

Geology of the Nanushuk Group and Related Rocks, North Slope, Alaska

U.S. GEOLOGICAL SURVEY BULLETIN 1614



Geology of the Nanushuk Group and Related Rocks, North Slope, Alaska

By A. Curtis Huffman, Jr., Editor

U.S. GEOLOGICAL SURVEY BULLETIN 1614

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, *Secretary*

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, *Director*



UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1985

For sale by the Branch of Distribution
U.S. Geological Survey
604 South Pickett Street
Alexandria, VA 22304

Library of Congress Cataloging in Publication Data

Geology of the Nanushuk Group and related rocks, North Slope, Alaska.

(United States Geological Survey bulletin ; 1641)

v, 129 p.

Bibliography: p. 124-129

Supt. of Docs. No.: I 19.3:1614

1. Sandstone—Alaska—North Slope. 2. Geology, Stratigraphic—Cretaceous. I. Huffman, A. C. II.

Series.

QE75.B9 no. 1614

557.3s [557.98'7]

84-60055

[QE471.15.S25]

CONTENTS

- Introduction to the geology of the Nanushuk Group and related rocks, North Slope, Alaska, by A. C. Huffman, Jr. 1
- Cretaceous tectonics, depositional cycles, and the Nanushuk Group, Brooks Range and Arctic Slope, Alaska, by C. G. Mull 7
- Subsurface correlations and depositional history of the Nanushuk Group and related strata, North Slope, Alaska, by C. M. Molenaar 37
- Depositional and sedimentologic factors affecting the reservoir potential of the Cretaceous Nanushuk Group, central North Slope, Alaska, by A. C. Huffman, Jr., T. S. Ahlbrandt, Ira Pasternack, G. D. Stricker, and J. E. Fox 61
- Petrography of sandstones of the Nanushuk Group from four measured sections, central North Slope, Alaska, by Susan Bartsch-Winkler 75
- An analysis of the Umiat delta using palynologic and other data, North Slope, Alaska, by F. E. May and J. D. Shane 97
- Uranium potential of the Cretaceous Nanushuk Group, North Slope, Alaska, by A. C. Huffman, Jr. 121

FIGURES

1. General index map of the North Slope 2
2. Measured sections from Corwin and Umiat deltas 4
3. Generalized nomenclature and stratigraphic relationships of the Nanushuk Group and related rocks, western and central North Slope 6
4. Stratigraphic relationships of lower Cretaceous deposits from the Brooks Range to the Beaufort Sea 8
5. Diagrammatic cross section from the Brooks Range to the Beaufort Sea 9
6. Generalized map showing the distribution of the Nanushuk and Colville Groups, and the major allochthons and tectonic features of the Brooks Range 10
7. Photograph showing the Nanushuk Group and Torok Formation in the Pitmegea River area 12
8. Table showing the vertical sequence of major allochthons in the Brooks Range 13
9. Photograph showing the Fortress Mountain Formation at Ekakevik Mountain 14
10. Chart showing global Cretaceous eustatic cycles compared to generalized Arctic Slope Cretaceous stratigraphy 15
11. Photograph showing the Okpikruak Formation 16
12. Photograph showing olistostrome, De Long Mountains 17
13. Chart describing the pebble shale unit and adjacent rock units in Kugrua and Inigok test wells 20
14. Diagrammatic maps of major tectonic elements during Neocomian and Aptian times 26
15. Photograph showing Mount Kelly Graywacke Tongue of the Fortress Mountain Formation 29
16. Diagrammatic map of major tectonic elements at the end of Aptian time 32
17. Index map of part of the North Slope 38
18. Diagram showing stratigraphic cross sections of Nanushuk Group and related rocks, National Petroleum Reserve in Alaska 42
19. Seismic cross section showing the relationship of the Nanushuk Group and Torok Formation 52
20. Seismic cross section showing disturbed zone in the Torok Formation 53

FIGURES

21. Isopach map of Nanushuk Group **54**
22. Isopach map of Torok Formation **55**
23. Plot of directional data in the Nanushuk Group and Torok Formation **56**
24. Paleogeographic maps, mid-Nanushuk and latest Nanushuk time **57**
25. Isopach map of seismic velocities in the lower Nanushuk Group **58**
26. Map showing percentage of sandstone, Nanushuk Group **62**
27. Generalized stratigraphic column of Nanushuk Group, central North Slope **66**
28. Diagram showing terminology and major depositional environments **67**
29. Plots showing porosity vs. permeability for Nanushuk Group rocks **69**
30. Plots showing distribution of sandstone within the Nanushuk Group by facies **70**
31. Paleogeographic maps showing depositional history of Nanushuk Group and related rocks **72**
32. Location map of four measured sections **76**
33. Compositional diagrams of Nanushuk Group sandstones **76**
34. Triangular plots of Nanushuk Group sandstones **77**
- 35–38. Triangular diagrams showing modal analyses plotted according to grain size:
 35. Kurupa anticline section **81**
 36. Tuktu Bluff section **82**
 37. Arc Mountain section **83**
 38. Marmot syncline section **84**
39. Diagrams of vectoral analyses showing compositional trends according to grain size **85**
40. Histograms of textural characteristics **86**
- 41–51. Photographs showing:
 41. Intergrain boundaries in sandstone **87**
 42. Tightly appressed sandstone showing grain deformation **88**
 43. Replacement by calcite cement in sandstone **88**
 44. Kaolinite pore-space filling in sandstone **89**
 45. Original porosity and minor secondary porosity **90**
 46. Chlorite coating on quartz grains in sandstone **90**
 47. Quartz overgrowths on sandstone after clay formation **91**
 48. Abundant quartz overgrowths on sandstone **92**
 49. Secondary porosity features in sandstone (scanning electron microscope) **93**
 50. Secondary porosity features in sandstone (photomicrograph) **94**
 51. Possible hydrocarbons in Nanushuk Group rocks **95**
52. Index map of Umiat delta area **98**
53. Diagrams showing locations of invertebrate megafossils observed in Nanushuk Group rocks **106**
- 54–62. Relative frequency diagrams of main palynomorph groups:
 54. Knifeblade–1 well **108**
 55. Titaluk–1 well **109**
 56. Oumalik–1 well **111**
 57. East Oumalik well **113**
 58. Wolf Creek–2 and –3 wells **114**
 59. Square Lake–1 well **116**
 60. Umiat–1 well **118**
 61. Umiat–11 well **119**
 62. Grandstand–1 well **120**

TABLES

1. Microfaunal and palynological data from Lower Cretaceous rocks **22**
2. Megafossil data from Kemik Sandstone Member **24**
3. Location of North Slope test wells shown in figure 17 **39**
4. Location of Nanushuk Group measured sections shown in figure 17 **40**
5. Resource-related data from sections measured in Nanushuk Group rocks **64**
6. Compositional data from four sections measured in Nanushuk Group rocks **78**
7. Sedimentologic data from transitional and nonmarine parts of sections measured in Nanushuk Group rocks **122**

Introduction to the Geology of the Nanushuk Group and Related Rocks, North Slope, Alaska

By A. Curtis Huffman, Jr.

Abstract

The Cretaceous Nanushuk Group has long been considered one of the major hydrocarbon plays on the North Slope and as such has been the focus of a number of investigations. The primary purpose of this four-year study was to evaluate the reservoir potential of the Cretaceous Nanushuk Group in and adjacent to the National Petroleum Reserve in Alaska (NPRA). This study sought to apply modern stratigraphic concepts as well as up-to-date geochemical, petrographic, and paleontologic methods in evaluating the hydrocarbon, coal, and uranium potential of the Nanushuk and related rocks. Preliminary results were published in Ahlbrandt (1979), which concentrated on the western North Slope. This report is primarily concerned with the central North Slope, although several preliminary regional syntheses are presented as well.

The results of this and previous investigations indicate that the Nanushuk Group was deposited as two delta systems onto a shelf of marine shale of the Torok Formation, which prograded into the Colville basin generally from west to east. Deposition of the western, or Corwin, delta began in early Albian or perhaps late Aptian time, and the delta prograded northeastward from the vicinity of the De Long Mountains, Tigara Uplift, and Herald Arch. The deltaic and shelf topsets can be traced basinward into large foresets and coeval bottomsets of the Torok Formation. Petrographic analyses confirm that sediment of the Torok Formation is closely related to that of the Nanushuk Group in the Corwin delta and is quite different from the Nanushuk of the Umiat delta.

The Umiat delta was an elongate to lobate, river-dominated delta, which prograded northward from the vicinity of the Endicott Mountains, beginning in mid-Albian time. Sandstones of the Umiat delta are dominantly phyllarenite, as compared with the sedimentary litharenite of the Corwin delta. The differences in sediment type between the two depocenters reflect the sequence of lithologies exposed in the various thrust slices of the Brooks Range. The Endicott Group of the central Brooks Range contains large thicknesses of Upper Devonian and Mississippian quartzitic conglomerate and phyllitic shale, whereas the sequences exposed in the western Brooks Range are dominantly shale, limestone, and chert. Because the Umiat delta was not subjected to high temperatures and deep burial as was the Corwin delta, micro-paleontological and palynological analyses have proven valuable in the interpretation of its depositional environments.

A detailed model of the Umiat delta and related deposits may be constructed through a combination of sedimentology, paleontology, and seismology studies. This model suggests that a belt of high-energy coastal-barrier deposits trending northwest from the northern edge of the Umiat delta may contain reservoir sandstones and stratigraphic traps.

INTRODUCTION

Much of the outcrop and subsurface work by the U.S. Geological Survey and the U.S. Navy in the 1940's and 1950's focused on rocks of the Nanushuk Group because the most significant oil field on the North Slope prior to the discovery of the Prudhoe Bay field in 1967 was the Nanushuk field at Umiat (fig. 1), estimated by Espach (1951) to contain as much as 122 million barrels. The transfer of jurisdiction of Naval Petroleum Reserve No. 4 from the U.S. Department of the Navy to the U.S. Department of the Interior by the Naval Petroleum Reserves Production Act of 1976 changed the name to National Petroleum Reserve in Alaska (NPRA) and called for a reevaluation of the resource potential of the reserve.

As a part of this evaluation, the Nanushuk Group and related rocks were studied by a team of U.S. Geological Survey scientists from 1977 to 1981. Fieldwork for this investigation was begun in the western part of the North Slope in 1977, and preliminary results were published in Ahlbrandt (1979). The 1978 and 1980 fieldwork concentrated on the central and eastern regions, and many of the results are presented in this report. Detailed measured sections from the western North Slope are described in Huffman and others (1981a) and from the central North Slope in Huffman and others (1981b).

Emphasis during this study has been on the interpretation of depositional environments and their relationship to one another and to reservoir potential. This regional approach was necessitated by several factors: (1) The Nanushuk Group was deposited in two large depocenters, the Corwin delta of the western North Slope and the Umiat delta of the central North Slope, with a region of low sandstone content and meager exposures in between. (2) No unit above the Torok Formation can be physically traced the length of the outcrop belt. (3) Very few data

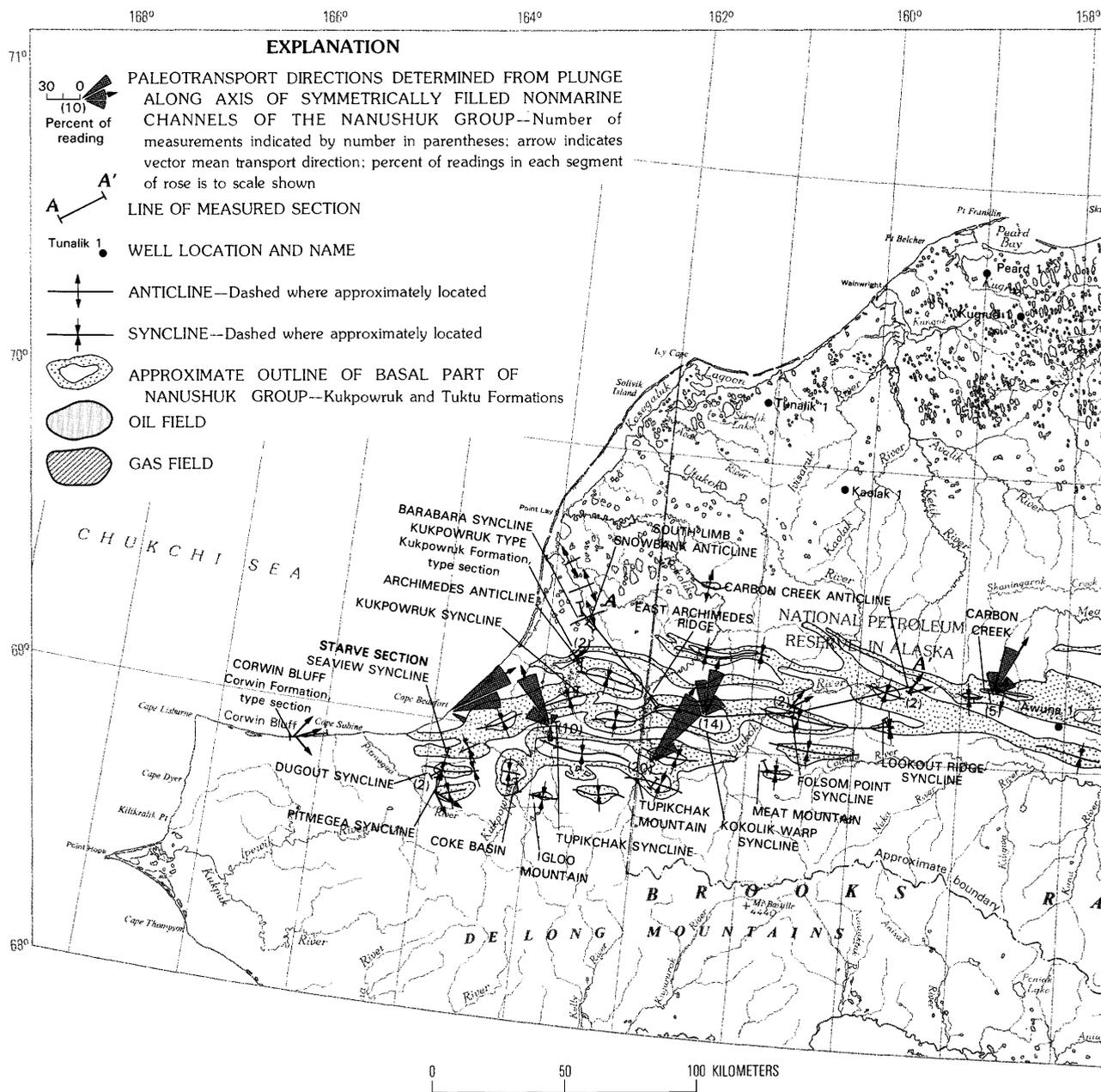


Figure 1. Index map showing the study area of Nanushuk Group rocks, locations of sections measured during 1977 and 1978, and locations of wells, western and central North Slope, Alaska.

have been found with which to precisely date or correlate the units. The cross sections in figure 2 illustrate these problems. Very few outcrops exist in the 150-km interval separating the Carbon Creek and Kurupa anticline measured sections (fig. 1). The widely separated exposures that are present in this region are predominantly shale and mudstone.

By concentrating on genetic units, equivalent environments can be compared between the two depocenters without regard to time or formal nomenclature. A stratigraphic nomenclature chart of the Nanushuk Group and related units (fig. 3) illustrates some of the problems in-

involved in trying to apply formal nomenclature to these units on a regional basis. The correlations implied on this chart are approximate at best.

During this study, a total of 25,000 m of section at 33 localities (fig. 1) were measured, described, and sampled in detail. Samples were collected for petrographic, geochemical, and paleontologic studies. Relationships observed in the surface exposures were combined with subsurface and geophysical data to build a depositional model that was tested and perhaps modified by subsequent drilling. Similar methods were used to project reservoir properties into the subsurface.

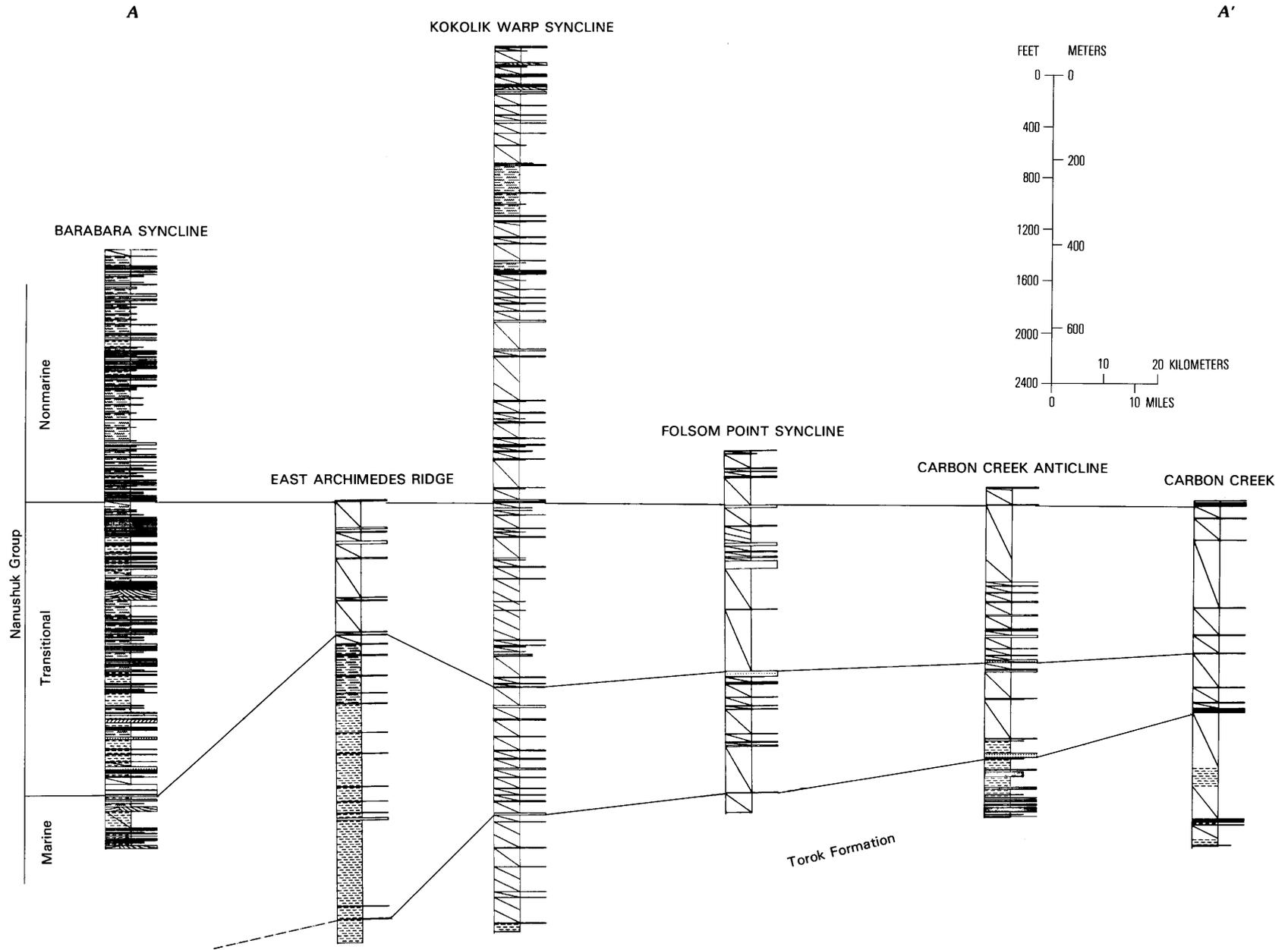


Figure 1. Continued

Petrographic and palynologic studies were particularly useful in the analysis and interpretation of depositional environments and their reservoir properties in the Umiat delta. Projections of trends northward into the subsurface of the central North Slope could be accomplished with some confidence based on petrographic and palynologic analyses of subsurface material. These projections were combined with geophysical and well-log information to produce a reservoir model.

The chapters of this report are arranged first regionally and then topically. In the chapter following the Introduction, Mull set the spatial and time framework for

Nanushuk Group deposition in a discussion of the tectonics and related deposition during the Early Cretaceous in the central and eastern Brooks Range and North Slope. Molenaar combined seismic data and well-log information to construct a regional correlation and depositional history for the Nanushuk Group. Huffman, Ahlbrandt, Pasternack, Stricker, and Fox analyzed depositional environments in surface exposures as well as from subsurface data in the central North Slope and proposed a regional model for the Nanushuk depositional system. Petrographic results from the Nanushuk of the central North Slope, reported by Bartsch-Winkler, show distinctive and signifi-



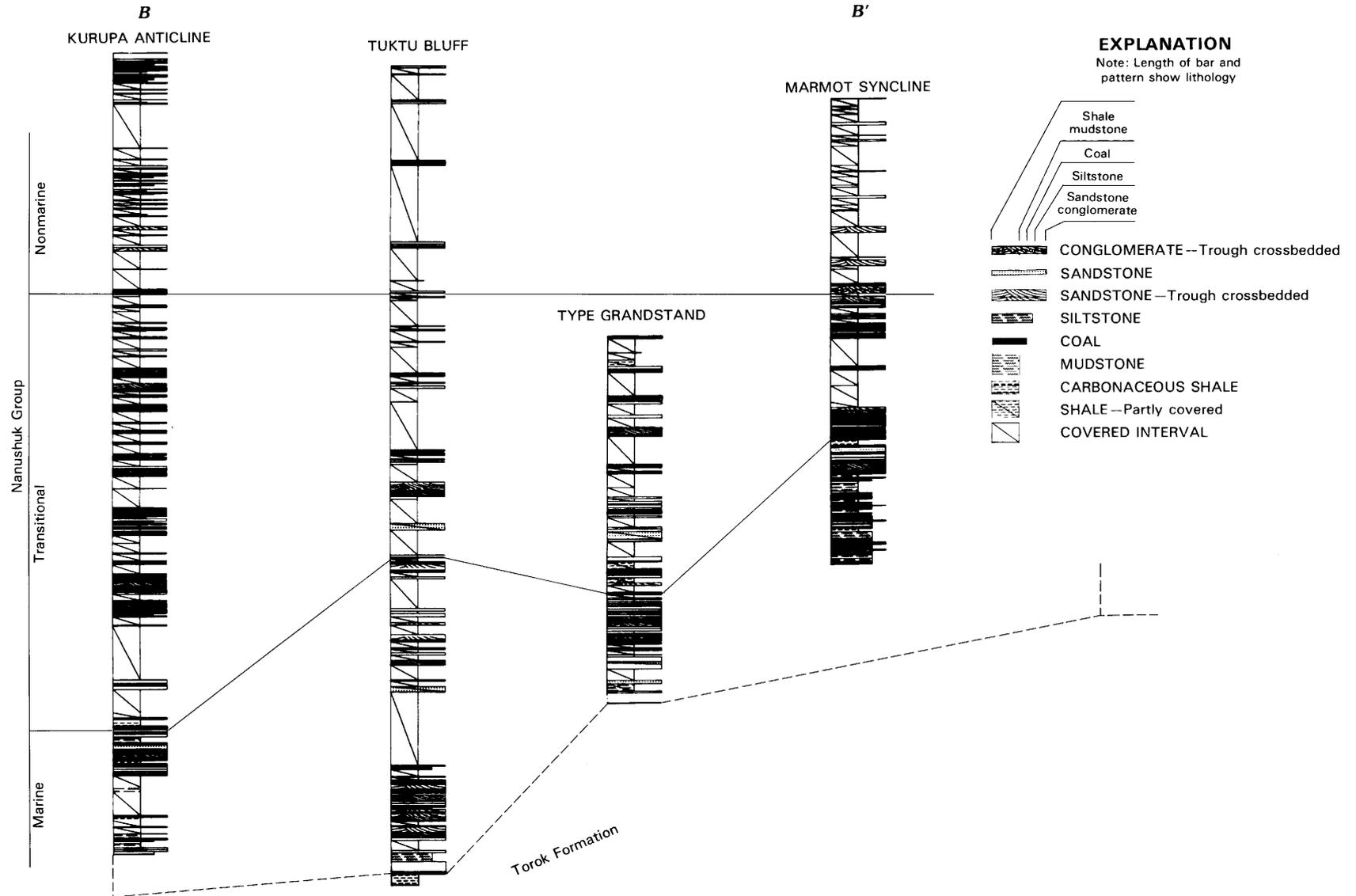


Figure 2. Measured sections along lines A-A' (Corwin delta) and B'-B' (Umiat delta) on figure 1. Distance between A' and B' is approximately 150 km. Datum for both sections is the base of the nonmarine facies, commonly marked by a conglomeratic fluvial sandstone.

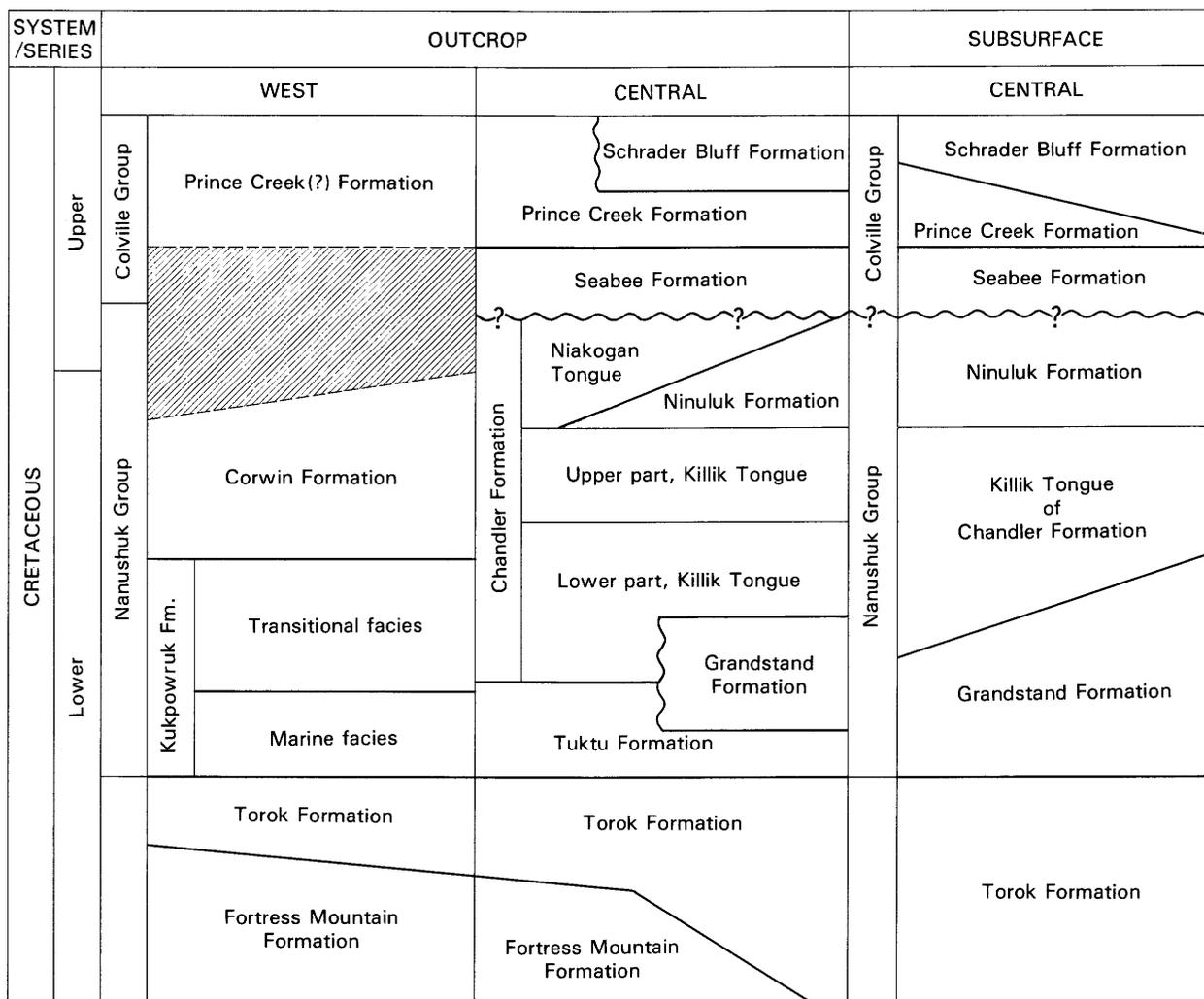


Figure 3. Stratigraphic nomenclature for the Nanushuk Group and adjacent rock units, western and central North Slope, Alaska (modified from Ahlbrandt and others, 1979). The correlations implied are approximate.

cant differences from those of the western area. May and Shane described the depositional environments in part of the Umiat delta utilizing dinoflagellate, pollen, and spore

analyses. The final chapter, by Huffman, is a brief discussion of the uranium potential of the Nanushuk Group and related rocks throughout the North Slope.

Cretaceous Tectonics, Depositional Cycles, and the Nanushuk Group, Brooks Range and Arctic Slope, Alaska

By C. G. Mull¹

INTRODUCTION

The Nanushuk Group, consisting of sedimentary rocks of Albian and Cenomanian Age, is widespread on the Arctic Slope of Alaska, where it is a hydrocarbon exploration objective in the National Petroleum Reserve in Alaska (NPR). A small oil field at Umiat and minor gas accumulations elsewhere have been found in NPR, but the hydrocarbon potential seems to be limited by reservoir quality. The study of the Nanushuk Group has had as its major objective the understanding of the depositional processes, distribution, and diagenesis of the sandstone bodies that are the potential reservoir beds. The Nanushuk Group represents the culmination of deposition that started near the beginning of the Cretaceous as a result of the major orogenic event that formed the present Brooks Range and its offshore extension beneath the Chukchi Sea, the Herald arch. This report summarizes the regional tectonic and depositional framework of the Early Cretaceous orogenic belt and depositional basin as an aid to understanding the character, distribution, and deformation of the Nanushuk Group rocks. Other chapters in this volume describe the Nanushuk in detail.

The generalized nomenclature and stratigraphic relationships of sediments of Early Cretaceous and early Late Cretaceous (Cenomanian) age of the western and central Arctic Slope are summarized on figure 4. Cretaceous stratigraphy and more detailed nomenclature is given by Detterman and others (1975) for the eastern Brooks Range and by Detterman (1956) for the central and western Arctic Slope. Generalized geologic maps of the Arctic Slope and Brooks Range have been compiled by Lathram (1965), Beikman and Lathram (1976), Beikman (1978), and Grybeck and others (1977).

The discussion of the tectonic evolution of the Brooks Range is from data of many workers, including Keller and others (1961), Detterman and others (1963), Tailleux and others (1967), Snelson and Tailleux (1968), Tailleux (1969), Tailleux and Brosgé (1970), Rickwood (1970), Martin (1970), Brosgé and Tailleux (1970, 1971), Tailleux (1973), Detterman (1973), Mull and others

(1976), Mull (1977), Mull and Tailleux (1977), Roeder and Mull (1978), Mayfield and others (1978), and Mull (1979, 1982). It is augmented by concepts and interpretations of the author based on data available through 1982.

The onset of the Brooks Range orogeny is recorded in Early Cretaceous deposits exposed within and adjacent to the Endicott and De Long Mountains of the central and western Brooks Range. These sediments record the abrupt shift in sediment dispersal from a predominantly northern source that persisted through the late Paleozoic and early Mesozoic, to a major southern and southwestern source derived from a Cretaceous orogenic belt.

Sediments from the orogenic belt were poured into a developing foredeep, the asymmetrical Colville basin; seismic data indicate that the total thickness of Lower Cretaceous and Cenomanian sediments may be 10,000 m. The sequence records the progressive filling of the basin, and it can be considered a typical gradational flysch-to-molasse sequence.

This basin fill is divided into three stratigraphic sequences: a relatively thin lower sequence of stable platform sediments, and two thick overlying sequences of flyschoid and molassoid sediments. Although the sequences can be related to specific tectonic events in the area of the Brooks Range and Arctic Slope, they also seem to coincide generally with the Early Cretaceous global eustatic cycles of Vail and others (1977, p. 85). The basal sequence of platform sediments is well developed in the subsurface of the Arctic coastal plain and is well exposed in the northeastern Brooks Range. It is also present at the base of the Cretaceous on some of the thrust sheets in the central and western Brooks Range. The lower flyschoid sequence is present in outcrop on the thrust sheets of the Endicott and De Long Mountains and their foothills, in a few areas in the Philip Smith Mountains, and in the subsurface of the northern foothills province of the Arctic Slope. The upper sequence, which contains the Nanushuk Group, is present only as part of the autochthonous complex that underlies the northern foothills and coastal-plain area of the Arctic Slope. The generalized relationship of the various rock units, their ages, and their interpreted basin positions are diagrammatically illustrated in figures 4 and 5.

¹Presently with Alaska Division of Geological and Geophysical Surveys.

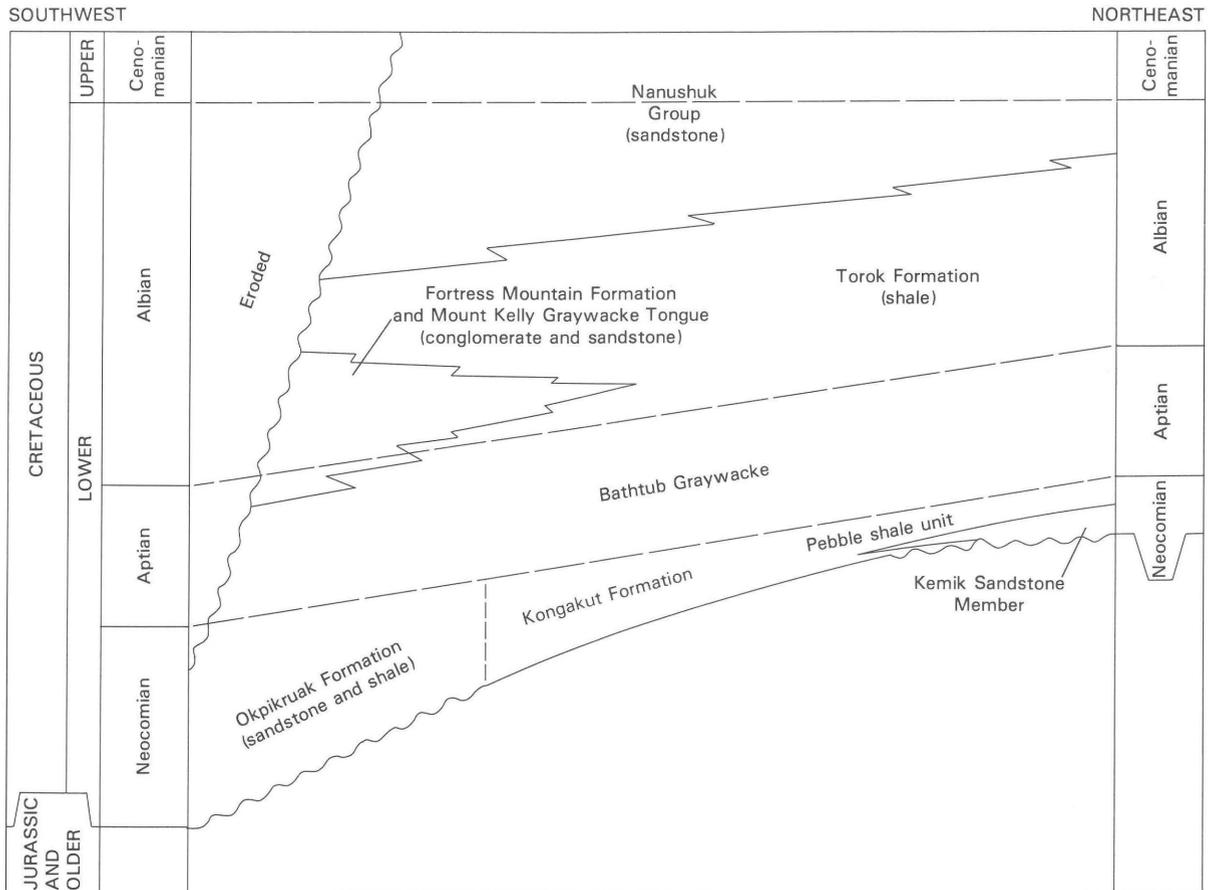


Figure 4. Stratigraphic relationships of Lower Cretaceous deposits across the central Colville basin from the Brooks Range to the Beaufort Sea. The Mount Kelly Graywacke Tongue of the Fortress Mountain Formation is confined to the western Arctic Slope, and the Kongakut Formation and Bath tub Graywacke are recognized only on the eastern Arctic Slope and in the Brooks Range. Dashed lines are time lines.

The stable platform sequence consists dominantly of clay shale containing scattered pebbles and quartz grains. Along the northern front of the northeastern Brooks Range and in the subsurface of the northern Arctic Slope a discontinuous sandstone and (or) conglomerate forms the base of the sequence. A thin coquinoid limestone horizon is interbedded with the shales locally on the thrust sheets in the central and western Brooks Range foothills.

