well, at depths of 3243 to 3246 m (10,641-10,649 ft) and 3296 to 3299 m (10,815-10,821 ft) in the Ivishak Formation. Holes are where plugs were drilled to determine porosity and permeability. The Ivishak Formation is the main producing horizon at the Prudhoe Bay oil field.

RESERVOIR ROCKS

The reservoir characteristics of the subsurface layers drilled in the NPRA have been systematically recorded and analyzed by the exploration contractors through the use of well logs and selected laboratory methods. The data and analyses, including all well logs, can be found in the Husky and Tetra Tech final reports and in the open-file materials available from the National Geophysical Data Center, NOAA, Boulder, Colorado 80303.

To supplement the subsurface testing and the reservoir studies and to gain a better understanding of the depositional and diagenetic history of the rocks in the NPRA, field surveys were made part of the exploration program. Some of the results of these studies are included in the geologic framework reports, but two chapters are included here to illustrate the type of reservoir studies initiated under this program.

From the drilling results and the studies recorded here, it can be concluded that the lack of good reservoirs is a major reason why hydrocarbon deposits of sufficient size to be developed under current economic conditions appear to be absent and have not been discovered in the NPRA.

35. SANDSTONE PETROGRAPHY OF THE NANUSHUK GROUP AND TOROK FORMATION

By SUSAN BARTSCH-WINKLER and A. CURTIS HUFFMAN, JR.

INTRODUCTION

Surface and subsurface samples of sandstone from the Lower and Upper Cretaceous Nanushuk Group and the Lower Cretaceous Torok Formation were examined to determine the textural and mineralogical factors that might indicate their source and affect reservoir characteristics. The samples were collected from scattered outcrops (samples number 1075 through 5475), from measured sections in the western and central outcrop belts, and from the subsurface (Bartsch-Winkler, 1979, 1981; Huffman, 1979; Bartsch-Winkler and Huffman, 1981) (fig. 35.1). The stratigraphic sections in the Nanushuk Group range in depositional setting from fluvial through deltaic to shallow marine and show variations in texture, composition, and diagenetic alteration. Samples of the Torok are believed by Bird and Andrews (1979) to be deeper water marine equivalents of Nanushuk sandstone; that is, the two units are lateral equivalents of a single depositional system. Sampling was not systematic; rather, it concentrated on the coarser grained, thicker sandstone beds, which are of greater interest from the standpoint of provenance and potential petroleum reservoirs; most surface samples examined were from the fluvial and deltaic regimes; the thicker beds were frequently sampled at several horizons. The surface samples were collected by James E. Fox (presently at the South Dakota School of Mines) in July 1975 from scattered outcrops of the Nanushuk Group, and so their depositional settings are known. The subsurface samples were obtained from cores stored at U.S. Geological Survey (USGS) warehouses in Fairbanks and Anchorage. Some of the thin sections were made from the remains of ''perm plugs'' used to determine porosity and air permeability (Robinson, 1956, 1958, 1959a, b, c, 1964; Collins, 1958a, b, 1959). These samples, taken from the wells drilled by the U.S. Navy before 1975, include those from Kaolak No. 1, Topagoruk No. 1, Simpson No. 1, Meade No. 1, Oumalik No. 1, Titaluk No. 1, Wolf Creek Nos. 1 and 3, Grandstand No. 1, Knifeblade No. 2A, Square Lake No. 1, and Gubik No. 2 wells. Samples analyzed from wells drilled more recently by the USGS include those from East Simpson No. 1, J.W. Dalton No. 1, Inigok No. 1, Seabee No. 1, Fish Creek No. 1, Tunalik No. 1, Peard No. 1, South Meade No. 1, and South Barrow Nos. 1 and 6 wells. The relative stratigraphic positions of the subsurface samples are well known, but environments of deposition have not been identified. Modal analyses were performed on a total of 199 thin sections, and observations on the textural details were made on many more samples. Preliminary results of the petrographic study of the sandstones were reported in USGS Circular 794 (Bartsch-Winkler, 1979; Huffman, 1979), USGS Circular 823-B (Bartsch-Winkler and Huffman, 1981), and USGS Bulletin 1614 (Bartsch-Winkler, 1985). Krynine (1947, 1948), Krynine and Ferm (1952), Fox (1979), and Fox and others (1979) studied the petrography of rocks from the Umiat test wells, and their sandstone descriptions served as invaluable introductions to the complexities and nuances of the sandstone in the Nanushuk Group and Torok Formation examined in this study.

METHODS OF STUDY

Sandstone samples were submitted for thin sectioning, staining, and impregnation to commercial laboratories under contractual agreement with the USGS. The thin sections were stained with sodium cobaltinitrite to aid in identification of potassium feldspar and with alizarin red to aid in identification of dolomite. Owing to the poor quality of the thin sections, especially for the impregnation and feldspar staining, in all samples except those from post-1975 wells, modal data on visible porosity and potassium feldspar content are considered tentative. For modal analyses, a minimum of 300 grains were counted per thin section. Framework and matrix materials were categorized according to the definitions of Dickinson (1970) except for chert grains (see following discussion). Whole-rock X-ray studies were conducted on some of the samples by Paul D. Blackmon and

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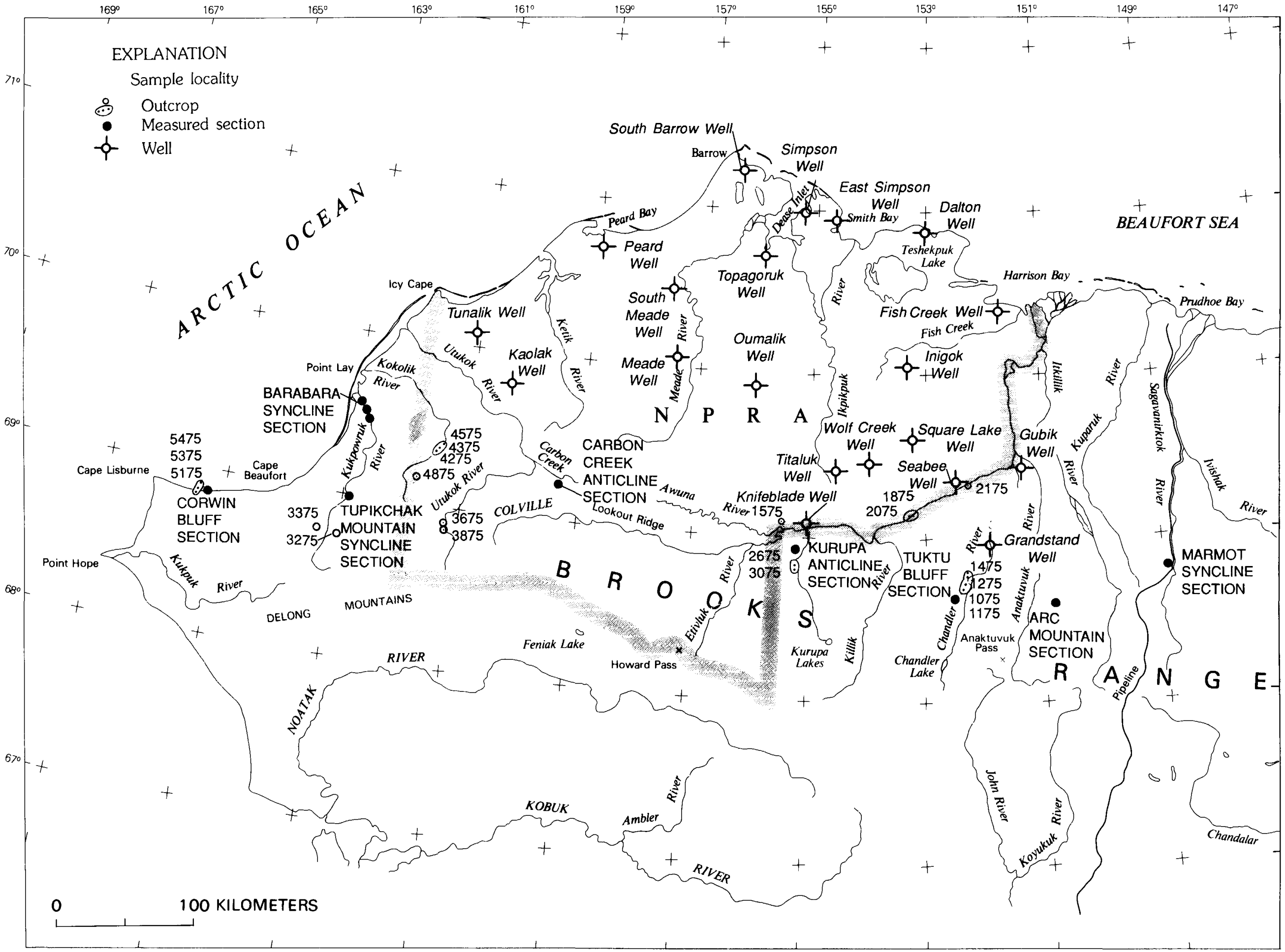


FIGURE 35.1.—Localities of samples for the petrographic study of Nanushuk Group and Torok Formation sandstones.

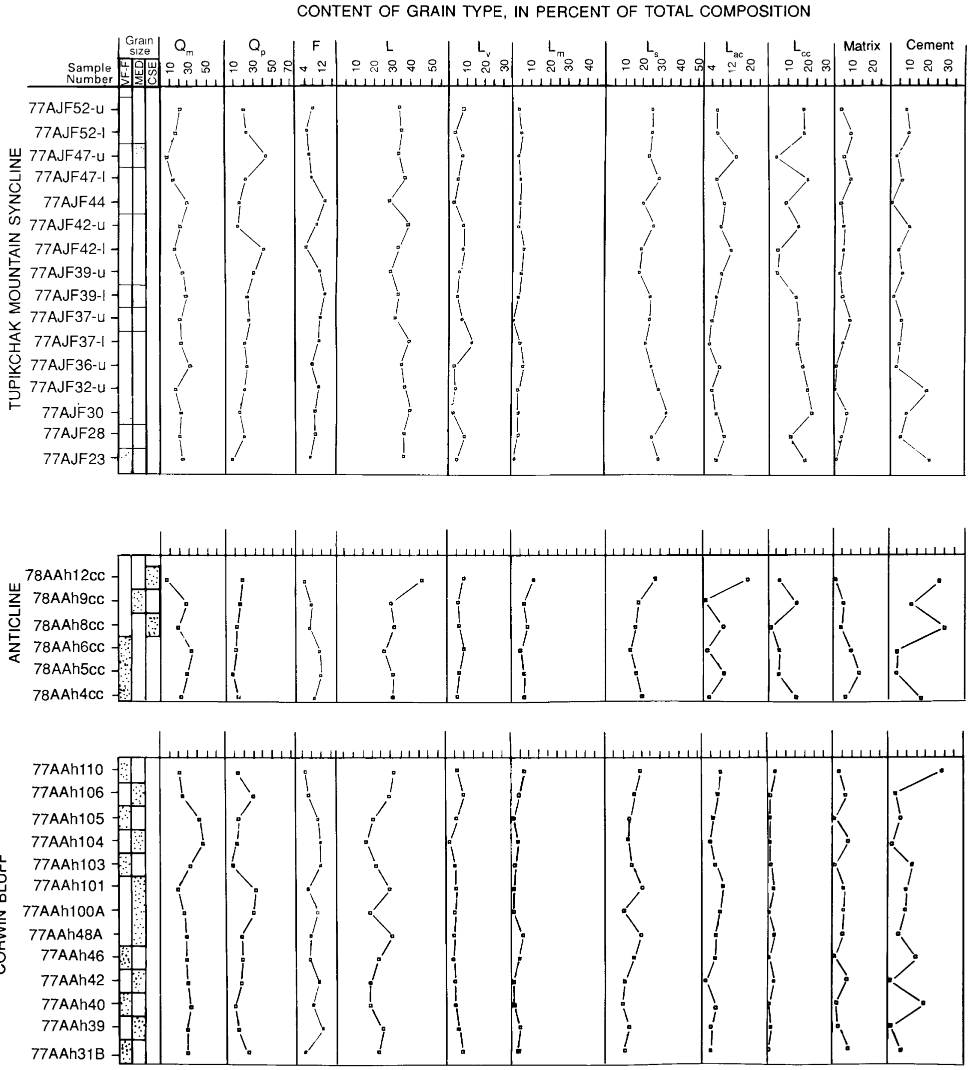


FIGURE 35.2.—Vertical variation in percentage compositions of sandstone samples of Nanushuk Group and Torok Formation from measured sections and wells. Starred samples from Torok Formation. Localities shown on figure 35.1. Q_m, monocrystalline quartz; Q_p, polycrystalline quartz; F, feldspar; L, lithic grains; L_v, volcanic lithic grains; L_m, metamorphic lithic grains; L_s, sedimentary lithic grains; L_{ac}, argillaceous and carbonaceous grains; L_{cc}, calcareous grains. VF-F, very fine to fine grained; MED, medium grained; CSE, coarse grained. No vertical scale.

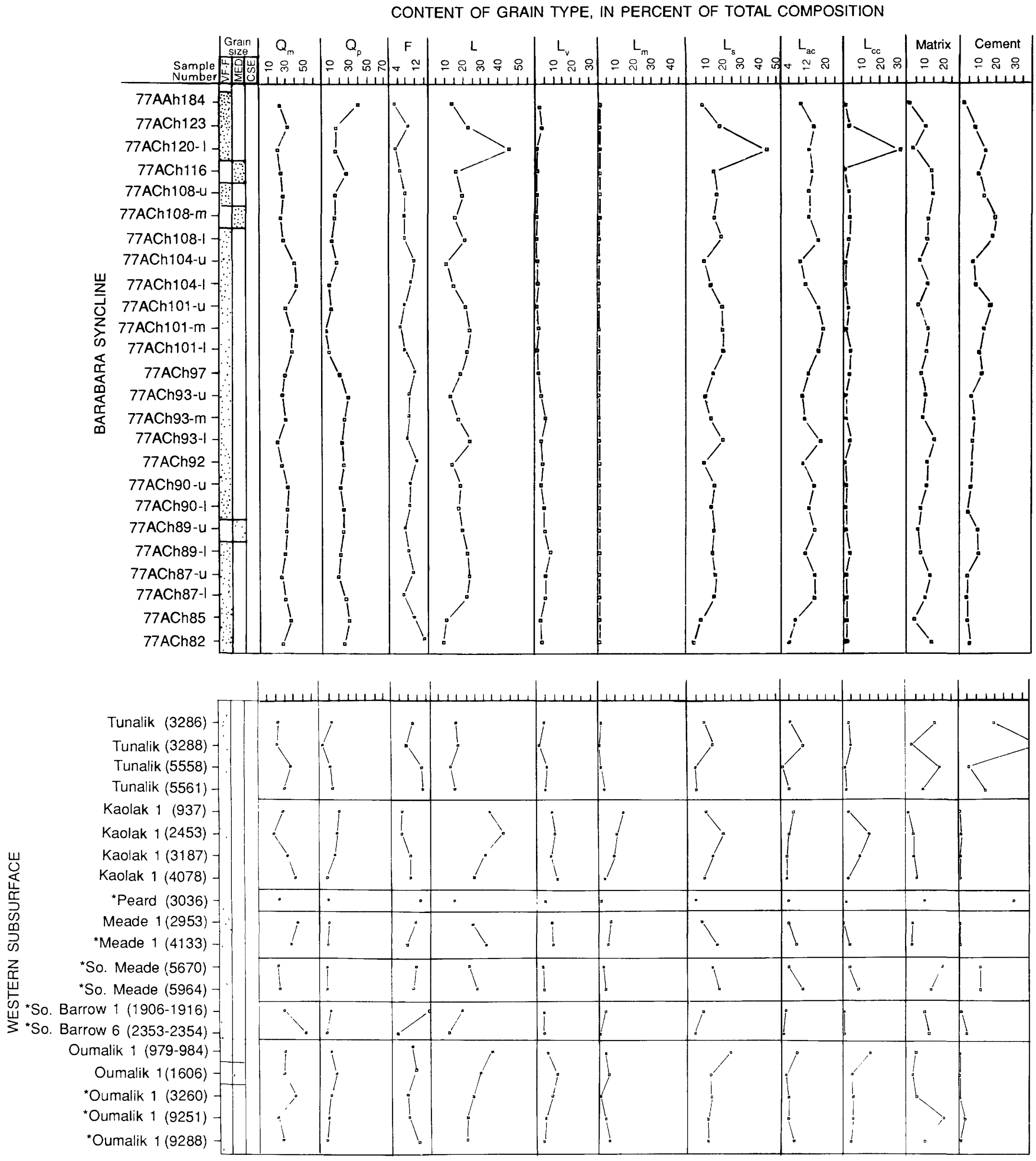


FIGURE 35.2.—Continued

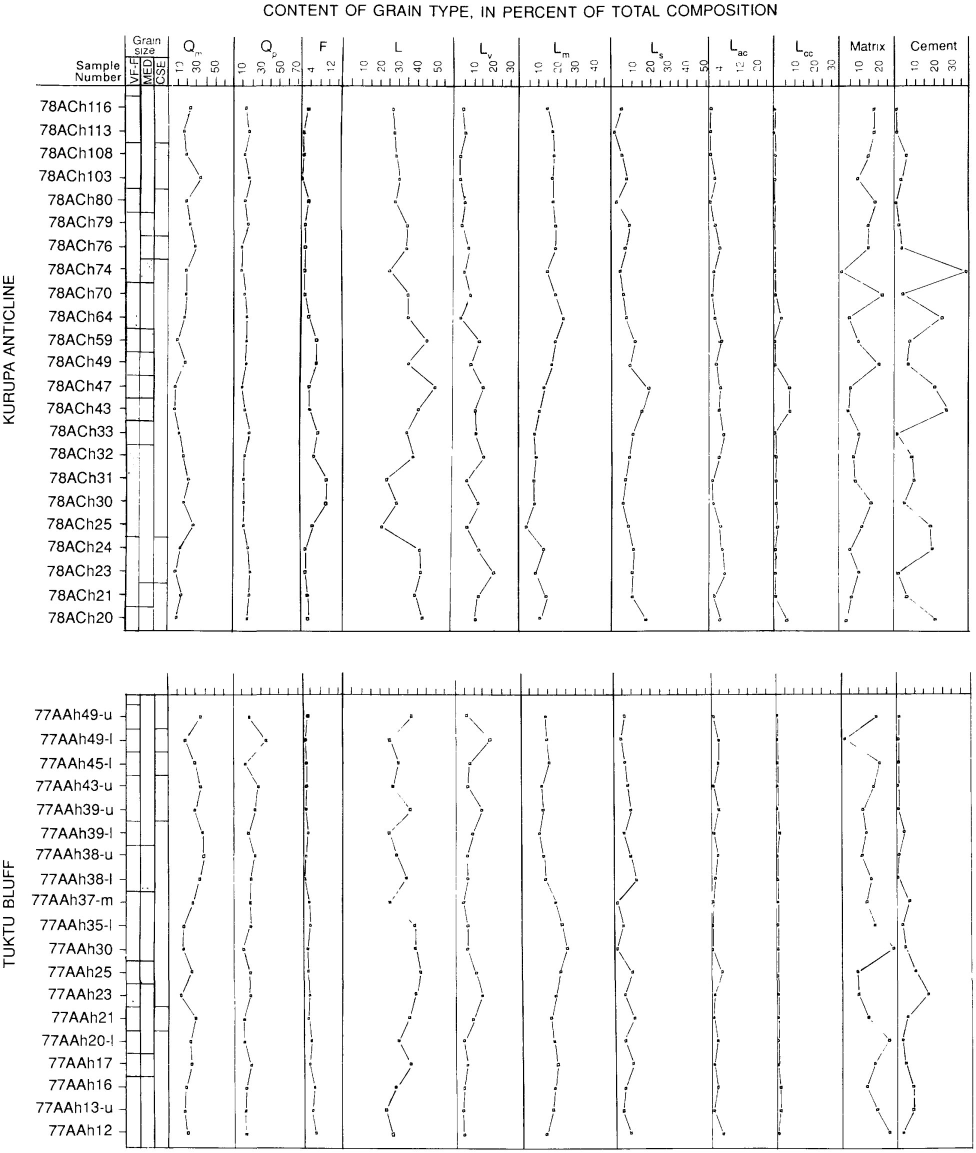


FIGURE 35.2.—Continued

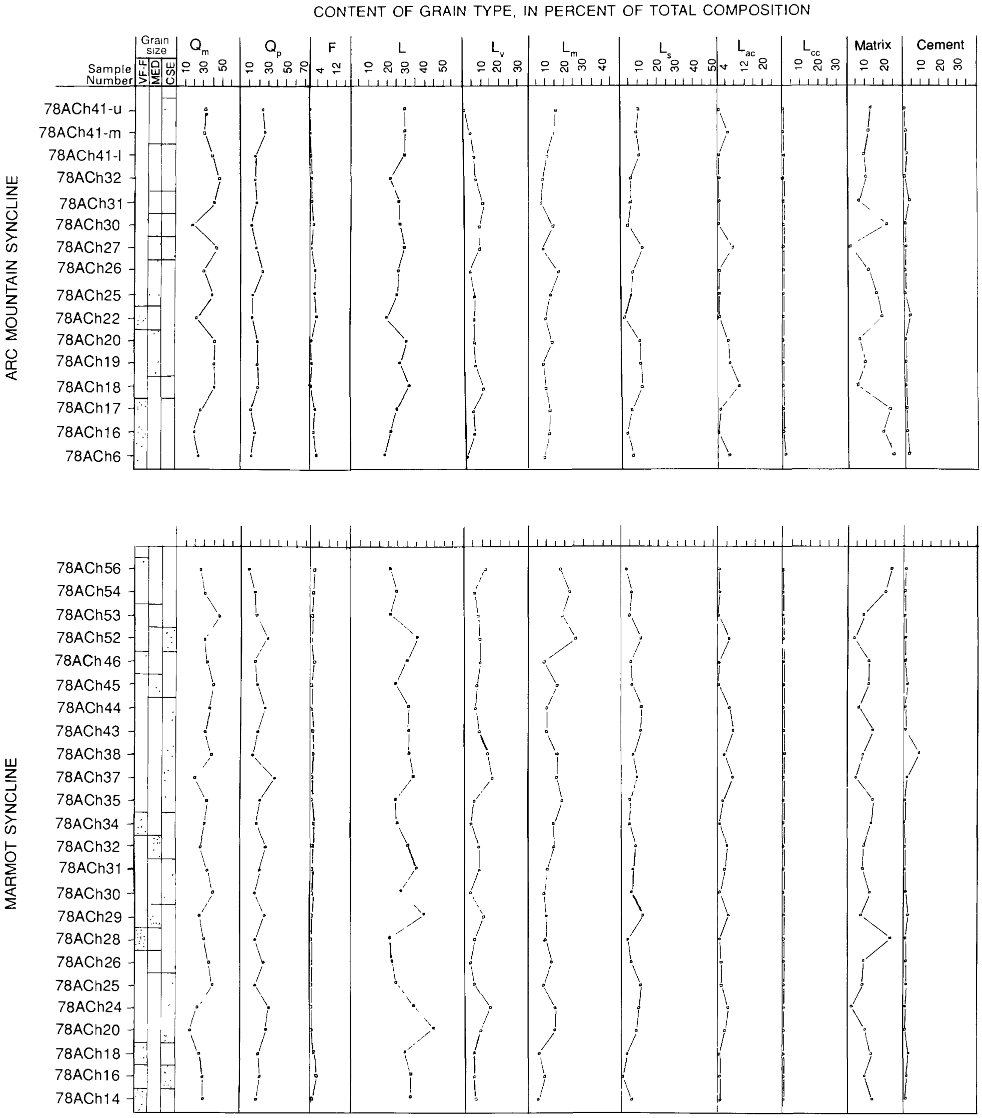


FIGURE 35.2.—Continued

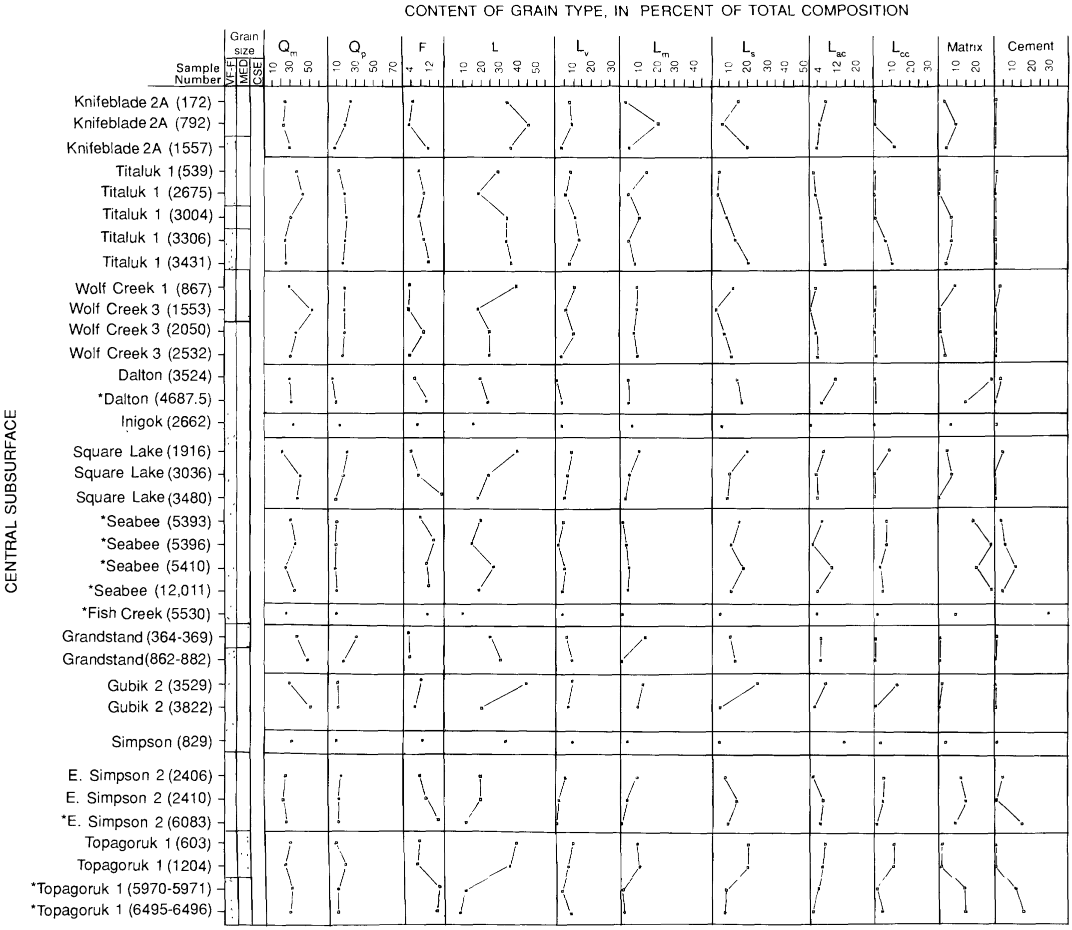


FIGURE 35.2.—Continued

TABLE 35.1.—*Modal compositions and textural data from petrographic examination of sandstone samples from the Nanushuk Group and Torok Formation*

[Locations of scattered outcrop samples, measured sections, and wells shown on figure 35.1. * indicates monocrystalline quartz; Q_p, polycrystalline quartz; F, feldspar; L, lithic grains; L_v, volcanic lithic grains; L_{cc}, calcareous grains. W, well sorted; M, moderately sorted; P, poorly sorted; VP, very poorly ---, not analyzed. Numbers in parentheses indicate sample depth in well]

Sample	Grain size (mm)		Textural data			
	Maximum	Modal	Sorting	Grain-contact type	Matrix (percent)	Cement (percent)
Scattered						
1075	0.15	0.07	VP	L, P, F	36.5	1.3
1175	.45	.20	VP	L, P, F	25.9	6.7
1275	.45	.20	P	C, L	21.6	6.6
1475	.70	.30	M	L, P	3.7	.9
1575	.70	.40	P	L, P	10.8	13.8
1875	.17	.11	W	C, L	18.1	1.7
2075	.77	.38	M	---	13.3	5.9
2175	.56	.18	W	C, L	9.1	2.6
2675	.45	.12	P	C, L, P, F	13.8	15.3
3075	.12	.18	VP	F	23.7	16.6
3275	.35	.18	P	S, C, L	15.0	15.3
3375	.76	.46	M	S, C, L	8.3	20.8
3675	.36	.18	P	C, L	15.3	16.5
3875	.38	.18	P	S, C, L	6.4	23.2
4275	.39	.23	M	P, F	.26	25.7
4375	.92	.38	P	C, L	13	12.3
4575	.18	.15	P	F	3.6	57.4
4875	.46	.24	M	C, L	27.3	5.2
5175	.45	.30	W	F	5.3	40.7
5375	.38	.16	VP	C, L, F	10.4	32
5475	.90	.58	M	C, L, P	11.7	8.8
Range	.12-.92	.07-.58	VP-W	---	3.6-37	.9-57.4
Average	.48	.25	M-P	---	15.2	15.7
Tupikchak Mountain syncline						
77AJF23	---	.15	M	S, C, L	1.6	22.4
77AJF28	---	.30	M	C, L	4.3	6.1
77AJF30	---	.18	W	S, C, L	6.6	9
77AJF32-u	---	.23	M	C, L, P, F	1.3	20
77AJF36-u	---	.23	W	S, C, L	2.3	3.4
77AJF37-l	---	.25	M	S, C, L	5	5
77AJF37-u	---	.30	P	S, C, L	7.7	6.4
77AJF39-l	---	.25	M	C, L	4.6	2
77AJF39-u	---	.30	M	S, C, L	3.3	7.3
77AJF42-l	---	.34	P	S, C, L	5.3	4.7
77AJF42-u	---	.30	P	S, C, L	5.4	11
77AJF44	---	.18	M	S, C, L	13.3	.3
77AJF47-l	---	.18	M	S, C, L, P	8	7
77AJF47-u	---	.45	M	C, L	5.3	3.3
77AJF52-l	---	.25	M	S, C, L	8.3	10
77AJF52-u	---	.25	P	S, C, L	4.3	8.3
Range		.15-.34	W-P	---	1.3-13.3	.3-22.4
Average		.26	M	---	5.4	7.9
Carbon Creek anticline						
77AAh4cc	---	.15	P	C, L, P	6.7	16.7
77AAh5cc	---	.23	P	C, L	13	4
77AAh6cc	---	.23	M	L	9.3	3.6
77AAh8cc	---	.50	M	L, P, F	4	28.9
77AAh9cc	---	.30	M	C, L	4.7	12.3
77AAh12cc	---	.60	P	L, P, F	1	27.4
Range		.15-.60	M-P	---	1-13	4-28.9
Average		.34	M-P	---	6.5	15.5
Corwin Bluff						
77AAh31b	---	.23	---	---	8.7	6.6
77AAh39	---	.30	M	S, C, L, P	14.3	2
77AAh40	---	.23	M	C, L, P	11.6	18.7
77AAh42	---	.46	P	L, P	17.7	2
77AAh46	---	.18	M	S, C, L	9.7	15.4
77AAh48a	---	.30	VP	C, L, P	15	6.3
77AAh100a	---	.30	W	S, C, L	6	8

TABLE 35.1.—*Modal compositions and textural data from petrographic examination of sandstone samples from the Nanushuk Group and Torok Formation*—Continued

samples from the Torok Formation; Q, monocrystalline and polycrystalline quartz, quartzite, and chert; Q_m, grains; L_m, metamorphic lithic grains; L_s, sedimentary lithic grains; L_{ac}, argillaceous and carbonaceous sorted. Grain contacts: S, sutures; C, concavo-convex; L, long, straight; P, point, tangent; F, floating.

Compositional data (percent of total composition)									
Quartz grains			Feldspar grains	Lithic grains					
Q	Q_m	Q_p	F	L	L_v	L_m	L_s	L_{ac}	L_{cc}
outcrop samples									
32.3	19.7	12.6	2.7	27.2	4.4	16.4	6.4	6.3	0.1
29.7	12.3	17.4	2.0	31.2	8.0	21.5	1.7	1.7	.0
38.1	11.0	27.1	2.7	26.4	7.6	16.8	2.0	2.0	0
52.7	24.8	27.9	2	21.3	9.9	8.6	2.8	2.8	0
42.0	16.7	25.3	3.7	28.1	3.1	23.9	1.1	.8	.3
57.2	34.3	22.9	2.6	17.9	5.5	8.5	3.9	3.9	0
56.5	15.7	40.8	2.7	19.5	9.7	6.5	3.3	3.3	0
42.8	21.3	21.5	2	28.0	12.2	13.0	2.8	2.5	.3
47.6	29.3	18.3	9.6	10.4	4	5.3	1.1	1.1	0
31.7	12.3	19.4	2	25.6	9.9	14.4	1.3	1.3	0
37.5	21	16.5	8	21.2	6.5	2.2	12.2	2.2	10
40.2	8.3	31.9	2.3	26.3	8.4	2.1	15.8	8.1	7.7
36.9	23.6	13.3	6.3	24.4	4.7	1.5	18.2	.9	17.3
40.9	11.3	29.6	2.7	26.4	9.7	3	13.7	4	9.7
15.2	11.3	3.9	1	31.7	1	0	30.7	.7	30
49.6	22.3	27.3	6	18.3	6.3	8	4	2.3	1.7
25.8	11.4	14.4	3.6	9.3	1	7	1.3	1	.3
36	13.3	22.7	2.3	32.5	3.6	2.6	26.3	.3	26
30.4	12.7	17.7	6	16.9	3.9	6.7	6.3	4	2.3
32.3	17.7	14.6	8.6	15.8	5	1.4	9.4	.7	8.7
43.9	8	35.9	1.7	26.2	18.5	4.3	3.4	3.4	0
15-57.2	8-34.3	3.9-40.8	1-8.6	9.3-32.5	1-18.5	0-23.9	1.1-26.3	.3-8.1	0-30
39	17.1	22.0	3.8	23.1	6.8	8.3	8.0	2.5	5.4
measured section									
33	24.7	8.3	6.7	35.6	6.4	1.6	27.6	6.3	20
44.3	23.3	21	9.3	37.3	9.3	3.4	24.6	9	12.3
37.3	24.3	13	9	38.8	3	2.7	33.1	5.7	26.7
32.7	16.7	16	10.3	36.4	5.3	2.7	28.4	3.7	24
52	31.7	20.3	8	35.2	4.3	5.6	25.3	6.7	18.3
39.7	22	17.7	10.7	39.3	13.7	3.7	21.9	3.3	16.3
42	21.3	20.7	11.7	32.4	8	1.4	23	3.7	17
49	29	20	13.3	33	6	3.3	23.7	6.3	14.7
51	25.3	25.7	11	29.3	7	5	17.3	8.3	4.7
53	16	37	4.7	33	8	6.3	18.7	12	4.7
37.7	22.3	15.4	9.7	38	9	2.7	26.3	8.3	16.7
45.4	29.7	15.7	12.7	28.4	3.7	4.4	20.3	9.3	8.3
36.4	14.7	21.7	7.3	37.4	6	3.7	27.7	5.7	20.7
52.6	7.3	45.3	6	34	8.3	2.6	23.1	13.7	2.7
41.3	17.3	24	5.3	34.4	4	5.4	25	6	17.7
44.3	23	21.3	8	35.1	7.7	2.7	24.7	6.3	17.7
32.7-52.6	7.3-31.7	8.3-45.3	4.7-13.3	28.4-39.3	3-13.7	1.4-6.3	17.3-28.4	3.3-13.7	4.7-26.7
43.2	21.8	21.4	9	34.9	6.9	3.6	24.4	7.1	15.2
measured section									
34	20.7	13.3	9.3	31	5.7	6.6	18.7	3	15
35	27	8	12.3	31	7.1	6.6	17.3	8.7	6.3
42.7	33	9.7	11.6	26.1	7.7	5.4	13	3.3	6
29.7	19	10.7	7.3	31.7	6.7	7.7	17.3	9	3.3
42.3	27	15.3	8	31	6	6.7	18.3	1	15.3
23.6	6.3	17.3	5.7	47.3	8	12.3	27	19	6
23.6-42.7	6.3-33	8-17.3	5.7-12.3	26.1-47.3	6-8	5.4-12.3	13-27	1-19	3.3-15.3
34.6	22.2	12.4	9	33	6.9	7.6	18.6	7.3	8.7
measured section									
51.9	29	22.9	6	24	8.7	4	11.3	3.7	.3
43	29	14	14.3	25	7.3	4.7	13	4.3	1.7
43	33	10	9	18.1	5.4	2.4	10.3	6.3	0
46.6	30.3	16.3	12	17.7	5	2	10.7	2	2.7
44.7	28	16.7	8.3	22.7	2.7	3.7	16.3	6	0
42	25.7	16.3	8	30.9	4.3	7.3	19.3	6.3	2.7
54	25	29	11.3	18.3	5	2	11.3	8	0

TABLE 35.1.—*Modal compositions and textural data from petrographic examination of sandstone samples from the Nanushuk Group and Torok Formation*—Continued

Sample	Textural data					
	Grain size (mm)		Sorting	Grain-contact type	Matrix (percent)	Cement (percent)
	Maximum	Modal				
						Corwin Bluff
77AAh101------	---	.30	M	C, L	6	8
77AAh103------	---	.23	P	C, L, P	11.7	12
77AAh104------	---	.25	M	S, C, L	8.3	1.3
77AAh105------	---	.18	P	S, C, L	11	5.6
77AAh106------	---	.30	P	C, L	7	2.7
77AAh110------	---	.18	P	L, P	2.7	27.7
Range----		.18-.46	W-VP	---	2.7-17.7	1.3-27.7
Average--	---	.27	M	---	10	8.9
						Barabara syncline
77ACh82-------	---	.25	M	C, L	14.7	5.6
77ACh85-------	---	.20	P	S, C, L, P	4.6	4.7
77ACh87-l-----	---	.25	M	S, C, L	10.3	3.3
77ACh87-u-----	---	.15	P	S, C, L	13.3	4
77ACh89-l-----	---	.25	M	S, C, L	8.7	10.3
77ACh89-u-----	---	.30	P	C, L, P	7.6	9.4
77ACh90-l-----	---	.25	M	S, C, L	8.3	4.3
77ACh90-u-----	---	.25	W	S, C, L	10.6	6
77ACh92-------	---	.25	M	S, C, L, P	12	6.6
77ACh93-l-----	---	.15	P	L, P, F	16	7
77ACh93-m-----	---	.20	M	L, P, F	9.9	7.7
77ACh93-u-----	---	.15	P	S, C, L	10.9	6.7
77ACh97-------	---	.20	M	S, C, L	8	12.6
77ACh101-l----	---	.20	M	S, C	9.6	11
77ACh101-m----	---	.25	M	C, L	12.3	14
77ACh101-u----	---	.25	M	C, L, P	8.6	17.6
77ACh104-l----	---	.18	W	S, C, P	12.6	9.9
77ACh104-u----	---	.18	W	S, C, L	7.3	8
77ACh108-l----	---	.20	M	S, C, L	12.6	17
77ACh108-m----	---	.30	M	C, L, P, F	12.6	20
77ACh108-u----	---	.20	M	S, C, L	16.9	13.7
77ACh116------	---	.30	P	S, C, L	15.6	11
77ACh120-l----	---	.23	P	S, C, L	4	13.6
77ACh123------	---	.15	M	C, L, P	11.7	8.3
77AAh184------	---	.25	M	L	2.2	3.7
Range----		.15-.30	W-P	---	2.2-16.9	3.3-20
Average--		.22	M	---	10.4	9.4
						Western
Tunalik (3286)------------	.23	.12	M-P	S, C, L	16.7	19.9
(3288)------------	.30	.08	M	F	3.3	45
(5558)------------	.46	.18	M	S, C, L	18.7	6
(5561)------------	---	.15	W	S, C, L	10.3	14.7
Kaolak 1 (937)------------	.58	.23	M-P	C, L, F	12.7	1.7
(2453)-----------	.60	.23	M	C, L, F	9	4
(3187)-----------	.30	.18	P	C, L, F	12	5.2
(4078)-----------	.30	.15	P	S, C, L, F	10.7	7.4
*Peard (3036)-------------	.23	.08	M-P	L, P, F	11.3	31
Meade 1 (2953)------------	.38	.23	W	C, L	3	3.6
*Meade 1 (4133)-----------	.45	.23	P	S, C, L	10.7	3.6
*So. Meade (5670)---------	.45	.23	M	S, C, L	21.3	12.3
* (5964)---------	.60	.15	P	S, C	15	12
*So. Barrow 1 (1906-1916)-	.46	.17	M	C, L	10.5	1.7
*So. Barrow 6 (2353-2354)-	.23	.09	W	C, L	12.7	5.4
Oumalik 1 (979-984)-------	.30	.23	P	C, F	10	5.6
(1606)----------	.43	.26	P	C, L	10.7	5
* (3260)----------	.45	.18	P	C, L, P, F	10.7	6.1
* (9251)----------	.23	.08	P	C, L	23	11.3
* (9288)----------	.30	.12	M-P	S, C, L	22	3.6
Range----------------	.23-.60	.08-.26	W-P	---	3-23	1.7-45
Average--------------	.38	.17	M	---	12.7	10.3
Average, Nanushuk Group	.39	.19	M	---	10.7	10.7
Average, Torok Formation	.38	.15	M	---	15.2	9.7

TABLE 35.1.—*Modal compositions and textural data from petrographic examination of sandstone samples from the Nanushuk Group and Torok Formation*—Continued

Compositional data (percent of total composition)									
Quartz grains			Feldspar grains	Lithic grains					
Q	Q_m	Q_p	F	L	L_v	L_m	L_s	L_{ac}	L_{cc}
measured section--Continued									
51.4	18.7	32.7	7.3	28.6	5.7	2.3	20.6	9.3	3
40.3	33	7.3	12.7	21.6	5.3	1.7	14.6	6.3	2
57	46.3	10.7	12.7	17.4	2	2.7	12.7	3.7	.3
49	36	13	11.3	21	6	2	13	4.7	.3
53	23	30	6.3	28.7	8.7	4	16	7	.7
32.6	20.3	12.3	5.7	32.3	5.7	7.3	19.3	8	4
32.6-57	18.7-46.3	7.3-32.7	5.7-14.3	17.4-32.3	2-8.7	1.7-7.3	10.3-20.6	2-9.3	0-4
46.8	29	17.8	9.6	23.6	5.5	3.6	14.5	5.8	1.4
measured section									
51.3	26	25.3	16.9	9	4	.3	4.7	4	.7
63.3	34.3	29	12	10.3	3	0	7.3	6.7	.6
54.7	28	26.7	7.6	22.2	6.6	0	15.6	15.6	0
44.6	25.3	19.3	11.6	23.6	6.6	0	17	15.7	1.3
49	28.3	20.7	9.3	22	8	0	14	11	3
54.6	30.1	24.5	7.9	19.9	5.2	0	14.7	14.7	0
55.7	31	24.7	10.6	17.6	5	0	12.6	12.3	0
52.6	32.3	20.3	10	19.3	3.3	.3	15.7	15.7	0
51	26.3	24.7	12.5	14.9	4	.3	10	10	0
42.9	20.6	22.3	8.6	24	3	0	21	18	3
53.6	29	24.6	9.3	17.6	5.3	0	12.3	10.7	1.6
58.3	26.7	31.6	8.6	13.3	3	0	10.3	9.7	.6
48	29	19	12	18	2	0	16	12.3	3.7
45	36.3	8.7	7.3	22.6	1.3	0	21.3	17.3	4
42.3	37.3	5	5.7	23.3	2.3	0	21	19	2
42.6	31.6	11	7.6	22	1.6	0	20.4	17.7	2.7
50	42	8	10.3	15	2	0	13	11.7	1.3
56.6	39.3	17.3	12	11.3	1	0	10.3	8.6	1.7
38.6	27.3	11.3	7.6	21.3	.6	0	20.7	17.3	3.4
40.6	25.3	15.3	7.3	16.3	0	0	16.3	13	3.3
40.6	26.6	14	6.6	19	1.3	0	17.7	13.6	4.1
48.9	22.6	26.3	4.3	16.6	.3	1.3	15	14	1
34.6	20	14.6	3.3	46.3	.3	1	45	13	32
47.3	32.3	15	8.6	22.5	3.6	.6	18.3	15.3	3
63.3	22.3	41	2.6	13.9	2.7	1.3	9.9	9.6	0
34.6-63.3	20-39.3	5-41	2.6-16.9	9-46.3	0-8	0-1.3	4.7-45	4-19	0-32
47.2	29.2	20	8.8	19.3	3	.2	16	13.1	2.9
subsurface									
3	24	12	10.3	15.3	3.7	2	9.6	4.3	3.3
27.4	23.4	4	7.4	16.3	2	.3	14	10	3.7
46.3	35.7	10.6	14	11.6	5.6	1	5	1	.7
41.7	29.7	12	14.6	14.2	5.4	2.7	6.1	3.7	1.7
44.3	23	21.3	5.3	34	8.7	14	11.3	6.3	3
31.3	13.7	17.6	4.7	42.4	10	11.3	21.1	3.7	14.7
43.7	27.7	16	8.7	31	8.3	9	13.7	2.7	8.7
42.6	36	6.6	9	25.2	12	3.6	9.6	3	3.3
30.7	21.7	9	13.7	12.8	5	2.4	5.4	3.7	1.7
49.9	40.3	9.6	11.7	22.9	8	6.6	8.3	4.3	.3
42.7	33.7	9	7.7	32.1	8.7	6	17.4	6.7	3.7
30.7	21.7	9	12.3	22	3.7	3	15.3	10.3	3
31.3	23.3	9	11.3	26.8	4.7	3.7	18.4	8	7.7
39.9	28.8	11.1	18.3	18.4	5.3	4.2	8.9	2.3	1.3
58.1	51.7	6.4	3.3	11.3	4.6	1.7	5	2	.7
36	24.7	11.3	10	35.3	6.3	4	25	7.3	15
41.3	24	17.3	12	28.3	11	4.7	12.6	3	6.3
47	35.7	11.3	8.3	25	9.4	2.3	13.3	4.3	6.3
33	23.7	9.3	9	21.6	5.7	4	11.9	4.3	6.3
33.3	27.3	6	13	22	4.7	5.6	11.7	6	5
27.4-58.1	13.7-51.7	4-21.3	3.3-18.3	11.3-35.3	2-12	.3-14	5-25	1-10.3	.3-15
38.9	28.5	10.9	10.2	23.4	6.6	4.6	12.2	4.9	4.8
40.1	27.5	12.6	9.8	25.1	7.4	5.4	12.4	4.5	5.5
37.5	29.7	8.9	10.8	21.3	5.8	3.7	11.9	5.3	4

TABLE 35.1.—*Modal compositions and textural data from petrographic examination of sandstone samples from the Nanushuk Group and Torok Formation*—Continued

Sample	Grain size (mm)		Textural data			
	Maximum	Modal	Sorting	Grain-contact type	Matrix (percent)	Cement (percent)
Kurupa anticline						
78ACh20-------	.60	.23	M	L, P, F	4.7	25.6
78ACh21-------	.70	.30	M	C, L	7	7.3
78ACh23-------	2.30	.60	W	C, L, P	11.6	3.7
78ACh24-------	1.20	.50	P	C, L, P, F	6.3	20.3
78ACh25-------	.60	.18	M	C, L, P, F	12.1	20
78ACh30-------	.45	.18	W	L, P, F	17	6.7
78ACh31-------	.60	.23	---	---	9.7	11.3
78ACh32-------	.60	.23	M	C, L	8	9.9
78ACh33-------	.60	.30	P	P, F	11	2
78ACh43-------	.50	.23	M	L, P	6	28.3
78ACh47-------	.60	.30	M	S, C, L, P, F	6.6	22.7
78ACh49-------	.40	.18	M	C, L	21.9	7.2
78ACh59-------	.70	.40	M	C, L, P	11	8.7
78ACh64-------	.50	.23	W	C, L, P	5.7	25.7
78ACh70-------	1.20	.23	M	C, L	24.3	4.9
78ACh74-------	.70	.30	M	L, P, F	1.7	39.7
78ACh76-------	.70	.60	M	C, L	16	4.7
78ACh79-------	.70	.30	M	C, L, P, F	17	3.7
78ACh80-------	.70	.23	W	S, C, L	19.3	.7
78ACh103------	.70	.50	W	S, C, L	11.3	4.3
78ACh108------	.70	.60	W	S, C, L	16	7
78ACh113------	.60	.23	W	S, C, L	18.7	1.6
78ACh116------	.60	.23	W	S, C, L	18.3	1.6
Range----					1.7-24.3	.7-39.7
Average--					12.2	11.6
Tuktu Bluff						
77AAh12-------	.70	.18	M	C, L, P, F	26	3
77AAh13-u-----	.23	.15	W	L, P, F	19.7	8.3
77AAh16-------	.60	.23	W	L, P, F	14.6	9
77AAh17-------	.70	.30	M	C, L	18.4	5
77AAh20-l-----	.50	.18	M	C, L, P, F	25.7	3
77AAh21-------	.70	.60	M	C, L	14.3	6.4
77AAh23-------	.40	.23	M	C, L	9.7	15.7
77AAh25-------	.70	.30	W	L	9.3	10
77AAh30-------	.75	.18	W	C, L	28	5
77AAh35-l-----	.40	.15	W	C, L	17.1	3
77AAh37-m-----	.60	.23	M	S, C, L	14.4	7.1
77AAh38-l-----	.70	.45	M	---	15.9	.6
77AAh38-u-----	.60	.40	W	C, L	11	1.1
77AAh39-l-----	.60	.15	P	C, L, P, F	13.6	4.3
77AAh39-u-----	1.70	.70	W	S, C, L	12.7	2
77AAh43-u-----	1	.60	W	C, L	17.4	0
77AAh45-l-----	.60	.23	W	S, C, L	21	1
77AAh49-u-----	.38	.18	W	S, C, L	19	1
77AAh49-l-----	.70	.55	W	C, L	2.3	1.3
Range----	.23-1.70	.15-.70	W-P	---	2.3-28	0-15.7
Average--	.56	.32	W-M	---	16.3	4.6
Arc Mountain						
78ACh6--------	.40	.15	M	S, C, L	25.3	3.3
78ACh16-------	.30	.20	W	S, C, L	19.7	2.2
78ACh17-------	.80	.18	W	S, C, L	23	1.6
78ACh18-------	2.30	1.20	W	S, C, L	5.3	1
78ACh19-------	1.20	.40	M	S, C, L	10	1.6
78ACh20-------	.60	.40	W	S, C, L	7.3	.6
78ACh22-------	.40	.15	M	S, C, L	18.7	4.7
78ACh25-------	.60	.25	W	S, C, L	16.4	.6
78ACh26-------	.80	.30	W	S, C, L	12	.3
78ACh27-------	1.20	.60	W	S, C, L	2.7	2
78ACh30-------	.45	.30	M	C, L	22	.7
78ACh31-------	1.20	.60	W	S, C, L	6.3	4.4
78ACh32-------	.80	.30	W	S, C, L	10.7	.6
78ACh41-l-----	1.08	.40	W	S, C	9	1
78ACh41-m-----	1.20	.60	W	S, C, L	12.3	1.6
78ACh41-u-----	1.20	.60	W	S, C, L	12.7	.3
Range----			M-W		2.7-25.3	.3-4.7
Average--			W		13.3	1.7

TABLE 35.1.—*Modal compositions and textural data from petrographic examination of sandstone samples from the Nanushuk Group and Torok Formation*—Continued

Compositional data (percent of total composition)									
Quartz grains			Feldspar grains	Lithic grains					
Q	Q_m	Q_p	F	L	L_v	L_m	L_s	L_{ac}	L_{cc}
measured section									
22.3	9.3	13	3.7	45	14.7	12.3	18	5	7
34.3	15.3	19	3.7	42	15.7	15	11.3	2.7	.3
29	9	20	3	44.7	24	9	11.7	7	.7
29	12	17	2.7	43.3	16.6	14.4	12.3	7.3	.3
38.8	27.4	11.4	6	22.9	9	4	9.9	6.6	2
31.6	18.3	13.3	11.7	30.6	15.7	8.6	6.3	3.3	1
34	21.7	12.3	12	24.9	9.6	8	7.3	2.3	1.7
28.7	16	12.7	6.3	39.3	18.4	10	10.9	5.3	1.3
31.3	13.3	18	8	35.8	14.7	9.7	11.4	7.7	0
21	7.7	13.3	4.3	48.4	14.7	12	16.7	4.7	7.7
18.9	8.3	10.6	3.7	51.4	18	13.3	20.1	5.7	8.7
32.2	17.9	14.3	5	36.4	9.3	17.9	9.2	4.3	1.3
23.4	8.7	14.7	6.7	47	14.4	20	12.6	6	.3
32.3	17.3	15	3.7	36	4.3	24	7.7	3.3	3.7
32	20	12	2.3	36.4	9.4	20.3	6.7	2.7	1.7
29.6	19.3	10.3	2.3	27	6.7	15.6	4.7	3.7	0
38	28.7	9.3	2.3	35	7.3	20	7.7	5	0
39.6	23.3	16.3	2.3	35.4	4.7	20.7	10	3.3	.7
31.3	19	12.3	3.7	28.4	6.7	18.7	3	1	.3
50.6	34.3	16.3	0	31.6	4	18	9.6	3	1.3
31.7	19	12.7	1.7	29.7	4.3	19.7	5.7	.7	1.7
33.3	16.3	17	1.7	28.7	7.3	18.7	2.7	1	0
38.3	23.0	15.3	3.3	27.7	6.7	15.7	5.3	1.3	.3
18.9-50.6	7.7-34.3	9.3-20	0-12	22.9-51.4	4-24	4-24	2.7-20.1	.7-7.7	0-8.7
31.8	17.6	14.2	4.4	35.8	11.1	15	9.6	4	1.8
measured section									
31.3	19	12.3	5.3	26.9	3.7	14.6	8.6	5.3	.3
29	16	13	2.7	25	3	17.4	4.6	.3	2
30	18	12	4.3	29.2	4	18.6	6.6	3.3	2
42	23	19	2.7	36.6	6	20	10.6	1.3	0
34.1	22.7	11.4	6	29.7	4.6	18.4	6.7	2.7	0
39	27.3	11.7	1.7	35.6	9	16.3	10.3	1	0
30	12.7	17.3	2.7	38	13	19.3	5.7	1.7	1.7
41	24	17	2	41.7	10.3	21.7	9.7	4.7	0
26	15	11	1.3	33.4	6	25.4	2	.7	.3
34.6	15.8	18.8	2.6	33.1	5.3	22.8	5	.7	.3
43.9	25.3	18.6	3.2	24.9	4.8	17.9	2.2	.3	0
51.5	33.1	18.4	.3	33.7	6.8	13.3	13.6	2	0
58.7	36.7	22	1.3	27.6	5.7	12.2	9.7	2.8	0
57.3	35.2	16.1	3.2	24.3	8.1	10.6	5.6	1	2.3
51.2	28.7	22.5	.7	35.4	13.3	12.4	9.7	2.9	0
59	33	26	1	26	6.6	12	7.4	1.7	0
42.1	28.7	13.4	1	28	7.6	14.7	5.7	2.7	0
50.3	34.3	16.0	2.7	24.6	5.6	13	6	1.3	0
53.6	17.3	36.3	.3	36.7	18.3	14	4.4	2.7	0
26-59	12.7-36.7	11-36.3	.3-6	24.3-41.7	3-18.3	10.6-25.4	2-13.6	.3-5.3	0-2.3
42	24.5	17.5	2.4	31.1	7.5	16.6	7.1	2.1	.5
syncline measured section									
38.7	25.7	13	3	17.4	2	8.4	7	4.7	.3
36.9	21	15.9	1.9	21.3	6.1	11.1	4.1	0	0
39.4	26	13.4	2.3	23.3	5	12	6.3	1.7	.3
62.9	42.7	20.2	0	31.5	10.9	9.3	11.3	9.6	0
62.6	42.3	20.3	1	26	7	8.6	10.4	5.7	0
63	43.3	20	.3	29.3	6.3	12.7	10.3	5	0
38.3	23.3	15	3.7	18.7	6	10	2.7	1.7	0
55.1	40.7	14.4	2.3	24.8	6.7	12.4	5.7	1.7	0
56.3	31.3	25	2.3	26.6	3.6	16	7	1	0
62.3	45	17.3	.7	28.7	8.7	8	12	7.3	0
34.3	19.7	14.6	2	26.7	8	14	4.7	.7	0
61.6	42.3	19.3	.7	25.2	11.3	7.6	6.3	1.3	0
64.7	47.3	17.4	.7	21.1	6.7	8.4	6	1.3	0
59.9	41.2	18.7	1	28.6	6.6	11.7	10.3	1.7	0
58.7	32.3	26.4	.3	28.4	4.3	14.7	9.4	4.7	0
58.6	33	25.6	.3	29.3	3.3	16	10	1.3	.7
34.3-64.7	19.7-47.3	13-26.4	0-3.7	17.4-29.3	2-11.3	7.6-16	2.7-12	0-9.6	0-.7
53.4	34.8	18.5	1.4	25.4	6.4	11.3	7.7	3.1	.1

TABLE 35.1.—*Modal compositions and textural data from petrographic examination of sandstone samples from the Nanushuk Group and Torok Formation*—Continued

Sample	Textural data					
	Grain size (mm)		Sorting	Grain-contact type	Matrix (percent)	Cement (percent)
	Maximum	Modal				
						Marmot syncline
78ACh14	.45	.23	W	S, C, L	13.6	2.3
78ACh16	3.50	.77	W	S, C, L	10	2.7
78ACh18	.24	.13	W	S, C, L	13	3
78ACh20	4	.60	W	S, C, L	10.3	.3
78ACh24	1.72	1.20	W	S, C, L	2.7	1.4
78ACh25	1.72	.60	W	---	8.3	2.1
78ACh26	.77	.48	W	S, C, L	9.4	2.0
78ACh28	2.30	.23	M-P	C, L	23.7	2.3
78ACh29	2.30	.40	---	---	7.4	2.9
78ACh30	1.30	.60	M	C, L, P, F	12.3	1
78ACh31	4.60	1.20	W	S, C, L	8.4	.3
78ACh32	.90	.30	W	C, L	9	.2
78ACh34	.60	.12	P	C, L, P	13.4	.3
78ACh35	.90	.60	W	C, L	14	.3
78ACh37	1.60	.60	W	L	5	2.6
78ACh38	1.20	.65	M	C, L	8.7	8.3
78ACh43	2	.60	W	S, C, L,	14.9	1.8
78ACh44	2.30	.60	W	C, L	6.6	.3
78ACh45	1.20	.40	W	C, L	11.3	2.3
78ACh46	1.54	.20	M-P	S, C	11	.6
78ACh52	1.20	1.20	P	L	3.6	.3
78ACh53	1	.38	W	S, C, L	9	.6
78ACh54	.60	.23	M	C, L	21	1.7
78ACh56	.40	.20	W	S, C, L	24.4	2.3
Range					2.7-24.4	.2-8.3
Average					11.3	1.7
						Central
Knifeblade 2A (172)	.45	.30	M	C, L	3	3
(792)	.77	.40	P	P, F	5.3	8.7
(1557)	.38	.15	W	C, L	7	4.7
Titaluk 1 (539)	.23	.15	M	C, L, P	11	1.3
(2675)	.30	.15	M	S, C, L	4.7	0
(3004)	.34	.27	P	L, P	6.6	6.7
(3306)	.36	.23	P	C, L, F	9.4	6.6
(3431)	.23	.17	M	P, F	11.7	3.6
Wolf Creek 1 (867)	.58	.30	VP	S, C, F	7	8.6
Wolf Creek 3 (1553)	.58	.30	W	C, L	.3	.6
(2050)	.45	.17	P	S, C, F	10	2
(2532)	.46	.20	P	S, C, F	12	3.7
Dalton (3524)	.30	.08	W-M	L, P, F	33.7	2.7
* (4687.5)	.60	.09	M-P	C, L	14.7	1.3
Inigok (2662)	.77	.18	W-M	S, C, L	6.6	.3
Square Lake (1916)	.48	.17	P	L, P, F	4	4.7
(3036)	.45	.23	M	S, C, L, P	2.7	7.3
(3480)	.18	.14	P	L, P, F	13.3	1
*Seabee (5393)	.23	.12	M	C, L	19.3	3.6
* (5396)	.17	.08	M-P	S, C, L	33	6
* (5410)	.27	.15	M	S, C, L, P	21.3	12
* (12,011)	.45	.15	M-P	L, P, F	29	4.6
*Fish Creek (5530)	.30	.11	M	L, P, F	9	30
Grandstand (364-369)	.90	.46	W	S, C, L	8.7	1.3
(862-882)	.38	.17	VP	S, C, L	8	.7
Gubik 2 (3529)	.45	.17	P	L, P, F	11.4	1.6
(3822)	.38	.18	W	S, C, L	8	.3
Simpson (829)	.23	.13	P	C, L, P, F	8.3	3.3
E. Simpson (2406)	.18	.06	M	C, L	11.7	4
(2410)	.29	.06	P	C, L	15.3	1
* (6083)	.16	.08	M	S, C, L	19.3	14
Topagoruk 1 (603)	.38	.15	M	L, P	14.3	2
(1204)	.77	.23	M	L, P	8.4	1.8
* (5970-5971)	.33	.15	M-P	C, L	14	11.7
* (6495-6496)	.40	.11	P	C, L	15.3	15.7
Range	.16-.90	.06-.46	W-VP	---	.3-33.7	0-30
Average	.41	.18	M	---	11.9	6.7
Average, Nanushuk Group	.43	.20	M	---	9.3	4.1
Average, Torok Formation	.33	.12	M	---	20.7	8.6

TABLE 35.1.—*Modal compositions and textural data from petrographic examination of sandstone samples from the Nanushuk Group and Torok Formation*—Continued

Compositional data (percent of total composition)									
Quartz grains			Feldspar grains	Lithic grains					
Q	Q_m	Q_p	F	L	L_v	L_m	L_s	L_{ac}	L_{cc}
measured section									
51.4	31	20.4	1.7	31.3	7.3	17.4	6.6	1.3	0
52.9	30.3	22.6	3.3	32	6	23	3	1	0
48	26.7	21.3	2	29.3	6.3	18.7	4.3	1.3	0
52.3	23.3	29.3	0	45.4	9	26.7	9.7	3.7	0
59.3	25.3	34	0	33.3	15	8	10.3	5.3	0
58.3	41	17.3	0	24.4	6.4	16.3	11.7	2	0
62.7	37	25.7	0	22.1	4.4	11	6.7	2	0
49	31	18	.7	21.7	6.4	10.3	5	.7	0
54.7	27	27.7	0	39.7	12	15.4	12.3	5.3	0
59.3	41	18.3	.3	27	4.7	15.3	7	1	0
59	25.3	23.7	.7	34.4	8.3	18.7	7.4	3.7	1.3
55.6	27.3	28.3	1	30.6	8	14.3	8.3	4.3	0
52.4	32.7	19.7	1.7	24.8	5	14.4	5.4	1.7	0
58	35.7	22.3	0	24.3	7	11	6.3	2.3	0
60.9	21.3	39.6	.3	33.3	15.7	9.3	8.3	7	0
53.3	39	14.3	1.3	31	13.4	10.3	7.3	3.7	1.3
54	33.2	20.8	1.5	31.1	8.8	10.4	11	7	0
63	37	26	0	31.4	7	12.7	11.7	5.7	0
62	41.7	20.3	.3	23.3	7.4	9.3	6.6	.3	0
53.3	35.7	17.6	2.3	30	9.7	15	5.3	1	0
62.7	32.7	30	0	35	9.7	15	10.3	5	0
67.7	49.7	18	1.3	21	8.3	6.3	6.4	.7	0
47.3	31.3	16	2.3	23.3	7	9	7.3	1.3	0
40.4	28.7	11.7	2.7	21	12.3	5.7	3	.3	0
40.4-67.7	21.3-49.7	11.7-39.6	0-3.3	21-45.4	4.4-15.7	5.7-26.7	3-12.3	.3-7	0-1.3
55.7	33.1	22.6	1	29.6	8.5	13.5	7.6	2.8	.1
Subsurface									
48.7	28.7	25	4.3	34.7	12.7	7.3	14.7	6.7	1.3
38.4	21.7	16.7	2.7	46.2	15.3	23	7.9	5.3	.3
38.2	29.3	8.9	10.7	36.7	9.4	8.6	18.7	3.7	12.3
47.3	36	11.3	7	28.7	8.7	15	5	2.3	0
59.4	42	17.4	9.3	18.6	6.6	7	5	3	0
49	29	20	6.7	32.6	12	12.3	8.3	5.3	1.3
40	22.3	17.7	9	34.2	14.4	6.4	13.4	5.7	6
37.1	23.7	13.4	11.3	35.7	7.7	7.7	20.3	7	7.3
43.7	26	17.7	3.7	32.8	10.7	10.4	11.7	2.7	1
69	52	17	3	19.2	6.6	9.6	3	1.3	0
52.3	35	17.3	9	25.2	10	8.6	6.6	3	1.3
43	26.7	16.3	3	24.7	3.7	10.3	10.7	4	2
32.4	27.7	4.7	5.7	20.3	1.3	5	14	11.3	.7
37	29.7	7.3	10	24.3	3.3	4.7	16.3	6.3	2
43.3	30.7	12.6	6.3	16.3	3.3	6.7	6.3	1	.3
39.4	18.7	20.7	4.3	39.7	9	10.7	20	6.7	8
54.3	39	15.3	7	23.7	7.4	6.3	10	3.7	.3
41.3	33	8.3	16.4	17.6	5	4	8.6	4.3	0
34.4	25.7	8.7	7.6	20.3	4.3	2	14	4.7	7.3
39.9	32.3	7.6	13.3	15.3	1.6	3	10.7	1.7	7
27.4	21.7	5.7	10.3	26.9	4.9	5	17	9.7	3.3
36.7	30	6.7	11.3	16.3	3.3	2.7	10.3	4	5
32.4	24.7	7.7	10.7	10.6	3.6	2	5	3	2
58.3	30	28.3	2	28	6.4	12.6	9	4.7	0
54.3	39.3	15	3.3	31.6	9.3	10.3	12	5	0
33.3	21.3	12	7.6	43.3	8	12.7	22.6	7.3	12
58.1	44.7	13.4	5.3	21.4	6.7	9.7	5	3.3	0
34.3	25.3	9	8.3	33.3	9.3	4.3	19.7	15.3	2.7
35.6	23.6	12	7	19.6	4.9	8	6.7	1.8	4.6
31.4	20.7	10.7	10	19.5	2.4	3.7	13.4	5.7	5
33.7	22.7	11	14.7	11.6	1	2	8.6	5.3	2
29	21.3	7.7	7	37.9	9.3	9	19.6	7	11.3
33.9	15.6	18.3	6	35.4	7.2	9.6	18.6	6	10.5
35	25.7	9.3	16	10.9	2.6	1.3	7	3.7	2.3
34.3	25	9.3	14.3	17.8	8.4	3.7	5.7	1.3	3.7
27.4-59.4	15.6-52	4.7-28.3	2-16.4	10.6-46.2	1-15.3	1.3-15.3	3-22.6	1-15.3	0-12.3
41.6	28.5	13.1	8.1	26	6.9	7.6	11.6	4.9	3.6
43.6	29	14.6	6.9	28.4	7.8	8.9	11.7	5	3.4
34.8	26.6	8.2	12.2	17.9	3.7	3.1	11.2	4.6	4.1

Harry C. Starkey, USGS, Denver, to identify clay types and confirm major mineral constituents. With the assistance of Eve Sprunt, Stanford University, polished thin sections of selected samples were examined under cathodoluminescent light in order to determine cement relations and possible grain overgrowths. Rock chips from surface and subsurface samples were examined using the Cambridge 180 scanning electron microscope with an attached electron-dispersive analyzer located at the USGS in Menlo Park, California, with the assistance of Robert L. Oscarson. Using the petrographic microscope, textural parameters were determined by estimation of sorting and type of grain contacts, measurement of grain size, and calculation of percentages of cement, matrix, framework grains, and visible porosity from modal data. In the laboratory, porosity and air permeability measurements on samples from the measured sections were made by Ira Pasternak (USGS) and by contract laboratories. Robinson and Collins reported results of measurements on samples from the wells drilled by the Navy (Robinson, 1956, 1958, 1959a, b, c, 1964; Collins, 1958a, b, 1959).

MINERALOGY AND GRAIN TYPES

Quartzose grains (Q) include monocrystalline quartz, polycrystalline quartz, chert, and quartzite. The monocrystalline grains (Q_m) include undulose types as well as those with straight extinction angles. Quartzite grains are those having elongated crystal shapes and lacking any mica. Polycrystalline quartz (Q_p) grains may have a wide range in crystal dimensions, even in a single grain; for this reason, grains with individual crystals smaller than 0.03 mm, which many workers would classify as chert (Dickinson, 1970), were not separated from the polycrystalline quartz category in this study. Chert grains include only fibrous types, which are rarely found in these rocks.

Feldspar (F) is not a significant component in the sandstone samples, averaging less than 10 percent. Potassium feldspar was stained yellow and thus was readily identifiable in most of the thin sections. Where feldspar is present, it is typically altered, and identification of untwinned feldspar grains in some of the poorly stained thin sections was made on the basis of their significant alteration. Most feldspar grains are blocky and display albite and Carlsbad twinning; perthitic and myrmekitic feldspar types are also present.

Lithic grains (L) are typically altered by compaction because of their internal structural incompetence, and specific lithic types are often difficult to identify, not only because of their generally smaller grain size but also because of their apparent susceptibility to alteration and dissolution. Metamorphic rock fragments (L_m) include quartzite and foliated quartz-mica (schist and phyllite) grains (Dickinson, 1970). Quartzite grains with only slightly elongate crystals are difficult to distinguish from polycrystalline quartz grains that are included in the quartzose grain category. Volcanic lithic grain types (L_v) include felsite, microlitic volcanic, and microgranular-hypabyssal grains (Dickinson, 1970). Felsite grains may be confused with polycrystalline quartz grains if they are unaltered and untwinned, or with metamorphic grains if they show slightly elongate crystals.

Sedimentary rock fragments (L_s) include polycrystalline quartz (Q_p) (see previous discussion), calcite clasts (L_{cc}), and argillaceous-carbonaceous fragments (L_{ac}). The argillaceous-carbonaceous fragments in the samples studied are here treated together because of their close association in many grains and the difficulty of distinguishing them. Commonly, though, the argillaceous fragments are laminated and may contain silt-size or smaller quartz grains, whereas the carbonaceous fragments and organic debris are massive and nearly opaque or deep orange along a very thin edge. Many of the sedimentary lithic fragments contain calcareous material, which varies from very finely crystalline to blocky sparry calcite. A few of the samples exhibit all stages of crystal development. Although some of this alteration may have taken place during diagenesis of the Nanushuk Group, much of it probably occurred in the source terrane before Nanushuk deposition. The resultant rounded, recycled clasts of recrystallized calcite(?) surrounded by blebs or coatings of dark-brown to reddish-brown clay material are characteristic, though not exclusively so, of the western area. Commonly these sedimentary lithic types are found associated with each other in various combinations in a single grain.

Most samples contain minor amounts of detrital muscovite, and a few contain small amounts of pleochroic straw-yellow to dark-brown detrital biotite in flakes that are nearly always bent and broken by compaction. Minor amounts of detrital chlorite(?) were also observed.

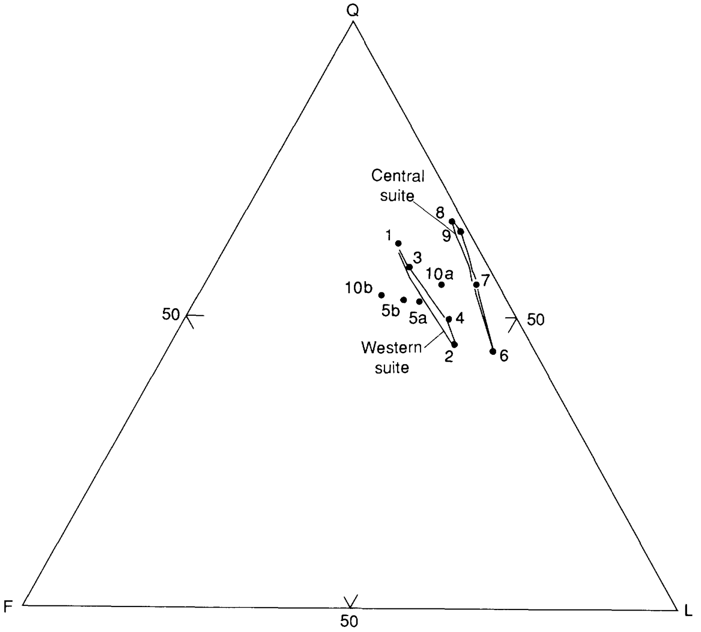
RESULTS OF COMPOSITIONAL ANALYSES—PROVENANCE AND SOURCE ROCKS

Complete results of the 199 modal analyses are shown on figure 35.2 and table 35.1. When the samples were grouped according to their localities on the map (table 35.1), compositional differences became apparent between samples from west of long 157° W. (western suite) and those from east of long

157° W. (central suite). Samples from the western suite include those from the Corwin Bluff, Tupikchak Mountain, Barabara syncline, and Carbon Creek measured sections and from the Tunalik, Peard, Kaolak, Meade, South Meade, Oumalik, and South Barrow wells. Samples from the central suite include those from the Kurupa anticline, Tuktu Bluff, Arc Mountain, and Marmot syncline measured sections and from the Simpson, East Simpson, Topagoruk, Dalton, Fish Creek, Inigok, Square Lake, Wolfe Creek, Seabee, Gubik, Grandstand, Titaluk, and Knifeblade wells. Sandstones of the Nanushuk Group and Torok Formation are composed of abundant quartz and lithic grains (fig. 35.3). An average surface sample from the western suite contains 54 percent quartzose grains, 11 percent feldspar, and 35 percent lithic grains, whereas an average surface sample from the eastern suite is composed of 58 percent quartzose grains, 3 percent feldspar, and 39 percent lithic grains. Subsurface samples of Torok sandstone have greater proportions of feldspar grains than those of Nanushuk Group sandstone.

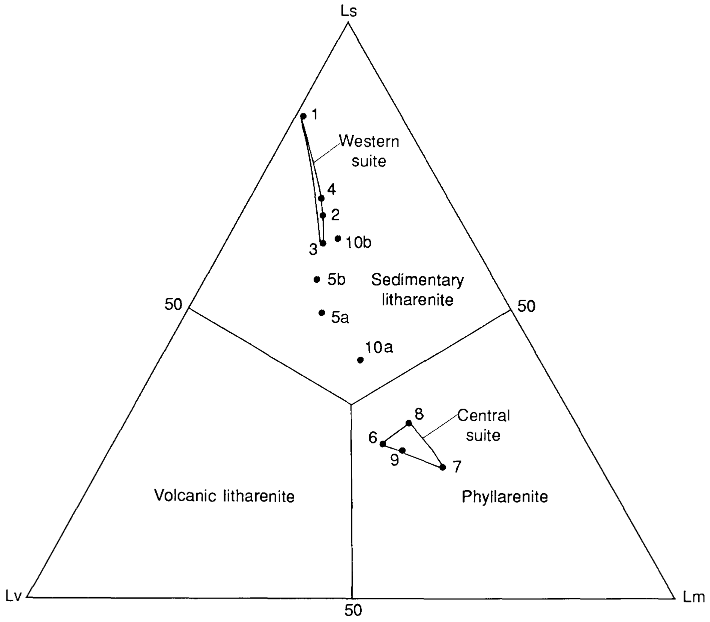
Proportions of detrital framework grains, particularly quartzose, feldspar, and lithic grains, are used to infer the provenance of Nanushuk sandstones. Dickinson and Suczek (1979), using a series of modal plots, classified the sandstones of the Nanushuk Group with those from a "recycled orogen provenance" of uplifted, folded, and faulted strata composed of recycled detritus of sedimentary or metasedimentary origin. They further classified them as rocks derived from a foreland uplift associated with foreland fold-thrust belts that have varied provenance characteristics, depending on the foreland setting.

The lithic grain compositions are the most useful modal tool in differentiating source areas of sandstone from the Nanushuk Group, as shown on figure 35.4. Two groups of sandstones having different lithic grain compositions can



Suite	Sample location	PERCENT		
		Q	F	L
WESTERN	1 Barabara syncline	62.7	11.7	25.6
	2 Carbon Creek	45.1	11.8	43.1
	3 Corwin Bluff	58.5	12.0	29.5
	4 Tupikchak Mountain	49.6	10.3	40.1
	5 Western subsurface 5a Nanushuk	53.5	13.1	33.4
	5b Torok	53.9	15.5	30.6
CENTRAL	6 Kurupa anticline	44.2	6.1	49.7
	7 Tuktu Bluff	55.6	3.2	41.2
	8 Arc Mountain	66.6	1.8	31.6
	9 Marmot syncline	64.5	1.2	34.3
	10 Central subsurface 10a Nanushuk	55.3	8.8	36.1
	10b Torok	53.5	18.8	27.6

FIGURE 35.3.—Relative proportions of quartz (Q), feldspar (F), and lithic (L) grains in averages of modal analyses of sandstone samples from the Nanushuk Group at eight measured sections and from the Nanushuk Group (N) and Torok Formation (T) in the subsurface. Samples from the western outcrop belt are richer in feldspar grains and poorer in lithic grains than samples from the central belt; range in percentages of quartzose grains is the same for both suites. Subsurface Torok samples have more feldspar grains than Nanushuk Group samples.



Suite	Sample location	END MEMBER		
		L_v	L_m	L_s
WESTERN	1 Barabara syncline	15.7	1.0	83.3
	2 Carbon Creek	20.9	23.0	56.1
	3 Corwin Bluff	23.3	15.3	61.4
	4 Tupikchak Mountain	19.7	10.3	69.9
	5 Western subsurface 5a Nanushuk	29.4	21.4	49.2
	5 Western subsurface 5b Torok	27.1	17.3	55.6
CENTRAL	6 Kurupa anticline	31.1	42.0	26.9
	7 Tuktu Bluff	24.0	53.2	22.8
	8 Arc Mountain	25.2	44.5	30.3
	9 Marmot syncline	28.7	45.6	25.7
	10 Central subsurface 10a Nanushuk	27.5	31.3	41.2
	10 Central subsurface 10b Torok	20.6	17.2	62.2

FIGURE 35.4.—Relative proportions of volcanic (L_v), metamorphic (L_m), and sedimentary (L_s) lithic grains in averages of modal analyses of sandstone samples from the Nanushuk Group at eight measured sections and from the Nanushuk Group (N) and Torok Formation (T) in the subsurface. Central outcrop belt of phyllarenites has high percentages of metamorphic rock fragments; western outcrop belt of sedimentary litharenites has high percentages of sedimentary lithic grains. Samples from the subsurface have compositions intermediate between the two suites; those from the Torok Formation have a higher proportion of sedimentary lithic grains than those from the Nanushuk Group. Sandstone classification after Folk, 1968.

be distinguished. In the western area, sedimentary lithic fragments (especially carbonate and argillaceous-carbonaceous lithic clasts) constitute a larger percentage of the samples, which are classified as sedimentary litharenites (Folk, 1968), whereas the samples from the central outcrop belt have an increased proportion of metamorphic rock fragments and are classified as phyllarenites (Folk, 1968). Samples from the subsurface have compositions intermediate between the two surface suites. Subsurface samples of Torok Formation sandstone contain a higher proportion of sedimentary lithic grains than subsurface samples of Nanushuk Group sandstone.

Extensive carbonate outcrops of the Mississippian and Pennsylvanian (and locally Permian) Lisburne Group, along with the Silurian and Devonian limestones making up the Baird Group (Bird, chapter 15; Tailleur and others, 1973), are probably primary sources for the calcareous clasts in Nanushuk sandstone of the western province (the Corwin delta of Ahlbrandt and others, 1979). Outcrops of these units occur in the Brooks Range to the south, the Tigara uplift near Cape Lisburne (Payne, 1955), and probably the offshore extension of the uplift, the Herald arch (Grantz and others, 1976; Mull, 1979). The Endicott Group, consisting of the Upper Devonian Hunt Fork Shale, the Upper Devonian and Lower Mississippian(?) Kanayut Conglomerate, and the Lower Mississippian Kayak Shale (Brosgé and Tailleur, 1971; Nilsen and Moore, 1982), has extensive outcrops in the central and eastern Brooks Range in the Endicott Mountains and may be the source for the metamorphic lithic (phyllite and slate) and quartzose grains that predominate in the centrally located Umiat delta (Ahlbrandt and others, 1979) of the Nanushuk Group.

TEXTURAL ANALYSIS

Primary factors thought by Fothergill (1955) and Fuchtbauer (1974) to contribute to the type and amount of interstitial matter in clastic rocks are (1) grain size, (2) thickness of beds, (3) amount of mixing of sediment layers by syndepositional processes such as burrowing by organisms, (4) proximity to shale beds, and (5) composition of framework grains. Secondary processes mainly responsible for the loss of porespaces in these sandstones are (1) weathering and (2) diagenetic alteration. Combinations of these primary and secondary factors are responsible for the low porosity and permeability in sandstone of the Nanushuk Group and Torok Formation. In this study, cement and matrix material have been distinguished and tabulated according to the categories defined by Dickinson (1970); the results of the textural observations are shown on figure 35.5 and table 35.1.

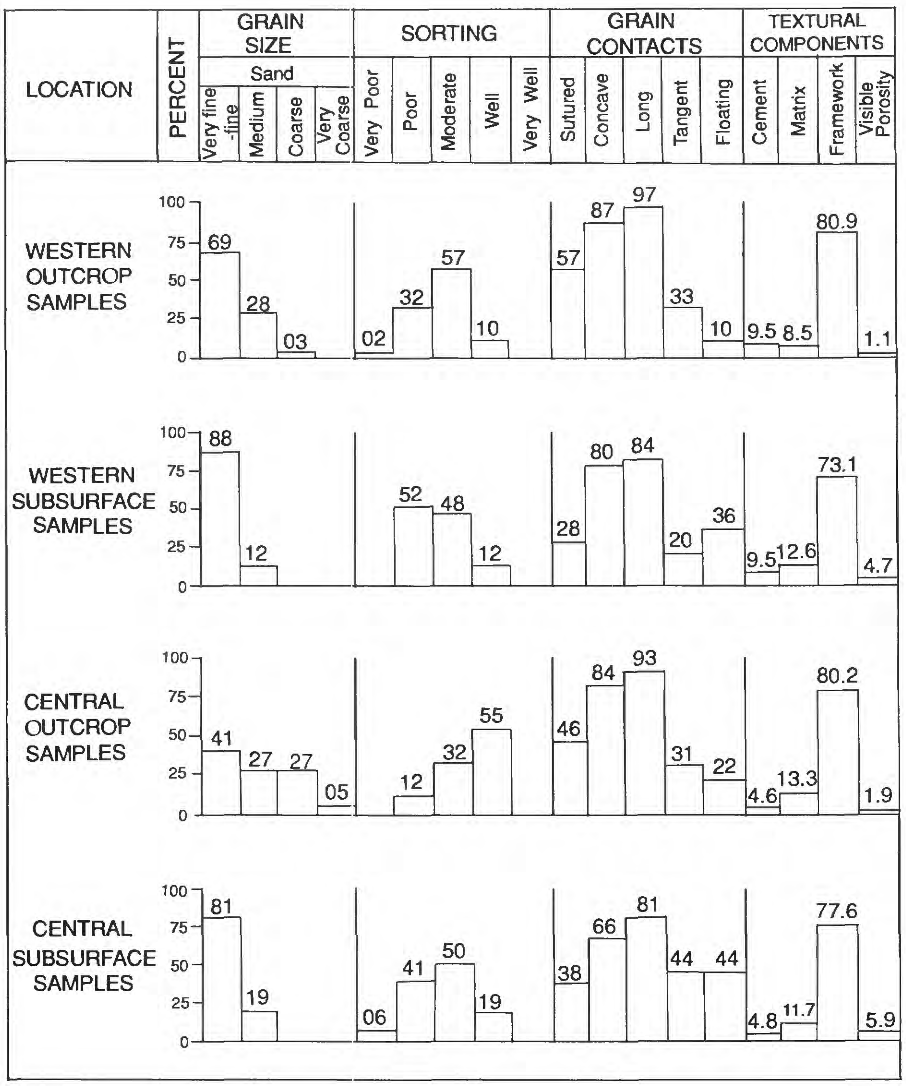


FIGURE 35.5.—Results of petrographic observations of textural properties in sandstones of the Nanushuk Group and Torok Formation. In general, the most favorable characteristics for high porosity and permeability are shown to the right in each histogram.

MATRIX MATERIALS

The principal matrix material in the sandstone samples of the Nanushuk Group and Torok Formation

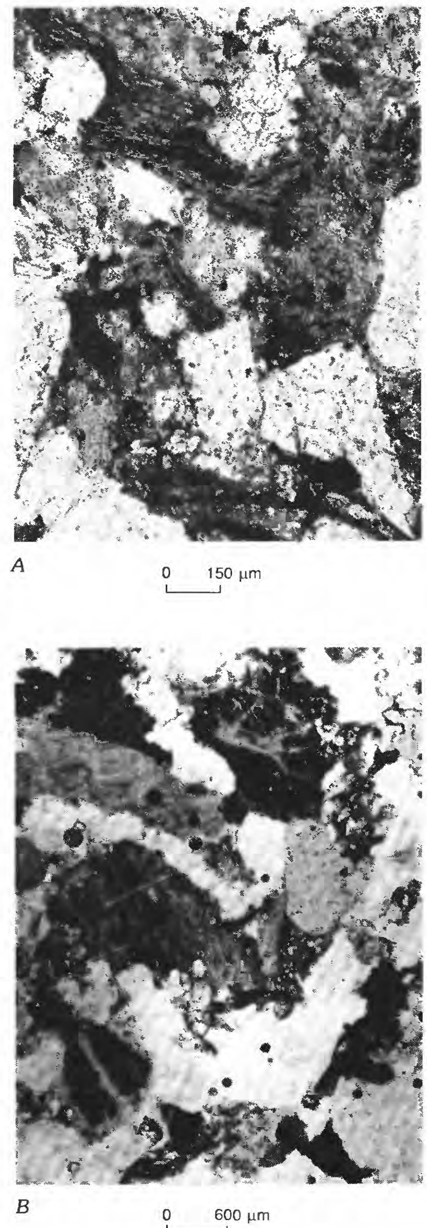


FIGURE 35.6.—Evidence of compaction in tightly appressed sandstone from the Nanushuk Group. Less competent micaceous and lithic grains are squeezed and bent around more resistant quartzose grains. Quartz grains show evidence of suturing as a result of silica dissolution under high pressure. Plane polarized light. *A*, Sample 77AAh21, Tuktu Bluff. *B*, Sample 78ACh27, Arc Mountain.

that are not well cemented is a pseudomatrix (Dickinson, 1970) probably resulting from the destruction of softer clastic grains. Significant quantities of this material, which is composed of unsorted and randomly oriented silt- and clay-size particles of quartz, chlorite, sericite, and much unidentifiable material, are found in the intergranular spaces in many of the sandstones. Commonly, less competent but still recognizable (lithic?) grains are molded around adjacent grains (usually quartzose grains) that are more competent (fig. 35.6).

CEMENTING MATERIALS

Authigenic cements and alteration products from diagenesis and weathering are common constituents in Nanushuk and Torok sandstone samples. Common cementing materials in the samples are calcite, silica, kaolinite, and chlorite; more rarely present are feldspar, sericite, illite-montmorillonite, and chalcedony. X-ray studies of the outcrop samples and of samples from the early (pre-1975) wells indicate that montmorillonite is present in only trace amounts (table 35.2). No zeolite minerals were observed petrographically or detected by X-ray analysis.

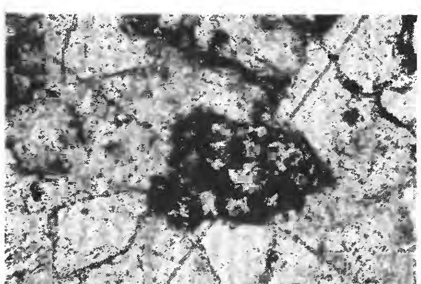


FIGURE 35.7.—Reworked calcite grain (under crossbars), outlined by opaque, brownish, ferruginous(?) coating, in a Nanushuk Group sandstone sample. Reworked grain is surrounded by secondary sparry calcite cement. Sample F3675, on the Utukok River. Plane polarized light.

The most common and volumetrically most abundant cement is calcite, which constitutes as much as 45 percent and averages almost 8 percent in the thin sections from the Barabara syncline. All stages of cementation and replacement by calcite are observed, from only minor occurrences in some samples to pervasive recrystallization in others. Calcite cementation, which is more common in the western outcrop belt, is probably related to weathering and diagenesis of the sandstone. The amount of cementation appears to vary directly with the detrital calcite-clast content, and cementing calcite commonly is observed growing out of these clasts (fig. 35.7). The calcite clasts, for the most part, were derived from crystalline limestone sources. After Nanushuk deposition, the clasts served as foci of calcareous cementation, obliterating original Nanushuk sandstone porosity and permeability. In some samples, ghosts of clastic calcite grains can be detected as relict outlines of clay material (fig. 35.8). When observed under cathodoluminescent light, the calcite grains luminesce red and orange and often show internal crystal-growth outlines, whereas the surrounding calcite cement luminesces bright yellow and is homogeneous, probably indicating an earlier origin for the calcite in the grains. In the most extreme examples, the sparry calcite cement completely replaces other detrital grains in the sandstone as well as the detrital calcite grains, except for a few remaining isolated and deeply embayed (partially replaced) quartz grains. Also present in many of the samples are small rhombohedrons of colorless dolomite.

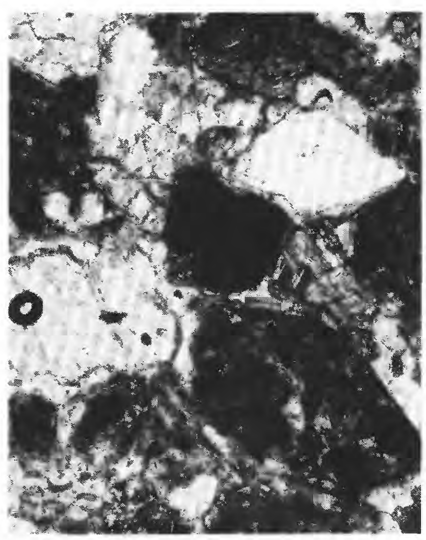


FIGURE 35.8.—Replacement of clastic grains in Nanushuk Group sandstone by sparry calcite cement, leaving relict "ghost" outlines of the original grains (for example, left center, probably a reworked calcite grain). Cement also fills interstices between grains, eliminating any primary porosity that may have existed and causing embayment of remaining grains. Sample 78ACh35, Kurupa anticline. Plane polarized light.

Silica for cementation is probably mobilized by the compaction pressures and temperatures in the sandstone. Mobile silica is thought to be produced as a result of pressure solution of framework grains (especially quartz), clay-mineral alteration during burial, kaolinization of feldspar, dissolution of grains in adjacent shale beds, and replacement of quartz and silicate grains by carbonate (Jonas and McBride, 1977). The higher pressure produced by compaction along resistant quartz-grain surfaces causes silica to dissolve on projecting surfaces that are under higher pressure. This silica may be redeposited as quartz overgrowths; these are observed petrographically as sutured, concave-convex, and long or straight grain boundaries. Silica cementation is widespread in sandstone of the Nanushuk Group, especially in the central outcrop belt. Siliceous cement is more readily observable in sandstone having visible porosity and lesser amounts of calcite

TABLE 35.2.—*Clay-mineral analyses of the clay-size fractions from sandstone samples from the Nanushuk Group and Torok Formation*

[Analyses by X-ray diffraction of clay-fraction separates of samples from scattered outcrops and the subsurface. Oriented mounts were made to aid in identification of the clay minerals; glycolation, potassium-acetate intersalation, and various heating techniques were incorporated. Amount of each mineral present was estimated from X-ray diffraction traces and is listed below as parts in ten; trace = less than 5 percent; <1 = 5-9 percent; + or - after number indicates that actual amount is slightly higher or lower than value reported. ---, not detected. p = test plug made to determine permeability parallel to bedding; n = test plug made to determine permeability perpendicular to bedding. Numbers in parentheses indicate sample depth in well. Paul D. Blackmon and Harry C. Starkey, analysts]

Sample	Clay types								
	Illite	Illite-mica or mica	Illite-montmorillonite, mixed	Montmorillonite	Chlorite-montmorillonite, mixed	Chlorite	Mica-chlorite, mixed	Kaolinite	Serpentine
Surface samples									
1075	---	4	---	---	---	5	---	---	---
1175	---	4+	---	---	---	4+	---	---	---
1275	---	3+	---	---	---	2+	---	2+	---
1475	---	5	---	---	---	1	---	1	---
1575	---	5	---	---	---	2	---	1+	---
1875	---	3+	---	Trace	---	2+	---	2+	---
2075	---	2+	---	1	---	2+	---	2+	---
2175	---	3+	---	1-	---	2+	---	1+	---
2675	---	1+	---	---	---	1+	---	---	4+
3075	---	3+	---	---	2	2+	---	---	---
3275	---	2	---	---	---	2	---	---	3+
3375	---	1+	---	Trace	---	1+	1	1-	---
3675	---	1+	---	1-	---	1-	---	1+	---
3875	---	1+	---	Trace	---	1	---	---	3+
4275	---	1+	---	---	---	1-	---	5	---
4375	---	2	1	---	---	Trace	---	4+	---
4575	---	2+	---	---	---	1-	---	3+	---
4875	---	1	1-	---	---	Trace	---	5+	---
5175	---	1+	Trace	---	---	Trace	---	4	---
5375	---	1+	1+	---	---	Trace	---	3+	---
5475	---	1-	1-	---	---	Trace	---	5+	---
Subsurface sampling									
Kaolak 1 (937)	<1	---	---	Trace	---	Trace	---	Trace	---
(2453)	1+	---	---	---	---	Trace	---	<1	---
(3187)	1	---	Trace	---	---	Trace	---	<1	---
(4078)	<1	---	Trace	---	---	Trace	---	1	---
(6739)	<1	---	Trace	---	---	Trace	---	Trace	---
Topagoruk 1 (304-p)	<1	---	Trace	---	---	Trace	---	Trace	---
(603-p)	<1	---	Trace	---	---	Trace	---	Trace	---
(1204-p)	1	---	---	---	---	Trace	---	Trace	---
(1790-p)	---	<1	Trace	---	---	Trace	---	Trace	---
(5972)	---	<1	---	---	---	Trace	---	Trace	---
(6498)	1+	---	Trace	---	---	Trace	---	---	---
Simpson (454)	---	1	Trace	---	---	<1	---	Trace	---
(829)	---	1	Trace	---	---	<1	---	Trace	---
(979)	---	1	---	---	---	<1	---	Trace	---
Meade 1 (2953)	<1	---	Trace	---	---	Trace	---	Trace	---
(4133)	<1	---	Trace	---	---	Trace	---	<1	---
Oumalik 1 (979-p)	<1	---	---	---	---	Trace	---	Trace	---
(1606-p)	<1	---	---	---	---	Trace	---	<1	---
(3260-p)	<1	---	Trace	---	---	Trace	---	Trace	---
(3752-p)	1	---	---	Trace	---	Trace	---	Trace	---
Titaluk 1 (539-p)	---	1+	---	---	---	<1	---	<1	---
(2675-p)	Trace	---	---	---	---	Trace	---	Trace	---
(3004-p)	<1	---	---	---	---	Trace	---	<1	---
(3306)	<1	---	---	---	---	Trace	---	Trace	---
(3431-p)	Trace	---	---	---	---	<1	---	---	---
Wolf Creek 1 (867)	---	1	---	---	---	Trace	---	<1	---
Wolf Creek 3 (1553)	Trace	---	---	---	---	Trace	---	Trace	---
(2050)	<1	---	---	---	---	Trace	---	Trace	---
(2532)	---	1+	---	---	---	1	---	---	---
(3109)	1	---	Trace	---	---	<1	---	Trace	---
(3509)	1	---	---	---	---	<1	---	---	---
Grandstand (364-69)	---	<1	---	---	---	Trace	---	Trace	---
(862-82)	---	<1	---	---	---	Trace	---	Trace	---
(2484)	---	1	---	---	---	Trace	---	---	---
Knifeblade 2A (172-p)	Trace	---	---	---	---	Trace	---	<1	---
(792-p)	<1	---	---	---	1	<1	---	---	---
(1557-n)	<1	---	---	---	---	<1	---	---	---
Square Lake (1685)	1+	---	---	Trace	---	Trace	---	Trace	---
(1854)	1	---	Trace	---	---	Trace	---	Trace	---
(1916)	1	---	---	---	---	Trace	---	Trace	---
(3036)	<1	---	---	---	---	Trace	---	Trace	---
(3480)	<1	---	---	---	---	Trace	---	Trace	---
(3856)	<1	---	---	---	---	Trace	---	Trace	---
Gubik 2 (3112)	---	1+	Trace	---	---	<1	---	---	---
(3529)	1+	---	Trace	---	---	<1	---	---	---
(3645)	1	---	Trace	---	---	Trace	---	Trace	---
(3822)	<1	---	---	---	---	Trace	---	Trace	---
(4243)	1+	---	---	---	---	Trace	---	Trace	---

cement and (or) pseudomatrix. Petrographic observations show a large number of quartz overgrowths that could be misinterpreted as being the result of an earlier cycle of deposition of the quartzose grains. However, the scanning-electron-microscope photographs reveal that many, if not all, the overgrowths have grown in place (fig. 35.9). Where detrital grains do not have dust rims of clay, or where siliceous cementation is widespread, overgrowths and areas with significant siliceous cement may be difficult to distinguish from the angular detrital grains; petrographic techniques using cathodoluminescent light were unsuccessful in reliably determining the extent of quartz-overgrowth development. Therefore, the amount of siliceous cementation in these sandstone samples may have been underestimated in the microscopic modal analyses.

Authigenic clays, such as sericite, chlorite, and kaolinite, are present as alteration products of detrital feldspar and also as secondary pore-filling masses of intergrown crystals (figs. 35.10-35.12). Kaolinite is the most abundant authigenic clay, followed by chlorite and then sericite. The clays were deposited after formation of quartz overgrowths resulting from compaction and dissolution of quartzose grains. Kaolinite commonly fills primary intergranular pores as well as secondary pores created by dissolution of framework grains. These platy minerals, because of their morphology, may produce abundant connected micropores and thus unexpectedly high values of porosity and permeability in laboratory tests (Sarkisyan, 1971).

TEXTURAL OBSERVATIONS AND CONCLUSIONS

Maximum and modal grain sizes were measured using the petrographic microscope and estimated in the field using the American Stratigraphic Company (Amstrat) grain-size chart. Sorting was estimated petrographically by referring to sorting images illustrated by Pettijohn and others (1972, p. 585); field estimations of sorting (using the Amstrat chart) indicate better sorting than the petrographic estimates. Types of grain contacts (Taylor, 1950) observed include (1) sutured grains, mutual stylolitic interpenetration of two or more grains (which must be carefully distinguished from grains of polycrystalline quartz); (2) concave-convex grain contacts; (3) long or straight contacts; (4) point or tangential contacts; and (5) floating grains that are not in contact with

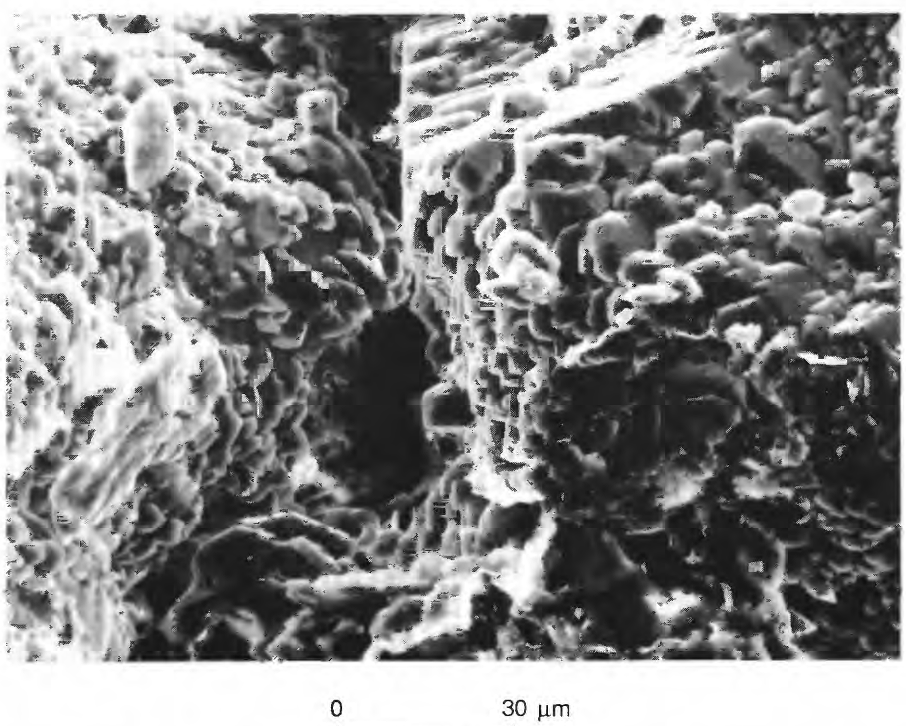


FIGURE 35.9.—Scanning-electron-microscope photograph showing microcrystalline quartz overgrowth filling interstices between detrital grains in sandstone of the Nanushuk Group. Note lack of kaolinite clay and retention of intergranular porosity. Sample 78ACh76, Kurupa anticline section.

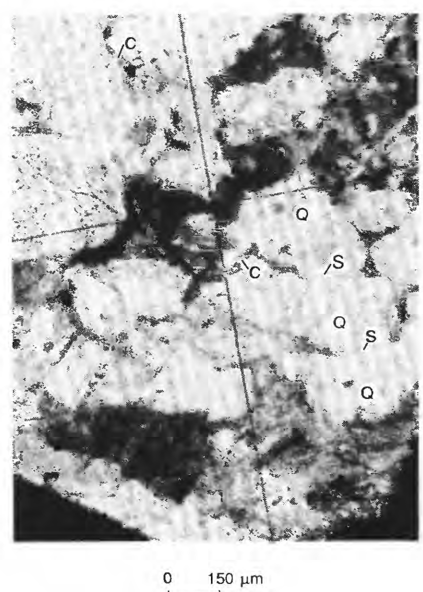


FIGURE 35.10.—Photomicrograph of Nanushuk Group sandstone showing diagenetic chlorite cement. Cement has grown around detrital grains but is notably absent where grains have been previously welded by compaction and dissolution of silica. C, chlorite; Q, quartz, S, sutured contact. Sample 77AAh25, Tuktu Bluff. Plane polarized light.

other framework constituents. Most samples exhibit more than one type of grain contact. Textural components of cement, matrix, pores, and framework grains were determined from the modal analysis of each thin section.

Histograms of these observations (fig. 35.5) show that the sandstone samples are typically composed of fine to very fine sand and are moderately to poorly sorted. Samples have grain contacts that reveal a history of compaction, dissolution, and cementation. Sutured, concave, and long grain boundaries typify samples from the Nanushuk; samples from the subsurface, which are finer grained, have higher percentages of grain boundaries that are tangent or floating. Quartz grains are typically strained and cracked (fig. 35.6), and many feldspar twins are offset or bent. Most mica grains are bent, and many have been altered to chlorite or expanded and disrupted by calcite or silica cement.

POROSITY AND RESERVOIR POTENTIAL

Surface samples average 1 to 2 percent of visible porosity (measured petrographically), whereas those from the subsurface are more favorable from a reservoir standpoint, averaging 5 percent in the western belt and 6 percent in the central belt. The percentage of framework grains is highest in the outcrop samples (80 percent). The relation of visible porosity (measured petrographically) to measured effective porosity (measured in the laboratory) is shown in table 35.3: A large discrepancy exists between visible and effective porosities. This discrepancy may be due to the large amounts of platy or fine-grained matrix materials, which provide submicroscopic pores that are too tiny to detect petrographically but still of importance from a reservoir standpoint.

From the petrographic evidence, the Nanushuk Group is apparently least favorable as a potential hydrocarbon reservoir in the Corwin delta (western) outcrop belt, slightly better in the Umiat delta (central) outcrop belt, and most favorable to the north in the subsurface. In the Corwin delta outcrop belt, average visible porosity totals 1.4 percent, average effective porosity totals 8.4 percent, and air permeability measurements average 14.0 mD (table 35.3; fig. 35.5). Petrographically, the sandstone samples from Corwin delta reveal higher percentages of matrix and cement than those from the Umiat delta outcrop belt. The Corwin samples are rich in sedimentary lithic grains, which are conducive to alteration and pore-plugging during compaction, thus reducing permeability. Nevertheless, an occasional sandstone bed may have excellent porosity and permeability and reduced amounts of matrix and

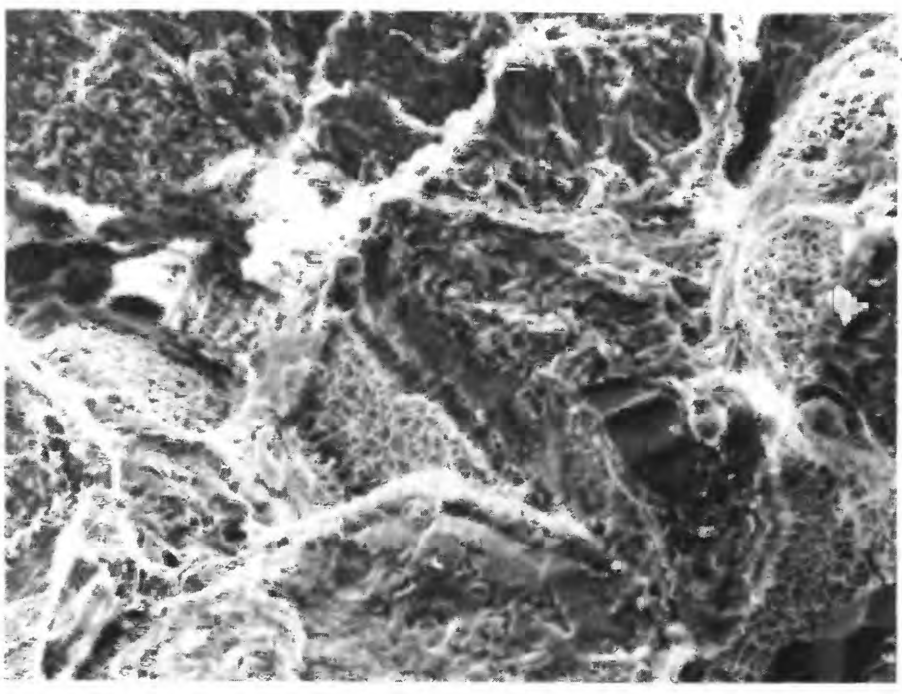


FIGURE 35.11.—Scanning-electron-microscope photograph showing extensive development of chlorite cement in sandstone sample from Kurupa anticline section. The chlorite bridges intergranular spaces, completely obliterating any pores that may have previously existed. Sample 78ACh32.

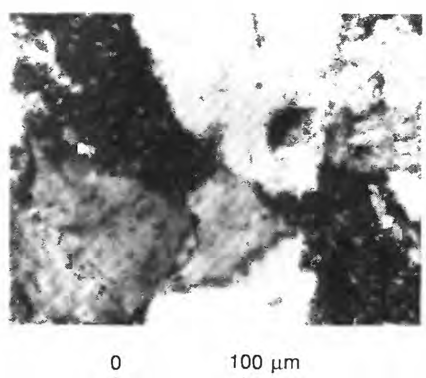


FIGURE 35.12.—Photomicrograph of Nanushuk Group sandstone sample showing pressolved quartz grains that have been replaced by kaolinite cement. Carbonate is the final alteration mineral in this sandstone. Sample 78ACh76, Kurupa anticline section. Crossed nicols.

TABLE 35.3.—*Modal grain size, visible porosity, effective porosity, and air permeability for selected sandstone samples from the Nanushuk Group and Torok Formation*

[n, number of samples; ---, no testing done; *, sample from Torok Formation. Averages take into account only those samples tested]

Sample	Modal grain size, estimated (mm)	Visible porosity (percent)	Effective porosity, Ø (percent)	Air permeability (mD)
Tupikchak Mountain syncline (n = 16)				
77AJF23	0.15	0.3	7.3	---
77AJF28	.30	.0	8.6	1.17
77AJF30	.18	.3	8.0	.16
77AJF32-u	.23	0	4.1	---
77AJF36-u	.23	0	4.6	---
77AJF37-l	.25	0	6.2	---
77AJF37-u	.30	0	7.3	---
77AJF39-l	.25	.7	6.8	---
77AJF39-u	.30	.7	5.6	---
77AJF42-l	.34	1.3	4.2	---
77AJF42-u	.30	0	6.1	---
77AJF44	.18	.3	6.6	---
77AJF47-l	.18	0	5.2	---
77AJF47-u	.45	1	5.3	---
77AJF52-l	.25	0	5.5	---
77AJF52-u	.25	0	6.4	---
Range	.15-.45	0-1.3	4.1-8.6	0-1.17
Average	.26	.29	6.1	.67
Carbon Creek (n = 6)				
77AAh4cc	.15	0	7.6	.12
78AAh5cc	.23	4.3	12.6	.43
78AAh6cc	.23	8	14.5	1.20
78AAh8cc	.50	0	4.5	.15
78AAh9cc	.30	6	13.6	2.20
78AAh12cc	.60	0	4.3	.07
Range	.15-.60	0-8	4.3-14.5	.07-2.20
Average	.34	3.1	9.5	.70
Corwin Bluff (n = 13)				
77AAh31b	.23	3.7	8.3	.45
77AAh39	.30	1.3	10.3	.35
77AAh40	.23	0	---	---
77AAh42	.46	.3	7.2	---
77AAh46	.18	0	1.4	---
77AAh48a	.30	0	4.8	---
77AAh100a	.30	3.3	10.1	3.9
77AAh101	.30	0	3.3	---
77AAh103	.23	0	3.9	---
77AAh104	.25	.7	8.8	1.44
77AAh105	.18	1	5.4	---
77AAh106	.30	1.7	9.2	0.84
77AAh110	.18	.3	3.4	---
Range	.18-.46	0-3.7	1.4-10.3	.35-3.9
Average	.26	.9	6.3	1.40
Barabara syncline (n = 25)				
77ACh82	.25	2	12.6	1.45
77ACh85	.20	.6	11.7	1.65
77ACh87-l	.25	.6	11.4	1.31
77ACh87-u	.15	1	11	0.27
77ACh89-l	.25	0	7.2	---
77ACh89-u	.30	.3	9.5	.61
77ACh90-l	.25	1.3	11.2	1.48
77ACh90-u	.25	.6	11.7	1.25
77ACh92	.25	2.3	11.3	1.25
77ACh93-l	.15	0	10.3	1.47
77ACh93-m	.20	0	10.7	.68
77ACh93-u	.15	0	10.5	.47

TABLE 35.3.—*Modal grain size, visible porosity, effective porosity, and air permeability for selected sandstone samples from the Nanushuk Group and Torok Formation*—Continued

Sample	Modal grain size, estimated (mm)	Visible porosity (percent)	Effective porosity, ϕ (percent)	Air permeability (mD)
Barabara syncline (n = 25)--Continued				
77ACh97	.20	.3	8.7	.30
77ACh101-l	.20	2	12	1.13
77ACh101-m	.25	1.3	10.4	1.04
77ACh101-u	.25	0	6.4	---
77ACh104-l	.18	1.3	14.6	2.75
77ACh104-u	.18	1.3	13.6	1.74
77ACh108-l	.20	0	8.9	.38
77ACh108-m	.30	0	8.1	.19
77ACh108-u	.20	1	12	.99
77ACh116	.30	0	8.2	33.37
77ACh120-l	.23	.7	12.8	1.51
77ACh123	.15	.6	9.6	1.40
77AAh184	.25	14.6	29.5	1,278.80
Range	.15-.30	0-14.6	7.2-29.5	.190-1,278.8
Average	.22	1.27	11.4	53.42
Kurupa anticline (n = 23)				
78ACh20	.23	0	6	34
78ACh21	.30	3.3	11.7	.26
78ACh23	.60	6.3	11.2	7.2
78ACh24	.50	2	6.8	39
78ACh25	.18	0	---	---
78ACh30	.18	3.3	11.1	.21
78ACh31	.23	10	---	---
78ACh32	.23	6.7	11.7	1.1
78ACh33	.30	6	13.8	2.4
78ACh43	.23	0	---	---
78ACh47	.30	0	---	---
78ACh49	.18	0	9.4	.33
78ACh59	.40	3	---	---
78ACh64	.23	.3	5.1	.05
78ACh70	.23	1.3	15.2	4.7
78ACh74	.30	0	4.9	.47
78ACh76	.60	5.7	17.7	62
78ACh79	.30	.7	9.8	.97
78ACh80	.23	.3	7.3	.18
78ACh103	.50	.3	6.6	.15
78ACh108	.60	0	6.6	.12
78ACh113	.23	0	---	---
78ACh116	.23	0	5.5	.13
Range	.18-.60	0-10	4.9-17.7	.05-62
Average	.32	2.14	9.4	6.66
Tuktu Bluff (n = 19)				
77AAh12	.18	0	6.5	---
77AAh13-u	.15	0	7.5	---
77AAh16	.23	.3	7.8	---
77AAh17	.30	0	6.1	---
77AAh20-l	.18	0	5.3	---
77AAh21	.60	.7	5.5	---
77AAh23	.23	3.7	---	---
77AAh25	.30	1.7	11	.79
77AAh30	.18	0	3.8	---
77AAh35-l	.15	.3	4.8	113 (hairline fracture)
77AAh37-m	.23	.6	6.2	.25
77AAh38-l	.45	1.7	4.2	.15
77AAh38-u	.40	3.8	7.7	.41
77AAh39-l	.15	.3	3.4	.07
77AAh39-u	.70	1.6	7.9	6.2
77AAh43-u	.60	1.3	6.9	.26
77AAh45-l	.23	.7	8.1	.33
77AAh49-u	.18	0	14.6	320
77AAh49-l	.55	16	11.2	6.6
Range	.15-.70	0-16	3.4-14.6	.07-320
Average	.32	1.7	7.1	40.7

TABLE 35.3.—*Modal grain size, visible porosity, effective porosity, and air permeability for selected sandstone samples from the Nanushuk Group and Torok Formation*—Continued

Sample	Modal grain size, estimated (mm)	Visible porosity (percent)	Effective porosity, Ø (percent)	Air permeability (mD)
Arc Mountain syncline (n = 16)				
78ACh 6	.15	0	4.2	.06
78ACh 16	.20	0	3.4	.06
78ACh 17	.18	0	5.2	.59
78ACh 18	1.20	2.3	5.7	1
78ACh 19	.40	1.3	6.6	.28
78ACh 20	.40	1.3	7.1	.38
78ACh 22	.15	.3	---	---
78ACh 25	.25	.3	5.2	.22
78ACh 26	.30	0	4.3	.12
78ACh 27	.60	5.3	8.4	3.90
78ACh 30	.30	0	---	---
78ACh 31	.60	3	5.1	.17
78ACh 32	.30	4	7.4	.31
78ACh 41-l	.40	1.7	2.7	.12
78ACh 41-m	.60	2.7	6	.26
78ACh 41-u	.60	0	3.7	.07
Range	.15-1.20	0-5.3	2.7-8.4	.06-3.90
Average	.42	1.4	5.4	.54
Marmot syncline (n = 24)				
78ACh 14	.23	0	3.1	.31
78ACh 16	.77	3.3	3.8	.10
78ACh 18	.13	.3	4.7	.08
78ACh 20	.60	.3	2.5	.11
78ACh 24	1.20	8.3	2.3	.06
78ACh 25	.60	.7	5	.17
78ACh 26	.48	1.7	3.7	.12
78ACh 28	.23	3	4.1	.06
78ACh 29	.40	.7	---	---
78ACh 30	.60	0	3.2	.13
78ACh 31	1.20	2	4.4	.10
78ACh 32	.30	0	---	---
78ACh 34	.12	1	3.1	.05
78ACh 35	.60	.3	2.9	.08
78ACh 37	.60	2.7	5.5	.19
78ACh 38	.65	1.3	7.6	13
78ACh 43	.60	0	4.8	.15
78ACh 44	.60	0	5	.65
78ACh 45	.40	.3	6.5	.20
78ACh 46	.20	1	4.7	.25
78ACh 52	1.20	3.0	6.9	.56
78ACh 53	.38	1.3	5.6	.10
78ACh 54	.23	0	3.4	.06
78ACh 56	.20	0	5.5	.17
Range	.12-1.20	0-8.3	2.3-7.6	.05-13
Average	.52	1.3	4.5	.80
Subsurface Samples				
Western: n = 9				
Kaolak 1 (937)	.23	6.3	11.55	Imperm.
(2453)	.23	2	11.90	Imperm.
(3187)	.18	1	10.04	Imperm.
(4078)	.15	5.3	11.28	Imperm.
Meade 1 (2953)	.23	7.7	19.2	13.48
* (4133)	.23	3.7	9.35	Imperm.
Oumalik 1 (979-984)	.23	3.3	15.2	34
(1606)	.26	1.7	10.9	8.8
* (3260)	.18	2	9.2	Less than 4
Range	.15-.26	1-7.7	9.2-19.2	
Average	.21	3.7	12.1	

TABLE 35.3.—*Modal grain size, visible porosity, effective porosity, and air permeability for selected sandstone samples from the Nanushuk Group and Torok Formation*—Continued

Sample	Modal grain size, estimated (mm)	Visible porosity (percent)	Effective porosity, Ø (percent)	Air permeability (mD)
		Subsurface Samples--Continued		
Central: n = 22				
Knifeblade 2A (172)-----	.30	9.3	16	41
(792)-----	.40	3.3	14.2	1.3
(552)-----	.15	4.7	11.6	Less than 1
Titaluk 1 (539)---------	.15	4.7	12	Imperm.
(2675)--------	.15	7.3	12.5	17.0
(3004)--------	.27	1.7	8.3	Imperm.
(3306)--------	.23	2.7	9.0	Imperm.
(3431)--------	.17	1.7	10.5	Imperm.
Wolf Creek 1 (867)------	.30	0	5.3	Imperm.
Wolf Creek 3 (1553)-----	.30	10.3	18.9	305
(2050)-----	.17	2	10.6	Less than 1
(2532)-----	.20	0	4.7	Imperm.
Sq. Lake (1916)---------	.17	5.3	17.5	---
(3036)---------	.23	6.3	13.3	17.6
(3480)---------	.14	8.7	12.7	Imperm.
Grandstand (364-69)-----	.46	2.3	10.6	---
(862-82)-----	.17	2.3	11.2	Less than 1
Gubik 2 (3529)----------	.17	3.7	13.5	2.3
(3822)----------	.18	8	14.1	22
Simpson (829)-----------	.13	12.3	28.8	---
Topagoruk 1 (603)-------	.15	13	27.2	316.2
(1204)------	.23	11.4	26	200.4
Range--------------	.13-.46	0-13	4.7-28.8	
Average------------	.22	5.5	14	

cement, resulting in a favorable reservoir rock (for example, sample 77AAh184 from the Barabara syncline; see table 35.1). Pores typically are lined with a reddish-brown, probably iron-rich coating. The overall paucity of sand bodies and the lack of continuous stacked beds in the whole western area are negative factors for hydrocarbon potential in the Corwin delta (Huffman, 1979).

As in the Corwin delta, sandstone bodies in the Umiat delta are lenticular and have extensive shale interbeds, and many of them are shaly or muddy. Samples from the central outcrop belt record nearly the same values of porosity and permeability as those from the western belt. Visible porosity in the Umiat delta samples averages 1.6 percent, effective porosity averages 6.6 percent, and air permeability measurements average 12.2 mD (table 35.3; fig. 35.5). However, as in the Corwin delta, sporadic occurrences of significant porosity and permeability (for example, sample 77AAh49-I from Tuktu Bluff; see table 35.1) indicate that isolated sand bodies in the central Umiat delta may have excellent reservoir potential. In general, the sandstone bodies are slightly coarser in the central outcrop belt (fig. 35.5) and have slightly lesser amounts of matrix and cementing material and higher percentages of quartzose grains (fig. 35.3), which resist squeezing and compaction.

SECONDARY POROSITY

Higher values of effective porosity, air permeability, and visible porosities were recorded and observed in sandstone samples from the Nanushuk Group and Torok Formation in the subsurface (table 35.3). These values may result from the lack of alteration by surface weathering; the mode of transport of the sand during deposition (a higher energy environment of deposition); or an increase in dissolution of framework grains and (or) cement combined with the lack of later stages of calcite cementation. Grains most often dissolved include the unstable types, such as lithic and feldspar grains, as well as quartzose grains and clays (figs. 35.13-35.17). Extensive interbedded shale sequences can provide large quantities of fluids, through compaction and expulsion of water, that are easily transported through the interbedded fine-grained sandstone.

Secondary porosity was recognized in these rocks by using the techniques and criteria described by Scholle (1979, p. 171). Such features as partial dissolution and corrosion of grains and cements, inhomogeneity of packing, oversized pore spaces, floating grains, and fractured or cracked grains were observed. Secondary porosity may subsequently be totally or partially destroyed by recementation and (or) infilling by diagenetic clays, especially kaolinite. In at least one

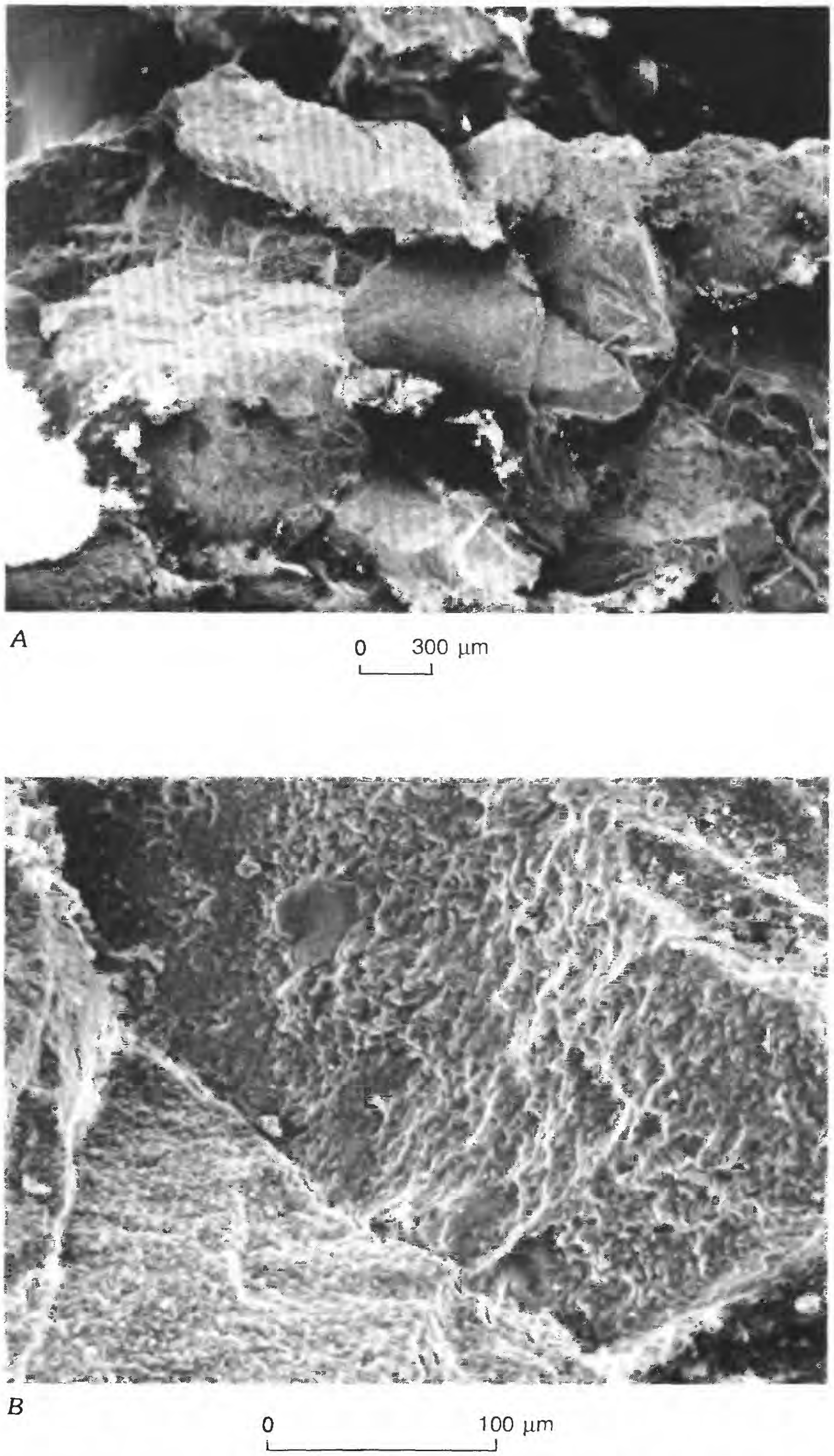


FIGURE 35.13.—Scanning-electron-microscope photographs showing Nanushuk Group sandstone sample having good porosity, probably a result of leaching and corrosion of detrital grains. Sample 78ACh41, Marmot syncline. *A*, Note development of quartz overgrowths, lower right corner. *B*, Note pitted surfaces of grains.

sample (and suspected in others), kaolinite has been dissolved to create secondary porosity (fig. 35.14). A sandstone sample from the Inigok well has developed abundant secondary porosity because some of the potassium feldspars have been dissolved and others have not (fig. 35.15). In some samples, quartz grains have been dissolved (fig. 35.16). This evidence indicates that secondary porosity in these rocks may have been created in several stages and may have involved complex and diverse dissolving fluids resulting possibly from changing pressure and temperature conditions in the host rocks.

Very small quantities of dark-brown to black, slightly translucent material was often observed; this was suspected to be oil, though no hydrocarbon tests were employed. Fragments of coal are also present in these rocks; the microscopic distinction between the two organic components is often difficult.

SUMMARY

Matrix and cementing materials found in the interstices between detrital grains in most samples of Nanushuk Group sandstone reduce their reservoir potential. The most promising sandstone bodies in the Nanushuk Group are those in the northern and eastern subsurface sections because it is in samples from those sections that preliminary tests of porosity and permeability show the highest values. Much of the porosity may be secondary and thus may improve the reservoir potential of these sandstones. At least three factors may be responsible for the northeastward increase in porosity and permeability. (1) Complex and diverse fluids capable of distributing dissolving agents may, at least in part, be derived by compac-

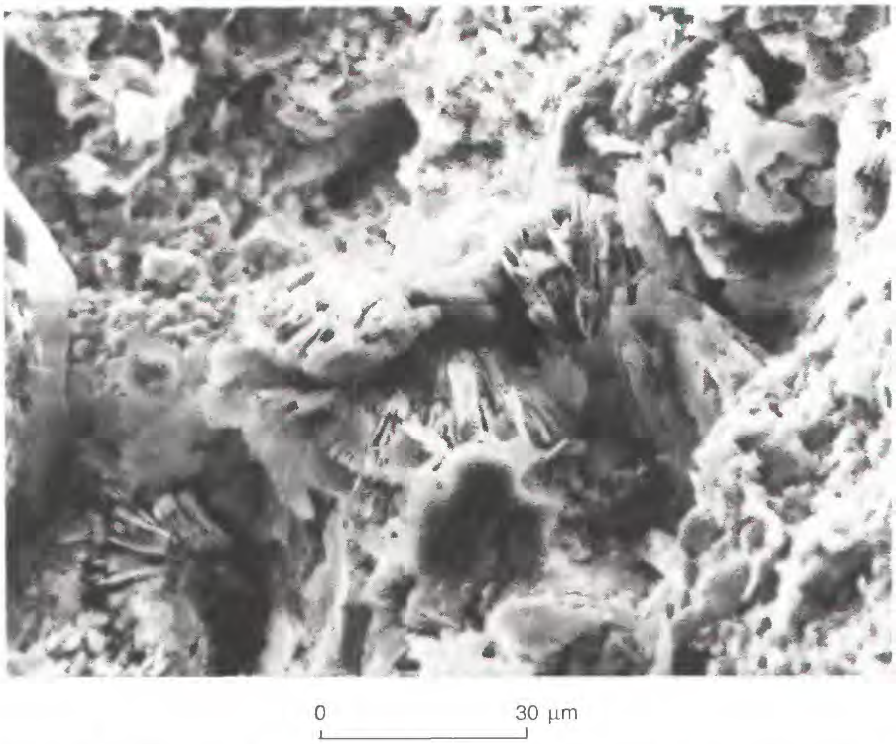


FIGURE 35.14.—Scanning-electron-microscope photograph of vermicular clay (probably kaolinite) and quartz overgrowths (left edge of photograph) in a sandstone sample from the Torok Formation. View shows kaolinite(?) crystals that have lost their hexagonal shape and have ragged edges, indicating that they may have been etched or dissolved by throughgoing fluids. Sample from depth of 581 to 584 m (1,906-1,916 ft), South Barrow No. 1 well.

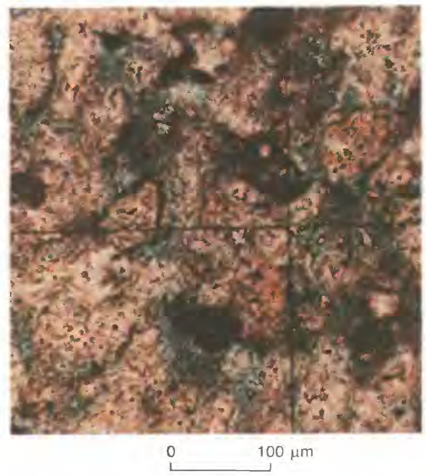


FIGURE 35.16.—Abundant development of leached-grain porosity in a Nanushuk Group sandstone sample from the 733-m (2,406-ft) depth in the East Simpson No. 1 well. Secondary porosity (shown by blue dye) has been created by dissolution of lithic volcanic grains and embayment of monocrystalline quartz grains. Potassium feldspar, plagioclase, and calcite grains remain intact. Plane polarized light.

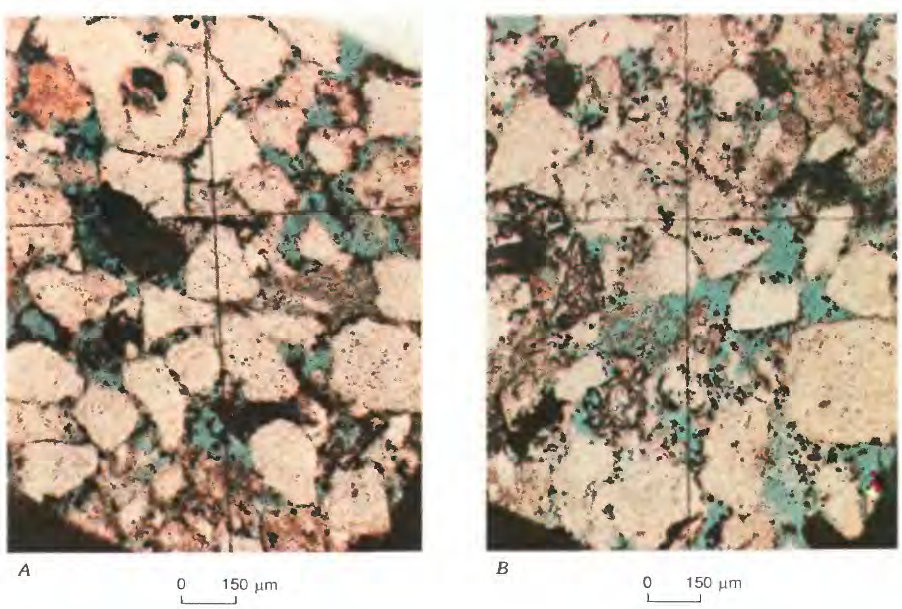


FIGURE 35.15.—Sandstone sample from the Nanushuk Group from 811-m (2,662-ft) depth in the Inigok No. 1 well. Sample contains abundant heavy minerals (opaque) and secondary porosity (shown by blue plastic dye injected into sandstone before grinding of thin section). Original grain boundaries are visible as opaque heavy-mineral outlines, but the grains have been dissolved. Remnants of original texture show framework grains having tangential, long, and concave boundaries, indicating that the original sandstone had undergone considerable compaction. Plane polarized light. *A*, View showing potassium feldspars (yellow) not dissolved. *B*, View showing potassium feldspars almost completely gone. Only remnants of lithic grains remain in the sandstone.

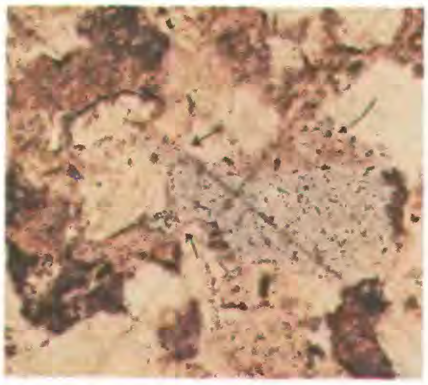


FIGURE 35.17.—Oversized pore (blue area in center), diagnostic of leached-grain porosity, in a sandstone sample from the Nanushuk Group along the Colville River north of Siksikpuk Ridge. Note dissolution of grains adjacent to the pore (arrows). Sample F2075. Plane polarized light.

tion and fluid expulsion from interbedded and downdip shale beds, which are more abundant to the north. (2) The detrital calcite grains, which came from the Brooks Range to the south and west and which are the source for much of the calcite cement, may decrease in numbers northeastward. (3) The style of Nanushuk deposition changes from low- to moderate-energy deltaic environments in the south and west to higher energy barrier-coastline environments in the subsurface to the north, resulting in a probable increase in the lateral extent and improvement of the sorting coefficient of the sandstone bodies.

REFERENCES CITED

Ahlbrandt, T.S., Huffman, A.C., Jr., Fox, J.E., and Pasternak, Ira, 1979, Depositional framework and reservoir-quality studies of selected Nanushuk Group outcrops, North Slope, Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of the Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 14-25.

Bartsch-Winkler, Susan, 1979, Textural and mineralogical study of some surface and subsurface sandstones from the Nanushuk Group, western North Slope, Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of the Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 61-76.

——— 1985, Petrography of sandstones of the Nanushuk Group from four measured sections, central North Slope, Alaska, *in* Huffman, A.C., Jr., ed., Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 75-95.

Bartsch-Winkler, Susan, and Huffman, A.C., 1981, Compositional variation in sandstones of the Nanushuk Group, Arctic North Slope, *in* Albert, N.R.D., and Hudson, Travis, eds., The United States Geological Survey in Alaska; accomplishments during 1979: U.S. Geological Survey Circular 823-B, p. B6-B8.

Bird, K.J., and Andrews, Jack, 1979, Subsurface studies of the Nanushuk Group, North Slope, Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of the Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 32-41.

Brosgé, W.P., and Tailleur, I.L., Northern Alaska petroleum province, *in* Cram, I.H., ed., Future petroleum provinces of the United States—their geology and potential: American Association of Petroleum Geologists Memoir 15, p. 68-99.

Collins, F.R., 1958a, Test wells, Topogoruk area, Alaska, *with a section on* Micropaleontologic study of the Topagoruk test wells, northern Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-D, p. 265-316.

——— 1958b, Test wells, Meade and Kaolak areas, Alaska, *with a section on* Micropaleontology of Meade test well 1 and Kaolak test well 1, northern Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-F, p. 341-376.

——— 1959, Test wells, Square Lake and Wolf Creek areas, Alaska, *with a section on* Micropaleontology of Square Lake test well 1 and the Wolf Creek test wells, northern Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-H, p. 423-484.

Dickinson, W.R., 1970, Interpreting detrital modes of graywacke and arkose: Journal of Sedimentary Petrology, v. 40, no. 2, p. 695-707.

Dickinson, W.R., and Suczek, C.A., 1979, Plate tectonics and sandstone compositions: American Association of Petroleum Geologists Bulletin, v. 63, no. 12, p. 2164-2182.

Folk, R.L., 1968, Petrology of Sedimentary Rocks: Austin, Tex., Hemphill's Book Store, 170 p.

Fothergill, C.A., 1955, The cementation of oil reservoir sands and its origin: World Petroleum Congress, 4th, Rome, 1955, Proceedings, Section 1, p. 301-314.

Fox, J.E., 1979, A summary of reservoir characteristics of the Nanushuk Group, Umiat Test Well 11, National Petroleum Reserve in Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 42-53.

Fox, J.E., Lambert, P.W., Pitman, J.K., and Wu, C.H., 1979, A study of reservoir characteristics of the Nanushuk and Colville Groups, Umiat Test Well 11, National Petroleum Reserve in Alaska: U.S. Geological Survey Circular 820, 47 p.

Fuchtbauer, Hans, 1974, Sediments and sedimentary rocks, 1, Part II: New York, Halsted Press, 464 p.

Grantz, Arthur, Holmes, M.L., and Kososki, B.A., 1976, Geologic framework of the Alaskan continental terrace in the Chukchi and Beaufort Seas, *in* Canadian continental margins: Canadian Society of Petroleum Geologists Memoir 4, p. 669-700.

Huffman, A.C., Jr., 1979, Stratigraphy and petrography of a measured section on the south limb of Barabara syncline, North Slope, Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 77-88.

Jonas, E.C., and McBride, E.F., 1977, Diagenesis of sandstone and shale—application to exploration for hydrocarbons: American Association of Petroleum Geologists Continuing Education Program Publication 1, 120 p.

Krynine, P.D., 1947, Reservoir characteristics indicated by thin-section analyses of sand cores from Umiat Test Well No. 1: U.S. Geological Survey Geological Investigations, Naval Petroleum Reserve No. 4 and adjacent areas, Alaska, Regular Report 9, 11 p., [Available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey]

——— 1948, Petrography and reservoir characteristics of selected Tertiary and Cretaceous sandstone cores from Naval Petroleum Reserve No. 4: U.S. Geological Survey Geological Investigations, Naval Petroleum Reserve No. 4 and adjacent areas, Alaska, Regular Report 20, 47 p. [Available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey]

Krynine, P.D., and Ferm, J.C., 1952, Petrography and reservoir characteristics of Umiat Test Well 9: U.S. Geological Survey Geological Investigations, Naval Petroleum Reserve No. 4 and adjacent areas, Alaska, Special Report 34, 31 p. [Available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey]

Mull, C.G., 1979, Nanushuk Group deposition and the Late Mesozoic structural evolution of the central and western Brooks Range and Arctic Slope, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of the Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 5-13.

Nilsen, T.H., and Moore, T.E., 1984, Stratigraphic nomenclature for the Upper Devonian and Lower Mississippian(?) Kanayut Conglomerate, Brooks Range, Alaska: U.S. Geological Survey Bulletin 1529-A, A1-A64.

Payne, T.G., 1955, Mesozoic and Cenozoic tectonic elements of Alaska: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-84, scale 1:5,000,000.

Pettijohn, F.J., Potter, P.E., and Siever, Raymond, 1972, Sand and sandstone: New York, Springer-Verlag, 618 p.

Robinson, F.M., 1956, Core tests and test wells, Oumalik area, Alaska, *with a section on* Paleontology of test wells and core tests in the Oumalik area, Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-A, 70 p.

——— 1958, Test wells, Gubik area, Alaska, *with a section on* Micropaleontologic study of the Gubik test wells, northern Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-C, p. 207-264.

——— 1959a, Test well, Grandstand area, Alaska, *with a section on* Micropaleontologic study of Grandstand test well 1, northern Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-E, p. 317-339.

——— 1959b, Test wells, Simpson area, Alaska, *with a section on* Core analyses, by S.T. Yuster: U.S. Geological Survey Professional Paper 305-J, p. 523-568.

——— 1959c, Test wells, Titaluk and Knifeblade areas, Alaska, *with a section on* Micropaleontologic study of test wells in the Titaluk and Knifeblade areas, northern Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-G, p. 377-422.

——— 1964, Core tests, Simpson area, Alaska, *with a section on* Temperature measurement studies, by M.C. Brewer: U.S. Geological Survey Professional Paper 305-L, p. 654-730.

Sarkisyan, S.G., 1971, Application of the scanning electron microscope in the investigation of oil and gas reservoir rocks: Journal of Sedimentary Petrology, v. 41, no. 1, p. 289-292.

Scholle, P.A., 1979, A color illustrated guide to constituents, textures, cements, and porosities of sandstones and associated rocks: American Association of Petroleum Geologists Memoir 28, 201 p.

Tailleur, I.L., Pessel, G.H., Carter, Claire, and Churkin, Michael, Jr., 1973, Biostratigraphic record extended to Early Silurian or Ordovician in the western Brooks Range, *in* Geological Survey Research 1973: U.S. Geological Survey Professional Paper 850, p. 63-64.

Taylor, J.M., 1950, Pore-space reduction in sandstones: American Association of Petroleum Geologists Bulletin, v. 34, no. 4, p. 701-716.

36. STRATIGRAPHY AND DIAGENETIC ALTERATION OF ELLESMERIAN SEQUENCE SILICICLASTIC ROCKS, NORTH SLOPE, ALASKA

By PETER C. VAN DE KAMP[1]

INTRODUCTION

PURPOSE AND SCOPE

The purposes of this study were (1) to interpret the general depositional settings of Carboniferous to earliest Cretaceous rocks in the Ellesmerian sequence, (2) to describe and interpret the mineralogy and petrography of Ellesmerian rocks in 19 wells in the National Petroleum Reserve in Alaska (NPRA), and (3) to predict where the porosity and permeability in sandstone reservoirs might be favorable for hydrocarbon production. For comparison, a survey of rocks of similar age was made for nine wells in and adjacent to the Prudhoe Bay oil field. Effort was concentrated on the Permian through Jurassic part of the Ellesmerian sequence because that interval contains productive reservoirs and potentially productive sandstones.

Wells sampled for this study are listed in table 36.1, and their locations shown on figure 36.1. They include 19 wells from the northern part of the NPRA and 9 wells from east of the reserve in the Prudhoe Bay area. Information was obtained from wireline logs and subsurface cores and cuttings from exploration test wells using petrographic, X-ray, and scanning-electron-microscope (SEM) techniques for analysis. Four hundred thin sections were analyzed petrographically, 16 sandstone samples were examined with the SEM, and 59 shale samples were analyzed by X-ray diffraction for mineral determinations.

The data obtained in this work have been combined with measurements of porosity and permeability, geochemical thermal-maturity data on organic matter, and stratigraphic data to develop a model for reservoir prediction.

PREVIOUS WORK

Only meager petrographic information on Ellesmerian rocks of the North Slope was available before this study. Early work by Collins (1958, 1961) and Robinson (1959) gave general descriptions of the composition of some Permian, Triassic, and Jurassic rocks penetrated in the first wells drilled in the NPRA during the period 1944-53. Detterman and others (1975) provided data on Ellesmerian-sequence outcrops in the Brooks Range. Jones and Speers (1976) described the depositional environment, age, general composition, and areal extent of rock units at Prudhoe Bay. Wadman and others (1979) described the petroleum-engineering characteristics of the reservoir units, the Sadlerochit Group, at Prudhoe Bay.

METHODS

This work is primarily a study of well cores from the NPRA and the Prudhoe Bay area. Cores from the NPRA were studied at the U.S. Geological Survey (USGS) in Menlo Park, Calif., and in the laboratories of the following oil companies: BP-Sohio in Anchorage, Alaska; ARCO in Dallas, Tex.; Mobil in Oklahoma City, Okla.; and Union in Santa Fe Springs, Calif. The cores were studied in conjunction with wireline logs and lithology logs to obtain information on lithology, sedimentary features, and stratigraphy. Samples from cores and, in some cases, cuttings were collected for thin sections, SEM analysis, X-ray-diffraction analysis of shale, and vitrinite analysis of organic matter for determining thermal alteration.

Thin sections impregnated with blue epoxy resin were made for 300 sandstone samples. Another 100 thin sections from previous collections of the USGS were also examined. All sections were studied in detail for texture, mineralogy, alterations, and porosity. Point counts of 300 to 500 points were made on 31 sections. The mineralogy was found to be similar in all of those rocks, and additional counts were deemed unnecessary. Sixteen sandstone samples were examined with a Cambridge Instruments SEM at the USGS in Menlo Park, Calif. Fifty-nine shale samples from seven NPRA wells and three Prudhoe Bay area wells were analyzed by X-ray-diffraction methods (see section below entitled "Details of Analytical Procedures").

ACKNOWLEDGMENTS

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TABLE 36.1.—*Wells studied and sampled for this chapter*

Well	Location			Operator
	Sec.	T.	R.	
National Petroleum Reserve in Alaska (NPRA)				
South Barrow No. 2	14	22 N.	18 W.	U.S. Navy
South Barrow No. 4	14	22 N.	18 W.	U.S. Navy
South Barrow No. 9	11	22 N.	18 W.	U.S. Navy
South Barrow No. 12	26	22 N.	17 W.	U.S. Navy
South Barrow No. 13	14	22 N.	18 W.	Husky - U.S. Navy
Avak No. 1	17	22 N.	17 W.	U.S. Navy
Iko Bay No. 1	16	21 N.	16 W.	Husky - U.S. Navy
Kugrua No. 1	8	14 N.	26 W.	Husky - USGS
South Meade No. 1	31	15 N.	19 W.	Husky - USGS
Topagoruk No. 1	25	15 N.	16 W.	U.S. Navy
Simpson No. 1	31	19 N.	13 W.	U.S. Navy
South Simpson No. 1	22	17 N.	12 W.	Husky - U.S. Navy
Drew Point No. 1	26	18 N.	8 W.	Husky - USGS
East Teshekpuk No. 1	16	14 N.	4 W.	Husky - U.S. Navy
Cape Halkett No. 1	5	16 N.	2 W.	U.S. Navy
W.T. Foran No. 1	13	17 N.	2 W.	Husky - U.S. Navy
West Fish Creek No. 1	11	11 N.	1 W.	Husky - U.S. Navy
South Harrison Bay No. 1	6	12 N.	2 E.	Husky - U.S. Navy
Atigaru Point No. 1	19	14 N.	2 E.	Husky - U.S. Navy
Prudhoe Bay area				
Kalubik Creek No. 1	10	12 N.	8 E.	Union Oil Co.
Gwydyr Bay South No. 1	8	12 N.	13 E.	Mobil - SOCAL
Put River J-1	9	11 N.	13 E.	BP Alaska, Inc.
Put River	24	10 N.	14 E.	BP Oil Corp.
Sag Delta	31	10 N.	16 E.	BP Alaska, Inc.
Sag River State No. 1	4	10 N.	15 E.	ARCO - Humble
Put River State No. 1	7	10 N.	14 E.	ARCO - Humble
DS 2-4	36	11 N.	14 E.	ARCO - Humble
Toolik Federal No. 1	4	8 N.	15 E.	ARCO

the following oil companies: ARCO, BP Alaska, Mobil, and Union Oil Co. of California.

STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS

The Ellesmerian sequence (Lerand, 1973) in the NPRA of northern Alaska (fig. 36.2) ranges in thickness from 300 to 1,200 m (1,000-4,000+ ft). It is composed of shale, siltstone, sandstone, conglomerate, and carbonate members that range in age from Mississippian to Early Cretaceous. The stratigraphic sequence is similar across the study area. A stratigraphic cross section representative of the NPRA area and showing facies interpretations is given in figure 36.3.

The Ellesmerian sequence from the Permian Echooka Formation through the Jurassic and, locally, Cretaceous Kingak Shale has been studied in this project. Sandstone units in the Devonian and Mississippian Endicott Group were not available for sampling. Major potential petroleum reservoirs in this sequence are the Ivishak Formation of the Sadlerochit Group and the Sag River Sandstone. The unnamed Middle Jurassic sandstone in the NPRA and the Kuparuk River Formation (Jones and Speers, 1976) in the Prudhoe Bay area are also potential reservoirs, although they do not have the wide distribution of the Ivishak and the Sag River.

The depositional history, facies, and stratigraphy of the Echooka-Kingak sequence are interpreted as follows:

After uplift and erosion of the Lisburne Group (Mississippian, Pennsylvanian, and locally Permian), a marine transgression began in the Early Permian that resulted in the deposition of the Echooka Formation. This series of glauconitic sandstone and carbonate rocks pinches out on the south flank of the Barrow arch. Conformably overlying and overstepping the Echooka is the Kavik Member of the Ivishak Formation. It is a gray marine siltstone and shale representing the maximum Permian transgression in the North Slope. The Kavik grades upward through siltstone into sandstone of the Ivishak Formation.