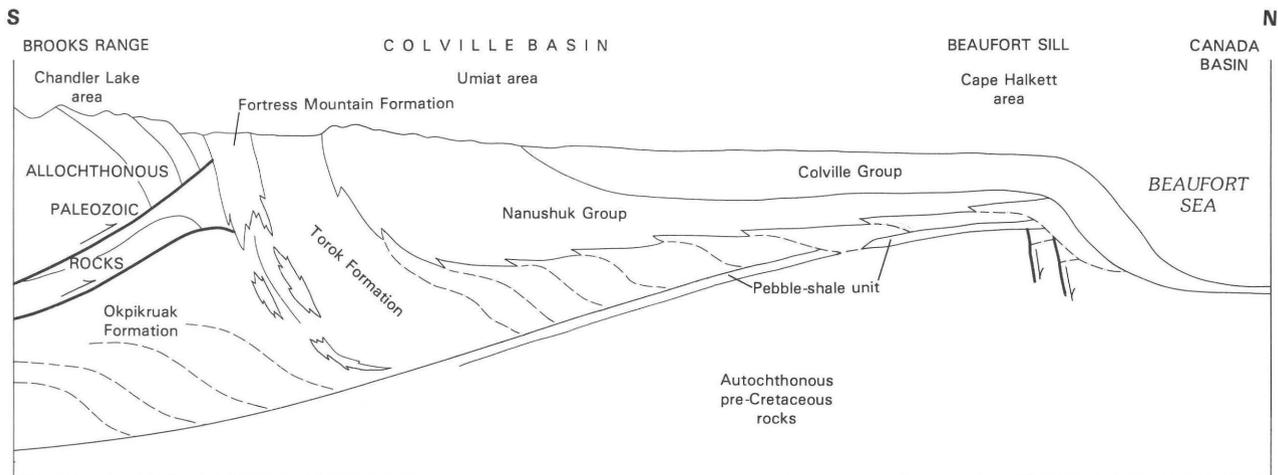
The lower flysch sequence consists dominantly of rhythmically alternating beds of sandstone, siltstone, and shale; the more distal equivalents to the north are almost entirely shale. It is of Neocomian to Aptian Age.

The upper sequence, referred to as the Albian and Cenomanian sequence, consists of coarse proximal conglomerates on the south that rapidly grade northward into basinal turbidites. The basinal deposits are succeeded by prodelta muds deposited in advance of a prograding deltaic complex, the Nanushuk Group, which represents the molassoid culmination of the depositional cycle that began in the Early Cretaceous. Along the margins of the basin the upper sequence seems to be separated from the lower

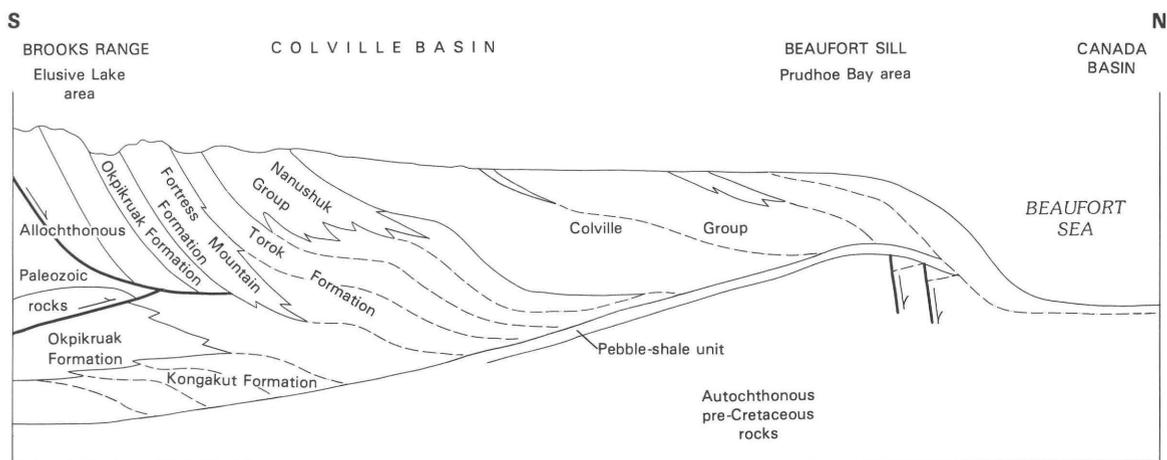
flysch sequence by a disconformity or depositional hiatus, but in the axial part of the basin the two sequences may be gradational.

The Nanushuk Group, a wedge of deltaic deposits, extends as a nearly unbroken outcrop belt from the Chukchi Sea on the west to the Sagavanirktok River area on the central Arctic Slope. It is also present in the subsurface of the Arctic coastal plain and beneath the Chukchi Sea. Throughout this area the Nanushuk contains potential hydrocarbon-reservoir beds. East of the Itkillik River, due to a facies change to basinal deposits, the Nanushuk is limited both in outcrop and in the subsurface, and has little reservoir potential. East of the Okpilak River, in the Arctic National Wildlife Refuge, little is known of the Early Cretaceous. In this area the Cretaceous stratigraphy is inferred from offshore seismic data and from extrapolations from the northern Yukon Territory of Canada.

Across the Arctic Slope, the southern part of the Nanushuk's outcrop belt has been detached from underlying strata and folded into a series of long linear anticlines and synclines that form a major décollement. To the south, the anticlines have been breached through the



A



B

Figure 5. Diagrammatic cross section of the central (A) and eastern (B) Colville basin from the Brooks Range to the Beaufort Sea. Regional décollement cutting Cretaceous strata is not shown. Heavy lines are faults; arrows show direction of movement. Dashed lines show foresets in marine sediments. Allochthonous Paleozoic rocks consist dominantly of Carboniferous Lisburne Group carbonate rocks, and Upper Devonian Kanayut Conglomerate and Hunt Fork Shale. The Beaufort sill, also known as the Barrow arch, trends from the area of Barrow southeast to the Sadlerochit Mountains area of the northeastern Brooks Range.

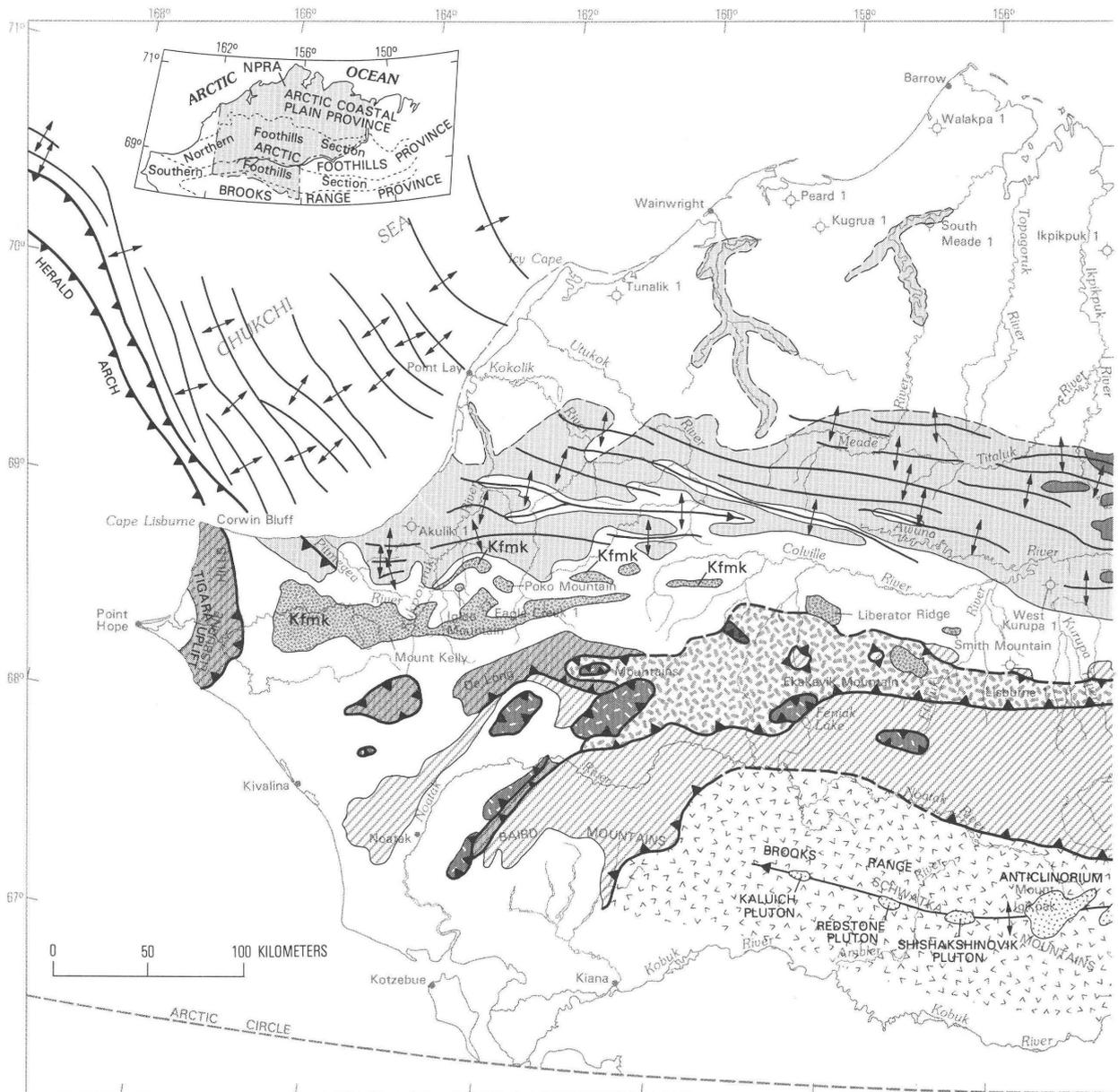
Nanushuk, but to the north, fold amplitudes decrease and the Nanushuk is unbreached.

PHYSIOGRAPHIC SETTING OF THE NANUSHUK GROUP

The Nanushuk Group crops out in the northern foothills part of the Arctic Foothills Province of northern Alaska; it is widespread in the subsurface beneath the coastal plain area of NPRA. Its outcrop belt extends nearly unbroken for about 650 km from the sea cliffs of the Corwin Bluff area on the west to the Sagavanirktok River area of the eastern Arctic Slope (fig. 6). Across this distance the province is characterized by generally

east-west-trending ridges and rolling upland terrain to an elevation of about 960 m. The typical expression of the Nanushuk and underlying strata is illustrated in figure 7.

The southern limit of the Nanushuk's outcrop belt is in many areas marked by a prominent south-facing escarpment rising above somewhat lower terrain in the adjacent southern foothills. The ridges and uplands of the outcrop belt are broken by numerous generally northward flowing streams and rivers, many of which rise in the Brooks Range. On the west, four small rivers, the Pitmegea, Kukpowruk, Kokolik, and Utukok, cross the outcrop belt of the Nanushuk Group and flow into the Chukchi Sea. These streams are relatively small, but in places they and their tributaries are incised more than 500 m into the Nanushuk terrain. As a consequence of this inci-



EXPLANATION

- | | |
|---|--|
| <p>AUTOCHTHONOUS ROCKS</p> <ul style="list-style-type: none">  Colville Group (Cretaceous: Maestrichtian to Cenomanian)  Nanushuk Group (Cretaceous: Cenomanian to Aptian)  Fortress Mountain Formation (Cretaceous: Aptian to Cenomanian). Kfmk, Mount Kelly Graywacke Tongue  Bathub Graywacke and Kongakut Formation (Cretaceous: Aptian to Neocomian)  Undifferentiated sedimentary rocks (Upper Triassic to Lower Mississippian)  Undifferentiated metamorphic rocks (Middle Devonian to Precambrian)  Granite (Cretaceous to Devonian) | <p>ALLOCHTHONOUS ROCKS—Arranged in order of superposition</p> <ul style="list-style-type: none">  Misheguk Mountain and Copter Peak allochthons (Triassic to Lower Paleozoic)  Nuka Ridge allochthon (Permian to Mississippian)  Ipsnavik River allochthon (Lower Cretaceous to Middle Devonian)  Kelly River allochthon (Lower Cretaceous to Mississippian)  Endicott Mountains allochthon (Lower Cretaceous to Upper Devonian) <p>— CONTACT—Dashed where inferred or concealed</p> <p>▲▲ THRUST FAULT—Dashed where inferred or concealed; sawteeth on upper plate</p> <p>↕ ANTICLINE—Showing direction of plunge</p> <p>⊕ EXPLORATORY WELL—Dry hole</p> |
|---|--|

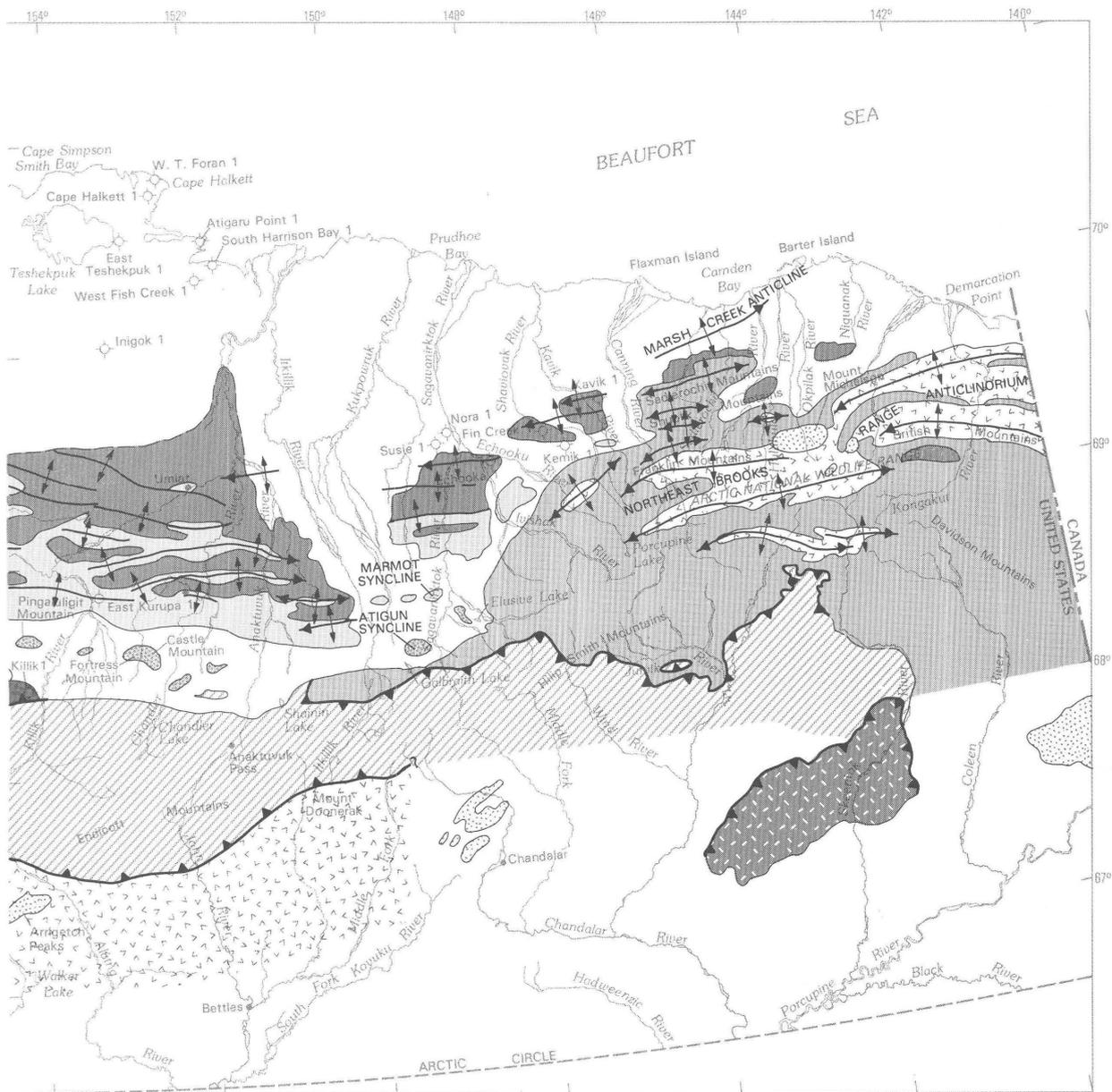


Figure 6 (above and facing page). Generalized geologic map showing the approximate distribution of the Nanushuk and Colville Groups, major allochthons, and tectonic features of the Brooks Range. The Okpikruak Formation, pebble shale unit, and Kemik Sandstone Members of the Kongakut Formation are not shown. Anticlinal axes in the Chukchi Sea are from Arthur Grantz and Steven May (written commun., 1982).

sion, the exposures of the Nanushuk on the western Arctic Slope are generally better than elsewhere on the Arctic Slope. This western area is frequently referred to as the Utukok-Corwin area and, because of its better exposures, was the center of the initial outcrop studies in this project.

East of the Utukok-Corwin area, the Colville River rises in the foothills of the De Long Mountains and has a generally east and northeasterly course for more than 360 km to near Umiat, where it turns northward and flows toward the Beaufort Sea. For more than 160 km, between long 160° W. and 156° W., the upper Colville River flows

south of the outcropping Nanushuk Group. As a result, the major Colville tributaries, which rise in the Brooks Range, do not cross the Nanushuk. From near the confluence of the Etivluk River with the Colville and eastward to the Umiat area, the Colville River crosses the outcrop belt of the Nanushuk. The major tributaries to the Colville in this area, the Kurupa, Killik, Chandler, and Anaktuvuk Rivers, all of which rise in the high Endicott Mountains to the south—are incised into the Nanushuk Group. This area, referred to as the Chandler River area, contains fair to good exposures along the major streams.



Figure 7. Nanushuk Group and underlying Torok Formation on the western Arctic Slope. The relatively competent Nanushuk is folded into a number of broad, gentle synclines. Note the scattered resistant beds that appear to pinch out eastward in the underlying incompetent shale. View northeast across the upper Pitmegea River. Kn, Nanushuk Group; Kt, Torok Formation. Short dashed lines, approximately located contacts; long dashed lines, anticline (opposing arrows) and syncline (converging arrows). Syncline is approximately 15 km long.

North of the Colville River, exposures of the Nanushuk Group are generally poor. This area, which encompasses about one-third of the outcrop belt of the Nanushuk, is drained by the Kuk, Meade, Topagoruk, Ikpikpuk, and Awuna Rivers and their tributaries. These rivers all head in a low rolling terrain on the Nanushuk about 300–500 m in elevation. The Kuk River trends northwestward into the Chukchi Sea; the Meade, Topagoruk, and Ikpikpuk drainages flow northward to the Beaufort Sea; and the Awuna flows eastward into the Colville River. These streams have generally low discharge, and, as a consequence, they do not incise the Nanushuk deeply; this lack of erosion results in generally poor outcrops. In addition, the detailed studies carried out in this project suggest that the Nanushuk in the Kuk-Ikpikpuk Rivers area may contain interdeltaic deposits (Ahlbrandt and others, 1979). The resulting low-sand content of the deposits thus may also have caused the small number of outcrops in this area. As a result, only limited field studies have been carried out in the Kuk-Ikpikpuk Rivers area of the Nanushuk outcrop belt. Most of the knowledge of the Nanushuk Group north of the foothills is derived from subsurface data from exploratory wells and from seismic data.

On the eastern Arctic Slope, east of the Itkillik River, outcrops of the Nanushuk and correlative beds are confined to several high mesalike hills, and to a few

stream and river cutbanks. The rolling upland terrain characteristic of the western part of the Nanushuk is present only in a limited area in the vicinity of the Sagavanirktok and Ivishak Rivers. The absence of the Nanushuk on the eastern Arctic Slope is caused by a rapid northeastward facies change to basal shales, combined with a northward swing in the trend of the mountain front that brings to the surface these nonresistant sediments. In addition, in contrast to the western Brooks Range, extensive Pleistocene glaciation in the eastern Brooks Range resulted in mantling of extensive areas north of the mountains by morainal and associated outwash deposits. Details of the glaciation and glacial deposits are given by Detterman (1953), Detterman and others (1958), and Hamilton and Porter (1975).

EVOLUTION OF THE BROOKS RANGE OROGENIC BELT

Evolution of the orogenic belt forming the Brooks Range, herein termed the Brooks Range orogenic belt, began during Neocomian time. This belt apparently developed as a result of counterclockwise rotation of a crustal plate composed of northern Alaska and adjacent areas (Tailleur, 1969; 1973; Tailleur and Snelson, 1969; Rickwood, 1970; Newman and others, 1979).

Paleomagnetic data and regional reconstructions suggest that this plate, the Arctic Alaska plate (Tailleur and others, 1976; Newman and others, 1979), moved relatively southward and, at its southern compressional margin, was obducted by oceanic crust at a south-dipping subduction zone (Mull, 1977, p. B31; Mull, 1982, p. 44; and Roeder and Mull, 1978). The relationships of continental and oceanic crust suggest that the orogenic belt developed by underthrusting (Tailleur and Snelson, 1969), rather than by the more commonly visualized mode of overthrusting. Underthrusting is the process by which slices of sediment are progressively detached from a down-going slab as it approaches a subduction zone (Seely and others, 1974). Following the stage of major crustal compression, a period of dominantly vertical uplift resulted in major modifications of the earlier structural style.

Neocomian and Aptian(?) Time

Tectonics

Underthrusting in the orogenic belt in the western Brooks Range resulted in formation of multiple allochthonous sheets of mafic igneous and sedimentary rock; each allochthon is underthrust by rocks that were formerly more northerly facies equivalents. Each allochthon is composed of a distinctive suite of formations, most of which maintain a relatively uniform character within the allochthon but differ markedly from coeval formations in other allochthons (fig. 8). Several major allochthons can be traced for more than 400 km through the De Long and western Endicott Mountains. In the central Brooks Range, most of the allochthons that are present in the western Brooks Range have been eroded so that in most places only one, the Endicott Mountains (or Brooks Range) allochthon, is present. Parts of some of the structurally higher allochthons are present in isolated areas, and abundant distinctive detritus in later Cretaceous deposits attests to their former widespread presence. During the Neocomian, the stack of allochthonous sedimentary and minor igneous rocks may have been as much as 10 km thick, with an overlying sheet of imbricated mafic to ultramafic rock that may also have been as much as 10 km thick.

Dating of the Orogeny

Fauna from orogenic sediments date the onset of orogenic activity as Neocomian. At Ekakevik Mountain (fig. 9) in the southern NPRA, autochthonous early Albian conglomerates unconformably overlie and truncate imbricated thrust sheets containing orogenic sediments of Berriasian and Valanginian Age (see mapping by Tailleur

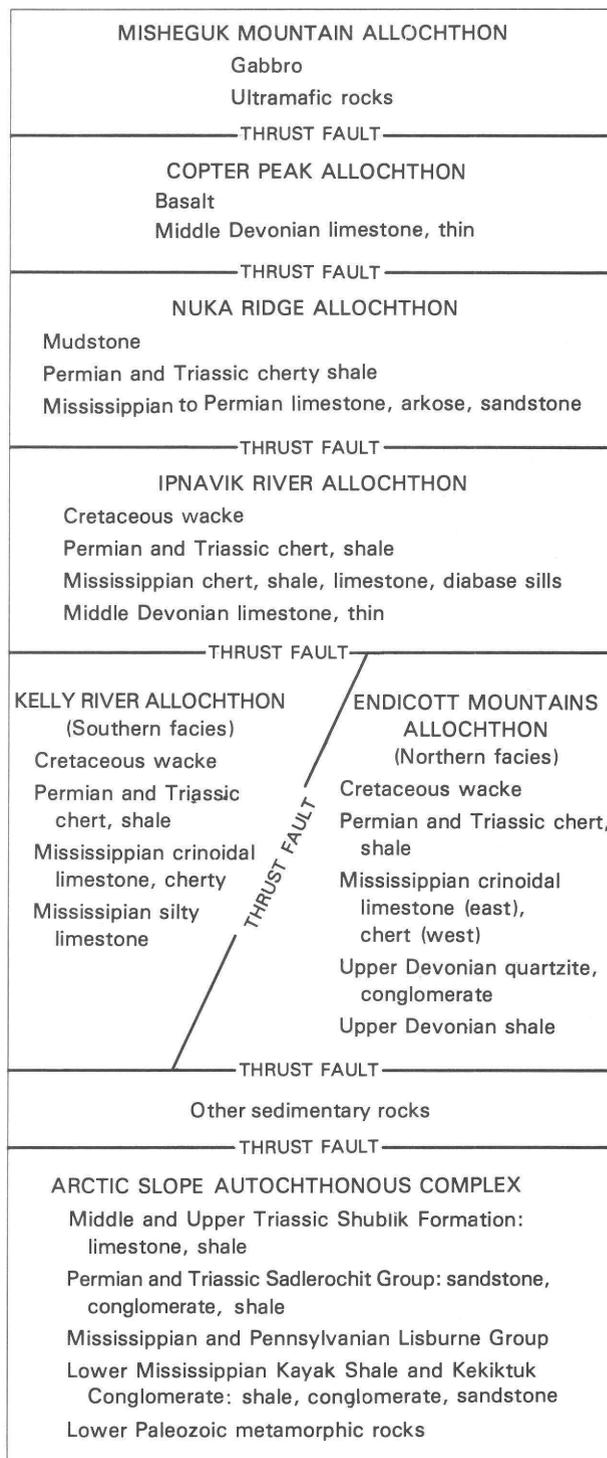


Figure 8. Vertical superposition of the basal autochthonous complex and the major allochthons in the Brooks Range. In general, each allochthon, where present, occurs in the same structural position relative to adjacent allochthons. Each allochthon represents a southern facies of rocks in the immediately underlying allochthon and has been telescoped relatively northward by thrust faulting over the underlying allochthon or by southward underthrusting of the underlying rocks.

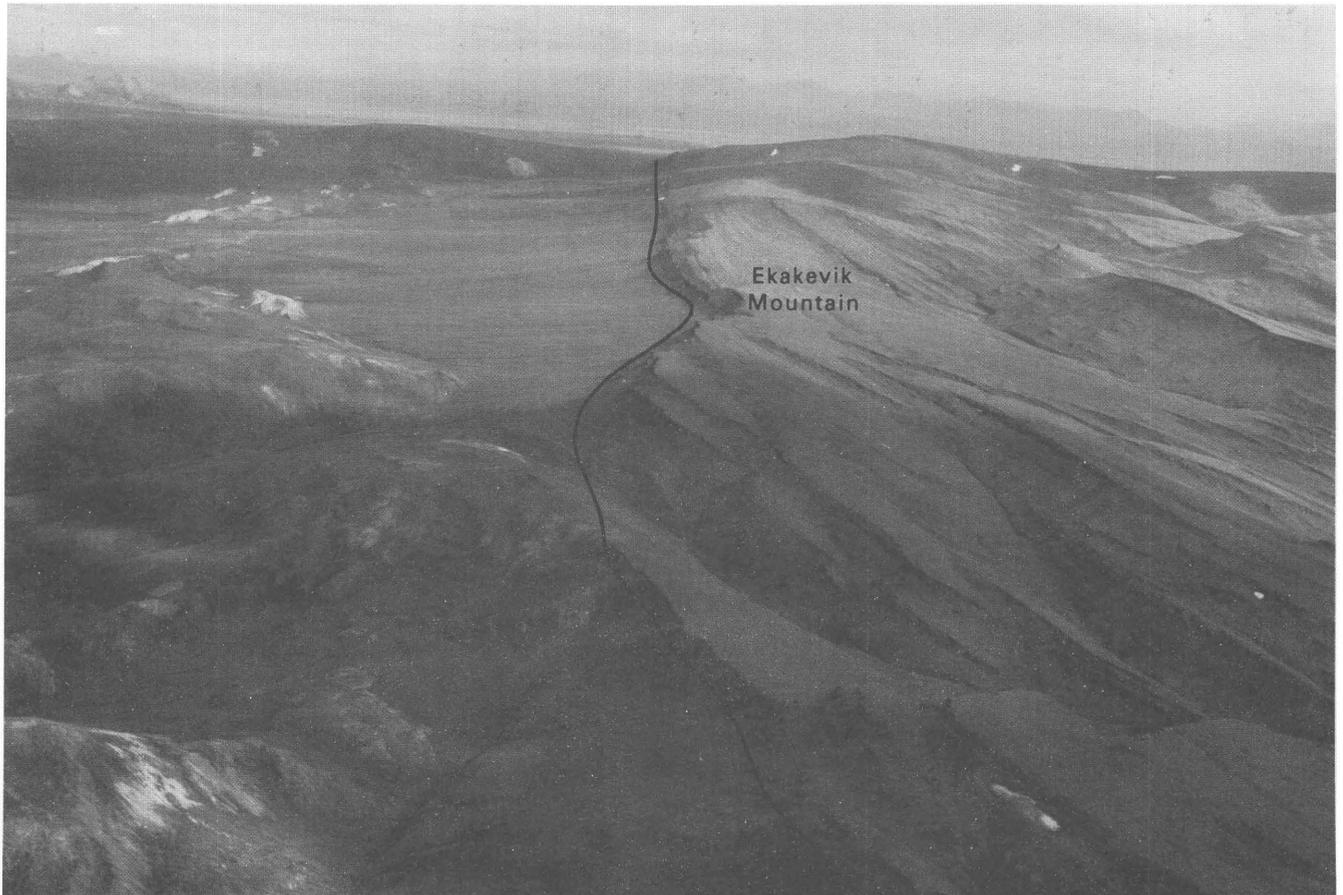


Figure 9. The Fortress Mountain Formation at Ekakevik Mountain (T. 10 S., R. 22 W.). A thick, uniformly south dipping section of interbedded conglomerate, sandstone, and shale unconformably overlies (line on photograph) a thrust-faulted terrane of Mississippian limestone, mafic igneous rocks, the Okpikruak Formation, and other rock units. Facies changes over short distances are characteristic of the Fortress Mountain here. View to the east.

and others, 1966, and Mayfield and others, 1978). Facies study of these conglomerates suggests alluvial-fan, fluvial, and shallow marine deposition very near an active source of coarse detritus (Hunter and Fox, 1976). Similar relationships are seen at Castle Mountain and Fortress Mountain on the central Arctic Slope and at Atigun syncline, east of Galbraith Lake. The data suggest that the major orogenic activity that formed the Brooks Range was pre-Albian, beginning during Berriasian time, and continuing into the Aptian.

Depositional Cycle and Nomenclature

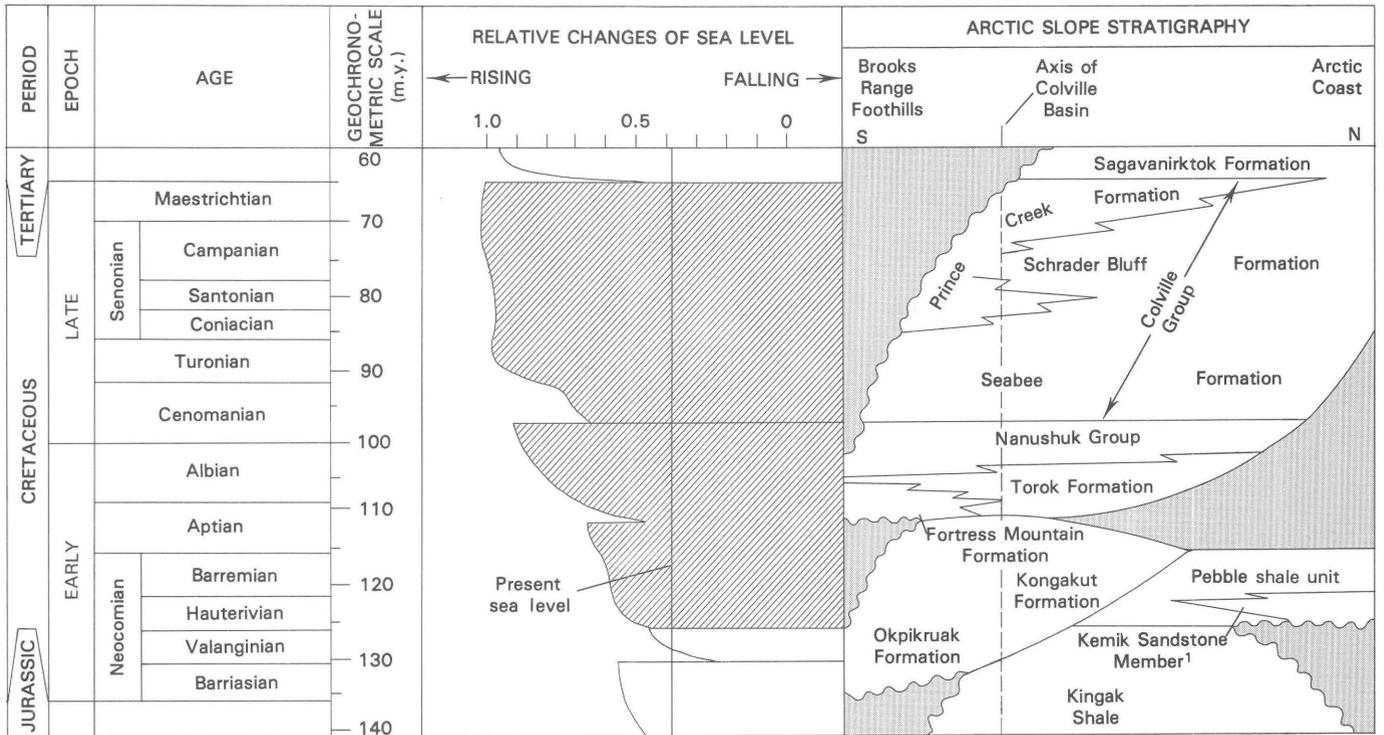
Neocomian rocks are discontinuously exposed along the entire north flank of the Brooks Range and in some areas within the mountains, particularly in the western Brooks Range. Thin Neocomian deposits are present in the subsurface of most of the Arctic Slope. The relationship of the various Neocomian rock units and the generalized configuration of the Colville basin north of

the central Brooks Range is diagrammatically illustrated in figure 5, and by Carter and others (1977, fig. 5, p. 24–25).

In general, the depositional sequence coincides with the worldwide global eustatic cycle of Vail and others (1977, fig. 2, p. 85) that ended during middle Aptian time (fig. 10). These cycles are described in the section of this chapter on “Depositional cycle and nomenclature,” in the section on “Albian and Cenomanian time.”

In the De Long Mountains and on the north flank of the Endicott Mountains, the Neocomian sequence, consisting dominantly of flysch, is known as the Okpikruak Formation (Patton and Tailleux, 1964, p. 445–449).

On the gentle northern flank of the Neocomian depositional basin, stable platform sediments coeval with the Okpikruak Formation are informally known as the “pebble shale unit” (Alaska Geological Society Newsletter, 1978; Bird and Andrews, 1979). Although these deposits are sometimes referred to the Okpikruak, the name is inappropriate inasmuch as they bear little resemblance to the thick flysch of the type Okpikruak. In outcrop in the



¹Of Kongakut Formation

Figure 10. Generalized global Cretaceous eustatic cycles (modified from Vail and others, 1977, fig. 2) and generalized Arctic Slope Cretaceous stratigraphy discussed in this report. The horizontal axis shows relative positions of sea level; 1 is the maximum relative highstand during the Late Cretaceous, and 0 is the Tertiary minimum relative lowstand. Relative rises of sea level are plotted toward the left; relative drops are plotted toward the right. Cycles in patterned area are generalized. Figures 4 and 5 show stratigraphic relationships in more detail.

northeastern Brooks Range, the beds were informally referred to as the pebble shale member of the Kongakut Formation (Detterman and others, 1975, p. 21–25).

In the western part of the Arctic National Wildlife Refuge, the Kemik Sandstone Member of the Kongakut Formation (Detterman and others, 1975, p. 21) underlies the pebble shale unit; the Kemik was formerly considered a basal member of the Okpikruak Formation (Keller and others, 1961, p. 196). In the Prudhoe Bay area, the Put River Sandstone of Jamison and others (1981, fig. 13; McIntosh, 1977, figs. 5, 6, 16, 17) occurs in a similar stratigraphic position.

Lithology and Distribution

The Okpikruak Formation is dominantly a thick flysch sequence and is present in allochthonous sheets throughout the De Long and Endicott Mountains. The flysch consists of rhythmically interbedded shale and sandstone (fig. 11), and pebble-to-boulder conglomerate in some areas. In addition, a sedimentary chaos or olistostrome is locally present as part of the Okpikruak. The olistostrome is composed of a heterogeneous assemblage of exotic blocks of sedimentary and mafic igneous rocks. Where well exposed, the blocks are clearly encased in

mudstone, graywacke, and associated channel conglomerates at depositional, not fault, contacts (Mull and others, 1976). In some places, the blocks exceed tens of meters in maximum dimension. A well-exposed outcrop of the olistostrome is illustrated in figure 12.

At the base of the Okpikruak on some of the allochthons in the western and central Brooks Range, a thin section of clay shale and interbedded coquinoid limestone of the stable platform sequence forms the base of the section; the limestone characteristically weathers reddish brown, and the shale is commonly maroon in color. In the western De Long Mountains, a thin quartzose sandstone-siltstone unit is also locally present at this horizon.