The Ivishak Formation represents a major regressive event in which a deltaic-alluvial clastic deposit was formed. The Ivishak thickens from north to south; grain size of the sandstone and the proportion of nonmarine red beds within the unit diminish southward. These data indicate a source area for the sandstone to the north—probably in the area of the Barrow arch and northward. Paleontologic and lithologic data obtained from wells in the NPRA by Anderson and Warren, Inc., indicate that the basin was probably open to the south; the Ivishak grades into totally marine deposits toward the south. Anderson and Warren, Inc., infer inner neritic to nonmarine environments near and on the Barrow arch; farther south, middle to outer neritic depths of water existed.

In the Early and Middle Triassic, deposition of the Ivishak Formation diminished and finally ceased as a marine transgression inundated the

North Slope. This transgression is recorded by the Shublik Formation, a shallow marine (inner to middle neritic) deposit composed of carbonate rocks and shale, commonly rich in organic matter.

Deposition of the Shublik Formation was terminated during the Late Triassic by a regressive cycle in which the Sag River Sandstone was deposited. This glauconitic sandstone was deposited in a neritic (nearshore to middle neritic) environment (Anderson and Warren, Inc., unpub. data). Its maximum thickness is 75 m (250 ft) in the Simpson-Topagoruk well area, and it thins to the south, west, and east. To the north it is truncated. The Sag River may be the seaward part of a delta that was transgressed beginning in Early Jurassic time by the Kingak Shale.

The Kingak Shale, composed of shale and siltstone, is a marine deposit laid down in middle neritic to upper bathyal water depths (Anderson and Warren, Inc., unpub. data). At least one significant regressive pulse of coarser clastic deposits within the Kingak is recorded by the unnamed Middle and Upper Jurassic sandstone in the middle part of the Kingak in the NPRA.

The Neocomian Kuparuk River Formation, which lies above the Kingak Shale, is another possible deltaic deposit—the last unit derived from a northern source and the uppermost unit in the Ellesmerian sequence beneath the pebble shale unconformity. The overlying Neocomian deposits were apparently formed by the reworking of sediment derived from older Ellesmerian units truncated by the unconformity.

There is a major difference between the present-day occurrences of the Ellesmerian sequence in the NPRA and at Prudhoe Bay. In the NPRA, all the Ellesmerian units lap onto the pre-Ellesmerian landmass successively, overstepping each other northward (fig. 36.2). All the units are present at Prudhoe Bay, but to the north and northeast the units are progressively truncated by the downcutting Lower Cretaceous unconformity (fig. 36.4). Thus, at Prudhoe Bay, paleoshorelines are farther north than in the northern part of the NPRA.

MINERALOGY

SHALE

Shale samples were studied in detail to determine quantitatively their bulk mineralogy as well as the mineralogy of the clay fraction. The data obtained have been used to characterize the samples with respect to composition and to analyze possible diagenetic alteration with increasing burial.

X-ray diffraction methods were used to determine the bulk mineralogy and clay mineralogy of shale and clay-rich sandstone from 10

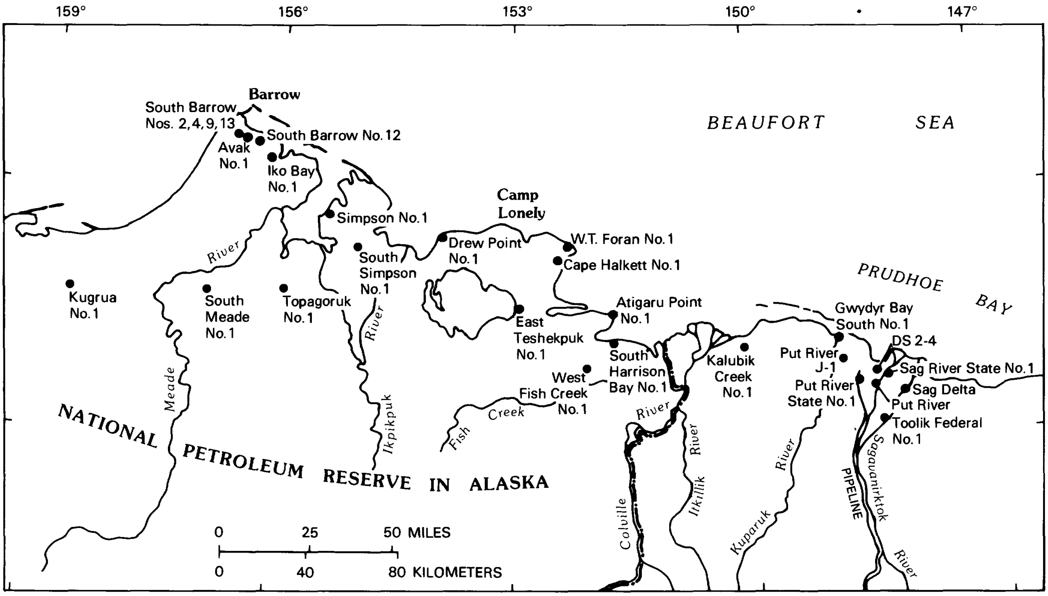

FIGURE 36.1.—Index map of the Alaska North Slope showing locations of wells that provided samples used in this study.

wells (see section below entitled "Methods of Shale Analysis"). R.L. Freed of Trinity University, San Antonio, Tex., performed the analyses. Most samples analyzed were shale; however, two samples of clay-rich sandstone from the South Barrow field were studied to determine the matrix mineralogy. The NPRA samples were from both Brookian and Ellesmerian sequences because these were available in cores. In the Prudhoe Bay field, only the Ellesmerian (mostly the Sadlerochit Group) was sampled.

The bulk mineralogy of the shale is fairly uniform and includes major amounts of quartz and clay and minor amounts of plagioclase, microcline, calcite, ankerite, siderite, and pyrite. Brookian shale contains less quartz (17-42 percent) and more plagioclase (6-13 percent) than Ellesmerian shale (quartz, 27-65 percent; plagioclase, 1-7 percent). This difference reflects the more feldspathic provenance of the Brookian rocks. Proportions of major minerals in the shale samples are plotted in figures 36.5 and 36.6.

Ankerite and siderite make up 1 to 19 percent of the shale and are present in most NPRA samples. Ankerite is scarce in the Prudhoe Bay samples; calcite was found in four samples, and siderite in all. Pyrophyllite was found in three samples from the Torok Formation in the Topagoruk well. Hematite was found in a sample from the Sadlerochit Group in the same well.

The clay mineralogy is quite uniform; the clays present are mica (illite and muscovite), kaolinite, chlorite, and mixed-layer clay of illite and montmorillonite. Proportions of clay minerals from the Topagoruk and Simpson wells are shown in figures 36.7 and 36.8. The proportions of the various clay minerals are similar for Brookian and Ellesmerian rocks. Kaolinite appears to diminish in some of the deeply buried Ellesmerian shale. Mixed-layer clay commonly exhibits a trend from a high proportion of montmorillonite at shallow depths to a low proportion at

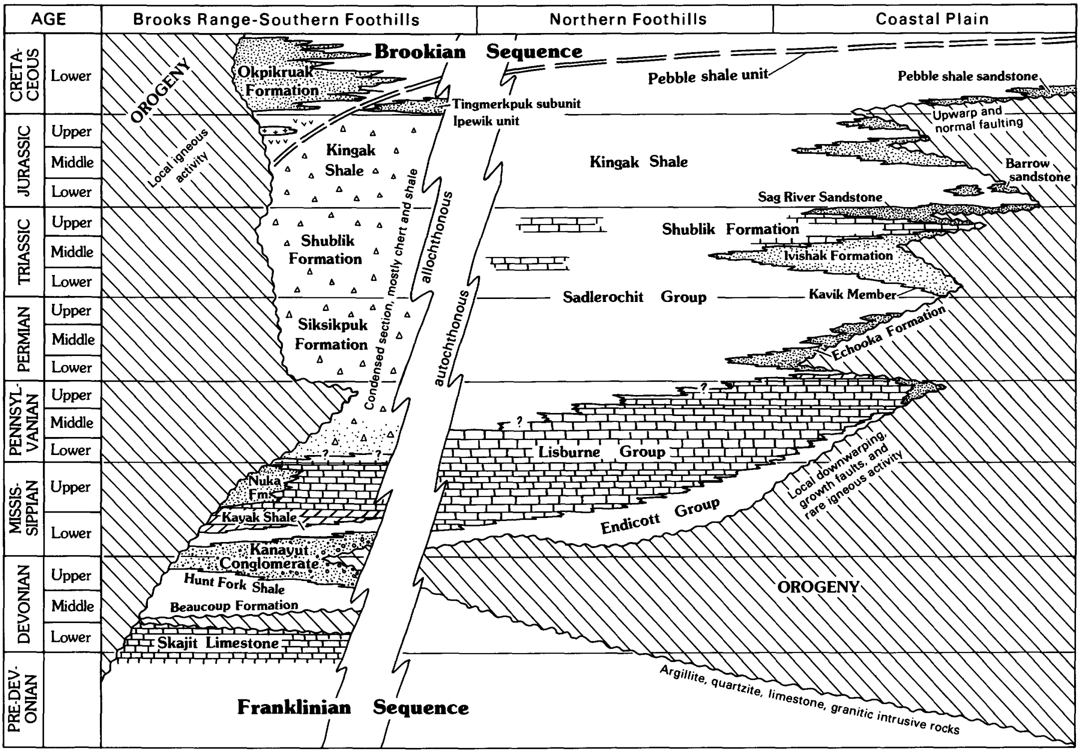

FIGURE 36.2.—Stratigraphic cross section (after Bird, 1981) through the Ellesmerian sequence in the NPRA. Relations are generally similar in the Prudhoe Bay area, except that at Prudhoe Bay all older units are truncated by the Lower Cretaceous pebble shale unconformity.

depths of 2,400 to 3,000 m (8,000-10,000+ ft) (Perry and Hower, 1970). No such trend is apparent in the shale samples analyzed in this study (figs. 36.7, 36.8.) In the rocks studied, mixed-layer clay contains variable amounts of montmorillonite with depth; it has not been determined why this is so. The montmorillonite present is a sodium-rich variety that swells on contact with freshwater. This swelling clay occurs as a significant phase in the matrix of the Barrow sandstone of local usage in the Barrow gas field. It may also be present in the Brookian reservoir rocks that have caused production problems, for example, at Umiat.

The clay mineralogy has been compared with the variation of a thermal indicator (vitrinite reflectance) in an attempt to determine possible temperature-related changes, such as the changes from montmorillonite to illite and from kaolinite to chlorite. The mixed-layer clay data are plotted against vitrinite reflectance in figure 36.9. They show no apparent trends with increasing reflectance. The kaolinite data (fig. 36.10) show lower amounts of kaolinite at higher reflectances. These data indicate that kaolinite may be altered to chlorite or mica at reflectance values above 0.6. Such kaolinite alteration is common in sedimentary basins (van de Kamp, 1976). The persistence of montmorillonite to high reflectance (R_o) values (>0.8) is puzzling because it commonly is transformed to illite at that level. Sample contamination is an unlikely explanation in this case because core material was used.

SANDSTONE

All the samples of Ellesmerian sandstone are similar in general composition (tables 36.2, 36.3). They consist of major amounts of quartz and chert and varying amounts of carbonate (both detrital grains and cement) and clays. Accessory minerals include pyrite, plagioclase, microcline, collophane, glauconite, zircon, sphene, tourmaline, and muscovite. Argillite and siltstone fragments occur as minor components in many samples.

Most of the quartz grains are monocrystalline; a few are polycrystalline. A few quartz grains contain inclusions, but most are clear and not strained. When initially deposited, the quartz grains were subangular to well rounded. Most now have angular quartz overgrowths, which constitute 1 to 18 percent of the rocks by volume (figs. 36.11, 36.12).

Chert is the second most abundant component in most of the sandstone samples; in a few it is

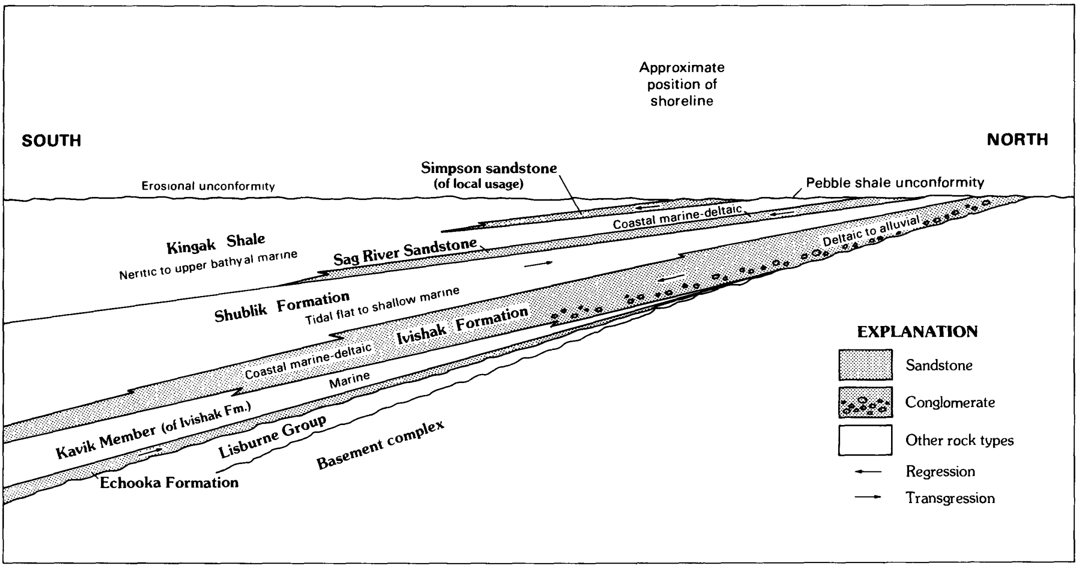

FIGURE 36.3.—Schematic north-south cross section through area of Foran and Drew Point wells showing depositional relations of clastic units of the Ellesmerian sequence in the NPRA. Major regressive and transgressive events indicated by arrows. Depositional environments inferred from well-log, core, and paleontological data are indicated for various units. At north end of section, relations between Ellesmerian units and pebble shale unconformity are indefinite; it is not certain whether the unconformity cuts the Ivishak Formation and (or) the Sag River Sandstone.

more abundant than quartz. In the coarser, conglomeratic sandstone most of the large clasts are chert. The chert is virtually all microcrystalline quartz; no feldspar, mafic, or opaque minerals that might indicate an origin from volcanic rocks were found. The degree of preservation of the chert varies; it ranges from fresh to highly altered and largely dissolved pieces (figs. 36.11, 36.12). The alteration is evidenced by a brownish coloring of the chert grains. Highly altered chert commonly has a residual skeletal framework containing many holes where solution has removed the silica. In hand specimens from outcrops and cores, altered chert is commonly referred to as "tripolitic." Kaolinite appears to be an alteration product. In a few samples, detrital grains of chalcedony were observed.

Plagioclase and K-feldspar are minor components in Ellesmerian sandstone. In thin section the feldspars appear generally fresh or moderately altered (fig. 36.13). They are more abundant (3-14 percent) in Ellesmerian shale than in the sandstone (<1 percent). Feldspars in sandstone were identified by optical and X-ray diffraction methods.

Carbonate occurs as detrital grains and as cement. Detrital carbonate includes shell fragments and pieces of dolomite rhombs. Minute siderite rhombs, apparently formed during or shortly after deposition, are included in the detrital components. In many samples, siderite forms a mosaic of large grains that constitute 30 percent or more of the rock (fig. 36.14). Siderite, as confirmed by X-ray diffraction analyses, is by far the most common carbonate in the sandstone samples. Most siderite probably was emplaced early in the burial history of the rock because enclosed quartz grains have loose packing and no overgrowths, whereas quartz grains outside the cemented area have tighter packing and many quartz overgrowths. Calcite, as poikilitic cement, occurs in some sandstone; such samples generally have low porosity and permeability. The calcite cement replaces silicate grains and quartz overgrowths, indicating that it was emplaced fairly late in the diagenetic history. This type of cement generally occurs in sandstone that has been buried to depths greater than 2,100 m (>7,000 ft).

Glauconite is a minor component of many of the sandstone samples (tables 36.2, 36.3). In the Barrow (gas) sandstone it occurs in pellets in bioturbated sandstones. It is very common in sandstone of the Echooka, Sag River, Barrow, and Kingak units. Also, it is common in the upper 15 to 45 m (50-150 ft) of the Ivishak Formation possibly related to the more marine facies beneath the Shublik Formation. The sandstone of the Echooka Formation is typically glauconitic.

Phosphatic material is generally rare or absent. It occurs as random

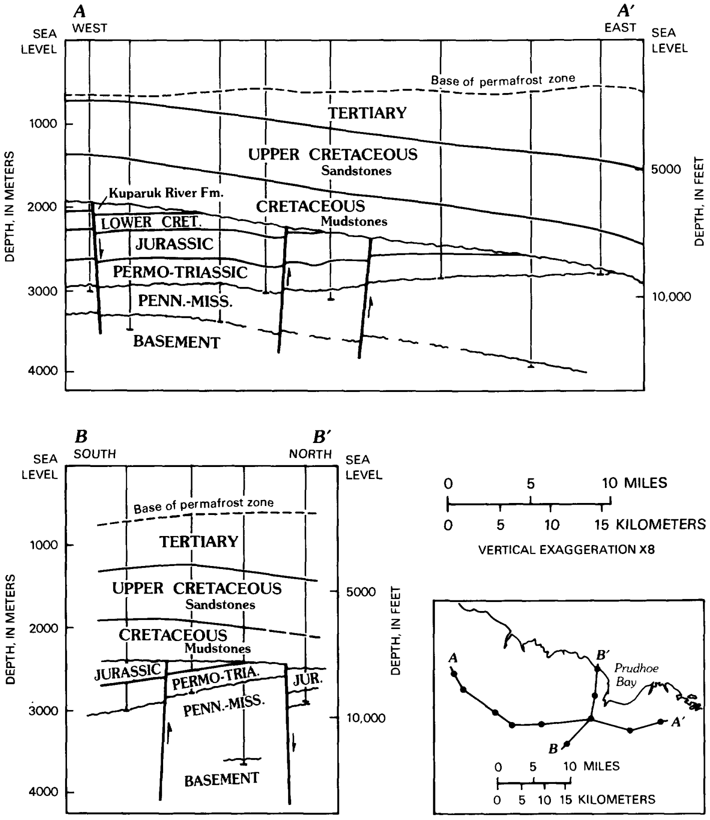

FIGURE 36.4.—Cross sections in the Prudhoe Bay area showing truncation of older units beneath the pebble shale unconformity (base of Cretaceous mudstones on these sections). From Jones and Speers (1976). Compare with figure 36.3 to note differences in the NPRA.

detrital pieces of indeterminate origin and as a replacement of organic shell remains. Phosphate is most common in the Shublik Formation.

Heavy minerals are present in very small amounts (<1 percent). In order of decreasing abundance they are: tourmaline, zircon, and sphene. They generally occur as rounded grains without overgrowths.

Rock fragments (other than chert) include siltstone and argillite. The siltstone may be rip-up clasts, and the argillite probably belongs to the pre-Carboniferous basement. These fragments generally constitute less than 5 percent of the sandstone.

Clay minerals are common as matrix in the sandstone; generally they constitute less than 10 percent of the rock. They include birefringent smectite-illite and kaolinite. The former is common as films on framework grains and pore fillings and shows the effects of compaction. Kaolinite is undeformed and is common as a pore filling (fig. 36.15). In many cases, clusters of kaolinite grains fill a space the size and shape of a framework grain and apparently replace some preexisting material (fig. 36.16). Some chert grains appear to be partly altered to kaolinite. The relatively low percentage of feldspar in the sandstone, as compared to the shale, may be a result of kaolinite replacement of feldspars in the sandstone. The least amount of clay matrix is found in the sandstone of the Ivishak Formation; high percentages of matrix occur in the Barrow (gas) sandstone and in the sandstone of the Echooka and Kuparuk River Formations.

The major opaque mineral is authigenic pyrite, which occurs as cubes and irregular masses. In some sandstone samples it constitutes 5 to 10 percent of the rock by volume and is present both as matrix and framework-grain re-

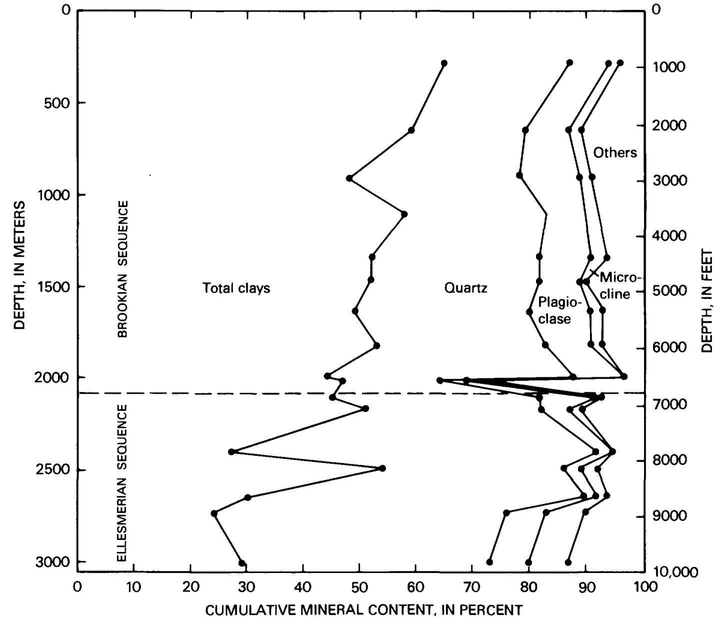

FIGURE 36.5.—Proportions of major minerals in shale samples from the Topagoruk No. 1 well. "Others" category includes carbonates and pyrite. The most significant differences between shales of the Brookian and Ellesmerian sequences are the generally greater amounts of clay and of plagioclase in Brookian rocks.

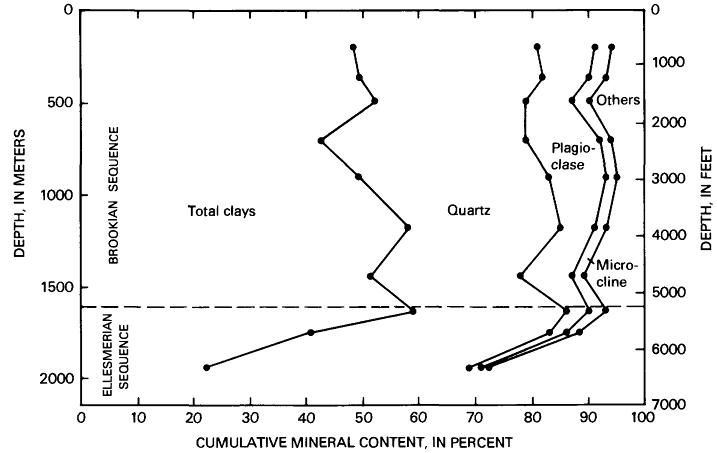

FIGURE 36.6.—Proportions of major minerals in shale samples from the Ellesmerian and Brookian sequences in the Simpson No. 1 well. Trends similar to those in the Topagoruk No. 1 well (fig. 36.5) are apparent: Amounts of plagioclase and clay are higher in the Brookian rocks.

placement. It is very common in the Ivishak Formation of the Prudhoe Bay area (Jones and Speers, 1976, p. 36).

Comparison of the composition of Ellesmerian and Brookian sandstone (fig. 36.17) shows that the Brookian rocks are less quartzose and much more feldspathic, reflecting their southern provenance.

SANDSTONE RESERVOIR DEVELOPMENT AND POROSITY PREDICTION

Although deposition was similar in the NPRA and Prudhoe Bay areas, subsequent histories differed. The Ellesmerian sequence in the NPRA represents an onlap onto basement; the entire Ellesmerian in the Prudhoe Bay region has been uplifted and truncated beneath the Lower Cretaceous unconformity. In the NPRA, the Sag River Sandstone and younger units have been truncated beneath this unconformity. Offshore to the northeast, the

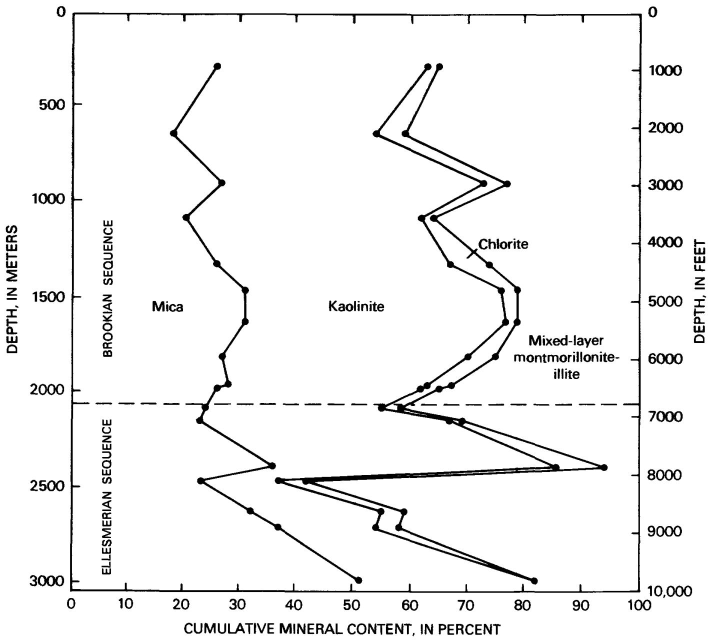

FIGURE 36.7.—Proportions of clay minerals in the clay fraction of shale samples from the Topagoruk No. 1 well. Note increasing mica (illite) and generally decreasing mixed-layer montmorillonite-illite with increasing depth. Kaolinite is reduced in the deeper samples; it may be transformed to mica, as chlorite remains fairly constant from top to bottom in this well.

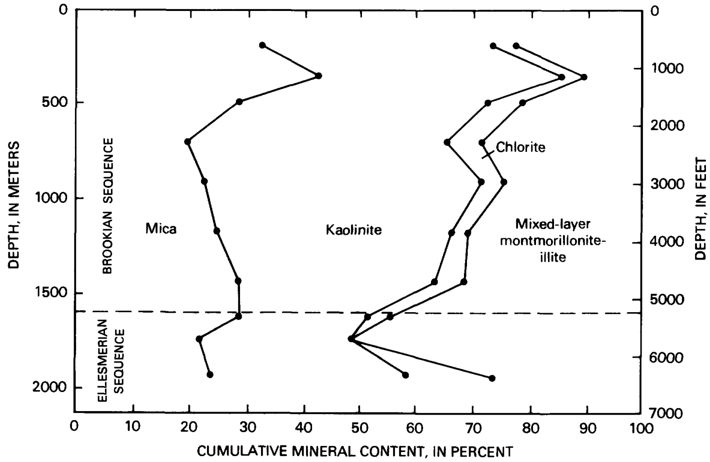

FIGURE 36.8.—Proportions of clay minerals in the Simpson No. 1 well, showing trends similar to those for Topagoruk No. 1 (fig. 36.7) except for the increase in mixed-layer montmorillonite-illite with depth.

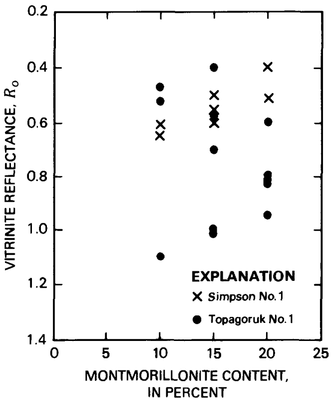

FIGURE 36.9.—Percentages of montmorillonite in mixed-layer montmorillonite-illite in shale samples from the Simpson No. 1 and Topagoruk No. 1 wells plotted against vitrinite reflectance (R_0). Low proportions of montmorillonite in mixed-layer phase are typical for level of thermal alteration in these rocks as shown by R_0 and agree with range of values found elsewhere.

Ivishak Formation may have been truncated.

Porosity of nonproductive sandstone in the Ellesmerian sequence in the NPRA generally ranges no higher than 18 percent, and in the Prudhoe Bay area it ranges no higher than 30 percent. The productive sandstone units at Prudhoe Bay have porosities of 15 to 30+ percent. The difference between the two areas may be explained by their different geologic and diagenetic histories.

Two models for diagenesis are necessary to explain the porosity development in the NPRA and Prudhoe Bay areas: (1) burial diagenesis, which accounts for the general increase in compaction and cementation with greater burial, and (2) the development of enhanced (secondary) porosity by solution.

The general model for burial diagenesis has been developed and described by van de Kamp (1976) and Lyons (1978) and is based on studies in numerous basins of North America. In essence, it is a correlation of thermal alteration (measured by vitrinite reflectance) with mineralogical and compaction changes in sandstone and shale (table 36.4). In a sequence of sandstone and shale buried progressively deeper and at progressively higher temperatures, mechanical compaction reduces original porosity by about half. Further framework compaction is impossible without solution or breakage of the grains. Additional reduction in porosity is caused by deposition of cement, generally quartz and carbonate. Although some cement is emplaced early in the diagenetic history of a sandstone, most cement appears after moderate to deep burial to >1,500 m (>5,000 ft) and at temperatures of 80-100+ °C for vitrinite reflectance (R_0) values of 0.5 and higher. Thus, for rocks with $R_0>0.5$, sandstone porosity is 5 to 15 percent and permeability 1 to 100 mD. This general case for porosity reduction is shown in table 36.4 and is outlined below.

The following three-stage model for development of sandstone reservoirs in the Ellesmerian sequence has been developed:

1. Deposition of sand composed of quartz and chert and partial cementation by siderite soon after deposition, before burial to 30 m (100 ft).

2. Burial to moderate depths, 600 to 1,800 m (2,000-6,000 ft), and attendant reduction in porosity by mechanical compaction and quartz cementation. This reduction in porosity occurs in the vitrinite R_0 range of 0.3 to 0.5. Within this stage, a rigid framework is developed by quartz cementation.

3. Deeper burial results in further quartz and calcite cementation. The calcite commonly has a poikilitic habit and partly replaces silicate grains. In quartz grains, both overgrowths and detrital cores are partly replaced. This alteration occurs in the vitrinite R_0 range of 0.5 to 1.0+.

The alterations depend upon both pressure (depth) and temperature. However, at moderate to deep levels of burial, temperature is increasingly important in controlling diagenetic reactions. Thus the reactions are keyed to vitrinite reflectance values, which are sensitive to temperature. This scheme yields a reference framework for assessing alteration in sandstones resulting from burial.

Where secondary porosity has not been developed, the burial-alteration sequence is believed to explain how the characteristics of the sandstone were derived. Em-

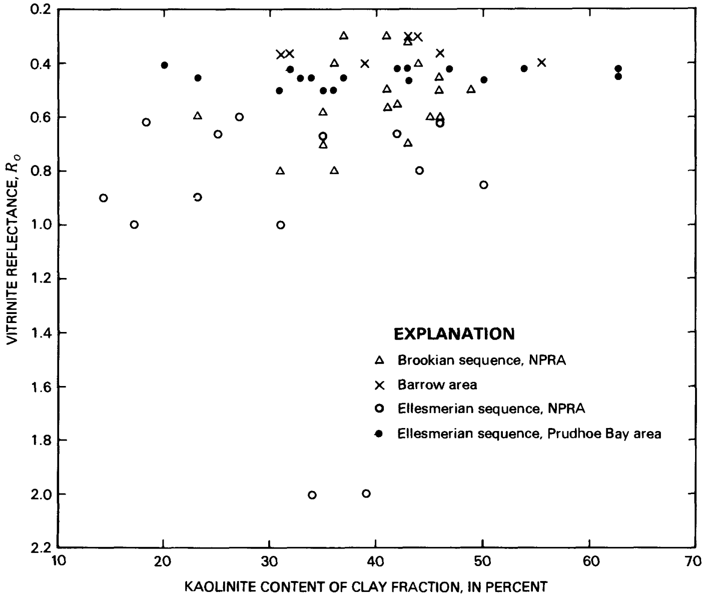

FIGURE 36.10.—Percentage of kaolinite in clay fraction of shale samples plotted against vitrinite reflectance (R_0) to show relation of kaolinite to thermal alteration. Generally, there is diminished kaolinite with increasing R_0; at $R_0>1.0$, kaolinite is largely transformed to mica and (or) chlorite (van de Kamp, 1976).

TABLE 36.2.—*Composition of sandstone samples from wells in the NPRA and the Prudhoe Bay area*

[Mineral constituents: Q_d, detrital quartz; Q_c, quartz overgrowth; Cl, chalcedony; Ch, chert; A, argillite and shale; C_d, detrital carbonate; C_c, carbonate cement; M, clay matrix; K, kaolinite; O, opaque material; H, heavy minerals; F, feldspar; G, glauconite; P, collophane. Grain-size classes: vf, very fine sand; f, fine sand; m, medium sand; c, coarse sand; cgl, conglomerate. tr, trace amount; -, not detected]

Well	Sample depth (ft)	Unit	Mineral constituents (volume percent)														Grain size
			Q_d	Q_c	Cl	Ch	A	C_d	C_c	M	K	O	H	F	G	P	
National Petroleum Reserve in Alaska (NPRA)																	
South Barrow No. 2----	2,380	Barrow ss.[1]	53.7	7.0	-	13.7	tr	0.3	-	24.7	-	0.7	tr	tr	tr	-	vf
---Do.---------------	2,394	---do.----	52.3	5.7	.3	9.7	-	1.0	-	29.0	-	1.7	.3	-	tr	-	vf
---Do.---------------	2,936	---do.----	50.0	7.7	-	14.0	-	22.3	-	3.7	-	2.3	-	tr	-	-	f
South Barrow No. 9----	2,438	---do.----	68.3	8.3	-	12.0	1.3	1.7	-	4.7	-	3.3	-	-	.3	-	vf
South Barrow No. 12---	2,040	---do.----	64.7	8.7	-	10.0	-	3.3	.3	11.7	-	tr	tr	.3	1.0	-	vf
---Do.---------------	2,245	Norian ss.[1]	73.0	9.0	-	9.3	-	.7	2.7	5.0	-	tr	.3	tr	-	-	vf
Kugrua No. 1---------	8,730-8,810	Sag River Ss.	66.1	17.4	-	4.5	1.5	.3	tr	9.0	-	.6	tr	.6	-	-	vf
---Do.---------------	9,543	Ivisahk Fm.	53.7	18.0	-	20.1	1.0	1.8	3.9	.3	1.2	tr	tr	-	-	-	m-c
Topagoruk No. 1-------	9,416-9,426	---do.----	64.3	10.3	-	16.7	.7	2.3	5.7	-	-	tr	-	tr	-	-	f
---Do.---------------	9,524	---do.----	50.3	11.7	-	35.0	tr	-	3.0	-	-	-	-	-	-	-	m-c
---Do.---------------	9,551	---do.----	52.3	12.0	-	27.0	2.0	3.0	2.7	1.0	-	tr	-	-	-	-	f
Drew Point No. 1------	6,979	Sag River Ss.	62.7	11.0	-	17.3	-	4.7	-	3.3	-	.3	-	-	.7	-	vf
---Do.---------------	7,628	---do.----	69.3	9.7	.3	13.0	1.0	6.7	-	-	-	tr	tr	-	-	-	vf
---Do.---------------	7,710	Ivishak Fm.	39.3	7.0	tr	34.3	1.3	.3	16.7	-	-	.3	.7	-	-	-	m-c
---Do.---------------	7,801	---do.----	51.0	9.0	-	16.7	1.7	-	12.0	8.7	-	1.0	-	-	-	-	vf
W.T. Foran No. 1------	7,539-7,540	Pebble shale unit	63.0	5.0	-	24.3	.3	.3	-	.3	-	1.7	tr	-	.3	4.7	vf
Atigaru Point No. 1---	8,723-8,724	Ivishak F.	64.7	6.7	-	25.3	1.0	tr	-	1.3	-	.7	tr	-	-	.3	f
---Do.---------------	8,740-8,741	---do.----	50.5	10.6	-	21.8	3.1	6.2	.9	6.5	-	.3	tr	-	-	-	vf
Prudhoe Bay area																	
Kalubik Creek No. 1---	8,453	Ivishak Fm.	42.9	12.0	-	33.0	.6	1.8	6.9	1.2	1.5	.1	tr	-	-	-	m-c
Gwydyr Bay South No. 1.	8,285	Kuparuk Fm.	63.3	7.3	-	3.3	-	-	17.7	-	-	-	-	.3	8.0	-	f-m
Put River------------	9.057	Ivishak Fm.	52.0	9.6	-	20.4	2.7	1.2	3.3	9.3	1.5	tr	-	-	-	-	f
---Do.---------------	9,268	---do.----	14.3	1.5	-	77.2	1.3	.5	.5	2.7	2.0	tr	-	-	-	-	cgl
---Do.---------------	9,483	---do.----	58.0	6.6	-	15.0	1.8	1.2	5.7	8.4	2.7	.6	tr	-	-	-	vf
Sag Delta------------	9.414	---do.----	38.4	9.0	-	39.6	.9	.4	6.3	4.2	.9	.3	tr	-	-	-	m-c
---Do.---------------	9,598	---do.----	55.0	8.7	-	26.7	.3	-	-	5.1	3.9	tr	.3	-	-	-	f
Sag River State No. 1-	8.600	---do.----	36.6	8.7	-	27.3	1.5	9.3	9.3	3.9	3.0	.3	tr	-	-	-	f-m
---Do.---------------	8,795	---do.----	55.0	9.0	-	21.6	3.3	2.1	5.1	2.7	.9	.3	tr	-	-	-	m-c
DS 2-4---------------	9,011	---do.----	50.2	7.8	-	28.2	1.2	tr	-	11.1	1.5	tr	tr	-	-	-	f
---Do.---------------	9,278	---do.----	44.1	7.2	-	36.3	1.2	-	5.7	3.6	1.2	.6	tr	-	-	-	m
Toolik Federal No. 1--	10,499	---do.----	38.5	16.8	-	36.9	1.2	-	-	2.7	2.7	1.2	tr	-	-	-	m-c
---Do.---------------	10,690	---do.----	42.7	18.0	-	23.4	1.5	-	-	2.7	3.7	7.7	.3	-	-	-	f-m

[1] Unit of local usage.

placement of hydrocarbons into the sandstone in traps during stage 2 would inhibit further alteration and preserve the reservoir; this appears to have occurred at the Barrow field.

Porosity values for NPRA sandstone samples (table 36.5) are plotted in figure 36.18 to show their relation with R_0 values. The porosity values, derived from core analyses and sonic-velocity data, are in the range 0-28 percent and show a good negative correlation with increasing R_0 resulting from increasing cementation. The best reservoir sandstone occurs in the R_0 range 0.3 to 0.6; at values above 0.6, porosity is generally below 15 percent. In the NPRA, the best reservoir sandstone is in the Barrow area, where the Barrow (gas) sandstone and the Sag River Sandstone have porosity in the range 10 to 30 percent.

Ellesmerian sandstone at Prudhoe Bay has values of R_0 in the range of 0.3 to 0.6 and porosity as high as 35 percent (fig. 36.18). These rocks have high porosity values for their R_0 values, commonly higher than the curve for maximum porosity shown in figure 36.18. The high porosity is a result of enhancement of original porosity by solution of unstable grains (feldspar and chert) and of siderite cement. It is estimated from the R_0/porosity plot that porosity was increased by 5 to 15 percent by leaching before the oil was emplaced in the reservoir. The leaching may have occurred in the Late Jurassic and Early Cretaceous, before transgression of the pebble shale unit, when the Barrow arch was high and meteroic water flushed the truncated Ellesmerian sedimentary rocks, dissolving unstable grains. When the leaching occurred, the rocks involved were at a very low value of R_o, probably <0.3. Today the same rocks are 2,100 to 2,700 m (7,000-9,000 ft) deep and have R_o at 0.3 to 0.6; the present R_o values were attained after leaching took place by heating upon deeper burial. In these deeply buried rocks, evidence of recementation following leaching was not observed, perhaps because of the presence of hydrocarbon saturation and (or) low-salinity pore waters.

Secondary porosity is recognized in Ellesmerian sandstone by the criteria outlined below:

The sandstone framework grains are quartz and subordinate amounts of chert. Quartz overgrowths provide a rigid framework of grains in which the less stable chert may be altered and removed by solution. The chert grains are generally the same size as the quartz grains in a given sandstone; therefore, when relics of altered chert appear in pores as large or larger than framework sand grains, it is interpreted that such pores resulted from the removal of chert grains (figs. 36.12, 36.19, 36.20). In some cases, kaolinite occurs as an apparent alteration product of chert (figs. 36.15, 36.16). Kaolinite is common in Ellesmerian sandstone with secondary porosity. It is a secondary mineral apparently formed at the time of leaching. Kaolinite commonly occurs in undeformed clusters (fig. 36.19). Sommer (1978) described similar relations for the Brent Sand Formation in the North Sea. Secondary porosity also results from the removal of carbonate in Ellesmerian sandstone.

Areas where carbonate has been removed are recognized by corroded quartz-grain boundaries on pore margins where carbonate originally replaced quartz but is now absent (fig. 36.19). In some cases, relics of carbonate occur in large pores apparently once filled with carbonate. Generally the quartz grains have few or no quartz overgrowths, implying that they may have been enclosed by carbonate precipitated

TABLE 36.3.—*Summary of petrographic observations on Ellesmerian sandstone samples from wells in the NPRA and the Prudhoe Bay area*

[Grain size classes: silt; sand (vf, very fine; f, fine; m, medium; c, coarse; vc, very coarse). Sorting classes: p, poorly sorted; m, moderately sorted; w, well sorted]

					Cements			Porosity		
Well	Grain size	Sorting	Feldspar	Glauconite[1]	SiO_2	CO_3	Kaolinite	Primary	Secondary	Oil stain
				Kuparuk River Formation						
Kugrua No. 1	vf	m-w	x		x		x	x		x
W.T. Foran No. 1	f	m	x		x			x	x	x
Gwydyr Bay South No. 1	vf-c	m-w	x	x	x	x		x	x	
Toolik Federal No. 1				x						
				Barrow gas sand[2]						
Iko Bay No. 1	silt-vf	p-m		x	x			x		
South Barrow No. 2	vf-f	m-w	x	x	x			x		
South Barrow No. 4	vf-f	m-w		x	x	x				
South Barrow No. 9	silt-vf	m-w		x	x			x		
South Barrow No. 12	vf-f	m-w	x	x	x			x		
South Barrow No. 13	vf	p-w	x	x	x			x		
				Kingak Shale[3]						
Kugrua No. 1	vf-f	m-w	x		x			x		x
South Meade No. 1	vf-m	m-w	x	x	x	x		x		
Topagoruk No. 1	vf-m	m-w	x	x	x	x		x		
Simpson No. 1	vf	m	x	x	x	x				
South Simpson No. 1	vf-f	p-m	x		x	x				
East Teshekpuk No. 1	vf-f	m-w		x	x	x				
West Fish Creek No. 1	silt			x	x	x				
Kalubik Creek No. 1	silt		x	x	x	x				
				Norian sandstone[2]						
South Barrow No. 12	vf-f	m-w	x		x		x			x
				Simpson sandstone[2]						
Kugrua No. 1	vf-f	m-w	x		x			x		
South Meade No. 1				x						
Topagoruk No. 1	vf-m	m-w	x	x	x	x		x		
South Simpson No. 1	vf-f	p-m	x		x	x				
				Sag River Sandstone						
Kugrua No. 1	vf-c	m-w			x	x	x	x	x	
South Meade No. 1	silt-vf	m		x	x	x		x		
Topagoruk No. 1	silt	p-m		x	x			x		
Simpson No. 1	silt-vf	p-m	x	x	x	x		x		
South Simpson No. 1	vf	m-w	x	x	x	x		x		x
Drew Point No. 1	vf-f	w	x	x	x	x		x		
East Teshekpuk No. 1	vf	m-w	x	x	x			x		
West Fish Creek No. 1	silt-vf			x	x	x				
South Harrison Bay No. 1	vf	m-w	x	x	x	x		x		
Atigaru Point No. 1		vf	m	x	x	x	x		x	
				Ivishak Formation						
Kugaru No. 1	vf	m	x		x	x		x		
Topagoruk No. 1	vf-vc	m-w	x		x	x		x	x	
South Simpson No. 1	f-c	m-w			x	x		x		
Drew Point No. 1	vf-c	m-w	x		x	x	x	x	x	x
East Teshepuk No. 1	vf	m-w	x	x	x	x	x	x	x	
Cape Hackett No. 1	vf-f	m-w	x	x	x	x	x	x	x	
W.T. Foran No. 1	vf	m-w	x	x	x	x		x	x	x
West Fish Creek No. 1	vf	m-w			x	x		x		
South Harrison Bay No. 1	vf	m-w	x	x	x	x		x		
Atigaru Point No. 1	vf-m	m-w			x	x	x	x	x	
Kalubik Creek No. 1	f-vc	m-w			x	x	x	x	x	x
Gwydyr Bay South No. 1	vf-vc	m-w	x		x		x	x	x	x
Put River J-1	f-c	m-w	x		x	x	x	x	x	x
Put River	vf-vc	m-w	x		x	x	x	x	x	x
Sag Delta	f-c	m-w			x	x	x	x	x	x
Sag River State No. 1	f-c	m-w			x	x	x	x	x	x
Put River State No. 1	f-c	m-w			x	x	x	x	x	x
DS 2-4	f-vc	m-w			x	x	x	x	x	x
Toolik Federal No. 1	vf-m	w			x	x	x	x	x	?
				Echooka Formation						
Atagaru Point No. 1	vf-f	m-p		x	x	x				

[1]Glauconite common in upper 100 ft of Ivishak.
[2]Denotes unit of local usage.
[3]Kingak Shale—refers to various thin sandstone interbeds in the Kingak Shale.

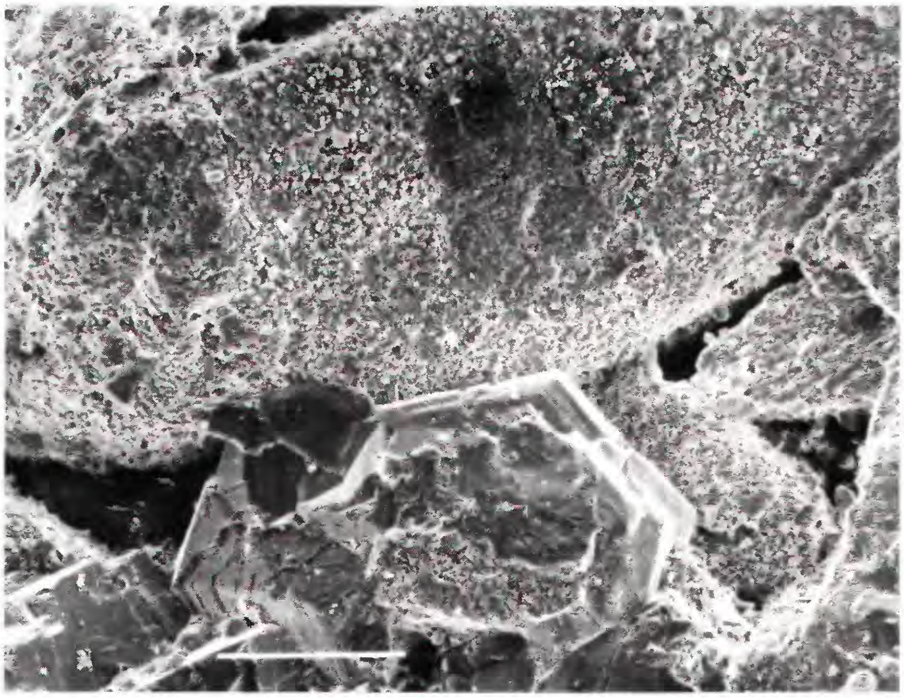

FIGURE 36.11.—Scanning electron micrograph of sandstone sample from the Ivishak Formation in Drew Point No. 1 well at 2,353 m (7,721 ft). View shows large chert grain at top (area of rough texture) and in lower center a quartz grain with extensive overgrowths (large crystal faces). In pores to right of center some small authigenic quartz crystals are visible. View about 0.5 mm across.

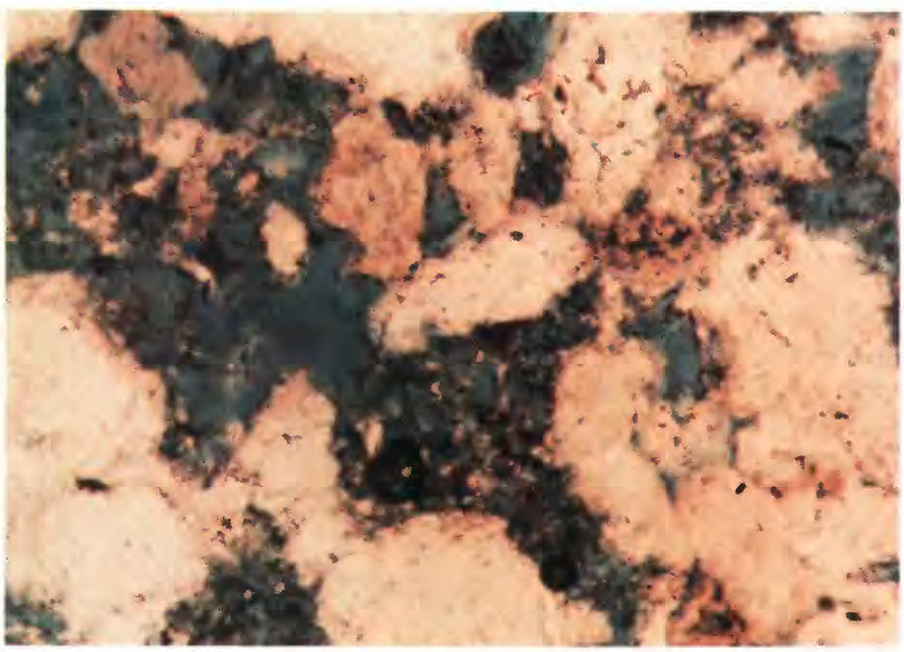

FIGURE 36.12.—Photomicrograph (plane-polarized light) of sandstone sample of the Ivishak Formation, Gwydyr Bay South No. 1 well, 3,093 m (10,147 ft). View is 0.9 mm across. Blue, epoxy impregnating medium filling pore spaces; light-colored material, quartz cemented with quartz overgrowths. In center of view and to upper left are skeletal remains (small irregular patches) of chert partially altered to kaolinite.

at an earlier time. These criteria are similar to those outlined by Schmidt and McDonald (1979).

Secondary porosity in oil-bearing sandstone is recognized in the Ivishak Formation in the Prudhoe Bay field wells, in oil-stained sandstone in the nonproducing wells outside the field (Toolik and Kalubik Creek), and in the NPRA wells at Topagoruk, Drew Point, Atigaru Point, and W.T. Foran. The Barrow sandstone and the underlying oil-stained Norian sandstone of local usage in South Barrow No. 13 have retained primary porosity; no secondary porosity was recognized in these sandstone units.

DISTRIBUTION AND PREDICTION OF SECONDARY POROSITY

In general, productive reservoir rocks outside the Barrow area have had their porosity enhanced by solution (secondary porosity). Thus it is important to know the distribution of secondary porosity so that the location of potential reservoirs can be predicted.

The criteria outlined above have been used to recognize secondary porosity in Ellesmerian sandstone bodies of the North Slope. Secondary porosity is recognized in all of the Prudhoe Bay area wells studied (fig. 36.21), in sandstone of the Ivishak Formation, Sag River Sandstone, and Kuparuk River Formation, in both productive and nonproductive wells. In the NPRA, secondary porosity has been identified in oil-bearing sandstone in the Ivishak Formation in the Simpson, Drew Point, Cape Halkett, W.T. Foran, and Atigaru Point wells and in the Sag River Sandstone in the Kugrua well (table 36.3; fig. 36.21).

The secondary porosity is believed to have developed beneath the pebble shale unconformity in Early Cretaceous time, before deposition of the pebble shale unit, when meteoric water circulated in the truncated sandstone bodies and dissolved unstable minerals. Isopach maps of intervals below the Lower Cretaceous unconformity in the study area (pl. 36.1) show the truncated Ellesmerian sandstone in the Prudhoe Bay area and the Ellesmerian sequence onlapping basement in the NPRA. It is important to note that where onlapping occurred, secondary porosity development is minimal because access of meteoric water was restricted. This condition also holds for the Ivishak, which was covered by the shale and carbonate rocks of the Shublik Formation, which acted as a barrier to freshwater influx to the Ivishak from Smith Bay westward. Where the Ellesmerian rocks are erosionally truncated, secondary porosity is well developed because of freshwater access to the sandstone. Thus in the NPRA, only minor development of secondary porosity has occurred at Simpson, Drew Point, W.T. Foran, Cape Halkett, and Atigaru Point. In the Prudhoe Bay area, leaching and the development of secondary porosity have been extensive, and a major petroleum reservoir resulted (fig. 36.21).

The distribution of rocks influenced by leaching and the development of secondary porosity is outlined in figure 36.21 and on plate 36.1. Secondary porosity is most extensively developed in the 600 m (2,000 ft) vertically below the unconformity in the Prudhoe Bay area. Farther below the unconformity, porosity diminishes because of the absence of leaching and the increased cementation at higher levels of thermal alteration, where R_0>0.6.

The moderate amount of secondary porosity in the Smith Bay-Harrison Bay area is puzzling. Despite the apparent exposure of the truncated Ivishak Formation to leaching, only minor to moderate

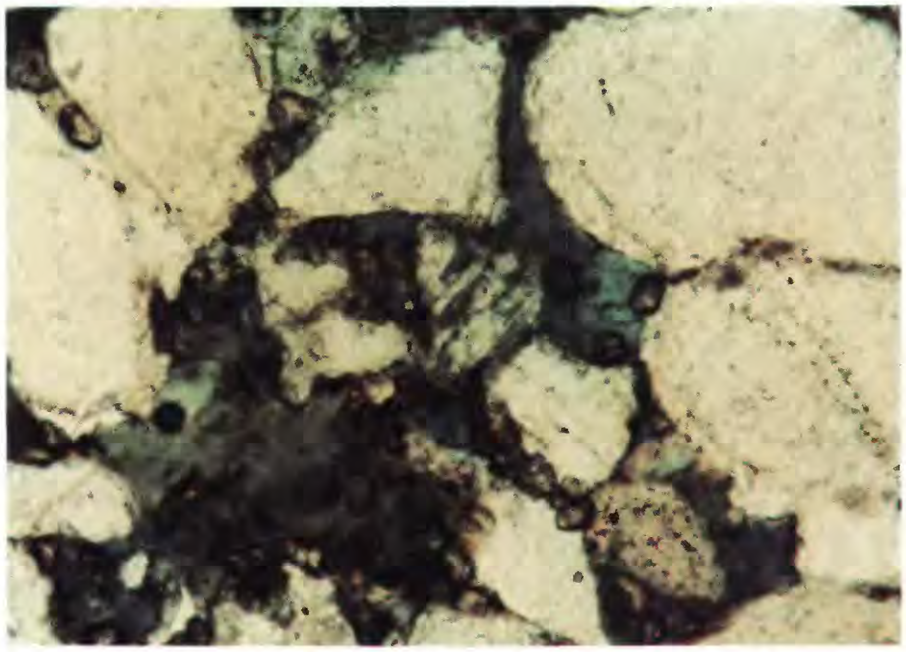

FIGURE 36.13.—Photomicrograph (plane-polarized light) of sandstone sample of the Kuparuk River Formation (Jones and Speers, 1976), showing partially dissolved plagioclase grain in center of view. White grains, quartz cemented with quartz; small grains with high relief, carbonate, probably siderite or dolomite; blue epoxy fills pores. View is 0.9 mm across. Gwydyr Bay South No. 1 well, 2,525 m (8,285 ft).

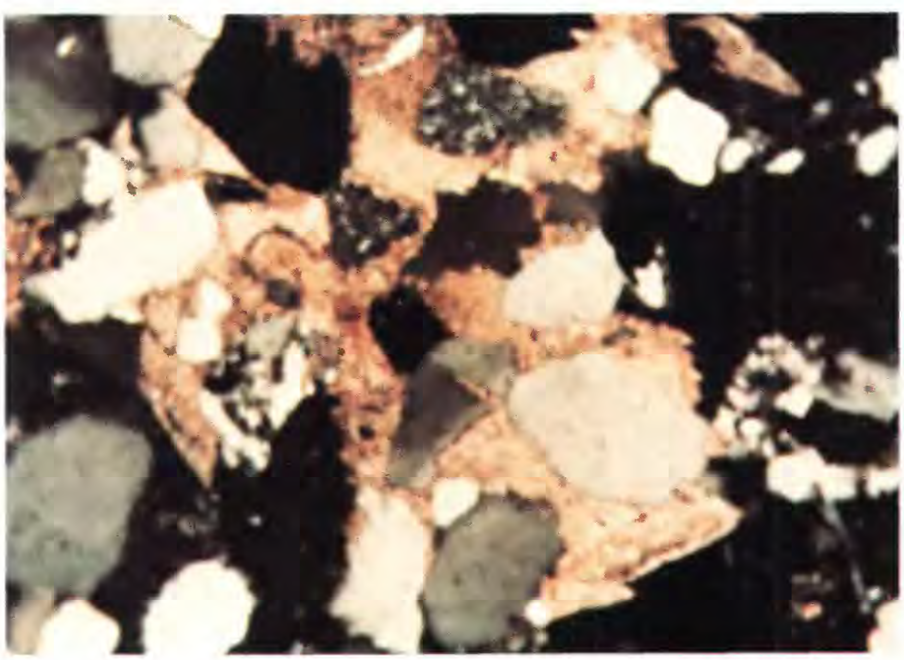

FIGURE 36.14.—Photomicrograph (crossed nicols) of sandstone sample of the Ivishak Formation, showing quartz and chert grains cemented by siderite (golden areas). Several grains show ragged edges due to replacement of quartz by carbonate. View is 2 mm across. Put River J-1 well, 2,744 m (9,003 ft).

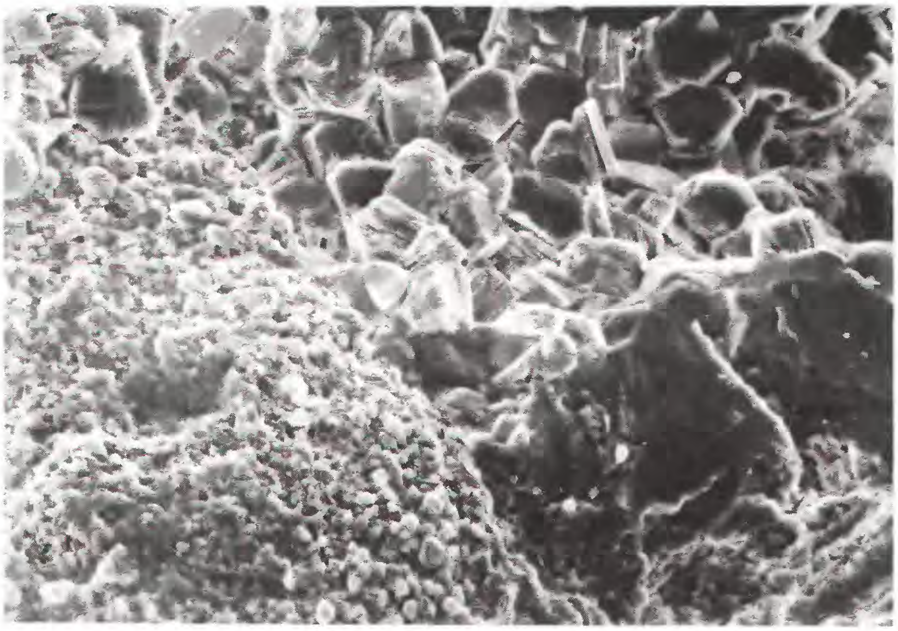

FIGURE 36.15.—Scanning electron micrograph of chert (lower left) and kaolinite (upper) in sandstone sample of the Ivishak Formation. The kaolinite is very well formed and shows no effects of compaction, implying that it was formed after most of the compaction that has affected the rock. It is probably an alteration product of chert and feldspar. View is 0.2 mm across. Drew Point No. 1 well, 2,353 m (7,721 ft).

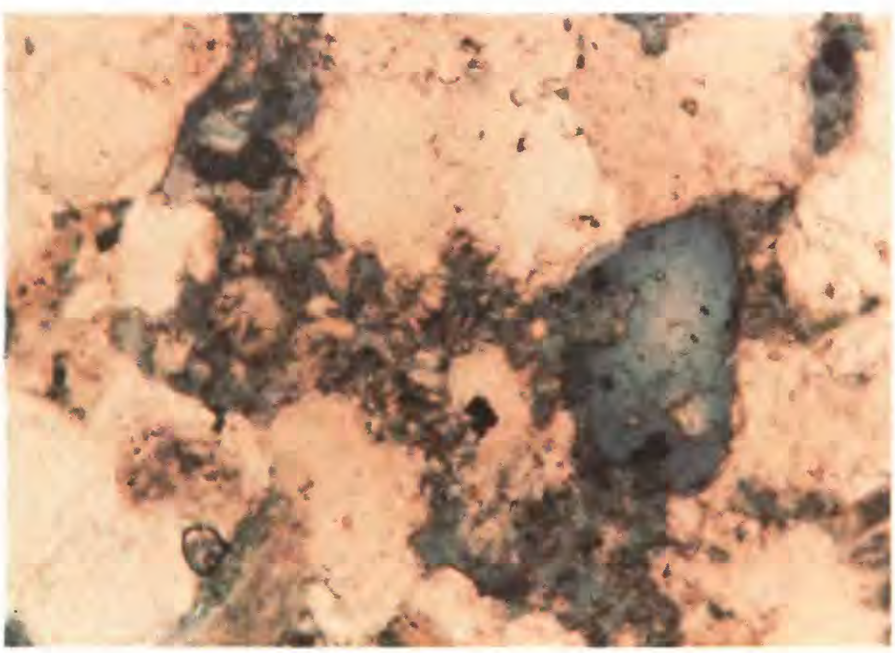

FIGURE 36.16.—Photomicrograph (plane-polarized light) showing books of undeformed kaolinite (center) associated with altered chert. The kaolinite was probably derived from alteration of the chert. View is 0.9 mm across. Gwydyr Bay South No. 1 well, 3,093 m (10,147 ft).

amounts of secondary porosity developed. Apparently the topographic and hydrologic regimes were different from those in the Prudhoe Bay area, such that less solution occurred. The vastly greater amount of truncation at Prudhoe Bay relative to that in the northern NPRA implies more uplift and probably greater elevation of the land mass at Prudhoe Bay (to a mountain range) than at Barrow (to low hills). Assuming that the amount of secondary porosity may be directly related to the amount of flushing, it is logical that the greater area and greater elevation at Prudhoe Bay would yield a greater volume and head of meteoric water for deep flushing.

Development of secondary porosity at burial depths of 1,500 to 3,000+ m (5,000-10,000+ ft) through leaching by water charged with HCO_3^- derived from organic matter in shale, as suggested by Schmidt and McDonald (1979), has generally not been recognized in the Ellesmerian rocks. An exception to this may be the 10-20 percent porosities at R_0 values of 1.6 to 2.0 in the Kugrua well (fig. 36.18). Samples from this well have not been investigated in detail.

The amount of secondary porosity may be predicted by analyzing its known distribution. As indicated above, the best development of secondary porosity is within 600 m (2,000 ft), vertically, of the pebble shale unconformity, where the Ellesmerian sandstone bodies are truncated against the unconformity. This information suggests that high-porosity reservoirs in the Ivishak Formation of the Prudhoe Bay type are not likely to be present in the NPRA. They may, however, be present north and west of the Prudhoe Bay field and north of the NPRA east of Smith Bay in the offshore Beaufort Sea (fig. 36.21), where Ellesmerian sandstone bodies may have been truncated.

In areas where secondary porosity is absent, reservoirs that were charged when vitrinite reflectance R_0 was less than 0.6 may retain their hydrocarbon charge and porosity to greater depths and higher values of R_0. These would be in structural and stratigraphic traps formed and charged relatively early. Such reservoirs have not yet been identified in the NPRA.

DETAILS OF ANALYTICAL PROCEDURES

METHODS OF SHALE ANALYSIS

Shales were analyzed by X-ray diffraction by R.L. Freed. His explanation of the techniques used for the analyses is reproduced below.

PROCEDURE

Each sample was hand ground in a mortar until the material passed through a 230-mesh sieve (63-μm opening). This powder was then analyzed in a Philips X-ray diffractometer from 4° to 70° 2Θ in order to determine the bulk mineralogy. An oriented mount of less than 2 μm of the material was prepared for each sample by pipetting 1 mL of suspended sample onto a glass slide. After drying in air, each sample was scanned from 2° to 34° 2Θ in order to determine the identity of the clay components. Another scan from 26° to 34° 2Θ was performed after treatment with ethylene glycol in order to determine the presence of swelling clays. Finally, each sample was heated for one hour at 550 °C and scanned in the diffractometer from 2° to 34° 2Θ. The purpose of this heating was to collapse the kaolinite structure and also to determine the type of chlorite.

Every X-ray scan was performed with CuK radiation and a scintillation detector. A pulse-height analyzer was used to eliminate the problem of iron fluorescence from the sample.

Two samples, Topagoruk 1978-1981 m (6,490-6,500 ft) and SB-12 630 m (2,067 ft), had to be treated

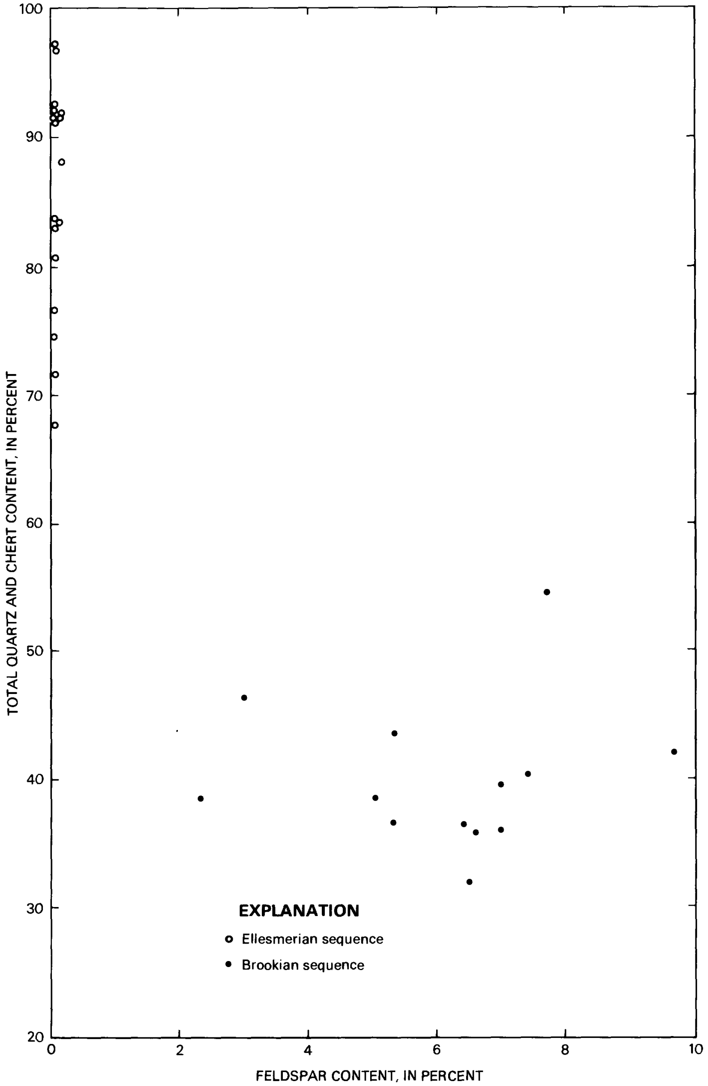

FIGURE 36.17.—Comparison of sandstone compositions of Ellesmerian and Brookian sequences. Ellesmerian rocks are dominantly quartz and chert with little or no feldspar and are thus readily distinguished from sandstone of the Brookian sequence. Data for the Ellesmerian are from this work; Brookian data are from Bartsch-Winkler (1979).

TABLE 36.4.—*Correlation of vitrinite reflectance, R_0, with other petrologic characters during burial alteration of siliciclastic rocks*

[Porosity and permeability data are for fine-grained, moderately to well-sorted sandstones. Temperatures are approximate for Tertiary basins, may be as much as 50 °C less in older basins. Compiled from subsurface data for more that 20 North American basins (unpub. data, van de Kamp, 1976)]

Approximate temperature (°C)	Vitrinite reflectance (R_o)	Shale mineralogy and approximate mineral-stability ranges	Shale density (g/cm³)	Alterations in sandstone occurring over ranges of temperature	Porosity (percent)	Permeability (mD)	Sandstone density (g/cm³)
0	—	Montmorillonite Kaolinite Illite Chlorite	<2				—
					35–40	100's and 1000's	<2
50		Carbonate stable		Mechanical compaction; low-temperature silica, carbonate, zeolite, and evaporite cements			
					15–25	10's	2.3–2.4
100	0.5	Mixed-layer montmorillonite-illite Kaolinite Illite Chlorite	2.0–2.3	Calcite cement precipitated in pore spaces Plagioclase, albitized	5–15	1–100	2.5
		Carbonate removed in solution	2.3–2.5				
150	0.8	Illite Chlorite					
200	2.0	Muscovite Chlorite	2.6–2.8		1–4	<0.1	2.6–2.7
					<1	<0.01	2.7

TABLE 36.5.—*Porosity of sandstone units in the NPRA and the Prudhoe Bay area determined from sonic logs*

[——, no data]

Well	Kuparuk River Fm.		Simpson sandstone[1]		Sag River Sandstone		Ivishak Fm.		Echooka Fm.	
	Transit times (μs)	Porosity range (percent)	Transit times (μs)	Porosity range (percent)	Transit times (μs)	Porosity range (percent)	Transit times (μs)	Porosity range (percent)	Transit times (μs)	Porosity range (percent)
Kugura No. 1	70-88	7-20	79-90	13-21	75-85	10-18	70-80	7-14	65-78	3-13
South Meade No. 1	——	——	60-90	0-21	61-689	0-6	60-65	0-3	——	——
South Simpson No. 2	——	——	75-90	10-21	68-85	6-17	——	——	——	——
Drew Point No. 2	——	——	——	——	70-85	7-17	63-78	2-13	——	——
Cape Hackett No. 1	——	——	——	——	65-79	3-7	58-78	0-13	——	——
W.T. Foran No. 1	——	——	——	——	——	——	65-80	3-14	——	——
West Fish Creek No. 1	——	——	——	——	65-80	3-14	61-73	0-9	56-67	0-5
South Harrison Bay No. 1	——	——	——	——	68-78	5-13	60-72	0-8	60-73	0-9
Atigaru Point No. 1	——	——	——	——	70-80	7-14	61-70	0-7	65-70	3-7
South Barrow 17	——	——	——	——	79-100	13-28	——	——	——	——
Gwydyr Bay South No. 1	80-88	14-20	——	——	——	——	65-92	3-23	——	——
Put River J-1	——	——	——	——	90-103	21-31	68-108	5-35	——	——
Put River	——	——	——	——	67-90	5-21	72-101	8-29	70-85	7-18
Sag Delta	——	——	——	——	——	——	80-98	14-27	60-70	0-7
Sag River State No. 1	——	——	——	——	95-105	25-32	71-100	8-28	——	——
Put River State No. 1	——	——	——	——	72-81	8-15	72-95	8-25	65-82	3-15
Kalubik Creek No. 1	70-85	7-18	——	——	70-80	7-14	70-92	7-23	68-93	5-23
Home Bush Federal	——	——	——	——	——	——	64-75	2-10	——	——

[1] Unit of local usage.

with a peptizing agent in order to disperse the less-than-2-μm fraction.

QUALITY OF DATA

The results of the X-ray analyses are summarized in table 36.6, which gives a semiquantitative estimate of the weight percent for each mineral. The precision of any individual value is probably about ±10 percent of the amount present, and the accuracy is not as good as the precision. Because all samples were prepared and analyzed in the same manner, these semiquantitative results are considered to be useful for observing mineralogical trends with both changing lithology and increasing depth.

BULK MINERALOGY

The relative abundance of each nonclay mineral is determined from the peak height for the strongest diffraction maxima of each mineral. In addition, total clay content is determined from the strongest nonbasal reflection.

Quartz.—SiO_2. Strongest peak position at 26.6° 2Θ.

Total clay.—Strongest nonbasal reflection at 19.9° 2Θ. This nonbasal reflection is used because it is not affected significantly by any accidental preferred orientation produced during sample preparation. The clay minerals are classified as kaolinite, mica, chlorite, and a mixed-layer clay that is a smectite/illite mixture. Each of these clay types will be discussed in the later section on "Clay mineralogy."

Plagioclase.—$NaAlSi_3O_8$. Strongest peak position at 28.0° 2Θ. The presence of the 18.9° 2Θ feldspar peak eliminates albite as the plagioclase variety; oligoclase would be a reasonable choice.

Microcline.—$KAISi_3O_8$. Strongest peak position at 27.5° 2Θ.

Calcite.—$CaCO_3$. Strongest peak position 29.4° 2Θ.

Ankerite.—$CaFe(CO_3)_2$. Strongest peak position at 30.8° 2Θ. Actually, this peak may also represent either dolomite, $CaMg(CO_3)_2$, or rhodochrosite, $MnCO_3$. Ankerite has been chosen because of the presence of siderite and pyrite in an assemblage of diagenetic minerals characteristic of a reducing environment.

Siderite.—$FeCO_3$. Strongest peak position at 32.0° 2Θ.

Pyrite.—FeS_2. Strongest peak position at 33.1° 2Θ.

Pyrophyllite.—$Al_2Si_4O_{10}(OH)_2$. Useful peak position at 29.1° 2Θ. Pyrophyllite is identified on the basis of a shoulder on the mica peak at about 9.6° 2Θ and a distinct reflection at 29.1° 2Θ.

Hematite.—Fe_2O_3. Strongest peak position at 33.2° 2Θ.

CALCULATION OF CLAY COMPONENTS

The clay components can be divided into two groups: (1) kaolinite and chlorite; (2) mica and mixed-layer clay. The contribution to the total clay content provided by both kaolinite and chlorite, called "(total K+C)," is determined by measuring the area of the 12.3° 2Θ peak for the less-than-2-μm sample. The contribution to the total clay content provided by both mica and mixed-layer clay is determined by measuring the area of the 8.9° 2Θ peak for the sample heated at 55 °C. This peak is used because the

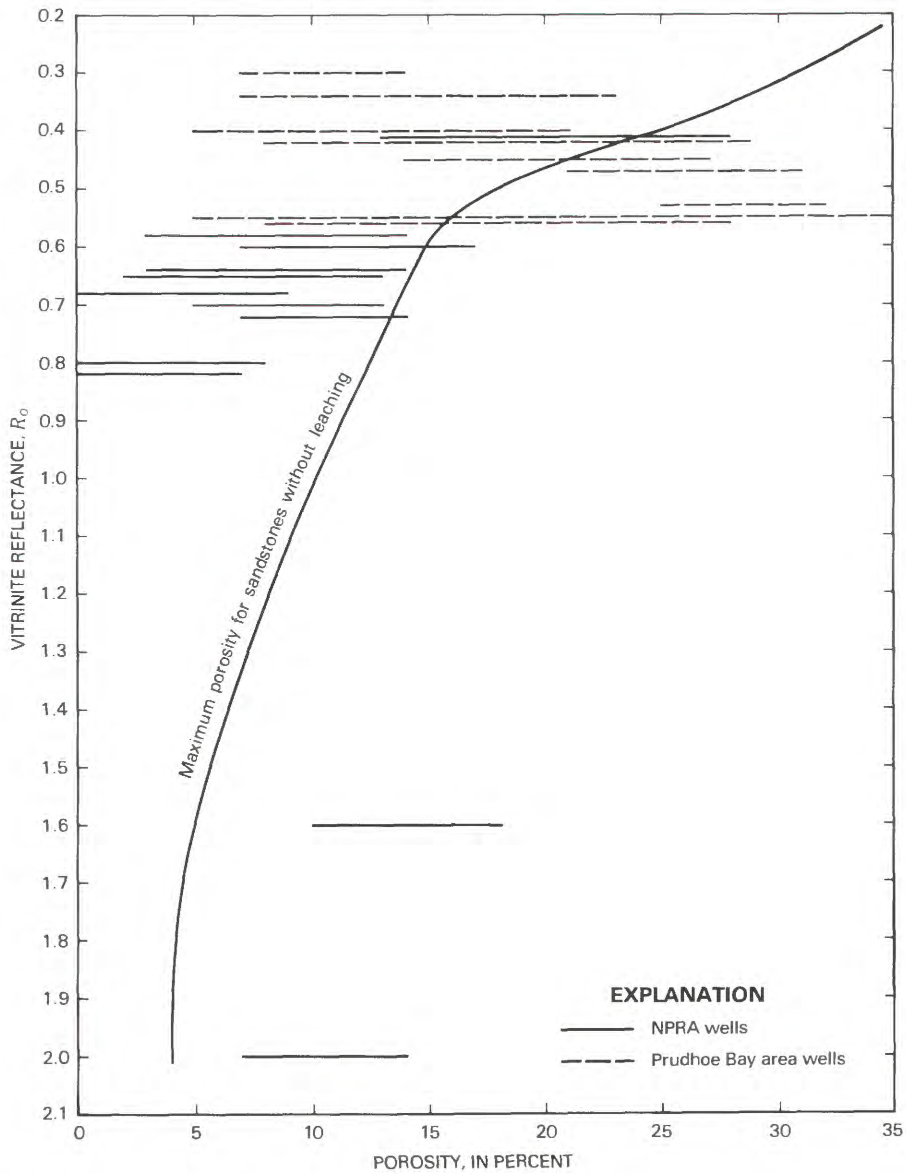

FIGURE 36.18.—Porosity in sandstone of the Ellesmerian sequence versus vitrinite reflectance (R_o), showing decrease in porosity due to increasing diagenetic alterations with increasing temperature. Solid lines, NPRA wells; broken lines, Prudhoe Bay wells. Curve shows approximate upper limit of porosity for sandstone in which no secondary porosity is developed. Sandstones to right of curve beween R_o values of 0.4 and 0.8 have secondary porosity. Sag River Sandstone and sandstone of the Ivishak Formation in the Kugrua No. 1 well have also apparently developed secondary porosity (lower part of diagram). Porosity values derived from sonic velocities.

mica is unaffected by the heating and the mixed-layer clay structure collapses to the mica structure at this temperature. The sum of the areas for these two peaks is called "(total clay content)." Note that this value contains a contribution from each clay component.

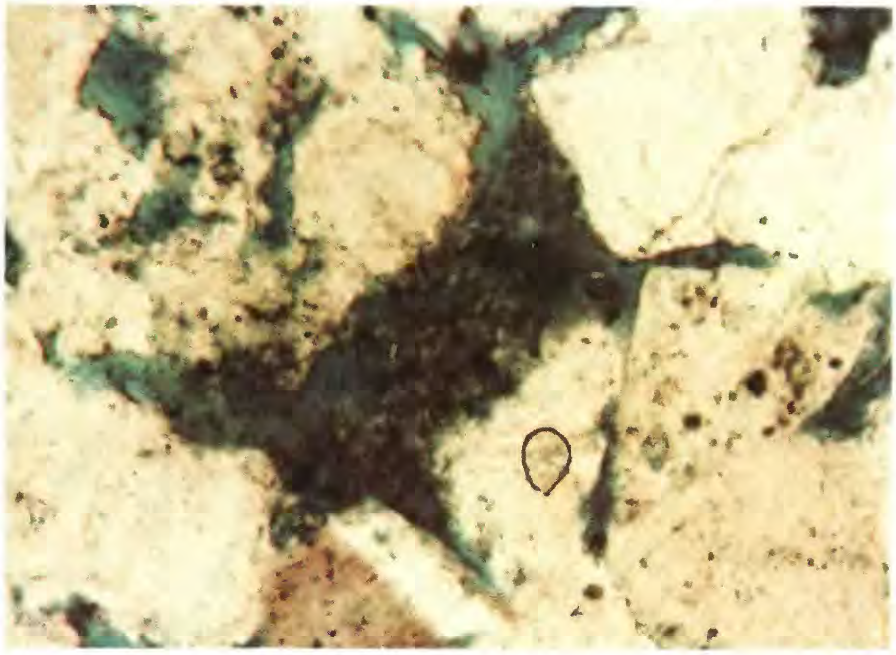

FIGURE 36.19.—Photomicrograph (plane-polarized light) of sandstone sample from the Ivishak Formation, Gwydyr Bay South No. 1 well, from a depth of 3,081 m (10,107 ft), showing degraded chert in porous sandstone. Much of the porosity in this rock formed by solution of cement and detrital grains. View is 0.9 mm across.

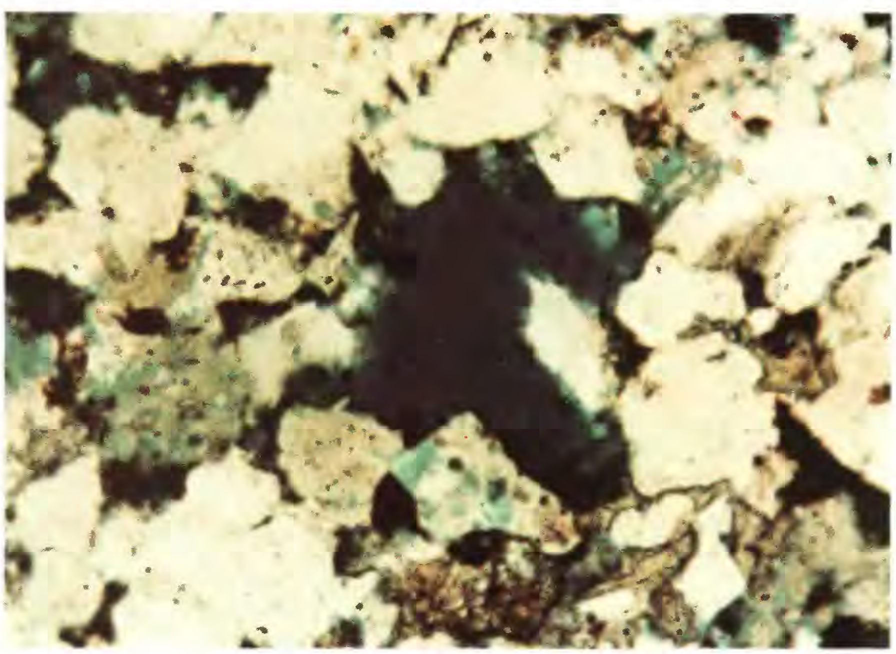

FIGURE 36.20.—Photomicrograph (plane-polarized light) of sandstone sample from the Ivishak Formation, Drew Point No. 1 well, from a depth of 2,375 m (7,793 ft), showing large secondary pore. Pore is larger than adjacent framework grains, implying that one or more grains have been dissolved. View is 0.9 mm across.

The contribution from mica alone is determined by measuring the 8.9° 2Θ peak area for the glycolated sample. The glycolation treatment removes any contribution to this peak from swelling clay. The following relation gives the mica component:

$$\text{mica} = \frac{\text{area of } 8.9^\circ\ 2\Theta \text{ glycol peak}}{\text{(total clay content)}}$$

Chlorite and kaolinite both have a peak at 12.3° 2Θ. Their contribution to the total clay content is calculated as follows:

$$\text{(total K+C)} = \frac{\text{area of } 12.3^\circ\ 2\Theta \text{ peak}}{\text{(total clay content)}}$$

At 550 °C the kaolinite structure is destroyed, and only chlorite is present at the 12.3° 2Θ position. Thus chlorite content alone is calculated as follows:

$$\text{chlorite} = \frac{\text{area of } 12.3^\circ\ 2\Theta \text{ peak at } 550\ ^\circ\text{C}}{\text{(total clay content)}}$$

Kaolinite content is now derived simply:

$$\text{kaolinite} = \text{(total K+C)} - \text{chlorite}$$

The mixed-layer clay component is now obtained by subtracting the mica, chlorite, and kaolinite components from unity:

$$\text{mixed-layer clay} = (1.0) - \text{mica} - \text{chlorite} - \text{kaolinite}$$

It should be noted that swelling clay, smectite, is found only in the mixed-layer clay phase. No evidence of independent swelling clay material was noted on any of the diffractograms.

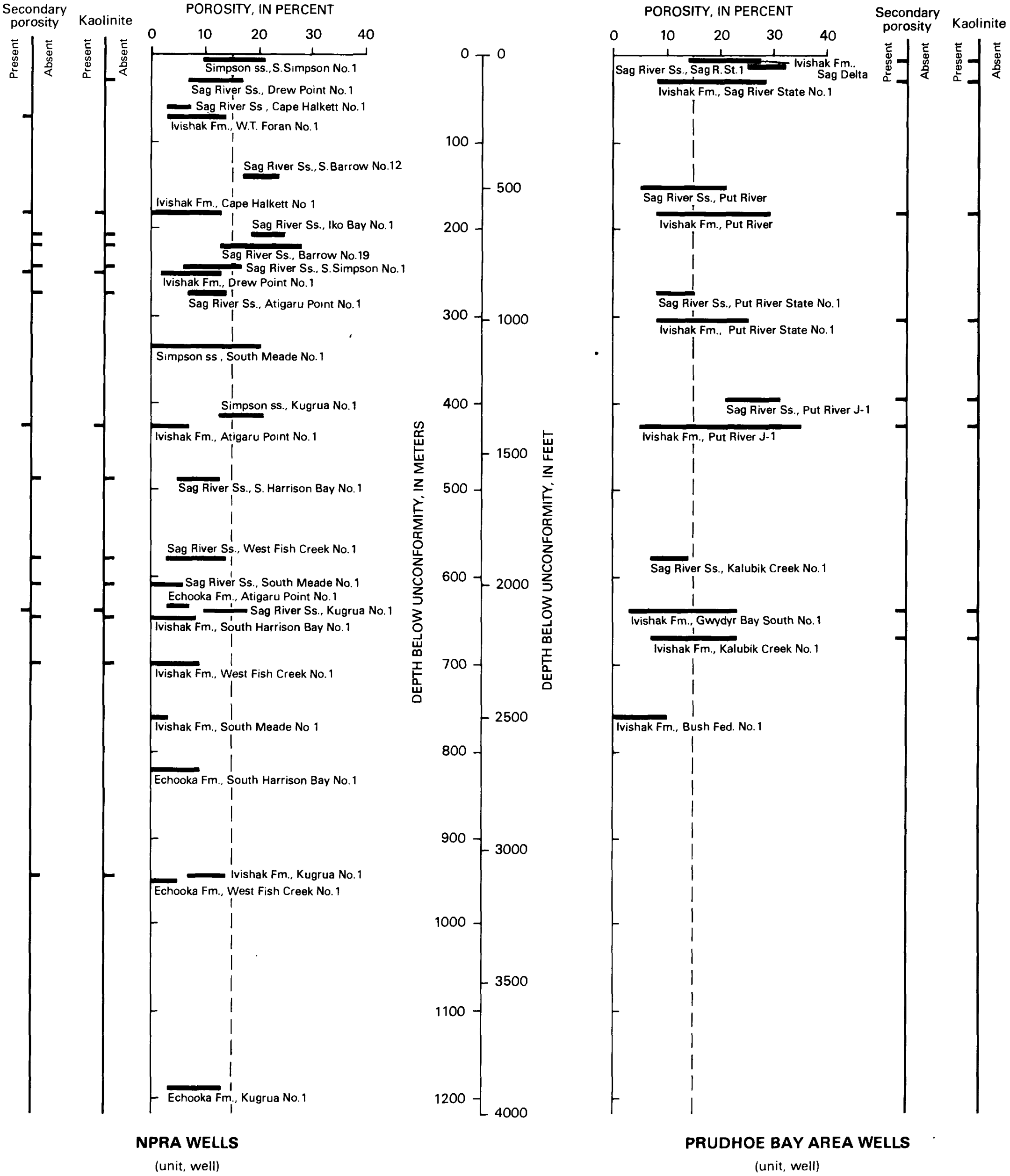

FIGURE 36.21.—Plots of sandstone porosity and observed occurrences of secondary porosity and of kaolinite in wells in the NPRA and the Prudhoe Bay area. High porosity is generally related to kaolinite and the development of secondary porosity. The 15-percent line (dashed) is the approximate cutoff for producible reservoirs. In the NPRA, outside of the Barrow area, there are few porous reservoirs because much primary porosity has been destroyed and the development of secondary porosity is much more limited than at Prudhoe Bay. Where presence or absence of secondary porosity and (or) kaolinite is not indicated, no thin-section observations were made. The Simpson sandstone used here refers to an informally named unit of local usage.

TABLE 36.6.—*Mineralogy of shale samples from wells in the NPRA and the Prudhoe Bay area*

[Mineral constituents: Q, quartz; Cl, total clays; Pl, plagioclase; M, microcline; C, calcite, A, ankerite; S, siderite; P, pyrite; O, other; Mi, mica; K, kaolinite; Ch, chlorite; ML, mixed layer; —, not detected]

Well	Sample depth (ft)	Unit	Bulk mineral constituents (volume percent)									Clay mineral constituents (percent of total clays)			
			Q	Cl	Pl	M	C	A	S	P	O	Mi	K	Ch	ML
Iko Bay No. 1	[1]2,369	Barrow sandstone	55	32	1	—	1	1	4	6		17	44	0	39
-----Do.-----	2,437	Kingak Shale	50	32	2	2	—	2	3	10		22	43	10	35
South Barrow No. 12	2,067	Kingak Shale	52	37	1	1	1	1	1	6		21	46	0	33
-----Do.-----	2,184	-----do.-----	34	52	1	1	—	1	6	4		17	32	0	51
-----Do.-----	2,187	-----do.-----	29	50	2	2	2	—	6	9		15	31	0	54
South Barrow No. 13	2,290	-----do.-----	39	41	1	—	—	19	—	—		13	39	0	48
-----Do.-----	[1]2,417	-----do.-----	59	24	1	1	2	33		10		18	56	0	26
Drew Point No. 1	6,952	-----do.-----	28	63	2	2	—	1	4	—		26	46	0	28
-----Do.-----	6,986	Sag River Sandstone	51	42	2	—	—	1	—	4		29	18	7	46
-----Do.-----	7,352	Shubilik Formation	54	33	2	2	6	3	—	—		21	25	1	53
-----Do.-----	7,717	Sadlerochit Group	46	47	2	1	—	1	2	—		54	42	0	4
Kugrua No. 1	10,483	Ivishak Formation	32	48	3	2	—	1	2	11		32	34	7	27
-----Do.-----	10,492	-----do.-----	34	50	3	2	—	1	3	8		38	49	0	23
Simpson No. 1	642	Nanushuk Group	33	48	10	3	—	2	4	—		33	41	4	22
-----Do.-----	1,157	Torok Formation	33	49	8	3	—	2	5	—		43	43	4	10
-----Do.-----	1,580	-----do.-----	27	52	8	3	—	8	3	—		29	44	6	21
-----Do.-----	2,275	-----do.-----	37	42	13	2	—	4	3	—		20	46	6	28
-----Do.-----	2,939-2,949	-----do.-----	34	49	10	2	—	3	3	—		23	49	4	24
-----Do.-----	3,810	-----do.-----	27	58	6	2	—	2	5	—		25	42	3	30
-----Do.-----	4,698	-----do.-----	27	51	9	2	—	2	9	—		29	35	5	31
-----Do.-----	5,303-5,308	Pebble shale unit	27	59	4	3	—	1	2	5		29	23	4	44
-----Do.-----	5,677-5,692	Kingak Shale	43	40	3	2	—	2	7	4		22	27	0	51
-----Do.-----	6,317	Shublik Formation	47	22	2	1	23	1	—	4		24	35	15	26
Topagoruk No. 1	911-919	Nanushuk Group	22	65	7	2	—	—	1	—	[2]2	26	37	2	35
-----Do.-----	2,096	-----do.-----	20	59	8	2	2	4	3	—		18	36	5	41
-----Do.-----	2,940-2,950	Torok Formation	30	48	11	2	—	5	4	2		27	46	4	23
-----Do.-----	3,560	-----do.-----	25	58	7	2	—	1	5	—	[2]2	21	41	2	36
-----Do.-----	4,345-4,348	-----do.-----	30	52	9	3	—	2	4	—		26	41	7	26
-----Do.-----	4,785-4,790	-----do.-----	30	52	7	1	1	4	5	—		31	45	3	21
-----Do.-----	5,360-5,365	-----do.-----	31	49	11	2	—	2	4	—		31	46	2	21
-----Do.-----	5,944-5,954	-----do.-----	30	53	8	2	—	1	3	—	[2]2	27	43	5	25
-----Do.-----	6,480-6,490	-----do.-----	42	44	9	—	—	2	2	—		28	35	4	33
-----Do.-----	6,490-6,500	-----do.-----	17	47	5	2	7	—	1	22		26	36	3	35
-----Do.-----	6,849-6,859	Pebble shale unit	37	45	10	1	—	3	4	—		24	31	3	42
-----Do.-----	7,052-7,062	Kingak Shale	31	51	5	2	—	—	5	5		23	44	2	31
-----Do.-----	7,829-7,839	-----do.-----	65	27	3	—	—	1	—	4		36	50	8	6
-----Do.-----	8,104-8,114	-----do.-----	32	54	3	3	—	2	3	4		23	14	5	58
-----Do.-----	8,629-8,634	-----do.-----	60	30	2	2	—	—	—	6		32	23	4	41
-----Do.-----	8,917-8921	Shublik Formation	52	24	7	7	—	—	10	—		37	17	4	42
-----Do.-----	9,816-9,821	Sadlerochit Group	44	29	7	7	—	—	—	—	[3]12	51	31	0	18
Put River J-1	8,539	Ivishak Formation	25	64	3	3	1	—	2	3		32	50	0	18
-----Do.-----	8,895	------do.-----	43	45	2	2	—	—	1	7		23	43	0	34
-----Do.----	9,009.5	------do.-----	26	67	2	2	—	—	3	—		29	36	0	35
-----Do.-----	9,064	------do.-----	15	75	3	3	2	—	2	1		21	35	0	44
-----Do.------	9,121	------do.-----	32	52	2	2	—	—	11	—		28	31	0	41
Put River	2,369	Ivishak Formation	20	48	1	2	1	—	28	—		40	43	0	17
-----Do.------	9,049.5	-----do.-----	16	76	3	2	—	—	3	—		23	63	0	14
-----Do.------	9,188	-----do.-----	29	61	2	2	—	—	3	3		25	32	1	42
-----Do.------	9,415.5	-----do.-----	26	62	2	2	—	—	6	—		37	33	0	30
-----Do.------	9,473	-----do.-----	32	62	3	2	—	—	2	—		46	33	0	21
-----Do.-----	9,585	-----do.-----	40	48	2	2	—	—	9	—		23	23	0	54
Sag Delta	9,222	-----do.-----	21	70	3	3	—	—	3	—		26	54	0	20
-----Do.-----	9,366	-----do.-----	40	37	2	2	—	—	19	—		26	54	0	20
-----Do.-----	9,424	-----do.-----	21	60	2	2	—	1	2	11		26	47	0	27
-----Do.-----	9,484	-----do.-----	12	71	3	3	—	—	2	8		43	42	0	15
-----Do.-----	9,602	-----do.-----	14	36	5	2	—	—	3	40				(4)	
-----Do.-----	9,603.8	-----do.-----	12	23	2	2	—	—	5	55				(4)	
-----Do.-----	9,627	-----do.-----	39	54	2	3	1	—	1	—		12	63	0	25
-----Do.-----	9,708	-----do.-----	26	50	2	2	—	—	2	16		26	37	0	37

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[1] Sandstones with abt. clay matrix.

[2] Pyrophyllite.

[3] Hematite.

[4] Clay separations not possible in these pyrite-rich samples.

CLAY MINERALOGY

Mica.—Most of the mica is probably detrital. This conclusion is based on the presence of peaks for many nonbasal reflections that correspond to an order 2M polytype. It is possible, however, that some portion of the mica reflections, especially the basal peaks in the oriented mounts, may be due to glauconite and (or) illite (1Md mica).

Kaolinite.—The 12.3° 2Θ peak is very sharp, indicating that the kaolinite is well crystallized. In fact, this sharpness of the peak profile may indicate the presence of dickite, a polytype of kaolinite. However, dickite is usually found in sandstone, not in clay-rich sediment. If the mineral is kaolinite, it is probably detrital. If it is dickite, it is probably authigenic.

Chlorite.—The chlorite is probably detrital in origin. The intensification of the 6.2° 2Θ peak at 550 °C indicates the probable presence of detrital Mg-chlorite, because the Fe-chlorite (sedimentary-chlorite) structure collapses between 450 and 500 °C. There may be some authigenic chlorite, but probably only a minor amount.

Mixed-layer clay.—The mixed-layer clay is probably a combination of illite and sodium-rich montmorillonite. This variety of montmorillonite has a basal interplanar spacing of 12.4°, compared to 15° for "normal" montmorillonite. The principal peak locations for this mixed-layer clay are: 8.0° 2Θ for the air-dried less-than-2-mm fraction; 6.5° 2Θ for the glycolated fraction; and 8.9° 2Θ for the sample heated at 550 °C.

ANALYSIS OF MIXED-LAYER MONTMORILLONITE-ILLITE

This chapter uses two methods to determine the relative proportions of illite and montmorillonite in the Topagoruk and Simpson samples.

METHODS

Unglycolated samples.-Burst (1969) showed that MacEwan's (1956, 1958) and MacEwan and Ruiz's (1959) system for analyzing the mixed-layer peak position of untreated, oriented samples could be used to determine the relative percentages of illite and montmorillonite. The peak position of the 5° to 9° 2Θ range is noted and compared to a graph.

Glycolated sample.-Reynolds and Hower (1970) developed a method for determining the illite and montmorillonite percentages by analyzing diffraction patterns of glycolated, oriented, less-than-2-μm clay samples. In this method, the peak position within the 15° to 28° 2Θ range is noted and compared to computer-generated profiles of known mixtures. For this method, each oriented less-than-2-μm fraction was glycolated overnight in a vaccum desiccator; then the 15° to 18° 2Θ region was scanned at 1/2° 2Θ per minute.

RESULTS

In the present study, both methods gave the same values for illite and montmorillonite percentages within the mixed-layer phase. These values are given in tables 36.1 and 36.2. The high illite content for all samples was not anticipated, especially for those from shallow depths. Studies of undeformed lower Tertiary samples in the Gulf Coast (Burst, 1969; Perry and Hower, 1970; Hower and others, 1976) have all shown that high illite content within the mixed-layer phase is not observed in samples from depths shallower than approximately 2,750 to 3,350 m (9,000-11,000 ft). In a study of the Pleasant Bayou No. 1 geothermal test well in Louisiana, the high illite values are not observed above 3,500 m (11,500 ft).

Another unexpected feature is that all Topagoruk and Simpson samples show distinct ordered interstratification. Gulf Coast samples show random interstratification above approximately 3,350 m (11,000 ft) (Hower and others, 1976); below that depth ordered interstratification is observed.

It appears that the Topagoruk and Simpson samples all show evidence of either prior burial diagenesis or of orogenesis, at least to the extent that the montmorillonite-to-illite transformation has proceeded to a high degree of completion, and ordered interstratification is the rule.

REFERENCES CITED

Bartsch-Winkler, Susan, 1979, Textural and mineralogical study of some surface and subsurface sandstones from the Nanushuk Group, Western North Slope, Alaska, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 61-76.

Bird, K.J., 1981, Petroleum exploration of the North Slope in Alaska, U.S.A.: U.S. Geological Survey Open-File Report 81-227, 41 p.

Burst, J.F., 1969, Diagenesis of Gulf Coast clayey sediments and its possible relation to petroleum migration: American Association of Petroleum Geologists Bulletin, v. 53, no. 1, p. 73-93.

Collins, F.R., 1958, Test wells, Topagoruk area, Alaska: U.S. Geological Survey Professional Paper 305-D, p. 265-316.

—— 1961, Core tests and test wells, Barrow area, Alaska: U.S. Geological Survey Professional Paper 305-K, p. 569-644.

Detterman, R.L., Reiser, H.N., Brosgé, W.P., and Dutro, J.T., Jr., 1975, Post-Carboniferous stratigraphy, northeastern Alaska: U.S. Geological Survey Professional Paper 886, 46 p.

Hower, John, Eslinger, E.V., Hower, M.E., and Perry, E.A., 1976, Mechanism of burial metamorphism of argillaceous sediment; 1. Mineralogical and chemical evidence: Geological Society of America Bulletin, v. 87, no. 5, p. 725-737.

Jones, H.P., and Speers, R.G., 1976, Permo-Triassic reservoirs of Prudhoe Bay field, North Slope, Alaska, *in* Braunstein, Jules, ed., North American oil and gas fields: American Association of Petroleum Geologists Memoir 24, p. 23-50.

Lerand, Monti, 1973, Beaufort Sea, *in* McCrossan, R.G., ed., The future petroleum provinces of Canada; their geology and potential: Canadian Society of Petroleum Geologists Memoir 1, p. 315-386.

Lyons, D.J., 1978, Sandstone reservoirs; petrography, porosity-permeability relationship, and burial diagenesis: Japan National Oil Corp., Technology Research Center Report 8, p. 1-69.

MacEwan, D.M.C., 1956, Fourier transform methods I, a direct method of analyzing interstratified mixtures: Kolloidzeitschrift, v. 149, p. 96-108.

——— 1958, Fourier transform methods II, calculation of diffraction effects for different types of interstratification: Kolloidzeitschrift, v. 156, p. 61-67.

MacEwan, D.M.C., and Ruiz, A.A., 1959, Fourier transform methods III, curves for some practically important cases: Kolloidzeitschrift, v. 162, p. 93-100.

Perry, Ed, and Hower, John, 1970, Burial diagenesis in Gulf Coast pelitic sediments: Clays and Clay Minerals, v. 18, no.3, p. 165-177.

Reynolds, R.C., Jr., and Hower, John, 1970, The nature of interlayering in mixed-layer illite-montmorillonites: Clays and Clay Minerals, v. 18, no. 1, p. 25-36.

Robinson, F.M., 1959, Test wells, Simpson area, Alaska: U.S. Geological Survey Professional Paper 305-J, p. 523-568.

Schmidt, Volkmar, and McDonald, D.A., 1979, Texture and recognition of secondary porosity in sandstones, *in* Scholle, P.A., and Schluger, P.R., eds., Aspects of diagenesis: Society of Economic Paleontologists and Mineralogists Special Publication 26, p. 209-225.

Schultz, L.G., 1964, Quantitative interpretation of mineralogical composition from X-ray and chemical data for the Pierre Shale: U.S. Geological Survey Professional Paper 391-C, 31 p.

Sommer, F., 1978, Diagenesis of Jurassic sandstones in the Viking graben: Geological Society of London Journal, v. 135, p. 63-67.

van de Kamp, P.C., 1976, Inorganic and organic metamorphism in siliciclastic rocks [abs.]: American Association of Petroleum Geologists Bulletin, v. 60, p. 729.

Wadman, D.H., Lamprecht, D.E., and Mrosovsky, Ivan, 1979, Joint geologic/engineering analysis of the Sadlerochit reservoir, Prudhoe Bay field: Journal of Petroleum Technology, v. 31, no. 7, p. 933-940.

Aerial view of 59-km (37-mi) ice road from Kikiakrorak River delta to Inigok No. 1 well site, used to transport 70,000 m^3 (90,000 yd^3 or about 6,000 truckloads) of gravel to build the drill pad and airstrip. A total of 135,000 m^3 (35 million gallons) of water was required to form the ice road. Photograph by Jeep Johnson.

SPECIAL STUDIES

In addition to geological and geophysical studies, operations in the remote wilderness areas of the Arctic require consideration of some unique aspects.

The Naval Petroleum Reserves Production Act of 1976, which mandated continued exploration of the Reserve, emphasized the need to protect other values during the exploration process. This requirement covered protection of recreational, fish and wildlife, historical, scenic, and environmental values. The protection of cultural resources, according to the Act and State laws, required an inventory at each site or alternative site targeted for drilling or other exploration activity.

Another special aspect of the exploration program was the design and construction of facilities in this Arctic region that is underlain by virtually continuous frozen ground—permafrost. The construction of such facilities as airstrips and roads required for year-round drilling presented an ideal opportunity for research in engineering geology. Hence cooperative studies with other USGS offices and the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) were undertaken and have been summarized for this volume.

Still another special problem was the storage and retrieval of the large amount of technical data that had already accumulated and that continued to accumulate at an accelerating rate. A machine-based system was the obvious solution, and therefore, beginning in 1977, a computer-based data and graphics system was set up. The building of these files and their use in studying the framework geology and petroleum potential of the NPRA is here recorded.

37. THE U.S. GEOLOGICAL SURVEY–BUREAU OF LAND MANAGEMENT CULTURAL RESOURCES PROGRAM IN THE NATIONAL PETROLEUM RESERVE IN ALASKA, 1977–1981

By Edwin S. Hall, Jr., and Robert Gal[1]

INTRODUCTION

Utilization of northern Alaska's riches long predates the recent oil exploration program in the National Petroleum Reserve in Alaska (NPRA). Though the earliest known archaeological site in the reserve dates back only 7,600 yr, most archaeologists believe human groups first occupied the area at least 4,000 yr earlier. The as-yet-undiscovered physical remains left behind by these first inhabitants of the area, as well as the known and unknown traces of the peoples who succeeded them through time, constitute the cultural resources of the NPRA.

"Cultural resources" is a catchall term covering a wide range of artifacts and relics, as well as places, villages, and campsites, that have been used by humans in the past and may be studied to reconstruct past ways of life. In the NPRA the cultural resources include stone tools, prehistoric housepits and cachepits, tent rings, rock carvings, burials, abandoned reindeer corrals and trading posts, and shipwrecks. The majority of these cultural resources have been reduced by time and the elements to archaeological sites. Cultural resources are, like petroleum deposits, nonrenewable. They are considered a valuable component of our national heritage, and a number of laws require that any Federal agency proposing an action that may affect these resources must, before implementation, consider and if necessary mitigate the adverse effects of its action.

First among the laws protecting cultural resources is the Antiquities Act of 1906, which is the basic legislation for the preservation and protection of antiquities on all Federal lands. The Antiquities Act provides for the establishment of national monuments by Presidential proclamation, sets up a permit system for the scientific investigation of cultural resources on Federal land, and details penalities for unauthorized disturbance of archaeological remains. The Archaeological and Historic Preservation Act of 1974, which extended the earlier Reservoir Salvage Act of 1960, authorizes funds for the preservation of historical and archaeological data that otherwise might be lost through any Federal construction project or federally licensed or assisted activity or program. The National Historic Preservation Act of 1966 established the National Register of Historic Places and a National Advisory Council to assist all Federal agencies in evaluating the effects of their actions on properties included, or eligible for inclusion, in the National Register. Finally, Executive Order 11593 of May 13, 1971, requires all Federal agencies to inventory cultural resources on lands they manage or affect in order to determine eligibility for the National Register, and to use due caution in regard to those resources until the inventory, evaluation, and nomination processes are completed. (For further discussion of the cultural resource protection laws, see Leicht, 1980.)

The oil exploration program in the NPRA is subject to this body of law for cultural resource protection.

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ESTABLISHMENT OF A CULTURAL RESOURCE PROTECTION PROGRAM FOR THE NPRA

The Naval Petroleum Reserve Production Act of April 5, 1976, transferred the administrative responsibility for the NPRA to the Secretary of the Interior. The Secretary of the Interior subsequently charged the U.S. Geological Survey (USGS) with management of the continuing exploration program and operation of the Barrow gas fields, and the U.S. Bureau of Land Management (BLM) assumed responsibility for surface management.

These two agencies signed a Memorandum of Understanding (MOU), effective January 18, 1977, to facilitate the interfacing of the responsibilities assigned by the Secretary of the Interior. Their responsibilities for the cultural resources in the NPRA overlapped and consequently were clarified in the MOU. The responsibility of the USGS derived from the petroleum exploration activities it was charged with directing; BLM responsibility derived from its mandate to manage the lands and resources of the NPRA. According to the MOU, the USGS is required to produce a cultural resource inventory report for each season of field operations: "An intensive cultural resource inventory must be conducted on those sites and alternative sites identified for exploration operations that involve surface disturbing activities. This inventory shall be conducted under the requirement of a Federal Antiquities Permit by a qualified professional. The need for an intensive inventory may be waived only if it is determined by BLM that equivalent data are available or that something less than intensive data are available and acceptable. These inventory data should be prepared in the form of a report" (Department of the Interior, 1977, p. B-3).

The format of this report is stipulated in Appendix I of the MOU, and the report should contain at a minimum the following:

a. Identification of the Federal Antiquities Permit under which the work was performed.

b. Description of data review and field inventory methods used, intensity of field inventories, the names of individuals employed in the work, and the commencement and termination dates of field inventory.

c. Identification of the project, and the BLM serial case file number, if any, for which the report is being written.

d. A general background discussion of cultural resources of the area.

e. Identification and description of specific cultural resource sites and values found, and the evaluation of their significance, and whether such sites might be eligible for placement in the National Register of Historic Places with specific citation to qualifying criteria under 36 CFR 60.4.

f. Site inventory records (BLM form 6230-2 or other acceptable form) completed for each cultural property inventoried with appropriate maps indicating the location of each site.

g. Suitable maps that clearly define all areas surveyed and intensity of survey in relation to identified cultural resources and the relationship of sites found to the project. Minimum acceptable base map should be with scale of 1:63,000 or other maps of sufficient detail.

h. Catalog of all cultural resource objects collected and indication of where they were stored.

i. Identification of the probability of finding additional sites and their probable significance.

j. Identification of the probable direct and indirect effects of the project upon known and unknown cultural resources.

k. Professional recommendations to realistically mitigate the direct and indirect adverse effects upon cultural resources which will result from the project.

The MOU between the USGS and the BLM clearly stated that the USGS was responsible for cultural resource surveys at proposed oil exploration locations and for recommendations to the prime drilling contractor to mitigate the impact of such activities on the cultural resources. However, as both agencies were charged with providing the Secretary of the Interior with the data to "take necessary and appropriate measures to protect the subsistence, environmental, fish and wildlife, historical, and scenic values of the Reserve during such exploration activities," it seemed appropriate that the two agencies work together in the effort to locate, evaluate, and protect cultural resources within the reserve. Accordingly, after the Department of the Interior assumed administrative responsibility for the NPRA, the USGS and BLM-NPRA archaeologists established a cultural resource clearance program in 1977 that implemented a common, coordinated approach to cultural resource protection efforts within the reserve. For example, in the field, virtually all of the proposed oil exploration activity areas were examined by the USGS archaeologist and either the BLM-NPRA archaeologist or one of his associates. In a similar manner, decisions regarding survey and test excavation procedures, evaluation of located cultural resources, commitment of resources to the program, and dissemination of the program's achievements were handled cooperatively. Additionally, the USGS archaeologist was regularly consulted concerning possible impacts to cultural resources of BLM-permitted actions outside the USGS areas of operation.

ARCHAEOLOGICAL RESEARCH IN THE NPRA BEFORE 1977

In order to appreciate the precepts that guided the USGS-BLM cultural resource program and to evaluate its success, it is necessary to understand what was known before about the cultural history of the NPRA. Archaeological research has been carried out in the NPRA since the late 1800's. Table 37.1 lists the researchers who have conducted surveys and excavations within the reserve boundaries.

As can be seen from table 37.1, all early survey and excavation activity was confined to the coast immediately around Barrow. After 1947, parts of several interior river valleys were investigated, though none of the surveys was intensive and several were conducted by nonarchaeologists. In the past 30 yr, major archaeological excavations were conducted at only four sites, two on the coast (Birnirk and Walakpa) and two inland (Etivluk Lake and Tukuto Lake). Thus, as of 1977, archaeological knowledge of an area the size of Indiana was derived from a few hurried surveys, some limited testing of sites, and very few major excavations.

Of necessity, any cultural history predicated on such skimpy data had to be considered extremely tentative. An outline of north Alaskan culture history based on data available as of 1977 is given in table 37.2. However, this framework appears more concrete, complete, and objective than our actual knowledge of the area's cultural history. For example, the cores and fluted points noted as possible cultural representatives for period I were scattered finds from undated surface sites; the 3,800 yr of period II were characterized by only three possible notched points, also recovered from undated surface sites; and for period III only two dated sites producing Arctic Small Tool tradition or Choris-Norton material were known. The paucity of scientific archaeological excavations in northern Alaska forced researchers to extrapolate from better known but still incomplete and poorly understood cultural histories for areas to the south of the Brooks Range. Such extrapolations were of doubtful utility and only minimally useful for ordering and ascribing significance to new sites and data, especially within a context of cultural resource management.

CULTURAL RESOURCE SURVEY AND CLEARANCE ACTIVITIES BY THE USGS AND BLM (ANTIQUITIES ACT PERMIT 77-AK-079)

THE PROCESS

According to the final environmental-impact statement (FEIS) for the "Continuing Exploration and Evaluation of Naval Petroleum Reserve No. 4," May 27, 1977, "Exploratory drilling, and construction of necessary facilities will not impact known historical or archaeological sites because they will be identified and avoided" (Department of the Navy, 1977, p. 602). The impracticability of mitigating all potentially adverse effects of oil exploration activities on cultural resources by activity relocation became obvious when, in mid-July 1977, permission was requested for excavation of three archaeological sites located on proposed borrow sites. The cultural resource sections of the FEIS were based on two false assumptions: (1) a relatively low site density in the NPRA and (or) a highly concentrated and well-understood settlement pattern for all time periods; and (2) an unrealistic view of the ability of archaeologists to locate all the sites present within extensive areas of oil exploration operation in a short time. During four seasons of clearance work, the USGS-BLM archaeologists were charged with surveying more than 8,000 km (5,000 mi) of seismic line, well over 1,600 km (1,000 mi) of winter trail, 47 proposed test well sites, and associated airstrips, borrow sites, and other construction areas. If all sites within these extensive potential impact zones had to be identified, time, personnel, and logistics became insurmountable obstacles to a cultural resource survey.

For this reason, the USGS-BLM survey was based on the premise that the level and intensity of survey and mitigation would be commensurate with, and appropriate to, the type of impact. The assumption that all cultural resource sites within all proposed construction areas had to be located and identified to avoid adverse effects was rejected. In some areas only certain sites with a high potential for adverse impact were identified. The specific field methods employed to achieve these ends and the basic assumptions underlying clearance of specific types of construction areas are noted below.

TABLE 37.1.—*Cultural resource identification research in the NPRA before 1977*

[List of references not meant to be exaustive; for further information, reader may consult Dekin (1978) and "Current Research" section of the journal *American Antiquity*. Nearly every explorer (and later ethnographer) mentions important cultural resource sites; such references are not included in this table because, in most cases, subsequent evaluation of the sites was undertaken by an archeologist or cultural resource specialist]

Researcher	Year	Area	Reference	Comments
Murdoch, John	1881–82	Barrow	Murdoch (1892)	Bought artifacts, some of which may have been archaeological; observed Birnirk site
Stefansson, Vilhjalmur	1912	Barrow	Stefansson (1914), Wissler (1916), Ford (1959)	Excavated at, and purchased artifacts from, Birnirk
Van Valin, William	1917-19	Kugusugaruk	Van Valin (1941), Mason (1930), Ford (1959)	Excavated sites
Rasmussen, Knud	1924	Barrow	Mathiassen (1930)	Purchased collection
Hopson, Alfred	1928-29	Kugusugaruk and Nunavak	Ford (1959)	Found Kugusugaruk completely excavated; excavated graves at Nunavak
USGS personnel	before 1930	Northwestern Alaska	Smith and Mertie (1930)	Summarized cultural resource sites seen by USGS parties before 1930
Ford, James	1931	Several sites along coast west of Barrow; Birnirk site; coast between Barrow and Barter Island	Ford (1959)	Began excavation of Birnirk; purchased artifacts from Nunagiak; briefly surveyed Beaufort Sea Coast
Ford, James	1932	Barrow and Point Belcher	Ford (1959)	Excavated at Birnirk; Nuwuk, Nuvuwaruk, Utkiavik, Koguk, Nunavak, and Walakpa
Ford, James	1936	Coast between Kotzebue and Barrow; Point Belcher, Barrow	Ford (1959)	Excavated at Nunagiak and Birnirk, examined Mitliktavik, Kilimatavik, Atanik and Pingasugaruk
Larsen, Helge	1942	Coast between Pt. Hope and some point beyond Wainwright	Larsen and Rainey (1948), Ivie and Schneider (1978)	Surveyed and tested excavations at lower and middle Utukok River, Icy Cape
Thompson, R.M.	1947	Upper Utukok River	Thompson (1948)	Located sites along river
Solecki, Ralph	1949	Kokolik and Kukpowruk River drainages; data collected from other USGS parties working in the National Petroleum Reserve in Alaska	Solecki (1950, 1951)	Survey
Whittington, C.	1950	Confluence of Carbon Creek and Utukok River	Solecki (1952)	Petroglyph discovered by USGS party
Carter, Wilbert	1951	Barrow	Carter (1952), [1953], (1966)	Excavated Birnirk
Irving, William	1952	Lower Colville River	Irving [1953]	Located one prehistoric site
Carter, Wilbert	1952	Barrow	Carter (1952), [1953], (1966)	Excavated Birnirk
Carter, Wilbert	1953	Barrow	Carter (1952), [1953], (1966)	Excavated Birnirk
Ford, James	1953	Point Belcher; Barrow	Ford (1959)	Mapped Nunagiak and Birnirk sites
Irving, William	1954	Etivluk Lake and Upper Nigu drainage	Irving (1962, 1964)	Surveyed and excavated
Hamilton, Thomas	1960	Near Meade River Village	Hamilton [1962]	Excavated
Irving, William	1961	Etivluk Lake and upper Nigu Drainage	Irving (1962, 1964)	Surveyed and excavated
Hall, E.S., Jr.	1964	Howard Pass proper	Hall, field notes	Surveyed; results essentially negative
Humphrey, Robert	1965	Upper Utukok River	Humphrey (1966, 1970)	Surveyed and did some excavation
Humphrey, Robert	1966	Upper Utukok River	Humphrey (1966, 1970)	Surveyed and did some excavation
Hall, E.S., Jr.	1967	Brooks Range and Arctic Foothills Province between Kokolik River and Chandler Lake	Hall (1975)	Surveyed
Campbell, John and Stanford, Dennis	1968	Arctic coast from Barrow to Colville River	Campbell (1970)	Surveyed from air only
Hall, E.S., Jr.	1968	Tukuto Lake, Etivluk drainage	Hall (1970, 1976a)	Excavated
International Biological Program	1968	Coast from Wainwright 40 mi N.	Campbell (1970)	Surveyed
Stanford, Dennis	1968	Barrow and Walakpa Bay	Stanford (1976)	Mapped and tested Utkiavik site; excavated at Walakpa
Stanford, Dennis	1969	Walakpa Bay	Stanford (1976), Campbell and Cordell (1975)	Excavated at Walakpa, Coffin, and Kahurok sites
Hall, E.S., Jr.	1970	Tukuto Lake, Etivluk drainage	Hall (1970, 1976a)	Excavated
Hall, E.S., Jr.	1974	Extreme Upper Utukok River drainage	Hall [1974]	Surveyed
Cook, John	1975	Northeast portion of the National Petroleum Reserve in Alaska	Cook [1976]	Surveyed by air only
Hall, E.S., Jr.	1976	Northeast portion of the National Petroleum Reserve in Alaska	Hall (1976b)	Surveyed by ground and air
Schneider, William	1976	Kuk River and Atanik	Ivie and Schneider (1978)	Survey of Traditional Land Use Inventory sites[1]
Scott, G.R.	1976	Barrow	Scott [1976]	Analysis of mass burial

[1] Data on cultural resource sites included in the Traditional Land Use Inventory were collected through interviews with local resource experts conducted by Flossie Hopson and Susie Franklin. This table includes only references dealing with on-site evaluations of these sites.

TABLE 37.2.—*Tentative outline of north Alaskan cultural history as of 1977*

[Modified from Anderson, 1984]

Period	Date	Cultural adaptation	Possible cultural representatives	Examples of sites in NPRA
I	Time of Bering land bridge to 6000 B.C.	Full-time tundra hunting	Core and blade, fluted points, Kahraok	Sites along Upper Utukok River, Walakpa Bay
II	6000–2200 B.C.	Taiga-tundra hunting and fishing	Notched points	Upper Utukok River
III	2200 B.C.–A.D. 500	Seasonal and year-round coastal hunting and fishing	Arctic Small Tool Tradition	Etivluk Lake, Tukuto Lake, Walakpa Bay
			Choris-Norton	Tukuto Lake (?), Walakpa Bay
IV	A.D. 500–1778	Prehistoric Eskimo	Birnirk	Barrow, Walakpa Bay
			Thule	Barrow, Walakpa Bay
			Pre-historic Interior Eskimo	Tukuto Lake
V	A.D. 1778	Historical Eskimo	Historical Eskimo	Many locations within NPRA

PROPOSED SEISMIC LINES

Winter geophysical survey activities over the four-year program involved seismic testing along more than 8,000 line km (5,000 mi) extending across the length and breadth of the reserve. The geophysical survey program resulted in thousands of miles of winter overland travel by support vehicles, with the consequent possibility of adverse effect on the cultural resources.

Each summer field season the USGS archaeologist was provided with 1:250,000-scale base maps detailing the proposed geophysical program for the following winter. The practical difficulties of surveying more than 1,600 km (1,000 mi) of seismic line during a summer field season for cultural resource sites are obvious, especially considering the following: (1) The final line locations were not available until after the archaeologists left the field; (2) the map lines covered a true ground width of 200+ m; (3) the activities of seismic testing were not actually restricted to the 200 m shown on the maps; (4) the lines detailed on the maps represented only proposed seismic lines, and therefore the routes camp trains took from one line to the next and the routes to and from the locations where seismic trains were stacked for the summer were not indicated; and (5) winter trails used by vehicles hauling fuel were not shown.

Given these difficulties, the most realistic approach to the seismic-line clearance appeared to be an archaeological survey that examined the previous winter's seismic lines as well as the lines under consideration for the following winter. An examination of previous seismic lines would indicate the nature and extent of actual and potential damage to archaeologically promising areas, while an examination of areas of high archaeological potential along the proposed seismic lines would identify cultural resource sites that could then be avoided.

Accordingly, various segments of earlier seismic lines were examined from the air for visible signs of damage in relation to varying types of ground cover and topography, such as wet tundra, rolling upland tundra, willow-cloaked stream beds, and unvegetated ridgetops. Locations of high archaeological potential were then isolated along the seismic lines shown on the maps of the current program. These locations were chosen on the basis of topography and a knowledge of the environmental parameters of previously discovered archaeological sites within the reserve, such as stream crossings, dry knolls and benches with good views, passes, and ridgetops. Ground checks were made in all cases where either the USGS or BLM archaeologist thought an archaeological site might be present and susceptible to damage. While flying from one such location to the next, the pilot followed proposed seismic lines as closely as possible in order to maximize the value of the survey. The final clearance report issued for each year's exploration program listed all located cultural resource sites in the vicinity of the proposed seismic lines.

The basic assumption underlying the USGS-BLM survey of proposed seismic lines was that the potential for damage to cultural resource sites exists whenever and wherever ground vehicles operated in the reserve. Examples of limited to

TABLE 37.3.—*Possible types of damage to archaeological sites as a result of ground vehicle travel*

[This table is intended only as a general summary; experimental field studies would be necessary for a more detailed analysis. Obviously, the type of vehicle involved and the nature of the part of the vehicle that comes into contact with the ground surface, as well as vehicle load, driver skill, and other factors will play a role in potential ground damage. This table is based on travel by heavily loaded, tracked vehicles, or vehicles pulling heavy loads on skids, as associated with the seismic program, the movement of drilling rigs, and related activities]

Conditions at archaeological site	Possible damage	
	Extent	Nature
	Summer	
Any subsurface, with or without ground cover; any ground cover	Moderate to extreme	Breaking of cultural objects, loss of association between cultural objects, mixing of components in stratified site, erosion and complete loss of cultural objects, lowering of permafrost table and subsequent deterioration of organic artifacts, and so forth
	Winter	
Bedrock or consolidated sand/gravel with no sod cover or with thin sod cover with or without denuded areas		
Frozen ground and substantial snow cover	Probably none	—
Frozen ground and little snow cover	None to slight	Some breakage and (or) slight lateral displacement of objects
Unfrozen ground and substantial snow cover	None to slight	Some breakage and (or) slight lateral/vertical displacement of objects
Unfrozen ground and little snow	Moderate to extreme, depending on whether vehicle runs in a straight line or turns	Breakage, lateral and vertical displacement; possible subsequent erosion with adverse effects
Wet tundra or other unconsolidated ground; upland tundra; sites unlikely but if present		
Frozen ground and substantial snow cover	Probably none	—
Frozen ground and little snow cover	Slight to moderate	Damage to tundra can change thermal regime and cause subsequent erosion
Unfrozen ground and substantial snow cover	Slight to moderate	As above
Unfrozen ground and little snow cover	Moderate to extreme	As above; potential for extreme erosion
	All seasons	
Any condition	Serious	Injection of fossil hydrocarbons into ground water because of leakage or spillage can cause contamination of organic material and eliminate the possibility of ^{14}C dating[1]

[1] Potentially this is the most serious problem connected with ground vehicle travel in the reserve. Studies of the old Fish Creek well site, where drilling took place 30 years ago, indicate that the effects of oil spills are pervasive and long term; soil samples from a depth of 40 cm still retain a strong smell of diesel fuel and thaw depth in some cases reached 70 cm, nearly twice that in adjacent unaffected areas (K.R. Everett, oral commun., 1979).

moderate damage to archaeological sites resulting from ground vehicle travel have been documented (Hall, 1977, p. 51-54; 1978, p. 49-50). These known adverse effects led to consideration of the general conditions under which ground-vehicle travel could potentially damage cultural resource sites; the conclusions are noted in table 37.3. In addition, that table indicates the following methods of minimizing potential damage to archaeological sites whenever ground vehicles must operate in the reserve: (1) Vehicles should travel in the winter and should be confined, wherever possible, to tundra areas; (2) if travel must take place on bedrock or consolidated sand-gravel areas, it should only be when the ground is frozen and snow covered; and (3) wherever ground vehicles travel, all known archaeological sites must be avoided.

These conclusions were verified or modified whenever possible by analyzing actual cases where cultural resource sites had been adversely affected by seismic activity. Such occurrences were carefully examined in the light of the more stringent regulations governing winter seismic work in recent years. There can be no doubt, as evidenced by the discovery of damaged sites, that ground vehicles can have adverse effects on archaeological sites. However, many hundreds of kilometers of ''tractor trail'' and other linear ground-vehicle-caused scars crisscross the NPRA landscape. These represent one legacy of the intensive oil exploration activities of the 1940's and 1950's, when environmental regulations governing ground travel were nonexistent. Such trails are shown on the USGS quadrangle maps published in 1955 and are still clearly visible—in fact, they are so plainly visible that they serve as air navigation markers. Most, if not all, known cases of trail damage to archaeological sites are associated with these older trails.

Examination of the trails left by ground vehicle traffic associated with the more recent geophysical programs indicates that the environmental stipulations that now govern geophysical exploration in the NPRA did indeed work. Relatively little disturbance to mineral soil resulted from these seismic programs, and, correspondingly, little or no damage to archaeological sites occurred. However, as long as a cultural resource program in conjunction with geophysical activities continued, all new trails were continually monitored to ensure that neither the original passing of the vehicles nor possible subsequent erosion resulted in damage to archaeological sites.

PROPOSED DRILLING PADS, AIRSTRIPS, AND BORROW SITES

The construction of drilling pads and permanent airstrips and the utilization of borrow sites result in the burial or complete destruction of any archaeological site within the construction zone. In general, field procedures involved flying at low elevations over proposed drilling pads, airstrips, and borrow sites in a helicopter, which maintained an altitude and speed of the archaeologists' choosing and landed at their discretion. Construction areas with high archaeological potential and all those areas situated on drier ground were checked by ground survey, and subsurface tests were dug where appropriate. When the location in question was on low, wet-sedge tussock-covered ground, clearance usually was issued without further ground check. In the experience of archaeologists working in northern Alaska, archaeological sites normally are found on surfaces that are reasonably well drained and stable.

The view that wet, swampy areas have a low probability of cultural resource potential was challenged by Lobdell (1979), who agreed in part with C.W. Davis' contention (oral commun. to Lobdell, 1978) that some sites may exist in poorly drained areas if other conditions are right. Although little philosophical distance may seem to separate the opinion that ''wet tundra is of low cultural resource potential'' from the claim that ''some sites may occur in wet tundra under certain circumstances,'' practically the two viewpoints are far apart. Based on Davis's contention, for example, Lobdell (1979, p. 8) advocated intensive surveying of all land that might be impacted by oil exploration activities, regardless of the potential for cultural resources.

Certainly, cultural resource sites can occur on wet, swampy ground in northern Alaska. For 9 months of the year, wet tundra does not exist at all in northern Alaska. During its frozen state, even the soggiest terrain provides a durable surface serviceable as a locus for human activity. Migratory researchers often overlook the fact that the summertime disposition of the physical, geographical, and biological resources available to human occupants of Northern Alaska persist only for the shorter portion of the year and are drastically transformed every year by the snows and freeze-up in early fall. ''Wet tundra'', as used here, connotes not only swampy summertime terrain with a thin active zone and shallow permafrost, but also uniform and generally featureless winter vastnesses. Whether soggy or frozen, wet-tundra areas do not offer a combination of resources (except where they bound other areas) such as would intensify human habitation over the short and long term.

The USGS and BLM archaeologists reviewed many of the supposed wet-tundra sites located by Davis (Davis and others, 1981) in the vicinity of Lake Teshekpuk. Most of the sites were historical or recent in origin, most were surface sites, and the locations of all were apparently determined by propinquity to Lake Teshekpuk rather than by attraction to wet-tundra areas.

Archaeological sites also can occur in wet-tundra areas well away from a resource locus like Lake Teshekpuk. The spot where a solitary caribou fell to a hunter's arrow, or the place where a sled broke down and had to be repaired, would not necessarily be on dry or well-stabilized ground and can be expected to be found anywhere.

Temporary sites, or those representing specialized activities, can reveal much about human behavior in the past, but these sites are extremely difficult to locate under the best of conditions. Extensive surveys of wet-tundra areas would not necessarily disclose the existence of such sites unless there were obvious surface manifestations. The success of any subsurface testing program depends on the relation between site size and density, number and size of sample-test units, and total area of interest. Where site size and density decrease (as in wet-tundra areas), the testing effort must be increased. Furthermore, any subsurface testing program would be frustrated by the presence of permafrost.

Thus, to ensure that no buried, ephemeral archaeological site exists within an area of wet tundra would require an exceedingly time-consuming, expensive, and highly sophisticated testing program. In fact, given the current state of testing techniques, there would be no guarantee of successfully locating such sites. While archaeological work related to oil exploration activities offers funding and opportunity to pursue research questions never pursued by traditional, academic inquiry (Schiffer and Gummerman, 1977), the opportunity must be tempered by ethical restraint. For these reasons, areas of wet tundra were not intensively surveyed.

No archaeological sites were located in close proximity to a proposed drill pad or airstrip. Proposed borrow sites, however, frequently coincided with archaeological sites, because locations of prehistoric camps, lookout stations, and hunting stands are often found on raised, well-drained ground composed of gravel and other materials appropriate for construction purposes. In most cases of conflict, alternate culturally sterile borrow sites were available, and the archaeological site could be designated as off limits. In four instances, excavation for mitigation was deemed necessary because practical alternatives were not available; the results of these excavations are discussed below.

Excavation to mitigate damage to the site was not a course of action taken lightly, for the following reasons: (1) As noted earlier, the FEIS that outlined the general operating procedures of the oil exploration program did not allow for archaeological excavation; (2) assuring that the required governmental agencies concur that excavation is necessary and appropriate involves far more time than is available in the brief Arctic field season, which is further shortened by the Congressionally mandated exploration schedule; and (3) acceptance of excavation as a possible mitigation measure requires a large standby archaeology crew.

Sometimes, however, circumstances dictate that excavation is the best approach. For example, in 1977 Tunalik No. 1 well was drilled in the northwest corner of the reserve, in an area where gravel is scarce. A potentially significant archaeological site was located on the primary borrow site. The only possible alternate borrow site contained less desirable construction material, which would have meant opening up a much larger area and would have caused even greater environmental disturbance. Also, this alternate source lay considerably farther from the test-well site and would have required the construction of a longer and more expensive (as much as $1.8 million) haul road. Although the opportunity to minimize both environmental damage and taxpayer expense provided a strong inducement to excavate the Tunalik Borrow No. 1 archaeological site, current law discouraged excavation unless it could be demonstrated that no adverse effect to the cultural resource would result through such action. Given the present state of knowledge about the reserve's cultural resources, a properly conducted archaeological excavation could only have a positive effect. Cultural resource managers will be unable to assess the potential significance of archaeological sites there, and thus determine whether or not sites should be nominated to the National Register, until sufficient data are available from intensive surveys and large-scale excavations to confidently construct an areal site classification. Therefore, excavation of the Tunalik site, which represented both an opportunity to study an unknown cultural expression in the reserve and to conduct the first scientific excavation of a large surface site, was deemed particularly appropriate in the effort to understand and protect the NPRA's cultural resources.

PROPOSED WINTER TRAILS

The procedures used in clearing winter trails between well sites and connecting individual well sites and their airstrips, borrow sites, and water sources were similar to those used for seismic lines. Each summer, trails from the previous and earlier winters were examined to determine the extent and nature of damage to the ground surface. Results of these inspections indicated both that winter trails may cause visible temporary damage to wet tundra and that the presence of archaeological sites in low wet tundra is highly unlikely. Where winter trails cross dry ground that is protected by a solid ground cover, damage to a buried archaeological site is likely to be, at most, minimal but usually nil. However, winter trails crossing dry ground that is only partially vegetated can cause significant damage to exposed cultural material. The cultural objects themselves may be damaged as well as the associations between them, and erosion resulting from such trails can destroy standing, fallen, or partially demolished structures such as sod houses.

Therefore, the USGS-BLM survey of proposed winter trails concentrated on identifying the following dry ground areas: (1) locations where cultural structures were visible on the surface; (2) locations that were partially vegetated and possessed potential archaeological sites; and (3) locations that were completely sod covered but had high archaeological potential. Very few locations along the proposed winter trails met any of these criteria and had to be ground checked, primarily because the proposed trails were located in low wet-tundra areas wherever possible. In most cases where the trails crossed dry ground, the areas were either completely sod covered or unlikely locations for archaeological sites.

However, the conclusion that archaeological sites would not be seriously threatened by winter trail activity was predicated upon assumptions of normal operating conditions, no deviations from the cleared trail routes, and exact adherence to the other environmentally dictated stipulations placed upon winter trail use in the NPRA. Otherwise, damage to cultural remains could have resulted.

MISCELLANEOUS CONSTRUCTION AREAS

Procedures similar to those just outlined were employed to ensure that construction of staging areas, gas wells, debris burial sites, and other facilities associated with the oil exploration program would not harm cultural resource sites.

THE PROBLEMS

Any cultural resource survey and clearance program encounters difficulties. Often these difficulties arise from logistics and time constraints, at other times from misunderstandings among the organizations involved about the force and thrust of the protection laws and the procedures for inventory and assessment. Such difficulties arose in the NPRA program and were magnified by the size of the reserve and the scale of the exploration program. Additionally, the nature of the Arctic environment posed problems that would not be encountered in more temperate regions.

Although it would not be useful to detail all these problems, several deserve comment. Problems of particular and continuing concern included (1) a lack of knowledge of the effects on the cultural resources of certain exploration activities, (2) the difficulty of complying with the prescribed procedures to determine if excavation was appropriate, given the prevailing time constraints, and (3) the potential danger to cultural resource sites posed by secondary and indirect effects of the oil exploration program.

EFFECTS OF CONSTRUCTION ACTIVITIES

The potential extent of damage to cultural resource sites as a direct result of the construction of an airstrip or test-well pad, or the use of a borrow site, can be predicted with some certitude. However, problems arise when archaeologists attempt to predict the potential damage associated with ground vehicle travel. In table 37.3 a preliminary attempt has been made to list the possible types of damage resulting from vehicular travel under different ground-cover, subsurface, and weather conditions. Unfortunately, the table cannot be based on empirical data, because no experimental studies have been conducted. Observations of cultural resource sites disturbed by ground vehicle travel indicate the nature and extent of possible damage, but the prevailing weather conditions (depth of frost and the depth of snow cover) at the time the vehicles passed over the sites are not known. Thus, until better data are forthcoming, archaeologists must err on the safe side by stipulating that vehicle travel in the vicinity of the sites take place only under optimum protective conditions.[2]

DIFFICULTY OF COMPLYING WITH PROCEDURES

Related to the lack of understanding of the effects of certain activities on cultural resources is the lack of adequate inventory data and knowledge of the procedures that Federal agencies are required to follow to protect those resources. For general application, the means of protecting cultural resources have been codified by the Advisory Council on Historic Preservation (ACHP) into a set of procedures (36 CFR 800), which agencies are required to follow in consultation with both State-centralized (the State Historic Preservation Office) and nationally centralized (the Advisory Council on Historic Preservation) cultural resource experts.

Cultural resource investigation and consultation at the earliest stages in project planning are made extremely difficult by a number of circumstances relating to the State of Alaska in general and Alaska's North Slope in particular.

Archaeological inventory and assessment almost universally in Alaska cannot be accomplished at the earliest stages of project planning because there is a lack of data. For all of the North Slope and most of the State, the earliest stages of project planning at which archae-

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[2] During 1982-1984, natural and vehicular (loaded sleigh pulled by D-7 Caterpillar tractor) impacts on manufactured surface-site test plots were compared (Bowers, 1984). The experimental results confirm the less rigorous observations of impacts detailed in table 37.3.

ological data can be considered is during field engineering design.

The lack of adequate inventory data limits archaeological input to providing estimates of cultural resource potential. Most often, therefore, field engineering and archaeological assessment are accomplished concurrently during the same brief summer season, which on Alaska's North Slope is limited to the period between June 20 and August 20.

One significant result of doing archaeological assessment and compliance at the field-engineering stage of project planning is that the options remaining to engineer and archaeologist alike are limited when conflicts are identified. The field engineering must be drastically changed, or impacts must be accepted or mitigated. One solution to this dilemma is to extend the time allowed for the planning process, which on the North Slope would necessitate scheduling the archaeological work one field season before the field engineering. However, because of the mandate of accelerated exploration, this solution was precluded. An acceptable middle ground was achieved for the NPRA program that satisfied both the FEIS' policy of avoidance of all cultural resources and the USGS and BLM archaeologists' management philosophy of limiting the use of nonrenewable cultural resources. The archaeologists urged and supported the approach that because engineering, cultural-resource, and other environmental assessments had to be conducted at the same time, concurrent rather than sequential consideration and evaluation of alternative components of the proposed action was the only workable solution. Thus, in general, more areas were proposed and evaluated than were used. For example, eight material sites and nine airstrip locations were examined for cultural resources for the Lisburne well site, but only two material sites and one airstrip location were actually used. However, this process deferred the final decision on project location and resultant impacts. This deferral of final decisionmaking (with overall environmentally sound results) in cases that involve areas of high cultural resource density or areas in which engineering or other environmental constraints are limiting factors, effectively reduces the archaeologists' time to complete mitigating measures and to obtain the required concurrence in the adequacy of those measures from the State Historic Preservation Officer (SHPO) and the Advisory Council.

In 1977, the first year of the archaeological program in the NPRA, consultation was attempted on a case-by-case basis. The time required, however, for consultation at the State and national level (SHPO and ACHP) critically affected the time available to implement mitigating measures. Weather, distance, remoteness, and communication lag combined to thwart strict compliance with the consultation procedures. Personal contact with the Alaska State Historic Preservation Officer from a proposed construction area in the reserve required as much as 2½ hours of travel by helicopter and 2½ hours by jet airplane. ACHP contacts are as remote as Seattle is to Miami. Although telecommunications at the major North Slope logistics bases reduced comment periods, and provision for memoranda of agreement in the revised Advisory Council procedures alleviated some of the problems, the lack of basic inventory data and the short field season left totally workable procedures for feedback between engineer, project decisionmaker, archaeologist, SHPO, and Advisory Council unrealized.

In a never-finalized Programmatic Memorandum of Agreement between the USGS, BLM, and the ACHP, a significantly flexible alteration of procedures was agreed to. Most of the sites encountered in the reserve were surface or shallowly buried deposits of principally lithic materials. Because of the lack of archaeological work in most of the reserve, the significance of these sites could not be determined without extensive excavation. Each of these sites therefore met the National Register criteria as being likely to yield information important to prehistory or history. The Advisory Council agreed to accept, without review or comment, mitigation measures developed jointly by the SHPO and the USGS and BLM archaeologists for those sites whose eligibility was based on their likelihood of yielding important information if the Council's "Guidelines for Making 'Adverse Effect' and 'No Adverse Effect' Determinations for Archaeological Resources" were followed.

While this tacit acceptance of State-centralized consultation by the Advisory Council reduces some of the difficult and time-consuming aspects of compliance, additional responsibility for timely response is shifted to the SHPO. The State of Alaska contains a disproportionate share of Federal inholdings and must respond to Federal agency requests for consultation within the narrow seasonal "window." Programs and guidlelines for classes of compliance actions must be pursued and based upon the measurable effects of development activities upon cultural resources. With the passage of the Alaska National Interest Lands Conservation Act and the national urgency for the exploration and development of energy resources on Federal lands, the Alaska SHPO will face increasing demands for timely consultation. Unless innovative approaches are proposed, project scheduling will continue to be pitted against cultural resource protection to the detriment of one or both.

INDIRECT AND SECONDARY EFFECTS

A major concern of cultural resource managers has been the possible damage to cultural resource sites as a result of a given construction project, or long after the completion of the project, but not as a direct outcome of construction. The problem is one of indirect effects or secondary effects, wherein effects are defined as "the events, activities and processes related directly or indirectly to a project's planning, construction, or use that have potential for altering archaeological resources" (Schiffer and Gummerman, 1977, p. 292). Indirect effects are a result of activities connected with the construction process itself, and secondary effects are "the results of other intended uses of a facility, or of other uses that might reasonably be expected" (Shiffer and Gummerman, 1977, p. 295). It should be noted that the use of these concepts here does not correspond exactly with that of Shiffer and Gummerman because they distinguish between the planning, construction, and operating stages of a project, whereas, for the purposes of this discussion, the planning, construction, operation, and abandonment stages of specific construction projects associated with the oil exploration program are lumped together. Although several examples of indirect and secondary effect might be discussed in relation to oil exploration in the NPRA, we will focus on only two very real dangers to cultural resource sites in the reserve.

Whenever a previously inaccessible area is opened up, obvious archaeological sites become easy prey to unauthorized collecting. For example, the dominant feature in the middle Iteriak Valley, in the southeastern part of the reserve, is a mesalike bedrock knoll that was located within 5 km (3 mi) of several proposed airstrips and was the original proposed location for the Lisburne well site. Early in the summer of 1978, this knoll aroused the interest of surveyors laying out the Lisburne construction area. They thought it would make a good survey control point; the BLM archaeology crew felt it was an ideal location for a lookout site. Fortunately the BLM crew reached the knoll first and found it to be an extensive archaeological site with chert spalls and numerous projectile point/bifaces exposed on the surface. Although it is not suggested that the surveyors would have disturbed the site had they noted its presence, the potential is obvious. Illegal removal of artifacts from archaeological sites by personnel connected with oil exploration activities in the reserve has not been an uncommon occurrence.

Two approaches can be taken simultaneously to alleviate potentially adverse indirect effects. One involves a combination of education and enforcement of existing laws protecting cultural resource sites. All personnel even peripherally associated with oil exploration activities in the reserve should be informed of the importance of not disturbing cultural resource sites and of reporting them to the appropriate authorities and, at the same time, made aware of Federal laws and regulations protecting such sites.

The second approach, which was followed in the Lisburne well-site area, is for cultural resource managers to make an intensive survey in the vicinity of proposed construction activities, well beyond the limits of areas actually to be impacted by construction. Sites can be left unmarked if there is no chance that construction personnel will disturb them, or posted and periodically inspected if there is a possibility that the site's existence might be discovered or disturbed by activities resulting from the nearby presence of construction works. However, if a site has obvious artifacts of potential interest to the casual collector, then it seems most appropriate that the site be carefully mapped and the more obvious artifacts removed to an appropriate depository.

The problem of secondary effects is more serious and long term. The construction of long, all-weather airstrips at locations such as Inigok, Tunalik, and Lisburne opens up casual use of large areas of the NPRA that previously were fairly inaccessible. For example, the middle Iteriak Valley region formerly could not be entered from the air except by helicopter or by fixed-wing craft on skis during the winter months, but since the Ivotuk Hercules strip was completed, any fixed-wing craft can land at any season. Hunters, geological parties, and others now use the airstrip as a logistics base.

At present, and for some time into the future, use of these airstrips will be controlled, but when they are deactivated, the surrounding countryside and its resources will be accessible to casual users who had seldom or never before used the areas. The resulting pressure on numerous cultural resource sites could be particularly acute in the Lisburne area, which lies on the edge of the Brooks Range and thus could attract hikers and others interested in outdoor recreation. Although most visitors to the area may not recognize archaeological sites as such, and some of those who do may be aware of the importance of not disturbing them, the potential for adverse effects exists and will increase with time. Adverse effects are many and could be deliberate or inadvertent. They include removal of artifacts from sites, random digging in buried sites, disturbance of tent rings and other surface structures, removal of ground cover and subsequent erosion of the sites, and introduction of hydrocarbons into archaeological sites leading to contamination of radiocarbon samples.

The situation is somewhat different in the Tunalik and Inigok areas. The greatest concentration of cultural resource sites in the vicinity of Tunalik is along the coast, and access is possible by boat or from the permanent airstrip at Icy Cape. The terrain within a 15-km (10-mi) radius of the Tunalik well site is mostly wet sedge-tussock tundra and thus not conducive either to recreational activities or prehistoric habitation. The USGS and BLM archaeologists made a specific effort to follow the elevated remnants of the old shoreline bluff on which the Tunalik Borrow No. 1 archaeological site was located. Numerous additional sites were found, apparently with the same cultural and temporal affiliations as Tunalik Borrow No. 1, but all were well removed from the Tunalik well site. Thus, the presence of an all-weather airstrip at Tunalik may not be as crucial, in terms of potential adverse effect on cultural resources, as that at Lisburne, although unrecognized archaeological sites may well exist in the Tunalik area.

The Inigok well site is situated in a gently rolling section of the Arctic coastal plain characterized by numerous lakes, some supporting substantial fish populations, and meandering streams. Sand blowouts are common along the margins of the lakes and the higher banks of streams—places where the wind has stripped the ground cover from the underlying sands. The USGS and BLM archaeologists surveyed the area for archaeological sites that might suffer because of the presence of the Inigok airstrip. The procedure employed was to fly circles of ever-increasing diameter around the Inigok well site out to a radial distance of approximately 13 km (8 mi) and to land where archaeological sites might be expected. Of the six site locations chosen, two large blowout areas on a tributary of Fish Creek produced prehistoric cultural material, and a historical campsite was found near a stream draining a large lake. Numerous other archaeological and historical sites undoubtedly exist in the vicinity. However, the area is not as attractive for recreation as that around Lisburne, and future human use of the Inigok area is apt to stress recreational and subsistence fishing—activities that can be accomplished by using float planes for access. The known sites in the area are all small and not obvious to the casual observer. Also, there are only a few of the easily recognizable artifact types that increase the chances of nonscientific collection. Thus, although the secondary effects of the Inigok airstrip are potentially more serious, in terms of cultural resources, than those of the airstrip at Tunalik, the primary concern is for the Lisburne area.

The only effective solution to the possibility of potential secondary effects in the Lisburne, Inigok, and Tunalik areas, and in others where future all-weather strips may be built, would be to render such airstrips inoperative when their usefulness to the oil exploration program is ended. A more practical approach would be the procedures described above for mitigating the indirect effects; that is, a combination of (1) education and enforcement of the existing laws and (2) a program for mapping and collecting at obvious sites that are apt to be impacted by increased human traffic. The general survey in the Lisburne area by the BLM archaeology crew and the mapping and collecting at the Mesa site were based on a concern for potential secondary, as well as indirect, effects as a result of the construction of the Ivotuk Hercules strip. It is difficult to be totally comfortable with the notion of collecting material from archaeological sites, as distinct from controlled excavations, because of the possible loss of important scientific data. However, the procedure of using gridded surface collection and placing permanent but unobtrusive grid markers—the procedure followed in the Lisburne area—is potentially less damaging than leaving obvious archaeological sites open to unauthorized and uncontrolled collecting.