Neocomian flysch is not known along the mountain front of the northeastern Brooks Range. In contrast to the flysch of the Okpikruak Formation, the pebble shale unit, the Kemik Sandstone Member, and the Put River Sandstone of the northeastern Brooks Range and subsurface Arctic Slope consist of stable platform deposits.

The pebble shale unit is present in the northeastern Brooks Range and in the subsurface throughout the entire northern Arctic Slope; its southern limit in the subsurface is unknown. It consists of about 100 m of fissile organic-rich clay shale containing scattered grains of medium- to coarse-grained quartz and a few cobbles and boulders of



Figure 11. Typical rhythmically interbedded sandstone and shale of the Okpikruak Formation flysch, central and western Brooks Range. Sandstone beds range from 10 cm to 15 cm thick.

chert, quartz, and quartzite. In outcrop it is exposed discontinuously from the Kemik Creek-Kavik River area eastward through the Sadlerochit Mountains; its easternmost known exposure is in the Niguanak River area near Barter Island. Except where truncated by an overlying unconformity, the pebble shale unit has been found in most of the subsurface of the northern Arctic Slope.

Locally, the pebble shale unit is underlain by the Kemik Sandstone Member of the Kongakut Formation. The Kemik consists of as much as 40 m of very fine grained quartzose conglomeratic sandstone. Facies study suggests a shoreface-to-beach environment of deposition and sediment derivation from a northern source area (Mull and Kososki, 1977, p. B21, and unpublished data), in contrast to the southerly derived turbidite deposits of the siltstone member of the Kongakut Formation, which overlies the pebble shale unit and Kemik Sandstone Member in the eastern part of the Arctic National Wildlife Refuge.

The Kemik Sandstone Member crops out in the Sadlerochit Mountains area, and along the mountain front as

far southwest as the Echooka River area north of the Philip Smith Mountains. This part of the Brooks Range is autochthonous; thus, the Kemik is not involved in the allochthonous part of the orogenic belt. It is not present in outcrop southwest of the Echooka River, but was found in the Atlantic Richfield Susie-1 and Nora Federal-1, Mobil Echooka-1, McCulloch Fin Creek-1, Forest Kemik-1, and Amoco Kavik-1 exploratory holes (Tailleur and others, 1978) drilled in the foothills belt between the Canning River and Sagavanirktok River area.

The Put River Sandstone of Jamison and others (1981; McIntosh, 1977) is present locally in the eastern part of the Prudhoe Bay oil field, where it consists of as much as 22 m of conglomeratic sandstone. The uppermost sandstone horizon in the Kuparuk Formation in the Kuparuk oil field probably also correlates with the Kemik. In NPRA, similar sandstones have been found in the Cape Halkett-1, W. T. Foran-1, Walakpa-1, Peard-1, South Meade-1, East Teshekpuk-1, and Ikpikpuk-1 exploratory holes.

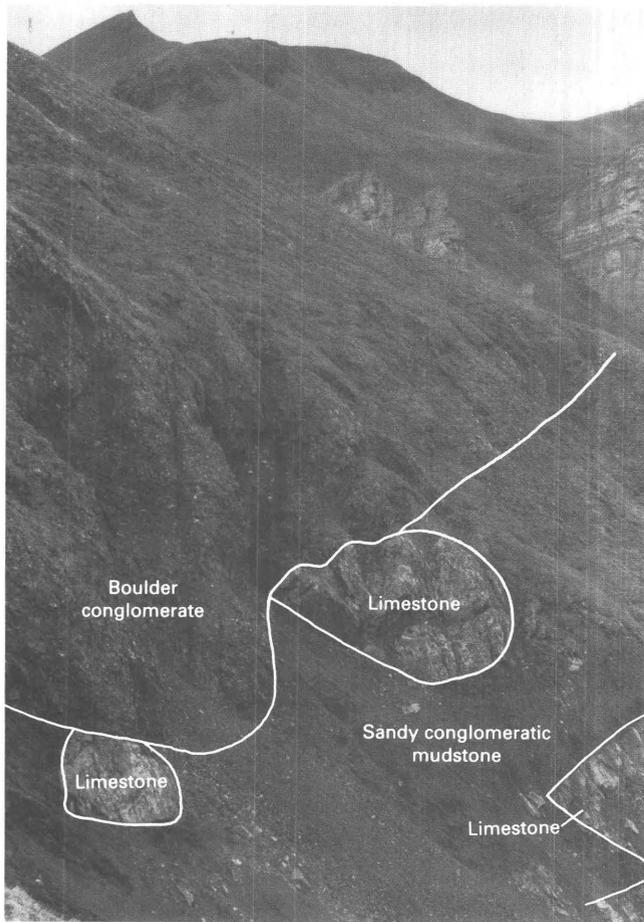


Figure 12. Olistostrome on the north side of the western De Long Mountains, North Slope. Exotic blocks of Mississippian limestone are encased in conglomeratic mudstone and are overlain by poorly sorted boulder conglomerate. Round limestone block in center is approximately 5 m high.

Thickness

In the western De Long Mountains, Sable and Mangus (1951, p. 11) reported a thickness of 500 m for the Okpikruak Formation; Chapman and Sable (1954, p. 7) and Mangus and others (1954, p. 9) suggested that its total thickness could be as much as 1,500–1,800 m. Near Anaktuvuk Pass on the north flank of the Endicott Mountains, the formation is about 650 m thick (Patton and Tailleir, 1964, p. 447). In the Elusive Lake area, both Brosgé and others (1979) and Keller and others (1961, p. 197) reported more than 600 m of Okpikruak.

In contrast to these orogenic deposits, the coeval stable platform deposits of the northern flank of the basin are very thin. Throughout the subsurface of the Arctic Slope and in outcrop in the northeastern Brooks Range, the pebble shale unit is of remarkably uniform thickness, about 100 m. However, in the British Mountains, Dettnerman and others (1975, p. 21, 25) reported a thickness

of 160 m. Where present, the underlying basal sandstone and (or) conglomerate of the Kemik, Put River, or unnamed beds may reach a thickness of about 40 m but in most places are much thinner.

Stratigraphic Relations

On the thrust sheets throughout the western and central Brooks Range, Neocomian rocks unconformably overlie condensed deposits of early Middle Jurassic, Triassic, and older age; the Jurassic Kingak Shale is not present on the allochthons. In many places, flysch of the Okpikruak is at the base of the section. However, on some allochthons, the base of the Neocomian contains a thin section of clay shale that in some places contains interbedded coquinoid limestone. These beds were apparently deposited in a stable shallow platform setting prior to the onset of subsidence and orogenic sedimentation. Similar relationships are present at the base of the Cretaceous within the mountains of the northeastern Brooks Range.

On the stable north flank of the basin, a major regional angular unconformity is present at the base of the pebble shale unit or at the base of the Kemik, Put River, or unnamed sandstone, where present. The contact of the pebble shale unit and Kemik is conformable and gradational through a ½- to 1-m interval. In the subsurface the basal unconformity truncates rocks as old as pre-Mississippian; in outcrops on the north side of the Sadlerochit Mountains in the Arctic National Wildlife Refuge, the pebble shale unit and Kemik Sandstone Member unconformably overlie the Permian and Triassic Sadlerochit Group. To the south, both in outcrops along the northeast Brooks Range front and in the subsurface, the unconformity dies out and the amount of truncation decreases so that thick sections of the Jurassic Kingak Shale are widespread beneath the Cretaceous.

In the Colville basin, regional relationships indicate that the orogenic belt and foredeep migrated progressively northward (Snelson and Tailleir, 1968), so that earlier orogenic deposits were themselves subsequently involved in the orogeny and, in places, were in turn cannibalized to form later deposits. The Okpikruak and related sediments likely prograded progressively northward over the pebble shale unit and related rocks in the center of the basin (fig. 5). Continuous deposition into the Albian may have occurred in some areas; elsewhere in the basin the top of the cycle may be a disconformity or nondepositional hiatus. This subject is discussed at greater length in the section of this report describing Albian-Cenomanian stratigraphic relations.

Toward the northern stable flank of the basin, the pebble shale unit and related rocks are overlain by rocks of the Albian to Cenomanian (Torok and Nanushuk) depositional cycle (fig. 5). The upper contact is sharp and

represents the abrupt onset of Albian and older orogenic sedimentation prograding over the subsiding platform. The hiatus represented by this contact is probably relatively short in the deeper parts of the basin, but to the north may encompass a large part of the Aptian. In the Atigaru-1, South Harrison Bay-1, and West Fish Creek-1 wells in the northeastern part of NPRA, an unconformity at the base of the Torok shows erosion of the entire pebble shale unit. This relationship is illustrated in figure 5 and by Molenaar (figs. 19 and 21, this volume).

Age

Based upon mollusk zonation in the central Brooks Range, the Okpikruak Formation is considered to be both Berriasian (Jones and Grantz, 1964, p. 1468) and Valanginian in age (Brosgé and others, 1979, table 1). Sable and others (1951), Sable and Mangus (1951), and Mangus and others (1954) also reported Berriasian and Valanginian fossils from the Okpikruak of the western Brooks Range.

At the type section of the Kongakut Formation, the Kemik Sandstone Member contains the Hauterivian ammonite *Simbirskites* sp. (Detterman and others, 1975, p. 25). Elsewhere at three localities in the Sadlerochit Mountains area of the Arctic National Wildlife Refuge, shale horizons interbedded with the Kemik contain a microfauna identified by M. B. Mickey (Biostratigraphics Inc., written commun., 1981) as Hauterivian to Barremian (late Neocomian) (table 1, localities 80AMu7-2, 80AMu16-17, and 80AMu27-8). In addition, on a tributary of the Kavik River, a horizon interpreted as an offshore marine equivalent of the Kemik has yielded a microfauna identified as Neocomian by Anderson, Warren, and Associates (written commun., 1978) (table 1, loc. 76AMu113-1). Pelecypods from several localities in the Kemik of the Sadlerochit Mountains area have been identified by J. W. Miller and D. L. Jones as *Astarte ignekensis* Imlay, *Tracia stelcki* McLearn, *Entolium utokokense* Imlay, *Panope(?) kissoumi* McLearn, and *Camptonectes dettermani* Imlay of early and (or) middle Albian age (table 2, locs. 76AMu15-1, 76AMu27-4, 80AMu12, 80AMu14-10, 80AMu17, 80AMu19-3, and 80AMu22). The close association of these pelecypod collections with the microfaunal collections suggests that the pelecypod fauna may have a longer range than previously recognized.

Microfauna from the pebble shale unit of the Kongakut Formation in the Sadlerochit Mountains area were dated as Hauterivian to Barremian by M. B. Mickey (Biostratigraphics, Inc., written commun., 1981) (table 1, locs. 80AMu7-4, 80AMu8-4, 80AMu14-12, 80AMu16-18, 80AMu16-18A, and 80AMu21).

Detterman and others (1975, p. 25) also reported

a Neocomian (late Hauterivian and Barremian) age for the pebble shale unit in the southern part of the Demarcation Point quadrangle of the eastern Brooks Range. A Jurassic microfauna reported in some collections was apparently reworked from beds eroded at the regional unconformity beneath the Kemik. In the northern Arctic Slope, many wells have penetrated the pebble shale horizon; many of these wells in NPRA yielded a definitive Neocomian microfauna. Typical of this horizon are the faunas from ditch cuttings in Kugrua-1 and Inigok-1 wells drilled in NPRA (Anderson, Warren, and Associates, written commun., 1979); these data are summarized on figure 13.

In the De Long Mountains, beds at the base of the Cretaceous similar to the pebble shale unit have yielded both micropaleontologic and palynological data reported by Anderson, Warren, and Associates (written commun., 1979) to be probably Neocomian (table 1, loc. 77AMu16). Elsewhere in the De Long and Endicott Mountains these beds are also dated by the interbedded coquinoid limestone. This limestone, composed of the pelecypod *Buchia sublaevis* Keyserling, is dated as early Valanginian (Imlay, 1959, p. 161, 165; Jones and Grantz, 1964, p. 1463).

Paleogeography

The generalized and inferred distribution of the major northern Alaska tectonic elements present during Neocomian and Aptian time is illustrated in figure 14. The boundaries of the elements are approximate and are intended to illustrate the basic concepts in the evolution of the Early Cretaceous depositional basin in northern Alaska.

To the north is the expanding Canada basin, formed by the rotation of the Arctic Alaska plate. Movement of this lithospheric plate apparently created an extensional (pull-apart or Atlantic style) plate boundary consisting of a broad zone of normal faults that are generally downdropped to the north. This zone underlies the Beaufort Sea continental shelf and slope and forms the north edge of the Arctic Alaska plate. The Brooks Range orogenic belt is the compressional plate boundary that marks the southern edge of the Arctic Alaska plate. Throughout the Brooks Range, the distribution and nature of the Neocomian facies suggest a roughly east-west trend to this orogenic belt. Beneath the Chukchi Sea, the extension of the orogenic belt is inferred to trend to the northwest. However, control is sparse and is inferred in part from the trends of the Herald arch (Grantz and others, 1970; Grantz, Holmes, and Kososki, 1976) and Tigara uplift (fig. 6; Payne, 1955). A limited number of measurements of flute casts and groove casts in Neocomian or Aptian flysch in the Tigara uplift near Cape Lisburne suggest current flow from west-northwest to east-southeast

(Mull, unpub. field data, 1974). Paleomagnetic data from the Tigara uplift (Newman and others, 1979, and unpublished data) do not suggest rotation of this area relative to the remainder of the Brooks Range; thus the current measurements are suggestive of a western rather than a southern source of sediment for this area during Neocomian to Aptian time.

During the Neocomian, the northern margin of the central and western Brooks Range orogenic belt lay far south of the present mountain front (fig. 14A). In this area, Neocomian orogenic deposits are widespread on allochthonous sheets that were thrust long distances northward prior to Albian deposition.

Stratigraphic relationships with allochthonous Neocomian rocks unconformably overlain by autochthonous Albian rocks, such as at Ekakevik Mountain (figs. 6 and 9), document a progressive northward migration of the orogenic front and foredeep during the Early Cretaceous. By Aptian time (fig. 14B), they are inferred to have migrated northward to locations near or north of the present western and central Brooks Range mountain front. Only in the northeastern Brooks Range does the evidence suggest that the orogenic belt and depositional trough lay south of the present mountain front.

Between the Brooks Range on the south and the Canada basin on the north lie the Colville basin and the Beaufort sill (fig. 14). The name "Beaufort sill" is here applied to the relatively narrow linear stable platform on the north side of the Colville basin. This area has generally been known as the Barrow arch (Brosgé and Tailleur, 1969; Rickwood, 1970; Detterman, 1973; Morgridge and Smith, 1972) or the Arctic platform (Payne, 1955, Brosgé and Tailleur, 1970). Tailleur and others (1976) referred to it as the Barrow inflection to emphasize the passive nature of the subsidence on its flanks; it was not an active uplift. The sill can be recognized in the Cretaceous outcrops of the Sadlerochit Mountains area of the northeastern Brooks Range, and can be traced in the subsurface northwest to beyond Barrow. It received relatively little sedimentation during the Early Cretaceous, and it separates the deep asymmetrical foreland basin on the south from the Canada basin to the north. The sill is the remnant of the much larger Arctic platform or cratonic area that was rifted during southward rotation of the Arctic Alaska plate. Its form results from the combination of northward onlapping mid-Paleozoic through Jurassic stable platform sedimentation, which formed its southern flank, and the Early Cretaceous rifting which formed its northern flank. The term "Barrow arch" is deemed inappropriate because in a structural-geology context, "arch" is defined as "a broad open anticlinal fold of a regional scale; it is usually a basement doming" (Bates and Jackson, 1980, p. 2). "Arch" thus carries an implication of genesis that is not supported by the structural and stratigraphic relationships in this part of Alaska.

Albian and Cenomanian Time

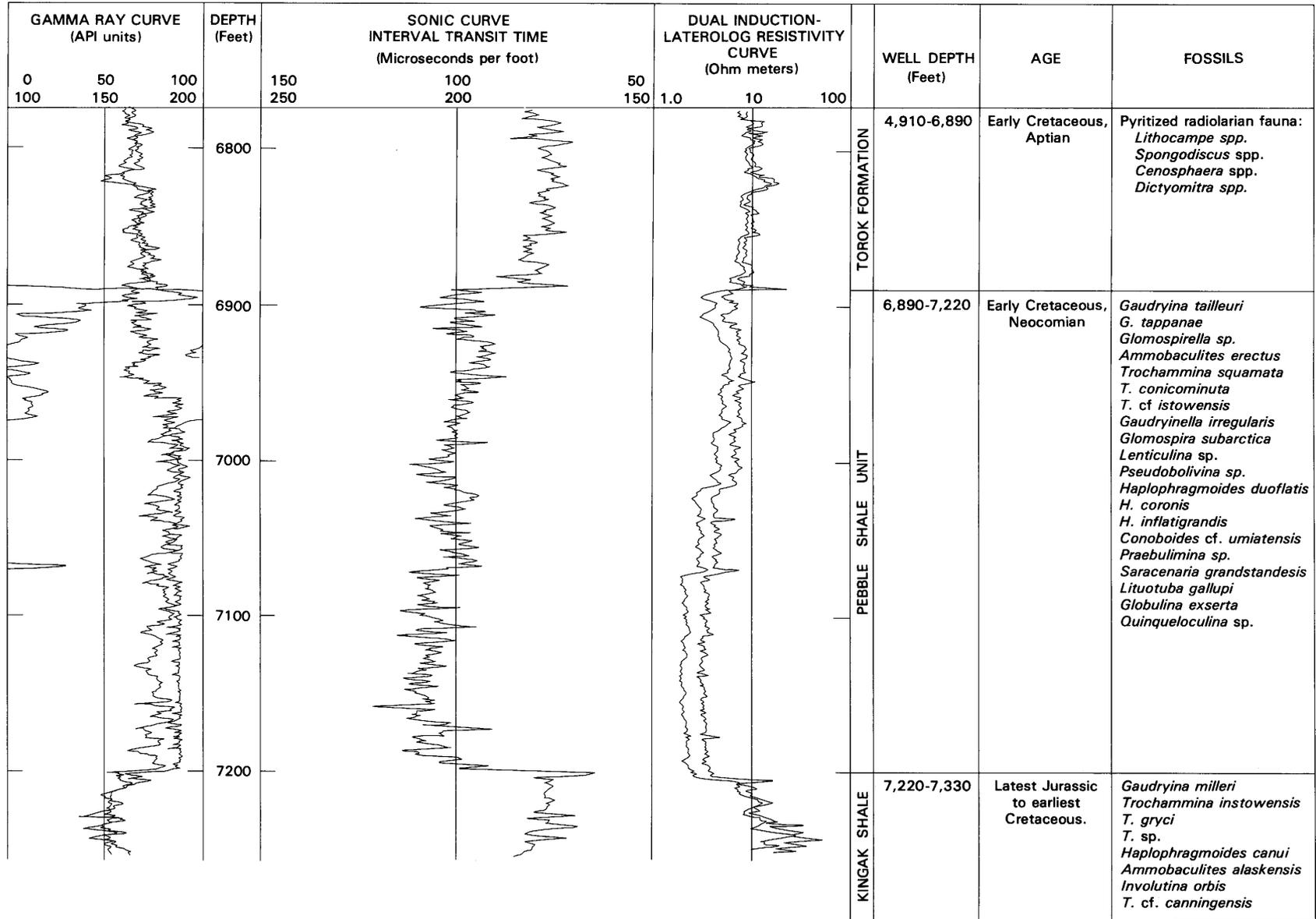
Tectonics

Regional relationships indicate that the Early Cretaceous stage of intense crustal shortening in the Brooks Range was followed by an episode of dominantly vertical tectonics (Mull, 1977, p. B28–B31; 1979, p. 9–10), possibly related to remobilization of granitic plutons in the southern Brooks Range. This event of predominantly vertical uplift may be the result of isostatic rebound of continental crust deeply depressed beneath oceanic crust at the south margin of the Neocomian orogenic belt. It coincides with the deposition of the Nanushuk Group.

The greatest vertical uplift occurred in the Arrigetch Peaks–Mount Igikpak area of the Schwatka Mountains in the south-central Brooks Range. Here, granite gneiss in two plutons is present in an area greater than 972 km² (375 mi²), and as high as 2,600 m (8,510 ft), forming the highest peaks of the southern Brooks Range (fig. 6; mapping by Brosgé and Pessel, 1977; Nelson and Grybeck, 1980). The amount of uplift appears to decrease both to the east and to the west in the Baird Mountains, where the Shishakshinovik, Redstone, and Kaluich plutons are much smaller and occur at much lower elevations than the Arrigetch-Igikpak pluton (see mapping by Pessel and Brosgé, 1977; and Mayfield and Tailleur, 1978). Regionally, the core of the range is a west-plunging anticlinorium that exposes autochthonous or parautochthonous rocks flanked by allochthonous sheets. These allochthons are particularly well defined in the Endicott and De Long Mountains north and west of the core of the range.

Of particular significance is the allochthon that forms the Endicott Mountains and extends from Feniak Lake on the west to the Philip Smith Mountains on the east (fig. 6). Evidence for this allochthon was given by Mull and Tailleur (1977, p. B27–B29), Dutro and others (1976), and Armstrong and others (1976). This allochthon includes stratified rocks termed the "Endicott sequence" (Mull, 1979, p. 11), the "Brooks Range sequence" (Martin, 1970; Mayfield and others, 1978), and the "Foothills sequence" (Tailleur and others, 1966). Unfortunately the geographic part of the name "Endicott sequence" is preempted by the rock-stratigraphic name "Endicott Group". Therefore, to avoid confusion with this well-established stratigraphic name, the sequence is here renamed the "Endicott Mountains allochthon" for its occurrence in that range. The Endicott Mountains allochthon consists of a thick section of Upper Devonian quartzose sandstone, quartz- and chert-pebble conglomerate, and shale (the Kanayut Conglomerate and Hunt Fork Shale of the Endicott Group) overlain by Mississippian cherty limestone of the Lisburne Group. Permian and Triassic siliceous beds (Siksikpak and Otuk Formations, Mull and others,

KUGRUA 1 TEST WELL



TOROK FORMATION

PEBBLE SHALE UNIT

KINGAK SHALE

INIGOK 1 TEST WELL

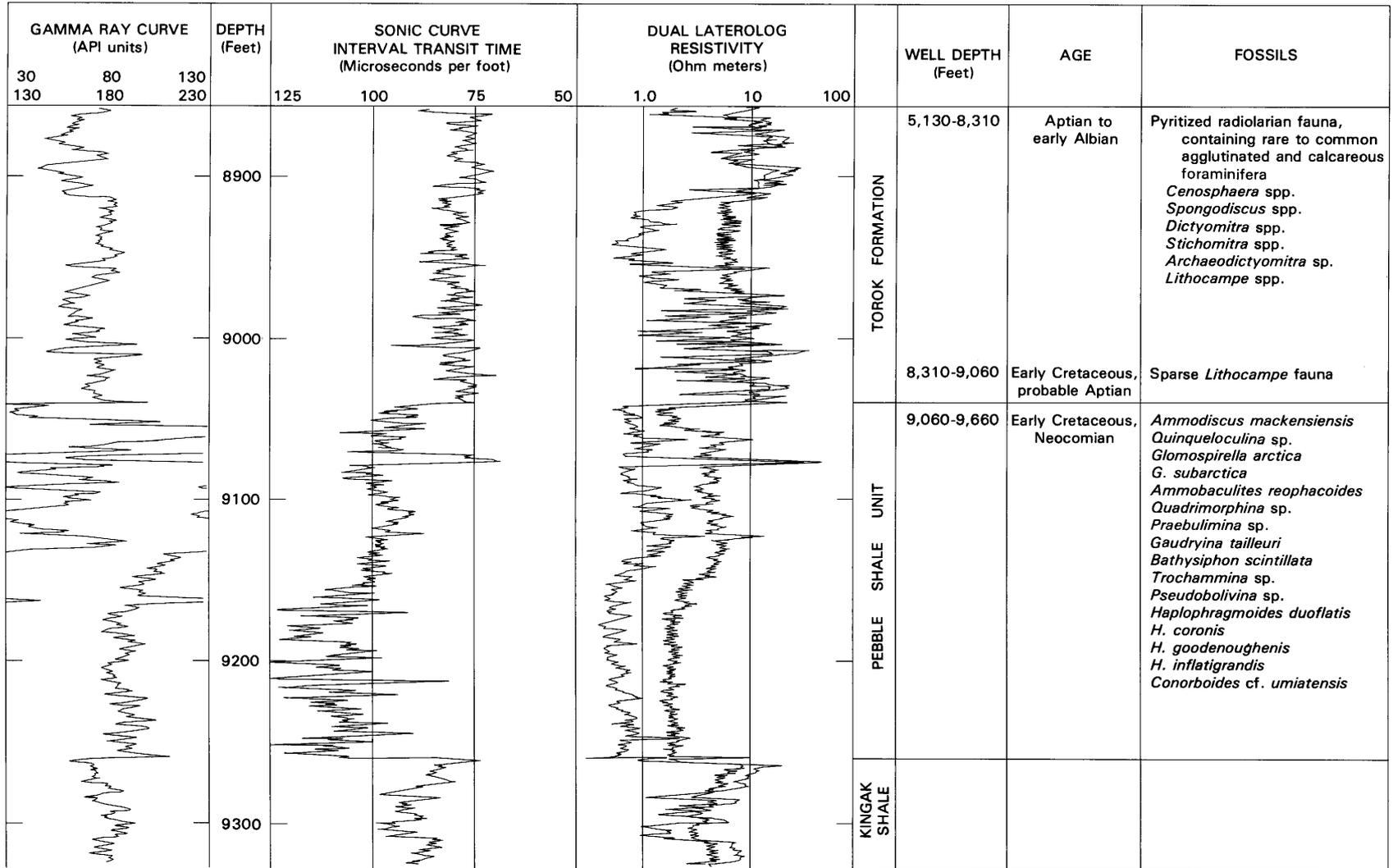


Figure 13. Log character and paleontological data for the pebble shale unit and adjacent rock units in the U.S. Geological Survey Kugrua-1 and Inigok-1 test wells in NPRA. The base of the pebble shale unit is a major regional erosional unconformity; the upper contact probably represents a nondepositional hiatus. Paleontology by M. B. Mickey of Anderson, Warren and Associates.

Table 1. Microfaunal and palynological data from Lower Cretaceous rocks, North Slope, Alaska

[Identifications and dating by Anderson, Warren, and Associates, written commun., 1979, and Biostratigraphics, Inc., written commun., 1981.
C, common; F, frequent; R, rare]

Locality No.	Stratigraphic position	Location (quadrangles scale 1:250,000)	Township and range	Fauna and flora	Age
75AMu99-1--	Lower part of Nanushuk Group (Corwin Formation).	Corwin Bluff, De Long Mountains quadrangle, western Arctic Slope.	NW1/4 sec. 34 T. 6 S., R. 55 W.	Undifferentiated bisaccates (F). <u>Gardodinium trabeculosum</u> (single), <u>Muderongia</u> sp.-5 (R), <u>Odontochitina operculata</u> (F), <u>Oligosphaeridium</u> complex (R).	Early Cretaceous (Aptian and Albian).
75AMu100A--	Upper part of Torok Formation.	Pitmegea River area, De Long Mountains quadrangle, western Arctic Slope.	SW1/4 sec. 11, T. 8 S., R. 53 W.	Undifferentiated bisaccates (C). <u>Cyclonephelium distinctum</u> (R), <u>Muderongia tetracantha</u> (single), <u>Odontochitina operculata</u> (R), <u>Oligosphaeridium</u> complex (F), O. c. (thick-wall) (R), <u>Palaeoperidinium cretaceum</u> (R).	Do.
75AMu100B--	-----do-----	-----do-----	SW1/4 sec. 11, T. 8 S., R. 53 W.	Undifferentiated bisaccates (C). <u>Gardodinium trabeculosum</u> (single), <u>Muderongia</u> sp.-5 (single), <u>Odontochitina operculata</u> (R), <u>Oligosphaeridium</u> complex (F), O. c. (thick-wall) (R), <u>Veryhachium</u> sp. (R).	Do.
75AMu16-1--	-----do-----	South of Tuktu Bluff, Chandler Lake quadrangle, central Arctic Slope.	SE1/4 sec. 25, T. 8 S., R. 2 W.	Undifferentiated bisaccates (F), <u>Osmundacidites</u> sp. (R), <u>Odontochitina operculata</u> (single), <u>Palaeoperidinium cretaceum</u> (R), <u>?Pseudocera-tium retusum</u> (single), <u>Tasmanaceae</u> (R).	Early(?) Cretaceous (possibly Aptian and Albian).
75AMu16-2--	-----do-----	South of Tuktu Bluff, Chandler Lake quadrangle, central Arctic Slope.	SW1/4 sec. 25, T. 8 S., R. 2 W.	<u>Bathysiphon vitta</u> (F), <u>Gaudryina</u> cf. <u>tailleuri</u> (R).	Probably Early Cretaceous (Aptian or older).
77AMu17--	Mount Kelly Graywacke Tongue of Fortress Mountain (pre-Torok sandstone).	Eagle Creek, De Long Mountains quadrangle, western Arctic Slope.	NE1/4 sec. 13, T. 9 S., R. 46 W.	<u>Cyclonephelium distinctum</u> (R), <u>Gardodinium trabeculosum</u> (R), <u>Oligosphaeridium</u> complex (F), <u>Palaeoperidinium cretaceum</u> (R).	Early Cretaceous (probably Aptian and Albian).

75AMu28-1--	Shale underlying Fortress Mountain Formation.	Base of Fortress Mountain, Chandler Lake quadrangle, central Arctic Slope.	SE1/4 sec. 14, T. 10 S., R. 5 W.	Arenaceous spp. (F), <u>Bathysiphon vitta</u> (R), <u>Glomospira corona</u> (R), <u>Glomospirella gaultia</u> (R), <u>Spongodiscus</u> sp. (R).	Early Cretaceous (Aptian or older).
75AMu28-3A--	-----do-----	-----do-----	-----do-----	Arenaceous spp. (R), <u>Bathysiphon</u> sp. (R), <u>Glomospirella gaultina</u> (R), <u>Haplophragmoides</u> sp. (R), shell fragments? (C), fecal pellets (F).	Do.
75AMu28-3B--	-----do-----	-----do-----	-----do-----	<u>Cenosphaera</u> spp. (F), <u>Lithocampe</u> sp. (F), fecal pellets (F).	Age not determined.
75AMu29--	-----do-----	-----do-----	SE1/4 sec. 2, T. 10 S., R. 5 W.	Arenaceous sp. (R), <u>Haplophragmoides</u> sp. (R), <u>Saccamina lathrami</u> (R), <u>Inoceramus prisms</u> (R).	Probably Early Cretaceous.
75AMu29--	-----do-----	-----do-----	-----do-----	Undifferentiated bisaccates (C). <u>Aptea polymorpha</u> (single), <u>Cyclonephelium distinctum</u> (R), <u>Odontochitina operculata</u> (R), <u>Oligosphaeridium</u> complex (R), <u>Palaeoperidinium cretaceum</u> (R).	Early Cretaceous (Aptian and Albian).
77AMu16--	Beds similar to pebble shale unit.	Tingmerkpuk Mountain, De Long Mountains quadrangle, western Brooks Range.	W1/2 sec. 21, T. 10 S., R. 45 W.	<u>Ammobaculites reophacoides</u> , <u>Gaudryina tailleuri</u> , <u>Haplophragmoides coronis</u> , <u>Cyclonephelium distinctum</u> , <u>Oligosphaeridium</u> complex, <u>Canningia/Cyclonephalium</u> sp.	Early Cretaceous (probably Neocomian).
76AMu29-2--	Shale interbedded with Kemik sandstone Member of Kongakut Formation.	Ignek Creek, Mt. Michelson quadrangle, eastern Brooks Range.	NW1/4 sec. 19, T. 3 N., R. 25 E.	<u>Ammobaculites reophacoides</u> , <u>Gaudryina tailleuri</u> , <u>G. milleri?</u> , <u>Haplophragmoides duoflatis</u> .	Early Cretaceous (Neocomian).
80AMu7-4--	Pebble shale, 2 m above top of Kemik Sandstone Member.	-----do-----	NW1/4 sec. 19, T. 3 N., R. 25 E.	<u>Bathysiphon scintillata</u> (F), <u>Conorboides</u> cf. <u>umiatensis</u> (R), <u>Glomospira corona</u> (R), <u>G. subarctica</u> (F), <u>Glomospirella arctica</u> (F), <u>Haplophragmoides duoflatis</u> (F), <u>H. coronis</u> (F), <u>H. inflatigrandis</u> (F).	Early Cretaceous (Hauterivian to Barremian).

Table 2. Megafossil data from Kemik Sandstone Member of Kongakut Formation, North Slope, Alaska

[Identifications and ages reported by J. W. Miller and D. L. Jones, written commun., 1981. C, common; F, frequent; R, rare]

Locality No.	Stratigraphic position	Location (quadrangles scale 1:250,000)	Township and range	Fauna	Age reported
76AMu15-1 (M7419).	Upper half of Kemik Sandstone Member.	North side of Sadlerochit Mountains, Mt. Michelson quadrangle.	N1/2 sec. 19, T. 4 N., R. 30 E.	<u>Astarte ignekensis</u> Imlay <u>Thracia stelcki</u> McLearn	Early Cretaceous (middle Albian).
76AMu27-4 (M7420).	Upper part of Kemik Sandstone Member.	Tributary of Katakaturuk River, north side of Sadlerochit Mountains, Mt. Michelson quadrangle.	SE1/4 sec. 6, T. 3 N., R. 28 E.	<u>Astarte ignekensis</u> Imlay	Early Cretaceous (early to middle Albian).
80AMu12--	-----do-----	Hogback ridge, upper Ignek Creek, south side of Sadlerochit Mountains, Mt. Michelson quadrangle.	SW1/4 sec. 27, T. 3 N., R. 26 E.	<u>Astarte ignekensis</u> Imlay <u>Ditrupa cornu</u> Imlay	Early Cretaceous (Albian).
80AMu14-10--	-----do-----	Katakaturuk River, south side of Sadlerochit Mountains, Mt. Michelson quadrangle.	E1/2 sec. 3, T. 2 N., R. 27 E.	<u>Astarte ignekensis</u> Imlay	Early Cretaceous (early to middle Albian).
80AMu17--	Top of Kemik Sandstone Member.	Marsh Creek, north side of Sadlerochit Mountains, Mt. Michelson quadrangle.	SW1/4 sec. 18, T. 4 N., R. 30 E.	<u>Astarte ignekensis</u> Imlay <u>Entolium utukokense</u> Imlay <u>Panope(?) kissoumi</u> McLearn	Early Cretaceous (Albian).
80AMu19-3--	Float from upper part of Kemik Sandstone Member.	-----do-----	SW1/4 sec. 18, T. 4 N., R. 30 E.	<u>Camptonectes dettermani</u> Imlay	Early Cretaceous (middle Albian).
80AMu22--	Upper half of Kemik Sandstone Member.	-----do-----	SE1/4 sec. 13, T. 4 N., R. 29 E.	<u>Astarte ignekensis</u> Imlay	Early Cretaceous (early to middle Albian).
80AMu8-4--	Pebble shale unit, composite sample 10-15 m above top of Kemik Sandstone Member.	Ignek Creek, Mt. Michelson quadrangle, eastern Brooks Range.	W1/2 sec. 27, T. 3 N., R. 25 E.	<u>Ammodiscus mackenziensis</u> (R), <u>Arenaceous</u> spp. (F), <u>Bathysiphon scintillata</u> (R), <u>Gaudryina tailleuri</u> (F), <u>Haplophragmoides duoflatis</u> (F), <u>H. coronis</u> (R), <u>Trochammina squamata</u> (R).	Early Cretaceous (Hauterivian to Barremian).