RESULTS

CLEARANCE

The USGS-BLM cultural resource survey and clearance program over the years 1977-1981 resulted in archaeological clearances for approximately 8,000 km (5,000 mi) of proposed seismic lines, more than 1,600 km (1,000 mi) of proposed winter trail, 47 proposed well sites (including gas wells in the Barrow area), approximately 81 proposed borrow sites, 39 proposed airstrips, 4 debris burial sites, and miscellaneous other construction areas.

SURVEY

Surveys associated with clearance activities resulted in the discovery of 113 archaeological sites scattered throughout the reserve (fig. 37.1). Some may view these sites as having been located by an essentially random survey, in that the requirements of the oil exploration program dictated the areas surveyed, and that little or no correlation exists between the below-ground targets of the geophysical or drilling program and specific surface topography. However, most of the sites were discovered when examining locations of high archaeological potential along the proposed seismic lines, or during the intensive survey of the lower Otuk-Iteriak Valley by a BLM crew. In general, the survey provides a nonsystematic sampling of archaeologial sites across the reserve. A definite bias for exposed surface sites situated on promontories was noted, and examples of the entire span of known culture history were revealed. Thus, the primary accomplishment of the USGS-BLM effort has been to provide an extensive, large-scale survey of the entire reserve; future survey activities, except those associated with oil exploration or similar programs, might well concentrate on intensive surveys similar to those conducted by the National Park Service at

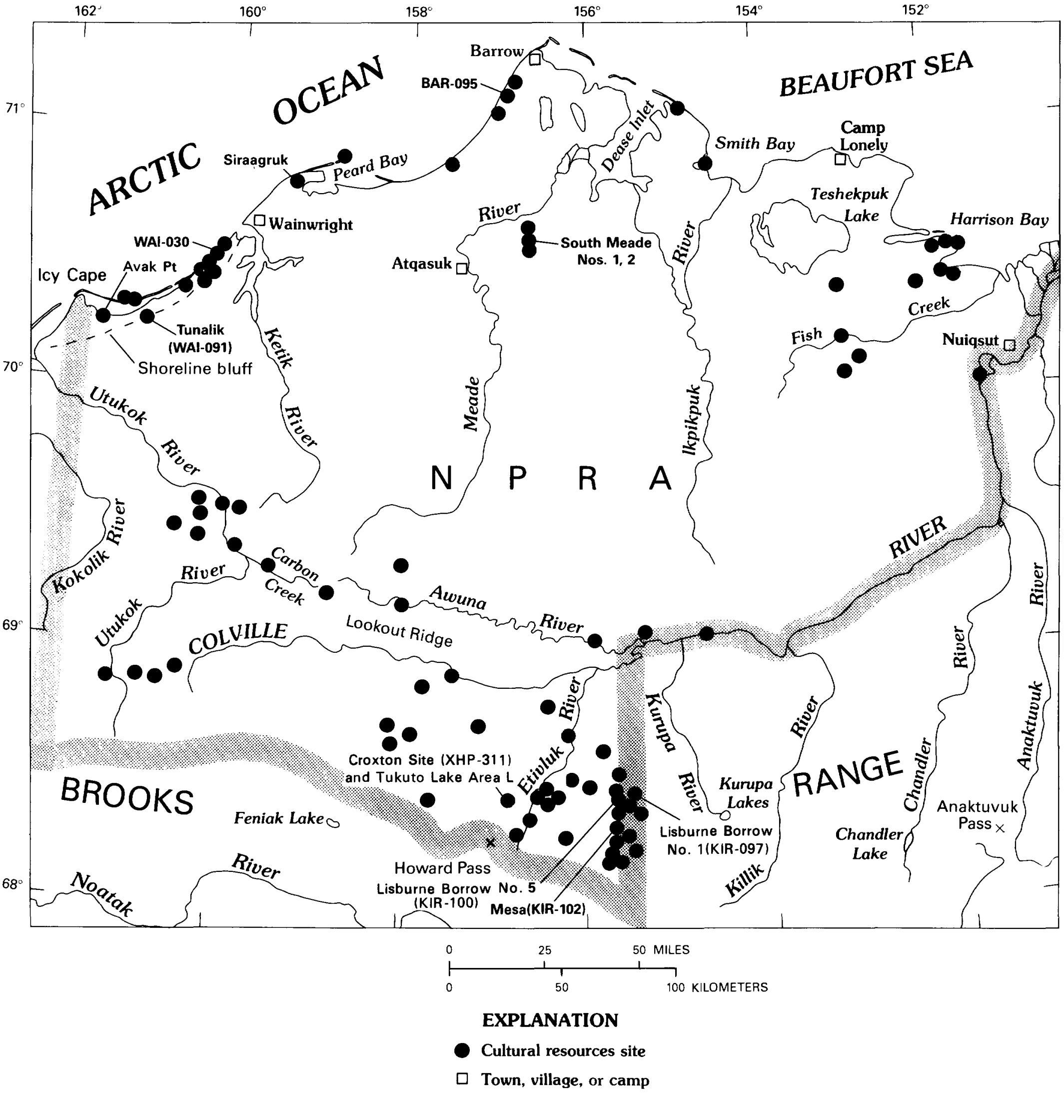


FIGURE 37.1.—Cultural resource sites in the NPRA discovered by the USGS-BLM cultural resources program, 1977-1981.

several locations within the NPRA (see below) and by the BLM crew working in the middle Otuk-Iteriak Valley.

TESTING PROGRAM

Test excavations were conducted at a number of localities in the reserve for a variety of reasons. At the Mesa site, surface collection and systematic subsurface testing were carried out to mitigate anticipated secondary impacts associated with the nearby Lisburne well site and to assess the site's size and significance. At Lisburne Borrow No. 5, nonsystematic tests were conducted to estimate the density and distribution of cultural resources to evaluate the site's significance and determine the strategy for, and magnitude of, possible mitigation efforts. At BAR-095, testing was initiated because the site was endangered by natural erosion. BAR-095 is the Alaska Heritage Resource Survey number of this site, indicating that it is the 95th site registered in the USGS Barrow quadrangle. However, because sites are not always designated serially, there may not be 94 known sites in the Barrow quadrangle. Similar designations are also to the Alaska Heritage Resource Survey.

The site of Siraagruk was tested during two summer seasons to determine the complexity of excavation of historical structures (feasibility of excavation for mitigation) and to develop procedures and a model for evaluation of the extent and significance of intra- and extradomicile cultural deposits at a historical village site. Test excavations at WAI-030 were conducted to estimate the technological relations of a group of similarly situated small sites located along a single physiographic feature. The test excavation results at WAI-030 supported expansion of the testing the following season to locate and assess the cumulative significance of similarly situated sites within the region. Finally, test excavations at the Croxton site (Tukuto Lake) during the 1981 season were designed to provide data on a previously unknown phase of interior Inupiat development and to help corroborate the analysis of aerial photographs taken as part of the nondestructive archaeology program (see below).

Testing was implemented for procedural as well as cultural and historical reasons. The decision as to when to protect and preserve and when and how to mitigate the impacts on the broad range of preponderantly unstudied and unreported cultural resources was considered best made outside the context of imminent impact and without, if possible, exhausting those resources in the process. Such a decision was also considered to be predominantly within the long-range purview of the NPRA's cultural resource managers and of incidental interest to the average researcher.

In contrast to the inventory and compliance program, which by nature was site specific and reactionary, the testing program was aimed at the long-range management problems, determinations of the regional significance, and adequacy and appropriateness of the methods.

MESA SITE (KIR-102)

The Mesa site is a large, apparently single-component archaeological site located on a mesalike gabbro dike or sill that rises 60 m above the Otuk-Iteriak Valley floor in the foothills province of the North Slope. Lithic artifacts and detritus are widely distributed across the top of the mesa, both buried and on the surface. The Mesa site lies outside the limits of the Itkillik glaciation.

The Mesa site was discovered during the summer of 1978 by BLM archaeologists evaluating the possible direct, indirect, and secondary impacts in the vicinity of the Lisburne No. 1 well. When the mesa was considered as a possible engineering survey control point, a small archaeological crew established a permanent datum at the site for mapping purposes. All artifacts on the surface were collected after their exact position was plotted, and provenance for each specimen was recorded.

In 1979 a small crew returned again to the mesa to continue assessment work after excavations were completed at the nearby Lisburne site. The archaeologists were to determine the extent and limits of the site, conduct limited test excavations to determine whether cultural materials had a subsurface distribution and whether this distribution was associated with a traceable paleosol or occupation surface, and obtain materials suitable for radiocarbon dating. Little time remained for archaeological work at the Mesa site after the Lisburne excavations were completed, and so the extent and limits of the site were not determined during the 1979 field season. However, 14 gridded excavation units were removed down to sterile soil; they revealed apparently undisturbed concentrations of buried artifacts and three hearth smears. Because the amount of charcoal recovered from each hearth was small and because the hearths were near each other, the three samples were combined. The combined sample (laboratory number DIC-1589) yielded a radiocarbon age of 7,620±95 yr B.P., which would give an uncalibrated date of 5670±95 B.C.

In 1980, a two-person BLM crew returned to the Mesa site and dug systematic shovel tests across the site to determine site size and boundaries. Richard Reanier of the University of Washington was contracted to analyze the soil in the hope that stable past-occupation surfaces suspected as a result of the 1979 test excavations would be identified.

Reanier (1981) analyzed two soil profiles at the site and described the degree of soil development as shown by morphology, chemical analysis, and clay mineralogy. He reported that local reworking of the bedrock material of the mesa itself, rather than eolian deposition, accounts for the soil profiles. From the position and age of the hearths in the profiles, he suggested that the two profiles analyzed developed on surfaces considerably older than 7,000 yr. Cultural materials deposited on the mesa were incorporated into the surface horizons or buried through soil-development processes, and their distributions have remained fairly stable since the burial. Reanier cautioned that the stability of the distribution of materials between time of deposition and time of burial cannot be determined. Vertical and lateral movement of cultural material by cryoturbation and other periglacial sorting processes have locally effected the long-term stability of the distribution of the buried cultural materials. However, Reanier suggested that additional detailed soil-profile analyses will enable the archaeologist to determine the relative stability and, therefore, age of subsurface distributions of cultural materials in various parts of the site. Soil profiles will be a significant adjunct to spatial analyses in interpreting the relation and significance of the distribution of cultural materials.

The 433 shovel test pits dug in 1980 were systematically placed. A trellis pattern of shovel tests at 1.2-m (4-ft) intervals was aligned so that each test was placed in the center of a 1.2- by 1.2-m (4- by 4-ft) excavation grid. The Mesa site was larger than expected, exceeding 0.25 ha; the full extent of the subsurface distribution of materials could not be determined in the time allotted for testing. Enough data have been obtained, however, for National Register and management purposes, so additional testing is not contemplated.

Cultural materials recovered from the Mesa site include unmodified and retouched flakes, large bifacial lance heads or knives, and knife-preform bifaces. Projectile point bases constitute the largest artifact class. The oblanceolate, round-, straight-, and concave-based thick projectile-point types are the most diagnostic artifact class recovered and show similarities to many other types occurring in different complexes reported from both flanks of the Brooks Range. One fragment is basally thinned and exhibits a long flake scar extending from the basal concavity that resembles a flute.

The combined test excavation and surface collections exhibit technological uniformity and indicate that the Mesa site is a special-use site, probably a prehistoric hunting stand where maintenance activities, involving blade (projectile point, lance, and knife) manufacture, refurbishing, and replacement, were carried out. The radiocarbon age of 5670 B.C., if corroborated, makes the Mesa occupation significant in our understanding of northern Alaska prehistory.

Lisburne Borrow No. 5 (KIR-100)

Site KIR-100 is located on a bluff on the east side of Iteriak Creek in the foothills province of the North Slope. The top of the bluff is 25 m above the creek bed and affords an excellent view of the west side of the Iteriak Valley from the southwest to the north. The bluff on which the site lies was designated in 1978 as possible borrow site No. 5 to provide material for construction of the airstrip, road, and drill pad for Lisburne No. 1 well.

The bluff rises abruptly from the creek and slopes gently to the east; its crest is 80+ percent vegetated. Cultural material was only rarely encountered on the surface in unvegetated areas, and the presence of the site was detected by test pits dug into the highest parts of the bluff. In places, soil depth reached 40 cm below the surface. Fifteen person-days were spent at the site to determine its size and complexity, to map the topography and test excavations, and to determine the magnitude of the mitigation effort should the site be required for construction material. More than 150 nonsystematic shovel test pits of 30-cm (12-in.) diameter and eight 1.2- by 1.2-m (4- by 4-ft) controlled grid squares were excavated and mapped to provide the necessary data without entering into full-scale excavation. The testing disclosed that cultural materials were distributed in a narrow band 4.5 m (15 ft) eastward of the bluff edge and occurred discontinuously for 120 m (400 ft) southeast from a small promontory at the northwest edge of the borrow area. More than 1,000 waste flakes, several crude biface fragments, and a single multiple-platform percussion blade core were recovered. Despite the availability in the adjacent creek bed of cobbles to ring hearths and weigh down tents, no evidence of structures was found. Any traces of a camp in the willows in the flood plain of Iteriak Creek, following a recent Inupiat pattern, would have been removed long ago by annual flooding during breakup.

KIR-100 was determined to be as large as the Lisburne site (discussed subquently). The wide distribution of cultural material along the bluff edge, despite the lack of diagnostic types recovered in the shovel tests, was suspected to be as significant and as complex as that revealed by the concurrently conducted test excavations at the nearby Lisburne site. Discourse with field engineers revealed that construction material available at borrow site No. 5 (KIR-100) was less desirable than material available at borrow site No. 2 (Lisburne site). As excavation at both borrow sites was impossible, archaeological work was concentrated at the Lisburne site and use of borrow siteNo. 5 was disallowed on archaeological grounds.

BAR-095

Site BAR-095 was a small, single-component, surface site located on the Chukchi seacoast about 1 km (0.5 mi) northeast of Walakpa Bay. The site was discovered in 1979 during a routine survey for cultural resource sites that might be adversely impacted by geophysical activities. Excavation was undertaken because culturally assignable artifacts were present on a rapidly eroding ground surface. Important cultural data might have been lost if winter geophysical activity in the area resulted in vehicular traffic over the site, if anyone happened across the site and noticed the obvious artifacts, or if erosion continued to a point where significant downslope migration of the cultural material occurred. BAR-095 was considered to be a test excavation (even though the site was removed in its entirety) because similar sites are known to exist along the coast between Barrow and the Utukok River.

Cultural material recovered from the 16 1-m squares excavated at BAR-095 included a total of 7 lithic tools, 6 retouched lithic flakes, 107 unworked lithic flakes, 75 pottery fragments, 15 seal-oil concentrations, and 3 fire-cracked rocks. The types of tools represented, the pattern of their distribution, the presence of seal oil, the location, and the obvious temporary nature of the occupation are all consonant with a site representing a temporary sealing camp used by Norton peoples in the centuries immediately preceding the birth of Christ. Analysis of additional similar sites will help archaeologists understand the nature of cultural adaptation in Norton times.

WAI-030

The Tunalik site, excavated by USGS and BLM archaeologists in 1977, was located on an old, elevated shoreline bluff that approximately follows the 30-m (100-ft) contour and trends northeastward from the Utukok River toward the modern village of Wainwright. Clearance work during 1978 and 1979 in the vicinity of the old beach remnant allowed a search for other similarly situated sites that might confirm the artifact associations and interpretations proposed for the Tunalik site. Five such sites were located during 1978 and 1979, and one of these was selected for testing in 1979.

WAI-030 was chosen for testing because of its small size, spatial discreteness, and apparent lack of complexity and because of the technological similarity of the artifacts visible on the surface to those recovered at Tunalik and identified at the other four shoreline bluff sites. WAI-030 appeared to be a surface site; microblades and core tablets were visible in the gravel of a deflated portion of the old beach remnant. Cultural materials appeared to be confined within an area 3 to 4 m in diameter; no other cultural materials were located in the extensive deflated area surrounding this single concentration.

The concentration of cultural materials at WAI-030 was not associated with any physiographic or other feature that might confine human activities through time to such a small area and was therefore interpreted as representing a single flaking event. The widths of the microblades visible on the surface seemed to replicate the wide range of variation found at the Tunalik site. Of especial interest in the materials lying on the surface were two wide oval-platform core tablets. One of these tablets had been reworked into a narrow microblade core by first delivering at least two burin blows to the back edge (opposite the faceted edge)—blows that removed burin spalls from one lateral edge of the tablet. The burin facets were then used as a platform from which at least two successful and one unsuccessful burin spalls were driven transverse to the longitudinal axis of the tablet. Apart from occurring on a core tablet rather than a thick flake, the technique was identical to that which produced two dihedral burins-microblade cores recovered from concentration H-3 at Tunalik. Like the Tunalik pieces, the WAI-030 specimen did not exhibit the wear patterns of a burin.

Gridded test excavation was carried out at the site, and it was recognized from the onset that testing would remove the site in its entirety. Fifteen contiguous 1-m squares were excavated, and all flakes, microblades, and artifacts were plotted. The excavation recovered 126 microblades, 6 possible burin spalls, and 222 waste flakes, including a few obsidian flakes. Cultural materials were distributed in a wide oval area approximately 3 by 2 m in which a "shadow," void of flakes or microblades, occurs. While this shadow area may indicate where a prehistoric flintknapper sat, the soils at the site raise suspicions that the distribution pattern is not cultural. Flakes and blades were encountered in vertical and horizontal orientation in the distinctively textured and mottled soil that occurred to depths of 60 cm below the surface. As at Tunalik, however, most of the cultural material occurred in the deflation lag gravels within 10 cm of the surface. Though nothing resembling tunnels appeared in either section or profile, the abruptness of the occurrence and discontinuation over very short horizontal distances of the distinctive soils containing cultural materials at depth supports the interpretation that an inconsiderate ground squirrel once constructed a burrow through the site. Abandoned and partially collapsed burrows occur nearby.

A complete narrow-platform microblade core made on a thick, steeply unifacially retouched flake was recovered from one of these presumed disturbed zones. The core is technologically identical to one recovered from concentration A at Tunalik. Preliminary analysis of WAI-030 substantiates some of the associations postulated for the Tunalik data. It underscores the essential contribution of small, briefly occupied archaeological sites to understanding other sites for which significance is usually based on size and productivity alone.

THE SHORELINE BLUFF

The excavation of WAI-030 and BAR-095 in 1979 indicated that certain small, single-component, essentially surface sites may have considerable potential for clarifying the cultural history of northern Alaska and for explaining behavioral correlations. However, identifying sites with similar potential on the basis of a few lithic flakes and occasional artifacts exposed on the surface was difficult because so little attention had been paid to this type of site in the past. Therefore, a testing program was formulated to ascertain the spatial parameters of such small sites, the relationship between surface manifestations and the quantity and distribution of buried materials, and the potential for explaining archeological data from such single behavioral and depositional sites.

An ancient shoreline bluff that is intermittently exposed between the village of Wainwright and the mouth of the Utukok River was chosen for the survey. The requisite type of site was known to occur along the bluff, because previous surveys had isolated five small, apparently single-component sites. These sites were identified by surface materials and were thought to contain additional flakes and artifacts (as did WAI-030) hidden immediately below the surface in unconsolidated sand and gravel.

Additionally, the sand and gravel of this shoreline bluff system represent the most accessible material for construction purposes in the immediate vicinity, and thus cultural resource sites along the bluff may be impacted if future construction associated with oil exploration programs takes place here. The program was designed to locate as many archaeological sites as possible along the bluff and to evaluate those that would not normally be thought eligible for nomination to the National Register, either because of their small size or because few culturally assignable artifacts were present.

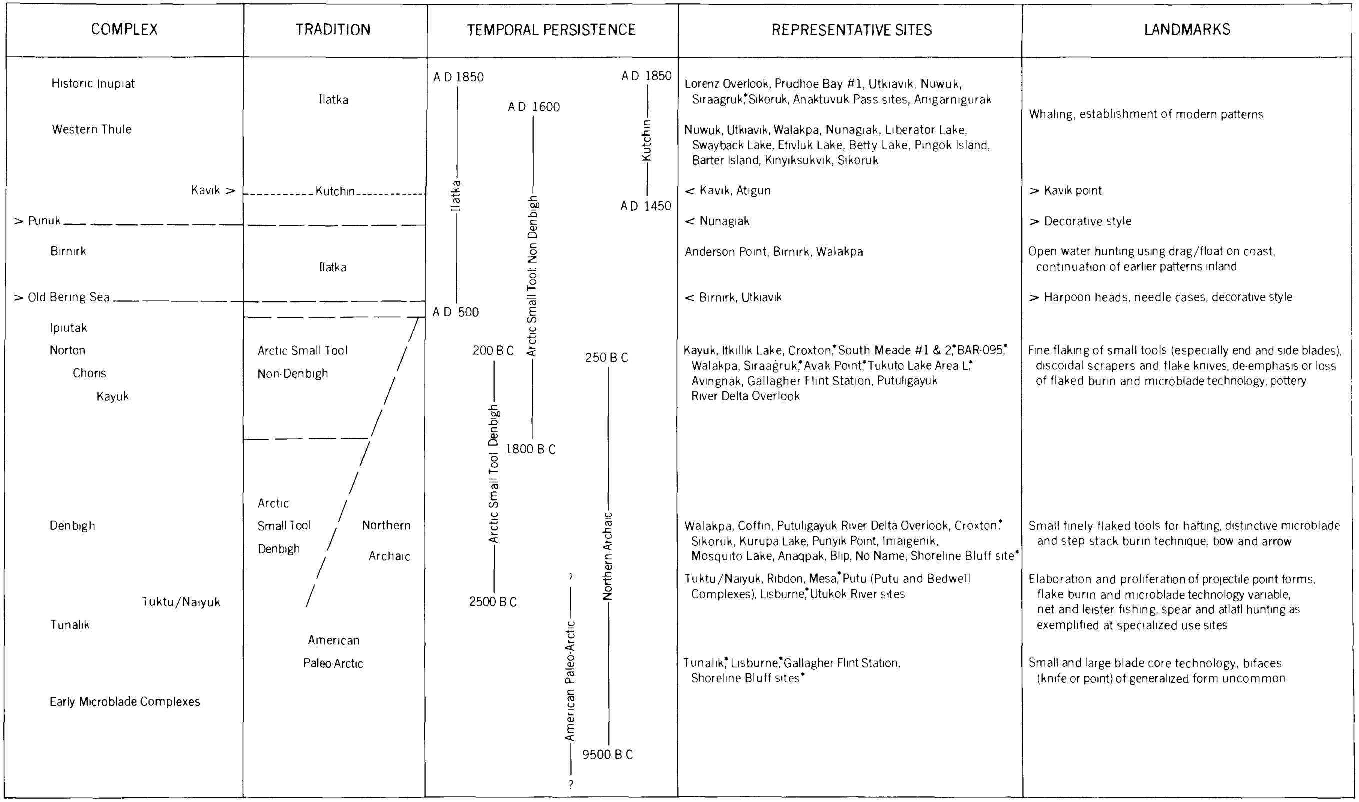
The shoreline bluff survey produced 2,149 lithic specimens recovered by systematic collection and test excavation at 17 sites, some of which had more than one productive locality. Recovered material included flakes representing various stages in the reduction process, microcores and blades, projectile points, bifaces, and burins. At least five of the sites are possibly assignable to the American Paleo-Arctic Tradition, and one to the Denbigh Flint Complex (fig. 37.2); the remainder did not produce artifacts of known cultural affiliation.

Analysis of the artifactual material and other data from the shoreline bluff sites will provide a better understanding of the nature and extent of single short-term behavioral episodes; the manner in which lithic tools were manufactured, used, and curated; the seemingly idiosyncratic behavior expressed at some of the bluff sites; and finally the manner in which archaeological sites are created, inhabited, and subsequently modified. Furthermore, data are now available to evaluate similar sites discovered in the NPRA in the future, in terms of their scientific potential.

SIRAAGRUK

Siraagruk is a historical coastal Inupiat village located approximately 4 km northeast of Point Belcher. The primary purpose of the test excavation at Siraagruk was to gain a better perspective on the nature and content of sites dating from the early-middle historical period. Given the considerable number of archaeological sites in the NPRA known from the late 19th and early 20th centuries, future oil exploration activities will have to accommodate protection of such sites. Thus, a knowledge of the probable physical extent of specific types of historical sites, their possible importance, and the resources and time necessary for testing or excavation is vital for future cultural resource management decisions. Another consideration dictating test excavation at Siraagruk was the lack of archaeological evidence available for understanding the background period and the resultant changes leading to the current sociopolitical situation in northern Alaska.

Test excavations at Siraagruk commenced in 1979 under the direction of Dale C. Slaughter of the University of Wisconsin and continued in the 1980 field season. The site consists of 17 dwellings, 9 semisubterranean and the rest surface, constructed along 260 m of a narrow dune field that fronts the



COMPLEX	TRADITION	TEMPORAL PERSISTENCE	REPRESENTATIVE SITES	LANDMARKS
Historic Inupiat	Ilatka	A D 1850 —Ilatka— A D 500 A D 1600 —Arctic Small Tool: Non Denbigh— 1800 B C A D 1850 —Kutchin— A D 1450	Lorenz Overlook, Prudhoe Bay #1, Utkiavik, Nuwuk, Siraagruk,* Sikoruk, Anaktuvuk Pass sites, Anigarnigurak	Whaling, establishment of modern patterns
Western Thule			Nuwuk, Utkiavik, Walakpa, Nunagiak, Liberator Lake, Swayback Lake, Etivluk Lake, Betty Lake, Pingok Island, Barter Island, Kinyiksukvik, Sikoruk	
Kavik >	Kutchin		< Kavik, Atigun	> Kavik point
> Punuk			< Nunagiak	> Decorative style
Birnirk	Ilatka		Anderson Point, Birnirk, Walakpa	Open water hunting using drag/float on coast, continuation of earlier patterns inland
> Old Bering Sea			< Birnirk, Utkiavik	> Harpoon heads, needle cases, decorative style
Ipiutak Norton Choris Kayuk	Arctic Small Tool Non-Denbigh	200 B C —Arctic Small Tool Denbigh— 2500 B C 250 B C —Northern Archaic— 9500 B C ? —American Paleo-Arctic— ?	Kayuk, Itkillik Lake, Croxton,* South Meade #1 & 2,* BAR-095,* Walakpa, Siraağruk,* Avak Point,* Tukuto Lake Area L,* Avingnak, Gallagher Flint Station, Putuligayuk River Delta Overlook	Fine flaking of small tools (especially end and side blades), discoidal scrapers and flake knives, de-emphasis or loss of flaked burin and microblade technology, pottery
Denbigh	Arctic Small Tool Denbigh Northern Archaic		Walakpa, Coffin, Putuligayuk River Delta Overlook, Croxton,* Sikoruk, Kurupa Lake, Punyik Point, Imaigenik, Mosquito Lake, Anaqpak, Blip, No Name, Shoreline Bluff site*	Small finely flaked tools for hafting, distinctive microblade and step stack burin technique, bow and arrow
Tuktu/Naiyuk			Tuktu/Naiyuk, Ribdon, Mesa,* Putu (Putu and Bedwell Complexes), Lisburne,* Utukok River sites	Elaboration and proliferation of projectile point forms, flake burin and microblade technology variable, net and leister fishing, spear and atlatl hunting as exemplified at specialized use sites
Tunalik	American Paleo-Arctic		Tunalik,* Lisburne,* Gallagher Flint Station, Shoreline Bluff sites*	Small and large blade core technology, bifaces (knife or point) of generalized form uncommon
Early Microblade Complexes				

FIGURE 37.2.—A provisional view of north Alaskan cultural history. Temporal-persistence data used all radiocarbon ages attributable to specific cultural complexes and traditions. Sites marked by asterisks were evaluated by USGS-BLM-NPRA personnel.

Chukchi Sea. Ethnographic evidence and the presence of Euro-American goods on the surface indicated that Siraagruk was occupied during the historical period. Of particular interest were large hewn timbers, salvaged from wrecked whaling ships, that were subsequently used as house structural members and now protrude from the collapsed house mounds.

Two semisubterranean houses were completely excavated, and one surface structure was tested. The semisubterranean houses were built to a plan that conforms roughly to that reported for the area in historical sources (Slaughter, 1980, p. 9-12):

> The major features of the house were the main room, kitchen storage area, and a long entrance tunnel. The tunnel ends under the floor of the main room so that entrance to that room is gained from below, i.e. the tunnel forms a cold trap. The kitchen and storage room are appended to the tunnel on the right and left sides respectively as one faces the main room. The floor of the main room is some 40 cm below the surrounding surface, although the floors of the kitchen and storage room are considerably nearer the surface. . . The extent to which wood salvaged from ships was used at Siraagruk is indicated by the fact that over 70% of the wood encountered in (one) house was commercially prepared lumber.

More than 900 kg (2,000 lbs) of cultural material was recovered from the excavation at Siraagruk. Organic preservation was excellent because of the relatively recent occupation and the presence of permafrost. Organic materials include hide, feathers, fur, cloth, and paper; in the last category was a scrap of newsprint with the date of 1891. Euro-American goods were common, ranging from playing cards to rifle parts to commercially manufactured whaling equipment. Traditional Inupiat manufactures also were present in the form of stone seal-oil lamps, lithic scrapers, and other items.

Supplemental data were secured during the two field seasons to complement the archaeological analysis of the Siraagruk material. Several nearby sites, of similar or slightly later age, with standing dwellings were studied to gain an understanding of house-construction techniques. Ethnographic data were collected through interviews with residents of Wainwright and by employing an Inupiat, acknowledged as a local cultural resource expert, on the site during the 1979 season.

Analysis of the Siraagruk data will provide a detailed glimpse of an important period in north Alaska history that presently is unknown archaeologically and poorly known ethnohistorically. Equally important, the test excavations of Siraagruk provide a model for managers faced with similar complicated, well-preserved sites threatened by construction or other surface alterations. The time, effort, and expense of mitigation by excavation of such sites can be measured to determine the most appropriate course of action.

THE CROXTON SITE

In 1980, BLM archaeologists involved in a project to determine the existence and scale of late prehistoric sites in the Brooks Range foothills with the use of aerial photography (see below) discovered a new site on the southern shore of Tukuto Lake. Limited test excavations disclosed abundant cultural material, including well-preserved bone and antler, and organic samples suitable for radiocarbon dating. Five ^{14}C determinations yielded ages averaging around 1,100 yr B.P.

A USGS party of archaeologists, under the direction of S. Craig Gerlach, returned to the area in 1981 for further tests. The site was subsequently named the Croxton site in honor of the late Ruth Croxton. The test excavations had three functions: (1) to study further a cultural phase previously unknown in the interior and especially important because it appears to immediately underlie the late prehistoric Inupiat continuum; (2) to obtain subsurface cultural distributional data to verify the correlation of an infrared signature with a cultural midden; and (3) to provide some estimate of the time and labor required to excavate a site of this nature.

The crew of eight excavated approximately one hundred 1.2- by 1.2-m (4- by 4-ft) squares and recovered several thousand lithic artifacts, numerous bone and antler artifacts, and large quantities of lithic debitage and faunal remains. Several methods and techniques that had not been used in northern Alaska previously were integrated into the testing program, including a magnetometer survey of the site and collection of samples for soil, pollen, and flotation analyses.

Analysis of the data recovered from the Croxton site is not yet completed. Additional radiocarbon samples have confirmed the dating (between A.D. 700 and 1100) of the main deposit at the site, and the artifact types are reminiscent of, but not identical to, those of the Ipiutak phase—as might be expected given the dating (fig. 37.2). One radiocarbon age, on material associated with artifacts referrable to the Denbigh Flint Complex, was much earlier (2470±410/430 B.C.; laboratory sample number DIC-2204). Confirmatory radiocarbon dates on material representing both time periods are forthcoming, as are dates on a supposed Norton site discovered near the outlet of Tukuto Lake during the summer of 1981.

Much of the artifactual material was associated with distinct living floors, and evidence of a possible structure was found. When analyses of the soil, pollen, and flotation samples are completed, along with analyses of the artifacts, faunal remains, and lithic debris, it will be possible to characterize the specific environmental and temporal adaptations represented at the Croxton site.

EXCAVATION FOR MITIGATION

As already discussed, excavation as a mitigation technique was not contemplated when joint USGS-BLM field assessments were initiated in 1977. The reasons for embarking upon this tactic differed in each case and each year, and they can only be understood in terms of the development of the program as a whole.

Excavation to mitigate program impacts was only undertaken during the 1977 and 1978 field seasons and only in four cases. Although technically the 1978 surface collection at the Mesa site was also a mitigation action, the procedure used was actually a testing strategy and consumption of the resource was limited and commensurate with the anticipated impact. Therefore, the discussion of the work conducted at the Mesa site is included in the previous section on site testing.

Between the 1978 and 1979 field seasons, a shift in petroleum exploration concepts occurred that greatly reduced the probability of impacts to cultural sites. Operations proposed in 1977 and 1978 called for the construction of gravel well pads 1.5 m (5 ft) thick for winter drilling operations, and the year-round drilling of three deep wells required the additional construction of gravel roads and mile-long airstrips also 1.5 m (5 ft) thick. Thus, many borrow sites to provide sand and gravel for construction were investigated by engineers and then by archaeologists. Cultural resource sites seemed to correlate uncannily well with upland borrow areas. The assessment of both suitability of construction material and archaeological value had to be completed within a single summer season. Geophysical data obtained the preceding winter were not available until May or June, and only then could well-site locations be chosen and field engineering begin. In many cases, field engineering was completed for more wells than were to be drilled in the following season to allow the geophysicists flexibility of choice as data were processed over the summer months. Thus, in some cases, impacts to cultural resources had to be mitigated before the end of the field season in late August and before the final selection of well sites was made.

In 1979, however, the civil construction requirements for exploratory wells were reconsidered and revised. Work pads for wells to be drilled in a single winter season were reduced in thickness, and poorer material for construction of these pads was accepted. Material removed during excavation of the reserve pit at the well site was determined sufficient to provide a durable winter work pad adjacent to the derrick. For single-winter-season drilling, potential impacts to cultural sites were greatly reduced by the elimination of borrow areas and were confined to the 14-ha (35-acre) well site itself and its winter trails and ice roads. Potential impacts to cultural resource sites were also reduced at wells that required more than a single winter season to drill. Suspension of drilling during the summer months and resumption the following winter eliminated the need for thick, summer-stable work pads, roads, and airstrips. Potential impacts to cultural sites thus also could be limited to the well pad and reserve pit, ice roads, and winter trails. Therefore, no excavation for mitigation of impacts to cultural resource sites was undertaken during the 1979 and 1980 field seasons.

In all cases where excavation was undertaken to mitigate impacts, the excavation strategy was predicated upon a 100-percent recovery of data. The paucity of excavated sites for assessing the potential significance of the data, coupled with an apparent scarcity of settlements for most time periods, made less than 100-percent sampling unacceptable. Furthermore, defining site limits to accomplish 100-percent recovery proved difficult enough within the time frame (Gal, 1979).

The excavation alternative was limited to archaeological sites whose significance derived from their potential to yield data important to prehistory or history. Site sampling was considered inappropriate because of the lack of previous work to develop sampling designs and the inability to schedule, staff, and conduct large-scale field investigations on short notice.

Because of the lack of means for formulating strongly data-based sampling designs and the necessity to operate within the constraints of a single short Arctic field season, adequate mitigation of impacts to the following types of sites was absolutely precluded: frozen deep midden sites, sites with complex archaeological details, and stratified deposits.

Excavation for mitigation was impractical except in specific instances, mostly because of tight project scheduling. Where and how far archaeologists looked beyond the immediate well-site area depended upon specific engineering proposals that often were developed only the day before, and sometimes only hours before, an archaeological assessment was requested. Such a procedure was advantageous in that conflicts could be identified and averted at the engineering conceptual stage, before large amounts of project funds and personnel time were committed. However, disadvantages resulted from attempts to assess in the same season. More areas of operation were identified than would actually be used. Thus, mitigation efforts had to be deferred; otherwise, efforts would be spent and resources consumed in areas that ultimately might not be impacted. This dilemma was especially troublesome when alternate areas of operation were proposed in regions where every alternative had adverse impacts (for example, the Lisburne well site).

The magnitude of the assessment and mitigation effort required in any one season could never be estimated. Every day's delay in finalizing the engineering reduced the time the archaeologists could employ to excavate and (or) to complete any consultation. Thus, the process of doing engineering planning and archaeological assessment as well as mitigation in the same short summer season limited excavation more effectively than any other factor.

TUNALIK (WAI-091)

During the summer of 1977, the first year of the USGS-BLM cultural resource program, an extensive archaeological site was located on the principal source of material for the construction of the pad and all-season airstrip for the Tunalik No. 1 well. The Tunalik site, WAI-091, was located by examination of the unvegetated surface. The survey disclosed concentrations of lithic (primarily chert) debitage. A wedge-shaped microblade core and a possible flake-burin were collected from one of the concentrations. Small wedge-shaped cores had not previously been reported from the Arctic coast, and their occurrence in one of the concentrations at Tunalik with a flake burin suggested affiliation with the American Paleo-Arctic tradition as defined at Onion Portage (Anderson, 1970) and with a possible Paleo-Arctic assemblage (lacking wedge-shaped cores) reported by Stanford (1971) at the Kahroak site near Barrow (fig. 37.2). An American Paleo-Arctic tradition site on the Arctic coast, possibly dating from between 6,000 and 8,000 years ago, was considered a significant new find; to comply with the FEIS for the exploration program, the USGS-BLM archaeologists advised that use of material from this proposed source be precluded.

However, the only other suitable source of civil construction material for the Tunalik well-site facilities was the barrier island system bounding Kasegaluk Lagoon, 15 km (10 mi) farther to the north. Use of these islands for construction materials was not feasible for a number of reasons. The barrier islands were considered ecologically sensitive because of the nesting habitat they provide for shorebirds. The greater haul distance would necessitate longer ice roads and increase the disturbance resulting from water withdrawal (to build ice roads), compaction, and possible retardation of tundra growth. Both cost and scheduling made use of the barrier islands imprudent. To maintain beach integrity and avoid starting coastal erosion, the islands needed to be "scalped" by removing the top 15-25 cm (6-10 in) of material over an extensive area. Material costs would rise because of the inefficiency of the scalping process, the lengthened haul distance, and the cost and time of building additional ice roads. Furthermore, winter construction could not begin until the lagoon ice between the islands and the mainland was thick enough (not always guaranteed) to support heavy truck traffic. In late July 1977, therefore, the USGS and BLM managers requested that archaeological excavations begin in order to mitigate the adverse impacts of use of material from the originally proposed source.

On short notice, a proposal was submitted to the Alaska State Historic Preservation Office requesting a finding of no adverse effect for the evaluation of the Tunalik site and of two small sites located on material sites for the South Meade well site. The State Historic Preservation Officer's concurrence was received before starting excavation, but the comments of the Advisory Council on Historic Preservation were not obtained until later that fall because of a procedural misunderstanding.

The Tunalik site was located on an old shoreline bluff deposit of sand and gravel that was elevated 9 to 15 m (30-50 ft) above the coastal plain and afforded an unimpeded view to the north. The area was essentially unvegetated, and all cultural material was recovered from the surface or from within the 5-cm-thick pavement of deflation lag gravel.

Considerable excavation time was saved by tying an excavation grid of 1.2- by 1.2-m (4- by 4-ft) squares into the 30-m (100-ft) grid established by the engineering surveyors to provide cross sections for material yield calculations. Artifact recovery was accomplished in four steps. First, each 30-m (100-ft) grid square was systematically inspected, and all flakes on the surface were marked with pin flags. Next, a string-grid of 1.2- by 1.2-m (4- by 4-ft) excavation squares was superimposed over all concentrations marked by the pin flags. All squares with cultural material on the surface were excavated, as were adjacent squares when material appeared to trend in their direction. Point provenience was recorded for all artifacts; excavation square provenience alone was recorded for debitage, although flake locations within an excavation square were recorded in the excavator's field notes to record distribution trends within a square. Depth provenience was recorded initially but was deleted from the notes when the stratigraphy was not ascertained.

After excavations within a 30-m (100-ft) grid were completed, the area was systematically examined a second time for any flakes on the surface that might have been missed initially or churned up by the excavator's traffic. A 1.2-m (4-ft) square was excavated when flakes were identified in this fashion (none of these squares produced more than a single flake). Lastly, a simple 2-percent random sample of grid squares was excavated for each 30-m (100-ft) grid within which concentrations were identified by surface signs. The random samples were taken to verify that surface indications reliably indicated the extent and density of subsurface materials. No new concentrations of lithic debris were located by the random sampling procedure.

Eleven lithic concentrations were identified and excavated within the designated material site. Nine of the concentrations were located in a 60- by 90-m (200- by 300-ft) area at the seaward edge of the bluff; two concentrations were 90 and 180 m (300 and 600 ft) inland from the nearest concentration in the seaward cluster. No hearths or structural remains were encountered, and no organic materials were associated with any of the lithic remains. Thus, no radiocarbon ages are available, and the analysis of the collection is limited to technological, typological, and functional comparisons of the spatially discrete concentrations.

Four concentrations lack any diagnostic formal types and are not very useful for comparative purposes. Each of the other concentrations at the site shows varying degrees of relatedness to one or more of the cultural traditions proposed for northern Alaska. Microblades or large bladelike flakes were recovered from all concentrations except one and suggest relationships with American Paleo-Arctic and later peoples who utilized core-and-blade technology between 8000 and 1000 B.C. Some of the blade-core forms and especially the bifaces are similar to those recovered from sites dated later in time and considered not to belong to the American Paleo-Arctic tradition. Anderson (1970) has postulated a "post-American Paleo-Arctic tradition" that links the American Paleo-Arctic tradition with the Arctic Small Tool tradition on the basis of some of his Noatak River sites (fig. 37.2). Because he found what he considered a distinctive technological tradition in the layers between American Paleo-Arctic and Arctic Small Tool levels at the Onion Portage site, Anderson (1970) has hinted at a population displacement in the Kobuk-Noatak Valleys and suggested that stronger evidence might be found that descendants of American Paleo-Arctic peoples had lived on the tundra north of the Brooks Range.

The spatially discrete concentrations of material at Tunalik, and the attention paid to intrasite distributions during excavation and analysis, allow interpretation of the separate concentrations as possible behaviorally based inventories, similar to grave furniture, in that the artifacts and debitage derived from each concentration were deposited by a single, short-lived human event. Although the contemporaneity of the Tunalik concentrations cannot be demonstrated, the individual concentration inventories are each interpreted as transitional between American Paleo-Arctic and later core-and-blade users. However, formal description of these transitional inventories in terms of new archaeological "complexes" or "traditions" was considered premature. Hence, one reason for initiating testing at WAI-030 and other shoreline bluff sites (discussed earlier) was to supplement the evidence from Tunalik in order to define the range of variation of suspected "post-American Paleo-Arctic" assemblages.

SOUTH MEADE SITES (XMR-091, 092)

Also during the summer of 1977, archaeological sites were found on two material sites proposed for the construction of South Meade No. 1 well. As at Tunalik, the USGS-BLM archaeologists alerted the engineers and exploration program managers that the two South Meade sites could not be used unless archaeological excavation was carried out.

The two South Meade sites illustrate a problem that continually confronts and confounds archaeologists working in Alaska. On the basis of the original survey, both sites were considered to be small and probably not very productive of cultural materials. However, the only previous archaeological work in the entire South Meade region was a minor excavation of two late-prehistoric housepits (Hamilton, 1962). Although the potential data yield from the newly discovered sites was considered very low, any data would increase the understanding of the region, hence qualifying both sites for the National Register of Historic Places (NRHP) under the criterion that they "may be likely to yield information important in prehistory or history" (36CFR60.4(d)). The actual eligibility of these sites could not be determined until either detailed testing or wholesale excavation was carried out. As part of the consultation with the Alaska State Historic Preservation Officer, the South Meade sites were considered not NRHP-eligible on the basis of available information, but excavations were proposed for both sites before construction to verify the original assessment. A second consultation was made before the second season at XMR-091.

South Meade No. 1 (XMR-091) was identified by chert flakes on the surface. A detailed surface survey before excavation disclosed three separate localities, which were gridded off and excavated. South Meade No. 1 was located on stabilized riverbank dune deposits elevated 3 m (10 ft) above an abandoned channel of the Meade River (the channel today lies 8 km or 5 mi to the north). Cultural materials generally were only shallowly buried in all three localities; however, cultural materials were recovered at depth at the southern edge of one locality that had been disturbed by soil creep, block slumpage, and solifluction. The day before the helicopter arrived to transport the crew from the field in 1977, datable organic materials together with lithic detritus and artifacts were discovered in the deeply buried soils. Consequently, the portion of the material source containing the archaeological localities was marked off by "Do Not Disturb" signs, and use of the site was denied.

It was not until the 1979 field season that a small crew could return to the site to confirm that the deeply buried zone was limited in extent. Completion of the South Meade No. 1 excavation in 1979 was undertaken to obtain additional specimens for radiocarbon dating and to complete the excavations at minimal cost while the logistic support of the USGS-BLM cultural resource program was still available. Seven radiocarbon ages ranging from modern to 1,400 yr B.P. were obtained at Locality 1 of South Meade No. 1 site. Artifacts associated with these ages included weapon sideblade insets of triangular and rounded outline, as well as flakeknives and larger knife-sideblades comparable to Norton, Near-Ipiutak, and Ipiutak forms. A date of A.D. 500-700 is accepted for the site by confirming two of the charcoal ages with the single age run on a caribou antler. Coastal assemblages of this time period (early Birnirk) lack the weapon sideblade insets of triangular form (small sideblade insets were only used on early Birnirk toggling harpoon heads). This difference suggests that between A.D. 500 and 700, or perhaps even later (early Birnirk is not well dated, and a later interpretation of the South Meade dates is possible), stylistic differences in flaked stone sideblades may indicate distinctive social groupings—one coastal and one interior—the interior group clinging to forms that were more common at an earlier time.

South Meade No. 2 (XMR-092) was identified by chert flakes found on the surface in a blowout and by worked wood fragments scattered over a partially stabilized dunefield on the inside of an oxbow lake. At first the materials were considered contemporaneous, possibly late prehistoric. However, gridded excavations in the vicinity of the chert flakes disclosed that the blowout had intersected two paleosols. At one time the upper paleosol was a vegetated surface upon which a flint knapper had worked, leaving behind nine waste flakes and two side- or end-blade fragments that fit together. The lithic materials from South Meade No. 2 could be assigned a date of A.D. 0-1000; not enough lithic material was recovered for detailed typological comparison.

Before collection, the worked wood fragments were mapped; their distribution focused upon the highest point of the dunefield. Many of the wood fragments were drilled; a few of the drilled holes still seated a wooden peg. Within the densest concentration of wood fragments, a human mandible was recovered. The mandible was examined by G. Richard Scott, of the University of Alaska, Fairbanks, and identified as belonging to an adult 30-35 years old, probably male. No other recognizable human bones were recovered. It is likely the mandible and wood fragments are all that remain of a 19th century sled burial (Brower, 1942, p. 58; Gubser, 1965, p. 217).

Although our limited testing suggested that the culture-bearing paleosol did not extend much beyond the excavated area, the possibility exists that other intact remnants of the paleosol, perhaps containing additional cultural remains, were deeply buried. The fact that the blowout exposed 2 of the 11 lithic fragments underscores the need for deep testing procedures even on the North Slope, where soil formation is slow and most archaeological sites are buried no deeper than 20 cm.

LISBURNE (KIR-096)

The Lisburne site was located on the prime source of material for the Lisburne test-well pad, its road, and all-season airstrip. The site was on a prominent bluff on the east bank of Iteriak Creek, a tributary to the East Fork of the Etivluk River in the foothills of the Brooks Range. The site commands an excellent view of most of the Iteriak Valley and was probably used as a game lookout, campsite, chipping station, and quarry source. The soils on the bluff are poorly to moderately developed, well-drained, shallow-phase Arctic Brown, and rarely more than 30 cm (12 in) thick. Organic remains were consequently not preserved, and no material for radiocarbon dating was obtained.

Cultural materials at the site were scattered on the surface and below the sod over an area of 7,592 m^2 (81,720 ft^2). Five sites were originally proposed for the Lisburne well, three of which included archaeological sites. Until the engineers finally determined that the bluff provided the only suitable construction material, the BLM field crew divided its time between testing, estimating the extent of the three sites, and evaluating other proposed construction areas.

Three testing strategies were employed. Initially, test excavations were conducted concurrently with two different subsurface sampling schemes (nonsystematic testing and systematic radial testing). However, results indicated that neither subsurface testing scheme reliably indicated the discontinuous distributions of the lithic materials. Therefore, as soon as the bluff was confirmed as the only suitable material source, intensive systematic shovel testing was started and additional crew members were hired. Shovel tests were dug in the center of 1.2- by 1.2-m (4- by 4-ft) grid units laid out over the most promising portions of the bluff, and all squares that yielded cultural material were excavated. Grid units with negative test results were excavated only when distributions in adjacent excavated squares suggested a continuation of cultural materials. However, some of these negative squares were excavated to determine the method's sensitivity to low-density distributions. The method was successful in detecting even minor flaking events that manifested no surface indications. Backdirt from shovel tests was run through a 0.6-cm (0.25-in.) screen and provided an approximate 5-percent sample of each grid unit. This intensive systematic shovel testing allowed effectively 100-percent recovery of all buried materials.

Two procedural problems arose in conjunction with the excavations of the Lisburne site. First, a Memorandum of Agreement with the Advisory Council on Historic Preservation (ACHP) was being circulated for final signatures when the USGS-BLM archaeologists departed for the field in 1978. When test excavations indicated that the site was eligible for inclusion in the National Register of Historic Places and use of the material site was determined essential, inquiries to the State Historic Preservation Office (SHPO) and the ACHP disclosed that the agreement had not been signed. However, the ACHP permitted excavation to proceed, and consultation with the Alaska SHPO alone was required. The SHPO's concurrence was obtained after a telephone discussion. Later in the summer James Hester, representing the ACHP, visited the NPRA to obtain some understanding of the difficulties of strict compliance with the Advisory Council procedures in the NPRA exploration program.

A more serious problem resulted from the lateness of the decision that this material source was indispensible to construction. The MOA called for 100-percent recovery of material from sites whose eligibility stemmed from their likelihood of yielding information important in prehistory or history. Because of snow and frozen ground in late August, the necessary program of systematic shovel testing could only cover those portions of the material source most likely to be productive of cultural materials. Other possible areas of past human occupation on the bluff would not be tested, much less excavated. The recovery of a fluted projectile point indicated that some of these untested areas could be very significant. Fortunately, neither the archaeological program nor the construction activity was compromised, because the test-well site and airstrip were relocated and an archaeologically sterile material source was found near the new locations. A BLM field crew returned to the Lisburne site in 1979 and completed the shovel testing and excavation. The 1979 testing and excavations revealed that all of the significant loci of prehistoric activity had been located and excavated the previous season.

Preliminary lithic analysis of the Lisburne site assemblage indicates that more than 97 percent of the more than 30,000 specimens recovered are unmodified debitage. Most of the tools recovered indicate the initial stages of lithic reduction activities (both in biface and core reduction). The presence of both tabular and cobble cortex specimens suggests both on-site quarrying and utilization of chert cobbles, probably from Iteriak Creek. The only exotic lithics recovered from the site are less than a dozen obsidian microblades and flakes. Obsidian hydration dates of these specimens range from A.D. 487 to 940 and average A.D. 690±250. Unfortunately, the obsidian was recovered from the highest portion of the bluff, where a number of possibly temporally different concentrations occur.

Artifacts recovered from the Lisburne site typologically represent nearly the entire cultural-historical sequence for northern and northwestern Alaska and include the American Paleo-Arctic tradition, the Northern Archaic tradition, the Arctic Small Tool tradition, and the late prehistoric Eskimo (fig. 37.2). The discontinuous concentrations of lithic detritus are interpreted as independent workshop-activity areas, and hence analysis of the site is proceeding with a spatial-distributional emphasis. Finished tools do occur, and preliminary indications are that reduction sequences for various tool types can be isolated within the spatially defined activity areas. Such reduction-sequence analyses within the clear spatial contexts at the Lisburne site will significantly increase our understanding of the variability and distinctiveness of other North Slope assemblages.

NONDESTRUCTIVE ARCHAEOLOGY

The testing and excavating just described were unsatisfying to a certain extent, principally because they destroyed resources under the guise of protecting them. Traditional archaeological testing or excavating consumes part or all of a nonrenewable resource. However, so little archaeological excavation had taken place within the NPRA that the scientific destruction of portions of the resources was justified both for short-term assessment and for identifying long-term priorities for conservation.

The testing program followed by USGS and BLM archaeologists in the NPRA between 1977 and 1981 was designed to provide data on the range of cultural resources likely to be impacted by petroleum exploration without exhausting those resources in the process. The approach was consistent with a burgeoning conservation ethic in American archaeology that explicitly recognizes the nonrenewable nature of cultural resources and that emphasizes research design and sampling techniques which maximize data recovery while limiting consumption. One outcome of such an ethic is that in the long term some portion of the nonrenewable data base will remain available for refutation or confirmation of new ideas as these arise. The USGS-BLM testing program sought to minimize impacts while obtaining necessary new data, and it also had the goal of further reducing or eliminating the adverse effects of certain kinds of archaeological investigations.

Additionally, it was felt that the joint program should include some other elements. The mitigation and testing programs arose from cultural resource issues, but their implementation derived from petroleum exploration. In order to manage the cultural resources, it was felt that some aspect of the joint USGS-BLM program should be motivated solely by the values of cultural resources themselves and not by the need for reconciliation with other values. Nondestructive techniques and a management program both have begun to be used in an investigation of late prehistoric village sites in the foothills of the NPRA.

In early surveys and excavations, Irving (1962, 1964) and Hall (1975, 1976a) had identified a number of late prehistoric villages with house and cache pit remains at Etivluk, Kinyiksukvik, Betty, Tukuto, Swayback, and Liberator Lakes. After visiting these villages in the summers of 1977 and 1978, the USGS and BLM archaeologists determined that they should be included in the National Register of Historic Places, perhaps as archaeological districts. Sufficient data were available to map, classify, and interpret the archaeological features visible on the surface without employing any destructive techniques. The extent and number of features visible at each of the sites, however, would have required a major field study at each lake over a number of seasons just to complete the mapping and recording of site condition for the National Register. Once completed, the inventory could be used to evaluate potential impacts on the resources and the validity of proposals by industry and academia to consume these cultural resources.

These same six lakes offer the recreationist, hunter, or geologist an easy point of entry to the surrounding country by amphibious aircraft in summer and by ski-equipped aircraft in winter. As the exploration for hydrocarbons intensifies in the foothills, the largest of these lakes will be used for ice landing strips for heavy aircraft supporting seismic, construction, and drilling activities (Betty Lake and Liberator Lake were used in the NPRA Federal exploration program).

Although the use of these lakes in the past has been short term or casual, lasting no more than a single season, an increase of impacts can be predicted. Early geological parties partially destroyed features at the south end of Tukuto Lake (Solecki and others, 1973) and at Liberator Lake (Hall, 1975). The cumulative impact of such seasonal use of these archaeological village sites can be devastating in the long term.

As the BLM had a camera-equipped airplane at its disposal through its Division of Photogrammetry in Anchorage, it was decided to map the archaeological features at the lakeside sites photogrammetrically rather than by traditional land survey. A number of advantages would accrue: Photogrammetric mapping can accomplish in a single season what would take many seasons by surface survey. Because of the high logistics costs associated with transporting and supplying a field party on the North Slope, photogrammetry is more cost effective. Aerial photography provides a comprehensive documentary record with which to monitor specific and general changes in site condition (natural or manmade), so that the manager may respond appropriately. Aerial photographs provide overviews from which minutiae can be derived, whereas standard survey procedures begin with details and assemble wholes. This difference of approach makes aerial photographs more versatile and subject to reinterpretation. Aerial photographs are also acceptable evidence in a court of law, should a suit for damages arise.

Low-level aerial data had never been systematically used as a research tool by Alaskan archaeologists, and its value was not known. Plans were made during the winter of 1978-79 to put out aerial ground-control panels the following summer. Color infrared NASA aerial photographs at scales of 1:60,000 and 1:120,000 were examined to plan the optimum alignment of flight centerlines. During the examination of these photographs, it became apparent that known site areas were marked by a strong white reflectance. Suspecting that this reflectance might correlate with the soil condition and vegetation over archaeological midden deposits, we decided that the ground survey should be expanded to establish the degree of accuracy of the photogrammetric mapping. Soil and vegetation transects across the areas of distinctive reflectance were needed in order to determine whether a ''signature'' for archaeological deposits could be identified. Small-scale infrared photographs might eventually prove useful in identifying midden deposits in other areas of the North Slope.

No low-level infrared photographs of the lakeside villages were obtained in 1979. However, during the summer of 1980, a BLM crew of three completed the placement of aerial panels at each of the lakes. Cross-shaped centerline panels for vertical and horizontal ground control and L-shaped wing panels for vertical control (to correct for parallax) were laid out and surveyed through each village area. Centerline panel points were permanently marked with a 60-cm (2-ft) piece of steel reinforcing rod and identified with a stamp-impressed aluminum cap. Permanent panel points were desired so that soil and vegetation transects and suspected archaeological features could be accurately located in subsequent field seasons by scaling distance and direction directly from the panel points visible on the photographs.

Very little ground checking was possible when the panel points were surveyed because only three work days were spent at each lake. Three separate flight lines were set out at Tukuto Lake over six working days, however, and some encouraging preliminary observations resulted. No support for the midden-reflectance hypothesis was obtained from Tukuto locality G, which, unlike the other seven localities reported by Hall (1976a), did not exhibit a distinctive reflectance on the small-scale photographs. This locality consists of a series of cache pits; no house features or extrahouse middens were present. The other Tukuto localities each contained the remains of late prehistoric semisubterranean structures and extradomicile refuse and supported the midden-reflectance correlation. A more exciting discovery, supporting the midden-reflectance correlation, was made at the southeast end of Tukuto Lake. There, two areas adjacent to the shore showed a reflectance similar to the late prehistoric middens, but this signature was darker. These midden deposits (originally designated localities J and K and now called the Croxton site) are believed to be several hundred years older than the late prehistoric localities at the lake. The darker signature may be significant. The signature may not only have greater temporal persistence than was first suspected, but may eventually be useful in indicating the relative ages of unexcavated archaeological deposits. No house pits were visible on the surface in these areas, but the inspection of areas disturbed by ground squirrels and grizzlies and the excavation of three test pits disclosed a rich archaeological midden and well-preserved bones.

Cultural materials recovered from the test pits and a series of radiocarbon ages suggest both an early Denbigh occupation and one perhaps transitional between the Arctic Small Tool and Eskimo traditions; late prehistoric materials were totally absent. These middens are the first unmixed ''intermediate'' (post-Denbigh, pre-late prehistoric) cultural deposits located inland on the North Slope.

Despite the ravages of voracious ground squirrels and curious bears, the plastic photo panels remained essentially intact until late August 1980, when the weather finally permitted a photography flight. The photographic products from all the flight lines are excellent. The overlapping (for stereoscopic viewing) 23- by 23-cm (9- by 9-in) color infrared transparencies obtained are at a scale of 1:1,800 and show remarkable detail; lines of toppled stone inuksuk are discernible. At Etivluk Lake, house structures with entrance tunnels, unnoticed during the placement of the panels, show clearly on the photographs.

The photographs of the village areas will be used to demonstrate the feasibility of nondestructive archaeological studies. Initial emphasis will be placed on completing site maps of all the villages for the National Register. These maps will be generated by two methods: (1) Working copies, made from the original transparencies, will be used in a photogrammetric plotter to produce topographic maps of each village locale; (2) a photogrammeter using the plotter will map all lineaments and topographic anomalies (presumed cultural features), while an archaeologist using a transferscope will use his experience to interpret suspected cultural features. The data derived from both techniques will be analyzed to classify features by form and size. The accuracy and cost of the two techniques will be compared with costs of the conventional field maps by Irving of Site 9 at Etivluk Lake and by Hall at Tukuto Localities A-I. Chronology and intrasettlement configuration will be extrapolated from existing excavation data.

Vegetation and soil transects are planned to identify positively the cause of the apparent site signature in the infrared. As time and funds allow, ancillary studies will be completed to develop a comprehensive management plan for all of these lakeside sites. The studies will be integrated through a seasonally differentiated catchment analysis. The studies will eventually include the correlation of slope/aspect (view and susceptibility to the elements) with lake-vicinity satellite settlement patterns, and the availability and movement of subsistence resources. Pollen cores and modern pollen counts obtained at each lake will allow for comparison to catchment potential between lakes and across time. These data will be useful in interpreting the differences in household inventories and faunal assemblages from excavated housepits. The lakes are approximately one day's winter-travel distance from each other. Settlement patterns along potential seasonal travel routes between the lakes will be correlated with route distance standardized by time and difficulty. The resulting interlake satellite settlement pattern will be useful in designing studies to investigate intervillage economic and social networks.

The development and implementation of nondestructive archaeological inquiries by Federal agencies is significant in a number of respects. First, proposals for consumptive use of these resources can be rationally evaluated, alternatives to the sharply dichotomized avoid-or-excavate recommendations will perhaps become possible, and the issuance of Antiquities Act permits will be based on consideration of the resource rather than the applicant's credentials. Second, the nondestructive approach promotes research that enables researchers to sample (and destroy) only that portion of the nonrenewable resource that is justifiable. It is critical in the study of nonrenewable resources to limit as far as possible the inductive portion of the inductive-deductive scientific process to nondestructive methods in order to minimize consumptive use of the resource. Lastly, increasing costs of labor-intensive activities and decreasing costs of high technology encourage the prudent researcher or agency to investigate nontraditional, nondestructive modes of inquiry.

CULTURAL RESOURCE SURVEYS AND EXCAVATION IN THE NPRA AFTER 1977 BY OTHER AGENCIES

Surveys and excavations in the NPRA after January 1, 1977, by other agencies added substantially to knowledge of the area's cultural resources. Table 37.4 lists all known archaeological work carried out in the reserve after 1977. The National Park Service located a considerable number of archaeological sites by intensively surveying selected limited areas (Davis and others, 1981).

Not listed in the table, but equally important, has been the recent work in the North Slope Borough to inventory cultural resources of importance to the native peoples. The North Slope Borough Traditional Land Use Inventory has been made by interviewing knowledgeable local people about traditional, historical, and contemporary land use at specified locations. At present, efforts are underway to field check the designated locations (Ivie and Schneider, 1978; Schneider and others, 1980). When completed, the North Slope Borough Traditional Land Use Inventory will be an exceedingly important management tool for those interested in understanding and preserving the more recent cultural resources.

PRESENTLY KNOWN CULTURAL HISTORY OF THE NPRA

The rapidly accumulating data on the prehistoric human utilization of the NPRA, and of northern Alaska as a whole, permit formulation of a tentative cultural-historical sequence (fig. 37.2) that is considerably more comprehensive than the one Anderson (see table 37.2) was able to offer only 5 years ago. However, any cultural-historical reconstruction must be viewed with skepticism, because so little is really known about the changing nature of human adaptation over time.

PROGRAM EVALUATION AND RECOMMENDATIONS

It is difficult to tally the successes and shortcomings of the cultural resource program over the years 1977-1981. However, in the larger perspective the program was successful. Our knowledge and appreciation of the cultural resources of the NPRA have benefited, while the nationally significant petroleum exploration activities have not been impaired. Three broad issues will be discussed in order to put the program in perspective: communications, contributions to anthropological inquiries, and procedures.

COMMUNICATIONS

The laws that required a cultural resource program as a part of the NPRA petroleum exploration program were enacted because United States citizens place a value upon the past—upon the knowledge ob-

TABLE 37.4.—*Cultural resource identification research in the NPRA after 1977*

[The list of references cited is not meant to be exhaustive. For further information, the reader may wish to consult Dekin (1978) and the "Current Research" series of the journal *American Antiquity*]

Researcher	Year	Area	Reference	Comments
Aigner, Jean, and Book, Pat	1977	Barrow	Aigner and Book (1977)	Archaeological impact report for construction in Barrow
Bureau of Outdoor Recreation	1977	Lower and Middle Utukok River	Ivie and Schneider (1978)	Located a few archaeological sites
Davis, Craig, Linck, C.D., Schoenberg, Kenneth, and Shields, Harvey	1977	Upper Ikikpuk drainage, Upper Colville River, Lookout Ridge area, Howard Pass	Davis and others (1981), Shields (1978)[1], Schoenberg [1978]	Intensive ground survey in limited areas
Hall, E.S., Jr., and Gal, Robert	1977	Selected locales across the National Petroleum Reserve in Alaska	Hall (1977), Gal and others (1980)	Ground and air survey; excavation of Tunalik site and two South Meade sites
Hastings, W.,	1977	Colville River	Hastings [1977]	Located one site
Schneider, William, and Ivie, Pam	1977	Coast between Utukok River mouth and Pingusugrak; Kuk, Utukok, and Ivasarak Rivers	Ivie and Schneider (1978)	Air and ground survey of Traditional Land Use Inventory sites[2]
Davis, Craig, Linck, C.D., Schoenberg, Kenneth, and Shields, Harvey	1978	Teshekpuk Lake, Middle Meade River, Middle Utukok River, Noluk Lake	Davis and others (1981), Davis (1979)[3], Schoenberg (1979), Shields (1979)[4]	Intensive ground survey in limited areas
Hall, E.S., Jr., and Gal, Robert	1978	Selected locales across National Petroleum Reserve in Alaska	Hall (1978), Gal and others (1980), Kunz (1979), Bowers (1979)	Ground and air survey; intensive survey in Otuk and Iteriak Valleys; test excavation and collection at Lisburne Borrow 1 and Mesa site
Schneider, William, Pedersen, Sverre, and Libbey, David	1978	Meade and Inaru Rivers (1980)	Schneider and others (1980)	Evaluation of Traditional Land Use Inventory sites
Stern, Richard	1978	Umiat area, Middle Ikpikpuk River	Stern [1978]	Survey along river
Aigner, Jean	1979	Atqasuk	Jean Aigner, oral commun., 1979	Archaeological clearance for Atqasuk airport
Aigner, Jean	1979	Nuiqsut	Jean Aigner, oral commun., 1979	Archaeological clearance for Nuiqsut airport
Bowers, Peter	1979	Lisburne Borrow No. 1 (Iteriak Valley)	Hall (1979a)	Test excavation
Cook, John	1979	Nuiqsut	Cook (1979a)	Survey of local roads
Cook, John	1979	Wainwright	Cook (1979b)	Survey of local roads
Davis, Craig	1979	South shore of Teshekpuk Lake	Hall (1979a)	Examination and collection of TES-014
Hall, E.S., Jr., and Gal, Robert	1979	Selected locales across National Petroleum Reserve in Alaska	Hall (1979a, b), Gal and others (1980)	Ground and air survey; text excavation of small sites near Walakpa Bay and along coast SW of Wainwright; completed excavation of South Meade sites
Kunz, Michael	1979	Mesa (Iteriak Valley)	Kunz [1981]	Test excavation
Slaughter, Dale	1979	Siraagruk (coast N. of Point Belcher)	Hall (1979a)	Test excavation
Gal, Robert	1980	Etivluk, Kinyiksukvik, Betty, Tukuto, Swayback, and Liberator Lakes	Gal, field notes	Set out photo panels for aerial survey of late prehistoric sites; located new site at Tukuto Lakes
Gerlach, S.C.	1980	Old shoreline bluff between Wainwright and Icy Cape	Gerlach, field notes	Survey and test excavation
Hall, E.S., Jr, and Gal, Robert	1980	Selected locales across National Petroleum Reserve in Alaska	Hall, field notes	Ground and air survey
North Slope Borough	1980	Harrison Bay	Rex Okokok, oral commun., 1980	Evaluation of Traditional Land Use Inventory sites[2]
Slaughter, Dale	1980	Siraagruk (coast N. of Point Belcher)	Slaughter, field notes	Text excavation
Yarlborough, Linda	1980	Barrow	Linda Yarlborough, oral commun., 1982	Survey for gas pipeline
Gerlach, S.C.	1981	Croxton site, Tukuto Lake	Hall (1982)	Test excavation
Hall, E.S., Jr., and Gerlach, S.C.	1981	Selected locales across the National National Petroleum Reserve in Alaska	Hall (1982)	Review of construction areas associated with oil exploration programs, excavation at Croxton
Hall, E.S., Jr., Dekin, Albert, and Newell, Raymond	1981	Utkiavik site, Barrow	Hall, field notes	Excavation

[1] Shields, H.M., 1978, Recent archaeoological developments in the Howard Pass region, Alaska: Paper presernted at the Alaskan Anthropological Association, Fifth Annual Meeting, Anchorage.

[2] Data on cultural resource sites included in the Traditional Land Use Inventory orginally were collected through interviews with local resource experts conducted by Flossie Hopson and Susie Franklin. This table includes only references dealing with on-site evaluation of Traditional Land Use Inventory sites.

[3] Davis, C.W., 1979, An archaeological survey in the vicinity of Teshekpuk Lake; methods, results, and a *sursum corda* (or 'mucking about' on the Arctic coastal plain): Paper presented at the Alaskan Anthropological Association, Sixth Annual Meeting, Fairbanks.

[4] Shields, H.M., 1979, Recent developments in the Noluck Lake-Storm Creek region, Alaska, *and* Prehistoric land use patterns in the western Brooks Range: Papers presented at the Alaskan Anthropological Association, Sixth Annual Meeting, Fairbanks, and the Society for American Archaeology, Forty-fourth Annual Meeting, Vancouver, British Columbia, respectively.

tained from the bits and pieces left behind by our predecessors. This value derives not from the intrinsic worth of the objects themselves but from the intellectual stimulation of contemplating past conditions and the wisdom gained to plan for the future.

As protection of cultural resources is required by public laws and is funded by public monies, an accounting of the cultural values is mandatory before any Federal project can be undertaken. Agency documentation of compliance with regulations and procedures is only one aspect of the archaeologist's accountability. Another more important aspect is the feedback that the program has offered to the sponsoring public, both lay and professional.

Providing feedback to the general public is less structured than input to the professional community. In this area of popular dissemination of information, more effort should be made. At the local level, frequent personal contacts were made with representatives of the North Slope Borough, especially members of the Planning Department. For example, Waldo Bodfish, a knowledgeable Inupiat elder and member of the Commission on History and Culture, was employed in the test excavations at Siraagruk. A slide presentation was made at a meeting of the North Slope Borough Commission on History and Culture, and slide presentations were also made in some North Slope Borough high school classes. A poster-slide display accompanied by a pamphlet explaining the NPRA cultural resource program was exhibited in Anchorage, Fairbanks, and Barrow. Presentations were also made in the Fairbanks North Star Borough grade school classes. A Fairbanks newspaper team visited an archaeological field crew at work in the NPRA in 1981; however, apart from a single feature article, no popular accounts for the general public were released.

Because the engineers, construction workers, and drillers who were employed in the petroleum exploration effort are also a part of the general public, a display for their benefit was set up on a bulletin board at the logistics base, Camp Lonely. This display had two objectives: (1) to inform them of the cultural resource activities in the NPRA, and (2) to familiarize them with the kinds of cultural resources they might encounter, and to instill a measure of appreciation for the significance of those resources in order to enlist their cooperation in resource protection. A formal briefing through a slide show or film and explanatory pamphlet would probably meet these objectives more effectively.

During the life of the program, the general public was thus only sporadically served. However, outputs for public consumption will not cease with the closedown of Federal exploration of the reserve. The assessment for general audiences of much of the data accumulated during the program is only possible now; some data may not be understandable for years, and then only in the light of new ideas or the discovery of new materials.

Interaction with the professional community has been more regular. One of the most positive and satisfying contributions of the program has been the opportunity for study afforded undergraduate and graduate students in anthropology. Students from the University of Alaska, University of Arizona, Brown University, University of Connecticut, University of California at Los Angeles, California State University at Chico, Louisiana State University, Michigan State University, University of Minnesota, University of New Mexico, Northern Arizona University, University of Oregon, State University of New York at Binghamton, University of Washington, Washington State University, and the University of Wisconsin over the years brought their anthropological training to the archaeological field efforts in the NPRA and enriched the field experience. For many of these students their NPRA experience was their first in the Arctic; many are now intent on careers in Arctic prehistory. Two doctoral dissertations will result directly from the NPRA cultural resource program—one at Brown University, the other at the University of Wisconsin at Madison. The USGS-BLM program has contributed to the training of anthropologists as it utilized their skills.

Yearly summaries of the NPRA fieldwork were submitted and published in the *Newsletter* of the Alaska Anthropological Association and in the "Current Research" section of *American Antiquity*, the journal of the national Society for American Archaeology. Professional papers were delivered and distributed yearly at the annual meeting of the Alaska Anthropological Association, and two papers were presented at the annual meeting of the Society for American Archaeology. Detailed site reports for the Tunalik and Lisburne excavations are in preparation for publication. A double issue of the *Anthropological Papers of the University of Alaska* (v. 20, no. 1-2, published September 1982) is devoted entirely to papers reporting on all work conducted under the joint USGS-BLM cultural resource program. (Appendix 37.1 lists all papers and reports emanating from the USGS-BLM project to date.) All the artifacts recovered from the NPRA have been accessioned to the University Museum, University of Alaska. Upon completion of the analysis and reports, the artifacts will be transferred to the University Museum for future study.

One aspect of communication has been mandatory—the yearly publication of a clearance report detailing the areas examined for cultural resources, the findings, an assessment of potential impacts to cultural resources, and an explanation of all mitigating measures (Hall, 1977, 1978, 1979a, 1980). Copies were distributed to the Advisory Council on Historic Preservation, the Department of Interior

Consulting Archaeologist, The State Historic Preservation Office, the Heritage Conservation and Recreation Service, Federal, State, and local governmental agencies, and a number of professional archaeologists. This annual clearance report is vital because it documents the compliance of the exploration program with the various antiquities laws and with the National Environmental Policy Act. It is disappointing that with one exception no comments, positive or negative, have been received in response to the four annual clearance reports. If the NPRA cultural resource program has been wanting in some regard, no indications of its deficiencies have been tendered.

CONTRIBUTIONS TO ANTHROPOLOGICAL INQUIRIES

As well as providing training for anthropologists, the NPRA cultural resource program has made a substantial contribution to anthropological inquiry north of the Brooks Range.

The substantive contributions could be quantified simply as number of sites discovered within the NPRA, but such a figure is misleading. One aspect of the survey strategy is significant—no regional strategy was employed in the clearance surveys, only in the testing program discussed earlier. In the NPRA, the mandate from Congress was to explore the entire reserve for its petroleum potential, and the clearance work necessarily focused upon isolated construction areas scattered widely. Areas were examined for cultural resources not because a particular archaeological problem orientation was being pursued, but because impacts to the land and its resources were expected. Thus, areas were examined that might have been excluded on the grounds of low research priority or low potential based upon current knowledge, irrelevance to current problem domains, or even difficult accessibility.

The parameters of the survey for any one season could not be stated by predetermined problem orientation, in part because areas requiring archaeological survey were not identified until archaeologists were in the field. The USGS-BLM archaeologists looked for and located cultural resources in areas that were not selected by any site-location paradigm. Rather, problem orientations were developed for regions about loci defined by proposed construction areas. The reasoning that directed the clearance surveys was based upon knowledge of proximity to known cultural resource sites and knowledge obtained on location of surficial geology and soils, topography, hydrology, and biome.

The difference in this approach is subtle but significant and was earlier demonstrated by surveys conducted before construction of the Trans-Alaska Pipeline. Along the pipeline corridor in 1970 and 1971, reconnaissance surveys disclosed a number of significant sites. However, surveys of specific construction areas in 1974 and 1975 revealed a great many more sites—many of them significant—in areas passed over by the earlier surveys. The clearance and mitigation excavations for the South Meade test well illustrate the same advantage of a nonpremeditated survey. The excavations at South Meade disclosed unexpected cultural resources sites in an apparent low-density distribution in a relatively inaccessible area where research returns per dollar expended would prudently be considered unprofitable. The South Meade investigations have thus brought into focus a new problem for future research.

The NPRA clearance surveys were successful for two reasons. First, the same personnel worked in a single season across many ecologically different areas. Thus, continuous feedback and reevalaution was possible as new insights were obtained—feedback that would have been delayed were well-site clearance surveys contracted piecemeal. Secondly, the same personnel worked from one field season to the next and so bridged the usual feedback delays occasioned by publication lag and meager clearance reports.

The substantive contribution of the surveys is not that sites were located, but that they were located widely through an unsystematic selection of locales (approximating a random sampling strategy). Thus, materials and problems were discovered that might otherwise have gone unsuspected for decades.

In a similar fashion, the excavations represent an unsystematic sample of North Slope prehistory. The excavations at Tunalik, South Meade, and Lisburne have raised many questions concerning our existing outline of the cultural history of the North Slope region.

The Tunalik materials have been interpreted as the leavings of peoples utilizing core-and-blade and burin technology between approximately 8000 and 2000 B.C. Some of the tool forms from the Tunalik site indicate a technological continuity between the earlier American Paleo-Arctic tradition and the later Arctic Small Tool tradition and may be elements of the ancestral cultural matrix that became Independence and Pre-Dorset culture farther east in Canada and Greenland and Proto-Denbigh and Denbigh in Alaska.

The South Meade materials indicate that Ipiutak-related caribou hunters lived in an area near the Arctic coast at a time when the maritime-adapted Birnirk people were well established along the Arctic littoral. Whether the South Meade site provides evidence of contemporary technologically and ethnically differentiated human groups or of an interior aspect of Birnirk culture remains to be seen.

At the Lisburne site, the manufacturing sequence of several tool forms dating to different time periods is being reconstructed. Archaeological comparisons in the past have focused upon "formal artifacts," which include unused completed forms, utilized completed forms, totally used-up completed forms, and forms discarded or lost at various stages of completion. Analysis of the large collection from the quarry workshop at the Lisburne site will assist archaeologists in comparing materials whose relatedness stems from the processes of their manufacture and use.

The testing program by design augmented our understanding of North Slope cultural history. For example, the Siraagruk excavations have enabled us for the first time to reconstruct a 19th-century semisubterranean Arctic coastal house. Furthermore, the knowledge gained at Siraagruk has proved useful in guiding excavations at the Utkiavik site at Barrow. The Shoreline Bluff survey data substantiated the findings at Tunalik and document the presence of non-Arctic Small Tool core-and-blade industries on the Arctic coastal plain. The Mesa material indicates a possible new cultural component in the north and provides one of the earliest dates thus far obtained for North Slope occupation by human groups. Excavations at BAR-095 provided the first solid evidence of Norton culture north of Point Hope. Analysis of material recovered from the Croxton site may throw light on a previously unknown phase of Inupiat development.

More important than any cultural-historical contributions the NPRA program has made are the two standards the program has set for future work. First, by setting the goal for mitigation as 100-percent recovery, emphasis was placed upon techniques for identifying the total distribution of cultural materials at each site. Past research on the North Slope has focused upon locating and retrieving artifacts rather than defining archaeological sites, and past mitigation work has only intuitively addressed the problems of site definition. The work conducted under the NPRA program for the first time implemented explicit procedures for site definition on the North Slope and employed both random and systematic testing strategies.

Secondly, the NPRA program has emphasized the spatial structuring of artifact distributions within sites. The earliest cultural-historical studies for northern Alaska were based upon artifact assemblages that had an underlying behavioral or temporal unit of organization—the household or the excavation level within deep middens. Later, workers concentrated on shallowly buried sites and relied upon the site as the organizational unit, comparing North Slope site assemblages to assemblages in distant areas. Throughout the NPRA program, the site has been recognized as a "unit of synthesis" (Binford, 1975, p. 254), and the spatial distribution of forms within the site as the principal means of organizing the recovered materials into units reflecting some behavioral or temporal event. Using this approach we grew to recognize the analytical significance of small, single-component, essentially surface sites. Most North Slope sites are shallowly buried and lack obvious behaviorally based units such as houses. Thus, many of the interpretations that have been offered for such sites in the past assume an admixture of remains of temporally distinct activities and emphasize the typological segregation of artifact forms. Such an approach does not identify "transitional" technologies or consider that one group may assume the technology or style of a contemporary group. The emphasis on within-site spatial distributions and small sites does, however, provide data for demonstrating both cultural contemporaneity and mechanical admixture. The search for the repetitive co-occurrence of forms in intrasite spaces is an approach that we hope other North Slope researchers will continue.

PROCEDURAL CONSIDERATIONS

Although many of the experiences of the NPRA cultural resource program pertain generally to cultural resource protection activities north of the Brooks Range, some situations specifically apply to the conduct of the Federal exploration program. In December 1980, Public Law 96-514 was signed into law, amending the original authorizing legislation (Public Law 94-258). The new law allows private industry to obtain oil and gas leases in the NPRA and to explore for, develop, and produce oil and gas resources. The role of the Federal archaeologists in the NPRA is therefore changed.

A potential conflict of interest arose at the beginning of the Federal exploration program in that the archaeological assessment and compliance work was conducted "in-house"; the USGS-BLM archaeologists were gathering the field data, judging its adequacy, and making recommendations to management and to the SHPO. However, this potential conflict of interest was dismissed for a number of reasons. First, the USGS-BLM MOU assigned one agency (the USGS) the archaeological assessment, the other (BLM) the review and compliance. Secondly, the consultation procedures specified in the implementing regulations (36 CFR 800) for the Historic Preservation Act of 1966, as amended, provided checks and balances at the SHPO and ACHP levels. Proposed areas of operation were examined jointly by the two agency archaeologists so that differences of judgment and procedure were resolved immediately and cost effectively. Given the tight decision and implementation schedule, the joint field inspections allowed the agency archaeologists to present a coherent statement of cultural resource facts, concerns, and recommendations at the earliest possible stage of the operation. Thus, recommendations were considered by management outside the context of project delay, and cultural resource protection was never pitted against completion of the yearly exploration program approved by Congress.

A third advantage of the joint conduct of field investigations was that the cultural resource specialists having on-the-ground familiarity with the relevant data, rather than a third-party reviewer or interpreter, had direct input to the USGS and BLM decisionmakers. Recommendations were presented forcefully and with conviction. Unlike hired consultants, the USGS-BLM archaeologists had an established place in the decisionmaking hierarchy, and information exchange was constant. Overall, the joint cultural resource program was eminently suitable within the context of the Federal petroleum exploration program. Such an arrangement might not, however, be suitable in other contexts.

One major problem was the completion of agency obligations after the field assessment and field mitigation actions were completed. This problem was lessened by the fact that both USGS and BLM-NPRA staffs were set up and, more importantly, funded as special projects; however, the archaeological laboratory space and equipment were barely adequate. Although shifting priorities and day-to-day business diminished the time available for analysis and publication, and final publication of the scientific findings was delayed, many interim reports were made available to the professional community.

Probably industry will contract its own archaeologists for the assessment of cultural resources on leaseholds obtained under Public Law 96-514. In the conduct of this work, as many archaeological contractors as there are leaseholds may be deployed each summer. New insights are bound to result in proportion to the number of investigators bringing new approaches to the fieldwork. Some disadvantages will also accrue. The consistency of the data may vary greatly, and piecemeal activity may reduce the potential for comparability. Communication and data exchange among contractors will be delayed unless a good information transfer is established.

Henceforth, the pace of exploration and impact to cultural resources will be set by industry. The mitigation of impacts to cultural resources can now be conducted on a multiseason basis, and the magnitude of mitigation actions and the kinds of sites for which mitigation is feasible will both increase.

A few general procedural recommendations may be offered, based on the experience of the USGS-BLM cultural resource program. Foremost is the need for consistent protection of cultural resources on all North Slope lands. While legal restraints on State and private lands differ from those on Federal lands, the officials responsible for the management of North Slope lands should be encouraged at every opportunity to adhere to a standard policy for cultural resource protection. Although such a policy could be construed as an obstacle to development, its effect would actually be the opposite. Instead of facing a seemingly capricious set of requirements and concerns, all sponsors of activities potentially impacting cultural resources would come to recognize and respect the legitimacy of the consistent policy.

For the forseeable future, impacts to the cultural resources of the North Slope will primarily result directly or indirectly from the exploration, development, and production of oil and gas. Virtually all of the 23 million ha (56 million acres) of the North Slope is managed by three Federal agencies, the State of Alaska, and Native regional and village corporations. All of these lands lie within a single State-borough administrative unit. Although each of these agencies has its own specific mandates, it seems both possible and desirable to seek uniform policies across the entire slope, at least within the context of petroleum exploration and development. For example, assessment of impacts to cultural resource sites from geophysical activities is now only required within the NPRA. It is inconceivable that geophysical impacts to cultural resources sites occur only in the NPRA.

On Federal lands, on the North Slope at least, the role of the agency archaeologist will become that of reviewer and overseer of the work contracted by the oil industry. All North Slope agency archaeologists should interact with contract archaeologists in a standard manner. The various agencies should reserve to themselves some small portion of the archaeological assessment work that they require of industry. By actually performing this work, the agency archaeologist will be forced to conform to and thereby test the suitability of the standards set for the contractors. Through such practice, guidelines and standards will also be subject to continual modification or refinement to accommodate unforeseen circumstances. Lastly, but importantly, participation in some assessment and clearance work subjects the agency archaeologist to the same professional scrutiny as archaeological contractors, thereby confirming his credibility (King, 1975).

A standard of eligibility of sites for cultural resource protection such as that of the ACHP should not form the basis of a policy for the North Slope. Instead, such policy should be based on guidelines for determining what cultural resources are expendable. The dilemma of dealing with nonrenewable resources is not solved by recognizing the significance of those resources. That is only a first step. Managing nonrenewable resources includes ensuring that those resources are expended in a reasoned manner and that maximum value is derived from their expenditure. The ACHP eligibility criteria and the State of Alaska Historic Preservation Plan should be considered. To ensure that cultural resources are expended in a reasoned manner, it is necessary to (1) determine the significance of the resources, and (2) understand the actual impacts that will result. The impact of the archaeologist needs to be included in the latter consideration.

Two procedural recommendations derive from the NPRA experience. First, the limited season for doing cultural resource assessment work must be recognized and made a primary concern. Only in special circumstances can both archaeological assessment and mitigation activities be scheduled in the same field season. A mitigation program should be carefully thought through before the field work is begun. Secondly, the reliability of procedures for delimiting an archaeological deposit once it is located is largely unknown. Termination of work before completion because of weather or of underestimation of the extent or complexity of the site constitutes wanton abandonment of the resource.

Assessment of sites can itself have an adverse impact. During the summer of 1977, limited surface collections were made from the sites identified. In 1978 this policy was reversed, and diagnostic materials found on the surface were sketched and photographed and then returned to their original location. The significance of both small and large sites with multiple concentrations of material can be drastically diminished if the exact original locations of the pieces collected cannot be identified. Recording the co-occurrence of forms in reconstructed behavioral spaces within sites is essential. As most sites on the North Slope are accessible to very few people, a general policy of noncollection is justified. But whenever surface collection is justified, a permanent datum such as a length of "rebar" with an aluminum cap should be emplaced at the site so that relocation of the materials is always possible.

Most mitigation recommendations are based upon the imagined impacts of certain activities on cultural resources. For example, if a hillside is removed for construction material, the impact to a cultural resource site on that hillside is obvious. The impact from a construction train moving across an archaeological site is probably less severe but is actually unknown. Both the USGS and BLM archaeologists had the advantage of evaluating the effectiveness of their mitigation recommendations through winter monitoring of potentially disturbing activities and through summertime reevaluation of areas approved the preceding summer. The effectiveness and appropriateness of mitigation recommendations and actions have not been considered elsewhere on the North Slope.

Our conservative recommendations may have resulted in the unwitting consumption of cultural resources if the impact of the mitigating measures exceeded the severity of impact of the proposed action. For example, is the displacement and breakage of artifacts resulting from a single pass of an overland vehicle justification for the scientific excavation of a site? Or is the site best conserved for future investigators, even though damaged? These questions, of course, cannot be answered without first understanding the severity of the impacts. Even though the North Slope has lost little of its cultural resource, experimental archaeology involving the quantification of impacts from natural and human causes seems essential for the long-term management of those resources. Mitigation commensurate with impact should guide the management of cultural resources, lest the old saying "The operation was a success, but the patient died" be the judgment of future generations.

CONCLUSION

Impetus for the USGS-BLM cultural resource program arose from the necessity to meet the requirements of Federal law and, as well, from the concern the involved agencies held for cultural resources in the NPRA. The general parameters of the program were set by Federal law and by the Memorandum of Understanding between the USGS and the BLM. The geographic locations of program operation were dictated by oil exploration activities. The specific methods used in the cultural resource surveys, the testing program, and the excavations evolved over the course of the program. The USGS and BLM archaeologists continually were faced with the necessity of balancing conflicting considerations, which included Federal law, the requirements of the MOU, the lack of knowledge about cultural resources in the NPRA, the absence of data bearing on the effects certain oil exploration activities have on cultural resources sites, the limited field season, complicated logistic problems magnified by the size of the reserve, and the desire to spend public monies as wisely as possible.

We are reasonably pleased with the solutions developed to meet these problems. In large part, the success of the cultural resource program can be attributed to the efforts of various contractors and subcontractors involved with the oil exploration program, firm support from USGS and BLM personnel, input from professional colleagues, and hard-working archaeology crews. As a result, the cultural resource program was both effective and inexpensive.

The total cost of the cultural resource program is estimated to have been approximately 0.1 percent of the total amount spent by the U.S. Government on the entire oil exploration program, well within the 1 percent of total costs permitted by Federal law.

During the summer of 1981, the USGS archaeologist reexamined all test-well sites, airstrips, borrow sites, burial sites, and other specific areas associated with the 1977-81 oil exploration program (Hall, 1982). Selected localities along winter trails, ice roads, and seismic lines that had been periodically monitored as part of the ongoing clearance program were also visited, as were known cultural resource sites and areas of special archaeological interest in close proximity to trails and lines actually used during the oil exploration program. Finally, all well sites and airstrips and selected seismic lines associated with the earlier Navy oil exploration programs (1944-53, 1975-77) were reviewed for comparison.

The available evidence indicates that the USGS-BLM program met its major objective of minimizing damage to cultural resources in the NPRA. With two minor exceptions, the current oil exploration program did not adversely affect the known cultural resources of the area; the exceptions are Kolovik and Nokotlek Point—historical sites that suffered relatively limited damage because of trespass by ground vehicles (Hall, 1978). There is no way to ascertain the possible nature and extent of damage to cultural resource sites that might have occurred without this program, but certainly the Tunalik site, at the very least, would not have been fully recognized. Undoubtedly, other sites would also have been missed.

The 1944-53 Navy oil exploration program operated under few, if any, environmental restrictions. At least two instances of damage to cultural resource sites are known to have occurred (Hall, 1977), and some indirect and secondary effects to sites (the late prehistoric site at Liberator Lake, for example) are also known. Still, it must be acknowledged that, considering its scope, the Navy program also caused little cultural resource damage. This record is primarily the result of well-site location, in that few wells were set in the culturally rich zone south of the Colville River and no well pads and associated facilities were built in or near a locality with high cultural resource potential.

Land managers might assume from past experience in the NPRA that a cultural resource program is not a requisite accompaniment of oil exploration. Such a viewpoint is not only contrary to public will as expressed in numerous Federal laws, but also does not take into account what has been learned about cultural resource sites in the NPRA. A cultural resource program was in effect during the period between 1977 and 1981 when the USGS was overseeing oil exploration in the reserve, and some effort to protect cultural resources was made by the Navy during their 1975-77 program. The presence of trained archaeologists as part of the oil exploration program ensured that proper surveys were conducted in the vicinity of construction areas, that sites in conflict with construction priorities were excavated, that potentially threatened sites were scientifically collected and (or) posted as off limits, and that all personnel connected with the oil exploration program were aware of the scientific importance and legal necessity of protecting the cultural resources. Without appropriate guidance by specialists, any oil exploration program in the NPRA inevitably will adversely affect the cultural resources.

Nor should land managers take refuge in the seeming richness of the NPRA's cultural resources. Some sites represent unique cultural expressions and are the only evidence we have for specific time periods or for specific human activities. The Mesa site, for example, produced artifacts that have no exact congeners elsewhere in the Arctic, and the site represents a time period poorly represented in the cultural-historical record. The possible transitional Denbigh-Choris layer at Walakpa (Stanford, 1971) also represents an otherwise unknown cultural phase. We do not know if the ravages of time have left other examples of human behavior at the Mesa or in the Denbigh-Choris layer at Walakpa. Therefore, these cultural resources must be fully protected until we know they are duplicated elsewhere, or until their full scientific potential can be realized.

Even if certain time periods or specific human activities are well represented by cultural resource sites, vigilance must be maintained. Although there are many known late prehistoric Inupiat sites in the NPRA, only six lakeside sites, such as the one at Tukuto Lake, are known. These sites represent a particular type of environmental adaptation during that time. If only one is lost as a result of oil exploration activities, the resource is significantly diminished. If only one such site is adversely affected every 10 years—seemingly a good record if intensive oil exploration activity occurs in the foothills area—in 60 years a resource that was several hundred years in the making, and unique in its existence, will be no more. Thus, the need for a cultural resource program in the NRPA will persist for as long as the search for other, similarly nonrenewable resources continues.

Finally, a cultural resource program should not be thought of as totally protectionist. The USGS-BLM program will leave its mark in a number of other ways. Knowledge of the area's cultural history has been considerably expanded. A method has been developed for efficient and effective clearance of oil exploration construction areas in the Arctic. Testing tactics are now available to quickly and effectively ascertain the nature and extent of the deposits. A start has been made toward establishing an overall strategy for managing the cultural resources of the NPRA. The archaeological profession is being informed of these results, and further efforts will be made to disseminate the information to the general public.

As with all things, time will be the ultimate judge of the USGS-BLM cultural resource program. For now, the cultural resources of the NPRA remain, bearing witness to the way humans adapted to an intractable environment in the past, as well as to the continuing desire of our generation that the evidence of past human behavior be protected and understood. Given the brief span of our time, it seems important that we do not intentionally or unwittingly destroy a record of human endeavor that took one hundred centuries or more to create.

REFERENCES CITED

Anderson, D.D., 1970, Akmak, an early archaeological assemblage from Onion Portage, northwest Alaska: Acta Arctica, fasc. 16, 80 p., 4 pls.

——— 1984, Prehistory of North Alaska, *in* Damas, David, ed., Handbook of North American Indians, Arctic (V): Washington, Smithsonian Institution, p. 80-93.

Aigner, J.S., and Book, P.A., 1977, A report on the potential archaeological impact of proposed development of Lot Area 41 (Utkiavik Village), Barrow, by the North Slope Borough: Barrow, North Slope Borough Planning Department, 21 p.

Binford, L.R., 1975, Sampling, judgment, and the archaeological record, *in* Mueller, J.W., ed., Sampling in archaeology: Tucson, University of Arizona, p. 251-257.

Bowers, P.M., 1979, Preliminary investigations of the Lisburne site (KIR-096), southeastern National Petroleum Reserve, Alaska: Paper presented at the Alaskan Anthropological Association Sixth Annual Meeting, Fairbanks, 30 p. [Available from Bureau of Land Management, Arctic District Office, 1541 Gaffney Road, Fairbanks, Alaska 99703]

Brower, C.D., 1942, Fifty years below zero: New York, Dodd, Mead, and Co., 310 p.

Campbell, J.M., 1970, Current research, Arctic: American Antiquity, v. 34, no. 2, p. 239-277.

Campbell, J.M., and Cordell, L.S., 1975, The Arctic and Subarctic, *in* Gorenstein, Shirley, ed., North America: New York, St. Martin's Press, p. 36-73.

Carter, W.K., 1952, Notes and news, Arctic: American Antiquity, v. 18, no. 1, p. 91-93.

——— [1953], Archaeological survey of Eskimo, or earlier, material in the vicinity of Point Barrow, Alaska: Final report on Contract N5041-07643, submitted to Office of Naval Research, U.S. Navy, 8 p. [Available from Rasmuson Library, University of Alaska, Fairbanks]

——— 1966, Archaeological survey of Eskimo, or earlier, material in the vicinity of Point Barrow, Alaska: Final report on Contract ONR-110, submitted to Office of Naval Research, U.S. Navy, 87 p. [Available from Rasmuson Library, University of Alaska, Fairbanks]

Cook, J.P., [1976], Archeological assessment within NPR-4: submitted to Commander, Naval Petroleum Reserve No. 4, 8 p. [Available from Edwin S. Hall, Jr., 291 Main Street, Brockport, New York 14420]

——— 1979a, Limited cultural resource survey in Nuiqsut: Barrow, Alaska, North Slope Borough, 8 p. [Available from Edwin S. Hall, Jr., 291 Main Street, Brockport, New York 14420]

——— 1979b, Limited cultural resource survey in Wainwright: Barrow, Alaska, North Slope Borough, 2 p. [Available from Edwin S. Hall, Jr., 291 Main Street, Brockport, New York 14420]

Davis, C.W., Linck, D.C., Schoenberg, K.M., and Sheilds, H.M., 1981, Slogging, humping and mucking through the NPR-A; an archeological interlude: Fairbanks, University of Alaska, Anthropology and Historic Preservation, Cooperative Park Studies Unit, 5 v., 1588 p., 68 pls.

Dekin, A.K., Jr., 1978, Arctic archaeology: a biography and history: New York, Garland Publishing, Inc., 279 p.

Department of the Interior, 1977, Memorandum of understanding, cooperative procedures for National Petroleum Reserve in Alaska between Bureau of Land Management and the U.S. Geological Survey: Federal Register, v. 42, no. 16, p. 4542-4546.

Department of the Navy, 1977, Final Environmental Impact Statement, continuing exploration and evaluation of Naval Petroleum Reserve No. 4: Washington, 2 v., 829 p.

Ford, J.A., 1959, Eskimo prehistory in the vicinity of Point Barrow, Alaska: New York, Anthropological Papers of the American Museum of Natural History, v. 47, pt. 1, 272 p., 13 pls.

Gal, Robert, 1979, Strategies for site definition; three examples: Paper presented at the Alaskan Anthropological Association Sixth Annual Meeting, Fairbanks, 14 p. [Available from Robert Gal, P.O. Box 1013, Kotzebue, Alaska 99752]

Gal, Robert, Bowers, P.M., Kunz, M.L., 1980, Recent Bureau of Land Management archeological fieldwork in the National Petroleum Reserve, Alaska: Fairbanks, Alaska, Bureau of Land Management, 57 p. [Available from Bureau of Land Management, Arctic District Office, 1541 Gaffney Road, Fairbanks, Alaska 99703]

Gubser, N.J., 1965, The Nunamiut Eskimos; hunters of caribou: New Haven, Conn., Yale University Press, 384 p.

Hall, E.S., Jr., 1970, The late prehistoric/early historic Eskimo of interior northern Alaska; an ethnoarchaeological approach?: Fairbanks, Anthropological Papers of the University of Alaska, v. 15, no. 1, p. 1-12.

——— [1974], Archaeological investigations in northern Alaska, summer 1974: Brockport, N.Y. State College, Department of Anthropology, 55 p., 3 tables. [Available from Edwin S. Hall, Jr., 291 Main Street, Brockport, New York 14420]

——— 1975, An archaeological survey of interior northwest Alaska: Fairbanks, Anthropological Papers of the University of Alaska, v. 17, no. 2, p. 13-30.

——— 1976a, A preliminary analysis of house types at Tukuto Lake, northern Alaska, *in* Hall, E.S., Jr., ed., Contributions to anthropology, the interior peoples of northern Alaska: Ottawa, National Museum of Canada (Mercury series), v. 49, p. 98-134.

——— 1976b, An archaeological reconnaissance of selected locales in NPR-4, Arctic Alaska: Report subcontracted by Husky Oil Naval Petroleum Reserve Operations under contract NCd-10066 with the Department of the Navy, 29 p. [Available from Edwin S. Hall, Jr., 291 Main Street, Brockport, New York 14420]

——— 1977, Cultural resource survey and clearance in NPRA, 1977: U.S. Geological Survey, Office of National Petroleum Reserve, 2 v.

——— 1978, Cultural resource survey and clearance: National Petroleum Reserve in Alaska, 1978: U.S. Geological Survey, Office of National Petroleum Reserve, 2 v., 168 p., 90 maps. [Available from Edwin S. Hall, Jr., 291 Main Street, Brockport, New York 14420]

——— 1979a, Cultural resource survey and clearance: National Petroleum Reserve in Alaska, 1979: U.S. Geological Survey, Office of National Petroleum Reserve, 2 v., 250 p., 20 maps. [Available from Edwin S. Hall, Jr., 291 Main Street, Brockport, New York 14420]

——— 1979b, The potential significance of small, single component archaeological sites for elucidating the cultural history of northern Alaska: Paper presented at Alaskan Anthropological Association Sixth Annual Meeting, Fairbanks, 12 p. [Available from Edwin S. Hall, Jr., 291 Main Street, Brockport, New York 14420]

——— 1980, Cultural resource survey and clearance: National Petroleum Reserve in Alaska, 1980: U.S. Geological Survey, Office of National Petroleum Reserve, 167 p., 10 maps. [Available from Edwin S. Hall, Jr., 291 Main Street, Brockport, New York 14420]

——— 1982, A review of cultural resource survey and clearance activities: National Petroleum Reserve in Alaska, 1977-82: U.S. Geological Survey, Office of National Petroleum Reserve, 65 p. [Available from Edwin S. Hall, Jr., 291 Main Street, Brockport, New York 14420]

Hamilton, T., [1962], Archaeological excavation near Meade River village, *in* Geist, O.W., ed., Final report; contracts ONR-274 and ONR-254 for the Office of Naval Research, p. 79-117. [Available from Edwin S. Hall, Jr., 291 Main Street, Brockport, New York 14420]

Hastings, Wink, 1977, Origins of the early Eskimos in northern Alaska: Anchorage, Bureau of Outdoor Recreation, Alaska Regional Office, 24 p. [Available from Edwin S. Hall, Jr., 291 Main Street, Brockport, New York 14420]

Humphrey, R.L., 1966, The prehistory of the Utukok River region, Arctic Alaska; early fluted point tradition with Old World relationships: Current Anthropology, v. 7, no. 5, p. 586-588.

——— 1970, The prehistory of the Arctic Slope of Alaska; Pleistocene cultural relationships between Eurasia and North America: Albuquerque, University of New Mexico, Ph.D. dissertation, 332 p.

Irving, W.N., [1953], An archaeological reconnaissance of the lower Colville River and delta regions: Final report on Contract NONR-773, 1953, 99 p., 9 pls. [Available from Edwin S. Hall, Jr., 291 Main Street, Brockport, New York 14420]

——— 1962, 1961 fieldwork in the western Brooks Range, Alaska; preliminary report: Arctic Anthropology, v. 1, no. 1, p. 76-83.

——— 1964, Punyik Point and the Arctic Small Tool Tradition: Madison, University of Wisconsin, Ph.D. dissertation, 433 p.

Ivie, Pamela, and Schneider, William, 1978, Wainwright; land use values through time in the Wainwright area: Barrow, Alaska, U.S. National Park Service, North Slope Borough and Cooperative Park Studies Unit, 210 p. [Available from Rasmuson Library, University of Alaska, Fairbanks]

King, T.F., [1975], Letter *in* American Society for Conservation Archaeology: Reno, University of Nevada, Desert Research Institute Newsletter, v. 2, no. 2, p. 5-9.

Kunz, M.L., 1979, Archaeological survey in the Otuk and Iteriak Creek drainages, Alaska: Paper presented at the Alaska Anthropological Association, Sixth Annual Meeting, Fairbanks, 36 p. [Available from Bureau of Land Management, Arctic District Office, 1541 Gaffney Road, Fairbanks, Alaska 99703]

——— [1981], The Mesa site (KIR-102); an early holocene hunting station in the Iteriak valley, northern Alaska: Fairbanks, U.S. National Park Service, Gates of the Arctic National Park, 50 p. [Available from M.L. Kunz, P.O. Box 80087, Fairbanks, Alaska 99708]

Larsen, Helge, and Rainey, Froelich, 1948, Ipiutak and the Arctic Whale Hunting culture: Anthropological Papers of the American Museum of Natural History, v. 42, 276 p., 101 pls.

Leicht, R.C., 1980, Alaska's cultural resources: Anchorage, U.S. Bureau of Land Management, 97 p.

Lobdell, J.E., 1979, Archaeological reconnaissance of proposed construction localities at Prudhoe Bay, Alaska for 1979: Anchorage, Atlantic Richfield Oil and Gas Co., 29 p. [Available from Edwin S. Hall, Jr., 291 Main Street, Brockport, New York 14420]

Mason, J.A., 1930, Excavation of Eskimo Thule culture at Point Barrow, Alaska: Proceedings of the 23rd Congress of Americanists, New York, p. 383-394.

Mathiassen, Therkel, 1930, Archaeological collections from the western Eskimos: Copenhagen, Denmark, report of the 5th Thule Expedition, 1921-1924, v. 10, no. 1, 100 p.

Murdoch, John, 1892, The ethnological results of the Point Barrow expedition: Washington, Bureau of American Ethnology Annual Report 9, 441 p.

Reanier, R.E., 1981, An application of pedological and palynological techniques at the Mesa site, northern Brooks Range, Alaska: Fairbanks, Alaska, U.S. Bureau of Land Management, Fairbanks District Office, 46 p. [Available from Edwin S. Hall, Jr., 291 Main Street, Brockport, New York 14420]

Schiffer, M.B., and Gummerman, G.J., eds., 1977, Conservation archaeology; a guide for cultural resources management studies: New York, Academic Press, 495 p.

Schneider, William, Pedersen, Sverre, and Libbey, David, 1980, Barrow-Atqasuk; land use values through time in the Barrow-Atqasuk area: U.S. National Park Service, North Slope Borough and Cooperative Park Studies Unit Occasional Paper 24, 236 p.

Scott, G.R., [1976], Isatkoak Lagoon archaeological project, Barrow, Alaska: Barrow, North Slope Borough Historical Commission, 24 p. [Available from Edwin S. Hall, Jr., 291 Main Street, Brockport, New York 14420]

Schoenberg, K.M., [1978], Lookout Ridge and travel routes: Paper presented at the Alaskan Anthropological Association Fifth Annual Meeting, Anchorage. [Available from Edwin S. Hall, Jr., 291 Main Street, Brockport, New York 14420]

—— 1979, The archeology of the Utukok River, Alaska: Anchorage, U.S. National Park Service Regional Office, 26 p.

Slaughter, D.C., 1980, The 1980 testing program at Siraagruk, *in* Hall, E.S., Jr., ed., Cultural resource survey and clearance; National Petroleum Reserve in Alaska, 1980: U.S. Geological Survey, Office of National Petroleum Reserve in Alaska, 17 p.

Smith, P.S., and Mertie, J.B., Jr., 1930, Geology and mineral resources of northwestern Alaska: U.S. Geological Survey Bulletin 815, 351 p.

Solecki, R.S., 1950, A preliminary report of an archaeological reconnaissance of the Kukpowruk and Koklik Rivers in northwest Alaska: American Antiquity, v. 16, no. 1, p. 66-69.

—— 1951, Archaeology and ecology of the Arctic Slope of Alaska: Washington, Smithsonian Institution Annual Report for 1950, p. 469-495.

—— 1952, A petroglyph in northern Alaska: American Antiquity, v. 17, no. 1, p. 63-4.

Solecki, R.S., Salwen, Bert, and Jacobsen, Jerome, 1973, Archaeological reconnaissances north of the Brooks Range in northeastern Alaska: Calgary, Alberta, University of Calgary, Department of Archeology Occasional Paper 1, 105 p.

Stanford, D.J., 1971, Evidence of Paleo-Eskimos on the north coast of Alaska: Paper presented at the Society for American Archaeology Thirty-sixth Annual Meeting, Norman, Oklahoma, 24 p. [Available from Robert Gal, P.O. Box 1013, Kotzebue, Alaska 99752]

Stanford, D.J., 1976, The Walakpa Site, Alaska; its place in the Birnirk and Thule cultures: Washington, Smithsonian Contributions to Anthropology, v. 24, 226 p.

Stefansson, Vilhjalmur, 1914, The Stefansson-Anderson Arctic Expedition of the American Museum; preliminary ethnological report: Anthropological Papers of the American Museum of Natural History, v. 14, pt. 1, 395 p.

Stern, R.O., 1978, Preliminary report; cultural resources survey of the Ikpikpuk and upper Chipp Rivers, with narrative on the historic uses of these rivers and portions of the Colville rivers: Nome, Alaska Department of Fish and Game, Subsistence Division, 55 p. [Available from Edwin S. Hall, Jr., 291 Main Street, Brockport, New York 14420]

Thompson, R.M., 1948, Notes on the archaeology of the Utukok River, northwestern Alaska: American Antiquity, v. 14, no. 1, p. 62-65.

Van Valin, W.B., 1941, Eskimoland speaks: Caldwell, Idaho, The Caxton Printers, 239 p.

Wissler, Clark, 1916, Harpoons and darts in the Stefansson collection: Anthropological Papers of the American Museum of Natural History, v. 14, no. 2, p. 399-443.

APPENDIX 37.1 PAPERS AND REPORTS EMANATING FROM THE U.S. GEOLOGICAL SURVEY - BUREAU OF LAND MANAGEMENT CULTURAL RESOURCE SURVEY AND CLEARANCE PROJECT IN THE NATIONAL PETROLEUM RESERVE IN ALASKA

The following is intended to be a comprehensive list of all published, unpublished, and presented contributions that were derived from the work of this project. The list has been updated and therefore includes more recent versions of some reports cited in the text of the chapter.

PUBLICATIONS

Bowers, P.M., 1982, The Lisburne site; analysis of a multi-component lithic workshop in the Iteriak Valley, Arctic foothills, northern Alaska: Anthropological Papers of the University of Alaska, v. 20, no. 1-2, p. 79-112.

Bureau of Land Management, 1980, National Petroleum Reserve—Alaska; archaeology and energy exploration: U.S. Department of Interior pamphlet.

—— 1982, Your fragile legacy: Washington, Bureau of Land Management, color brochure.

Gal, Robert, 1982a, Archaeological sites in the vicinity of the South Meade test well: Anthropological Papers of the University of Alaska, v. 20, no. 1-2, p. 51-59.

—— 1982b, Excavation of the Tunalik site, northwestern National Petroleum Reserve in Alaska: Anthropological Papers of the University of Alaska, v. 20, no. 1-2, p. 61-78.

—— 1982c, Appendix I; An annotated and indexed roster of archaeological radiocarbon dates from Alaska, north of 68° latitude: Anthropological Papers of the University of Alaska, v. 20, no. 1-2, p. 159-180.

Gal, Robert, and Hall, E.S., Jr., 1982, A provisional view of North Alaskan cultural history: Anthropological Papers of the University of Alaska, v. 20, no. 1-2, p. 3-5.

Gerlach, S.C., 1982a, Prehistoric Inupiat adaptation at Tukuto Lake; a land-use history and cultural sequence for the Arctic foothills, interior northern Alaska [abs.]: American Quaternary Association Program and Abstracts, v. 94.

—— 1982b, Small site archaeology in northern Alaska; the Shoreline Bluff survey: Anthropological Papers of the University of Alaska, v. 20, no. 1-2, p. 15-49.

Gerlach, S.C., and Hall, E.S., Jr., 1988, The later prehistory of northern Alaska; the view from Tukuto Lake, *in* Shaw, R.D., Harritt, R.K., and Dumond, D.E., eds., The late prehistoric development of Alaska's native people: Aurora, Alaska Anthropological Association Monograph 4, p. 107-135.

Hall, E.S., Jr., 1982, The potential significance of small, single component archaeological sites for elucidating the culture history of northern Alaska: Anthropological Papers of the University of Alaska, v. 20, no. 1-2, p. 7-13.

Hall, E.S., Jr., and Gal, Robert, 1982, Introduction; archaeological investigations in the National Petroleum Reserve in Alaska: Anthropological Papers of the University of Alaska, v. 20, no. 1-2, p. 1-2.

Kunz, M.L., 1982, The Mesa site; an early Holocene hunting stand in the Iteriak Valley, northern Alaska: Anthropological Papers of the University of Alaska, v. 20, no. 1-2, p. 113-122.

Reanier, R.E., 1982, An application of pedological and palynological techniques at the Mesa site, northern Brooks Range, Alaska: Anthropological Papers of the University of Alaska, v. 20, no. 1-2, p. 123-139.

Slaughter, D.C., 1982, The Point Barrow type house; analysis of archaeological examples from Siraagruk and other sites in northern Alaska: Anthropological Papers of the University of Alaska, v. 20, no. 1-2, p. 141-158.

Stern, R.O., 1982, National Petroleum Reserve - Alaska; cultural resource investigations and management under Arctic conditions, *in* Stern, R.O., ed., Miscellaneous Publications, History and Archaeology Series, no. 31: Anchorage, Alaska Office of History and Archaeology, p. 318-326.

EDITED CONTRIBUTIONS

Bowers, P.M., ed., 1983, 1982 research news: Alaska Anthropological Association

Newsletter, v. 7, no. 3, p. 3-4.

Bowers, P.M., and Shaw, R.D., eds., 1981a, Research notes: Alaska Anthropological Association Newsletter, v. 6, no. 1, p. 4.

—— 1981b, Research notes: Alaska Anthropological Association Newsletter, v. 6, no. 2, p. 4.

Hall, E.S., Jr., and Gal, Robert, eds., 1982, Archaeological investigations in the National Petroleum Reserve in Alaska: Anthropological Papers of the University of Alaska, v. 20, no. 1-2, 191 p.

Myers, T.P., and Workman, W.B., eds., 1980, Current research, Far North, northwest Alaska: American Antiquity, v. 45, no. 1, p. 191-192.

—— 1981, Current research, Far North, northern Alaska: American Antiquity, v. 46, no. 2, p. 433-434.

Rothchild, N.A., and Workman, W.B., eds., 1982, Current research, Far North, northern Alaska: American Antiquity, v. 47, no. 4, p. 878-879.

Shaw, R.D., and Bowers, P.M., eds., 1980, Individuals and project news: Alaska Anthropological Association Newsletter, v. 5, no. 1, p. 5-6.

Workman, W.B., ed., 1979, Current research, northwest Alaska: Alaska Anthropological Association Newsletter, v. 4, no. 1, p. 8-9.

UNPUBLISHED MANUSCRIPTS AND REPORTS

Bowers, P.M., 1981, The Croxton site, Tukuto Lake, Arctic Alaska; background data for computer analysis of magnetometer survey data collected during the 1981 field season: MS., 14 p.

—— 1984, An experimental study of the effects of selected types of winter-time travel on surface archaeological sites on the Arctic Slope, Alaska: Bureau of Land Management interim final report, June 1984, 29 p.

Bowers, P.M., Kunz, M.L., and Gal, Robert, 1978, Appendix B; Archaeological investigations of Lisburne Borrow #1, KIR-096; preliminary report, *in* Hall, E.S., Jr., Cultural resource survey and clearance, National Petroleum Reserve in Alaska, 1978: U.S. Geological Survey unpublished report, 13 p.

Burch, E.S., Jr., 1980, Appendix D; Seasonal concentration zones in the NPR-A during the early historic period; report of an investigation carried out in July 1980, *in* Hall, E.S., Jr., Cultural resource survey and clearance, National Petroleum Reserve in Alaska, 1980: U.S. Geological Survey unpublished report, 10 p.

Davis, C.W., 1979, Appendix E; Field report, archaeological testing of site TES-014, Teshekpuk Lake, Alaska, *in* Hall, E.S., Jr., Cultural resource survey and clearance, National Petroleum Reserve in Alaska, 1979: U.S. Geological Survey unpublished report, 20 p.

Gal, Robert, 1980, Appendix E; BLM cultural resource survey activities in the NPR-A, *in* Hall, E.S., Jr., Cultural resource survey and clearance, National Petroleum Reserve in Alaska, 1980: U.S. Geological Survey unpublished report.

Gal, Robert, Bowers, P.M., and Kunz, M.L., 1979, Appendix B; BLM/USGS archaeological investigations in the NPR-A, summer 1979, *in* Hall, E.S., Jr., Cultural resource survey and clearance, National Petroleum Reserve in Alaska, 1979: U.S. Geological Survey unpublished report, 5 p.

Gerlach, S.C., 1981, An archaeological survey of an ancient shoreline bluff, Wainwright quadrangle, Alaska; a description of the lithic industries from seventeen prehistoric sites: MS.

—— 1982, Appendix A; A summary of archaeological research at Tukuto Lake, National Petroleum Reserve in Alaska, *in* Hall, E.S., Jr., A review of cultural resource survey and clearance activity, National Petroleum Reserve in Alaska, 1977-1982: U.S. Geological Survey unpublished report, 31 p.

Gerlach, S.C., Redding-Gubitosa, D., and Reinhard, K.J., 1980, Appendix C; Archaeological investigations of an ancient beach ridge, Wainwright quadrangle, Alaska, *in* Hall, E.S., Jr., Cultural resource survey and clearance, National Petroleum Reserve in Alaska, 1980: U.S. Geological Survey unpublished report, 25 p.

Hall, E.S., Jr., 1977, Cultural resource survey and clearance in NPR-A, 1977: U.S. Geological Survey unpublished report, 2 v., 99 p., 71 maps.

—— 1978, Cultural resource survey and clearance, National Petroleum Reserve in Alaska, 1978: U.S. Geological Survey unpublished report, 2 v., 168 p., 90 maps.

—— 1979a, Cultural resource survey and clearance, National Petroleum Reserve in Alaska, 1979: U.S. Geological Survey unpublished report, 2 v., 250 p., 20 maps.

—— 1979b, Appendix D; Examination of the Turner River overlook site, Arctic National Wildlife Range, *in* Hall, E.S., Jr., Cultural resource survey and clearance, National Petroleum Reserve in Alaska, 1979: U.S. Geological Survey unpublished report, 3 p.

—— 1980, Cultural resource survey and clearance, National Petroleum Reserve in Alaska, 1980: U.S. Geological Survey unpublished report, 167 p., 10 maps.

—— 1982, A review of cultural resource survey and clearance activity, National Petroleum Reserve in Alaska, 1977-1982: U.S. Geological Survey unpublished report, 65 p.

Huggins, R.J., 1982, Magnetic survey of the Croxton site, Tukuto lake, Blocks 1 and 3; final report: MS., 12 p.

Krause, R.A., 1979, Toward a formal account of Tukuto potting practices: MS.

Kunz, M.L., 1981, The Mesa site (KIR-102), an early Holocene hunting station in the Iteriak Valley, northern Alaska: MS., 50 p.

Newby, P., 1983, Flotation at the Croxton site, Tukuto Lake, Alaska; a survey of procedures and results: Providence, Rhode Island, Brown University, senior honors thesis, 60 p.

Reanier, R.E., 1981, An application of pedological and palynological techniques at the Mesa site, northern Brooks Range, Alaska: MS., 46 p.

Slaughter, D.C., 1979, Appendix C; Excavation at the site of Sisraruq, *in* Hall, E.S., Jr., Cultural resource survey and clearance, National Petroleum Reserve in Alaska, 1979: U.S. Geological Survey unpublished report, 9 p.

—— 1980, Appendix B; The 1980 testing program at Siraagruk, *in* Hall, E.S., Jr., Cultural resource survey and clearance, National Petroleum Reserve in Alaska, 1980: U.S. Geological Survey unpublished report, 18 p.

Speiss, A.E., 1978, Tukuto Lake site analysis; report on a collection of caribou bones from a late prehistoric Eskimo site: MS.

—— 1982, Croxton phase faunal analysis, Croxton site, Tukuto Lake, Alaska: MS.

Suter, S.M., and Gerlach, S.C., 1983, A description of the pollen in sixteen soil samples from the Croxton site, Tukuto Lake, Arctic Alaska: MS.

PAPERS PRESENTED AT PROFESSIONAL MEETINGS

Bowers, P.M. 1979a, Preliminary investigations of the Lisburne site (KIR-096), southeastern NPR-A, Alaska: Alaska Anthropological Association, Sixth Annual Meeting, Fairbanks, April 6-7, 30 p.

—— 1979b, Recent BLM/USGS archaeological fieldwork in the National Petroleum Reserve, North Slope, Alaska: Society for American Archaeology, Forty-fourth Annual Meeting, and Canadian Archaeological Association, Twelfth Annual Meeting, Joint session on recent research in Eskimo prehistory, Vancouver, British Columbia, April 25-27 [oral presentation only].

—— 1980, Technological and spatial considerations of the Lisburne site, Arctic foothills, northern Alaska: Alaska Anthropological Association, Seventh Annual Meeting, Anchorage, March 21-22 [oral presentation only].

—— 1982, Geoarchaeology of the Tukuto Lake Croxton site; geophysical and soils investigations in the Arctic foothills, northern Alaska: Alaska Anthropological Association, Ninth Annual Meeting, Fairbanks, April 2-3 [oral presentation only].

Gal, Robert, 1977, Archaeologists in the National Petroleum Reserve in Alaska: Alaska Anthropological Association, Fourth Annual Meeting, Fairbanks, April 8-9 [oral presentation only].

—— 1978, Preliminary report of USGS/BLM excavations at Tunalik, near Icy Cape, in the National Petroleum Reserve in Alaska: Alaska Anthropological Association, Fifth Annual Meeting, Anchorage, April 6-8 [oral presentation only].

—— 1979a, Archaeological applications of small-scale false-color infrared photography in the National Petroleum Reserve-Alaska: Alaska Anthropological Association, Sixth Annual Meeting, Fairbanks, April 6-7, 27 p.

—— 1979b, Strategies for site definition; three examples: Alaska Anthropological Association, Sixth Annual Meeting, Fairbanks, April 6-7, 14 p.

—— 1980, Tunalik; a preview of the final report: Alaska Anthropological Association, Seventh Annual Meeting, Anchorage, March 21-22 [oral presentation only].

—— 1981, Post-Denbigh occupations of Alaska's North Slope: Alaska Anthropological Association, Eighth Annual Meeting, Anchorage, March 14-15 [oral presentation only].

—— 1982a, An archaeologist's tour of northern Alaska: Alaska Anthropological Association, Ninth Annual Meeting, Fairbanks, April 2-3 [oral presentation only].

—— 1982b, Radiocarbon dating archaeological sites in northern Alaska; cultural-historical implications and problems: American Association for the Advancement of Science, Arctic Division, Thirty-third Alaska Science Conference, Fairbanks, September 15-16 [oral presentation only].

—— 1984, Photogrammetric mapping archaeological sites in Arctic Alaska; a feasibility test at the Sikoruk site at Tukuto Lake: Alaska Anthropological Association, Eleventh Annual Meeting, Fairbanks, 14 p.

Gal, Robert, Bowers, P.M., and Kunz, M.L., 1980, Recent Bureau of Land Management archaeological fieldwork in the National Petroleum Reserve-Alaska: Draft MS. distributed as supplement to poster presentation at Forty-fifth Annual Meeting of the Society for American Archaeology, Philadelphia, Pennsylvania, May 1-3, 57 p.

Gerlach, S.C., 1982, Croxton site, Tukuto Lake, northern Alaska; preliminary report: Alaska Anthropological Association, Ninth Annual Meeting, Fairbanks, April 2-3 [oral presentation only].

Gerlach, S.C., Reinhard, K.J., and Redding-Gubitosa, D., 1981, Some technological aspects of the core and microblade industry from WAI-107, a small site in northern Alaska: Alaska Anthropological Association, Eighth Annual Meeting, Anchorage, March 14-15 [oral presentation only].

Hall, E.S., Jr., 1980, The value of small site analysis for elucidating the culture history of northern Alaska: Alaska Anthropological Association, Seventh Annual Meeting, Anchorage, March 21-22, 12 p.

Kunz, M.L., 1979, Archaeological survey in the Otuk and Iteriak Creek drainages, Alaska: Alaska Anthropological Association, Sixth Annual Meeting, Fairbanks, April 6-7, 36 p.

—— 1980a, The Mesa site (KIR-102); an archaeological site in the Iteriak Valley, Alaska: Alaska Anthropological Association, Seventh Annual Meeting, Anchorage, March 21-22 [oral presentation only].

—— 1980b, Two archaeological sites in the vicinity of the South Meade test well: Alaska Anthropological Association, Seventh Annual Meeting, Anchorage, March 21-22 [oral presentation only].

—— 1981, The Mesa site; a summary of the 1978, 1979, and 1980 field seasons: Alaska Anthropological Association, Eighth Annual Meeting, Anchorage, March 14-15 [oral presentation only].

Speiss, A.E., and Gerlach, S.C., 1983, Some observations on the faunal remains from the Croxton Site, Tukuto Lake, Alaska: Alaska Anthropological Association, Tenth Annual Meeting, Anchorage, March 11-12, 22 p.

POSTER PRESENTATIONS AT PROFESSIONAL MEETINGS

Gal, Robert, 1980, National Petroleum Reserve-Alaska; archaeology and energy exploration: Society for American Archaeology, Forty-Fifth Annual Meeting, Philadelphia, Pennsylvania, May 1-3.

—— 1981, National Petroleum Reserve-Alaska; archaeology and energy exploration: American Association for the Advancement of Science, Arctic Division, Thirty-Second Alaska Science Conference, Fairbanks, August 25-27.

38. ENGINEERING GEOLOGY STUDIES IN THE NATIONAL PETROLEUM RESERVE IN ALASKA

By REUBEN KACHADOORIAN[1] and FREDERICK E. CRORY[2]

INTRODUCTION

PURPOSE AND SCOPE

The U.S. Geological Survey (USGS) has been charged with the responsibility of evaluating the petroleum potential of the National Petroleum Reserve in Alaska (NPRA). This work had already been initiated by the U.S. Navy, from whom the NPRA was transferred to the Department of the Interior. To help fulfill its responsibility, the USGS in February 1977 started an engineering geology program to provide the geotechnical support necessary for the exploration program. The USGS requested the U.S. Army Waterways Experiment Station (WES) at Vicksburg, Mississippi, and the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) at Hanover, New Hampshire, to conduct studies to obtain the physical parameters required to evaluate and solve some of the geotechnical and engineering problems.

All of the NPRA is underlain by permafrost, and thus virtually all of the engineering and geotechnical problems encountered during the construction of the well sites and subsequent drilling were associated with permafrost. The widespread occurrence of permafrost containing large amounts of near-surface ground ice in the form of wedges, masses, and intergranular ice required that construction activity not disturb the thermal regime of the ground surface, because such disturbance could lead to thawing of permafrost. Once the permafrost was thawed, ground subsidence, sediment flow, and impassable conditions would result. Construction problems were compounded by the necessity that all construction in the NPRA be done during the winter months to meet the environmental requirements. Therefore, the engineering geology program consistently addressed the impact of the environment on the facilities and the effect of the facilities on the environment.

LOCATION

The NPRA lies in the North Slope of Alaska north of lat 68° N. (fig. 38.1). Its northern boundary extends from the mouth of the Colville River on the northeast edge of the reserve along the Arctic coast west to Icy Cape, at about long 161°52′32″ W, on the west edge of the reserve. From there the boundary extends south to the crest of the DeLong Mountains, then eastward following the crest of the DeLong and Endicott Mountains of the Brooks Range to about long 155°22′30″ W. The boundary then goes north, intercepts the Colville River in the vicinity of Killik Bend, and follows that river east and then north to the Arctic Ocean.

GEOGRAPHY

The northern half of the NPRA lies in the low, poorly drained, lake-dotted Arctic Coastal Plain physiographic province (Wahrhaftig, 1965). The Arctic Coastal Plain rises imperceptibly from the Arctic Ocean to an altitude less than 150 m (500 ft). The southern half of the reserve lies in the rolling plateaus and low linear mountains of the Arctic foothills and in the rugged glaciated terrain of the DeLong Mountains and Central and Eastern Brooks Range physiographic provinces. With the exceptions of Seabee, Lisburne, and Awuna (fig. 38.1), all of the wells drilled in the reserve between 1975 and 1981 are in the Arctic Coastal Plain physiographic province.

GEOLOGIC SETTING

The NPRA is underlain by unconsolidated sediment of Quaternary age that overlies bedrock ranging from Devonian to Cretaceous in age. The unconsolidated sediment consists of marine silt, sand, and beach deposits, upland silt, eolian sand, alluvium, and glacial debris (fig. 38.2; Williams and others, 1977). The marine beach deposits, consisting chiefly of fine gravel, occur north of Barrow, on barrier islands, and along the coast as isolated patches west of Barrow to the edge of the reserve. The marine silt occurs along the coast from Barrow to about the eastern edge of the

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reserve. Marine sand occurs chiefly in the western part of the reserve but also in isolated patches in the eastern part. The most widespread unconsolidated sediment is eolian silt and sand that occur mainly in the flat-lying, lake-dotted central and eastern parts of the reserve. Much of the eolian silt and fine sand has been reworked by stream and lake action. A band of upland silt extends all the way from the eastern to the western boundary of the reserve and marks the geologic boundary between the unconsolidated sediment in the north and the outcrop area of bedrock in the south. Alluvium occurs along the courses of all the streams and rivers and consists of fine sand and silt in the low-lying area of the reserve and gravel in the larger rivers, such as the Colville, that drain the mountainous terrain of the reserve. Glacial debris occurs only in the southern part of the reserve and consists chiefly of till and minor amounts of outwash.

The bedrock underlying the unconsolidated sediment in the north-

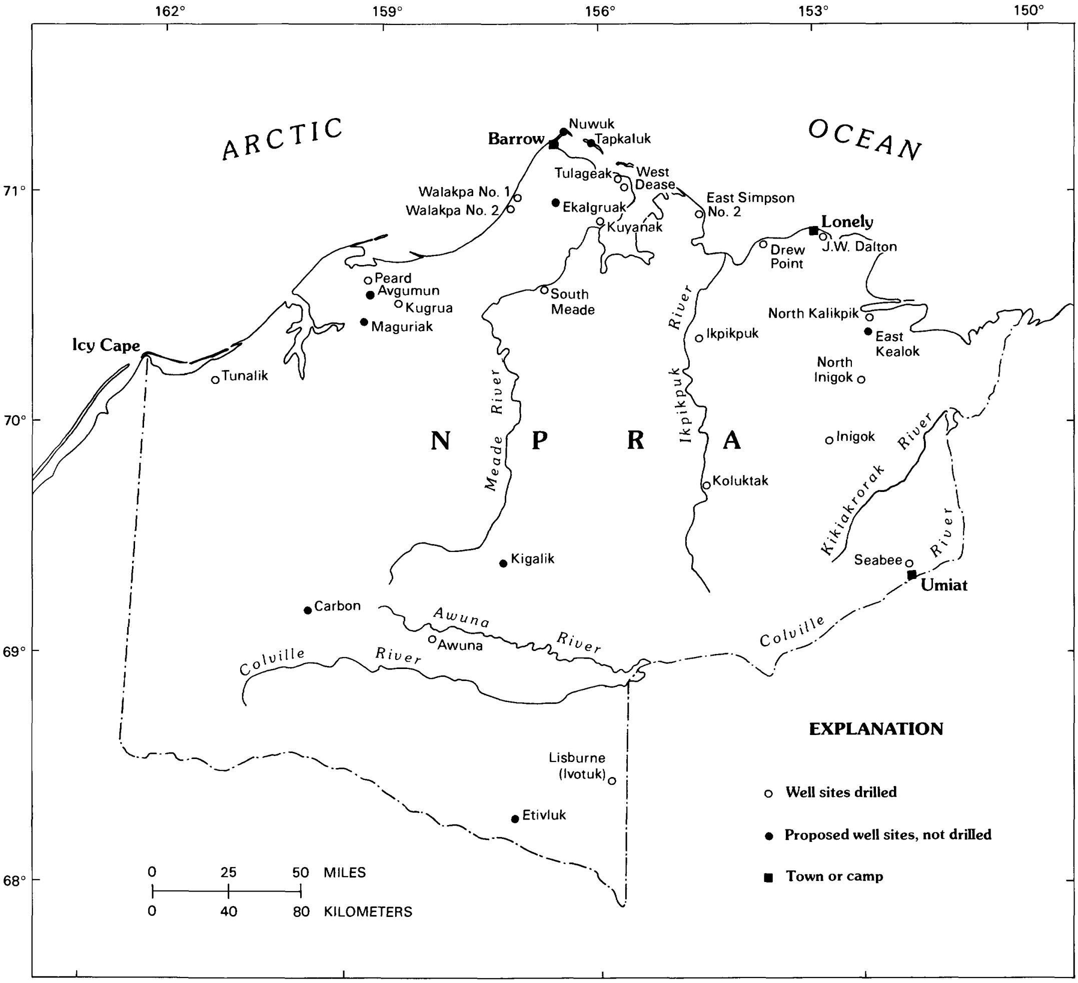
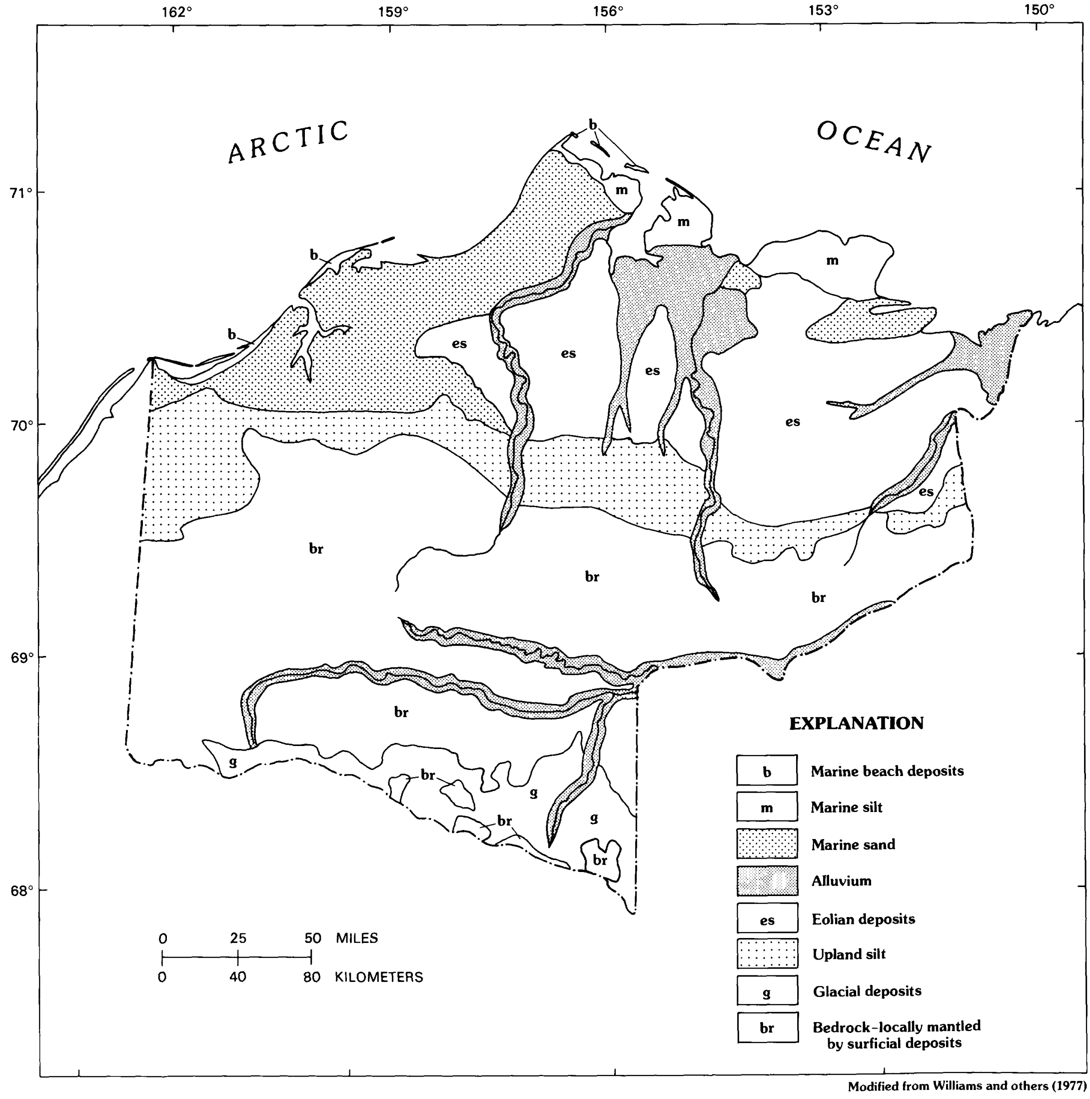


FIGURE 38.1.—Locations of proposed and drilled well sites in the National Petroleum Reserve in Alaska (NPRA).

ern part of the reserve consists chiefly of sedimentary rocks. Igneous and metamorphic rocks occur in the southern part of the reserve but are locally mantled by colluvium and glacial debris.

INVESTIGATIONS

The engineering geology program in the NPRA consisted of engineering studies by CRREL and WES under contract to the USGS' Office of the National Petroleum Reserve in Alaska (ONPRA) and geologic studies by the USGS. The engineering and geologic studies consisted of cooperative and interrelated investigations



Modified from Williams and others (1977)

FIGURE 38.2.—Surficial geology of the National Petroleum Reserve in Alaska.

between CRREL, WES, and the USGS and were designed to help solve, or minimize the effects of, permafrost-related geotechnical problems. CRREL conducted both field and laboratory investigations. Laboratory studies included thermal analysis of insulation, gradation of available soils in relation to compaction and bearing capacity, and thaw settlement. The field studies concentrated on installation of thermocouples and monitoring of ground temperatures at the facilities and special test sections.

WES conducted several large-scale tests at Vicksburg, Miss., to evaluate different concepts for runway construction. Five separate test sections were trafficked by a test cart simulating the wheel loading of C-130 Hercules aircraft.

We conducted geologic and engineering field investigations at 29 proposed well sites during the field seasons of 1977 to 1980 inclusive (fig. 38.1; table 38.1). The investigations included determination of the geologic setting, a search for sources of construction material, and determination and evaluation of possible geotechnical and construction problems. All of the sites selected were drilled during the winter months with the exception of Tunalik, Inigok, and Lisburne, which were drilled the year round. The Awuna well required two winters of drilling. The field studies concentrated on evaluating the geotechnical problems at the deep all-year well sites of Tunalik, Inigok, and Lisburne (the airstrip at the Lisburne well site was called Ivotuk). Such studies were necessary because these facilities required the construction of all-season airstrips and associated facilities to support the long and continuous drilling effort.

The major purpose of this chapter is to discuss the all-season well sites of Tunalik, Inigok, and Lisburne (Ivotuk). We have also included a discussion of the winter-only drilling site at Seabee because special engineering studies were made at that site.

Acknowledgments.—The engineering geology investigations program in the NPRA, which included all work done under contract by CRREL and WES, was funded by ONPRA. Fieldwork was greatly facilitated by the cooperation and support of John Ireton and Tom Brooks of Husky Oil NPRA Operations, Inc., and of the Husky Oil personnel at Camp Lonely. Arthur Gidney, David Atwood, Mark Connolly, and Richard Berg of CRREL provided office and field support. Ronald Hutchinson, Alfred Joseph, and Cecil Burns of WES furnished advice and counsel on many of the engineering problems.

WINTER WELL SITES

Investigations of the winter well sites included geologic and engineering evaluations of the proposed sites, drilling pads, and ice airstrips and searches for sources of construction materials. The location, geologic setting, sources of construction, and pertinent remarks regarding each site are given in table 38.1. Special studies were made at the winter Seabee site, and those are discussed in more detail in the following section. The wells at the winter sites, with the exception of Awuna, were each drilled in a single winter and thus were not subjected to the effects of thaw during the summer months. The Awuna well required two winters to drill and was shut down during the intervening summer. The Awuna drill pad and reserve pit had some subsidence because the frozen material in the pad and reserve pit thawed during the summer. This subsidence required maintenance before it was possible to start up for the second winter of drilling.

SEABEE WELL SITE

The Seabee well was located about 1.5 km (1 mi) northwest of the existing State-owned airport at Umiat. The well site was at lat 69°22′48.12″ N., long 152°10′31.29″ W. During the summer of 1978 the airfield was closed to all large aircraft because a C-130 blew a tire on landing. Large surface cobbles and boulders were considered the cause of the blowout. The Umiat airfield, accordingly, was overlaid with a new gravel surfacing in the spring of 1979, permitting drill-rig movements and year-round access for supplies and crew changes. To avoid congestion at the existing parking apron near the south-central portion of the airfield, a new parking apron with a short taxiway was constructed just north of the west end of the runway. From this new parking apron an uninsulated gravel road was constructed to the well site. Gravel borrow pits, on both sides of this road, provided the gravel for the parking apron, road, drill pad, and runway resurfacing.

Previously constructed gravel roads on a thin pad at Umiat, especially to the north of the airfield, had suffered serious damage from permafrost degradation (Ferrians and others, 1969). The uninsulated access road to the Seabee well was designed on the basis of a gravel-fill section 1.2-1.8 m (4-6 ft) thick. The drill pad was also constructed as a thick gravel-fill section like the road; only the areas beneath and adjacent to the drill rig and camp were underlaid with insulation.

A view of the Seabee drill pad is shown in figure 38.3. All construction took place between January and April 1979. Personnel were based at a temporary construction camp located just east of the new parking apron.

Only minor maintenance was required on the new access road to the Seabee well. To evaluate the effectiveness of this thicker gravel roadway, thermocouples were placed at two locations, several hundred meters apart. One assembly was installed in a new section of the road, while the other assembly was in a section where the new road was built over an old road. Although little road damage was anticipated in the first year or two, these initial temperature observations will be important in assessing the long-term changes. Both assemblies were left in place for future monitoring. The greatest problem experienced was on the Seabee access road, where several culverts were washed out during the sudden spring breakup of 1980.

Selected pilings around the Seabee well were instrumented with thermocouples to define the radial heat flow. Attempts to monitor the temperature on the outside of the conductor pipe failed when the thermocouple temperature assembly was ruined during the initial cement-grouting operations. The thermocouples on the rig piling, however, provided the desired information throughout the drilling period. Two additional temperature assemblies were used to determine the effectiveness of the reserve-pit slope insulation, in the area where the drill cuttings were deposited and beneath the bottom of the reserve pit. Another assembly in the north dike, in an active erosion area, will be used to measure the long-term thermal changes at this location.

Two attempts were made to install temperature assemblies beneath the uninsulated Umiat runway for direct comparison with the insulated runways installed at Tunalik, Inigok, and Lisburne (Ivotuk). Both attempts failed, however, when large cobbles and caving holes stopped the drilling efforts below 1.8-2.4 m (6-8 ft).

ALL-SEASON WELL SITES

The Tunalik, Inigok, and Lisburne wells had target depths greater than 5,000 m (17,000 ft) and required more than 360 days of continuous drilling to complete. In support of these all-season wells, geologic and engineering studies were made to evaluate the geotechnical problems of the proposed well sites, airstrips, parking aprons, and roads and to determine sources of construction materials. These all-season wells required all-year airstrips to provide a means of getting continuous supplies to the well sites, including the bringing in of another drill rig in the event of a blowout. This required an airstrip 45 m (150 ft) wide and 1,600 m (5,200 ft) long to handle the C-130 aircraft necessary to support the drilling programs.

A thorough search was made during the summer of 1977 for a source of gravel to construct the all-year airstrips, parking aprons, roads, and construction pads for the Tunalik and Inigok wells. However, no ample and readily available local source of gravel was found, and therefore a serious design problem for the Tunalik and Inigok wells arose. The lack of readily available gravel to construct an all-gravel airstrip at least 1.5 m (5 ft) thick led us to consider other design concepts such as the use of a landing mat or insulation. Such insulation had been recently used for several roads, portions of the work pad for the Trans-Alaskan Pipeline, and the Kotzebue airport (Penner, 1976; Esch and Rhode, 1977; Wellman and others, 1977).

TESTS OF DESIGN CONCEPTS

Local frozen material, overlain by insulation and covered by a limited thickness of gravel, had not been used to construct an airstrip where heavy aircraft were to land. Consequently, WES was requested to undertake large-scale tests to obtain the physical parameters necessary to design and construct such airstrips. The results of these tests were published by Burns (1979).

Five separate test sections were constructed to evaluate the following designs:

(1) Prefabricated aluminum landing mat over Styrofoam[3] insulation overlying a high-strength subgrade representing frozen material,

(2) Gravel base course overlying Styrofoam insulation overlying a high-strength subgrade representing frozen material,

(3) Gravel base overlying a loosely placed saturated sand fill,

(4) Sand-grid confinement in loosely placed saturated sand fill, and

(5) Sand-grid confinement in highly compacted sand fill.

Small-scale runway test sections were constructed for each of the designs, traffic-tested with a load cart simulating a C-130 aircraft, and evaluated on their performance. CRREL conducted laboratory analyses of the sand from selected borrow sites in the vicinity of the airstrips, gravel from a borrow pit about 10 km (6 mi) from the Tunalik site, and gravel from the confluence of the Colville and Kikiakrorak Rivers about 58 km (36 mi) from the Inigok site. WES used the data to simulate as closely as possible the type of sand and gravel that would

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[3] Extruded-polystyrene foam-board insulation manufactured by the Dow Chemical Co.

TABLE 38.1.—*Location, geologic setting, and construction-material sources of proposed and drilled well sites in the National Petroleum Reserve in Alaska*

Well site	Location	Geologic setting	Construction material	Remarks
Awuna	Lat: 69°09'11.58" N. Long: 158°01'21.37" W.	Site on 5° slope underlain by colluvium with ice-rich permafrost within 1 ft of surface. Locally, ice 30 ft thick. Shale underlies colluvium.	From terrace deposits along Awuna River 1 mi N. of site or from reserve pit.	Ice-rich permafrost and slope presented maintenance problems because well drilled during two winters. No summer drilling.
Drew Point	Lat: 70°52'47.14" N. Long: 153°53'59.93" W.	Site on low-lying area underlain by marine silt containing permafrost, locally ice-rich; permafrost within 2 ft of surface.	From reserve pit containing silt.	No major geotechnics-related problems encountered; drilled during winter.
E.Simpson No. 2	Lat: 70°58'42.51" N. Long: 154°40'25.74" W.	Site on flat-lying area underlain by marine silt containing permafrost, locally ice-rich; permafrost within 2 ft of surface; site in center of one of many polygons that are common in area.	From shoreline of Smith Bay about 2 mi E. of site or from reserve pit containing silt.	Do.
Ikpikpuk	Lat: 70°27'19.68" N. Long: 154°19'52.78" W.	Site on reworked sand dune in low-lying swampy area underlain by eolian silt and sand containing permafrost; permafrost within 1.5 ft of surface.	From ancient lake shoreline containing silt and sand or from reserve pit containing silt.	Do.
Inigok	Lat: 70°00'17.48" N. Long: 153°05'56.92" W.	Site on dune sand modified by lake action; eolian sand is fine grained; permafrost within 1 ft of surface. See text.	See text.	See text.
J.W.Dalton	Lat: 70°55'13.79" N. Long: 153°08'15.10" W.	Site on flat-lying area underlain by marine silt with some sand. Depth of permafrost unknown but probably within 3 ft of surface.	From ancient bay mouth bars 3.5 mi SE. of site. Deposits are sandy gravel of marine origin.	Borrow sites are about 3 to 3.5 ft above sea level. Inward side of bay mouth bars are lagoon areas containing liquefiable silt and sand; drilled during winter.
Koluktak	Lat. 69°45'08.62" N. Long. 154°36'40.12" W.	Site on terrace containing sand that has been modified by eolian sand and silt. Site underlain chiefly by fine- to medium-grained sand containing permafrost within 1.5 ft of surface.	Ample supply of material can be obtained locally. Material fine- to medium-grained sand with some gravel about 1.5 mi NNW. of site.	No major geotechnics-related problems encountered; drilled during winter.
Kugrua	Lat. 70°35'12.28" N. Long. 158°39'43.26" W.	Site on flat, poorly drained area underlain by lake sediments overlying marine silt. Permafrost within 1.5 ft of surface in ice-wedge polygons.	Best source from terrace containing marine and nonmarine medium-grained sand with some gravel about 1.5 mi NNW. of site.	Do.
Kuyanak	Lat. 70°55'53.48" N. Long. 156°03'53.08" W.	Site in abandoned lake, generally swampy, and underlain by lake sediments that, in turn, are underlain by marine silt and sand. Permafrost is within 1.5 ft of surface and, locally, is ice rich.	From reserve pit containing marine swampy lake sediments.	Do.
Lisburne	Lat. 68°29'05.44" N. Long: 155°41'35.51" W.	Site on dry moderately steep slope underlain by colluvium and glacial debris. Depth to permafrost unknown but may be within 5 ft of surface. See text.	See text.	See text.
N. Inigok	Lat. 70°15'27.32" N. Long. 152°45'57.53" W.	Site on dune sand, about 100 ft wide and 0.5 mi long, that was once shoreline of ancient lake. Eolian sand is fine grained with generally ice-poor permafrost. Permafrost within 3 ft of surface.	From local area or reserve pit consisting of fine-grained sand.	Upper 5 ft of permafrost is dry permafrost. No major geotechnics-related problems encountered; drilled during winter.
N. Kalikpik	Lat. 70°30'33.023" N. Long. 152°22'04.169" W.	Site on low-lying swampy area in old drained lake underlain by silt. Permafrost is within 1 ft of surface.	From borrow sites about 4.5 mi SE. of well site containing silty sands.	No major geotechnical problems encountered; drilled during winter.
Peard	Lat: 70°42'56.21" N. Long: 159°00'02.52" W.	Site on low-lying swampy area underlain by swamp debris that in turn is underlain by marine silt. Permafrost is within 1 ft of surface and locally ice rich.	From Kugrua Bay about 4.5 mi NNE. of site and from reserve pit. Kugrua Bay site contains fine gravel, peat; reserve pit contains swamp debris.	Kugrua Bay borrow site contains peat debris. No major geotechnics-related problems encountered; drilled during winter.
Seabee	Lat: 69°22'48.12" N. Long: 152°10'31.29" W.	Site on high relatively dry old Colville River terrace containing gravel; permafrost within 3 ft of surface. See text.	See text.	See text.