80AMu14-12--	Pebble shale unit, 3 m above top of Kemik Sandstone Member.	Upper Kataktuvuk River, Mt. Michelson quadrangle, eastern Brooks Range.	Center of N1/2 sec. 3, T. 2 N., R. 27 E.	Arenaceous spp. (large, coarse) (F), <u>Bathysiphon scintillata</u> (F), <u>Conorboides cf. umiatensis</u> (R), <u>Gaudryina tailleuri</u> (R), <u>Glomospirella arctica</u> (R), <u>Haplophragmoides duoflatis</u> (F), <u>H. coronis</u> (F), <u>H. inflatigrandis</u> (F), <u>Trochammina cf. sablei</u> (R).	Do.
80AMu16-18--	Pebble shale unit, 0.5 m above shaly siltstone of Kemik Sandstone Member.	Marsh Creek, Mt. Michelson quadrangle eastern Brooks Range.	SE1/4 sec. 19, T. 4 N., R. 30 E.	<u>Ammodiscus</u> sp. (very small) (R), <u>Gaudryina subcretacea</u> (F), <u>G. cf. tailleuri</u> (R), <u>Haplophragmoides coronis</u> (C), <u>Thuramminoides</u> sp. (R).	Do.
80AMu16-18A	Pebble shale unit, same location as above, composite sample 7-13 m above shaly siltstone of Kemik Sandstone Member.	-----do-----	----do----	<u>Ammobaculites reophacoides</u> (R), <u>Conorboides cf. umiatensis</u> (R), <u>Gaudryina tailleuri</u> (F), <u>Haplophragmoides duoflatis</u> (F), <u>H. inflatigrandis</u> (R).	Do.
80AMu21----	Pebble shale unit, uncertain position above Kemik Sandstone Member.	-----do-----	NE1/4 sec. 13, T. 4 N., R. 29 E.	<u>Ammodiscus mackenziensis</u> (R), <u>A. cf. elongatus</u> (R), Arenaceous spp. (large, coarse) (F), <u>Bathysiphon scintillata</u> (R), <u>Gaudryina tailleuri</u> (F), <u>G. tappanae</u> (F), <u>Glomospira subarctica</u> (R), <u>Haplophragmoides duoflatis</u> (F), <u>H. coronis</u> (C), <u>Thuramminoides</u> sp. (R).	Do.
80AMu7-2----	Shale interbedded with Kemik Sandstone Member, approximately 10 m below upper sandstone unit of Kemik (same location as 76AMu29-2).	Ignek Creek, Mt. Michelson quadrangle, eastern Brooks Range.	NW1/4 sec. 19, T. 3 N., R. 25 E.	Arenaceous spp. (C), <u>Bathysiphon scintillata</u> (F), <u>Gaudryina subcretacea</u> (R), <u>G. tappanae</u> (F), <u>Glomospira subarctica</u> (F), <u>Haplophragmoides coronis</u> (C), <u>H. goodenoughensis</u> (R), <u>Lituotuba gallupi</u> (R), echinoid spines (R).	Do.
80AMu27-8--	Silty mudstone interbedded with sandstone in top of Kemik Sandstone Member.	Tributary of Katakturuk River, Mt. Michelson quadrangle, eastern Brooks Range.	NE1/4 sec. 32, T. 4 N., R. 28 E.	<u>Ammobaculites reophacoides</u> (R), Arenaceous spp. (F), <u>Gaudryina tailleuri</u> (R), <u>Haplophragmoides duoflatis</u> (C), <u>H. coronis</u> (F).	Probably Early Cretaceous (Neocomian, undifferentiated).
76AMu113-1--	Shales, stratigraphically equivalent to Kemik Sandstone Member.	Kavik River area, Mt. Michelson quadrangle, eastern Arctic Slope.	NE1/4 sec. 6, T. 1 S., R. 24 E.	<u>Ammodiscus mackenziensis</u> , <u>Bathysiphon scintillata</u> , <u>Gaudryina tailleuri</u> , <u>Glomospira corona</u> , <u>Glomospirella arctica</u> , <u>Haplophragmoides duoflatis</u> , <u>H. coronis</u> , <u>H. inflatigrandis</u> .	Early Cretaceous (Neocomian).

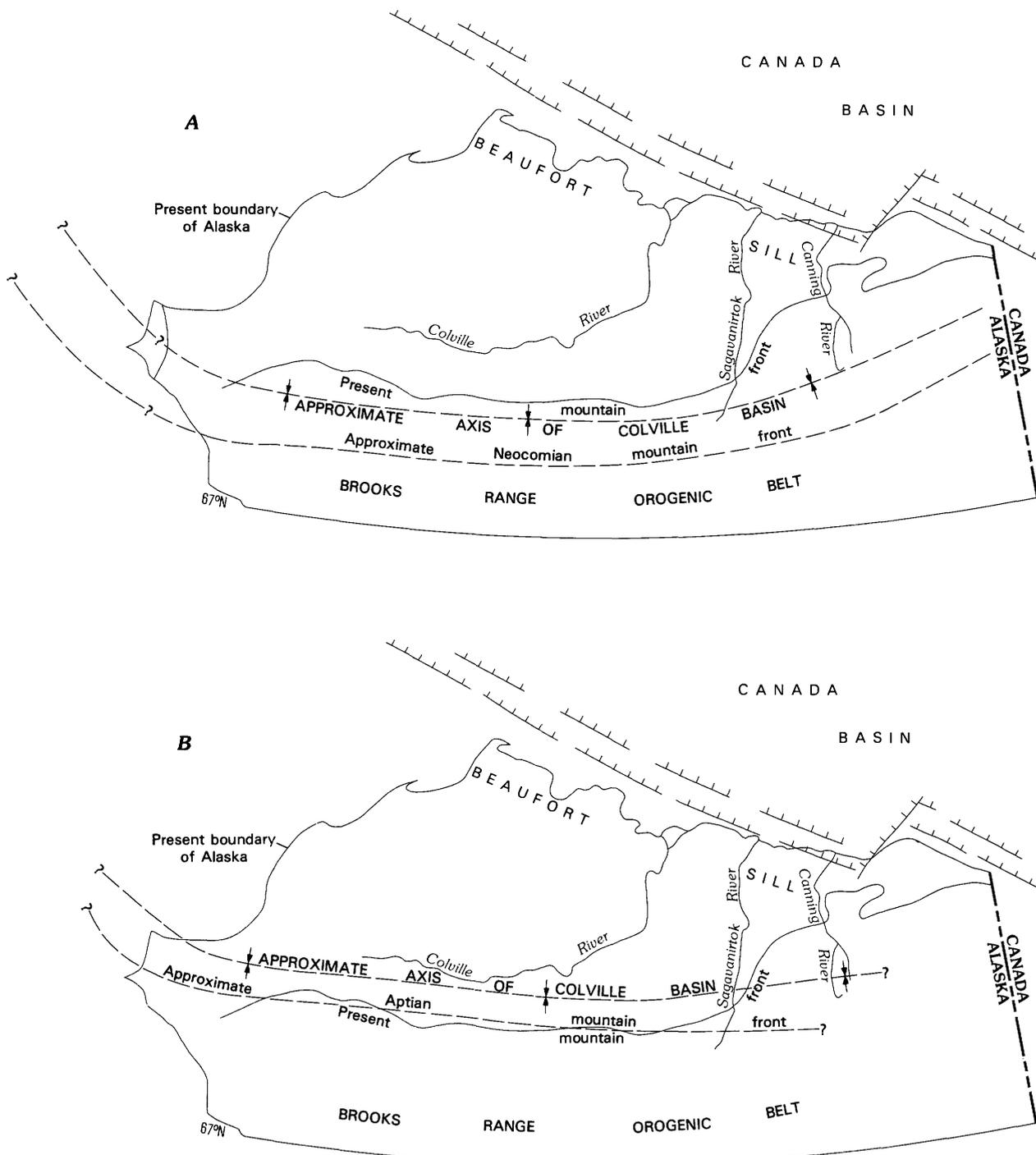


Figure 14. Diagrammatic map of major tectonic elements in what is now northern Alaska, showing inferred trends and approximate boundaries of elements. *A*, Neocomian time; *B*, Aptian time. Hachured lines, diagrammatic fault locations, hachures on downthrown sides. Queries indicate inferred locations.

1982) and a thin, distinctive Early Cretaceous (Valanginian) coquinoid limestone form the top of the sequence. The allochthon is as much as several kilometers thick; Upper Devonian rocks make up at least one third of the allochthon. It is widespread in the Endicott Mountains, but crops out only in local fensters in the De Long Mountains.

The mid-Cretaceous uplift of the core of the Brooks Range resulted in refaulting and folding of the Endicott Mountains allochthon, and development of regional northern dip into the basin north of the range. Although the folding and faulting resulting from this uplift appear complex, by comparison with the thrust faults formed by extreme crustal shortening during the Neocomian, they are

relatively minor in magnitude. Coincident with the uplift of the core of the range was the accentuation of the Colville basin, the deep successor basin north of the mountains.

Grantz and others (1970) suggested that faulting along the east margin of the Herald arch was younger than the folds that warp the Albian beds to the east. However, stratigraphic data (discussed in the section on "Paleogeography") suggest that deformation along the Herald arch and Lisburne Hills structural trends was probably occurring at the same time as uplift within the Brooks Range.

Dating of Orogeny

Evidence from uranium-lead and rubidium-strontium dating, regional structural-stratigraphic relationships (Mull and TAILLEUR, 1977), and metamorphic relationships (Nelson and Grybeck, 1979) indicates that the plutons were emplaced during the Paleozoic (Turner and others, 1979; Dillon and others, 1980; Silberman and others, 1979; Grybeck and Nelson, 1981). However, potassium-argon dating of these plutons has yielded dates ranging from 88 ± 4 m.y. to 98.8 ± 2.7 m.y. (Senonian to Cenomanian) (Pessel and others, 1973; Brosgé and Reiser, 1971; Turner and others, 1978). Similar relationships have been documented in the Romanzof Mountains in the northeastern Brooks Range (Sable, 1977, p. 57). In addition, Turner and others (1979) suggested that dates from the 300-km-long schist belt in the southern Brooks Range indicate a pervasive thermal event that cooled to argon-retention temperatures for micas in mid-Cretaceous time.

Paleontological data from the sediments resulting from this orogeny is summarized in the section on "Age" and in table 1.

Depositional Cycle and Nomenclature

Rocks of the Albian-to-Cenomanian depositional cycle lie unconformably upon older sediments along the margins of the Colville basin. Major rock units deposited during this cycle are the Nanushuk Group, Torok Formation, Bath tub Graywacke, Fortress Mountain Formation, and the Mount Kelly Graywacke Tongue (new name, this report) of the Fortress Mountain Formation; their nomenclature and generalized relationships are diagrammatically illustrated in figures 4 and 5.

Most of the Nanushuk Group deposition appears to have taken place during the Albian, but paleontological data, summarized in the section on "Age" and in table 1, from the Torok and Fortress Mountain Formations, both at the surface and in the subsurface, suggest that the depositional cycle began during the Aptian. Although Aptian-age sediments are probably present at its base in many areas, for convenience this cycle is referred to as the Albian-to-Cenomanian cycle.

This depositional sequence coincides with the generalized Aptian-to-Cenomanian eustatic cycle illustrated by Vail and others (1977, p. 85, fig. 2). They indicate the end of one global eustatic cycle during the late Aptian, and the beginning of another that continued through the Albian into the Cenomanian. Figure 10, modified from Vail and others (1977), illustrates the two eustatic cycles, which, in general, coincide with the Neocomian-to-Aptian and Albian-to-Cenomanian depositional cycles in northern Alaska. The relative drop in sea level that separates the two eustatic cycles may coincide with the stratigraphic break separating the Albian-to-Cenomanian depositional cycle from older sediments along the margins of the Colville basin.

The relationship of these northern Alaska depositional cycles to the global cycles may be more than coincidence. Rona (1973), Vail and others (1977), Pitman (1978), and many other authors have related eustatic sea-level and ocean-volume changes to changes in elevation or volume of midocean ridges, which in turn may be related to changes in the rate of sea-floor spreading. A possible relationship between the major Early Cretaceous orogenic activity in northern Alaska and plate movement in the Arctic has been mentioned by Rickwood (1970), TAILLEUR (1973), and Newman and others (1979), and this plate movement is assumed to have resulted from sea-floor spreading and rifting in the Canada basin. However, it is not known whether ocean-volume changes inferred from tectonic activity in the Arctic would be sufficiently large to be noticeable when combined with the effects of spreading and orogeny elsewhere.

In northern Alaska, a major regression during deposition of the Nanushuk Group, Torok Formation, and Fortress Mountain Formation at a time of rising sea level can be explained as a function of the rate of sediment influx from the orogenic belt exceeding the rate of sea-level rise and isostatic subsidence. Pitman (1978) pointed out that regression on a passive plate margin may occur as a result of a decreasing rate of sea-level rise. Such a decrease could be related to a decreasing rate of sea-floor spreading in the Arctic, which can, in fact, be inferred from the evidence of waning orogenic activity during Albian time in northern Alaska. In northern Alaska, the relatively close proximity of the passive extensional plate margin to the compressional margin and its orogenic belt undoubtedly complicates the interpretation of the control of eustatic cycles on sedimentation.

Lithology, Thickness, and Distribution

Fortress Mountain Formation

Along the south flank of the Colville basin, the Fortress Mountain Formation crops out discontinuously in a narrow, nearly east-west-trending line of isolated mesas

and buttes (figs. 6, 9). It typically consists of thick, proximal, cobble-to-boulder conglomerate that varies from well sorted to chaotic and poorly sorted. The conglomerate is interbedded with shale, siltstone, and sandstone. Very rapid facies changes are characteristic. At Fortress Mountain, its type locality, and at Castle Mountain, it is more than 3,000 m thick (Patton and Tailleux, 1964). In the Killik-Etivluk River area, Chapman and others (1964) suggested a thickness of about 2,000 m. At other localities, such as at Atigun syncline and Ekakevik Mountain, it contains conglomerate of comparable coarseness but in thinner sections. Hunter and Fox (1976) interpreted the coarse beds at Ekakevik Mountain and Castle Mountain as generally shallow marine to fluvial deposits. Clasts consist dominantly of chert, fine-grained mafic igneous rocks, quartzite, and minor amounts of limestone, and they were apparently derived from erosion of the allochthons that form the Endicott and De Long Mountains. The associated sandstone is poorly sorted and very silty, and contains argillaceous lithic graywacke. Other prominent exposures along this trend, such as at Pingaluligit Mountain near the Killik River, Smith Mountain near the Etivluk River, and Liberator Ridge near the Kiligwa River, consist dominantly of thick graywacke and only minor conglomerate. Elsewhere along the Fortress Mountain trend, exposures are few and are generally confined to stream cutbanks; in these places, the formation consists almost entirely of thinly interbedded rhythmic turbidites of fine-grained sandstone, siltstone, and shale. The intermittent distribution of coarse-grained fluvial to shallow-marine facies that seem to grade laterally to submarine fan deposits suggests a series of major depocenters of coarse debris built out into the Colville basin. These depocenters probably coincide in general with the location of the major outcrops of Fortress Mountain Formation mapped north of the Endicott Mountains (fig. 6).

In the eastern Brooks Range, the Bathub Graywacke (Detterman and others, 1975, p. 25–28) is an apparent equivalent of the lower Torok and the Fortress Mountain. It consists of about 750 m of thin and rhythmically interbedded graywacke and shale. Graded beds and flute casts and load casts are common; the unit represents turbidites deposited on a submarine fan.

For nearly 100 km northward from the outcrop belt of the Fortress Mountain Formation, little is known about it. Information is available from only two exploratory holes, Texaco East Kurupa-1, and West Kurupa-1, that apparently reached this stratigraphic level but did not completely penetrate the rocks representing the depositional cycle. In these wells, the section penetrated consists predominantly of very fine grained, argillaceous, lithic graywacke and shale. Although gas shows are common in this part of the stratigraphic section, the rapid rate of facies change observed in outcrop, the very dirty character of the sediments, and the facies distribution indicating

deposition of turbidites into a deep basin, suggest that the horizon has very little reservoir potential in the axial part of the Colville basin.

In NPRA, a number of exploratory holes have penetrated the Albian-to-Cenomanian depositional cycle. However, because of poor paleontologic control, the exact correlation of the basal beds of the cycle with the Fortress Mountain Formation in outcrop is uncertain. Typically, the basal 100 m of the cycle contains a number of silty and clayey sandstone beds, in contrast to a predominantly shaly section above. This sandy section may be a distal basin equivalent of the Fortress Mountain Formation, but is here considered to be basal Torok Formation.

Mount Kelly Graywacke Tongue (new name) of the Fortress Mountain Formation

In the southern foothills belt of the De Long Mountains, a widespread unit of distinctive calcareous, micaceous graywacke is in a stratigraphic position similar to the Fortress Mountain Formation. These rocks were assigned to the Fortress Mountain by Chapman and Sable (1960, p. 71–73) who noted (p. 71) that “No exact time or stratigraphic correlations between these rocks and the rocks in the type area of the Fortress Mountain Formation are implied.” Because the lithology is quite different from that of the type Fortress Mountain Formation, this rock unit is here named the Mount Kelly Graywacke Tongue of the Fortress Mountain Formation for its characteristic development on Mount Kelly (sec. 21, T. 11 S., R. 50 W., Umiat meridian), considered its type locality. It is distinguished from the main body of the Fortress Mountain Formation by its calcareous cement and abundant detrital muscovite. The Fortress Mountain Formation is here restricted to the sections of massive conglomerate, shale, and noncalcareous, nonmicaceous graywacke and associated rhythmic turbidites present generally north of the Endicott and eastern De Long Mountains. The generalized distribution and the type locality of the Mount Kelly Graywacke Tongue are shown on figure 6. Throughout much of the western De Long Mountains foothills the tongue is exposed on prominent, rather sharp rubble-covered ridges; scattered well-exposed beds are on some hillsides and in stream cuts. Nonresistant, poorly exposed, gray silty shale and mudstone constitute 30–50 percent of the tongue. A typical exposure of Mount Kelly Graywacke Tongue is illustrated in figure 15.

Sandstone in the Mount Kelly Graywacke Tongue ranges from very fine to coarse grained and is slightly conglomeratic in some places. The sand is composed of quartz, chert, lithic rock fragments and abundant muscovite flakes in an extremely argillaceous matrix. In thin section, the grains consist of about 20 percent monocrystalline quartz, as much as 10 percent metamorphic quartz, 20–40 percent lithic fragments, as much as 10 percent



Figure 15. Complexly folded and thrust-faulted beds of Mount Kelly Graywacke Tongue of the Fortress Mountain Formation, in the foothills of the western De Long Mountains, Arctic slope. Resistant ridges in center of view are about 1 km apart. View to the southwest.

chert and the remainder grains of muscovite, plagioclase, magnetite, pyrite, pyroxene, and olivine (R. M. Egbert, written commun., 1981). Limestone fragments constitute 30–75 percent of the lithic grains; metamorphic, volcanic, and argillaceous sedimentary-rock fragments constitute the remainder of the lithic component. Clasts of shale are abundant in some beds; abundant carbonaceous material is also seen at the top of some beds. Beds range from 3 to 6 cm in thickness and are interbedded with shale, silty shale, and siltstone that commonly is not well exposed. Many beds are massive and apparently homogeneous; however, graded and convolute bedding are common, and flute, groove, and load casts are abundant. Other beds have large- to medium-scale crossbedding; low-amplitude current and oscillation ripples are abundant on the tops of some beds; climbing ripples have been observed in a few places. In general, the range of bedding features is suggestive of turbidite deposition, but deposition in rather shallow water is also evident.

No sections of the Mount Kelly Graywacke Tongue have been measured; however, it may be as much as sev-

eral hundred meters in thickness in some areas. In most places no top or base of the formation is exposed; it is often structurally deformed by folding and apparent thrust faulting so that no thickness determination is possible.

The base of the tongue seems to be an unconformity, although the base is everywhere obscured by covered intervals of varying extent. In various areas, the exposures underlying the covered interval range from Triassic chert, shale and limestone, to Jurassic clay shale, to Neocomian clay shale and some coquinoid limestone. The top of the tongue appears to be gradational and to interfinger with the overlying Torok Formation. Although exposures are not good, this relationship is best seen on aerial photographs of a southwest-plunging anticlinal nose in T. 8 S., R. 46 W., between Poko Mountain and Igloo Mountain. This area was referred to by Chapman and Sable (1960, p. 71, 133, 134, and pl. 8) as the Tingmerkpuk "high."

The Mount Kelly Graywacke Tongue is dated as Aptian and Albian (late Early Cretaceous) based upon a flora obtained from shale interbedded with massive

graywacke apparently near the center of the formation as exposed at a locality south of Poko Mountain (table 1, loc. 77AMu17). The apparently interfingering relationship of the tongue and the Torok Formation also suggests that the tongue is part of the Albian and Cenomanian depositional cycle.

The distinctive micaceous and calcareous character of the Mount Kelly Graywacke Tongue suggests a different source terrain than that which was the major source of detritus for the remainder of the Fortress Mountain Formation. Clasts in the Fortress Mountain in general suggest derivation from the multiple allochthons of sedimentary and igneous rock comprising the De Long and Endicott Mountains. The abundance of muscovite in the Mount Kelly Graywacke Tongue suggests sediment derivation from a western extension of the schist belt that forms the southern margin of the Brooks Range. This belt is composed predominantly of quartz muscovite schist and associated calcareous schist. In the central Brooks Range, regional structural evidence suggests that the schists were deeply buried by the overlying allochthons and were not exposed to erosion during the Albian. However, in the western Brooks Range, evidence suggests that the schists may also have been involved in the allochthons of that area.

Torok Formation

In NPRA, seismic and subsurface data indicate that the Torok Formation is more than 2 km thick and is a record of the progressive filling of the Colville trough. The Torok consists predominantly of shale that is silty and hard in many places. In outcrops in the southern part of its area, it interfingers with the underlying Fortress Mountain Formation and the Mount Kelly Graywacke Tongue. It appears to represent turbidite deposition in the axis of the Colville basin. In many places in the subsurface, the lower part of the Torok consists of more than 1,000 m of rhythmic turbidite lacking paleobathymetric indicators. The nature of the sediments and the general absence of calcareous microfauna suggest submarine fan deposition below carbonate compensation depth. Upward in the section, the Torok may represent prodelta deposits in advance of the prograding deltaic deposits of the Nanushuk Group.

The Torok Formation thins to the northeast but is present across most of the Arctic Slope, with the exception of the northeastern Arctic Slope and the southern foothills belt. Many of the areas in which the Torok is absent in the northeastern Arctic Slope are high on the flank of the Beaufort sill and are apparently beyond the Torok depositional limit. In this area, the Torok progressively onlapped but did not overstep the crest of the sill (fig. 5B). Elsewhere, in parts of northeastern NPRA and the Beaufort Sea, the Torok may have been truncated by

an overlying unconformity. In the southern foothills belt, it is absent by Holocene erosion.

Nanushuk Group

From the Chukchi Sea to the area of the Colville River, the Torok Formation grades upward into deltaic deposits of the Nanushuk Group. The Nanushuk grades upward from shallow marine to nonmarine deltaic sediments and represents the final filling of the Colville basin by a prograding deltaic complex. The relationships of the Torok and Nanushuk across NPRA are illustrated in figure 5, and by Molenaar (figs. 18–22, this volume).

The Nanushuk Group forms a nearly unbroken outcrop belt from the Chukchi Sea on the west to the Sagavanirktok River on the east (fig. 6); this outcrop belt constitutes the northern foothills belt of the Brooks Range. In many areas a prominent escarpment formed by the resistant, gently north dipping clastic rocks of the Nanushuk marks the southern limit of the Nanushuk. Regionally these rocks dip gently into the subsurface beneath the Arctic coastal plain and are present throughout most of the northern part of NPRA. In NPRA the Nanushuk is absent only in the Brooks Range, the southern foothills belt (where it was removed by Holocene erosion), in a limited area near Barrow (where it is absent due to an overlying unconformity), and to the northeast (beyond its depositional limit). Its original southern depositional limit is unknown.

Inasmuch as details of the Nanushuk of the central and western Arctic Slope are discussed by Ahlbrandt and others (1979), Bartsch-Winkler (1979), Bird and Andrews (1979), Fox (1979), Huffman (1979), and in other papers in this volume, similar discussion is not repeated here.

Nanushuk Group, eastern Arctic Slope

On the Arctic Slope east of the Sagavanirktok River, rocks of the Albian and Cenomanian depositional sequence are limited and consist of a markedly different facies than the Nanushuk Group to the west. Major exposures are limited to a mesalike syncline east of the Ivishak River and to cutbanks along its west bank. In this area the sediments are rhythmically interbedded shale and sandstone, in many places with well-developed graded bedding and sole markings, suggesting turbidite deposition in a submarine fan setting. Apparently correlative beds in the subsurface also appear to be basal deposits.

In the Arctic National Wildlife Refuge east of the Canning River, submarine fan deposits possibly correlative with the Nanushuk are present along Arctic Creek, between the Sadlerochit and Hulahula Rivers in the Sadlerochit Mountains area (Reiser and others, 1971). East of the Hulahula River, Reiser and others (1978) have rec-

ognized rocks that may also be correlative with the Nanushuk. However, the area is remote from the typical Nanushuk outcrop area, well control is sparse, correlations are uncertain, and other major changes in structure and stratigraphy are known to exist. Data from the Yukon Territory (Young and others, 1976) suggest that only Albian flysch is present in the British Mountains.

Stratigraphic Relations

A sharp depositional break marks the top of the Albian and Cenomanian cycle in some areas. In the Umiat-Chandler Lake area, deltaic sediments of the Nanushuk Group are overlain by the dominantly marine Upper Cretaceous deposits of the Colville Group (Brosgé and Whittington, 1966, and Detterman and others, 1963). To the east, in the Sagavanirktok-Ivishak River area, continuous deposition may have prevailed from the Nanushuk into the Colville Group. To the west of the Umiat area, a Holocene erosion surface marks the top of the Nanushuk.

The unconformity at the base of the cycle is clearly evident in outcrop mapping along the basin margin. At localities such as Castle Mountain and Ekakevik Mountain (figs. 6, 9) on the central Arctic Slope, proximal conglomerate of the Fortress Mountain Formation overlies a major angular unconformity. Under the Arctic coastal plain in northern NPRA, well penetrations also reveal a sharp break between the distal sediments of the Torok Formation and the underlying sediments on the gentle north flank of the Colville trough. This contact may be a nondepositional hiatus in much of the area, but locally it is an erosional unconformity. Typical subsurface log character and paleontologic data at this basal contact are shown in figure 13.

In the central Colville basin beneath the foothills province, no wells have penetrated the basal contact of the Albian depositional sequence, and here the nature of its base is unknown. However, if the magnitude of eustatic sea-level lowering during the Aptian was great enough, it is possible that a disconformity may separate the deposits of the two cycles throughout the Colville basin.

Alternatively, continuous deposition throughout the Early Cretaceous can be inferred in the axial part of the Colville basin. In outcrops between the Sagavanirktok River and Elusive Lake, rocks mapped as the Okpikruak and Fortress Mountain Formations by Keller and others (1961, p. 196–200, pl. 21) and by Brosgé and others (1979) total at least 2,000 m of interbedded shale, siltstone, graywacke, conglomeratic sandstone, and conglomerate. Keller and others (1961, p. 196) noted that the Okpikruak is indistinguishable from the overlying Fortress Mountain Formation, although the rhythmic alternation that characterizes the Okpikruak is lacking in the Fortress Mountain. Formation contacts appear to be gradational.

Within the depositional cycle, the stratigraphic relationships seem to be entirely gradational. The Fortress Mountain Formation interfingers both northward and stratigraphically upward with shale of the Torok Formation. Similarly, the marine Torok interfingers with the overlying Nanushuk Group.

Age

Relatively abundant foraminifera and palynomorph assemblages from shale in the upper part of the Torok Formation and from the Nanushuk Group date these rocks as middle Albian to Cenomanian (Sliter, 1979; and May, 1979). Microfossil data and megafossils (which include ammonites) date the Fortress Mountain Formation as early Albian (Patton and TAILLEUR, 1964, p. 456–458). Data for the lower part of the depositional cycle (lower Torok and Fortress Mountain Formations) are limited; fossils consist dominantly of pyritized radiolaria and some agglutinated and calcareous foraminifera. Radiolarian fauna from two wells in NPRA are tabulated in figure 13; the fauna is considered to be Aptian and early Albian (Anderson, Warren, and Associates, written commun., 1979). However, C. M. Molenaar (written commun., 1980) pointed out that in some areas on the northern flank of the basin, strata inferred to be Aptian can be traced on seismic records up foresets into strata yielding an Albian fauna. Outcrop samples from a number of localities, tabulated in table 1, have also yielded foraminifera and (or) palynomorph assemblages considered to be Aptian or Aptian and Albian age by Anderson, Warren, and Associates. Although the faunas may be time transgressive, some localities contain forms restricted to Aptian rocks in the Canadian Arctic (M. B. Mickey, Biostratigraphics, Inc., oral commun., 1981).

Paleogeography

The generalized distribution of the major tectonic elements at the end of the Albian and Cenomanian depositional cycle is shown in figure 16. In general, the margin of the Canada basin and the Brooks Range orogenic front appear to have been in positions approximating those in the Aptian, reflecting the shift to dominantly vertical uplift in the mountains. However, a major change in the form of the Colville basin is evident. During the Neocomian and Aptian, the Colville basin was apparently a linear trough parallel to the orogenic front, but by Cenomanian time, progradation of the Torok Formation and the deltaic Nanushuk Group resulted in a basin restricted to the eastern Arctic Slope. Northeastward and eastward progradation is indicated by a combination of outcrop, subsurface, and seismic studies (Payne, 1951; Chapman and Sable, 1960; Ahlbrandt and others, 1979,

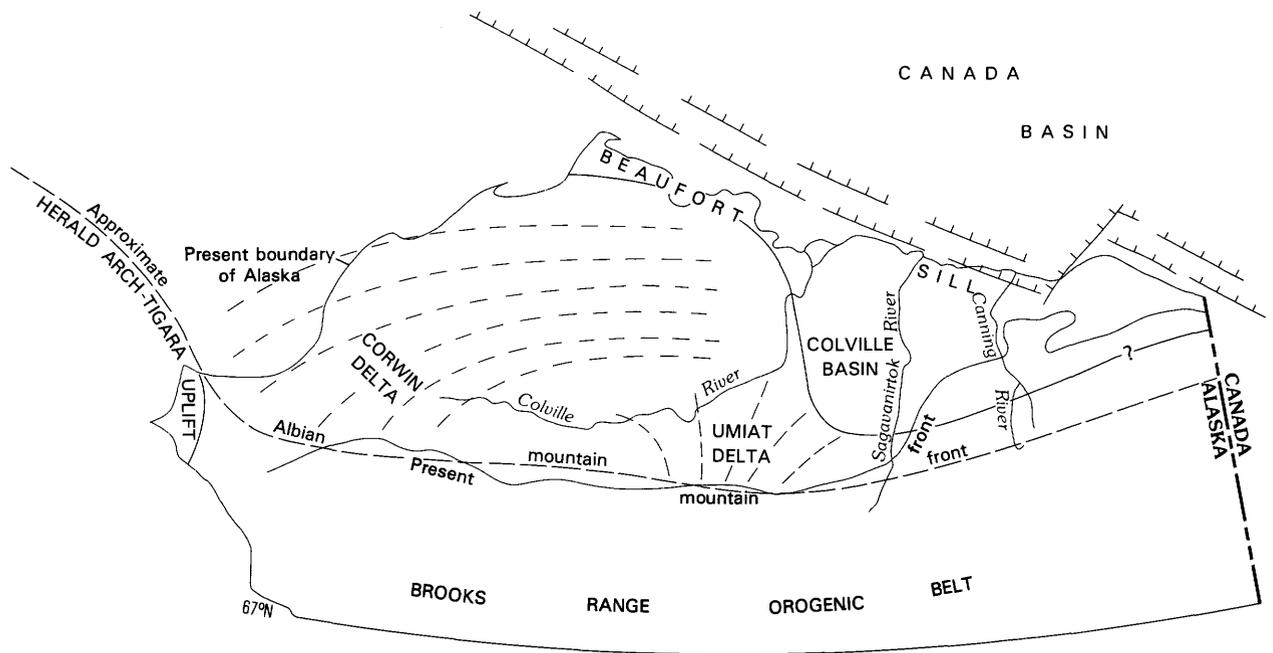


Figure 16. Diagrammatic map of major tectonic elements near the end of Albian time in what is now northern Alaska, showing inferred trends and approximate boundaries of elements.

p. 14–25; Bird and Andrews, 1979, p. 37–40, figs. 15, 18; Mull, 1979, p. 10). In the Barrow area, the deltaic wedge prograded over the crest of the Beaufort sill, so that detritus from the orogenic belt was, for the first time, deposited onto the oceanic crust of the Canada basin. However, on the eastern Arctic Slope, the Beaufort sill remained high relative to the basin to the south, and in the area from Prudhoe Bay to the Sadlerochit Mountains the sill received little sedimentation during the Albian-to-Cenomanian cycle.

Ahlbrandt and others (1979) recognized a deltaic complex, the Corwin delta, that dominates the Nanushuk of the western Arctic Slope. The progradation of this delta suggests a major sediment source to the west or southwest of the western Arctic Slope as well as a source of sediment from the Brooks Range to the south. The Tigara uplift (Payne, 1955) in the area of Cape Lisburne, and its offshore extension beneath the Chukchi Sea, the Herald arch (Grantz and others, 1970, 1976), were probably a major source of detritus for the Corwin delta.

In the Brooks Range foothills of the central Arctic Slope (Chandler River to Sagavanirktok River area), the generalized Albian facies trends suggest northward progradation. Both the Nanushuk Group and the Fortress Mountain Formation have nearly east-west trends of outcrops (fig. 6) that appear to be generally comparable in thickness and facies. To the north the Nanushuk becomes thinner and finer grained. Current measurements in fluvial sandstones define a lobate deltaic complex, named the Umiat delta, which also appears to prograde generally northward (Huffman and others, this volume). The east-

west facies trends and the form of the Umiat delta suggest sediment derivation from the east-west-trending Endicott Mountains.

Between Shainin Lake and the Sagavanirktok River, the Brooks Range front trends slightly to the northeast. East of the Sagavanirktok River the front trends about N. 40° E. for more than 100 km to form the major northeast salient of the Philip Smith, Franklin, Romanzof, and British Mountains of the eastern Brooks Range. Because of this salient, the eastern Brooks Range mountain front is more than 120 km further north than the mountain front at Anaktuvuk Pass. But, east of the Sagavanirktok River, the structural trends mapped by Brosgé and others (1979) continue into the Philip Smith Mountains toward Porcupine Lake on a trend of about N. 70° E., and are not parallel to the mountain front. In addition, Albian facies trends intersect the mountain front near the Sagavanirktok River. Where the mountain front begins to change to its northeasterly trend, the Fortress Mountain and Nanushuk facies maintain their generally east-west trend. In the Chandler River area of the central Endicott Mountains, coarse Fortress Mountain conglomerates are 20 to 25 km north of the mountain front, but at Atigun syncline, they are at the eastern Endicott Mountain front. Similarly, in the Chandler River area, Nanushuk facies are more than 40 km north of the front, but at Marmot syncline north of the eastern Endicott Mountains, similar facies are only 10 km north of the mountain front. The convergence of these trends is illustrated in figure 7.

In summary, regional structural trends suggest that the source of Nanushuk sediment was an upland area,

probably having a generally east-west trend that changed to a N. 70° E. trend in the eastern Brooks Range. The data of Huffman (1979), Bartsch-Winkler (1979), and Ahlbrandt and others (1979), and in this volume from the central Arctic Slope suggest a discrete delta lobe possibly related to one major drainage system. The highlands probably persisted eastward, but at some distance south of the mountain front that forms the salient of the present northeast Brooks Range. The eastern limit of this trend is unknown, but the thin and relatively fine grained Albian sediments in the Canning-Sadlerochit Rivers area suggest that Albian uplands lay some distance south of the present mountain front or had much less relief than to the west.

Provenance

The nature of the rocks forming the Herald arch beneath the Chukchi Sea is unknown. However, the Tigara uplift and the remainder of the Brooks Range have been mapped in fair detail. The nature of the allochthonous rocks that were the source terrain for at least part of the sediment in the Nanushuk of the western Arctic Slope (Mull, 1979, p. 10–12) is summarized below.

In general, the structurally low allochthons of the western Brooks Range are composed of Mississippian to Triassic sedimentary rocks, dominantly chert, limestone, and shale, some of which is silicified. Lower Cretaceous graywackes are present on most of the allochthons. The structurally higher allochthons contain more siliceous sediment and abundant mafic igneous rock; the highest allochthon is composed dominantly of gabbroic to ultramafic igneous rock (Roeder and Mull, 1978). The characteristics of the allochthons are summarized in figure 8; their generalized distribution is shown in figure 6. In general, the source terrain for the Nanushuk in the western Arctic Slope was deficient in stable detritus other than chert. This deficiency, and the relative abundance of mineralogically unstable detritus, is seen in the nature of the Nanushuk sediment deposited in the western or Corwin delta (Ahlbrandt and others, 1979; Huffman, 1979; and Bartsch-Winkler, 1979, p. 61–69, and this volume). This deltaic complex is characterized by a relatively low sand-shale ratio and by relatively clay-rich sands having low porosity and permeability.

In the Endicott Mountains to the east, the lowest allochthon, the Endicott Mountains allochthon, differs from the allochthons of the De Long Mountains by having a thick section of Upper Devonian quartzitic sandstone and conglomerate. Although the structurally higher allochthons are presently limited in the Endicott Mountains, there is an abundance of igneous clasts of various types in the Fortress Mountain Formation (Chapman and others, 1964, p. 353–356; Patton and Tailleux, 1964, p. 451–458). These clasts suggest that prior to the Late Creta-

ceous vertical uplift and erosion of the core of the range, allochthons similar to those of the western Brooks Range were also widespread in the central Brooks Range. The presence of the thick quartz-rich Upper Devonian sediments in the lower part of the source terrain in the Endicott Mountains is seen in the higher sand-to-shale ratio and better reservoir quality of the Nanushuk Group in the Umiat delta in contrast to the Corwin delta as discussed by Ahlbrandt and others (1979, p. 25), Bartsch-Winkler (1979; this volume), Fox (1979), and Huffman (1979; this volume).

East of the Sagavanirktok River, the belt of allochthonous rocks trends approximately N. 70° E., to near the head of the Sheenjek River. This trend is most obvious in areas in which the Upper Devonian Kanayut Conglomerate is in thrust contact over the Carboniferous Lisburne Group and younger rocks; it is less obvious in areas in which the allochthonous Lisburne is in regional thrust contact with the autochthonous part of the Lisburne. These thrust-fault relationships were mapped by Brosgé and Reiser (1965) and Brosgé and others (1979). Because of the apparent close relationship of the allochthons of the Endicott Mountains to the source terrain of the Nanushuk, it is likely that the trend of allochthons in the Philip Smith Mountains may approximate the trend of the sediment source for Albian rocks that have been stripped from most of the northeast Brooks Range.

Late Cretaceous and Tertiary Tectonics and Deposition

The record of Late Cretaceous and Tertiary tectonics and deposition in northern Alaska is confined predominantly to the eastern Brooks Range and Arctic Slope. A thick Upper Cretaceous and Tertiary sedimentary section is present, and evidence suggests that the northern salient of the eastern Brooks Range resulted from Late Cretaceous and Tertiary vertical uplift.

Tectonics and Dating of Orogeny

Late Cretaceous and younger uplift of the northeastern Brooks Range apparently involved the eastern end of the Colville basin, and included both the Lower Cretaceous orogenic deposits of its southern margin and the coeval stable platform deposits of its gentle north flank. Evidence for vertical uplift of the northeastern Brooks Range is:

1. Albian facies trends do not parallel the present northeastern Brooks Range mountain front east of the Sagavanirktok River. North of the Endicott Mountains, the trends are approximately parallel with the mountains, but near the Sagavanirktok River they converge with the

mountain front; this convergence of trends has been discussed previously.

2. The Late Cretaceous stratigraphy suggests Late Cretaceous uplift of part of the northeast Brooks Range. In the Juniper Creek-Kavik River area, several hundred feet of nonmarine sandstone, conglomerate, and interbedded shale has been mapped as the Tertiary Sagavanirktok Formation (Keller and others, 1961, p. 208, pl. 21); however, micropaleontological evidence indicates a Late Cretaceous age (H. R. Bergquist, *in* Keller and others, 1961, p. 208–209). This faunal evidence and close lithologic similarities suggest a more likely correlation with the lower part of the Upper Cretaceous Kogosukruk Tongue of the Prince Creek Formation of the Colville Group mapped by Brosgé and Whittington (1966, p. 563–570) in the Umiat area. Brosgé (1970, p. D6, fig. 1) and Pessel and others (1978b) also assigned these deposits in the Kavik River area to the Late Cretaceous. In the Umiat area the Kogosukruk interfingers with the underlying marine beds of the Schrader Bluff Formation of the Colville Group (Brosgé and Whittington, 1966, p. 570), but in the Kavik River area, the base of the beds here considered to be Kogosukruk Formation appear to be an erosional unconformity (Keller and others, 1961, p. 206–207). In addition, the Upper Cretaceous beds underlying the unconformity seem to contain more sandstone and conglomerate than coeval beds in the Umiat area. The increased thickness of Upper Cretaceous strata in the Sagavanirktok-Ivishak River area, indicated on isopach mapping by Pessel and others (1978b, 1978d), may also suggest Late Cretaceous uplift in the northern salient of the eastern Brooks Range.

3. The Neocomian pebble shale unit, the Kemik Sandstone Member of the Kongakut Formation, and the Upper Cretaceous Colville Group of nearly identical facies as the coeval sediments exposed elsewhere, are widespread in the valley between the Sadlerochit and Shublik Mountains and to the east. This distribution indicates that at least the Sadlerochit and Shublik Mountains area of the northeastern Brooks Range was not uplifted until the Tertiary.

4. The dominant structural style of the frontal Brooks Range east of the Sagavanirktok River is of vertical, basement-involved tectonics, in contrast to a style of dominantly compressional tectonics in the Endicott Mountains to the west. The Franklin, Romanzof, and British Mountains, which form the northern salient of the eastern Brooks Range, contain autochthonous Mississippian and younger rocks folded into a series of broad anticlinoria and synclinoria. Erosional breaching of the axes of the anticlinoria exposes extensive areas of metamorphic basement consisting of lower Paleozoic low-grade meta-sedimentary rocks, metavolcanic rocks, and a pre-Mississippian granitic body (Reiser and others, 1971, 1978; and Sable, 1977). In contrast, most of the Endicott and De

Long Mountains in the central and western Brooks Range consist of allochthonous Upper Devonian and younger unmetamorphosed rocks that have been telescoped many tens of kilometers relatively northward (Mull and Tailleir, 1977, p. B27–B29). These allochthons contain none of the metamorphic rocks of the type exposed in the northeastern Brooks Range. The contrasting structural styles are clearly illustrated in regional geologic maps by Grybeck and others (1977) and Beikman (1978). In the eastern Brooks Range, thrust sheets indicative of major crustal shortening are 75 km and more south of the mountain front. Although this evidence does not bear directly on the timing or sequence of tectonic events, it is indicative of a fundamental tectonic difference between the northeastern Brooks Range and the mountains to the west.

Arctic Slope Décollement

Much of the Cretaceous section beneath the northern foothills belt has been folded into a series of long, generally east-west-trending gentle synclines and sharp anticlines (Lathram, 1965; Beikman and Lathram, 1976). In general, fold amplitudes decrease from south to north and die out in an area of essentially homoclinal dip beneath the Arctic coastal plain.

In the southern part of the Nanushuk outcrop belt, south-dipping high-angle reverse faults or thrust faults cut the Nanushuk Group along some of the anticlinal axes. Many of the anticlines are breached through the Nanushuk into the underlying incompetent shale of the Torok Formation. The shale, which is commonly crumpled and contorted in contrast to the gently dipping overlying Nanushuk, generally forms poor exposures. The characteristic expression of these folds is illustrated in figure 7. To the north where fold amplitudes are less, the Nanushuk extends unbroken across the crests of the anticlines. This structural style has long been interpreted as detachment of the Nanushuk (Brosgé and Tailleir, 1971, p. 71), which has been deformed independently from the underlying strata. The inferred zone of Torok detachment has been confirmed by seismic data that show a relatively uniform southward dip of Jurassic and older strata beneath the anticlines and synclines of the foothills belt.

The décollement was probably an indirect result of the later stages of uplift and compression in the core of the Brooks Range. A minor gravitational component of movement of the Nanushuk Group and overlying beds northward may have contributed to the décollement. On the central and western Arctic Slope, deformation probably began during early Tertiary or latest Cretaceous time and waned during the Tertiary. No clear evidence of deformation contemporaneous with either the Nanushuk or with later Cretaceous deposition is known.

On the eastern Arctic Slope the décollement is probably younger than to the west, because, as discussed

above, the uplift of the northeastern Brooks Range is apparently younger than to the west. In the northern Arctic National Wildlife Refuge, the Marsh Creek anticline has beds as young as Miocene or Pliocene (Reiser and others, 1971), dipping as much as 30°. Similarity in structural style of this anticline to the foothills anticlines to the west suggests that much of the deformation of the Tertiary beds in the wildlife refuge may also be a décollement that does not involve underlying, more competent beds. Grantz and Mull (1978) referred to these folds as thrust folds.

Depositional Cycle

Regional compilations of geologic mapping of northern Alaska (Beikman and Lathram, 1976; Lathram, 1965) and the results of drilling in NPRA show that post-Nanushuk deposits in northern Alaska are confined to the coastal plain and northern foothills of the central and eastern Arctic Slope. No Upper Cretaceous or Tertiary rocks are known west of approximately long 157° W. In the Umiat area, Upper Cretaceous deposits are relatively thin; but to the east in the Sagavanirktok River area, the Upper Cretaceous section is more than 3 km thick (Pessel and others, 1978d). Tertiary rocks are even more restricted in distribution, and outcrops are found still farther east and north. Details of the Upper Cretaceous and Tertiary outcrop stratigraphy are given by Brosgé and Whittington (1966) and Keller and others (1961); generalized discussion and isopach maps including subsurface data are given by Pessel and others (1978a, b, c, d) and Brosgé and Tailleux (1970).

In general, the areal distribution of Upper Cretaceous and Tertiary rocks records a continuation of the eastward and northward progradation that occurred in the Early Cretaceous. However, in addition, there is evidence of a major sediment influx from the northeastern Brooks Range; this evidence has been discussed previously.

Late Tertiary and Holocene erosion has stripped some of the Upper Cretaceous and Tertiary deposits. However, the distribution of nonmarine facies in both the Upper Cretaceous and Tertiary suggests that these deposits may not have been deposited very far west and south of their present outcrop limits.

SUMMARY

The Cretaceous sedimentary rocks of Arctic Alaska can be divided into three discrete depositional cycles, here referred to as the Neocomian to Aptian, Albian to Cenomanian, and Late Cretaceous cycles. These cycles coincide very closely with the global eustatic cycles of Vail and others (1977).

The Nanushuk Group of the Arctic Slope is a major deltaic complex at the top of the Albian to Cenomanian cycle. It is derived from erosion of an orogenic belt in

the central and western Brooks Range. On the western Arctic Slope, a major source of sediment from the west is evident; this terrain probably coincided with the Tigara uplift and its offshore extension, the Herald arch. Development of the Brooks Range orogenic belt began in Neocomian time with the obduction of oceanic crust over continental crust at a major compressional plate boundary at the south margin of a small continental plate that rotated counterclockwise out of the Canada basin. Major northward thrusting in the orogenic belt continued into the Aptian. A foredeep north of the orogenic belt, the Colville basin, was filled with thick flysch derived from erosion of the Brooks Range allochthons. The flysch grades upward into progressively shallower water Aptian and Albian prodelta shales, which culminate in the molasse deposits of the Albian and Cenomanian Nanushuk Group. From the Albian into the Late Cretaceous, sedimentary rocks filled the basin and progressively overlapped the Beaufort sill, which separates the Colville basin from the oceanic Canada basin to the north.

Erosion of the generally east-west-trending orogenic belt in the Brooks Range and filling of the Colville basin was accentuated by vertical uplift of the core of the range in Albian time. This vertical uplift became the dominant tectonic force, possibly due to isostatic rebound of the deeply depressed continental crust at the compressional plate margin. However, in the area of the eastern Arctic Slope, the rate of basin subsidence apparently exceeded the rate of sediment influx, so that deltaic deposits prograded only a short distance into the basin. As a result, flyschoid sediments correlative with the deltaic complex forming the Nanushuk Group to the west are present in this area. These basinal sediments are north of the Philip Smith Mountains, which are oblique to the trend of the Early Cretaceous orogenic belt and foredeep and were uplifted in the Late Cretaceous.

The reservoir potential of the Nanushuk Group is strongly influenced by the nature of its provenance, which contained abundant quartzose and quartzitic sediments in the central Brooks Range but was deficient in stable detritus to the west. As a result, the best reservoir potential is on the central Arctic Slope where these sediments prograded far to the north. In the subsurface to the east, where progradation of the delta was inhibited, the Nanushuk has no reservoir potential.

Continuing Late Cretaceous and Tertiary uplift in the Brooks Range resulted in a regional décollement on the Arctic Slope. The relatively competent Nanushuk Group was detached and folded independent of the Jurassic and older rocks. The structural style resulting from this décollement consists of broad synclines and sharp shale-cored anticlines which die out in amplitude to the north.

In the southern part of the décollement belt, the anticlines are breached through the Nanushuk into the un-

derlying Torok Shale, so that there is little potential for hydrocarbons in the Nanushuk. The northern part of the décollement belt, where the Nanushuk has not been breached, contains structural and mixed structural-stratigraphic hydrocarbon prospects.

To the north of the décollement, hydrocarbon prospects are probably dominantly stratigraphic in combination with regional dip. A discussion of the organic geochemistry of the Nanushuk Group and its control on hydrocarbon potential was given by Magoon and Claypool (1979).

Subsurface Correlations and Depositional History of the Nanushuk Group and Related Strata, North Slope, Alaska

By C. M. Molenaar

INTRODUCTION

The Nanushuk Group of Albian to Cenomanian Age (mid-Cretaceous) is present in the subsurface in the western and central Arctic Slope from the northern foothills to the Arctic coast. Except for a narrow band in front of the outcrop belt that extends as far east as the Sagavanirktok River, most of the Nanushuk in the subsurface extends only a little farther east than the north-trending course of the Colville River. Because most of the subsurface Nanushuk occurrence is in the northern two-thirds of the National Petroleum Reserve in Alaska (NPRA), most of the areal descriptions used here relate to NPRA (fig. 17).

This chapter: (1) presents a regional stratigraphic synthesis of the Nanushuk Group and related strata by means of facies-correlated stratigraphic cross sections, (2) presents quantitative data on the basin geometry and basin paleobathymetry, and (3) relates the depositional history to the development of potential hydrocarbon reservoir facies.

The Torok Formation of Albian Age, which underlies and is largely coeval with the Nanushuk, is included in this study in order to better understand the Nanushuk depositional system.

Subsurface information was provided by more than 60 wells and core holes that penetrate the Nanushuk in and adjacent to NPRA. Forty-eight of these wells, as well as selected outcrop sections, are shown in figure 17 and are listed in tables 3 and 4. Eighteen of the wells have been drilled since 1975 and have modern log suites for more detailed evaluation. In addition, about 10,000 line-kilometers of six-fold common-depth-point seismic data acquired since 1974 cover most of the area in a 10- to 20-km grid. (The seismic surveys were made in conjunction with the NPRA exploration program, and the data are available from the National Oceanic and Atmospheric Administration, EDIS/NGSCD, 325 Broadway, Boulder, CO 80303). Integrating the seismic data with the well data, plus the lack of structural deformation in the area north of the foothills, provide an excellent means to study the Nanushuk-Torok depositional system.

Nanushuk outcrops have been studied by many workers over the years. Some of the more definitive works are Gryc and others (1956); Chapman and Sable (1960); Detterman and others (1963); Chapman and others (1964); Patton and Tailleux (1964); Brosgé and Whittington (1966); Ahlbrandt and others (1979); and Huffman and others (this volume). Much of these works were used in extrapolating depositional environments and styles to the subsurface. Subsurface studies by Collins and Robinson (1967) were also used in the well correlations. However, additional wells and modern seismic data have greatly enhanced the understanding of subsurface relations.

Bird and Andrews (1979) explained and presented data on the subsurface stratigraphic relationships of the Nanushuk Group and the Torok Formation; how the alluvial-deltaic and shallow marine shelf deposits of the Nanushuk are laterally equivalent to and underlain by outer shelf topsets, slope foresets, and basinal bottomsets of the Torok; and how the Nanushuk delta prograded generally from west-southwest to east-northeast across the subsiding Colville basin. This chapter describes the continuation of these subsurface studies.

EXPLANATION OF STRATIGRAPHIC CROSS SECTIONS

A network of five stratigraphic cross sections of the Nanushuk Group and related strata, correlating most of the wells in and adjacent to NPRA, is shown in figure 18. Seismic data, well data, and surface stratigraphic studies have been integrated in the construction of these sections. The sections (1) show the facies relationships and correlations between wells, (2) show how the facies are time-transgressive and how they rise stratigraphically as the deltaic sequence progrades over a subsiding basin, and (3) show zones or trends of thicker sand development. Also, these cross sections can be used to (1) correlate data from new wells, and (2) make additional observations or interpretations.

The entire Torok Formation and the basal Lower Cretaceous transgressive pebble shale unit are included on

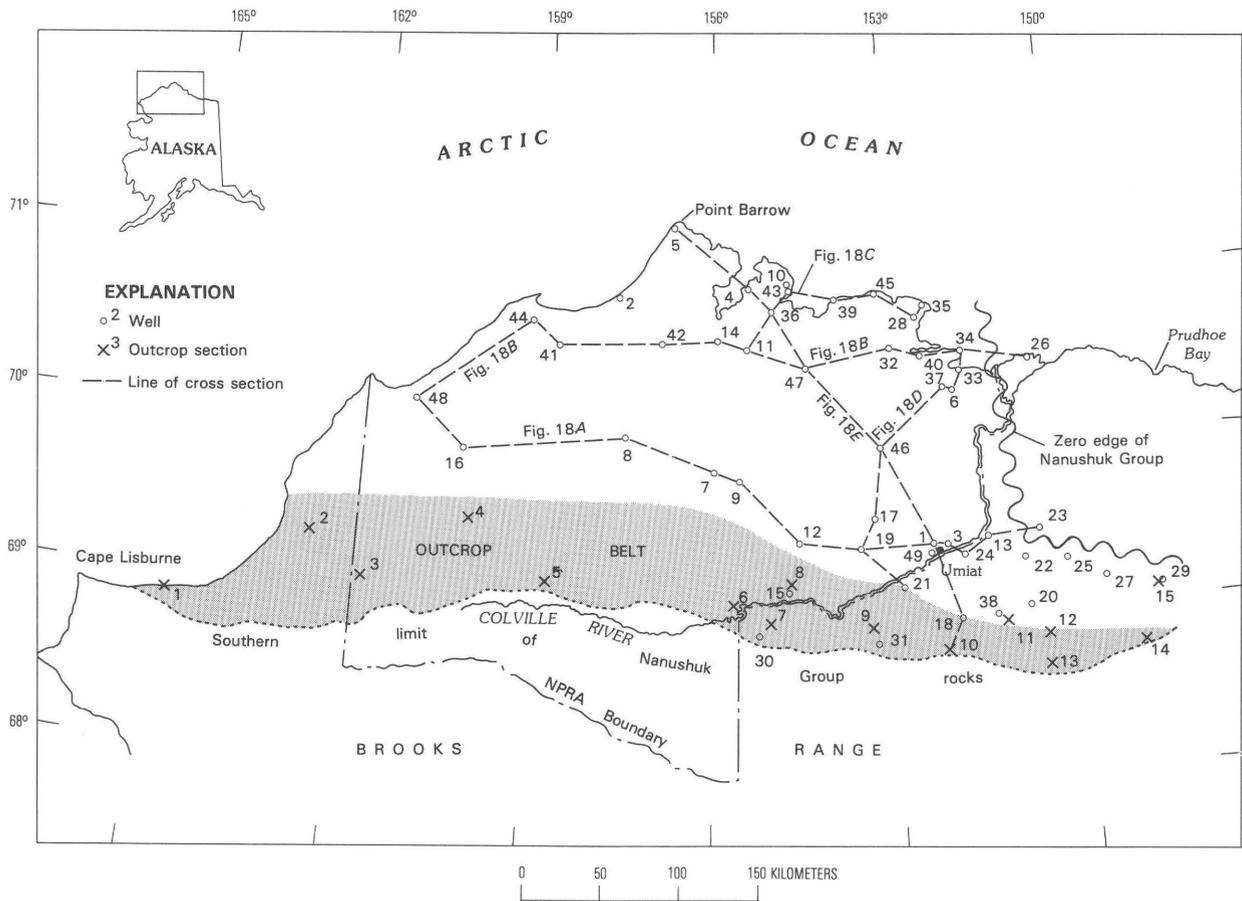


Figure 17. Index map of part of the North Slope of Alaska showing selected Nanushuk Group control points (wells and outcrops), eastern extent of Nanushuk Group, lines of stratigraphic cross sections, and boundary of the National Petroleum Reserve in Alaska (NPRA). Refer to tables 3 and 4 for listing of wells and outcrop sections. Shaded area is Nanushuk Group outcrop belt.

the cross sections in order to show the gross stratigraphic relationships of these units to the Nanushuk. These units are clearly shown by seismic data, which depict the depositional pattern of topset bedding (alluvial-delta plain and shallow marine shelf), foreset bedding (basin slope), and bottomset bedding (basin floor). (The terms "topset," "foreset," and "bottomset" refer to the large geomorphic forms of the basin-edge profile and not to parts of an individual delta front such as a Gilbert-type delta.) Figures 19 and 20 are examples of these relationships as displayed by seismic data. The relationships of the Nanushuk with the overlying Colville Group, where it is present, are also shown on the cross sections.

Correlating between wells on the cross sections was greatly aided by seismic data. Where possible, the individual wells were correlated to the nearest seismic line by using either synthetic seismograms or transit-time logs. Topset reflector beds were then correlated between wells, where possible. This method worked fairly well in north-eastern NPRA (north and east of the East Topagoruk and Inigok wells), the area covered by 1974 seismic lines. However, seismic data are of inferior quality on the 1975,

1976, and 1977 lines, which cover the other areas. This reduction in quality is reportedly because the geophone placement along these lines did not optimize the relatively shallow reflections from the Nanushuk-Torok interval. Additional processing may enhance the shallow data from these lines. Despite these lower quality data, however, gross correlations can usually be made by projecting a weak or nonexistent seismic reflection between more pronounced reflections. Also, the base of the topset reflectors (or shelf break) can be identified on these lines and hence related to nearby wells. However, in the northern foothills area where most of the old U.S. Navy wells were drilled, structural complications generally precluded correlating those wells to seismic lines.

The base of the Colville Group is used as a horizontal datum in the eastern part of the area where this unit is preserved. This surface was a very low gradient shelf or delta plain prior to the transgression of the Colville sea except possibly in the southernmost area where clastic material derived from the ancestral Brooks Range continued to build an aggradational coastal plain while the area to the north was being transgressed.

Table 3. Location of wells shown in figure 17, and stratigraphic data on Nanushuk Group, North Slope, Alaska

[?, data not resolved; ±, approximate top of section; +, eroded top of Nanushuk Group, incomplete section]

Locality No. (fig. 1)	Well name	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 ¹ 65	1 ¹ 355
2	USN Skull Cliff C.T.-1--	23	18 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.	16 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-----	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.				
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

¹Fault repetition of 760 ft (232 m) has been removed.

²Base of Nanushuk Group not reached.

The two outcrop sections (fig. 18D and 18E) were correlated to subsurface data by correlating the marine deposits at the base of the Ninuluk Formation, which actu-

ally represents initial deposits of the Colville transgression. The base of the Ninuluk is inferred to rise to the south, owing to intertonguing. The Killik River surface

Table 4. Location of outcrop sections of Nanushuk Group shown in figure 17, North Slope, Alaska

[+, incomplete section]

Locality No.	Outcrop name	Location		Nanushuk Group thickness (m)	Source
		T.	R.		
1	Corwin Bluff-----	6-7 S.	53-56 W.	4,723+	Chapman and Sable, 1960.
		6-7 S.	53-56 W.	3,444+	Smiley, 1969b.
2	Barabara 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+	Brosge and Whittington, 1966.
9	Killik River-----	5-6 S.	6-7 W.	1,361+	Detterman and others, 1963.
10	Mammoth Creek and Chandler River. Tuktuk Bluff-----	7-8 S.	1-2 W.	1,430	Detterman and others, 1963; Huffman and others, 1981b.
11	Type Grandstand----	6 S.	4 E.	1,842+	Huffman and others, 1981b.
12	Rooftop-----	7 S.	6-7 E.	812+	Do.
13	Nanushuk River-----	9 S.	6 E.	195+	Do.
				1,070+	Detterman and others, 1963.
14	Marmot syncline----	8 S.	13 E.	853+	Huffman and others, 1981b.
15	Lupine River-----	4 S.	14 E.	563+	Do.

section shown on the south-to-north cross section across eastern NPRA (fig. 18D) is generalized from the measured section of Detterman and others (1963, pls. 29, 32, and 33). The Tuktuk Bluff section shown on the southeast-to-northwest cross section across northeastern NPRA (fig. 18E) is a combination of a section by Detterman and others (1963) and one by Huffman and others (1981b). The thickness used here for the pre-Ninuluk part of the Nanushuk is the average of 1,180 m (3,870 ft) measured by the earlier workers and 1,842 m, plus approximately 394 m to the base of the Ninuluk (6,040+1,300 ft), measured by the later workers. This wide discrepancy in thickness is probably due to a different choice of dips (7-13°) in measuring across a long, flat area along the Chandler River.

The Grandstand-1 well, which was located at the surface near the top of the main marine part of the section (Grandstand Formation), was placed about 365 m (1,200 ft) below the Ninuluk datum as projected by Detterman and others (1963, pl. 37) (fig. 22). In areas where the top of the Nanushuk is not preserved, the vertical placement of the wells on the cross sections is related to a near-horizontal assumed time datum (topset bedding) near the base of the Nanushuk between adjacent wells. This datum can be either a thick marine shale tongue and shelf sandstone bed that may be correlated between wells, or a seismic reflector in the topset bedding. The correlations

of the lower part of the Nanushuk and upper part of the Torok between the South Meade and Topagoruk wells shown on the northern coastal plain cross section (fig. 18B) are the result of this technique. These units are assumed to have been deposited on a nearly horizontal or very gently sloping surface at approximately the same water depth, and that differential subsidence between wells was negligible. This assumption may not hold for the entire section because the different rates of subsidence between areas may be significant for thicker sections and more time. However, this method shows the overall time-stratigraphic relationships quite well.

In general, the horizontal correlation lines on the cross sections within the Nanushuk are considered near-horizontal time lines. The dashed correlation lines shown within the Torok correlate from topset to foreset to bottomset beds and are considered to be time lines.

Because the wells are logged in the inch-pound system of measurement, this system is used for the cross sections to facilitate comparisons with other well logs.

STRATIGRAPHY AND DEPOSITIONAL SETTING

Nanushuk Group

The Nanushuk Group is a deltaic sequence of complexly intertonguing marine and nonmarine deposits. It ranges in thickness from at least 3,444 m in outcrops at

Corwin Bluff (Smiley, 1969b) on the far southwest of the study area to a pinchout edge in the area of the present Colville River delta (fig. 21). The thickest subsurface penetration is about 1,900 m (top eroded) in the Tunalik-1 well on the west. As indicated by foreset dip directions in the Torok Formation on seismic sections, the deltaic sequence prograded east-northeast across the subsiding Colville basin (fig. 23; Bird and Andrews, 1979). The basin was bounded on the north by the passive Barrow arch, which separated it from the actual continental margin farther north. The ancestral Brooks Range bounded the south side of the Colville basin.

The term "delta" or "deltaic system" is used in a broad sense. The Nanushuk sediments in most of the area were supplied by many distributaries, and undoubtedly there were many interdeltic areas. The main or western delta complex, which has been called the Corwin delta, is considered to be a river-dominated, high-constructive delta (Ahlbrandt and others, 1979, p. 17). It had a relatively low-sand and high-mud content in contrast to the southern-source Umiat delta of the outcrop belt south of Umiat (Huffman and others, this volume).

The overall prograding regressive sequence was interrupted many times by marine transgressions due in part to delta shifting, but more importantly, to episodic pulses of basin subsidence. Basinal subsidence (or relative sea-level rise) is necessary to account for stacking of shallow marine sequences or for the stratigraphic rising of the section as the sequence progrades. (Refer to the section on "Stratigraphic Rise and Basin Subsidence.") Therefore, the Nanushuk is not one simple regressive sequence but a composite of intertonguing shallow marine shale, shallow marine sand, and subaerial delta-plain deposits.

In this chapter, the term "shoreface sandstone" refers to a sandstone body that separates open marine environments from lagoonal, marsh, back-bay, or nonmarine environments. These bodies would include barrier islands, tidal channels and deltas, strand-plain coastal barriers, and distributary-mouth bars. Distributary-mouth bars are probably the most common in the Nanushuk, especially in the western part of the area.

The lower part of the Nanushuk consists of intertonguing marine shoreface or shelf sandstones and neritic shales and siltstones. For convenience and uniformity, the contact with the underlying Torok Formation in the subsurface is usually placed at the base of the sandy section as determined by electric log or gamma ray-transit time log response. Because of the gradational and intertonguing nature of the contact and because of differing log qualities, the selection of the contact becomes quite arbitrary in some wells. An example of this arbitrariness is the selection of the contact at about 2,800 ft in the Umiat-1 well shown on the cross section across the northern foothills (fig. 18A). Actually, there are several thin sandstone beds with poor spontaneous-potential (SP) log response

for more than 1,000 ft below. Another example is the selection of the contact at about 2,150 ft in the Topagoruk-1 well shown on the cross section across the northern coastal plain (fig. 18B). There are three or four thin sandstone beds in the 1,200-ft interval below. One must be aware of these variations when evaluating isopach or sand-percentage maps.

Seismically, the base of the Nanushuk occurs within the lower part of the topset reflectors. The distance between the base of the topset beds and the base of the Nanushuk ranges anywhere from 15 m as in the W. T. Foran-1 well, to 335 m, as in the South Simpson-1 well. In some places the basal Nanushuk sands extend to the shelf break as at Fish Creek-1 and West Fish Creek-1 wells shown on the cross section across the eastern part of NPRA (fig. 18D), but generally the basal sand occurs well back from the shelf edge. Figures 19 and 20 show the relationship of the base of the Nanushuk to the base of the topsets.

On the cross sections, the Nanushuk Group is divided into a lower, dominantly marine facies (Kukpowruk Formation on the west or Grandstand and Tuktuk Formations on the east) and an upper dominantly nonmarine facies (Corwin Formation on the west or Chandler Formation on the east) to show the lateral relationships. These major facies are the basis for the differentiation of most of the formations of the group. Bird and Andrews (1979) referred to these parts as facies A (predominantly nonmarine) and facies B (predominantly marine). In the subsurface, the differentiation is based on log character, the presence or absence of marine fauna, and the presence or absence of coal or highly carbonaceous beds. In many places the boundary is transitional in a zone of intimate intertonguing of the two facies. In these transitional zones, the contact is usually placed at the top of the highest well-developed shoreface sandstone or the highest occurrence of marine fauna. In most wells, the selection of this contact is highly interpretive, especially in western NPRA where the Corwin delta was more river dominated.

Because of the complex intertonguing of the two major facies of the Nanushuk and the shales of the Torok, and because of the distance between wells, better than gross correlation of the major facies is difficult. Some of the correlations of individual sandstone or shale tongues are shown only where wells are relatively close together. Also, the small scale of the cross sections mitigates against showing these details.

The generalized time-stratigraphic relationships of the formational units of the Nanushuk Group that were described by Detterman (1956) from outcrops in the Colville River area southeast of NPRA and by Sable (1956) from outcrops on the west side of NPRA are portrayed on the cross sections. Two of the cross sections are tied to outcrop sections south of Umiat where some of these units were originally named. The outcrop sections are por-

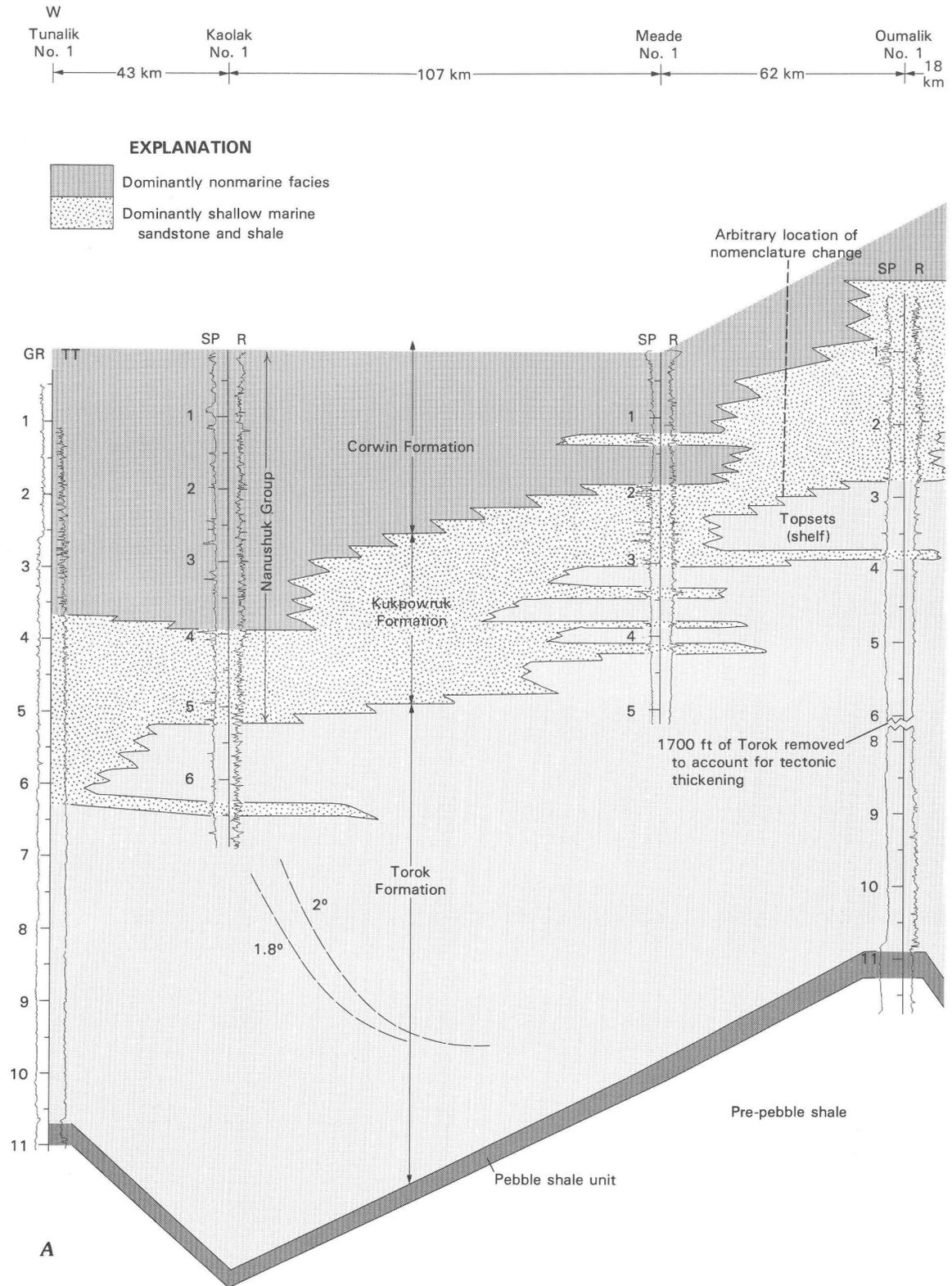


Figure 18. Stratigraphic cross sections of Nanushuk Group and associated strata across National Petroleum Reserve in Alaska and adjacent areas. See figure 17 for location of sections. Horizontal distance between wells or sections is indicated. Well depths are numbered at 1,000-ft intervals. Vertical exaggeration is approximately 58 ×. SP, spontaneous potential; R, resistivity; GR, gamma ray; TT, transit time. Dashed lines are correlations of miscellaneous beds or reflectors. Dip angle

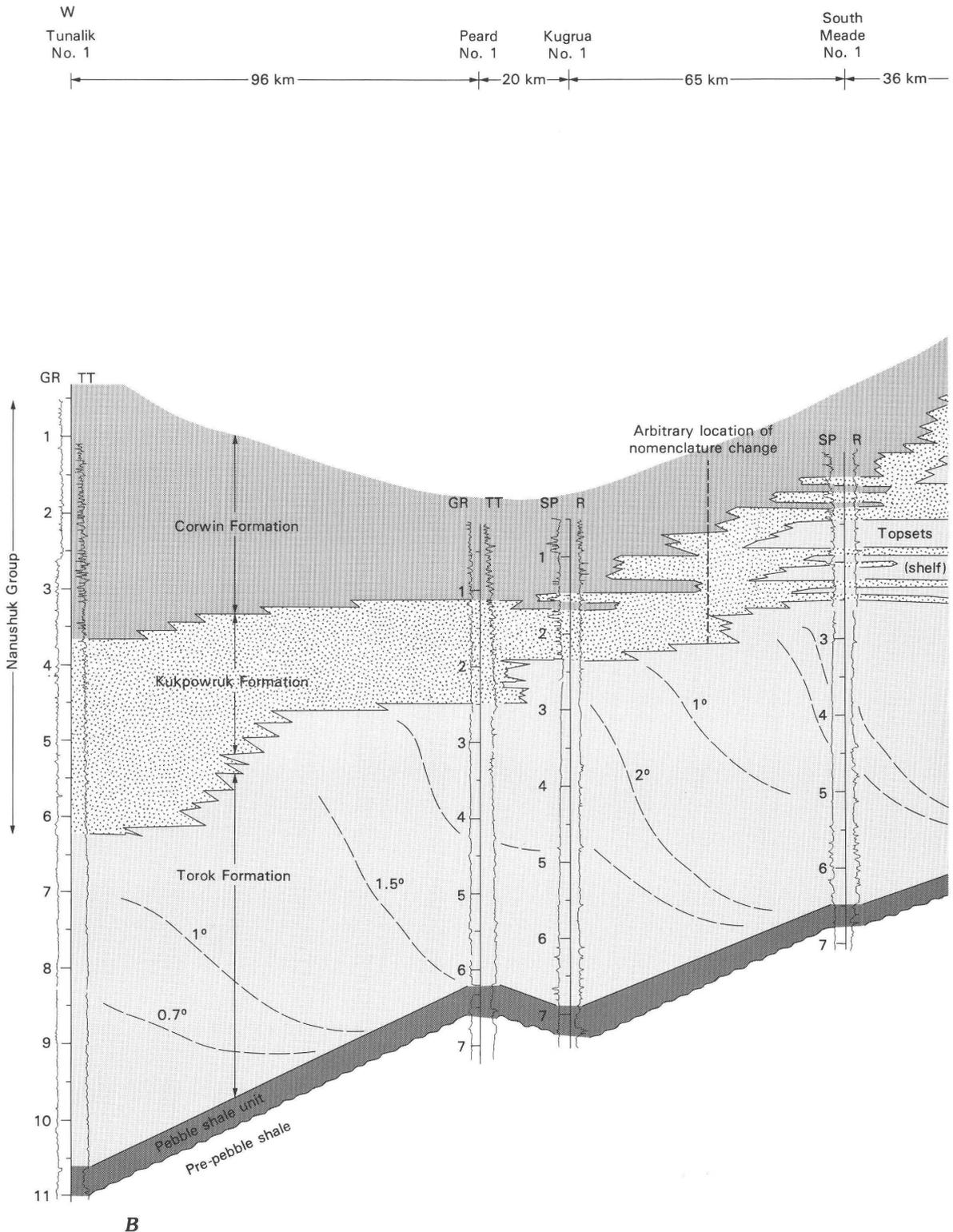


Figure 18. Continued

trayed in a generalized way to show the gross facies relationships.