S. Meade	Lat: 70°36'53.92" N. Long: 156°53'23.60" W.	Site is an old terrace of Meade River and is underlain by fine-grained sand containing permafrost; permafrost within 2 ft of surface.	From terrace deposits at site containing fine-grained sand.	No major geotechnics-related problems encountered; drilled during winter.
Tulageak	Lat: 71°11'26.62" N. Long: 155°44'00.82" W.	Site in flat-lying area with less than 2 ft of relief underlain by marine silt containing ice-rich permafrost; permafrost within 1 ft of surface.	From reserve pit containing ice-rich silt.	Do.
Tunalik	Lat: 70°12'21.45" N. Long: 161°04'09.15" W.	Site on relatively high area underlain by marine silts with some sand; permafrost within 1 ft of surface. See text.	See text.	See text.
W. Dease	Lat: 71°09'32.65" N. Long: 155°37'45.19" W.	Site on old drained lake in low-lying swampy area; underlain by frozen silt that, in turn, is underlain by marine silt; permafrost within 9 in. of surface and locally ice rich	From reserve pit containing silt.	No major geotechnics-related problems encountered; drilled during winter.
Walakpa No. 1	Lat: 71°05'57.63" N. Long: 156°53'03.79" W.	Site on flat-lying terrain underlain by marine site containing permafrost, locally ice rich; permafrost within 10 in. of surface.	-------------Do.--------------	Do.
Walakpa No. 2	Lat: 71°3'00" N. Long: 156°57'10" W.	Site in low-lying swampy area containing polygons and underlain by frozen marine silt, locally sandy; permafrost within 10 in. of surface and locally ice rich.	-------------Do.--------------	Do.
Avgumun	N1/2 sec. 12, T. 15 N., R. 29 N., Umiat Meridian	Site on flat-lying area with polygons. Site underlain by locally ice-rich marine silt. Permafrost within 1 ft of surface.	-------------Do.--------------	Well not drilled.
Carbon	NW1/4NE1/4, sec. 31, T. 2 N., R. 34 W., Umiat Meridian	Site on relatively high dry slope underlain by colluvium of unknown thickness overlying sandstone.	From borrow site about 0.25 mi SE. of site containing colluvium and friable sandstone.	Do.
E. Kealok	NW1/4 sec. 19, T. 12 N., R. 2 W., Umiat Meridian	Site on 1° to 2° sloping surface, generally dry and underlain by marine fine-grained sand and silt. Permafrost within 1.5 ft surface.	From reserve pit containing fine-grained sand and silt.	Do.
Ekalgruak	Sec. 34, T. 19 N., R. 11 W., Umiat Meridian	Site is low-lying swampy area underlain by frozen marine silt; permafrost within 1 ft of surface and locally ice rich.	From reserve pit containing silt.	Do.
Etivluk	NW1/4SE1/4, sec. 20, T. 12 S., R. 21 W., Umiat Meridian	Site on relatively high dry area underlain by windblown silt and sand that in turn is underlain by colluvium of unknown thickness. Depth to permafrost unknown but estimated to be about 3 ft below the surface.	From four borrow sites 0.5 mi N. and E. of well site in cherty or quartzitic sandstone and from site about 4.75 mi SE. of well site containing terrace gravels.	Do.
Kigalik	SE1/4, sec. 6, T. 1 N., R. 22 W., Umiat Meridian	Site on relatively high dry area underlain by colluvium of unknown thickness overlying sandstone; depth to permafrost unknown but probably within 3 ft of surface.	From borrow site about 0.3 mi NW. of site containing arkosic sandstone, locally friable.	Do.
Maguriak	NE1/4, sec. 15, T. 12 N., R. 8 W., Umiat Meridian	Site on swampy area of drained lake. Underlain by lake sediments that in turn are underlain by marine silt; permafrost, locally ice rich, within 1.5 ft of surface.	From borrow site, about 1.5 mi NNE. of well site, containing medium- to coarse-grained sand.	Do.
Nuwuk	Sec. 32, T. 24 N., R. 17 W., Umiat Meridian	Site on beach gravel about 10 ft above sea level; permafrost at unknown depth but estimated to be 10 ft below surface.	From reserve pit containing gravel.	Well not drilled; locally gravel beach has ice scars caused by overriding of winter ice from Arctic Ocean.
Tapkaluk	On largest of Tapkaluk Islands between Elson Lagoon and Beaufort Sea,about 13-1/2 mi E. of Barrow	Site on gravel island about 3 ft above sea level; depth of permafrost unknown.	From reserve pit containing pea-sized gravel.	Well not drilled.

be actually used in the construction of the Tunalik and Inigok airstrips.

LANDING MAT AND GRAVEL OVER INSULATION

The objective of this test section was to evaluate the performance of a runway using Styrofoam insulation over frozen material, with a prefabricated landing mat or gravel surfacing over the insulation. The test section was 24 m long by 8 m wide (80 ft by 25 ft) and divided into two test items, each 12 m (40 ft) long. The subgrade of both test items consisted of a lean clay, well compacted to produce a relatively high-strength soil representing frozen material, and was overlaid with two layers of HI-60 (414 MPa or 60 psi compressive strength) Styrofoam insulation material 4 cm (1.5 in) thick. One of the test items was surfaced by an XM 19 aluminum landing mat and the other by 50 cm (20 in.) of gravelly sand.

The test items were then subjected to 1,250 passes, equivalent to about 850 C-130 operations, with a 155,000-N (35-kip) single-wheel C-130 load. No damage to the insulation was evident at the conclusion of the testing. Since there had been no damage to the insulation under the 50 cm (20 in.) of gravel, it was decided to remove the top 25 cm (10 in.) to determine if the lesser thickness of gravel would still protect the insulation. About 240 passes of the 35-kip single-wheel load were then made on the gravel-covered test section. An examination of the insulation at the conclusion of this test indicated that the Styrofoam boards had been compressed.

As a result of these tests, it was concluded that (1) an XM 19 aluminum mat placed over HI-60 Styrofoam insulation would provide a satisfactory runway for C-130 aircraft, provided the insulation kept the subbase frozen, (2) a good-quality gravel base course 50 cm (20 in.) thick over HI-60 Styrofoam insulation would protect the insulation from compressing under the C-130 aircraft loading, but it might require some surface maintenance during repeated aircraft operations, especially during the spring thaw, and (3) a gravel base course 25 cm (10 in.) thick over the insulation was insufficient to protect the HI-60 Styrofoam. If the insulation were crushed or cracked it was assumed that the insulating value would degrade and that the subbase would thaw and subside, rendering the airfield inoperable.

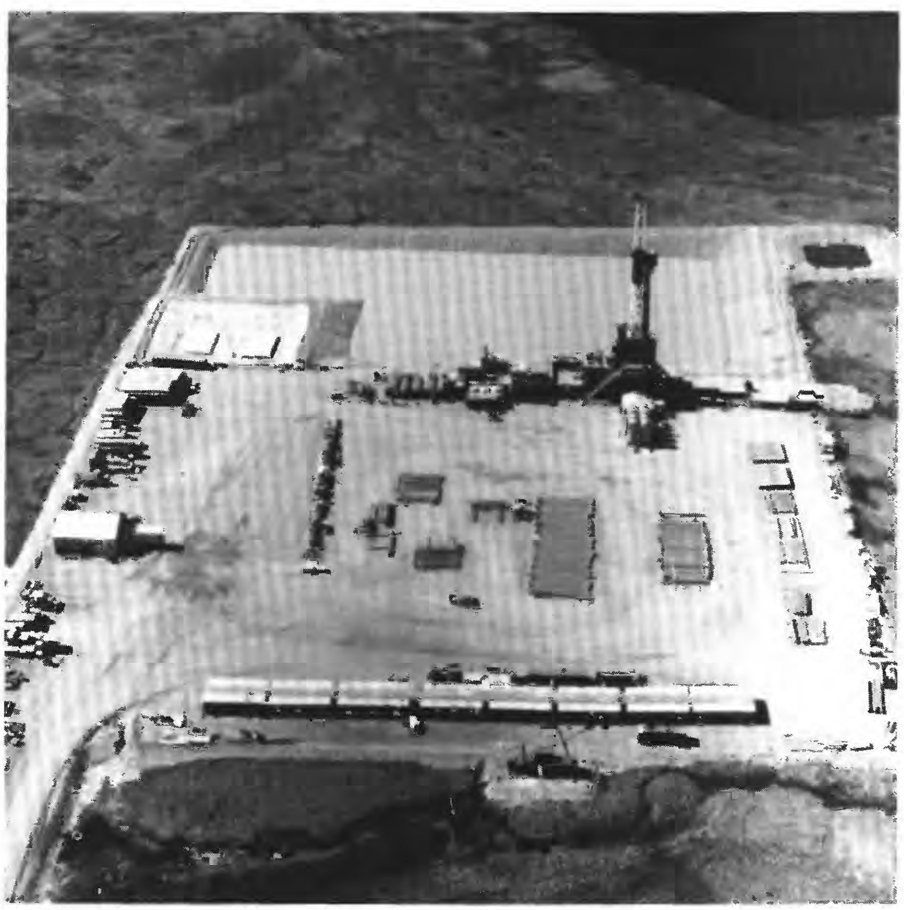

FIGURE 38.3.—Seabee well site with drill camp in foreground and reserve pit in background. Note polygonal ground features. Photograph taken in July 1979, looking west.

GRAVEL OVER SATURATED SAND

The objective of this investigation was to determine if a fill initially consisting of frozen sand and overlain by 50 cm (20 in.) of gravel would sustain C-130 aircraft traffic after the sand thawed and was in a saturated condition.

The section in which gravel overlying saturated sand was tested was 43 m long by 8 m wide (140 ft by 25 ft) and consisted of three test items, each 12 m (40 ft) long, with 3-m (10-ft) transitions between them. Surfacing of item 1 consisted of 50 cm (20 in.) of gravel overlying 15 cm (6 in.) of saturated sand; on item 2 it consisted of 50 cm (20 in.) of gravel overlying 90 cm (36 in.) of saturated sand; on item 3 it was the same as on item 2 except that filter-cloth fabric[4] was used to line the walls of the excavation and was placed horizontally at 30-cm (1-ft) intervals in the sand fill. The filter fabric was used to reinforce the sand and improve the drainage of the sand, thereby increasing its load-carrying capacity.

All the items in this test section were subjected to 155,000-N (35-kip), single-wheel C-130 loads and a 310,000-N (70-kip), single-tandem gear assembly representing one main landing gear of the C-130 aircraft. The results from this test indicated that 50 cm (20 in.) of gravel placed over a frozen sand similar to that at Inigok, without insulation, would be marginal at best for C-130 aircraft operations after the sand thawed, depending on how well the sand drained. If the sand were saturated, an unstable condition would probably exist. If the sand at Inigok could be completely drained and consolidated as thawing progressed, stability could be maintained by surface compaction and maintenance. However, this might render the runway unserviceable during the first spring breakup following construction.

SAND-GRID CONFINEMENT

The lack of readily available gravel for airfields, roads, and drill pads in the NPRA prompted an investigation of ways to confine the widespread sands in a flexible grid, so that perhaps only limited gravel would be required. This concept was studied at WES by placing a paper grid in the upper portions of sand fills[5].

This test section was constructed in a trench, 8 m wide by 49 m long (25 ft by 160 ft), and consisted of five test items, each about 9 m (30 ft) and 8 m (25 ft) wide. The sand in items 1 through 4 was 120 cm (48 in.) deep, overlaid with 15 cm (6 in.) of washed gravel. In item 1 a single layer of grids 15 by 15 by 15 cm (6 by 6 by 6 in.) was placed in the top 15 cm (6 in.) of the sand underlying the gravel. In item 2, two layers of the same grids were constructed in the top 30 cm (12 in.) of sand fill. In item 3, three layers of the grids were placed in the top 45 cm (18 in.) of the sand fill underlying the gravel. These items were designed to determine the depth of sand confinement needed to support the C-130 aircraft loading. Item 4 had two layers of sand-filled grids overlying a variable-strength subgrade. This item was designed to determine the performance of the sand-grid system when differential thawing and settlement occurred. Item 5 had two layers of the sand-filled grids placed on insulation lying on a firm foundation simulating a frozen material.

In addition to the test section described above, WES also made studies to determine the feasibility of placing frozen sand in the grid confinement system.

The section was tested by using a load cart equipped with a 310,000-N (70-kip) single-tandem gear load simulating one main gear of a C-130 aircraft. Results of the test indicated that (1) a single 15-cm (6-in.) layer of the paper grid will not confine saturated loose sand adequately to sustain traffic of C-130 aircraft or vehicular traffic, (2) two or three such grid layers, 30-45 cm (12-18 in.) thick, filled with highly compacted sand will adequately confine the sand and prevent shear and displacement of the sand below the grid layers under C-130 aircraft traffic, (3) the paper grid overlying a variable-strength foundation conforms to the settlement in the foundation but is still effective in confining the sand, (4) using grids filled with saturated frozen sand is not feasible because of the difficulties in placing the frozen sand in the grids, the low density and high water content of the sand after thawing, and the probability of very slow drainage after the sand thawed, and (5) after drainage and drying to about optimum water content, the sand can be compacted in the grids to high densities with standard techniques without damaging the grid.

GRAVEL THICKNESS REQUIRED TO PROTECT THE INSULATION

The earlier tests by WES indicated that 50 cm (20 in.) of gravel over HI-60 Styrofoam would protect the board insulation from compression under the C-130 aircraft loading, but a 25-cm (10-in.) thickness of gravel overlying the insulation was inadequate to protect the insulation. Once the decision to use gravel over insulation for the runway construction at the Inigok and Tunalik well sites was made, it became imperative to determine the lower limit of gravel thickness required to protect the insulation. The high costs of mining and hauling the gravel, especially at Inigok during the limited winter construction period, made a clear determination of this minimum required thickness of gravel extremely important.

Accordingly, a new test section 23 m long by 8 m wide (75 ft by 25 ft) consisting of three test items, each 8 m (25 ft) square, was constructed. Gravel 38, 44, and 50 cm (15, 17.5, and 20 in.) thick, overlying a lean, compact, clay soil representing a frozen soil, was placed on the three test items. Fourteen patterns of C-130 traffic, in 480 passes, were applied to the test section, resulting in 280 coverages of a loaded tire in the center 115 cm (45 in.) of the traf-

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[4] The filter fabric was a span-bonded, needle-punched, polyester, nonwoven material called "Bidim," with a unit weight of 468 g/m² (12 oz/yd²), manufactured by the Monsanto Textiles Co.

[5] The paper grid was manufactured by the Hexcell Corp. and employed linerboard treated with a phenolic resin.

fic lane or an equivalent of 1,134 C-130 aircraft operations. Based on these tests it was determined that a minimum thickness of 38 cm (15 in.) of good-quality well-compacted gravel would protect the HI-60 Styrofoam insulation material from detrimental crushing under C-130 aircraft.

INIGOK WELL SITE

The exploration well at Inigok was to be deeper than 5,800 m (19,000 ft). Such a well would require about 380 days to drill. For such a prolonged drilling period an all-season airstrip was required. In the summer of 1977, immediately following the siting of the well at lat 70°00′17.48″ N., long 153°05′56.92″ W. (fig. 38.1), the search for a suitable location for the all-season airstrip was initiated. The most promising location was a long ridge, about 0.8 km (0.5 mi) southeast of the well, approximately paralleling the direction of the prevailing winds (northeast). This location required only the shortest connecting road and no crossing of any streams between well site and airfield.

The Inigok site is surrounded by numerous lakes, which are common in the Arctic Coastal Plain province. The well and airstrip were just south and north of two large lakes (fig. 38.4). The site is underlain by fine reworked eolian sand and silty sand that are permanently frozen, except in the active layer, which annually thaws and refreezes to a depth of 30-90 cm (1-3 ft). Polygonal ice wedges are found on the gentle slopes of ridges and on low-lying terrain throughout the area, although in some parts there is little or no surface indication of such features. The ground surface is mantled by low grass tussocks and dwarf willows except on the hilltops, where the exposed sand supports isolated grass tussocks, moss, lichen, and wildflowers. The organic layer or A horizon at the Inigok airfield is seldom more than 30 cm (1 ft) thick along the ridge, and no peat or other organic material is found at depth.

Although many low-level helicopter flights were made to locate gravel along nearby streams, the closest sources were found to be on the Kikiakrorak River, 56 km (35 mi) to the southeast of the Inigok site, and at the confluence of the Kikiakrorak and Colville Rivers, 58 km (36 mi) to the east of Inigok. The latter source was easier to develop, because of the absence of frozen overburden and the easier route over which the gravel would have to be transported.

The lack of nearby gravel sources forced the consideration of several alternative design options for the Inigok airstrip, road, and drill pad. These options included the use of soil cement, military landing mats, or insulation with a relatively thin layer of gravel. Laboratory studies at CRREL, using the Inigok sand, indicated that acceptable soil-cement pavements would require 10-15 percent cement and would have to be constructed at temperatures above freezing (Crory and others, 1978; Crory, 1979). Problems associated with the availability of landing mats from military supply depots and the intensive hand labor required to place and remove the mats made the landing-mat option seem less attractive. If the mats could have been used successively at three or more airfields in the NPRA, they would have been more attractive financially.

A full-depth gravel runway 1.2-1.8 m (4-6 ft) thick would have required an amount of gravel that was unobtainable and would have imposed great geotechnical problems as well, because the local sand would have thawed and subsided in both cut and fill sections. Laboratory studies of the Inigok sand, both at in-place density and in the frozen remolded state (simulating frozen fill conditions), indicated that substantial settlement could be expected when the sand thawed (Crory, 1973; Crory and others, 1979). Deep and abrupt depressions would have also formed at the edges of the polygonal ice wedges, particularly in the cut sections. The cost of hauling the gravel from remote locations and the limited time available to haul it led to the decision that an insulated runway at Inigok was the best option.

The construction of the Inigok airfield and its taxiway and parking apron made maximum use of the locally available sand and a minimum amount of gravel. The design, using insulation on top of the frozen sand, assumed that the insulation would be sufficient to keep the sand frozen, provided the insulation was in place before the advent of warm weather. The thickness of the insulation was based on calculations using both the modified Bergren equations and Lachenbruch's equations of periodic heat transfer (Brewer, 1958; Lachenbruch, 1959; Aitken and Berg, 1968; Berg, 1976). The possible range of seasonal thawing and freezing indices was estimated, using records from Barrow and Lonely to the north and Umiat to the south. Conservative estimates of the density and thermal properties of the gravel, the insulation, and the underlying frozen sand indicated that 7.5 cm (3 in.) of insulation would be required to prevent any thawing of the sandy subbase. The insulation selected, which had both the desired thermal properties and the compressive strength, was the extruded polystyrene foam board Styrofoam HI-60. This material was to be placed in two layers, each about 4 cm (1.5 in.) thick, with overlapping joints between each layer, and covered with a plastic membrane. The insulation would then be covered with gravel to complete the temporary runway. A typical cross section of the airstrip is shown in figure 38.5.

Construction of the Inigok airstrip and drill pad began in February 1978. The major portion of the construction and camp equipment had been brought overland on snow trails, and additional supplies and personnel were flown to an ice airstrip on the large lake just north

FIGURE 38.4.—Inigok well site, road, and airstrip. Area on runway centerline darker because sprinkled with water. Large lake on right used as airstrip in winter. View looking westward in July 1978.

of the well site. This temporary airstrip on the lake was also used for the airlift of the drill rig and camp. The ice runway was used until May 22, when spring melting rendered it unusable.

Construction began at the knoll at the south end of the runway. First, all organic material was stripped off and later placed on the shoulders of the runway and along the north edge of the parking apron. The drier and cleaner sand from the top of the knoll was then easily ripped and stockpiled for later use. Construction by late February had settled into conventional cut-and-fill operations. The frozen sand in the borrow area was mined by repeated passes of large ripper-equipped tractors. After ripping, the frozen sand was crushed by repeated passes of heavily loaded segregated wheels and sheepsfoot rollers. When the sand had been broken down so that it contained only small frozen lumps in a matrix of loose sand, it was removed and pushed into stockpiles. While the rippers proceeded to loosen the next layer, the stockpiled material was loaded and trucked to the fill sections.

The snow cover was removed just before placing the fill, but no stripping of the original vegetative cover was permitted. The fill was constructed in lifts, each lift being compacted by rollers. The special sand previously scraped from the surface of the knoll was placed last and the subbase brought up to grade by careful grading and rolling, producing a hard, smooth surface upon which the insulation was placed.

Insulation boards 60 by 240 cm (2 by 8 ft) were placed with their long dimension parallel to the runway centerline, care being taken to keep the joints tight and the rows straight. Placement of both layers commenced at the south end of the runway and proceeded northward. No wooden stakes or other types of tiedowns were used to secure the insulation. Immediately following placement of the two layers of insulation, a plastic membrane was laid on top of the insulation. The membrane[6], a cross-laminated, 4-mill plastic having a tensile strength of 55 GPa (8,000 psi), was used to keep water from seeping down into the joints between the insulation. The membrane, supplied in rolls 6 m (20 ft) wide, was shingle lapped 60 cm (2 ft) and sealed. Gravel was placed, by end dumping, immediately after the placement of the membrane.

The gravel was carefully placed in a single lift of 30 cm (1 ft) or more; the end-dumped gravel was advanced with a bulldozer. Rolling the gravel off the raised dozer blade was essential, because any substantial horizontal push could have displaced the insulation. The thick initial 3 cm (1 ft) or more lift of gravel also served to protect the insulation from being crushed under the direct loading of the gravel trucks or other heavy equipment. Compaction of the gravel by sheepsfoot rollers was forbidden. Only smooth-wheel rollers were used in compacting the gravel above the insulation. The second and final lift, generally 23-30 cm (9-12 in.) thick, was a screened gravel with a maximum diameter of about 4 cm (1.5 in.). The screened gravel was unfortunately poorly graded, lacking fines. To remedy this deficiency, sand from the borrow pit was added after the screened gravel had been placed. This procedure was only partially successful, however, because the stockpiled sand was still frozen and difficult to spread uniformly. At first the sand was blended into the surface gravel by using a disc harrow, but this proved to be ineffective; in the end the blending was primarily accomplished by windrowing and spreading with road graders. Finally, the runway surface was compacted by using both rubber-tired rollers and vibratory smooth-wheel rollers. Plans and specifications called for a minimum of 85 percent (modified AASHO) of maximum density of the finished gravel surface when first placed,

[6]TU-TUF 4, a product of Sto-Cote Products, Inc., Richmond, Va.

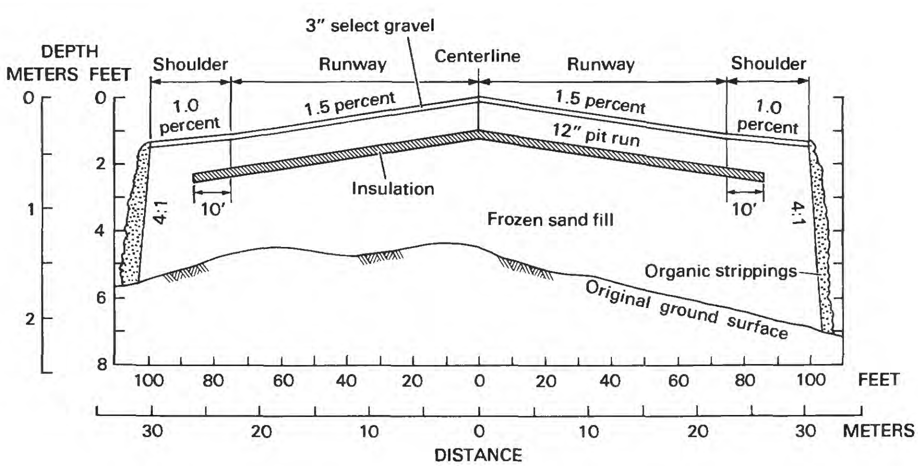

FIGURE 38.5.—Typical section through insulated airfield at Inigok. Depth of fill, thickness of gravel over insulation, and lateral width of shoulder insulation are different from those at Tunalik and Ivotuk.

and then recompaction to 95 percent as thawing of the gravel progressed.

The runway, taxiway, parking apron, road, and drill pad at Inigok used a total of only 67,000 m^3 (88,000 yd^3) of gravel, obtained from the confluence of the Kikiakrorak and Colville Rivers. The gravel was hauled in 7.5-m^3 (10-yd^3) dump trucks with pup trailers at normal highway speeds over a 58-km (36-mi) snow/ice road. The road was routed across a series of lakes in order to reduce the amount of roadway to be constructed. The route avoided the high banks along some lakeshores, which would have created steep grades and necessitated the building of snow ramps. The roadway across the tundra was constructed by first compacting the existing snow cover and then building up the thickness and strength of the roadway by multiple applications of snow and water. In some sectors, ice aggregate was used to build up the roadway; the ice was obtained by ripping in the shallow lakes that freeze to the bottom each winter. Such work does not pose a threat to the dozer, whereas it might break through the ice in deep lakes. The steepest grade on the snow/ice road was from the bluff into the Kikiakrorak River bed, near the gravel borrow pit. This section of the road, after being ramped to an acceptable grade with snow, which in places was more than 6 m (20 ft) high, was covered with gravel for better traction. The gravel was removed at the conclusion of the work, leaving the slope virtually undisturbed after the snow and ice melted.

Construction of the Inigok facilities was nearly finished when the spring breakup occurred during the last week of May 1978. Forced to abandon the airstrip on the lake, all light aircraft (Twin Otter) operations were shifted to the new runway. After several days in which the runway froze at night but was soft and wet during the day, the runway suddenly began to dry out and respond to compaction efforts. The first C-130 aircraft landed on June 6, 1978, and the airstrip continued in service for more than a year without interruption. A view of the completed airfield is shown in figure 38.6.

Grading and rerolling were continued on a daily basis during the first half of summer 1978. Considerable watering was required for compaction and to limit the loss of fines caused by the operation of large aircraft. Only one section of the runway had to be dug up and replaced. Apparently, a truckload of sand and organic material, originally destined for the runway shoulder, had been inadvertently dumped and spread as part of the pit-run gravel. Upon thawing, this small area turned wet and soft and

FIGURE 38.6.—The all-season airstrip at Inigok, showing insulated runway, taxiway, parking apron, and road to drill site. Darker area along road was result of tundra fire in 1977. View looking northeast taken in July 1978.

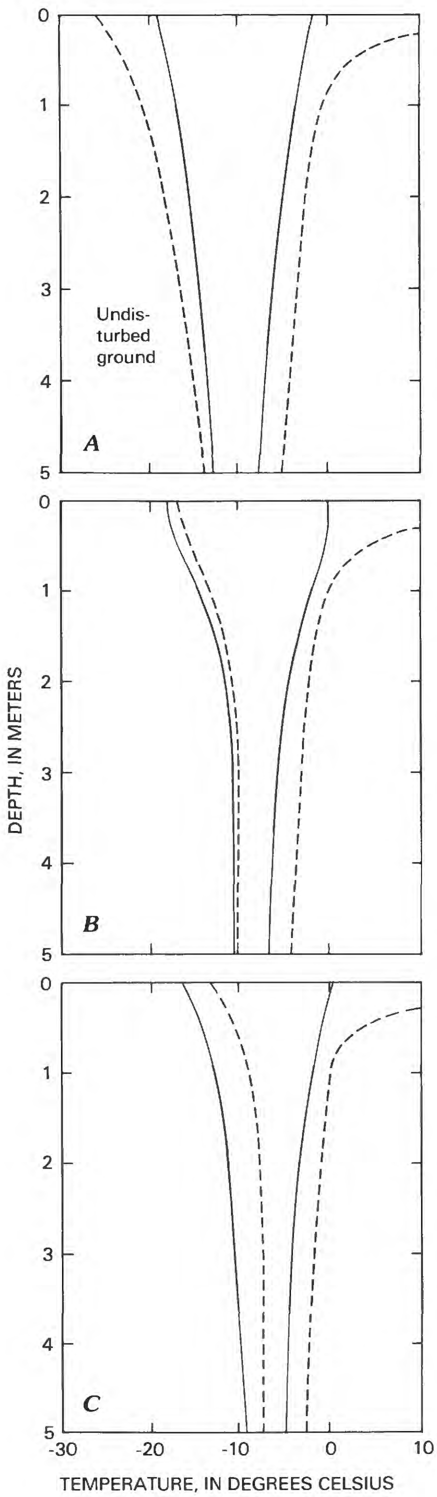

FIGURE 38.7.—Maximum and minimum ground temperatures and depths beneath centerline of insulated runways and adjacent undisturbed tundra at Inigok (*A*), Tunalik (*B*), and Ivotuk (*C*) during their periods of active use in 1978 and 1979. Solid lines represent temperatures below insulation; dashed lines, temperatures in tundra.

had to be removed. Only minor maintenance was required to regrade and recompact the gravel on the parking apron and at the ends of the runway where large aircraft made locked-wheel turns. Throughout the year of active operations the Inigok runway was acclaimed by pilots as one of the smoothest and best runways in Alaska.

In June 1979, after completing the well to a depth of 6,127 m (20,102 ft), the drill rig and camp were airlifted in C-130's to Umiat for the Seabee well. Several inspections of the Inigok airstrip made during the summers of 1980, 1981, and 1982 revealed no change in the excellent condition of the runway, taxiway, and parking apron; no rutting, differential displacement, or erosion was evident. Vertical-movement observations taken at 60-m (200-ft) intervals along the centerline of the runway immediately following construction and several times during the summers of 1978, 1979, and 1980 confirmed the stability of the runway.

During construction, ground-temperature sensors (thermocouples) were installed in 6-m-deep (20-ft) drill holes at stations 14+00 (cut section) and 34+00 (fill section) beneath the centerline of the runway. Similar assemblies were placed beneath the shoulder of the runway and in the undisturbed tundra, south and east of station 14+00. Four test sections were also incorporated into the southeast corner of the parking apron, to determine the effect of different thicknesses of insulation. These and other special thermocouples, installed later above and below the insulation, were observed twice weekly during the summer of 1978, and monthly during the following winter and spring, to monitor the effectiveness of the insulation. The extreme maximum and minimum temperatures beneath the runway, for the period of active use, are shown in figure 38.7*A*. The maximum recorded temperature immediately beneath the insulation was −2 °C. The penetration of cold temperatures through the insulation during the winter was increased by snow removal while the runway was in active use. Temperature observations have been continued in order to define the long-term thermal regime of this insulated runway, particularly the effect of the snow cover on the abandoned runway.

Another problem in drilling deep wells through permafrost is finding the best foundation design for the drill rig. Mud temperatures in such deep wells increase with time, and the heat is dissipated radially during the year or more of drilling. Although extremely high temperatures on the wall of the 107-cm (42-in.) surface conductor pipe could be reduced by insulating the upper section of the pipe and controlling the mud temperatures, the influence of this long-term heating on the nearby frozen piling is still a major concern.

The foundation design for the rig placed the timber foundation piles no closer than 3.7 m (12 ft) from the center of the well, the area around the well being spanned by steel girders. The rest of the foundation consisted of timber piles, laid out in five rows, about 2m (6.5 ft) apart, with piles 0.9-1.8 m (3-6 ft) apart in each row. The locations of the piles and the timber-pile caps were specifically designed for the actual drill rig to be used. A total of 207 timber piles were used at Inigok for the rig and for the auxiliary buildings, mud tanks, pipe racks, and other facilities. All piles were set tip down and to a depth of 7.5 m (25 ft), with the exception of the 10 piles closest to the well and the rat hole, which were 13.7 m (45 ft) long. The piles were installed in dry augered holes, with the annulus backfilled with sand and water. Because of the cold ground temperatures at this site, the piles were frozen into place within a few hours. The ground surface beneath the drill rig was also protected with 15 cm (6 in.) of insulation and sealed with the plastic membrane. An area 44 by 177 m (144 by 580 ft) around the drill rig was insulated with 5 cm (2 in.) of insulation and covered with gravel. The central portion of the drill pad, about 30 by 75 m (100 by 250 ft), was also insulated, as was the entire area under the drill camp. The remainder of the 164- by 177-m (537- by 580-ft) drill pad was a 1.2-1.5-m (4-5-ft) embankment of sand, with a thin gravel surfacing.

Eight piles beneath the drill rig were equipped with temperature-measuring assemblies to monitor the three-dimensional heating around the well. The temperature observations, taken at the same frequency as the runway observations, were compiled and plotted monthly. These data were periodically compiled in status reports, indicating the changes in temperature to date and short-range forecasts of temperatures expected in the forthcoming months. Vertical-movement surveys taken periodically of the Inigok drill rig confirmed the stability of the foundation.

The access road between the drill pad and the parking apron was one of the last facilities to be constructed at Inigok; a temporary ice road was used during the initial construction period. The 7.3-m-wide (24-ft) roadway with 1.2-m (4-ft) shoulders was constructed by first placing a nominal 30-cm (1-ft) thickness of frozen sand on the unstripped tundra surface. After compaction, a single layer of insulation (HI-35) 5 cm (2 in.) thick was laid down and covered with the plastic membrane. Although the specified thickness of gravel over the insulation called for 23 cm (9 in.) of pit run and 7.5 cm (3 in.) of select gravel, the actual thickness was less than specified and included a high percentage of sand. By early summer the road showed signs of distress, and repairs were required. During the repairs it was noted that the single layer of insulation in many areas had been deformed, the edges of the insulation being much lower than the center of the boards. Thus a gap formed between the boards, and thawing of the sand between the boards was initiated. The insulation was also crushed and compressed, to the extent that in some sections the insulation was only 1 cm (0.5 in.) thick, whereas it originally had been 5 cm (2 in.) thick. The plastic membrane was also punctured in many places, allowing water to infiltrate between the insulation boards and cause soft spots. Failure of sections of the road was also blamed on the heavy vehicle loads (of pipe, cement, and other equipment), as well as the frequent passage of the heavily loaded Foremost vehicle used to supply water to the equipment maintenance camp north of the parking apron and to sprinkle the runway, taxiway, and parking apron.

The road was repaired, in sections, by replacing the original insulation with 7.5 cm (3 in.), and sometimes 11 cm (4.5 in.), of the HI-60 insulation left over from the runway construction. The insulation was then covered with 30 cm (1 ft) or more of sand and gravel from stockpiles left for just such contingencies. By late summer the road was firm, well drained, and easily maintained by periodic grading and rolling. The road was still in excellent shape when inspected on visits during the summer and fall of 1981, although minor settlement was evident in those areas having the least insulation.

To evaluate the possible use of military landing mats for roads, airfields, and drill pads in the NPRA, three types of military matting were installed at Inigok in late May 1978. Test sections were installed on a level area of the borrow pit, just southeast of the parking apron; this area represented a cut section in the frozen sand. Two smaller test sections were installed directly on undisturbed tundra, to the west of the parking apron.

The installation on the bare sand consisted of four continuous sections of AM-2 matting on loan from the U.S. Marine Corps. The first two sections had 7.5 and 3.8 cm (3 and 1.5 in.) of insulation under the matting, while the last two sections were placed directly on the frozen sand. The mat section having 3.8 cm (1.5 in.) of insulation and one of those placed on the frozen sand were painted white, while the matting in the other two sections was olive drab. Thermocouples were installed above and below the matting, and at close intervals to a depth of 3 m (10 ft), to monitor the effectiveness of the white paint and the insulation.

A second series of tests on the bare sand used the square XM19 matting. Since this mat had been previously painted white, it was simply given a new coat of white paint. The first two sections of this matting were underlain with 7.5 and 3.8 cm (3 and 1.5 in.) of insulation and similarly equipped with temperature sensors. The last two sections were placed directly on the sand.

Both types of matting, when not underlain with insulation, caused thawing of the underlying frozen ground. The depth of thawing in the sand ranged from 84 to 135 cm (33 to 53 in.), and caverns as large as 1.2 m (4 ft) developed beneath the mats where ice wedges existed. The insulated sections had only a few centimeters (an inch or two) of thawing and no melting of the massive ice wedges, confirming the original assumption that the military matting could have been used for this and other airfields. These two test sections were removed in early September 1978.

The matting installed on the undisturbed tundra consisted of XM18 and AM-2 matting, both in pieces 3.8 cm by 60 cm by 3.7 m (1.5 in. by 2 ft by 12 ft). One section was installed on insulation, half being on 7.5 cm (3-in.) and the other half on 3.8-cm (1.5-in) insulation board. The entire test section was painted white. This test section experienced no subgrade thawing in a year's time, and when it was removed in May 1979, there was a layer of ice as thick as 10 cm (4 in.) directly beneath the insulation. The other test section was placed directly on the tussocks, without insulation, and left olive drab. This test section had only about 35 cm (14 in.) of thawing in the subgrade when removed in the fall of 1978. The insulating effect of the organic material and of the dead air space beneath the matting was apparently instrumental in limiting the depth of thawing to that which normally occurs in the undisturbed tundra at that location. The testing of the landing mats at Inigok has been described in detail by Crory (1981).

Experimental grass plots were laid out in the borrow-pit area at Inigok to determine the best types of grasses and optimum rates of application of fertilizer to restore a site following the completion of drilling. Initially, 20 plots were laid out in late May 1978, some plots receiving no fertilizer, others with 1, 1½, and 2 times the normal rate of 674 kg/ha (600 lb/acre). Several varieties of grasses were sown, using 1, 1½, and 2 times the normal seed quantity of 56 kg/ha (50 lb/acre). On three of the plots a surface tackifier was applied to limit wind erosion and retain the surface moisture in the sand. Ten additional test plots were seeded and fertilized in mid-July to determine the effect of the time of seeding. Additional test plots were laid out in the stripped organic material, along the edge of the road, and around the landing-mat test sections. Good stands of grass were obtained at normal rates of application of seed and fertilizer at all sites planted in the spring. Poor results were attained in the midsummer plantings and in all the plots on organic material. An accurate assessment of the growth of each species of grass was impossible, because of the severe browsing by a small herd of caribou that, despite the nearby activity, visited the grass plots almost daily during August and September 1978. Initial seeding of the borrow areas by Husky and its contractors began with dormant seeding in the fall of 1978; further seeding was done during the spring of 1979. Both seedings were successful, and all exposed sand areas had good stands of grass during the summers of 1980 and 1981.

TUNALIK WELL SITE

The Tunalik well, like the Inigok well, was a deep exploratory test hole and required a temporary all-year airfield to support the year or more of continuous drilling required to complete the well. The Tunalik well is located at lat 70° 12′21.45″ N., long 161°04′09.15″ W., just east of Icy Cape (fig. 38.1). Although there were several suitable locations for a runway at Tunalik because of the relatively flat terrain surrounding the well, the final location was based on runway grades. A location was selected that avoided deep fills and required no cut sections. Easy access to the borrow sites and the availability of a lake for a winter airstrip were also important. The magnetic bearing at the runway centerline was N. 75°53′ E., parallel to the prevailing winds.

Although there are several small lakes 3-5 km (2 to 3 mi) east and west of the Tunalik site, the area is drained by the Ongorakvik River, which flows northwest for about 16 km (10 mi) and empties into the Kasegaluk Lagoon and the Chukchi Sea. The area appears to be quite flat but in fact has gentle grades. The site is underlain by varying thicknesses of organic material (peat) and organic marine silt and sand, covered with a uniform stand of grass and sedge tussocks. Beneath the organic layer, which in places was found to be only 30-60 cm (1-2 ft) thick, the soils grade to a silty sand or sand. In some places, such as at runway station 32+40 and at the drill-site reserve pit, more than 3 m (10 ft) of ice was found immediately below the 45-cm (1.5-ft) organic layer. At depths of 4.5 cm (15 ft) or more, the sand was virtually free of silt-size particles in some of the drill holes. Although bedrock was exposed in some of the valleys to the north, bedrock at the runway and well sites was below the bottom of the test holes drilled to depths of 15-24 m (50-80 ft).

Extensive deposits of sand were located along the left bank of the Ongorakvik River at the confluence with the Nokotlek River about 10 km (6 mi) north of the well. Development of such a borrow site so close to the river, however, was not considered desirable. An ancient Pleistocene beach deposit on a bluff about 7 km (4.5 mi) west of the drill site provided a closer and better source of construction material. This material varied from sandy gravel at the surface to gravelly sand at depth. Borrow was obtained from two pits that were well drained and easily developed. The snow road to the borrow pits was extended another 2.5 km (1.5 mi) to a large lake, capable of accommodating the C-130 aircraft when frozen. A smaller lake, 1.5 km (1 mi) northwest of the runway, was used only for the Twin Otters and smaller aircraft during construction.

The design options at Tunalik, as at Inigok, were limited by the amount of gravel available. Because of winter construction, the only viable option was to prepare a subgrade using the local sand, maintaining the sand in a frozen state with insulation, and using the limited gravel for the wearing course. The runway had a downhill grade of about 0.3 percent from west to east and required fill depths ranging from only 0.6 to 1 m (2-3.5 ft); no cuts were required. The thickness of insulation required to maintain the sand in a frozen state was calculated to be only 5 cm (2 in.) because of the cooler and foggier weather at such a coastal location (Crory and others, 1978). The high-density (HI-60) insulation was used on the runway, taxiway, and parking apron, while the lower density (HI-35) insulation was used on the road and drill pad, as at Inigok.

The building of a snow/ice road to the borrow pits commenced in January 1978. This haul road made good use of the local snow cover but utilized ice as the major construction material. The ice was readily available from the shallow ponds on both sides of the road and required much less water than compacted snow to build up a 45-75-cm (1.5-2.5-ft) roadway. The road surface was periodically scarified with a road grader, producing a rough surface, so that the rubber-tired dump trucks could travel at close to normal highway speeds.

Borrow pits were developed by first removing all snow and stockpiling the drier surface gravel. This gravel was later used as the surface wearing course for the runway and road. The borrow pits were worked in the same manner as the Inigok borrow site. Since the two borrow pits were relatively small, the borrow material was quickly loaded into the 7.5-m^3 (10-yd^3) trucks with pup trailers for the short haul to the runway, road, and drill pad. An ice road just north of the runway, and west of the 0.8-km (0.5-mi) road connecting the runway to the well, kept traffic flowing smoothly.

Placement of the gravelly sand fill began on the higher west end of the runway and proceeded eastward. The snow cover was removed just before placing of the gravelly sand. No stripping of the surface vegetation was permitted. As soon as the subbase had been brought to final grade (fig. 38.8), the insulation placement began, also working from west to east. The insulation was placed as a single layer, 5 cm (2 in.) thick, with the long dimension parallel to the runway centerline. Care was taken to ensure that all joints between the 60- by 240-cm (2- by 8-ft) boards were tight and the rows were kept straight. The boards were staggered in each row and covered with the same kind of plastic membrane as was used at Inigok. No pins or other fasteners were used to secure the insulation to the frozen subgrade.

The pit-run gravelly sand was placed atop the insulation by end-dumping and spreading of the gravel with a bulldozer, care being taken not to displace the insulation. The initial lift was 30 cm (1 ft) or more in thickness and compacted to 85 percent of maximum density, using the segregated and smooth-wheel rollers. The 15-cm (6-in.) wearing course of the stockpiled, select pit-run sandy gravel was similarly placed and compacted. No sheepsfoot rollers were permitted to operate above the insulation. The completed runway is shown in figure 38.9.

The roadway between the parking apron and the well site at Tunalik was to be constructed in the same manner as the insulated workpad at Inigok, where a single layer of 5-cm (2-in.) insulation

FIGURE 38.8.—Placing final lift of sand on subbase before placing insulation at Tunalik runway. Photograph taken in March 1978.

boards was placed directly on the carefully prepared tundra surface. To maintain a smooth grade for the insulation, a thin leveling coarse of sand was used. In some sections, however, the 30-cm (12-in.) nominal depth of sand used at Inigok was not placed at Tunalik. No membrane was used above the insulation on the Tunalik road. The 7.3-m-wide (24-ft) roadway was completed by using a 30-cm (1-ft) layer of pit-run gravelly sand and then a 15-cm (6-in.) layer of the select sandy gravel for the wearing surface, both layers being compacted to 85 percent of maximum density. The entire road was constructed as a fill section.

As at Inigok, the drill pad was constructed at the same time as the runway. The 45- by 177-m (150- by 580-ft) area surrounding the drill rig was underlain with 5 cm (2 in.) of insulation, as was the area beneath the drill camp and a rectangle 30 by 84 m (100 by 275 ft) between the drill rig and the camp. HI-35 insulation was used and was placed in the same manner as in the roadway. Fifteen centimeters (6 in.) of insulation was used under the drill rig. The membrane above the insulation was tightly sealed around all the timber foundation piles. Although the original intent was to use the sand or silty sand from the excavation of the reserve pit for the initial subbase fill at the Tunalik drill pad, this plan was changed when massive ice was encountered in the excavation of the pit. The spoil from the reserve pit, which included organic material and silt, was stockpiled and later spread as topsoil for

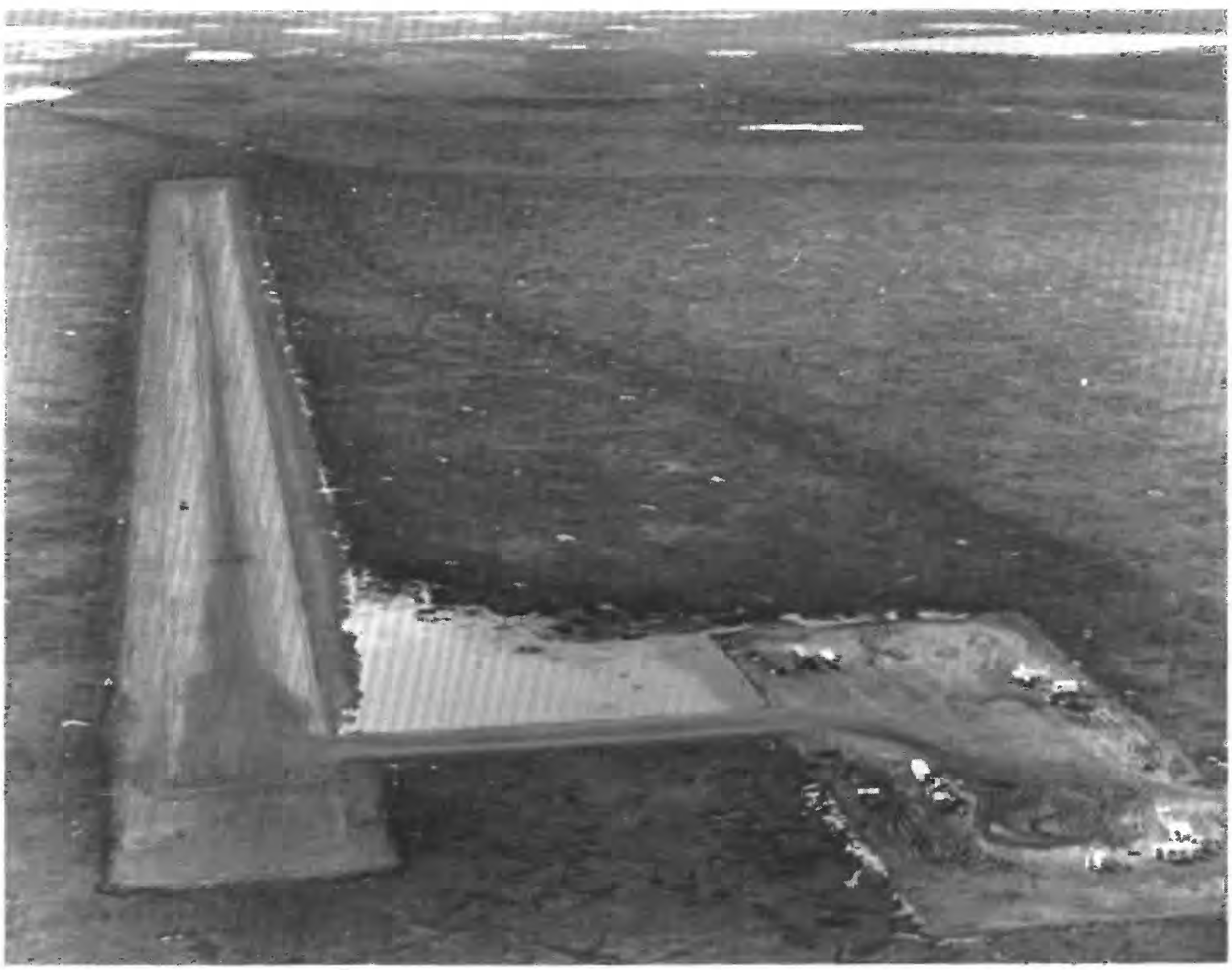

FIGURE 38.9.—All-season airstrip at Tunalik, showing ponding by taxiway and parking apron. Dark line shows location of winter snow/ice road to borrow sites. Note polygonal ground patterns. Cleanup of construction camp is underway on lower portion of parking area. View looking west taken in 1979.

reseeding. Material from the borrow sites was used for the initial subbase and surface at the drill-pad site.

Because of the shorter haul distance and the use of only fill sections, the Tunalik facilities were completed before those at Inigok. The first C-130 landed at Tunalik on May 1, 1978, and made several more trips that day. The pilot reported that the still-frozen runway surface was in excellent shape. However, the drill rig was delayed at Kugrua because the spring breakup occurred before the rig could be moved to Tunalik by land or by air. Accordingly, the start of drilling at Tunalik was delayed until the winter of 1978, and construction and maintenance activities at Tunalik were drastically reduced throughout the summer of 1978.

During the first week of June 1978, active thawing of all gravel surfaces began with little or no overnight refreezing. Compaction of the gravel surfaces, particularly the runway and parking apron, were hampered by both excessive moisture and the mechanical failure of the rubber-tired roller. The gravel was dried primarily by windrowing with a grader, although the foggy weather hampered the operation. Because of the soft condition, the airfield facilities were closed to all but light aircraft during June. Earlier, during the spring breakup, a culvert beneath the road had washed out. This washout, together with the soft condition, rendered the road unusable. Because there was no activity at the drill pad, the small maintenance crew was able to concentrate on the runway, taxiway, and parking apron.

With improving weather in late June and July 1978, the maintenance crew was able to regrade and compact the runway, road, and other facilities to their prescribed 95-percent compaction. Except for the drill pad, all facilities at Tunalik performed well from midsummer of 1978 until the well was completed in late January 1980. No problems were reported during the spring breakup of 1979, but during the summers of 1978 and 1979 the drill pad was consistently a problem. Although additional gravel had been placed there in the late summer of 1978, the pad was still soft and wet throughout the major portion of the summer of 1979. The lack of sufficient slope for drainage and the poor quality of the material above the insulation were considered the major factors responsible for the poor performance in those areas underlain by insulation, and the lack of insulation was the major factor in other areas.

In mid-March 1978, before the placing of the insulation, two thermocouple assemblies were installed to a depth of 6 m (20 ft) along the centerline of the Tunalik runway. The thermocouples were installed at stations 16+10 and 32+40, the stationing beginning on the east end of the 1,500-m (5,000-ft) runway. A similar thermocouple assembly was installed about 15 m (50 ft) south of the runway shoulder at station 32+40 to monitor the normal thermal regime of the undisturbed tundra. The maximum and minimum temperatures beneath the tundra and insulated runway are shown in fig. 38.7*B*. The temperatures directly beneath the insulation reached 0 °C in the midsummer of 1978 and were very close to 0 °C during 1979 and 1980. Two test pits along the centerline of the runway, dug in mid-August 1978, confirmed that the subbase was indeed still frozen. Another test pit, to examine the condition of the insulation, was dug in early September 1980 beneath the taxiway. The subbase was again found to be frozen, with ice in the joints between the boards. Level surveys and careful inspection of the runway did not reveal any low spots or depressions that would indicate localized thawing beneath the insulation. The grass, planted in early June 1978, in the overrun section on the east end of the Tunalik runway continued to show good growth through the summer of 1980.

During the abrupt breakup in the spring of 1980, a section of the taxiway 1.2-1.8 m wide (4-6 ft) was washed out. A pond had been formed at the junction of the parking apron, taxiway, and runway since the original construction (fig. 38.9). The breach through the 50 cm (20 in.) or more of gravel and gravelly sand above the insulation was at the location of a buried fiberglass pipe used to pump water into and out of the small pond. The washout across the taxiway had not been repaired as of our last visit in July 1982.

Eight foundation pilings at Tunalik were equipped with ground-temperature sensors to evaluate the thermal regime immediately surrounding the well, as at Inigok. Installation of the foundation piles at Tunalik is shown in fig. 38.10. Two additional thermocouple assemblies were installed on June 21, 1979, near the southeast corner of the drill rig, where a cavity formed by thawing of ground ice in permafrost was noted. The temperature observations indicated that thawing was occurring only near the ground surface and that the pilings were not in jeopardy. After the rig was removed in the early spring of 1980, these cavities had enlarged to form several depressions 1.2-1.5 m (4-5 ft) deep. The fill beneath the rig had originally been graded level with the top of the pile caps.

LISBURNE (IVOTUK) WELL SITE

Because the insulated runways at Inigok and Tunalik worked well during the summer of 1978, a similar runway was constructed in early 1979 at Ivotuk to service the deep exploration well at Lisburne. The Lisburne well was only a few kilometers west of the north-south boundary of the NPRA in the northwest corner of the rolling Ivotuk Hills north of the Brooks Range (fig. 38.1). The Lisburne well site is connected by a 3 km (2-mi) gravel road running west across Otuk Creek to the Ivotuk runway. The gravel-surfaced runway, 45 m wide and 1,500 m long (150 by 5,000 ft), is oriented north-south (magnetically) at about lat 68°29′ N., long 155°45′ W.

The well site is in an east-west valley between two ridges at lat 68°29′05.44″ N., long 155°41′35.51″ W. The ridges have extensive exposures of bedrock, but the valley is underlain by organic material, silt, and gravel chiefly of glacial origin. Because the well site was located on a steep grade, the drill pad was constructed at three different elevations: the upper level for the camp and rolling stock; the middle level for the drill rig, service buildings, and pipe storage; and the third level for the reserve pit. The fill for the camp and drill pads was obtained from the excavation of the reserve pit.

The runway was oriented parallel to the major drainage, its profile on a 1- to 1.5-percent grade sloping to the north. The original site was covered with low tussock grasses and sedges grown on a brown to black organic surface layer. The soil at shallow depths varied from organic silt to silty colluvium, overlying weathered bedrock that was 1.5-4.5 m (5-15 ft) deep. The bedrock beneath the airfield consisted of sandstone and shale, with occasional layers of limestone. Frost-rived boulders were exposed along the ridge just west of the runway. Gravel was found along virtually every stream in this area, although only limited quantities were available for the construction of the all-season airstrip, road, and drill pad within 1.5 km (1 mi) of the Otuk Creek crossing (fig. 38.11).

Two main considerations influenced the design and construction sequences for the facilities at the Lisburne well: (1) To meet drilling schedules and avoid any trafficking over bare tundra, all work had to be done in the winter, and (2) the only frozen lake large enough to accommodate C-130 aircraft was Lake Betty, about 30 km (20 mi) to the west. Thus the plan was to construct quickly a thin frozen-gravel mobilization airstrip, which could later be used as the subbase for the all-season airfield. This subbase, of pit-run gravel from Otuk Creek, was leveled and iced to provide a smooth, rock-free surface. Runway construction was then halted, providing a limited time interval during which the drill rig, drill camp, and other supplies, including the insulation for the airfield, could be brought in by C-130 and other aircraft. The mobilization strip was then closed to all but short-takeoff-and-landing (STOL) aircraft while the insulation and gravel overlay were placed to complete the all-season airstrip. The major design problem for this airfield was the layer of ice on the surface of the mobilization strip, 2.5-7.5 cm (1-3 in.) thick, and the thickness of insulation required to prevent this ice and the underlying gravel from thawing during the summer. As a result of the experience gained at

FIGURE 38.10.—Installing piling for drill rig at Tunalik. Rig in background is drilling conductor hole for well. View looking east taken in March 1978.

Inigok and Tunalik, 6 cm (2.5 in.) of insulation was recommended for Ivotuk. The insulation was placed in two 3-cm (1.25-in.) layers and was covered with a plastic membrane like that used at Inigok and Tunalik.

After a winter trail had been constructed from Lake Betty, a temporary construction camp was set up just north of the proposed road to the west of Otuk Creek. The screening and crushing plant was set up on the east side of Otuk Creek just south of the newly constructed road leading to the well site. The gravel borrow pits along Otuk Creek (fig. 38.11) both upstream and downstream of the bridge were developed by first stripping off the snow and the organic cover, which was later used to restore the pits. The size and depth of each borrow pit were carefully controlled to avoid any possibility of changing the channel of the creek.

While there was some anxiety about completing the mobilization strip in time for the planned shutdown period, it was completed without difficulty. During this initial construction period and while the airlift was still underway, the screened and crushed gravel for the airfield was being processed and stockpiled. The insulation for the runway, in plastic covered bundles, was temporarily stored along both shoulders of the runway, making it readily available for placement after the mobilization strip was closed to the larger aircraft. After that closure, the Twin Otters and other small aircraft continued to use sections of the airfield during placement of the insulation and the overlying gravel. The completed all-season airstrip is shown in figure 38.12. Although no problems had been experienced with wind during the placement of insulation at Inigok and Tunalik, the strong winds at Ivotuk, particularly during the

FIGURE 38.11.—Otuk Creek bridge on access road between Ivotuk airfield and Lisburne well. Disturbed areas are former borrow pits. View looking north taken in July 1979.

FIGURE 38.12.—Insulated all-season airstrip at Ivotuk, with parking apron and equipment storage area at left. Note wet overrun section at end of runway. View looking south taken in July 1979.

third week of April 1979, made it necessary to stop work for several days.

Although the shorter access roads at Inigok and Tunalik were built with insulation, the longer road between the Ivotuk airstrip and the Lisburne well was constructed using gravel without insulation. This construction made it possible to place the oversize gravel from the screening and crushing operation in the lower sections of the roadway embankment. That embankment at the centerline was normally 1.2-1.8 m (4-6 ft) thick, although several sections on abrupt grades were even thicker. To minimize both the construction cost and the amount of gravel used, the design road width was only 3.6 m (12 ft) with 1.2-m (4-ft) shoulders. This width tended to increase with time as the traveled way was regraded. The narrow road was used without serious traffic delays by building turnouts at intervals of 300-450 m (1,000-1,500 ft).

Otuk Creek was bridged with a double-span, laminated timber bridge supported by timber piling (fig. 38.11). The abutments of the bridge were protected by rock-filled gabions upstream and downstream of the bridge. The single-pile bent in midstream was protected by a steel raker extending from the pile cap into the streambed at a 45° angle on the upstream side. This protection against ice during the spring breakup was later found to be unnecessary.

The Lisburne drill pad was a difficult construction undertaking compared to other pads in the NPRA that were built on relatively flat ground. Because of the limited working area and steep slopes, excavation was by blasting rather than ripping. The blasted material from the reserve pit was used to form the two sidehill benches for the drill pad and camp. Insulation was used beneath and adjacent to the drill rig, under the camp, and on the high slope of the reserve pit adjacent to the drill. All slopes and pad surfaces were blanketed with pit-run gravel, as were the reserve-pit dikes. These dikes had to be quite steep to avoid the small creek that drains the valley.

During construction, the runway, road, bridge, and drill pads were instrumented with temperature sensors. Initial elevations were taken, the level observations being referenced to frost-free bench marks near the taxiway, the southwest end of the bridge, and the south end of the drill pad. Thermocouples were installed beneath the centerline of the airstrip at stations 29+00 and 52+00; station 12+50 is the north end of the airstrip and station 64+00 is south end. Station 29+00 was selected as being representative of the thinner cross sections; station 52+00 had the greatest depth of subbase because this location had originally been a low swale. Temperature assemblies were also installed in the undisturbed tundra at stations 29+00 and 64+00 to the west of the runway. Station 64+00 was selected rather than station 52+00 for this tundra assembly because the original plan was to incorporate several test sections in the 60-m (200-ft) overrun on the south end. Unfortunately, the incorporation of these test sections, using several thicknesses of two different types of insulation, could not be coordinated with the airfield construction schedule, so they were switched to the drill pad. Two additional thermocouple assemblies were installed, however, in the uninsulated north overrun, to determine the thermal regime of a thin gravel overlying undisturbed tundra. An additional, deep thermocouple assembly, to a depth of 30 m (100 ft), was installed near the tundra assembly at station 29+00 in mid-June 1979 to determine the permafrost temperatures at depth. The envelope of maximum and minimum temperatures beneath the insulated runway and the undisturbed tundra at Ivotuk is shown in figure 38.7C. Although the temperatures just beneath the insulation approached the melting point, no apparent thawing or subsidence of the runway was noted during the summers of 1979 and 1980. The only operational problems at Ivotuk were those encountered during the initial thaw in May 1979, when soft spots and rutting under the C-130 traffic occurred in isolated areas. The remedy was to excavate the affected areas and refill them with select compacted gravel. The wet spots were directly related to what appeared to be about a truckload of silty sand and organic material that had been placed directly on the insulation. The wet, soft conditions lasted about 10 days, during which time dozens of such soft areas were replaced by select gravel. After the repairs were completed and the gravel overlying the insulation had become thawed and recompacted, according to specifications, the runway was easily maintained by periodic blading and rolling. No recurrences of the soft spots were noted during the spring of 1980.

Ground-temperature assemblies were also installed at three locations to a depth of 4.5 m (15 ft) beneath the centerline of the road. The temperature observations, taken weekly during the thawing period and monthly in the winter, measure the thermal regime beneath the uninsulated road. Six temperature assemblies were installed on the abutments and center pier of the Otuk Creek bridge were designed to define the temperatures beneath the streambed and to confirm the design temperatures for the frozen-in piles. The data indicated that no deep thawing occurred around the frozen piles. There was, however, about 2.5 cm (1 in.) of heave of the upstream side of the bridge pier cap because of the heaving of the ice raker.

At the Lisburne well site the temperatures at depth along the conductor pipe, as well as on selected foundation piles beneath the rig, were monitored throughout the active drilling period. Because of the high dikes surrounding the reserve pit at this site, in contrast to Inigok and Tunalik, special temperature assemblies were installed beneath the bottom of the reserve pit, within the core of the highest dike, and on the insulated slope beside the drill rig. Eight test sections were also incorporated in the drill pad, to compare the effect of two thicknesses of two different types of insulation board. All dikes and pads performed well and in accordance with design assumptions. The only wet and soft spot on the drill pad was at the uninsulated south end—an area that received drainage from the adjacent ramp road to the upper camp pad.

Small revegetation plots were established in the spring of 1979 in a borrow pit south of the Otuk Creek bridge and just northeast of the bridge. Initial growth was encouraging, but to determine whether these grasses will become firmly established or replaced by native species requires long-term observations.

SUMMARY AND CONCLUSIONS

The information gathered during the design, construction, and performance of these facilities in the NPRA could only be described in general terms in this chapter. However, the three insulated airstrips constructed in the NPRA have demonstrated that such facilities can be built in the winter, using both cut and fill sections. The insulated airstrips provided a viable design alternative at locations having limited quantities of gravel. Maintaining a frozen subbase by the use of 5-7.5 cm (2-3 in.) of insulation overlain by at least 38 cm (15 in.) of clean compacted gravel provides the desired bearing capacity for C-130 aircraft and avoids the undesirable settlements associated with the thawing of frozen fill or permafrost.

The failure of sections of the insulated road at Inigok confirmed the requirement for 30 cm (12 in.) or more of gravel above the insulation and the necessity for the high-compressive-strength insulation when the road is subjected to heavy loads. The incorporation of undesirable material in the gravel above the insulation, which caused the isolated soft wet spots in some sections of the runways and parking aprons during the initial spring breakup, can be minimized or eliminated by closer inspection during construction. Rolling and rerolling of the gravel above the insulation is apparently essential during the initial thawing period. The grades on large areas, such as parking aprons and drill pads, should be sufficient to accommodate the initial meltwater and subsequent precipitation during the first and subsequent spring breakups. The almost flat grades on the large drill pads for the deep wells do not appear to be justified because much of the pad is used for storage. The failure of culverts on the Tunalik and Seabee roads during the spring breakup suggests that more attention should be given to the design, construction, and maintenance of these drainage structures.

The strict control of all off-road construction activities associated with the NPRA exploration program, using well-prepared snow/ice roads and trails and prohibiting traffic over bare tundra, minimized or avoided the environmental disruptions experienced a generation ago in the reserve. The airfields, roads, and well sites constructed since 1977 reflect the current state of the art of northern engineering. Since that time the interrelations between the environment and the facilities have been considered to the advantage of both. The facilities constructed in support of the deep explorations performed remarkably well, considering that they were built in the winter, with frozen material, and were intended for use over such a short length of time.

The new concepts for winter construction of large all-year airstrips at Inigok, Tunalik, and Lisburne (Ivotuk) are also applicable to permanent airfields, roads, and construction pads. With the use of insulation, only 38 cm (15 in.) of compacted gravel is required, compared to the 1.8 m (6 ft) required to prevent thawing of permafrost beneath uninsulated airstrips in the Arctic.

REFERENCES CITED

Aitken, G.W., and Berg, R.L., 1968, Digital solution of modified Berggren equation to calculate depths of freeze or thaw in multilayered systems: U.S. Army Cold Regions Research and Engineering Laboratory Special Report 122, 18 p.

Berg, R.L., 1976, Thermoinsulating media within embankments on perennially frozen soil: U.S. Army Cold Regions Research and Engineering Laboratory Special Report 76-3, 161 p.

Brewer, M.C., 1958, Some results of geothermal investigations of permafrost in northern Alaska: American Geophysical Union Transactions, v. 39, no. 1, p. 19-26.

Burns, C.D., 1979, Traffic tests of expedient airfield construction concepts for possible application in the National Petroleum Reserve Alaska (NPRA): U.S. Army Engineer Waterways Experiment Station Technical Report GL-79-2, 53 p.

Crory, F.E., 1973, Settlement associated with the thawing of permafrost, *in* Permafrost, North American Contribution to Second International Conference on Permafrost, Yakutsk: Washington, National Academy of Sciences, p. 599-607.

—— 1979, Design and construction of temporary airfields in the National Petroleum Reserve-Alaska: Northern

Engineer, v. 10, no. 3, p. 13-15.

—— 1981, Landing mat test sections on permafrost: U.S. Army Cold Regions Research and Engineering Laboratory Special Report.

Crory, F.E., Berg, R.L., Burns, C.D., and Kachadoorian, Reuben, 1978, Design considerations for airfields in NPRA, *in* Proceedings of the Conference on Applied Techniques for Cold Environments: Anchorage, American Society of Civil Engineers, p. 441-458.

Esch, D.C., and Rhode, J.J., 1977, Kotzebue airport runway insulation over permafrost, *in* Proceedings of the Second International Symposium on Cold Regions Engineering: College, University of Alaska, p. 44-61.

Ferrians, O.J., Jr., Kachadoorian, Reuben, and Greene, G.W., 1969, Permafrost and related engineering problems in Alaska: U.S. Geological Survey Professional Paper 678, 37 p.

Lachenbruch, A.H., 1959, Periodic heat flow in a stratified medium with application to permafrost problems: U.S. Geological Survey Bulletin 1083-A, 36 p.

Penner, E., 1976, Insulated road study: Washington, National Academy of Sciences, Transportation Research Record 612, p. 80-83.

Wahrhaftig, Clyde, 1965, Physiographic divisions of Alaska: U.S. Geological Survey Professional Paper 482, 52 p.

Wellman, J.H., Clarke, E.S., and Condo, A.C., 1977, Design and construction of synthetically insulated gravel pads in the Alaskan arctic, *in* Proceedings of the Second International Symposium on Cold Regions Engineering: College, Alaska, University of Alaska, p. 62-85.

Williams, J.R., Yeend, W.E., Carter, L.D., and Hamilton, T.D., 1977, Preliminary surficial deposits map, National Petroleum Reserve, Alaska: U.S. Geological Survey Open-File Report 77-868, 2 sheets, scale 1:500,000.

39. THE NATIONAL PETROLEUM RESERVE IN ALASKA COMPUTER DATA AND GRAPHICS SYSTEM—AN AID TO GEOLOGIC INTERPRETATION

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INTRODUCTION

The Naval Petroleum Reserve Production Act of April 6, 1976, transferred jurisdiction of the Naval Petroleum Reserve No. 4 from the Department of the Navy to the Department of the Interior. At that time it was also renamed the National Petroleum Reserve in Alaska (NPRA). On June 1, 1977, the U.S. Geological Survey (USGS) was assigned the responsibility by the Secretary of the Interior to determine the hydrocarbon and mineral-resource potential of the NPRA. In late 1976, the USGS decided to build a digital geologic data base for the purpose of storing and organizing the large amount of geophysical, well, and outcrop information that would be acquired over the years from 1977 to 1982. As more data were added to the data base, this data system became increasingly useful. It was able to interrelate disciplines and synthesize large geologic data bases. Not only was this computerized system used in assessing the resources of the NPRA, but it also provided a foundation for estimating resources over the entire North Slope and the Beaufort and Chukchi Seas. Upon completion of the NPRA exploration program, the data files and software were made available for all types of geologic research in northern Alaska.

By 1977, exploration programs from 1944 through 1955 and from 1972 into 1977, both initiated by the Department of the Navy, had already produced substantial amounts of geological and geophysical data. The USGS planned a more comprehensive exploration program than that of the U.S. Navy. The program included the acquisition of an additional 8,000 line kilometers (5,000 mi) of seismic-reflection and gravity data, and the drilling of 22 exploratory and 5 development wells. Additional plans included measuring 24,460 m (80,250 ft) of surface sections, analyzing rocks from 63 wells using petroleum geochemical techniques, and dating rocks from 44 wells using paleontological methods. These data would have to be obtained with few people over a 6-yr period (1977 through 1982). With these long-range goals in mind, it was decided to collect and store most of the geological information on a computer as the data became available from USGS geologists, contractors, and subcontractors. The computer had many advantages: (1) The USGS publishes much of its information, and this computerized data system would facilitate the publication process by allowing the release of data on magnetic tapes and computer-made reports and graphics; (2) the computerized system would allow large amounts of data to be distributed by mail on a weekly basis to the many subcontractors, consultants, geologists, and geophysicists working for the USGS on the NPRA; and (3) the computerized data base would help maintain program continuity even though there was a turnover of personnel.

In 1974, the USGS contracted with Petroleum Information Corporation (PI) to provide the Well History Control System (WHCS) information and to write geologic data-processing software. Under this contract, geologists from the USGS would describe the file content and software requirements (reports, graphics, and maps), and computer specialists from PI would build the files and write the necessary software. There were 13 different geotechnical data files on this system. As information was gathered, a file management system (TECH/SYS) began to evolve.

The purpose of this chapter is to explain the NPRA computer data and graphics system. The term graphics includes reports, listings, and graphical displays. Each of the 13 digital data files is discussed as to the content, cost, and products. In addition, a description is provided on how the computer data files are related to the file management system and the applications software.

DIGITAL DATA FILES

There are 13 separate data files in the NPRA computer data and graphics system. These files are organized in two ways: by API number and by latitude and longitude. The 10 data files that are organized by API number include exploratory

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well and outcrop information. The data filed by latitude and longitude are the base-map file and two geophysical files. Whether new information would be included as part of an older, expanded file or whether it would be a separate new file was determined by the structure of, and the information included in, the old digital data files. The relations of these data files to each other are shown on figure 39.1.

FILES ORGANIZED BY API NUMBERS

NORTH SLOPE WELL FILE

The North Slope well file contains drilling information on all wells located north of lat. 68° N. However, only 121 test wells and core tests drilled within the NPRA and 3 wells outside the NPRA (Gubik Nos. 1 and 2 and Grandstand No. 1 wells) will be discussed. The file contains such information as identification data, casing data, location, initial potential, rock units penetrated, core data, test data, logs and surveys, and miscellaneous data. The cost to construct this file was $207,968 for 150,057 m (492,313 ft) drilled; the cost per foot of well depth was 42¢. The North Slope well file was one of the most expensive files to build but has become one of the most important files for studying the geologic framework and petroleum potential.

Information for the 79 wells drilled from 1946 through 1953 came from the USGS Professional Papers by Robinson (1956, 1958a, b, 1959a, b, 1964), Collins (1958a-c, 1959, 1961), and Robinson and Collins (1959). A USGS Open-File Report by Collins and Robinson (1967) summarizes the geologic information acquired during this early exploration program. Information on the South Barrow wells drilled from 1955 through 1977 was obtained from U.S. Navy and USGS files and was subsequently released to the public through the National Geophysical Data Center (National Oceanic and Atmospheric Administration (NOAA), 1978b). Information from the wells drilled from 1977 through 1981 by the USGS was also released by the USGS through the data center mentioned above (NOAA, 1979, 1980f, 1981j, k). The rock units included in the well file are those described by Bird (1982c). The sources of the information for the wells included in this file are indicated on table 39.1.