The upper contact of the Nanushuk is an erosional surface underlying Pleistocene deposits in most of the area except for the eastern third of NPRA, where the Seabee

Formation (Cenomanian-Turonian) of the Colville Group overlies the Nanushuk (fig. 21). In the latter area, the top of the Nanushuk is placed at the base of a transgressive bentonitic shale section, which is usually easily identified on the logs. In some places, however, a basal trans-

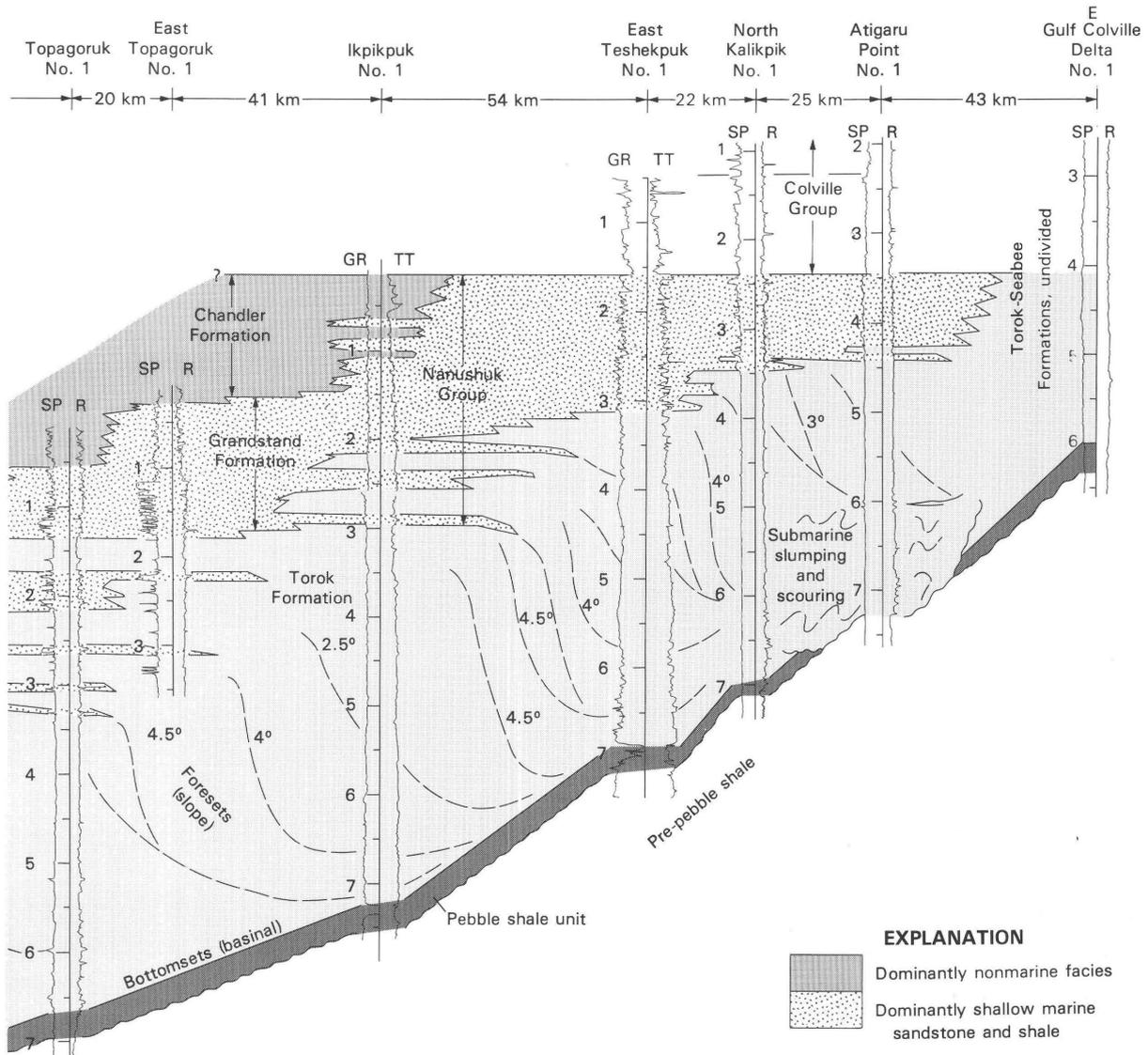


Figure 18. Continued

gressive sand or sandy zone occurs at the base of the Seabee Formation, thereby making the precise boundary selection somewhat interpretive; micropaleontologic data are helpful in selecting this boundary.

The Ninuluk Formation of Cenomanian Age occurs in the upper part of the Nanushuk Group in the outcrop belt in 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 nonmarine Niakogon Tongue of the Chandler Formation (of the Nanushuk Group) and is as thick as 350 m (Detterman and others, 1963, p. 264). As portrayed on the cross sections in the southeastern part of the area (fig. 18E), it is interpreted as representing 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 east-

northeasterly prograding delta to the north became inactive and was being transgressed by the Colville sea.

The facies relationships and the seismic data do not indicate an unconformity at the base of the Seabee Formation in the subsurface. The Ninuluk and Seabee appear to be parts of the same major cycle of transgression. However, in the outcrop belt to the south, earlier workers have reported a significant unconformity (Detterman, 1956, p. 233; Detterman and others, 1963, p. 270; Chapman and others, 1964, p. 382). Continuing tectonic activity in the ancestral Brooks Range could have resulted in an unconformity at that time along the outcrop belt. Brosgé and Whittington (1966, p. 527) suggested that warping in the folded belt could have started during Nanushuk time. This suggestion is supported by the apparent thickening of section within the Aiyak Mesa syncline 50 km south of Umiat, as indicated on an old, poor-quality U.S. Navy

seismic line in that area (Detterman and others, 1963, pl. 42).

Torok Formation

The Torok Formation represents offshore or deeper water deposition of shale, siltstone, and minor amounts of sandstone. It is largely coeval with the Nanushuk Group in the northern half of the area, but to the south the lower part thickens and intertongues with or is equivalent to the Fortress Mountain Formation of early Albian age (Chapman and others, 1964, p. 357). The lower Torok in that area appears to be older than any part of the Nanushuk Group.

The thickness of the Torok is largely controlled by the asymmetry of the preserved part of the Colville basin, especially to the south, as shown in figure 22. This isopach map was constructed by using the widely scattered well data, and where a well did not completely penetrate the Torok, seismic data were used (Miller and others, 1981). In the anticlinal belt of the northern foothills, the Torok has been thickened tectonically by thrust faulting and possible diapirism in the cores of the anticlines. An attempt was made to adjust for this thickening in the cross sections and the isopach map by subtracting the amount of structural relief of each anticline from the present Torok thickness (fig. 22).

The Torok interval is represented on seismic lines by the lower part of the topset reflectors and the foreset and bottomset reflectors. The Torok in the topset beds consists of neritic shelf shales and siltstones; the foreset beds consist of slope shales and siltstones and minor sandstone beds; and the bottomset beds consist of deep-water shales containing common thin turbidites or deep-water sandstones and siltstones.

Well penetrations indicate that these deep-water sandstones are generally very fine grained, as would be expected inasmuch as they were filtered through the Nanushuk delta where the coarser grained sands would have been deposited in the fluvial facies. A possible exception to this deltaic filtering would be if there were times of lowered sea level when fluvial deltaic facies extended to the shelf break. Wells recently drilled in the northern part of NPRA have had numerous gas shows from these deep-water sandstones. Torok foreset reflectors that can be correlated to wells seem to be either silty or sandy zones or thin zones of low-velocity shales. The sandy intervals could serve as paths for hydrocarbons migrating from source rocks within either the Neocomian pebble shale unit or the lower Torok interval to reservoirs in the Nanushuk.

On some seismic lines, reflectors can be traced continuously from topset beds within the Nanushuk to bottomset beds within the Torok deep-water deposits. These reflectors, which are represented by short dashed lines on

the cross sections, are time lines and represent the near-original depositional profile of the basin.

In the northern part of NPRA where the seismic data are of good quality, bottomset beds downlap (Mitchum, 1977, p. 207) onto or near the basal Cretaceous pebble shale unit of Neocomian Age as shown on three of the northern cross sections (fig. 18). Because these bottomset beds can be correlated seismically to beds of Albian Age, the hiatus or thin interval of Torok between these downlapping beds and the pebble shale unit is interpreted to be 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 of the seismic data, that is, less than 25 m. Indeed, this condensed section may be included in the upper part of the pebble shale unit. This starved depositional system is interpreted to have occurred as a result of the deeper part of the Colville basin to the south receiving all the sediments being derived from the south and southwest after deposition of at least most of the pebble shale unit. Not until the latest stages of the Nanushuk-Torok depositional cycle did the Colville basin fill enough for sediments to reach the northern part of NPRA. A similar depositional pattern continues to the northeast of the Nanushuk depositional limit in younger Cretaceous and Tertiary formations. On seismic lines in northeastern NPRA, topset, foreset, and bottomset bedding can be seen in the overlying shales of the Colville Group (figs. 19 and 20). In the Prudhoe Bay area, bottomset beds of the Colville Group downlap onto or near the pebble shale unit (Bird and Andrews, 1979, p. 35).

In the southern part of NPRA (south of a line connecting the Inigok and Tunalik wells, fig. 17), seismic data indicate a southward-thickening wedge of strata that onlap the south-dipping pebble shale unit as shown on the two cross sections in the southeastern part of NPRA (fig. 18D and E). Some of these beds can be traced to east-northeasterly dipping foresets on the west, but the lower part of this wedge may be deep-water basinal beds or distal turbidites of southerly derived Torok and (or) Fortress Mountain Formation equivalents. Structural complexities and poor data quality preclude tracing these beds to the south.

In northeastern NPRA, in the area from the Fish Creek wells to beyond Atigaru Point, the lower Torok interval is disturbed, as indicated by seismic data (fig. 20). 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 either that it was involved in the slumping, or that it was scoured by submarine currents that may have triggered the subsequent slumping. The areal association of the

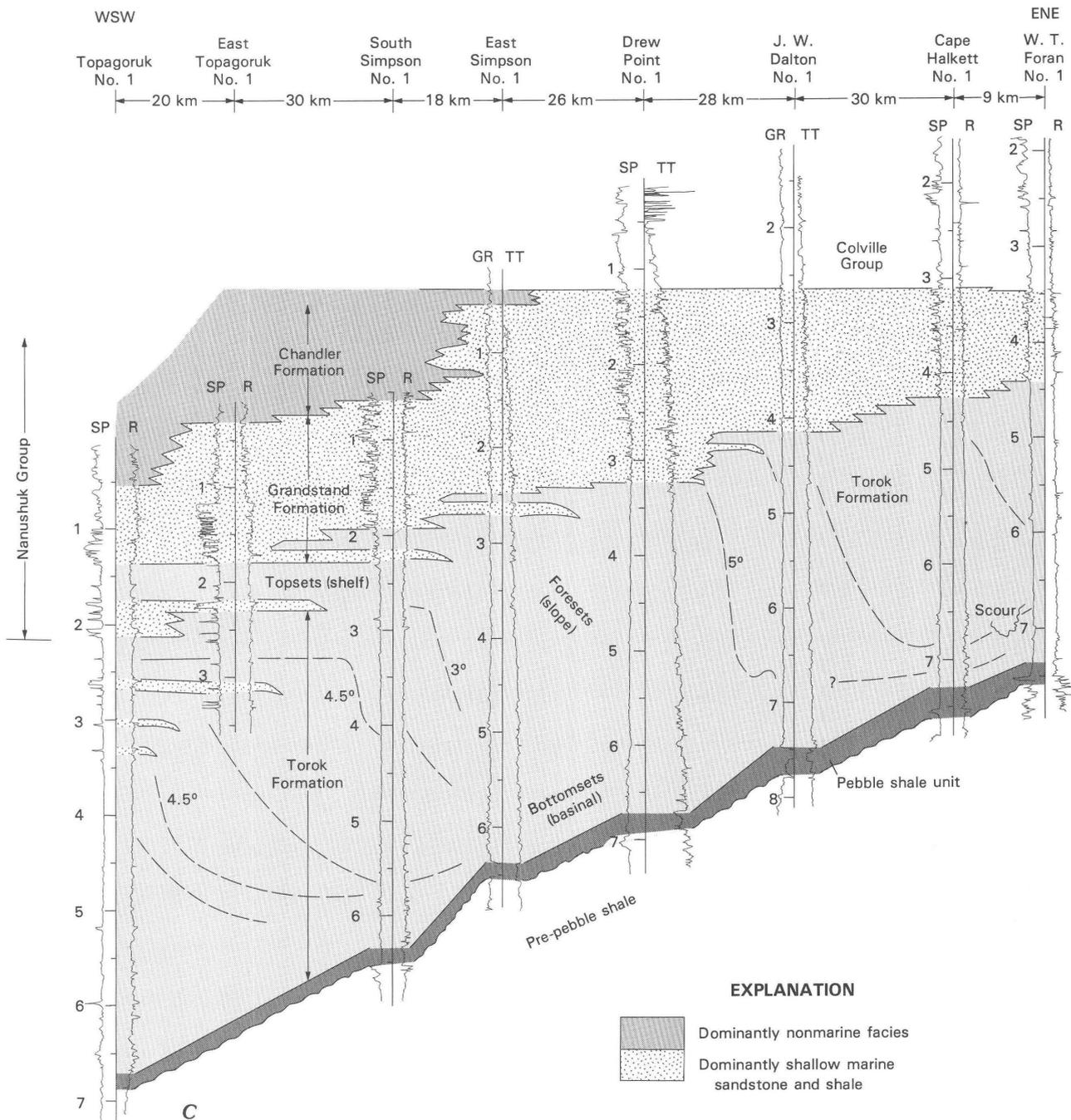


Figure 18. Continued

slumping and scouring suggests that they were caused by related events.

Provenances—Their Effect On Depositional Patterns

The provenance for the Nanushuk Group has been discussed and summarized by Mull (1979, p. 10–12), Bartsch-Winkler (1979, p. 67), and Huffman (1979, p. 84). Based on the interpretation of regional paleogeog-

raphy and compositional differences in the Nanushuk sandstones, all these workers agree that the western De Long Mountains, the adjacent Tigara uplift south of Cape Lisburne, and its northwestern offshore extension, the Herald arch (fig. 31), was a dominant source area for the western or Corwin delta complex, and that the ancestral Brooks Range on the south was a predominant source area for the Umiat delta. I am in general agreement with these interpretations, but I offer additional comments about the relative size or extent of these two major source areas.

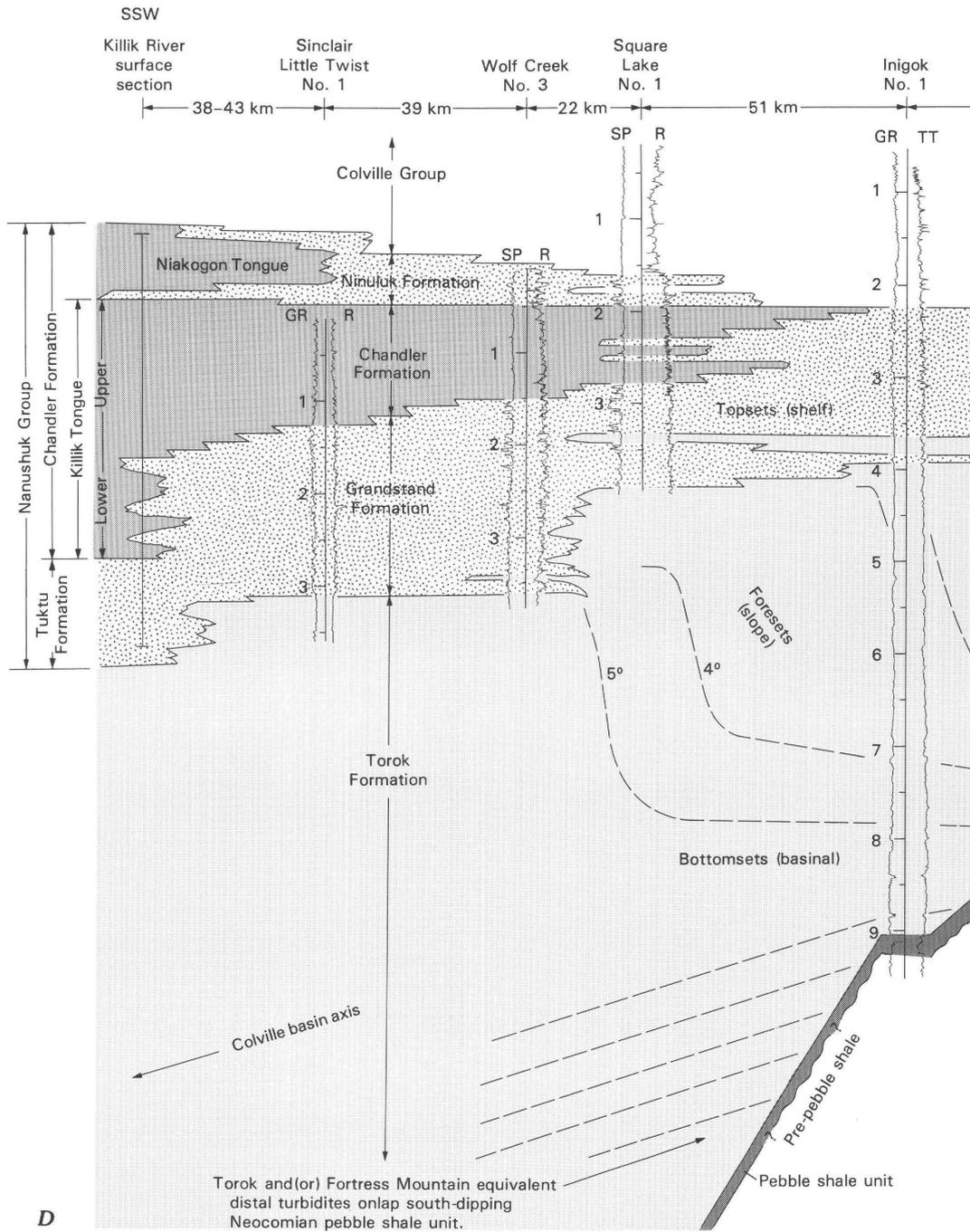


Figure 18. Continued

Except for some coarse units such as the conglomerate member at Corwin Bluffs (Chapman and Sable, 1960), which must have been derived from a nearby source such as the Tigara uplift, most of the Nanushuk in the western area had a relatively low-sand and high-mud content (Ahlbrandt and others, 1979, p. 25). This mud-rich delta system controlled the east-northeasterly direction of progradation across the Colville basin, as indicated by foreset dip directions in the prodeltaic Torok Formation (fig. 23).

The huge volume of mud-rich sediments represented by this western delta complex suggests that a relatively large source area encompassing a large drainage area was present to the southwest, undoubtedly much more extensive than the western De Long Mountains, Tigara uplift, and Herald arch as they were defined by Mull (1979, fig. 3), and Grantz and Eittrheim (1979, fig. 3). Furthermore, the Herald fault zone, which bounds the northeast side of the Herald arch, is considered, at least in part, a post-

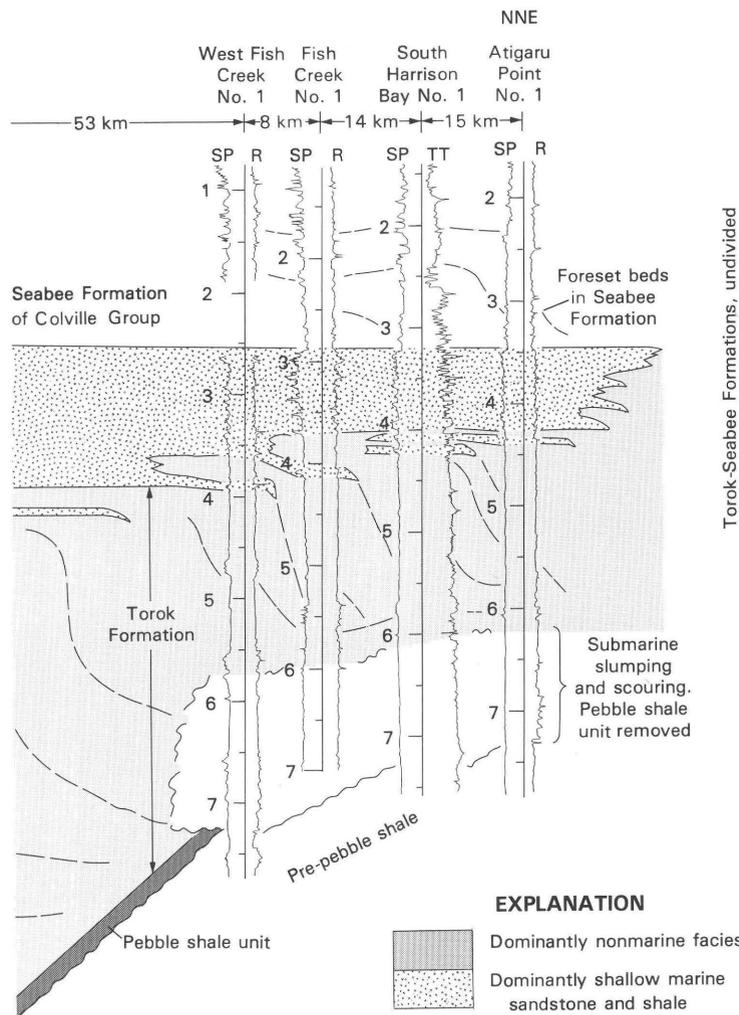


Figure 18. Continued

Nanushuk feature because it offsets Nanushuk Group strata (Grantz and Eitrem, 1979, p. 26). Therefore, I suggest that during Nanushuk time a land mass of larger areal extent lay farther west or southwest than the present Tigara uplift and Herald arch, probably in the area of the present Hope basin farther southwest in the Chukchi Sea or beyond.

The ancestral Brooks Range was undoubtedly a prominent highland that contributed sediments both to the Colville basin on the north and to the Koyukuk basin on the south during Nanushuk time. However, because of a limited drainage area and because of more rapid subsidence on the south side of the Colville basin, the southern source deltas did not control the progradational pattern of the Nanushuk except along the south side of the basin in the area of the present outcrop belt. However, the sands from this delta probably contributed significantly to the east-northeasterly prograding system when the prodelta shelf of the western delta had built out adjacent to the southern deltas. (Refer to the section on "Hydrocarbon

Reservoir Sand Development" for additional comments.) If it were not for the presence of the easterly prograding western delta, the southern-source Nanushuk would not have extended too far to the north. This contention is supported by observations southeast of Umiat and east of the pinchout of the easterly prograding system where well-developed southern-source alluvial-deltaic clastics such as those at the Marmot syncline outcrop section (the southeasternmost section with the 853+ value, fig. 21) grade rapidly into finer clastics of the Torok. The Nanushuk at this section, which is more than 850 m thick, 800 m of which is nonmarine and contains coarse clastics (Huffman and others, 1981b), grades to Torok shales and siltstones within 60 km to the north as shown on the east in figure 21. Some of the 60 km may have been shortened by folding and thrusting, but even so, the gradation is abrupt when compared to that of the western delta complex. Inferred paleogeographic maps of a part of northern Alaska and adjacent areas at middle and late Nanushuk time are shown in figure 24.

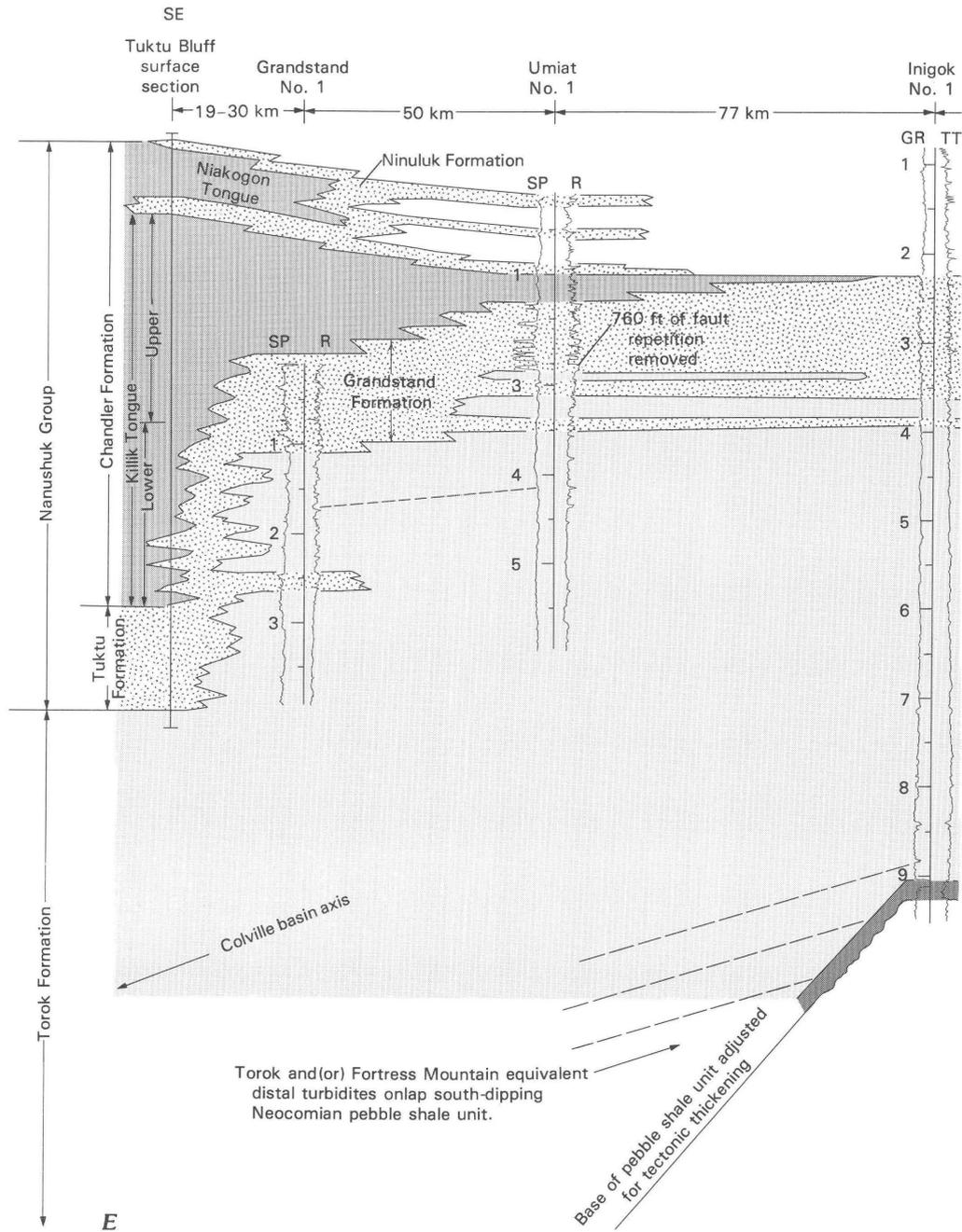


Figure 18. Continued

STRATIGRAPHIC RISE AND BASIN SUBSIDENCE

In prograding across the Colville basin, the shallow marine part of the Nanushuk, that is, the part between the basal contact and the marine-nonmarine boundary, becomes younger and shifts upward in the section owing to facies changes. Because these shallow marine facies are largely confined to a rather narrow range of water depths, possibly no more than 50 m and probably much less, these upward shifts or rises are then a measure of relative sea-level rise (or basin subsidence). The term

“stratigraphic rise” is used to denote these upward stratigraphic shifts of water-depth-related deposits.

Stratigraphic rises are directly observable on seismic lines. The change from topset beds to foreset beds represents the shelf break, a geomorphic feature separating the basin shelf from the basin slope. As indicated on seismic lines, this break is abrupt, especially in the eastern half of NPRA (figs. 19 and 20). There are several interpretations of the origin of shelf breaks, and discussion of them is beyond the scope of this report, but most hypotheses relate the shelf breaks to water depth. The breaks are assumed herein to be water-depth controlled, possibly deter-

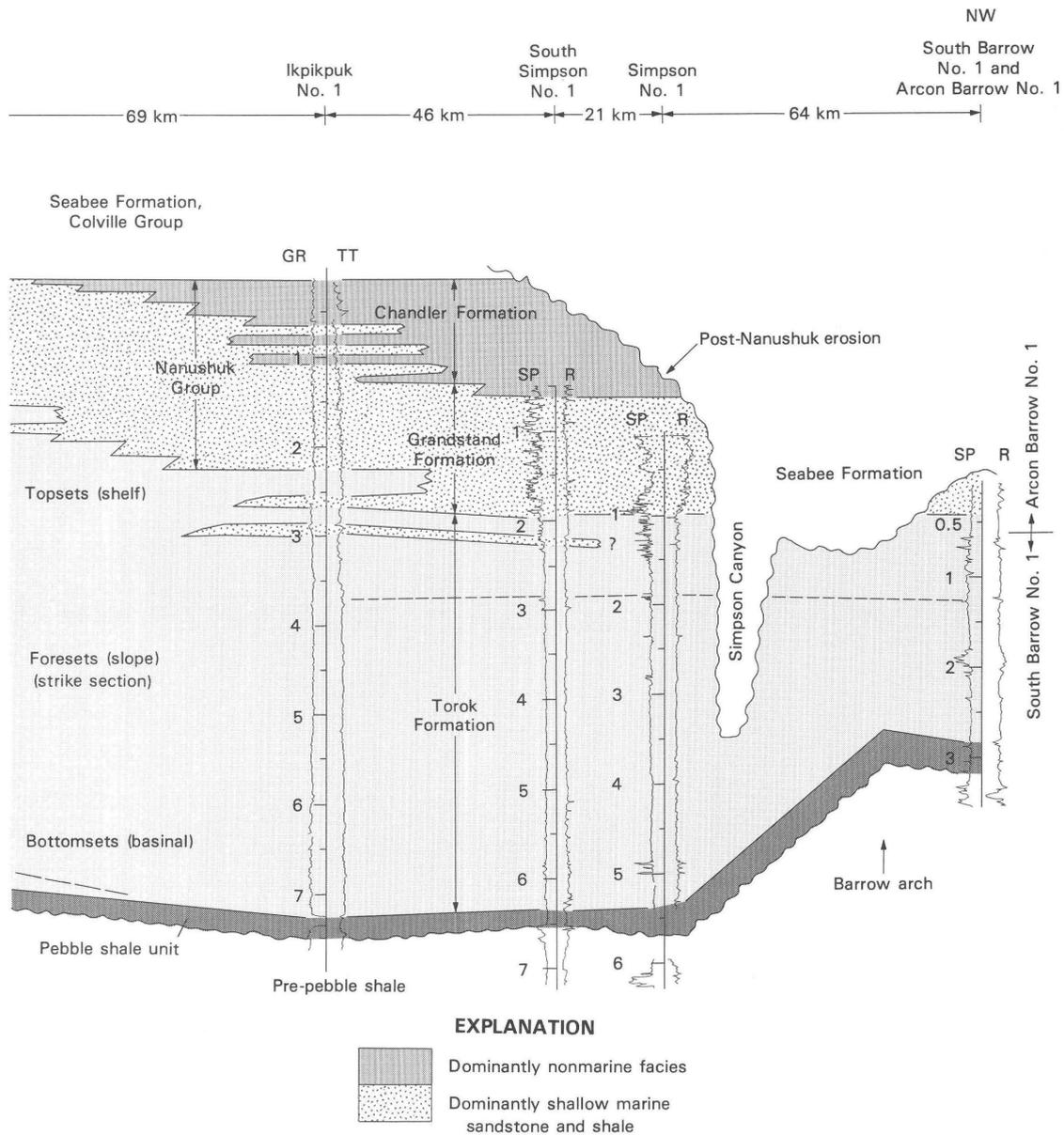


Figure 18. Continued

mined by tidal or other marine currents on the shelf. Most modern shelf breaks are at an average water depth of 132 m (Shepard, 1963, p. 257). However, most of these features resulted from Pleistocene low stands of sea level (Emery, 1965, p. 1383). Therefore, the Nanushuk-Torok shelf breaks must have formed at much shallower depths than the 132-m average of present shelf breaks; a range of 50 to 75 m is suggested.

As the Nanushuk progrades and rises to the north-east, the shelf break (or base of the topset bedding) also rises upward in the section, as observed on seismic sections. Like the Nanushuk deltaic deposits, the shelf break appears to be predominantly a constructional feature in which the basin-slope deposits prograded seaward. Figure 19 shows that between shot points 49 and 29, a distance

of 8 km, the base of the topsets rises about 180 milliseconds (two-way time) or approximately 260 m (850 ft). The Nanushuk-Torok contact shows these vertical rises of the shelf break, although it would be offset toward land. An example of this landward offset is shown by the vertical rise of the base of the Nanushuk between the Peard-1 and Kugrua-1 wells on the northern coastal plain cross section (fig. 18B). The actual rise of the shelf break occurs about 8 km east of the Kugrua-1 well as indicated by seismic data (seismic line 26-76 between shot points 643 and 653). This location places the rise of the base of the Nanushuk about 10 km from the rise of the shelf break as projected across depositional strike.

The rise of the shelf break would be indicated in Nanushuk deposition either by vertically stacked shoreface

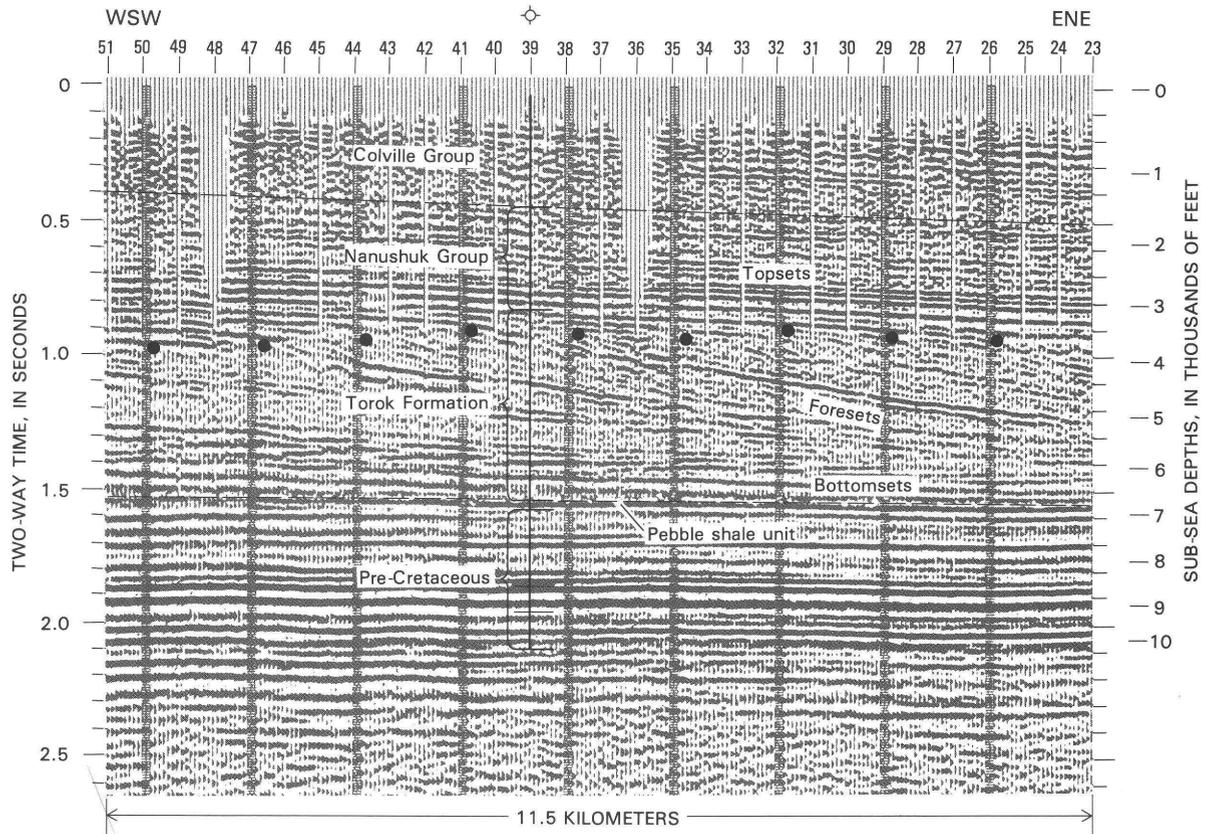


Figure 19. Seismic section in northeastern National Petroleum Reserve in Alaska showing relationships of topset bedding of Nanushuk Group and uppermost Torok Formation, foreset bedding of Torok, and bottomset bedding of lower Torok. Upper dashed line is Colville-Nanushuk contact, lower dashed line is Torok-pebble shale contact, and dots represent position of shelf break. Note stratigraphic rise of shelf break from west to east. See figure 17 and table 3 for location of East Teshekpuk well (32). Numbers across top of figure are shot-point numbers.

sandstones or, more likely, by minor transgressions and neritic shale deposition between prograding Nanushuk shoreface or shelf sandstones. The major stratigraphic rises may be correlatable basin-wide transgressive events. Smaller rises could be caused by the local effect of delta shifting, or by basin subsidence caused by isostatic loading of delta lobes.

In some areas, the shelf break remains at the same stratigraphic level, indicating that relative sea level must have been constant as the shelf break prograded seaward. A relative drop in sea level and a subsequent beveling of the top of the foreset beds could also cause this feature. As well as being detectable on seismic lines, the shelf break can also be noted on dipmeter logs of wells in northeastern NPRA by a 3–5° dip increase in the upper part of the Torok.

The total incremental stratigraphic rise of the base of the Nanushuk from the Tunalik-1 well on the west to the Atigaru Point-1 well on the east, a distance of

350 km, is about 2,100 m as shown on the northern coastal plain cross section (fig. 18B). The average rate of rise is about 6 m/km. A significant additional rise takes place between the Tunalik-1 well and the Corwin Bluff surface section 220 km to the southwest, but correlation from the outcrops to the subsurface in that area is too imprecise. However, Chapman and Sable (1960, p. 91–95), in an excellent photogeologic and surface study of a large part of the western outcrop belt between Corwin Bluff and the Kaolak well, determined the average rate of facies change (or stratigraphic rise) of the base of the Nanushuk to be 21 m/km in a N. 32° E. direction. This amounts to about 3,000 m of rise in their study area, a distance of about 145 km across depositional strike. This rate may be excessive, but it does help to explain the change from the 3,444+ m-thick Corwin Bluff section to thinner sections in the subsurface to the northeast. Also, the high rate of stratigraphic rise may indicate an increased rate of subsidence toward the south.

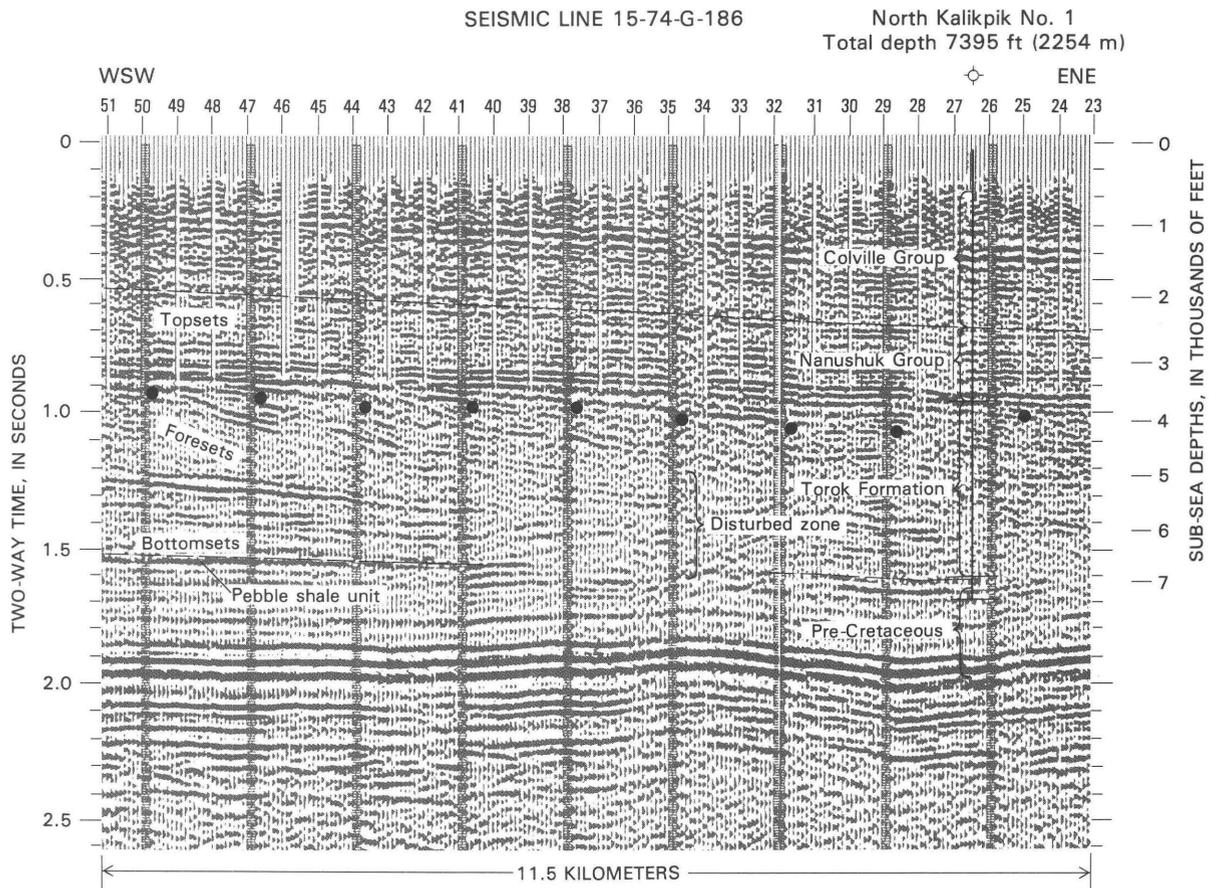


Figure 20. Seismic section in northeastern National Petroleum Reserve in Alaska showing disturbed zone in Torok Formation and discontinuity of the pebble-shale reflector. This disturbed zone and discontinuity is thought to be caused by submarine slumping and scouring. Upper dashed line is Colville-Nanushuk contact, lower dashed line is Torok-pebble shale contact, and dots represent position of shelf break. Note development of slope-foreset beds in lower Colville Group. Apparent structure in pre-pebble shale reflectors is due to seismic velocity of disturbed zone being greater than velocity of undisturbed adjacent sections. See figure 17 and table 3 for location of North Kalikpik well (40). Numbers across top of figure are shot-point numbers.

Further evidence for the increased rate of subsidence to the south is indicated by less and (or) later subsidence of the Barrow arch on the north side of the Colville basin. The Barrow arch was probably a passive high, but was never high enough to be subjected to erosion during Nanushuk time, as indicated by the presence of the distinctive pebble shale unit of Neocomian Age over the arch. (The absence of pebble shale in the area between the Fish Creek and Atigaru Point wells was caused by postdepositional submarine slumping or scouring, as previously explained.) The cross sections that extend to the north or northeast part of NPRA show the basal Torok Formation onlapping the pebble shale unit (fig. 18). This onlapping indicates that the northern side of the Colville basin subsided at a lower rate and (or) later time. A lower rate is indicated by the progressive southward depositional thickening of the Torok shown on the two cross sections in the southeastern part of NPRA (fig. 18D and E) as

opposed to the facies-controlled southwestward thickening of the Nanushuk (fig. 21).

An interesting pattern of depositional thinning of the Nanushuk in a landward direction (west or southwest) is indicated on many of the east-west-trending seismic lines in the northern part of NPRA. Several measurements of topset-bed convergence were made along line 26-74 from the Fish Creek area to the area near the Ikpikpuk-1 well and on line 26-76 from the area of the South Meade well to the western coast (fig. 17). Topset reflectors traced continuously for distances of from 8 to 60 km along these lines showed westward convergence ranging from 0.2 to 2.3 cm/km for each meter of thickness. This convergence may be explained by either compactional differences or actual differences in basement subsidence. Compactional differences may be caused by the delta front prograding over prodelta shales that were less compacted than adjacent, but older, prodelta shales to the west, thus allowing

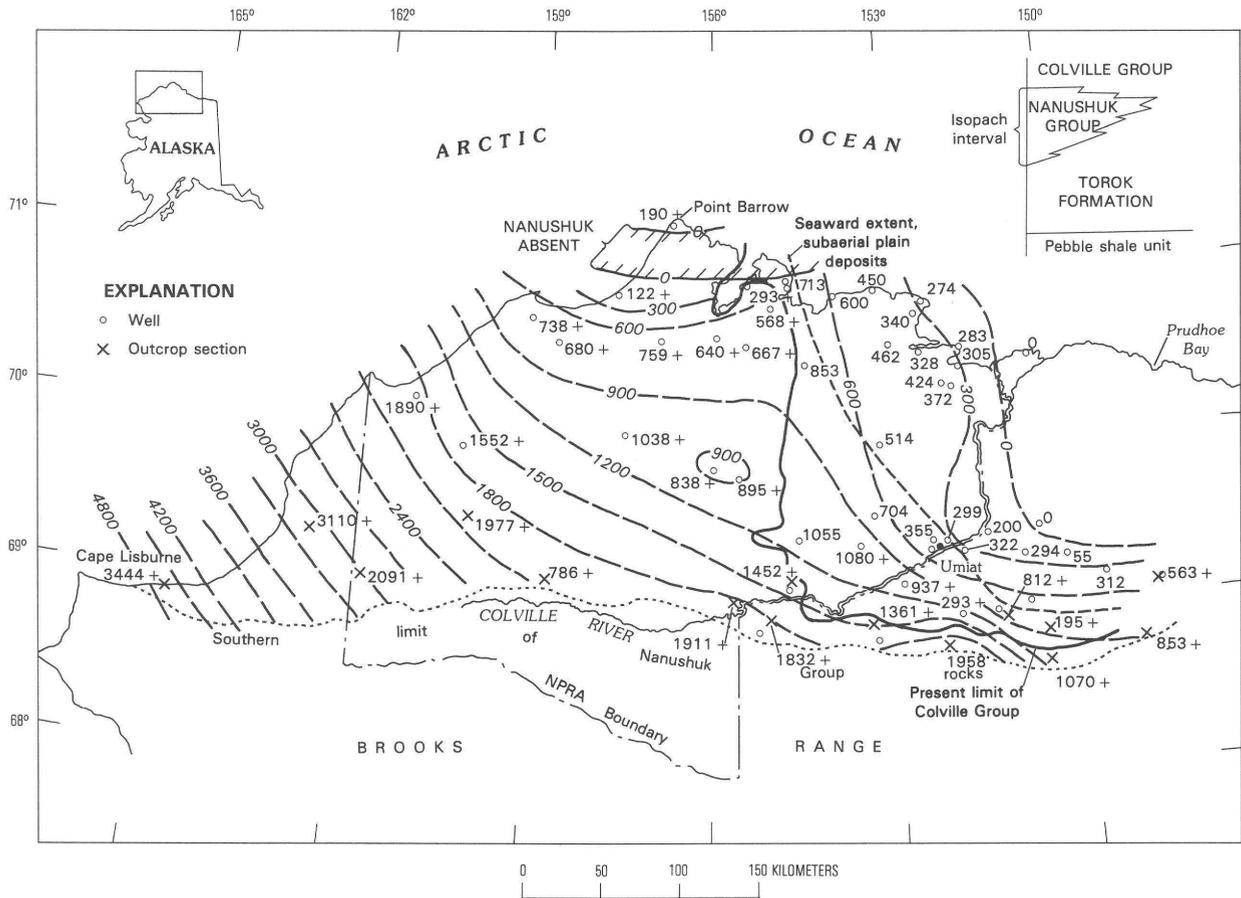


Figure 21. Isopach map of Nanushuk Group (modified from Bird and Andrews, 1979). Refer to both figure 17 and tables 3 and 4 for identification of control points. Numbers beside control points indicate thickness of Nanushuk Group; a + after number by well indicates minimal thickness owing to top of Nanushuk having been eroded. A + after number by an outcrop section indicates an incomplete section of Nanushuk.

a greater Nanushuk thickness to accumulate. Differences in basement subsidence, on the other hand, may be the result of deltaic loading in which slightly greater subsidence occurred in the delta-front area. In both explanations the locus of greater subsidence would migrate as the delta prograded.

SHORELINE TRENDS AND BASIN CONFIGURATION

Most of the Corwin delta and, to a lesser extent, the Umiat delta were river-dominated systems (Ahlbrandt and others, 1979, p. 17), and, as a result, the shorelines were probably moderately to extremely digitate, or in other words had a bird's-foot pattern. However, the overall shoreline trend of most of the basin throughout Nanushuk time was north-northwest or normal to the dip of the slope-foreset bedding of the Torok as indicated by seismic data and facies patterns from well data (figs. 21 and 23). East-dipping foresets can be seen on seismic lines as far as 8 km south of the Umiat and Wolf Creek wells (fig. 17). Immediately to the south of that area,

however, the shoreline trends abruptly change to east-west because of the effect of north-prograding deltaic systems from the ancestral Brooks Range (fig. 24). This east-west orientation is indicated in the outcrop belt south and southeast of the Colville River by north-directed fluvial channel trends (fig. 23; Huffman and others, this volume) and the long linear east-west trend of Tuktuk Bluff, which is made up of thick, stacked delta-front sands of the Tuktuk Formation.

Because the preserved part of the Colville basin was asymmetric with the greatest subsidence on the south, the north-prograding deltas from the ancestral Brooks Range probably had narrow delta or coastal plains and more abrupt facies changes. More deep-water sandstones might be expected in the Torok to the north in front of these active sediment sources. An example would be the 790-m-thick section of sandstone and shale in the Gilead Creek-Ivishak River area 65 km northeast of the Marmot syncline section (Keller and others, 1961, p. 204) that are thought to be deep-water equivalents of the Nanushuk (Huffman and others, this volume). The southern parts of the two cross sections that connect to outcrop sections

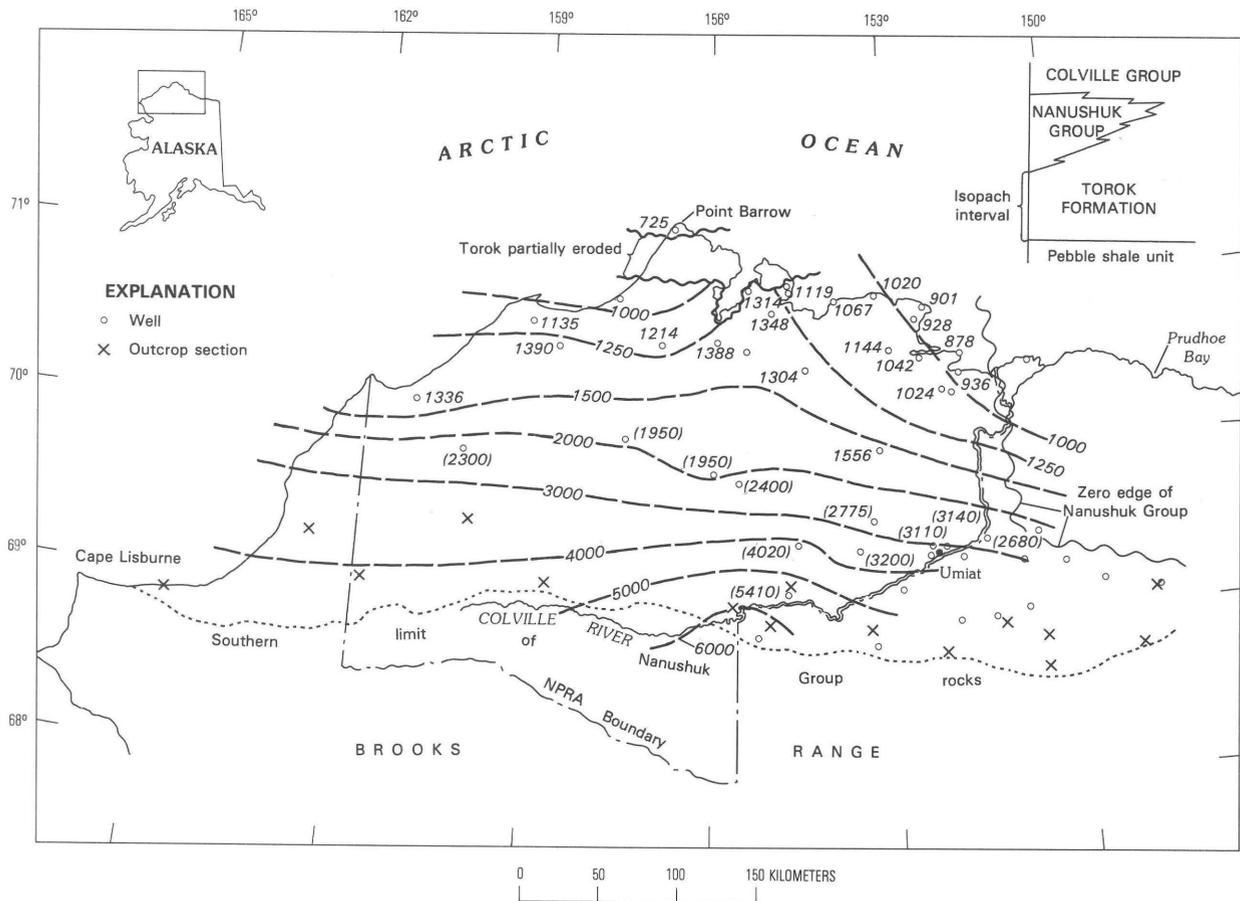


Figure 22. Isopach map of Torok Formation (modified from Bird and Andrews, 1979). Numbers beside wells indicate thickness of Torok Formation; thickness values in parentheses have been corrected (approximately) for tectonic thickening in thrust-faulted anticlines. Refer to both figure 17 and table 3 for identification of control points.

at Killik River and Tuktu Bluff, respectively (fig. 18D and E), show the inferred relationships of the southern-source Umiat delta and the areas to the north. These sections also demonstrate the southward thickening of basin fill during Early Cretaceous time.

In addition to the rapid facies change of the Tuktu Formation grading to Torok shale between the Tuktu Bluff section and the Grandstand-1 well, depositional thickening of the Nanushuk to the south similar to that noted in the underlying Torok Formation, probably has occurred. However, this thickening could not be verified by the poor-quality old U.S. Navy seismic line in that area.

Foreset bedding is better developed in the east or northeast parts of NPRA. In the western part, these features become more obscure and less numerous partly because of poor seismic data in the shallow Nanushuk-Torok interval. Some foreset bedding can be seen, however, as far west as the Tunalik-1 well and just east of the Kaolak-1 well where the foreset beds are at a much lower angle than the foresets to the east.

By measuring the time intervals on the seismic sec-

tion from top to base of foresets and applying proper velocities from nearby well data, calculations were made of the approximate foreset slope angle and the relief of the foresets, which approximate the depth of water (less compaction) at the time of deposition. The dip angles of the foreset beds are calculated relative to the topset beds, which are considered to have been almost flat at the time of deposition (probably less than 0.25° dip seaward). The calculated foreset dips range from less than 2° on the west to 4–6° on the east and northeast part of NPRA. These calculations were made on the steeper upper parts of the foresets averaged over at least 4 km of horizontal distance. The calculations are from unmigrated seismic data, but migrated data would not change the figures significantly. The relief of the foresets from top to base is 450–900 m. Allowing for compaction, the basin slope was slightly steeper than the indicated dip, and the water depth at the base of the slope was slightly greater than 450–900 m. Water depths probably increased to the south beyond the areas of interpretable seismic data.

No large canyons cutting the slope or foreset bedding have been observed or reported on any of the seismic

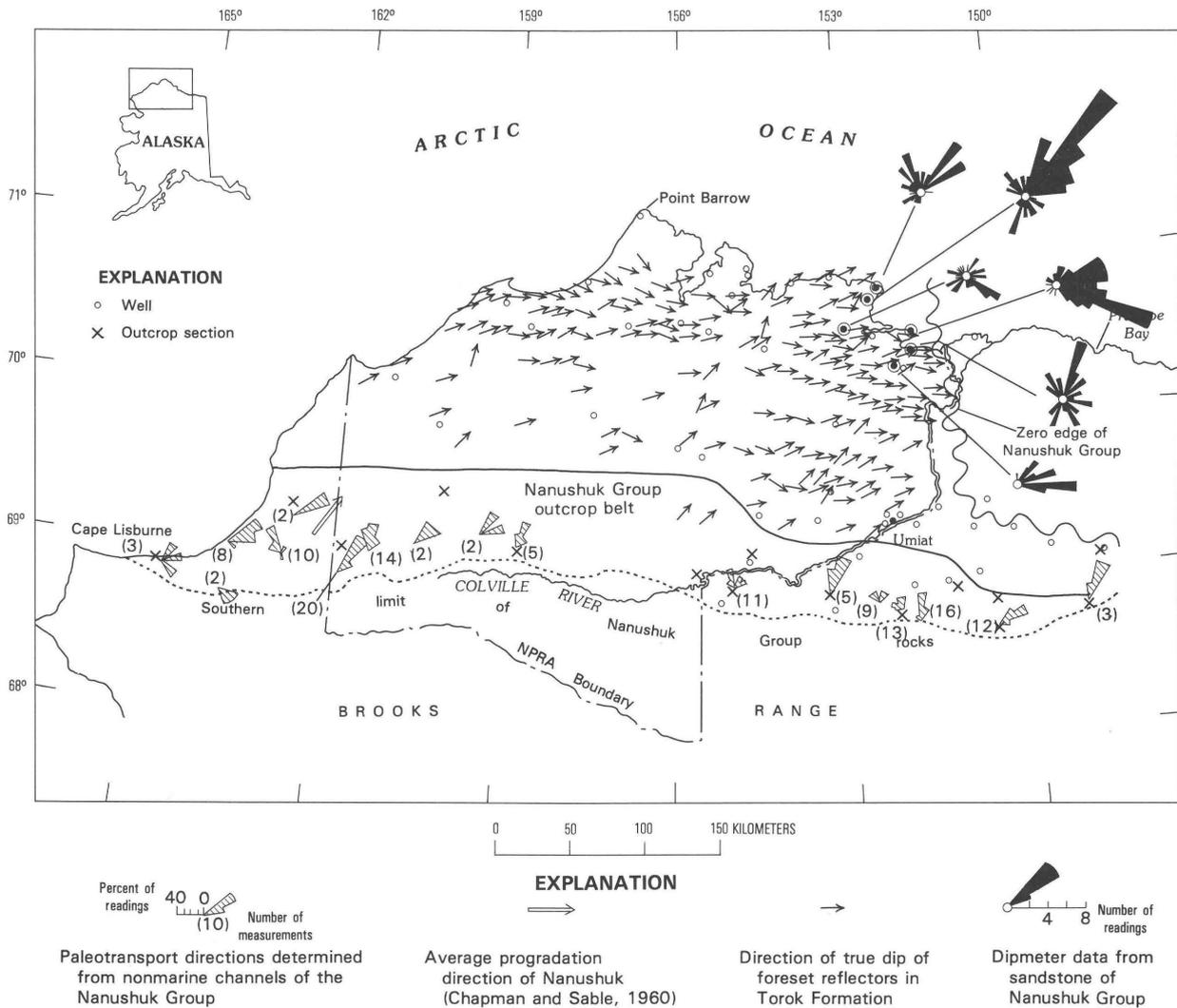


Figure 23. Plot of directional data from seismic foreset dips in the Torok Formation, dipmeter data from Nanushuk Group sandstones, direction of Nanushuk progradation from outcrop (Chapman and Sable, 1960), and direction of plunge of symmetrically filled nonmarine channels of the Nanushuk Group as measured by Ahlbrandt and others (1979) and Huffman and others (this volume) (modified from Bird and Andrews, 1979).

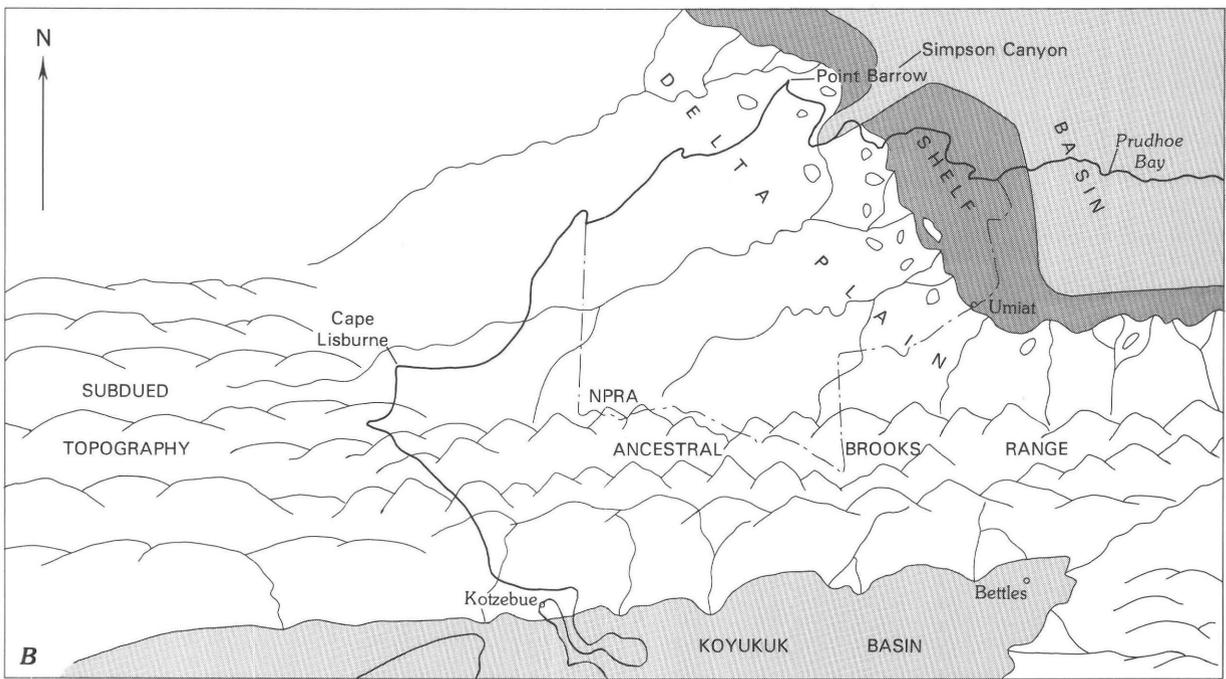
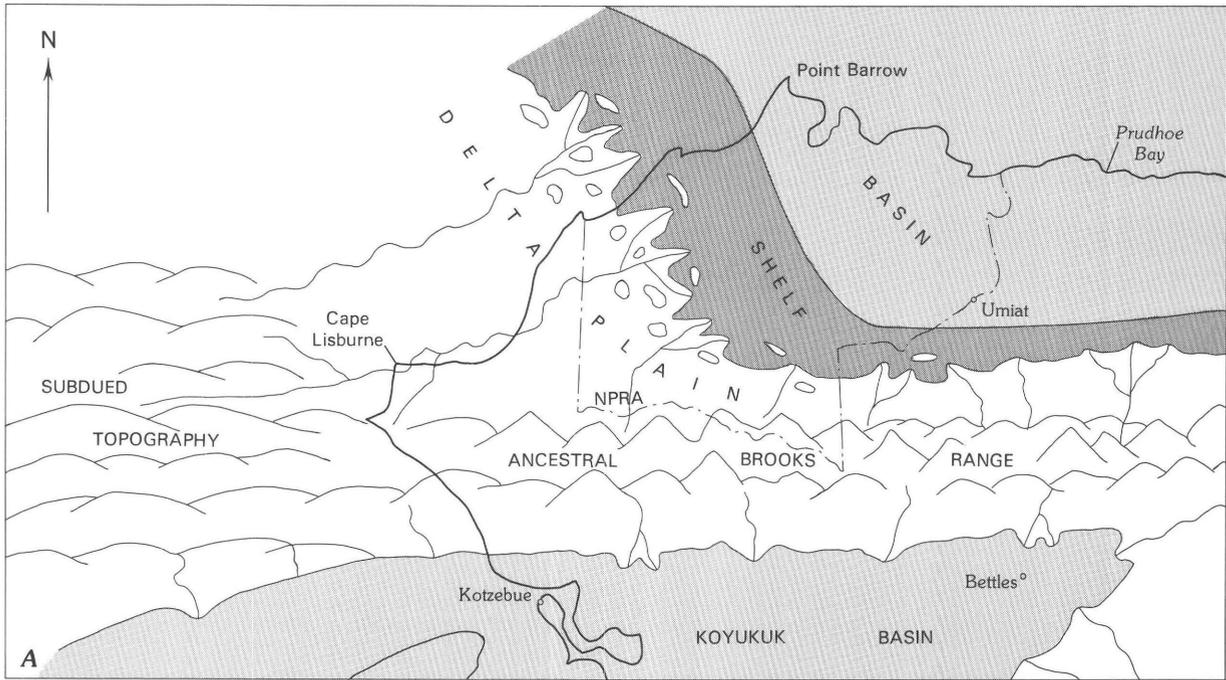
lines (excluding the Turonian-shale-filled Simpson canyon, which was probably cut as a submarine canyon in late Nanushuk time). However, there are probably small gullies or slumps that may be feeder channels for deep-water sands or turbidites at the base of the foreset or in bottomset beds. Many irregularities, in fact, are visible on the seismic lines, suggesting slumping and truncation of beds (figs. 19 and 20).

The width of the basin shelf during Nanushuk time can be estimated from the cross sections. The distance from the marine-nonmarine boundary to the apparent time-equivalent shelf break on the sections, adjusted for depositional strike, ranges from 75 to 150 km. Undoubtedly, the shelf was much narrower along the east-west-trending shoreline southeast of NPRA. Seventy-five to 150 km seems reasonable when compared with modern continental

shelves of passive plate margins. For instance, the continental shelf of the Atlantic-type margin ranges in width from 30 to more than 300 km (Heezen, 1964, p. 13). However, as mentioned previously, the present shelf breaks are relict Pleistocene features, and shelves were obviously narrower during Pleistocene low stands of sea level.

HYDROCARBON-RESERVOIR SAND DEVELOPMENT

Factors reducing the porosity and permeability of Nanushuk sandstones are clay content, alteration of immature mineral grains, compaction, and cementation. These factors are all influenced by depositional environments and depositional history. The following interpretation and



0 200 KILOMETERS

Figure 24. Inferred paleogeographic maps of a part of northern Alaska and adjacent areas. *A*, at mid-Nanushuk time; and *B*, at latest Nanushuk time (maximum regression).

line of reasoning regarding depositional history and basin shape may be useful in outlining areas of more favorable reservoir development.

The east-northeast delta progradation is thought to have been controlled by a large source area to the south-

west, by subsidence of the Colville basin, and by the silting effect of the passive Barrow arch. The presence of the arch would also explain the low marine energy and relative paucity of good marine fauna in much of the Nanushuk, especially to the west. It is interpreted that

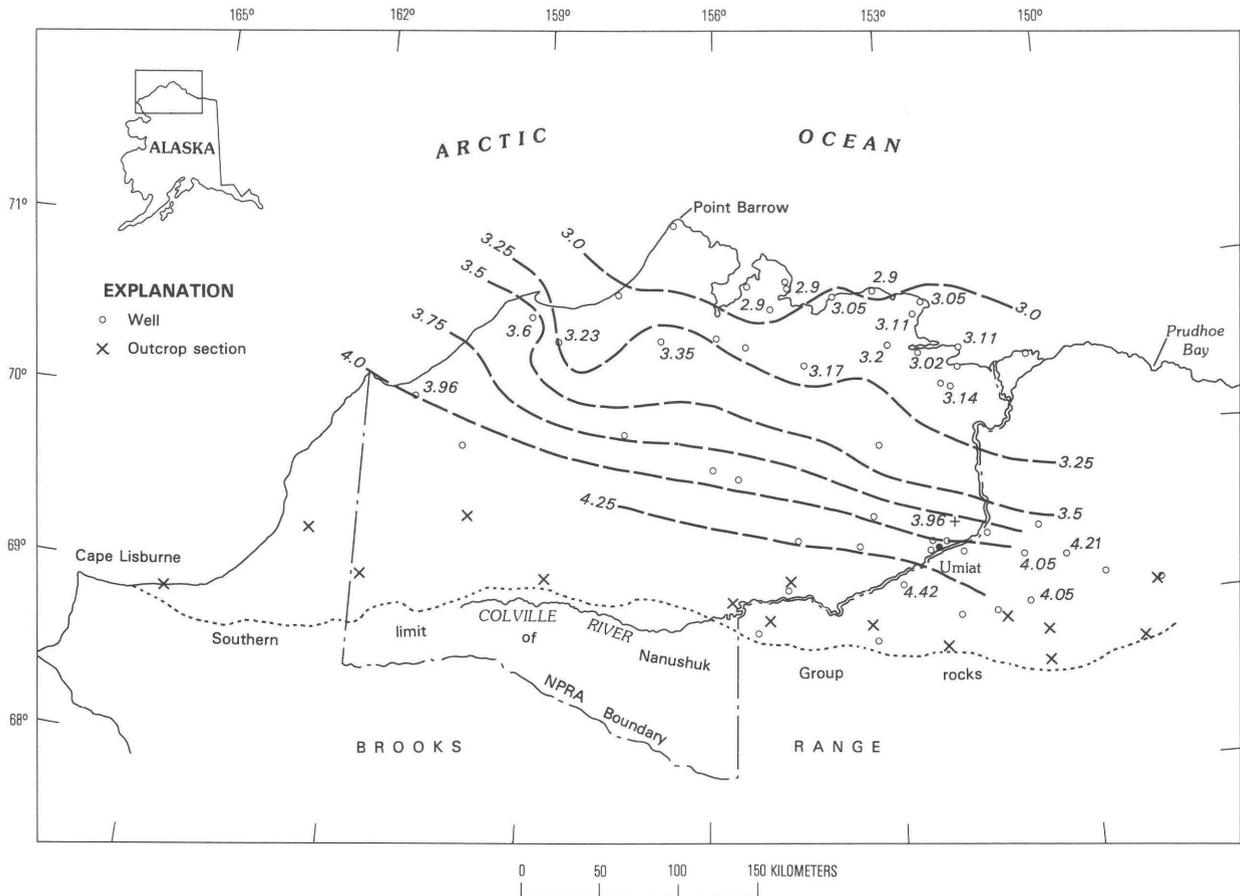


Figure 25. Isopach map of average seismic velocities of sandstones in the lower 150 m of the Nanushuk Group. Velocities are in kilometers per second. Isopach interval is 0.25 km/s.

as the arch continued to subside, it reached a level that reduced or eliminated the silling effect on the Colville basin, presumably in late Nanushuk time. The subsidence of the passive arch resulted in more open marine conditions and increased wave energy, thereby permitting thicker shoreface sands to develop. The increased wave energy may account for the zone of thicker, better sorted sand along the Umiat-Inigok-Simpson shoreline trend (fig. 17). Also, an important aspect of this favorable reservoir sandstone trend is the contribution to the deltaic system by the sands of the Umiat delta on the south (Ahlbrandt and others, 1979). These sands, which are relatively richer in quartz (although still classified as lithic sands) than sands of the Corwin delta (Ahlbrandt and others, 1979, p. 24), were brought into the basin by north-trending fluvial systems in late Nanushuk time. Longshore currents are postulated to have then transported the sands to the north-northwest across the broad prodelta shelf of the larger northeasterly prograding western delta, depositing the sand either along that shoreline or as offshore bars. These events would account for the greater percentage of sandstone in the eastern part of the delta compared with that in the western part, which was deposited by a sand-poor delta. Another explanation for the higher sand

percentage in the northeastern part of NPRA may be the contribution from the western fluvial system late in Nanushuk time. Evidence for such a fluvial system is lacking because of erosion of that part of the section in areas to the west (fig. 18). A third possibility may be simply the change from a river-dominated to a wave-dominated delta setting related to lowering of the sill (Barrow arch). This change would concentrate sands into thicker shoreface sequences.