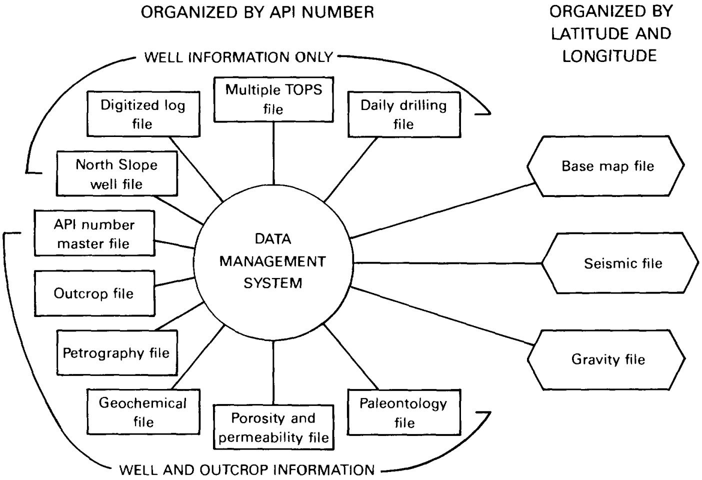

FIGURE 39.1.—The 13 data files included in the NPRA computer data and graphics system that are organized by API number and latitude and longitude. The data management system and other computer software are needed to create reports, graphics, and maps.

In 1977, the North Slope well file was created as a subfile from PI's WHCS file. The file was stored at PI on an IBM model 370 computer to facilitate access to all the programs and formats for encoding, updating, and editing. The file, which has remained in the WHCS format, was transferred in 1980 from the IBM 370 computer to a PRIME 400 minicomputer. This change was made so that all the NPRA data files could be maintained and manipulated on the same computer.

Of all the files developed for this data system, this file was the most difficult to update for four main reasons: (1) A large amount of information was available on each well drilled in the NPRA; (2) data formats of the daily drilling file (discussed in a later section) were not compatible with the WHCS formats, so that much of the well data had to be transferred manually into the North Slope well file; (3) a geologist had to edit the file item by item to check for errors in transferring the data from the original source document to the computer file, and (4) the decision was made to switch the North Slope well file from the IBM 370 to the PRIME 400 computer to facilitate encoding and editing. These major problems have now been solved.

To date, the products that have been created using this file include reports, graphics, and maps that are listed on table 39.2. Three of the more important reports include the completion report, the rock-unit report, and the cross-reference report. Graphical displays include the burial history charts and many organic geochemical displays (chapter 19). Isopach, structure, and organic-carbon maps have been produced from data in this file for this volume.

DIGITIZED LOG FILE

The digitized log file was created to display selected log curves and other types of geologic and geophysical information from all wells within NPRA and some wells outside the NPRA that are important to the evaluation of the North Slope hydrocarbon potential. Products generated from this file are synthetic seismograms (NOAA, 1981g, h), compaction gradient plots, and digitized temperature logs (NOAA, 1978b, 1979, 1980f; table 39.1). The cost to digitize, edit, construct, and display the six-curve log displays for the wells within the NPRA was $359,729. Other costs include synthetic seismograms on 34 wells for $64,944, compaction gradient plots on 25 wells for $25,740 (Ervin, 1981), and digitized temperature logs on 16 wells for $11,586.

There are five types of digital well-log tapes for the NPRA: (1) well-log data digitized from paper logs, (2) well data digitially recorded by a logging service company at the well site, (3) six log curves edited or modified from the first two sources, (4) selected curves depth-corrected or otherwise modified by application of seismic-velocity well surveys, and (5) digital information for special plots.

The first type of tape was digitized from wells drilled before and during 1974. The wells drilled from 1946 through 1953 were digitized from paper prints in reports by Robinson (1956, 1958a, b, 1959a, b, 1964), Collins (1958a-c, 1959, 1961), and Robinson and Collins (1959). The development wells drilled at South Barrow from 1953 through 1974 were digitized from paper prints provided by PI (NOAA, 1978b).

The second type of tapes were from wells drilled since 1974. Logs from wells drilled by the U.S. Navy (1974 into 1977) and by the USGS (1977 through 1981) were digitized in the field at the well site by the logging contractor. The logging contractor, after reformating these field tapes, sent the final tapes directly to PI in Dallas (NOAA, 1979, 1980f, 1981c, j, k). The contractor took from 1 to 8 months to reformat the field tapes into the final tapes.

In 1977, six widely used well-log curves were chosen by Bird (1981 a-c) to be used in almost all subsequent geochemical displays; these represent the third type of digital tape. The six basic curves were extracted and edited by PI in about 2 months. Editing of the first two types of tape involved despiking sonic logs, eliminating log data where the borehole was oversized or where drilling fluid or formation affected the response, and correcting for borehole size. A differential-caliper curve was also created for this tape. Lithologic descriptions were provided by K.J. Bird for use with this kind of tape for all wells in the NPRA. A complete catalog of the edited log curves is available in a report by Bird (1982a). This six-curve log file has been one of the most useful files initiated in the North Slope study. Numerous displays have been created by using the information (table 39.2). One of the most frequently published displays shows the six basic logs (Claypool and Magoon, 1980a-d; Magoon and Claypool, 1980a-f; Bird, 1981a-e, 1982b). After the log curves have been edited, the six curves are displayed together with the lithology, at three scales—1:1,200, 1:2,400, and 1:6,000. These six-curve log displays were used in this volume to make cross sections (chapter 17) and geochemical displays (chapter 19).

The fourth type of tape was created during the process of correcting curves with check-shot surveys. The log curves, as well as the downhole seismic-velocity surveys, were used to compute synthetic seismograms for velocity analysis. Synthetic seismograms are available for all wells drilled by the U.S. Navy and the USGS from 1974 through 1981 (NOAA, 1981g, h; table 39.1).

The basic working files for most USGS work orders were from the last three types of tapes. The information included in the digitized log file were used to make the reports and graphics listed in table 39.3.

A fifth, but separate, type of log file was generated from the fourth tape or synthetic seismogram depth-to-time conversion data. These data were used in the construction of plots of time versus depth, velocity versus depth, and compaction gradients.

MULTIPLE TOPS FILE

The multiple tops file was created in late 1980 to catalog different types of well information as interpreted by different authors. At present, this file contains information provided by K.J. Bird, I.L. Tailleur, Tetra Tech, Inc., and R.J. Witmer. The multiple tops file gives each geologist the opportunity to encode his or her interpreted top and base for any unit penetrated in a well. The rock-unit file by Bird (1982c) is kept in both this file and the North Slope well file. Previously published information for the NPRA wells that were nearest the area of the Prudhoe Bay oil field was provided by Tailleur and others (1978). Tetra Tech's file in-

TABLE 39.1.—*National Petroleum Reserve in Alaska digital data files—file content by well*

Identification data			North Slope well file			Digitized-log file				
Well name and No.	API well No.	Total depth (ft)	Well-file references	Rock units	Mapping	Lithology	Digitized-log curves	Synthetic seismograms	Compaction-gradient plots	Digitized temperature logs
National Petroleum Reserve No. 4 program (1944-53)										
Simpson (Core Test) No. 21	50-023-10001	1,502	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 23	50-023-10002	1,035	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 24	50-023-10003	901	305-L	82-278	-	-	-	-	-	-
North Simpson No. 1	50-023-10004	3,774	305-J	82-278	X	81-1033	81-1033	-	-	-
Barrow Core Rig No. 1	50-023-10005	344	305-K	82-278	-	-	-	-	-	-
Barrow Core Rig No. 2	50-023-10006	236	305-K	82-278	-	-	-	-	-	-
Barrow Big Rig No. 1	50-023-10007	685	305-K	82-278	-	-	-	-	-	-
Barrow (Core Test) No. 1	50-023-10008	1,442	305-K	82-278	-	-	-	-	-	-
South Barrow No. 1	50-023-10009	3,553	305-K	82-278	X	81-1033	81-1033	-	-	-
South Barrow No. 2	50-023-10010	2,505	305-K	82-278	X	81-1033	81-1033	-	-	-
South Barrow No. 3	50-023-10011	2,900	305-K	82-278	X	81-1033	81-1033	-	-	-
South Barrow No. 4	50-023-10012	2,538	305-K	82-278	-	81-1033	81-1033	-	-	-
Avak No. 1	50-023-10013	4,020	305-K	82-278	-	81-1033	81-1033	-	-	-
Grandstand No. 1	50-057-10001	3,939	305-E	82-278	X	81-1036	81-1036	-	-	-
Fish Creek No. 1	50-103-10001	7,020	305-I	82-278	-	81-1034	81-1034	-	-	-
Ikpikpuk (Core Test) No. 1	50-119-10001	178	305-A	82-278	-	-	-	-	-	-
Oumalik (Core Test) No. 1	50-119-10002	392	305-A	82-278	-	-	-	-	-	-
Oumalik (Core Test) No. 11	50-119-10003	303	305-A	82-278	-	-	-	-	-	-
Oumalik (Core Test) No. 12	50-119-10004	300	305-A	82-278	-	-	-	-	-	-
Oumalik	50-119-10005	11,872	305-A	82-278	X	81-1032	81-1032	-	-	-
East Oumalik No. 1	50-119-10006	6,035	305-A	82-278	X	81-1032	81-1032	-	-	-
Square Lake No. 1	50-119-10007	3,987	305-H	82-278	X	81-1035	81-1035	-	-	-
Wolf Creek No. 1	50-119-10008	1,500	305-H	82-278	-	81-1035	81-1035	-	-	-
Wolf Creek No. 2	50-119-10009	1,618	305-H	82-278	-	81-1035	81-1035	-	-	-
Wolf Creek No. 3	50-119-10010	3,760	305-H	82-278	X	81-1035	81-1035	-	-	-
Titaluk No. 1	50-119-10011	4,020	305-G	82-278	X	81-1035	81-1035	-	-	-
Knifeblade No. 1	50-119-10012	1,805	305-G	82-278	X	-	-	-	-	-
Knifeblade No. 2	50-119-10013	373	305-G	82-278	-	-	-	-	-	-
Knifeblade No. 2A	50-119-10014	1,805	305-G	82-278	-	81-1035	81-1035	-	-	-
Skull Cliff (Core Test) No. 1	50-163-10001	779	305-K	82-278	X	-	-	-	-	-
Meade No. 1	50-163-10002	5,305	305-F	82-278	X	81-1032	81-1032	-	-	-
Simpson (Core Test) No. 1	50-279-10001	116	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 2	50-279-10002	226	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 3	50-279-10003	368	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 4	50-279-10004	151	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 5	50-279-10005	130	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 6	50-279-10006	149	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 7	50-279-10007	532	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 8	50-279-10008	580	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 9	50-279-10009	320	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 10	50-279-10010	500	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 11	50-279-10011	580	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 12	50-279-10012	460	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 13	50-279-10013	1,438	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 14	50-279-10014	1,270	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 14A	50-279-10015	290	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 15	50-279-10016	900	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 16	50-279-10017	800	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 17	50-279-10018	1,110	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 18	50-279-10019	1,460	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 19	50-279-10020	1,061	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 20	50-279-10021	1,001	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 22	50-279-10022	903	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 25	50-279-10023	1,510	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 26	50-279-10024	1,171	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 27	50-279-10025	1,500	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 28	50-279-10026	2,505	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 29	50-279-10027	700	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 30	50-279-10028	693	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 30A	50-279-10029	701	305-L	82-278	-	-	-	-	-	-
Simpson (Core Test) No. 31	50-279-10030	355	305-L	82-278	-	-	-	-	-	-
Minga Velocity Test No. 1	50-279-10031	-	-	-	-	-	-	-	-	-
Simpson No. 1	50-279-10032	7,002	305-J	82-278	X	81-1033	81-1033	-	-	-
Topagoruk No. 1	50-279-10033	10,503	305-D	82-278	X	81-1032	81-1032	-	-	-
East Topagoruk No. 1	50-179-10034	3,589	305-D	82-278	X	81-1032	81-1032	-	-	-
Umiat No. 1	50-287-10001	6,005	305-B	82-278	X	81-1035	81-1035	-	-	-
Umiat No. 2	50-287-10002	6,212	305-B	82-278	-	81-1035	81-1035	-	-	-
Umiat (Core Test No. 1) No. 3	50-287-10003	572	305-B	82-278	-	81-1035	81-1035	-	-	-
Umiat (Ruby No. 1) No. 4	50-287-10004	840	305-B	82-278	-	81-1035	81-1035	-	-	-
Umiat (Ruby No. 2) No. 5	50-287-10005	1,077	305-B	82-278	-	-	-	-	-	-
Umiat (Ruby No. 3) No. 6	50-287-10006	825	305-B	82-278	-	-	-	-	-	-
Umiat (Ruby No. 4) No. 7	50-287-10007	1,384	305-B	82-278	-	81-1035	81-1035	-	-	-
Umiat No. 8	50-287-10008	1,327	305-B	82-278	-	-	-	-	-	-
Umiat No. 9	50-287-10009	1,257	305-B	82-278	-	-	-	-	-	-
Umiat No. 10	50-287-10010	1,573	305-B	82-278	-	-	-	-	-	-

TABLE 39.1.—*National Petroleum Reserve in Alaska digital data files—file content by well*—Continued

Multiple-tops file				Daily-drilling file	Paleontology file			Porosity and permeability file	Geochemistry file		Petrography file	API No. master file
Bird	Tailleur	Tetra Tech	Witmer	Well	Foraminifers	Palynology	Biostratigraphy	Core analyses	Cores	Canned cuttings	Thin sections	Well
National Petroleum Reserve No. 4 program (1944-53)--Continued												
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	X	-	-	-	-	-	-	305-J	X	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	305-K	-	-	-	X
82-278	X	-	-	-	TGY-0030	TGY-0030	-	305-K	TGY-0150A	-	X	X
82-278	X	-	-	-	TGY-0030	TGY-0030	-	305-K	TGY-0150A	-	-	X
82-278	X	X	-	-	TGY-0030	TGY-0030	-	305-K	TGY-0150A	-	-	X
82-278	-	-	-	-	-	-	-	305-K	TGY-0150A	-	-	X
82-278	-	-	-	-	-	-	-	-	TGY-0150A	-	-	X
82-278	-	-	-	-	-	-	-	305-E	TGY-0150A	-	-	X
82-278	X	-	-	-	TGY-0030	TGY-0030	-	305-I	X	-	X	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	305-A	-	-	-	X
82-278	-	-	-	-	-	-	-	305-A	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	X	X	-	-	TGY-0030	TGY-0030	-	305-A	TGY-0150A	-	X	X
82-278	-	-	-	-	-	-	-	305-A	TGY-0150A	-	-	X
82-278	-	-	-	-	-	-	-	305-A	TGY-0150A	-	X	X
82-278	-	-	-	-	-	-	-	305-A	TGY-0150A	-	X	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	305-H	X	-	X	X
82-278	-	-	-	-	-	-	-	305-G	TGY-0150A	-	X	X
82-278	-	-	-	-	-	-	-	305-G	TGY-0150A	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	305-G	TGY-0150A	-	X	X
82-278	-	-	-	-	-	-	-	305-K	-	-	-	X
82-278	-	-	-	-	-	-	-	305-F	X	-	X	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	305-L	-	-	-	X
82-278	-	-	-	-	-	-	-	305-L	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	305-L	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	305-L	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	X	X	-	-	TGY-0030	TGY-0030	-	305-J	X	-	X	X
82-278	X	X	-	-	TGY-0030	TGY-0030	-	305-D	TGY-0150A	-	X	X
82-278	-	-	-	-	-	-	-	305-D	TGY-0150A	-	-	X
82-278	-	-	-	-	-	-	-	305-B	X	-	-	X
82-278	-	-	-	-	-	-	-	305-B	TGY-0150A	-	-	X
82-278	-	-	-	-	-	-	-	305-B	-	-	-	X
82-278	-	-	-	-	-	-	-	305-B	-	-	-	X
82-278	-	-	-	-	-	-	-	305-B	-	-	-	X
82-278	-	-	-	-	-	-	-	305-B	-	-	-	X
82-278	-	-	-	-	-	-	-	305-B	-	-	-	X
82-278	-	-	-	-	-	-	-	305-B	-	-	-	X
82-278	-	-	-	-	-	-	-	305-B	-	-	-	X
82-278	-	-	-	-	-	-	-	305-B	-	-	-	X

TABLE 39.1.—*National Petroleum Reserve in Alaska digital data files—file content by well*—Continued

Identification data			North Slope well file			Digitized-log file				
Well name and No.	API well No.	Total depth (ft)	Well-file references	Rock units	Mapping	Lithology	Digitized-log curves	Synthetic seismograms	Compaction-gradient plots	Digitized temperature logs
National Petroleum Reserve No. 4 program (1944-53)--Continued										
Umiat No. 11--------------------	50-287-10011	3,303	305-B	82-278	X	81-1035	81-1035	-	-	-
Sentinel Hill (Core Test) No. 1-	50-287-10012	1,180	305-I	82-278	-	-	-	-	-	-
Gubik No. 1---------------------	50-287-10013	6,000	305-C	82-278	X	81-1036	81-1036	-	-	-
Gubik No. 2---------------------	50-287-10014	4,620	305-C	82-278	X	81-1036	81-1036	-	-	-
Kaolak No. 1--------------------	50-297-10001	6,952	305-F	82-278	X	81-1032	81-1032	TGY-0090	-	-
Barrow program (1955-81)										
South Barrow No. 5--------------	50-023-10014	2,456	305-K	82-278	-	-	-	-	-	-
South Barrow No. 6--------------	50-023-10015	2,363	TGY-0011-MF	82-278	-	81-1033	81-1033	-	-	-
South Barrow No. 7--------------	50-023-20001	2,351	TGY-0011-MF	82-278	-	81-1033	81-1033	-	-	-
South Barrow No. 8--------------	50-023-20002	2,359	TGY-0011-MF	82-278	-	81-1033	81-1033	-	-	-
South Barrow No. 9--------------	50-023-20003	2,450	TGY-0011-MF	82-278	-	81-1033	81-1033	TGY-0090	-	-
South Barrow No. 10-------------	50-023-20004	2,349	TGY-0011-MF	82-278	-	81-1033	81-1033	-	-	-
South Barrow No. 11-------------	50-023-20005	2,350	TGY-0011-MF	82-278	-	81-1033	81-1033	-	-	-
South Barrow No. 12-------------	50-023-20006	2,285	TGY-0011-MF	82-278	-	81-1033	81-1033	-	-	-
Iko Bay No. 1-------------------	50-023-20007	2,731	TGY-0011-MF	82-278	X	81-1033	81-1033	TGY-0090	-	-
South Barrow No. 13-------------	50-023-20008	2,535	TGY-0011-MF	82-278	-	81-1033	81-1033	TGY-0090	GC-80-11	-
South Barrow No. 14-------------	50-023-20009	2,257	TGY-0011-MF	82-278	-	81-1033	81-1033	-	-	-
South Barrow No. 16-------------	50-023-20010	2,400	TGY-0021-MF	82-278	X	81-1033	81-1033	TGY-0090	GC-80-11	TGY-0021-MF
South Barrow No. 17-------------	50-023-20011	2,382	TGY-0021-MF	82-278	X	81-1033	81-1033	TGY-0090	-	TGY-0021-MF
South Barrow No. 19-------------	50-023-20012	2,300	TGY-0021-MF	82-278	-	81-1033	81-1033	TGY-0090	-	-
South Barrow No. 20-------------	50-023-20015	2,356	TGY-0080	82-278	-	81-1033	81-1033	-	GC-80-11	-
South Barrow No. 15-------------	50-023-20016	2,278	TGY-0080	82-278	-	82-290	82-290	-	-	-
South Barrow No. 18-------------	50-023-20017	2,125	TGY-0080	82-278	-	82-290	82-290	-	-	-
National Petroleum Reserve No. 4 program (1973-77)										
Cape Halkett No. 1--------------	50-103-20004	9,900	TGY-0011-MF	82-278	X	X	X	TGY-0090	GC-80-11	TGY-0011-M
East Teshekpuk No. 1------------	50-103-20006	10,664	TGY-0011-MF	82-278	X	81-1034	81-1034	TGY-0090	GC-80-11	-
South Harrison Bay No. 1--------	50-103-20007	11,290	TGY-0011-MF	82-278	X	81-1034	81-1034	TGY-0090	GC-80-11	-
Atigaru Point No. 1-------------	50-103-20008	11,535	TGY-0011-MF	82-278	X	81-1034	81-1034	TGY-0090	GC-80-11	-
West Fish Creek No. 1-----------	50-103-20009	11,427	TGY-0011-MF	82-278	X	81-1034	81-1034	TGY-0090	GC-80-11	-
W. T. Foran No. 1---------------	50-103-20010	8,864	TGY-0011-MF	82-278	X	81-1034	81-1034	TGY-0090	GC-80-11	-
South Simpson No. 1-------------	50-279-20001	8,795	TGY-0011-MF	82-278	X	81-1033	81-1033	TGY-0090	GC-80-11	-
National Petroleum Reserve in Alaska program (1977-81)										
Walakpa No. 1-------------------	50-023-20013	3,666	TGY-0080	82-278	X	81-1033	81-1033	TGY-0090	GC-80-11	-
West Dease No. 1----------------	50-023-20014	4,173	TGY-0080	82-278	X	81-1033	81-1033	TGY-0090	GC-80-11	-
Tulageak No. 1------------------	50-023-20018	4,015	TGY-0110	82-278	X	82-290	82-290	X	-	-
Walakpa No. 2-------------------	50-023-20019	4,360	TGY-0110	82-278	X	82-290	82-290	X	-	-
North Kalikpik No. 1------------	50-103-20011	7,395	TGY-0021-MF	82-278	X	81-1034	81-1034	TGY-0090	GC-80-11	TGY-0021-MF
North Inigok No. 1--------------	50-103-20017	10,170	TGY-0110	82-278	X	82-290	82-290	X	-	-
Koluktak No. 1------------------	50-119-20001	5,882	TGY-0110	82-278	X	82-290	82-290	X	-	-
Lisburne No. 1------------------	50-137-20003	17,000	TGY-0080	82-278	-	81-1035	81-1035	TGY-0090	GC-80-11	-
Awuna No. 1---------------------	50-155-20001	11,200	TGY-0110	82-278	X	82-290	82-290	X	-	-
South Meade No. 1---------------	50-163-20001	9,945	TGY-0041-MF	82-278	X	81-1032	81-1032	TGY-0090	GC-80-11	TGY-0041-MF
Kugrua No. 1--------------------	50-163-20002	12,588	TGY-0021-MF	82-278	X	81-1032	81-1032	TGY-0090	GC-80-11	TGY-0041-MF
Kuyanak No. 1-------------------	50-163-20003	6,690	TGY-0110	82-278	X	82-290	82-290	X	-	-
Drew Point No. 1----------------	50-279-20002	7,946	TGY-0021-MF	82-278	X	81-1034	81-1034	TGY-0090	GC-80-11	TGY-0021-MF
Inigok No. 1--------------------	50-279-20003	20,102	TGY-0041-MF	82-278	X	81-1035	81-1035	TGY-0090	GC-80-11	TGY-0041-MF
Ikpikpuk No. 1------------------	50-279-20004	15,481	TGY-0080	82-278	X	81-1034	81-1034	TGY-0090	GC-80-11	-
East Simpson No. 1--------------	50-279-20005	7,739	TGY-0041-MF	82-278	X	81-1033	81-1033	TGY-0090	GC-80-11	TGY-0041-MF
J. W. Dalton No. 1--------------	50-279-20006	9,367	TGY-0041-MF	82-278	X	81-1034	81-1034	TGY-0090	GC-80-11	TGY-0041-MF
East Simpson No. 2--------------	50-279-20007	7,504	TGY-0080	82-278	X	81-1033	81-1033	TGY-0090	GC-80-11	-
Seabee No. 1--------------------	50-287-20007	15,611	TGY-0080	82-278	X	81-1035	81-1035	TGY-0090	GC-80-11	-
Tunalik No. 1-------------------	50-301-20001	20,335	TGY-0080	82-278	X	81-1032	81-1032	TGY-0090	GC-80-11	-
Peard No. 1---------------------	50-301-20002	10,225	TGY-0041-MF	82-278	X	81-1032	81-1032	TGY-0090	GC-80-11	TGY-0041-MF

REFERENCES.

GC-80-11: Ervin (1981)
TGY-0011-MF: NOAA (1978b)
TGY-0021-MF: NOAA (1979)
TGY-0030: NOAA (1980c)
TGY-0041-MF: NOAA (1980f)
TGY-0060: NOAA (1980a)
TGY-0080: NOAA (1981h)
TGY-0085: NOAA (1981j)
TGY-0090: NOAA (1981f)

TGY-0090A: NOAA (1981g)
TGY-0110: NOAA (1981e)
TGY-0120: NOAA (1981k)
TGY-0150A: NOAA (1981h)
305-A: Robinson (1956)
305-B: Collins (1958c)
305-C: Robinson (1958b)
305-D: Collins (1958b)

TABLE 39.1.—*National Petroleum Reserve in Alaska digital data files—file content by well*—Continued

Multiple-tops file				Daily-drilling file	Paleontology file			Porosity and permeability file	Geochemistry file		Petrography file	API No. master file
Bird	Tailleur	Tetra Tech	Witmer	Well	Foraminifers	Palynology	Biostratigraphy	Core analyses	Cores	Canned cuttings	Thin sections	Well
National Petroleum Reserve No. 4 program (1944-53)--Continued												
82-278	-	-	-	-	-	-	-	305-B	TGY-0150A	-	-	X
82-278	-	-	-	-	-	-	-	305-I	-	-	-	X
82-278	-	-	-	-	-	-	-	305-C	X	-	X	X
82-278	-	-	-	-	-	-	-	305-C	X	-	X	X
82-278	-	X	-	-	-	-	-	305-F	X	-	X	X
Barrow program (1955-81)--Continued												
82-278	-	-	-	-	TGY-0030	TGY-0030	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	X	-	-	X	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	X	-	-	-	TGY-0030	TGY-0030	-	TGY-0085	TGY-0150A	-	-	X
82-278	-	-	-	-	-	-	-	-	-	-	-	X
82-278	X	-	-	-	-	-	-	TGY-0085	-	-	-	X
82-278	X	-	-	-	TGY-0030	TGY-0030	-	TGY-0085	X	-	-	X
82-278	X	X	-	-	TGY-0030	TGY-0030	-	TGY-0085	-	-	-	X
82-278	X	X	81-1166	-	TGY-0030	TGY-0030	81-1166	TGY-0085	X	X	-	X
82-278	X	-	81-1166	X	TGY-0030	TGY-0030	81-1166	TGY-0085	-	X	-	X
82-278	X	X	81-1166	X	TGY-0030	TGY-0030	81-1166	X	TGY-0150A	TGY-0150A	-	X
82-278	X	X	81-1166	X	TGY-0030	TGY-0030	81-1166	TGY-0085	X	X	-	X
82-278	X	-	81-1166	X	TGY-0030	TGY-0030	81-1166	TGY-0085	X	X	-	X
82-278	-	X	-	X	-	-	-	X	X	-	-	X
82-278	-	-	-	X	-	-	-	TGY-0110	X	-	-	X
82-278	-	-	-	X	-	-	-	X	X	-	-	X
National Petroleum Reserve No. 4 program (1973-77)--Continued												
82-278	X	X	81-1166	-	TGY-0030	TGY-0030	81-1166	-	-	X	-	X
82-278	X	X	81-1166	-	TGY-0030	TGY-0030	81-1166	-	-	-	-	X
82-278	X	X	81-1166	-	TGY-0030	TGY-0030	81-1166	TGY-0110	X	X	-	X
82-278	X	X	81-1166	-	TGY-0030	TGY-0030	81-1166	TGY-0085	X	X	-	X
82-278	X	X	81-1166	-	TGY-0030	TGY-0030	81-1166	-	-	TGY-0150A	-	X
82-278	X	X	81-1166	-	TGY-0030	TGY-0030	81-1166	TGY-0085	X	X	-	X
82-278	X	X	81-1166	-	TGY-0030	TGY-0030	81-1166	TGY-0110	-	X	-	X
National Petroleum Reserve in Alaska program (1977-81)--Continued												
82-278	X	X	81-1166	X	TGY-0060	TGY-0060	81-1166	X	TGY-0150A	TGY-0150A	-	X
82-278	X	X	81-1166	X	TGY-0060	TGY-0060	81-1166	TGY-0110	TGY-0150A	TGY-0150A	-	X
82-278	-	-	81-1166	X	TGY-0120	TGY-0120	81-1166	X	X	X	-	X
82-278	-	-	81-1166	X	TGY-0120	TGY-0120	81-1166	X	X	X	-	X
82-278	X	X	81-1166	X	TGY-0030	TGY-0030	81-1166	-	TGY-0150A	TGY-0150A	-	X
82-278	-	-	81-1166	X	TGY-0120	TGY-0120	81-1166	X	X	X	-	X
82-278	X	-	81-1166	X	TGY-0120	TGY-0120	81-1166	-	-	X	-	X
82-278	-	X	81-1166	X	TGY-0060	TGY-0060	81-1166	-	X	X	-	X
82-278	X	X	81-1166	X	TGY-0120	TGY-0120	81-1166	X	X	X	-	X
82-278	X	X	81-1166	X	TGY-0030	TGY-0030	81-1166	TGY-0110	X	X	X	X
82-278	X	X	81-1166	X	TGY-0030	TGY-0030	81-1166	TGY-0110	TGY-0150A	TGY-0150A	-	X
82-278	-	-	81-1166	X	TGY-0120	TGY-0120	81-1166	X	X	X	-	X
82-278	X	X	81-1166	X	TGY-0030	TGY-0030	81-1166	TGY-0085	X	X	-	X
82-278	X	X	81-1166	X	TGY-0030	TGY-0030	81-1166	TGY-0085	TGY-0150A	TGY-0150A	X	X
82-278	X	X	81-1166	X	TGY-0060	TGY-0060	81-1166	X	X	X	-	X
82-278	X	X	81-1166	X	TGY-0030	TGY-0030	81-1166	TGY-0085	TGY-0150A	TGY-0150A	X	X
82-278	X	X	81-1166	X	TGY-0060	TGY-0060	81-1166	TGY-0085	X	X	X	X
82-278	X	X	81-1166	X	TGY-0060	TGY-0060	81-1166	X	X	X	-	X
82-278	-	X	81-1166	X	TGY-0060	TGY-0060	81-1166	TGY-0110	TGY-0150A	TGY-0150A	X	X
82-278	X	X	81-1166	X	TGY-0060	TGY-0060	81-1166	X	TGY-0150A	TGY-0150A	X	X
82-278	X	X	81-1166	X	TGY-0030	TGY-0030	81-1166	TGY-0085	X	X	X	X

305-E: Robinson (1958a)
305-F: Collins (1958a)
305-G: Robinson (1959b)
305-H: Collins (1959)
305-I: Robinson and Collins (1959)
305-J: Robinson (1959a)
305-K: Collins (1961)
305-L: Robinson (1964)

81-1032: Bird (1981d)
81-1033: Bird (1981e)
81-1034: Bird (1981a)
81-1035: Bird (1981h)
81-1036: Bird (1981c)
81-1166: Witmer and others (1981b)
82-278: Bird (1982c)
82-290: Bird (1982b)

TABLE 39.2.—*Software programs available for each NPRA data file*

[G, graphical display; M, map; R, report]

					API No.	
	Well information only				Well	
Software program	North slope well file	Digitized-log file	Multiple-tops file	Daily-drilling file	Paleontology file	Porosity and permeability file
Completion report	R	-	-	-	-	-
Well-data summary	R	-	-	-	-	-
Cross-reference report	R	-	-	-	-	-
6-log curve with lithology (1:100, 1:200, 1:400)	-	G	-	-	-	-
Log display (1:50)	-	G	-	-	-	-
Petros © Porosity calculations	-	R,G	-	-	-	-
Synthetic seismograms	-	R,G	-	-	-	-
Compaction-gradient plots	-	G	-	-	-	-
Temperature graphs	-	G	-	-	-	-
Biostratigraphic reports	-	-	G	-	G	-
Species-diversity plots	G	G	G	-	G	-
Rock-unit report	R	-	G	-	-	-
Daily-drilling report	-	-	-	R	-	-
Well summary report	-	-	-	R	-	-
Sample-preparation description	-	-	-	-	-	-
Sample-preparation lithology	-	-	-	-	-	-
C_{1-7} headspace gas [1]	-	-	-	-	-	-
C_{1-7} cuttings gas [1]	-	-	-	-	-	-
C_{1-7} generation curve and reservoir horizons [1]	-	-	-	-	-	-
C_{1-7} headspace plus cuttings gas [1]	-	-	-	-	-	-
C_{4-8} gasoline-range hydrocarbons	-	-	-	-	-	-
C_7 gasoline-range hydrocarbons	R,G	-	-	-	-	-
C_7 gasoline-range saturated hydrocarbons	R,G	-	-	-	-	-
Carbon and TEA-FID analysis	-	-	-	-	-	-
Organic-carbon report	R	-	-	-	-	-
C_{15+} solvent extraction and column chromatography	-	-	-	-	-	-
C_{15+} solvent-extraction data	R,G	-	-	-	-	-
Thermal-history summary	-	-	-	-	-	-
Vitrinite-reflectance data [1]	-	-	-	-	-	-
Vitrinite-reflectance histograms	-	-	-	-	-	-
Visual kerogen-1	R,G	-	-	-	-	-
Visual kerogen-2	R,G	-	-	-	-	-
Elemental analysis of kerogen	-	-	-	-	-	-
Atomic HC/OC ratio plots	G	-	-	-	-	-
$S^{13}C_{15+}$ hydrocarbon fractions	R,G	-	-	-	-	-
Carbon-isotope display	G	-	-	-	-	-
Analysis-completed report	-	-	-	-	-	-
Header information	-	-	-	-	-	-
Geochem cross-reference report	R	-	-	-	-	-
Oil analysis	-	-	-	-	-	-
Oil graphics	G	-	-	-	-	-
Gas analysis	-	-	-	-	-	-
Vitrinite-reflectance and C_{1-7} data [1]	G	G	-	-	-	-
Well-geochemistry summary	G	G	-	-	-	-
Ternary-diagram point-count data	-	-	-	-	-	-
X,Y-coordinate point-count data	-	-	-	-	-	-
Histogram point-count data	-	-	-	-	-	-
Porosity vs. permeability	-	-	-	-	-	G
Histogram -- grain size	-	-	-	-	-	-
Histogram -- rock fabric properties	-	-	-	-	-	-
Measured section display	-	-	-	-	-	-
API well and outcrop number glossary	R	-	-	-	-	-
Pics © Base map	M	-	M	-	-	-
Structure map	M	-	M	-	-	-
Isopach map	M	-	-	-	-	-
Organic-carbon map	M	-	-	-	-	-
Visual-kerogen map	M	-	-	-	-	-
Burial-history chart	G	-	-	-	-	-

[1] Same technical-applications program

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TABLE 39.2.—*Software programs available for each NPRA data file*—Continued

				Latitude and longitude		
and outcrop information				Geography	Shotpoint	
Geochemical file	Petrography file	Outcrop file	API No. master file	Base-map file	Seismic file	Gravity file
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
R	-	-	-	-	-	-
R	-	-	-	-	-	-
R	-	-	-	-	-	-
R	-	-	-	-	-	-
R	-	-	-	-	-	-
R,G	-	-	-	-	-	-
R	-	-	-	-	-	-
R,G	-	-	-	-	-	-
R,G	-	-	-	-	-	-
-	-	-	-	-	-	-
R	-	-	-	-	-	-
R	-	-	-	-	-	-
R,G	-	-	-	-	-	-
R	-	-	-	-	-	-
R	-	-	-	-	-	-
G	-	-	-	-	-	-
R,G	-	-	-	-	-	-
R,G	-	-	-	-	-	-
-	-	-	-	-	-	-
G	-	-	-	-	-	-
R,G	-	-	-	-	-	-
G	-	-	-	-	-	-
R	-	-	-	-	-	-
R	-	-	-	-	-	-
R	-	-	R	-	-	-
R	-	-	-	-	-	-
G	-	-	G	-	-	-
R	-	-	-	-	-	-
G	-	-	-	-	-	-
G	-	-	-	-	-	-
-	G	G	G	-	-	-
-	G	G	G	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	G	G	G	-	-	-
-	G	G	G	-	-	-
-	-	G	G	-	-	-
-	-	-	R	-	-	-
-	-	-	-	M	M	-
-	-	-	-	M	M	-
-	-	-	M	M	M	M
M	-	-	-	M	-	-
M	-	-	-	M	-	-
-	-	-	-	-	-	-

TABLE 39.3.—*National Petroleum Reserve in Alaska digital data files—file content by measured outcrop section*

[x, unpublished data; -, no data available]

Measured outcrop section name	API outcrop No.	Total thickness (ft)	API No. master file outcrop	Petrography file thin sections	Geochemistry file samples
Tuktu Bluff	50-057-90001	6,129	x	x	x
Type Grandstand	50-057-90010	2,663	x	-	x
Rooftop anticline	50-057-90011	1,238	x	-	x
Arc Mountain	50-057-90012	1,690	x	x	x
Tupikchak syncline	50-073-90001	5,890	x	-	x
Pitmegea syncline	50-073-90002	2,585	x	-	x
Dugout syncline	50-073-90003	1,694	x	-	x
Starve section	50-073-40005	188	x	-	x
Coke Basin	50-073-90006	1,226	x	-	x
Igloo Mountain	50-073-90007	1,030	x	-	x
Ninuluk Bluff	50-119-90001	1,036	x	-	x
Awuna River	50-119-90002	555	x	-	x
Section Creek	50-119-90003	519	x	-	x
Killik Bend	50-137-90001	519	x	-	x
Killik Type	50-137-90002	1,017	x	-	x
Kurupa anticline	50-137-90003	5,963	x	x	x
Carbon Creek	50-155-90001	2,704	x	x	x
Tupikchak Mountain	50-171-90001	4,092	x	x	x
Meat Mountain	50-171-90002	1,922	x	-	x
Marmot syncline	50-203-90001	3,476	x	x	x
Corwin Bluffs	50-205-90001	689	x	x	x
Kukpowruk syncline	50-207-90002	237	x	-	x
Archimedes anticline	50-207-90003	1,734	x	-	x
Kukpowruk type section	50-207-90004	4,044	x	-	x
Snowbank anticline	50-207-90005	614	x	-	x
Barabara syncline	50-207-90006	4,671	x	x	x
Lupine River	50-223-90001	1,848	x	-	x
Schrader Bluff	50-287-90003	2,626	x	-	x
East Archimedes Ridge	50-297-90001	3,455	x	-	x
Kokolik Warp syncline	50-297-90002	6,927	x	-	x
Folsom Point syncline	50-297-90003	2,832	x	-	x
Carbon Creek anticline	50-297-90004	2,597	x	-	x
Lookout Ridge syncline	50-297-90005	1,840	x	-	x

cludes tops and bases for the parastratigraphic and stratigraphic units used in their reports to the USGS. Biostratigraphic information from Witmer and others (1981b) is also in this file as well as in the paleontology file. The multiple tops file has been designed so that more fields of information can be added as the need arises. The products from this file are the biostratigraphic report, species diversity plot, rock unit report, and a variety of map types as indicated in table 39.2.

DAILY DRILLING FILE

The daily drilling file includes information acquired while a USGS well was being drilled in the NPRA. The file was designed to collect geologic information from wells on a daily basis, so that each week drilling reports could be mailed to geologists who were not in the area. Furthermore, when the well reached total depth, the well summary report could be easily and quickly obtained from the computer. The total cost of building the daily drilling file for 28 wells was $140,120. Included in this cost were the well summary reports.

The types of information that were included in this file are the drilling status or activity, previous day's depth, present day's depth, footage drilled, rock units, sample descriptions of cores or cuttings, shale density, sample quality, hydrocarbon shows, mud temperatures, date samples shipped, and name of the well-site geologist. Daily drilling files were maintained for 1 U.S. Navy well and 27 USGS wells (table 39.1).

This file had a slow start in its development because there was no clear understanding of how to enter data in a consistent manner and how it would eventually be used. Finally, once a geologist supervised the data entry, a glossary was prepared to avoid wording inconsistencies, and a program was written to place all narrative information about the conventional cores into the North Slope well file. Unfortunately, since the drilling data collected for the daily drilling file were much more diverse and voluminous than those of the North Slope well file, only limited portions of the daily drilling information could be transferred directly into the North Slope well file. When the well reached total depth, a series of well summaries was created by reformating the daily drilling report from a daily basis to a depth basis to show the drilling activity, sample descriptions, and those items included on the daily drilling report.

PALEONTOLOGY FILE

The paleontology file was initiated in 1978 to include the Anderson, Warren and Associates paleontology data for all the wells drilled within the NPRA (NOAA, 1980d, e, 1981f). Included in the file are notations on approximately 1,000 different species of Foraminifera, Radiolaria, pollen, spores, dinoflagellates, and architarchs. To date, information on foraminifers and palynology from nine wells drilled between 1946 and 1974 is included in the file (NOAA, 1980e; table 39.1). Except for some wells in the South Barrow area, all 35 wells drilled from 1974 through 1981 have complete paleontology records (NOAA, 1980d, e, 1981f; Witmer and others, 1981a, b). The cost to develop the species dictionary and to build the paleontology file was $76,787. For 44 wells (106,158 m or 348,289 ft drilled), the total cost to acquire the paleontology information was $1,047,177. That is, the cost to build the file was 22¢ per foot, or 7.3¢ per analytical dollar.

At present, three subfiles make up the paleontology file. The first subfile is the header file, which contains information such as the API well number, location, well name and number, and a 3-digit number that is unique for each well. The unique 3-digit number was needed to eliminate the need for a 14-digit API number on each record in the species data file. The second subfile, the species data file, contains the unique 3-digit number, sample type, core number, interval of analysis, recovery code, and abundance code for each species. The third subfile, the biostratigraphic file, was constructed in 1981 and includes the unique 3-digit number and the faunal-zone and geologic-age codes (Witmer and others, 1981a, b). This subfile was created to eliminate the need to assign the faunal-zone and geologic-age codes to every record in the species file. Information from this third subfile also appears in the multiple tops file (table 39.1).

Present use of this file has been limited to creating a biostratigraphic report and a species-diversity plot. Information included in this file is also pertinent, however, to the age and depositional environment of the rock units and is important in the resource assessment of this province.

POROSITY AND PERMEABILITY FILE

The porosity and permeability file was initiated in 1981 and includes those physical properties required to evaluate the petroleum reservoir potential. This file has cost $37,305 and includes all the available porosity and permeability information on 76 wells within the NPRA: 42 wells from the 1945 to 1953 exploration program (Robinson, 1956, 1958a, b, 1959a, b, 1964; Collins, 1958a-c, 1959, 1961; Robinson and Collins, 1959), 11 wells from the 1953 to 1977 drilling (NOAA, 1981i, k), and 23 wells from the latest program (NOAA, 1981i, k).

The file contains porosity, permeability, and water-saturation data derived from laboratory core analysis and porosity data from reservoir studies. Also included are density values that were either measured in the laboratory or calculated from well logs. Detailed core descriptions similar to those found in the North Slope well file are included when pertinent.

GEOCHEMICAL FILE

The purpose of the geochemical file is to provide a data base of petroleum geochemical analyses for the wells drilled in the NPRA. The cost of building and using the geochemical file can be evaluated by comparing three separate costs: analysis, file construction, and software development. The geochemical analyses for rock samples from the 63 wells listed in table 39.1 within the NPRA was $908,126. The cost of encoding the entire geochemical file, which includes wells outside the NPRA and other analyses on oil and gas samples, was $134,482 for $1,434,245 worth of geochemistry, or 9.4¢ per analytical dollar. The cost to develop the 30 software programs to create reports, displays, and maps from the file was $222,881, or 15.5¢ per analytical dollar.

Geochemical analyses from measured sections (Magoon and Claypool, 1979; table 39.3), random outcrops, and samples of oil (Magoon and Claypool, 1981) and gas are included in the geochemical file. Analyses of geochemical cores and well cuttings have been published by the USGS (Magoon and Claypool, 1979, 1980a-f; Claypool and Magoon, 1980a-d) and released to the public through the National Geophysical Data Center (NOAA, 1981d). The analyses included in this file were made under contract by Geochem Research, Inc., and Global Geochemistry Corp. (Claypool and Magoon, chapter 18). The analytical data were added to the geochemical file on a monthly or quarterly basis from mid-1977 into 1982. The wells and measured sections included in this file are outlined in tables 39.1 and 39.3, and the displays are listed in table 39.2. The types of analytical data are discussed elsewhere in this volume (Magoon and Bird, chapter 17; Claypool and Magoon, chapter 18).

Numerous reports and graphic displays have been developed for use with this file, as listed in table 39.2.

PETROGRAPHY FILE

The petrography file is designed to contain all petrographic data, from potential sandstone reservoirs, that have been acquired from well and outcrop studies during the NPRA exploration program. To date, this file contains only petrographic data derived from the study of the Nanushuk Group (Bartsch-Winkler, 1979; Bartsch-Winkler and Huffman, 1981; Huffman, 1979; table 39.3). The file contains 210 samples. The data include percentage values of petrographic constituents, results of porosity and air permeability analyses, and estimated values for certain textural properties and fabric elements. Four graphical programs are available for evaluation of the data (table 39.2). Software programs include generation of histograms, crossplots, and ternary diagrams.

OUTCROP FILE

The purpose of the outcrop file is to store rock data obtained from surface exposures, either measured sections or grab samples, so that information from surface and subsurface rocks can be compared. This file contains geologic information that was collected on the North Slope in the summers of 1977 and 1978 by several field parties that were studying the Nanushuk Group and related rocks (Ahlbrandt, 1979). Data from 24,460 m (80,250 ft) of measured section are in this file (table 39.3). The cost of encoding this information was $77,405; the cost to display the data (as shown in Ahlbrandt, 1979, p. 26-29) was $6,917.

Measured sections can be plotted in the mapping portion of the program as though they were deviated wells in order to facilitate comparisons. The top of the measured section is plotted as the surface location of the hypothetical deviated well, and the bottom of the section is plotted as the total depth location. Information on grain size, porosity and permeability, thickness of sand, and the general composition of sands are included (table 39.2).

API-NUMBER MASTER FILE

The purpose of the API-number master file was to keep a record of the API numbers assigned to wells and to outcrops. API well numbers are assigned by the State of Alaska, whereas the API outcrop numbers are assigned by PI. Each well has a unique number that identifies it with the well and outcrop information in the other nine files organized by API numbers. The maintenance of this file is essential because it allows similar types of information from both well and outcrop to be shown together on reports, graphics, and maps. One report, the API-number master-file report, lists all the information included in this file.

The API well number is a unique numeric identifier assigned to a well that is drilled for the purpose of finding or producing oil or gas or for providing related information (American Petroleum Institute, 1979; fig. 39.2). For the North Slope of Alaska, the API number requires 14 digits (aa-bbb-ccccc-dd-ee) to define the state (aa), quadrangle (bbb), and unique well codes (ccccc). The four additional digits describe whether or not the well was side tracked (dd) and any small change in hole location (ee). For the North Slope well file and this file, wells drilled before January 1, 1967, are serially numbered from 10001 within each quadrangle, whereas wells drilled after January 1, 1967, are serially numbered from 20001 (fig. 39.2).

The API outcrop numbers start with 90001 and are separated into three categories: (1) single grab samples, (2) more than one sample from a single, unmeasured stratigraphic section, and (3) more than one sample from a measured stratigraphic section. State and quadrangle codes are the same as in the API well number (fig. 39.2).

For a well, other information in the API-number master file includes the surface and subsurface locations in latitude and longitude, the section, township, and range, and the elevations of the kelly bushing and ground level. Rock units exposed on the surface and penetrated by total depth are included, together with the spud and completion dates. For the measured section, the base or oldest part of the section (generally measured first) is considered the rock unit at total depth; the thickness of the section is the total depth; and the rock unit at the top or the youngest unit is the surface rock unit. The elevation at the top of the measured section (as read from a topographic map) is the ground elevation. In this manner, a measured section can be treated as a well for isopach maps. A map that posts both well and outcrop locations as well as indicating results from geochemical analyses would be an example of the use of this interrelated information.

The majority of well and outcrop data is stored in the other files. This file was specifically designed to be a bridge between well and outcrop data, hence this file contains only minimal information. It is updated in two ways. The well information is updated directly from the North Slope well file, but the outcrop information is keypunched directly into the file.

FILES ORGANIZED BY LATITUDE AND LONGITUDE

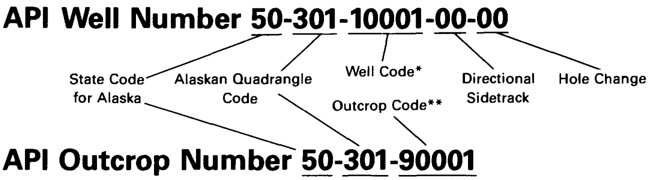
BASE-MAP FILE

The base-map file provides a base on which to plot wells and geologic and geophysical data. To provide this geographic information, the file contains digits for the coastline, selected boroughs, most major drainages, township-and-range grid, the outlines for the NPRA and the William O. Douglas Wildlife Range, and the route of the Trans-Alaska Pipeline. The base map was digitized from lat 71°30′ to 66°45′ N. and from the Canadian border on the east to Cape Lisburne on the west. The coastline and drainage were digitized from USGS quadrangle maps within the NPRA at a scale of 1:125,000 (enlarged from 1:250,000) by the Petty-Ray Geophysical Co., and the township-and-range grid for Alaska was acquired from the Bureau of Land Management. PI then digitized the remaining coastline, selected boroughs, political boundaries, and major drainages as requested by the USGS from the 1:250,000-scale topographic maps. All these data were combined into the base map file.

The base map can be retrieved and plotted with any of these elements at almost any scale on three different projection systems: (1) Universal Transverse Mercator; (2) American Polyconic, and (3) Lambert Conformal. In addition to the elements that are part of the base map, other information can be plotted. For example, well locations, seismic-reflection lines or shotpoints, and gravity symbols can be plotted in various combinations.

SEISMIC FILE

The seismic file contains the location of each seismic line or shotpoint and the time or depth to each reflector. For seismic data acquired from 1974 through 1978, the file includes the location of all shotpoints, the line and shotpoint identifier, the two-way traveltime, and the average velocity to a picked horizon (NOAA, 1981i). Only seismic shotpoint locations, not picked reflections, are included for seismic lines acquired in 1979. Except for the 1979 data, Tetra Tech, Inc., picked



*On January 1, 1967, State began numbering current wells serially within quadrangles, starting with 20001. All wells previously drilled have been assigned API well numbers serially within each USGS quadrangle, starting with 10001.

**Outcrop code informally assigned by PI.

North Slope Quadrangle Name	Quadrangle Code
ARCTIC	011
BARROW	023
BARTER ISLAND	025
BEECHEY POINT	029
CHANDLER LAKE	057
DE LONG MTS.	073
DEMARCATION PT.	075
FLAXMAN ISLAND	089
HARRISON BAY	103
HOWARD PASS	111
IKPIKPUK RIVER	119
KILLIK RIVER	137
LOOKOUT RIDGE	155
MEADE RIVER	163
MISHEGUK MTN.	171
MT. MICHELSON	179
PHILIP SMITH MTS.	203
POINT HOPE	205
POINT LAY	207
SAGAVANIRKTOK	223
TABLE MTN.	263
TESHEKPUK	279
UMIAT	287
UTUKOK RIVER	297
WAINWRIGHT	301

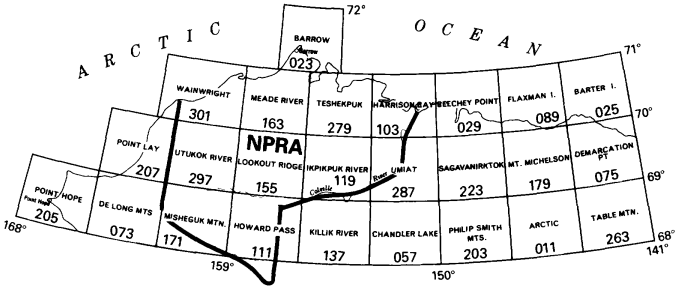


FIGURE 39.2.—Explanation of the American Petroleum Institute (API) well-number system as applied to North Slope wells. API outcrop-number system uses a similar number informally assigned by Petroleum Information Corporation (PI).

26 seismic horizons, of which 5 are continuous over most of the northern part of the NPRA and the remaining 19 are of local importance only. Presently, more than 17,600 line kilometers (11,000 mi) of seismic data are included in this file.

Tetra Tech, Inc., acquired all shotpoint locations from various seismic contractors on 9-track magnetic tapes, and they placed the time and velocity to a picked seismic horizon for each shotpoint on a floppy disk. The information on the floppy disk was placed on a 9-track tape for PI to include in the seismic file (NOAA, 1981e). The source documents for this file have been released through the National Geophysical Data Center (NOAA, 1978a, 1980a, b, 1981a, b, 1982). In order to check the data file, the values for the Lower Cretaceous structure map were posted and contoured. Subsequently, these seismic data have been used in conjunction with the rock units (Bird, 1982c) to develop structure and isopach maps (Bird, chapter 16, figs. 16.3-16.22). In addition to these maps, the seismic file has been used to construct shotpoint maps at various scales to help in the interpretation and exploration.

GRAVITY FILE

The gravity file contains information about line identification and station number, latitude and longitude, ice or water depth, station elevation, observed gravity, and free-air and simple Bouguer anomaly data. The data were gathered in the field along with the seismic-reflection data. Hence the gravity stations coincided with the seismic shotpoints. The data included in this file were obtained during 1974 through 1980.

PI received the gravity data from Tetra Tech, Inc., on magnetic tape (NOAA, 1980c). These data have been used to produce contoured Bouguer anomaly maps.

FILE CONSTRUCTION PROCEDURE

The 13 data files have been built and software developed from the time in 1976, when the NPRA computer data and graphics system was initially conceived, to 1982. This system was implemented on the premise that in addition to the information acquired during previous exploration programs, large volumes of geological and geophysical data would be acquired during the exploration from 1977 through 1982. Placing this new geologic information into computer data files and developing software to use the files would facilitate the evaluation process. Data had also been systematically collected from 1944 by the U.S. Navy and the USGS, and it was possible to encode much of this older information into the computer files.

These computer files had two parallel tracks of development (A and B), each track involving specific steps. The first step of track A was the creation of the file—its definition, design, and building. This step was critical because it placed an upper limit on the user's access to the file by defining the type and nature of the data to be included. The second step was the standardization of abbreviations, nomenclature, and descriptions. For example, in the encoding of data for the daily drilling file, a glossary of terms was created. The third step of track A involved the building of the file by encoding or entering the data from source documents into the computer data file in the prescribed formats. In most cases, at least three people—geologist, programmer, and data encoder—were involved in all phases of file construction. The computer programmer learned from the geologist what type of data elements were to be included and how the files were to be used. The computer programmer and the geologist worked with the data encoder to be sure that the data were entered into the file properly and correctly.

The first step of file software development, or track B, started at the same time as step one of track A. First, a report outline was produced that contained all or almost all of the data being entered. The geologist presented this report outline to the programmer at the time the file structure was initiated. Second, as soon as possible, the data file was displayed in the proposed report form. Third, the geologist and computer programmer devised some simple machine-editing procedure to check quickly for faulty data. Fourth, the geologist requested graphic or map displays to show visually the data in the file. This procedure was repeated each time the file was updated, so that small errors and inconsistencies could be detected before the file got very large. The computer data file became a useful geologic tool when the file content could be displayed graphically or in report form. The next phase involved development of a data management system that allowed the geologist to use at least two separate data files in conjunction.

SYSTEM OF DATA MANAGEMENT AND TECHNICAL APPLICATIONS

The system of data management and technical applications is composed of three parts. The first is the computer file that contains data pertinent to a particular exploration or research project. Second is the data-management system that provides the user with the means to retrieve, edit, and update data elements from more than one computer file. The retrieved data are placed in a temporary work file to be edited, updated, or run in other application programs. The third part is the technical-applications program that can be used to generate reports, graphics, or maps. The name for PI's data management and technical applications system is GEODE (fig. 39.3). For the NPRA, the data and graphics GEODE system consists of four parts: (1) the 13 data files, (2) TECH/SYS, (3) RAGS, and (4) PICS. These last two acronyms stand for Reports and Graphics System (RAGS) and Petroleum Information's Contouring System (PICS). The 13 data files have already been discussed. TECH/SYS is the data-management portion of this system, which can be used to provide data to the technical-applications portion of the system (PICS and RAGS). TECH/SYS, at present, has the capability of extracting data from three files: the North Slope well file, the seismic file, and the basemap file. The technical-applications programs, RAGS and PICS, extract and manipulate data from the remaining 10 files to produce reports, graphics, and maps, as listed in table 39.2.

TIME

One of the most important reasons for using machine processing is that the computer, with its various types of printers and plotters and its large memory capacity, enables the geologist to manipulate large amounts of data into a form that can be interpreted quickly. To get the data into such form involves at least three different time frames. The first time frame, perhaps the most frustrating for the geologist, is the long leadtime that is required to build an embryonic data file and to develop the minimum amount of software needed to use the file. This time is usually measured in months, but for some of the more complex files—for example, geochemistry—the time was measured in years. To implement the NPRA data system, work orders were written to initiate file construction and software development (fig. 39.4). PI was able to complete most work orders in 2 months (fig. 39.4). The total length of this time frame was usually 4 to 6 months.

The second time frame is much shorter. At this level, the file structure and software are already available, but PI enters new data and runs the software on their computer. Because of the existing software, reports or displays for the new data have to be handled by mail, so the time is measured in days or weeks.

The third and shortest time frame is the "interactive time." Here the geologist enters data remotely into the PI or USGS computers and then quickly receives the data electronically in the form of reports, graphic displays, or maps. This time is measured in minutes or hours. Part of the NPRA computer data and graphics system is in the first time frame, and part is in the second. The third, interactive time, is still to be developed.

CONCLUSION

Experience has shown that the NPRA computer data and graphics system, begun in early 1977, is a powerful aid in interpreting and synthesizing geological data. Experience has also shown that this computer system is an efficient way to disseminate drilling information throughout the country to the many geologists working on the NPRA. Presently, the North Slope of Alaska (NPRA, the Arctic National Wildlife Refuge, and offshore Alaska) is in an early stage of exploration. As time passes, these geological and geophysical data bases in the NPRA computer data and graphics system will grow and become more complete, thus increasing their usefulness in evaluating the North Slope resource

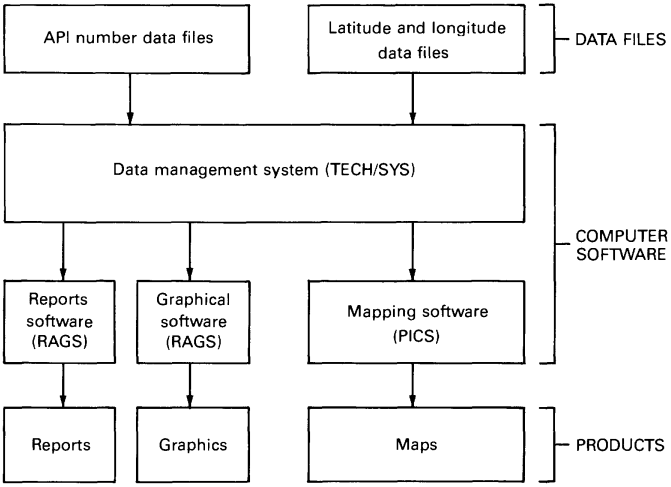


FIGURE 39.3.—The NPRA computer data and graphics system (GEODE), showing its three important elements: data files, computer software, and products. Data files are shown in figure 39.1 and tables 39.1 and 39.3; computer software, which includes the data management system (TECH/SYS), RAGS, and PICS, is the necessary link between data files and products; and products are listed in table 39.2.

potential. Even though the NPRA geologists were not able to use the data system fully during their exploration and evaluation program (because the system was being developed concurrently with the drilling program), this computer system can, in the future, be used as a research tool to assess more fully the oil and gas potential of the NPRA and adjacent areas.

REFERENCES CITED

Ahlbrandt, T.S., 1979, Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, 163 p.

American Petroleum Institute, 1979, The API well number and standard state and county numeric codes including offshore waters: American Petroleum Institute (API) Bulletin D12A, 136 p.

Bartsch-Winkler, Susan, 1979, Textural and mineralogical study of some surface and subsurface sandstones from the Nanushuk Group, western North Slope, Alaska, *in* Ahlbrandt, T.S., *ed*, Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 61-76.

Bartsch-Winkler, Susan, and Huffman, A.C., 1981, Petrography of the Nanushuk Group and Torok Formation: U.S. Geological Survey Open-File Report 81-1222, 60 p.

Bird, K.J., 1981a, Machine-generated displays of well logs and lithology from selected wells on the North Slope of Alaska; 11 wells from the northeastern part of the National Petroleum Reserve in Alaska (NPRA): U.S. Geological Survey Open-File Report 81-1034, 7 p., 11 oversize sheets.

——— 1981b, Machine-generated displays of well logs and lithology from selected wells on the North Slope of Alaska; 15 wells from the southeastern part of the National Petroleum Reserve in Alaska

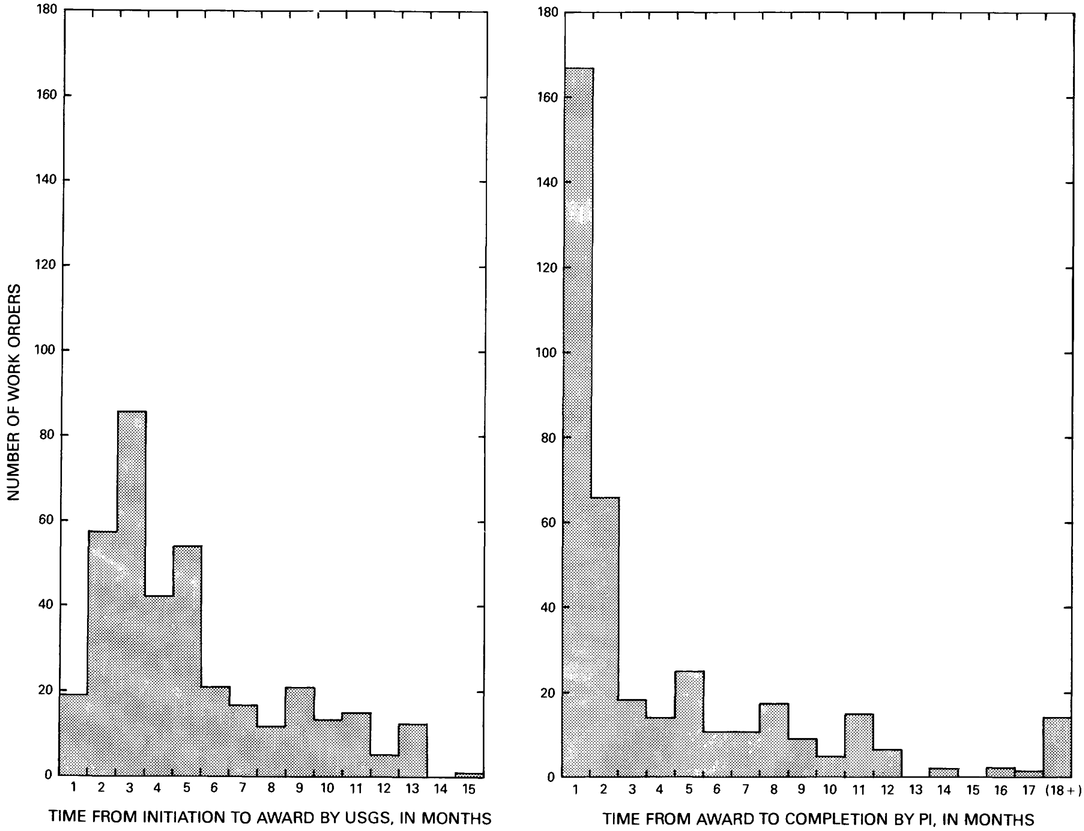


FIGURE 39.4.—Distribution of time taken to process work orders in the NPRA computer data and graphics system. Histogram on left indicates that work orders have taken as long as 15 months to be awarded, but 58 percent have taken from 2 to 4 months. Histogram on right indicates that most work was completed by PI in 2 months.

(NPRA): U.S. Geological Survey Open-File Report 81-1035, 7 p., 15 oversize sheets.

——— 1981c, Machine-generated displays of well logs and lithology from selected wells on the North Slope of Alaska; 7 wells from the east-central North Slope: U.S. Geological Survey Open-File Report 81-1036, 7 p., 7 oversize sheets.

——— 1981d, Machine-generated displays of well logs and lithology from selected wells on the North Slope of Alaska; 10 wells from the western part of the National Petroleum Reserve in Alaska (NPRA): U.S. Geological Survey Open-File Report 81-1032, 7 p., 10 oversize sheets.

——— 1981e, Machine-generated displays of well logs and lithology from selected wells on the North Slope of Alaska; 26 wells from the northern part of the National Petroleum Reserve in Alaska (NPRA): U.S. Geological Survey Open-File Report 81-1033, 7 p., 26 oversize sheets.

——— 1982a, Catalog of digital log data for government-drilled wells in and adjacent to the National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 82-800, 30 p.

——— 1982b, Machine-generated displays of well logs and lithology from 12 wells on the North Slope of Alaska: U.S. Geological Survey Open-File Report 82-290, 6 p., 12 oversize sheets.

——— 1982c, Rock-unit reports of 228 wells drilled on the North Slope, Alaska: U.S. Geological Survey Open-File Report 82-278, 106 p.

Claypool, G.E. and Magoon, L.B., 1980a, Vitrinite reflectance and C_1-C_7 hydrocarbon data for Cape Halkett No. 1 well, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-97.

——— 1980b, Vitrinite reflectance and C_1-C_7 hydrocarbon data for Drew Point No. 1 well, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-100.

——— 1980c, Vitrinite reflectance and C_1-C_7 hydrocarbon data for Kugrua No. 1 well, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-101.

——— 1980d, Vitrinite reflectance and C_1-C_7 hydrocarbon data for North Kalikpik No. 1 well, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-96.

Collins, F.R., 1958a, Test wells, Meade and Kaolak areas, Alaska: U.S. Geological Survey Professional Paper 305-F, p. 341-376.

——— 1958b, Test wells, Topagoruk area, Alaska: U.S. Geological Survey Professional Paper 305-D, p. 256-316.

——— 1958c, Test wells, Umiat area, Alaska: U.S. Geological Survey Professional Paper 305-B, p. 71-206.

——— 1959, Test wells, Square Lake and Wolf Creek areas, Alaska: U.S. Geological Survey Professional Paper 305-H, p. 423-484.

——— 1961, Core tests and test wells, Barrow area, Alaska: U.S. Geological Survey Professional Paper 305-K, p. 569-644.

Collins, F.R. and Robinson, F.M., 1967, Subsurface stratigraphic, structural and economic geology, northern Alaska: U.S. Geological Survey open-file report, 252 p.

Ervin, L.D., 1981, The geologic significance of compaction gradient plots of wells in the National Petroleum Reserve in Alaska: Stewart Folk and Co. [Available from Technical Data Unit, Branch of Alaskan Geology, U.S. Geological Survey]

Huffman, A.C., Jr., 1979, Stratigraphy and petrography of a measured section on the south limb of Barabara syncline, North Slope, Alaska, *in* Ahlbrandt, T.S., ed, Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 77-88.

Magoon, L.B. and Claypool, G.E., 1979, Hydrocarbon source potential of the Nanushuk Group and the Torok Formation, a preliminary report, *in* Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 54-60.

——— 1980a, Vitrinite reflectance and C_1-C_7 hydrocarbon data for Atigaru Point No. 1 well, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-98.

——— 1980b, Vitrinite reflectance and C_1-C_7 hydrocarbon data for South Barrow Nos. 14, 16, 17, and 19 wells, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-99.

——— 1980c, Vitrinite reflectance and C_1-C_7 hydrocarbon data for South Harrison Bay No. 1 well, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-93.

——— 1980d, Vitrinite reflectance and C_1-C_7 hydrocarbon data for South Simpson No. 1 well, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-92.

——— 1980e, Vitrinite reflectance and C_1-C_7 hydrocarbon data for West Fish Creek No. 1 well, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-95.

——— 1980f, Vitrinite reflectance and C_1-C_7 hydrocarbon data for W.T. Foran No. 1 well, North Slope, Alaska: U.S. Geological Survey Oil and Gas Investigations Chart OC-94.

——— 1981, Two oil types on North Slope of Alaska; implications for exploration: American Associaton of Petroleum Geologists Bulletin, v. 65, no. 4, p. 644-652.

National Oceanic and Atmospheric Administration, 1978a, National Petroleum Reserve in Alaska (NPRA); CDP seismic reflection data 1972-77 (1978 Q-Q): National Geophysical Data Center, Data Set Nos. TGX-0011, TGX-0012, TGX-0013. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

——— 1978b, National Petroleum Reserve in Alaska (NPRA); well logs, 1955-77 (1978-R): National Geophysical Data Center, Data Set No. TGY-0011-MF. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

——— 1979, National Petroleum Reserve in Alaska (NPRA); well logs, 1977-78 (1979-U): National Geophysical Data Center, Data Set No. TGY-0021-MF. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

——— 1980a, National Petroleum Reserve in Alaska (NPRA); CDP seismic reflection data, FY 1979 (1980 SE-LL): National Geophysical Data Center, Data Set No. TGX-0071. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

——— 1980b, National Petroleum Reserve in Alaska (NPRA); CDP seismic reflection data, 1977-78 (1980 SE-M): National Geophysical Data Center, Data Set No. TGX-0040. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

——— 1980c, National Petroleum Reserve in Alaska (NPRA); gravity data, 1974-80 (1980 SE-NN): National Geophysical Data Center, Data Set No. TGR-0010. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

——— 1980d, National Petroleum Reserve in Alaska (NPRA); palynology/micropaleontology reports for 8 wells (1980 SE-CC): National Geophysical Data Center, Data Set No. TGY-0060. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

—— 1980e, National Petroleum Reserve in Alaska (NPRA); palynology/micropaleontology reports for 30 wells (1980 SE-I): National Geophysical Data Center, Data Set No. TGY-0030. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

—— 1980f, National Petroleum Reserve in Alaska (NPRA); well logs, 1978-79 (1980 SE-J): National Geophysical Data Center, Data Set No. TGY-0041-MF. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

—— 1981a, National Petroleum Reserve in Alaska (NPRA); CDP seismic reflection data, FY 1980 (1981 SE-D): National Geophysical Data Center, Data Set No. TGX-0080. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

—— 1981b, National Petroleum Reserve in Alaska (NPRA); CDP seismic reflection data, 1981 (81-TGB-28): National Geophysical Data Center, Data Set No. TGX-0140. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

—— 1981c, National Petroleum Reserve in Alaska (NPRA); digitized well logs, 1946-81 (81-TGB-23): National Geophysical Data Center, Data Set No. TGY-0100. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

—— 1981d, National Petroleum Reserve in Alaska (NPRA); geochemical data for rock analyses in paper format for 28 wells: National Geophysical Data Center, Data Set No. TGY-0150A. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

—— 1981e, National Petroleum Reserve in Alaska (NPRA); miscellaneous geophysical data tapes, 1972-81 (81-TGB-19): National Geophysical Data Center, Data Set No. TGX-0120. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

—— 1981f, National Petroleum Reserve in Alaska (NPRA); paleontology/micropaleontology reports for 6 wells (81-TGB-25): National Geophysical Data Center, Data Set No. TGY-0120. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

—— 1981g, National Petroleum Reserve in Alaska (NPRA); synthetic seismograms (81-TGB-21): National Geophysical Data Center, Data Set No. TGY-0090. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

—— 1981h, National Petroleum Reserve in Alaska (NPRA); synthetic seismograms for 4 wells 1981: National Geophysical Data Center, Data Set No. TGY-0090A. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

—— 1981i, National Petroleum Reserve in Alaska (NPRA); well core analyses, 1970-79 (1981 SE-E): National Geophysical Data Center, Data Set No. TGY-0085. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

—— 1981j, National Petroleum Reserve in Alaska (NPRA); well logs, 1979-80 (1981 SE-E): National Geophysical Data Center, Data Set No. TGY-0080. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

—— 1981k, National Petroleum Reserve in Alaska (NPRA); well logs, 1981 (81-TGB-25): National Geophysical Data Center, Data Set No. TGY-0110. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

—— 1982, National Petroleum Reserve in Alaska (NPRA); Inuit (Eskimo) seismic data (82-TGB-01): National Geophysical Data Center, Data Set No. TGX-0160. [Available from National Geophysical Data Center, E/GC, Dept. CNP, 325 Broadway, Boulder, Colorado 80303]

Robinson, F.M., 1956, Core tests and test wells, Oumalik area, Alaska: U.S. Geological Survey Professional Paper 305-A, p. 1-70.

—— 1958a, Test well, Grandstand area, Alaska: U.S. Geological Survey Professional Paper 305-E, p. 317-339.

—— 1958b, Test wells, Gubik area, Alaska: U.S. Geological Survey Professional Paper 305-C, p. 207-264.

—— 1959a, Test wells, Simpson area, Alaska: U.S. Geological Survey Professional Paper 305-J, p. 523-568.

—— 1959b, Test wells, Titaluk and Knifeblade areas, Alaska: U.S. Geological Survey Professional Paper 305-G, p. 377-422.

—— 1964, Core tests, Simpson area, Alaska: U.S. Geological Survey Professional Paper 305-L, p. 645-730.

Robinson, F.M. and Collins, F.R., 1959, Core test, Sentinel Hill area, and test well, Fish Creek area, Alaska: U.S. Geological Survey Professional Paper 305-I, p. 485-521.

Tailleur, I.L., Pessel, G.H., Engwicht, S.E., and Levorson, J.A., 1978, Maps showing land status and well locations and tables of well data, eastern North Slope petroleum province, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-928-A, 8 p., 5 sheets, scale 1:500,000.

Witmer, R.J., Mickey, M.B., and Haga, Hideyo, 1981a, Biostratigraphic correlations of selected test wells of National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 81-1165, 96 p., 6 oversize sheets.

Witmer, R.J., Haga, Hideyo, and Mickey, M.B., 1981b, Biostratigraphic report of thirty-three wells drilled from 1975 to 1981 in National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 81-1166, 50 p.