Thus, the sandstones occurring along the Umiat-Inigok-Simpson shoreline trend and extending east several kilometers beyond the eastern extent of subaerial plain deposits (fig. 21) are likely to be in the zone of highest marine energy, and hence to be more winnowed, less clayey sands. In addition, the northern part of this trend is likely to contain mineralogically more mature sands because the labile constituents would have been removed by winnowing and abrasion due to longer transport distance or higher wave energy in that area. Partly offsetting these favorable factors may be a slight decrease in grain size, owing to increased distance from the sediment source, especially the Umiat delta. Permeability retention is generally reduced in finer grained sandstones.

A comparative measure of porosity reduction by

compaction can be correlated with acoustic-velocity trends of these rocks. Increases in velocities are caused by compaction (greater depth of burial) and (or) cementation. Interval transit times of all comparable lithologies in the Nanushuk Group as determined from transit-time logs show a south-southwest increase in velocities. (Data are from only the post-1960 wells; transit-time log surveys were not available for the old U.S. Navy wells.) The average velocities of sandstones in the lower 150 m of the Nanushuk range from about 2.9 km/s (9,500 ft/s) in the East Simpson-1 and J. W. Dalton-1 wells on the north to 4.0 km/s (13,000 ft/s) and higher in the Tunalik, Seabee (Umiat), and Sinclair Little Twist (southwest of Umiat) wells (fig. 25). Exceptions to the trend and lower velocity porous zones do occur in an otherwise higher velocity sandstone, as in the Umiat area where porosities are as high as 20 percent (Fox and others, 1979, p. 23).

Higher acoustic velocities for the Nanushuk in the southern or southwestern areas suggest that it probably had been more deeply buried in that area. Compressional tectonic forces could have caused some of this increase, but this increase is also apparent in areas of undeformed rocks. In general, therefore, reservoir potential of Nanushuk sandstones is expected to be lower in the southern and southwestern areas.

In summary, on the basis of regional trends, the most favorable area for thicker, better sorted, and cleaner Nanushuk sandstones with better reservoir properties appears to be in northeastern NPRA along a broad belt between the Umiat and Simpson wells. Within this belt, better porosity and permeability would be expected in the north because of less compaction in that area.

SUMMARY

The Nanushuk Group of Albian to Cenomanian Age is a deltaic deposit in which a main delta system, the Corwin delta, prograded across the Colville basin from west-southwest to east-northeast. The provenance was probably a large landmass to the southwest in the area of the present Chukchi Sea or beyond. The Colville basin was bounded on the north by the passive Barrow arch, which was covered by the deltaic system late in Nanushuk time. The ancestral Brooks Range bounded the south side of the asymmetric basin and was a secondary but important source area. The depositional system represented by deposits from this southern source has been called the Umiat delta.

Seismic data indicate that the Nanushuk is laterally equivalent to and prograded over shelf, slope, and basinal deposits represented by the Torok Formation. Measurements of these geomorphic features on seismic sections indicate that (1) the basin slope angle generally steepened from less than 2° on the west to as much as 6° on the

east, (2) the depth of water in the deep part of the basin in the area of study ranged from 450 to 900 m plus the amount of compaction, and (3) the prodelta shelf was 75–150 km wide. The foreset and bottomset beds in the Torok downlap onto or near the Neocomian pebble shale unit in the northern part of NPRA. The hiatus or very thin interval of Torok between the downlapping bottomset beds and the pebble shale represents part of Neocomian, all of Aptian, and a large part of Albian time.

The total incremental stratigraphic rise (a measure of relative sea-level rise and (or) basin subsidence) of the base of the Nanushuk from the Tunalik-1 well on the west to the Atigaru Point-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.

Because of the relatively rapid subsidence on the south side of the basin, the southern-source deltas probably did not extend too far to the north. However, the growth of the Umiat delta just southeast of NPRA coincided with the presence of the prodelta shelf of the larger, easterly prograding western delta so that the southerly derived clastics could be distributed along the north-northwest-trending shoreline and shelf, probably by longshore currents. 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 prior to that time marine circulation was somewhat restricted in the Colville basin. This restricted circulation would account for the low marine energy and the relative paucity of good marine fauna in much of the Nanushuk in its western part.

Thus, the eastern part of NPRA along the alignment of the Umiat, Inigok, and Simpson wells has thicker, better sorted, cleaner sandstone units. In addition, the sand contribution from the Umiat delta was relatively richer in quartz than sands from the Corwin delta, especially farther north where labile constituents were more likely to have been removed by winnowing and abrasion. Alternate hypotheses for the better sandstone development along that trend may be simply that increased wave energy could have concentrated sand into thicker units, or that a western fluvial system in late Nanushuk time may have been responsible for the increase in sand percentage. Evidence for such a fluvial system is lacking because of erosion of that part of the section to the west.

The northeastern part of NPRA has been less deeply buried than areas to the southwest, as indicated by transit-time logs. The resulting reduced compaction coupled with deposition of better winnowed, although finer grained, sandstone beds in that area makes it a more favorable area for petroleum reservoir development.

Depositional and Sedimentologic Factors Affecting the Reservoir Potential of the Cretaceous Nanushuk Group, Central North Slope, Alaska

By A. Curtis Huffman, Jr., Thomas S. Ahlbrandt¹, Ira Pasternack², Gary D. Stricker, and James E. Fox³

INTRODUCTION

The Nanushuk Group of Albian to Cenomanian Age is a regressive sequence of marine, transitional, and non-marine 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. 1). Field and laboratory studies suggest that the Nanushuk Group was deposited in deltaic systems throughout most of the length of the outcrop belt and that it can be divided into two sedimentary provinces separated roughly by the 157° W. longitude line. West of long 157° W., deposition was in the elongate, river-dominated Corwin delta (Ahlbrandt and others, 1979), which prograded to the northeast from the vicinity of the De Long Mountains, Tigara uplift, and Herald arch (fig. 26). Along the central North Slope, from long 157° W. to the Sagavanirktok River, deposition took place in the lobate to elongate river-dominated Umiat delta (Ahlbrandt and others, 1979), which prograded to the north, northwest, and northeast from the vicinity of the Endicott Mountains.

The Corwin delta was studied by a team of U.S. Geological Survey geologists during the 1977 field season, and the results were reported in Ahlbrandt and others (1979), Ahlbrandt and Huffman (1978), and Huffman and others (1981a). Other investigations of the Nanushuk Group outcrop of the western North Slope were done by Chapman and Sable (1960), Smiley (1966, 1969b), and Roehler and Stricker (1979). These studies described the Nanushuk of the western area as having a high mud content, few stacked sandstone bodies, and no extensive delta-front sandstones, and that it prograded and was thus time transgressive to the north and east from the Corwin Bluff area. Recent work in the Kaolak well on the subsurface extension of this delta has resulted in further documentation of the delta's muddy character and the interpretation that, at this location, concentrations of sand are in distributary mouth bars (Pasternack, 1981).

The Umiat delta of the central North Slope was studied during the 1978 field season (Huffman and Ahlbrandt, 1979) using methods identical to those described by Ahlbrandt and others (1979). Stratigraphic sections totaling approximately 8,000 m were measured and sampled in detail (fig. 1) and are described in Huffman and others (1981b). Various aspects of these sections are summarized in table 5, in addition to being discussed elsewhere in this volume. Previous studies of the Nanushuk outcrop of the central North Slope were reported on by Gryc and others (1956), Detterman and others (1963), Chapman and others (1964), Brosgé and Whittington (1966), and Smiley (1969a). Fisher and others (1969) used a deltaic model in discussing the Nanushuk and concluded that it was deposited in a high-constructive delta. The present investigation confirms this model and suggests a lobate-to-elongate form.

Along the outcrop belt northeast of the Marmot syncline measured section (fig. 1), much of the Nanushuk apparently grades laterally into a thick sequence of interbedded mudstone and sandstone having many characteristics of a turbidite deposit. East of the Ivishak River, these rocks were mapped as the Ignek Formation by Keller and others (1961), but the name was later abandoned (Detterman and others, 1975). The lower member of the Ignek was assigned to the Nanushuk Group and the upper member to the Colville Group by them. No detailed work was done in the Ivishak River area as a part of this project; however, reconnaissance inspections and sampling at several localities indicate that these deposits represent a deltaic to deep-marine sequence.

In the subsurface north of the outcrop belt, the Umiat delta rapidly loses its identity. The belt of high sand content extending from Umiat to the vicinity of the Ikpikuk well (fig. 26) appears to be composed primarily of coastal barrier sandstone bodies (a general term used here to denote coastal and shallow marine sandstone bodies deposited along a regressive strand line). The buildup of sandstone in the South Simpson-1 well area (fig. 1) probably reflects the interaction of several factors such as deposition on an extension of the Corwin delta and longshore drift from the southeast.

¹Hereford, Colo.

²AMOCO Production Company, Denver, Colo.

³South Dakota School of Mines, Rapid City.

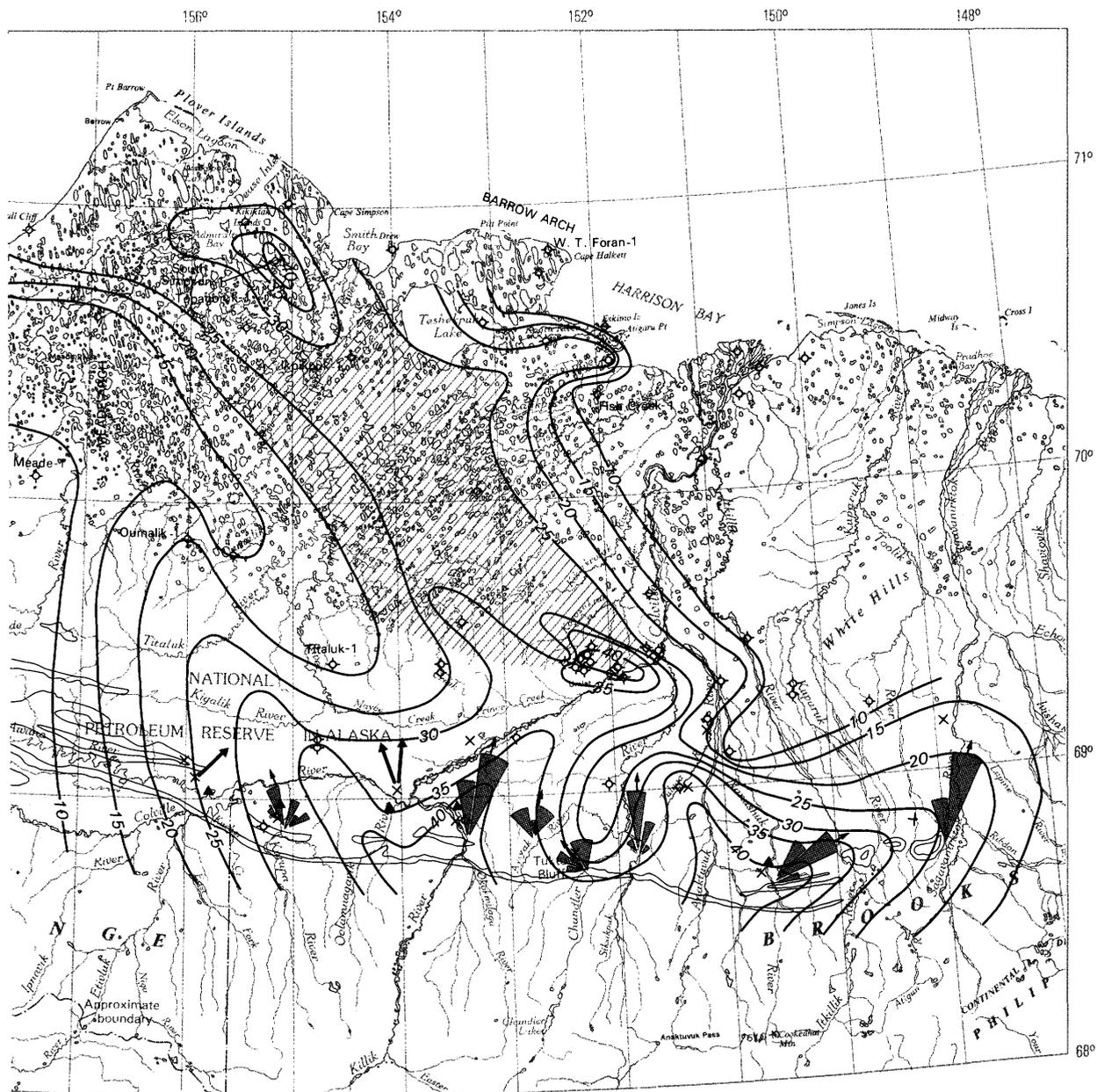


Figure 26. Continued

The following discussion briefly describes the major depositional environments (fig. 28) associated with the Umiat delta. In ascending stratigraphic order, these environments are: prodelta, distal bar, distributary mouth bar and coastal barrier, interdistributary fill, and delta plain. Environments associated with the succeeding transgressive facies are then briefly discussed. Terminology used in these descriptions of depositional environments is modified from Coleman (1976); "delta front" is used as a general term including the distal bar and distributary mouth bar environments.

Prodelta

Prodelta deposits are well exposed at only two of the measured sections, Tuktu Bluff and Marmot Syncline (fig. 1). At both locations they are indistinguishable from the underlying shelf deposits and are included in the Torok Formation. They consist of medium-gray to olive-gray laminated shale and mudstone with thin interbedded siltstone layers that are iron stained and ripple laminated in places. Fossils and trace fossils are rare, possibly due to unsatisfactory living conditions produced by high

Table 5. Synthesis of resource-related data from measured

[M, marine; T, transitional; NM, nonmarine; ss, sandstone; No., number;

Measured section	Environment	Amount of section exposed (percent)	Base of section		Top of section		Total measured thickness (m)	Total ss thickness (m)	Ss (percent)
			lat N.	long W.	lat N.	long W.			
Carbon Creek-----	M,T,NM-----	11	69°13'26"	158°45'35"	69°14'51"	158°44'15"	969	20	2
Section Creek-----	M,T-----	27	69°04'33"	156°00'16"	69°03'31"	155°58'16"	161	20	12
Awuna River-----	T, NM-----	65	69°01'27"	155°52'51"	69°02'03"	155°52'08"	169	30	18
Kurupa anticline---	M,T,NM-----	36	68°52'44"	155°26'21"	68°56'16"	155°02'23"	1832	413	23
Killik type-----	M,T-----	97	68°51'07"	153°22'03"	68°52'05"	153°23'34"	313	237	76
Tuktu Bluff-----	M,T,NM-----	22	68°43'30"	152°15'50"	68°46'10"	152°06'54"	1868	385	21
Type Grandstand---	M,T-----	44	68°56'47"	151°13'20"	68°55'46"	151°13'03"	812	298	37
Roof Top anticline-	M,T-----	58	68°50'37"	150°33'31"	68°50'30"	150°34'49"	195	103	53
Arc Mountain-----	M,T-----	97	68°40'09"	150°36'31"	68°36'57"	150°33'28"	516	205	40
Marmot syncline---	M,T,NM-----	47	68°43'37"	149°01'11"	68°44'34"	149°03'56"	1060	271	26
Lupine River-----	M,T-----	21	69°05'41"	148°46'48"	69°05'23"	148°45'19"	563	91	16

sedimentation rates. Grain size increases upward as does the thickness and number of siltstone units and the amount of included carbonaceous plant debris. The total thickness of prodelta sediments was not determined but probably is several hundred meters.

Distal Bar

The distal bar deposits (fig. 28) are very fine grained, poorly sorted sandstones and siltstones as thick as 25 m, interbedded with mudstone and shale intervals as thick as 90 m. The sandstones and siltstones are dark gray to olive gray, as are the mudstones and shales. The predominant sedimentary structures are laminations, but the sandstones may be rippled or rarely crossbedded. Carbonaceous plant debris is a common constituent of both the sandstones and mudstones. Both vertical and horizontal burrows (for example, *Cruziana* and *Planolites*) and bioturbated beds are common. Molds and casts of pelecypods (*Pleuromya*, *Corbicula*, and *Tellinimerids*) are scarce but widespread. Although the distal-bar deposits could not be traced their full length in outcrop, they extend several kilometers parallel to depositional strike (roughly east-west) where exposed on the Tuktu escarpment (fig. 26). In the subsurface 75 km to the north, such as in the Umiat and Square Lake wells, there is no evidence of thick delta-front sandstones or siltstones.

Distributary Mouth Bar and Coastal Barrier

The primary sites of clastic sedimentation in the southern part of the Umiat delta were distributary mouth bars (fig. 28). 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. Their down-dip extent to the north is unknown because of limited outcrop and lack of suitable marker horizons. Grain size and porosity increase upward in individual bars.

The distributary mouth bars commonly have low- to moderate-angle trough crossbedding in the lower and middle parts and some parallel bedding in the upper part. Bases and tops are variable; the basal contact of a bar with a distal-bar deposit produced by normal regressive succession is typically gradational, whereas the contact with fine-grained deposits of the prodelta or interdistributary bay is commonly marked by contorted bedding probably caused by rapid sediment loading and an abrupt change in grain size and energy regime (fig. 27). In a normal regressive or prograding succession, the bar deposits are overlain by fluvial deposits of the distributary channel at a scour surface or by fine-grained interdistributary bay sediments. Locally they may be overlain by prodelta or delta-front mudstone and siltstone at a sharp erosional surface, indicating a transgressive event and the beginning of another delta cycle.

Distributary mouth bars of the Umiat delta contain a wide variety of both trace fossils and megafossils. The fossil assemblages change with the energy of the environment so that the lower bar assemblage is similar to that of the distal bar, and the trace fossils *Cruziana* and *Planolites* are common. The higher energy deposits are characterized by *Scolithos*, *Diplocraterion*, *Rhizocorallium*, *Gyrochorte*, and *Helicodromites*. Carbonaceous plant fragments increase in both size and quantity upward in the bars. Both pelecypods (*Inoceramus*, *Corbicula*, *Nucula*, *Pecten*, and *Tellinimerids*) and scaphopods (*Ditirupa*) are common in the upper parts as well. Stacked

sections of Nanushuk Group rocks (1978), North Slope, Alaska

mD, millidarcy; leaders (--), not observed]

No. ss beds	Average ss thickness (m)	Maximum ss thickness (m) and environment	Porosity (percent)		Permeability (mD)		Coal beds		
			Range	Average and (no. of measurements)	Range	Average and (no. of measurements)	Thickness (m)	No.	Average thickness (m)
14	1.4	2.4 T	4.3-14.5	8.84 (7)	0.07-2.2	0.67 (7)	---	---	---
8	2.5	8.2 T	4.6-14.5	7.9 (3)	0.11-6.6	2.29 (3)	---	---	---
17	1.8	9.7 NM	5.5-11.1	7.25 (4)	0.099-0.29	.18 (3)	0.5	3	0.17
143	3.0	33.8 T	2.6-17.7	7.34 (48)	0.2-374	15.77 (45)	12.75	16	0.79
63	3.8	69.2 T	4.1-17.2	9.53 (10)	0.04-2.9	4.94 (8)	1.5	4	0.38
78	4.9	43.6 T	3.4-16.4	7.06 (39)	0.7-320	23.58 (25)	0.15	1	0.15
48	6.2	32.6 T	2.8-14.9	9.79 (31)	0.4-89	15.31 (30)	0.45	3	0.15
13	7.9	21.3 M	5.4-10.2	7.82 (6)	0.13-4.4	1.03 (6)	---	---	---
55	3.7	67.1 M	2.7- 8.4	5.22 (18)	0.5-3.9	.44 (18)	1.5	2	0.75
63	4.3	29.5 T	2.3- 8.0	4.69 (29)	0.3-13	.71 (28)	---	---	---
57	1.6	9.7 T	3.7- 7.2	5.5 (13)	0.3-0.36	.19 (13)	---	---	---

regressive beach sequences are present within the Umiat delta complex such as at the Kurupa anticline measured section and may record periods of increased wave and current activity as well as decreased sediment supply or periods of more rapid basin subsidence. Net-sand and sand-percentage contour maps (fig. 26) as well as electric logs of test wells just north of the outcrop belt suggest that deposition was in coastal-barrier rather than delta-front sandstone bodies (Molenaar, this volume), also probably due to increased wave and current activity and a change in the balance of sediment supply to subsidence.

Interdistributary

Embayments between active delta lobes (interdeltaic subembayments of Fisher and McGowen, 1967) or between distributaries on a lobe are filled with deposits of organic-rich shale and mudstone; crevasse-splay deposits of siltstone and sandstone; and claystone, siltstone, and coal deposited in marsh and swamp environments (fig. 28). Because large amounts of interdistributary bay sediments are fine grained, they are less resistant to erosion and are therefore poorly exposed, making accurate thickness and lateral extent measurements difficult to obtain.

Fine-grained bay-fill deposits consist of laminated and rippled, bioturbated, brownish-black to olive-gray carbonaceous shales, mudstones, and siltstones that range in thickness from 10 m to more than 100 m. The areal extent of these deposits was not determined. Overlying and interbedded with the fine-grained deposits are crossbedded and ripple-laminated, olive-gray to light-gray sandy siltstones and fine-grained sandstones deposited in crevasse splays and small distributary channels (fig. 27). These sandstones are typically 3 to 6 m thick, but may be as much as 30 m thick, and contain *Corbicula* and *Unio*. Marsh deposits of claystone, siltstone, and coal, which may be

rooted in crevasse-splay sandstones, are typically less than 1 m and rarely more than 3 m thick. Complete sequences of bay-fill environments were seldom observed in the Umiat delta primarily because of the paucity of good exposure but also because of periodic interruptions of local sedimentation and progradation, resulting in deltaic cycles similar to those described by Coleman and Gagliano (1964). Three or more cycles involving bay-fill sediments are apparent in the transitional part of the section at Kurupa anticline and Tuktu Bluff.

Delta Plain

Sediments deposited on the delta plain of the Umiat delta are predominantly fluvial-channel and overbank deposits and minor fine-grained lacustrine and swamp or marsh deposits (fig. 28). In the transitional part of the section, these nonmarine deposits are interbedded with interdistributary bay and distributary mouth bar sequences.

The channel deposits are typically light-gray to light-olive-gray, fine- to medium-grained, trough-cross-bedded sandstones or conglomeratic sandstones. They range in thickness from 1 to 25 m and were deposited by both braided and meandering streams. The contact between the transitional and nonmarine parts of the Nanushuk is typically marked by high-energy fluvial conglomerate beds (fig. 27) as thick as 14 m. These conglomerates are composed predominantly of well-rounded white quartz and gray chert clasts as large as 30 cm (but more commonly 4 to 8 cm) and contain large plant fragments. Transport-direction measurements on trough and channel axes taken in the fluvial deposits (fig. 1) indicate a general northerly progradation from the vicinity of the Endicott Mountains, as do the sand-percentage contours of figure 26.

Poorly exposed intervals of fine-grained overbank

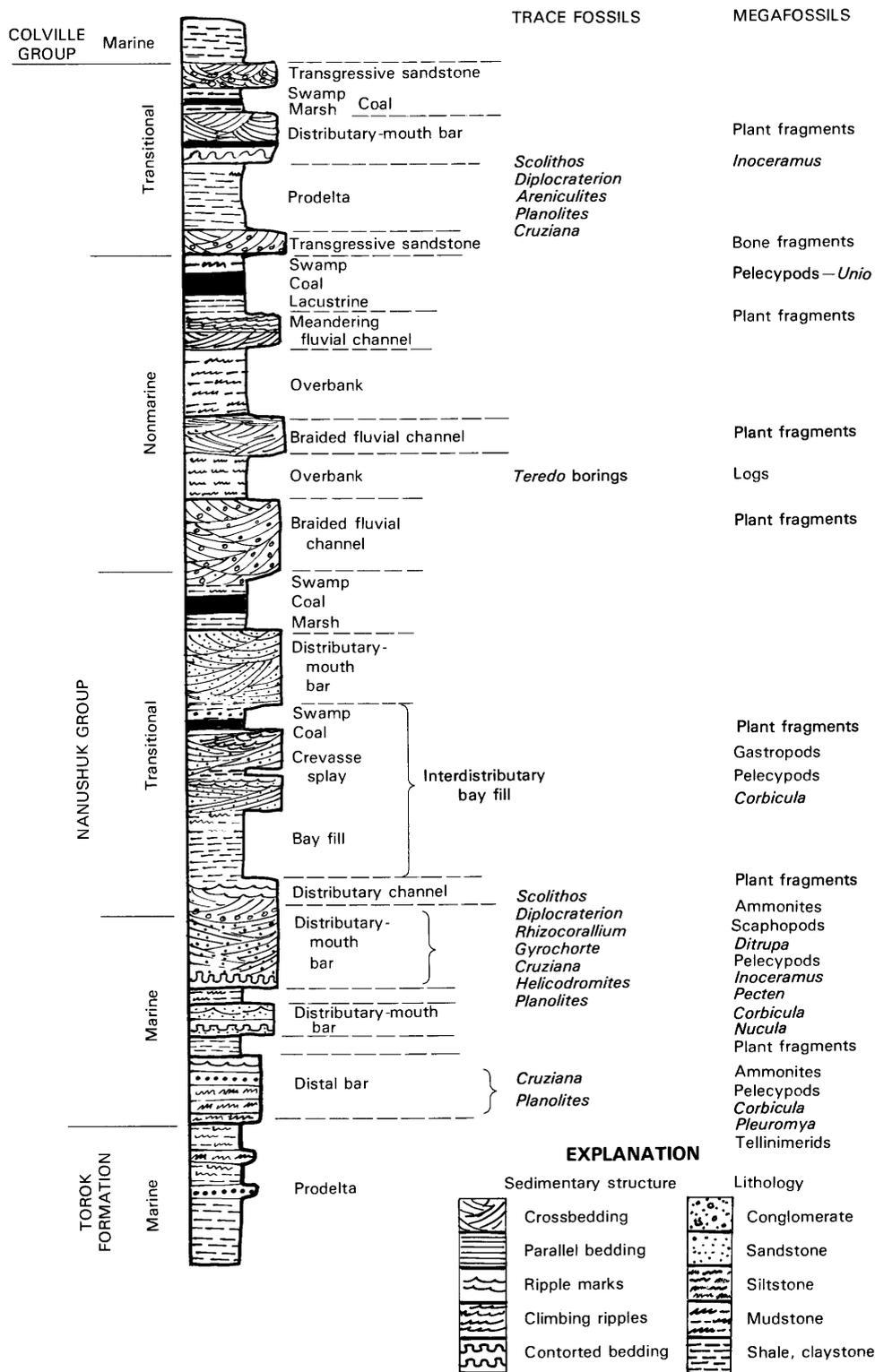


Figure 27. Generalized stratigraphic column of the Nanushuk Group, central North Slope.

deposits as much as 150 m thick are composed primarily of medium-gray to dark-yellowish-brown siltstones and mudstones that are laminated, rippled, and rarely contorted. Burrowing and bioturbation and significant

amounts of carbonaceous plant debris are common. Interbedded with the mudstones and siltstones are thin (10–30 cm) crossbedded and ripple-laminated silty sandstones. Marsh and swamp deposits commonly consist of lami-

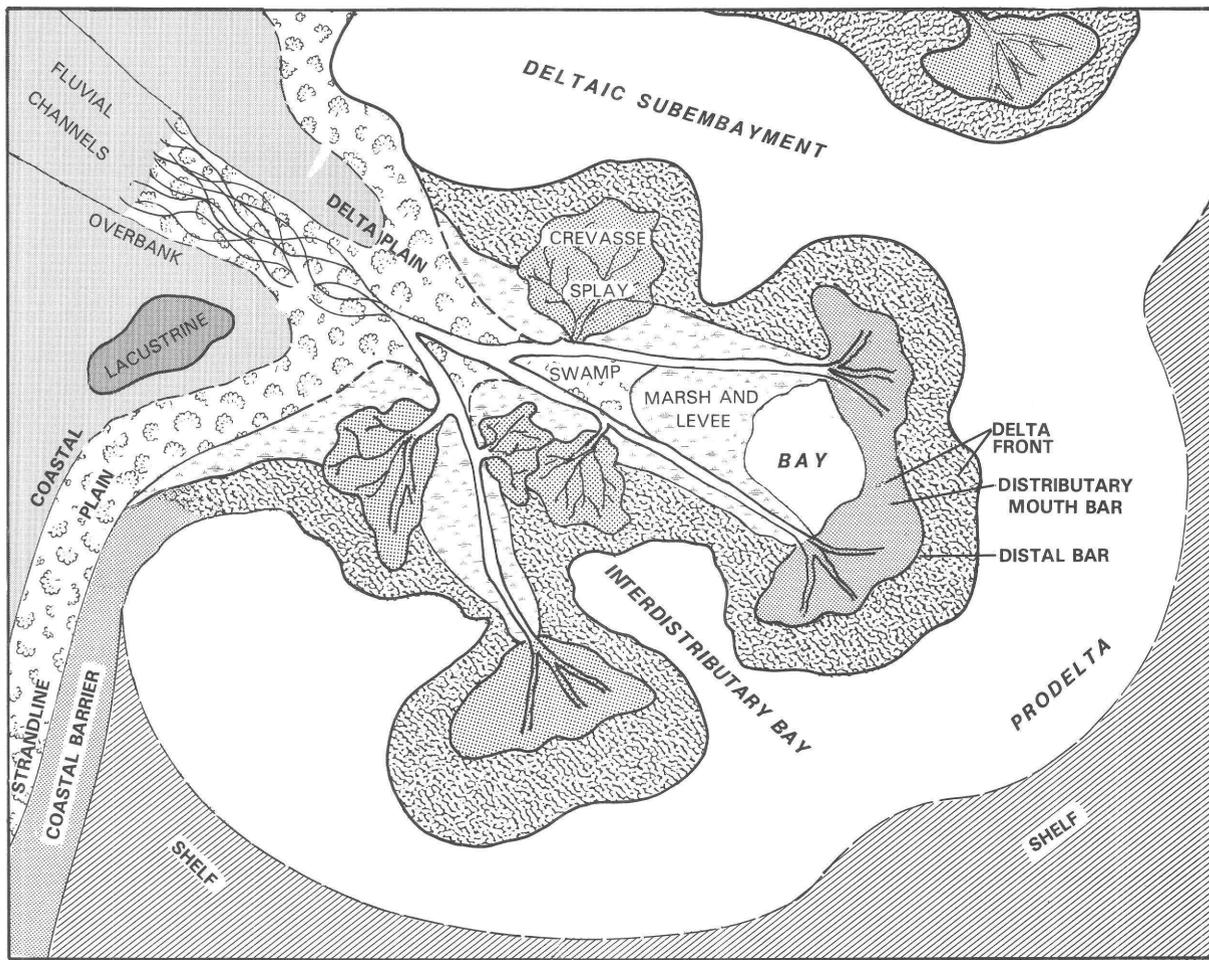


Figure 28. Schematic diagram showing terminology and major depositional environments discussed in text.

nated and rippled siltstones and mudstone interbedded with claystone, carbonaceous shale, and coal beds. Individual coal beds rarely exceed 2 m.

Marine Transgression

A major regional transgression in the early part of Late Cretaceous time (Detterman and others, 1963) halted growth of the Nanushuk deltas. In the outcrop area this transgression is characterized by intertonguing marine and nonmarine deposits similar in gross aspect to the transitional beds in the regressive phase of Nanushuk deposition. However, there are two major differences: the presence of abundant bentonitic shale and bentonite beds (7–30 cm thick), and the high sandstone content (37 percent at Ninuluk Bluff). Where observed at Ninuluk Bluff, several thin (30–60 cm) beds of crossbedded, conglomeratic sandstone containing both pelecypod and bone fragments are interpreted to be transgressive sandstones that record several pulses that occurred during the regional transgression. Most of the marine intervals are typical regressive

distributary mouth bar and coastal-barrier sandstones interbedded with fine-grained prodelta and bay-fill deposits. The intertongued nonmarine sediments are predominantly fluvial channel sandstones, overbank mudstones, and coal beds (30 cm to 1 m thick) deposited on the delta plain. This sequence of intertonguing sandy marine and coal-bearing nonmarine units is overlain by marine bentonitic shales and thin sandstones of the Seabee Formation of the Upper Cretaceous Colville Group. Detterman and others (1963) recognized an angular relationship between the Nanushuk and Colville Groups in the Chandler River region. We were unable to confirm this relationship during the course of this study.

Northeastern North Slope

Nanushuk sediments change facies in a short distance along the outcrop belt to the northeast of Marmot syncline and apparently grade into a thick sequence of mudstone and turbidites that were mapped as the lower

member of the Ignek Formation east of the Ivishak River by Keller and others (1961). The lower member of the Ignek (now the Nanushuk) was described as being composed of subgraywacke-type sandstone, siltstone, shale, and less commonly conglomerate, and the sandstone as being locally crossbedded and ripple marked, and characterized by "curly bedding or hassock structure" (Keller and others, 1961, p. 204).

Reconnaissance examination and sampling of the outcrops along the Saviukviayak and Ivishak Rivers and Gilead Creek (fig. 26) by Ahlbrandt supports the correlation of at least a part of these deposits with the Nanushuk Group based on the occurrence of Nanushuk-like fluvial lithologies in the uppermost part. Although some of the exposures are structurally complex, the general sequence includes a thin nonmarine section overlying thick shallow-marine deposits, which in turn overlie a thick deep-marine turbidite sequence. Observed lithologies in the turbidite deposits include thick mudstone or silty claystone sequences and very fine grained sandstones. Sedimentary structures in sandstone and siltstone beds include parallel laminations, current ripples and climbing ripples, sole markings, and rare low-angle cross bedding. Parts of Bouma cycles, especially the C, D, and E intervals, are common. All indications are that the turbidites were deposited in deep-marine environments and are approximately time equivalent to the lower deltaic Nanushuk deposits (Keller and others, 1961). These observations help to establish the position of the shelf break during Nanushuk deposition.

Farther to the northeast, in the vicinity of the Sadlerochit Mountains and the Jago River (fig. 26), Dettnerman and others (1975) measured reference sections in what were thought to be Nanushuk or equivalent rocks. Both their Arctic Creek and Sabbath Creek sections were examined and sampled during the present study. Lithologically, there is little resemblance between these sections and the typical Nanushuk Group sections other than general environments of deposition. Detailed petrographic and paleontologic analyses have not yet been completed, however, and any conclusions would be premature.

North-Central North Slope

The Umiat delta as an entity extends a very short distance northward into the subsurface. The actual shape and northward extent of the delta as well as the effect and influence of the Corwin delta are open to various interpretations (for example, Molenaar, this volume). The belt of relatively high sandstone concentrations extending generally northward from the vicinity of Umiat to the Ik-pikpuk well and the apparent sandstone buildup in the vicinity of the South Simpson-1 well (fig. 1) are both probably due in part to redistribution of sand from the

Umiat delta as well as to some influence from the Corwin delta.

Petrographic results reported by Bartsch-Winkler (1979) indicate that in most of the wells sampled, the sandstones in the lower parts of the section bear a strong compositional similarity to Corwin delta sediments. Higher in the section, however, there is a marked change, and the sandstones show stronger affinities to the Umiat delta sediment types. Although the data are not yet complete enough to warrant definitive conclusions, most of the sampled wells also suggest a degree of mixing of sediment types in some beds as well as possible interbedding of the two sediment types.

Several explanations for the different lithologies satisfying both the outcrop and petrographic data are possible. The most probable at this time is that the Umiat delta prograded northward onto a shelf built in part by sediment from the Corwin delta. In the vicinity of Umiat, the Umiat delta was subjected to strong wave and current activity that tended to move sediment to the northwest. A coastal-barrier-type shoreline was built by sediment transported to the coast by Corwin streams and by sediment transported northward by longshore drift from the Umiat delta.

The sand buildup in the vicinity of the South Simpson-1 well was also probably due to an interaction between Corwin deltaic sedimentation and sand redistribution from the Umiat delta. The reason for the actual concentration of sand in this area is unknown, but it may have been due at least in part to the effects of the Barrow arch and the Meade arch on wave energy and current directions as well as drainage patterns.

RESERVOIR CHARACTERISTICS

Both the quantity and quality of petroleum reservoir rocks depends a great deal on geographic and stratigraphic position in a deltaic system, because the higher energy environments generally produce the more porous and permeable sandstone deposits. In a river-dominated delta such as the lobate to elongate Umiat delta, the highest energy environments are the fluvial channels and the distributary mouth bars which are concentrated on the depositional lobes. North of the delta, between Umiat and the South Simpson-1 well, the highest energy deposits are the coastal-barrier sandstones.

In the sections measured, distributary mouth bars and coastal-barrier deposits make up 44 percent of the total sandstone. These deposits have an average bed thickness of 6.5 m and considerable lateral extent, whereas the fluvial-channel deposits that compose 25 percent of the total sandstone have an average bed thickness of 4.7 m and limited lateral extent. Porosity values within distributary mouth bars range from 2.8 to 17.2 percent and

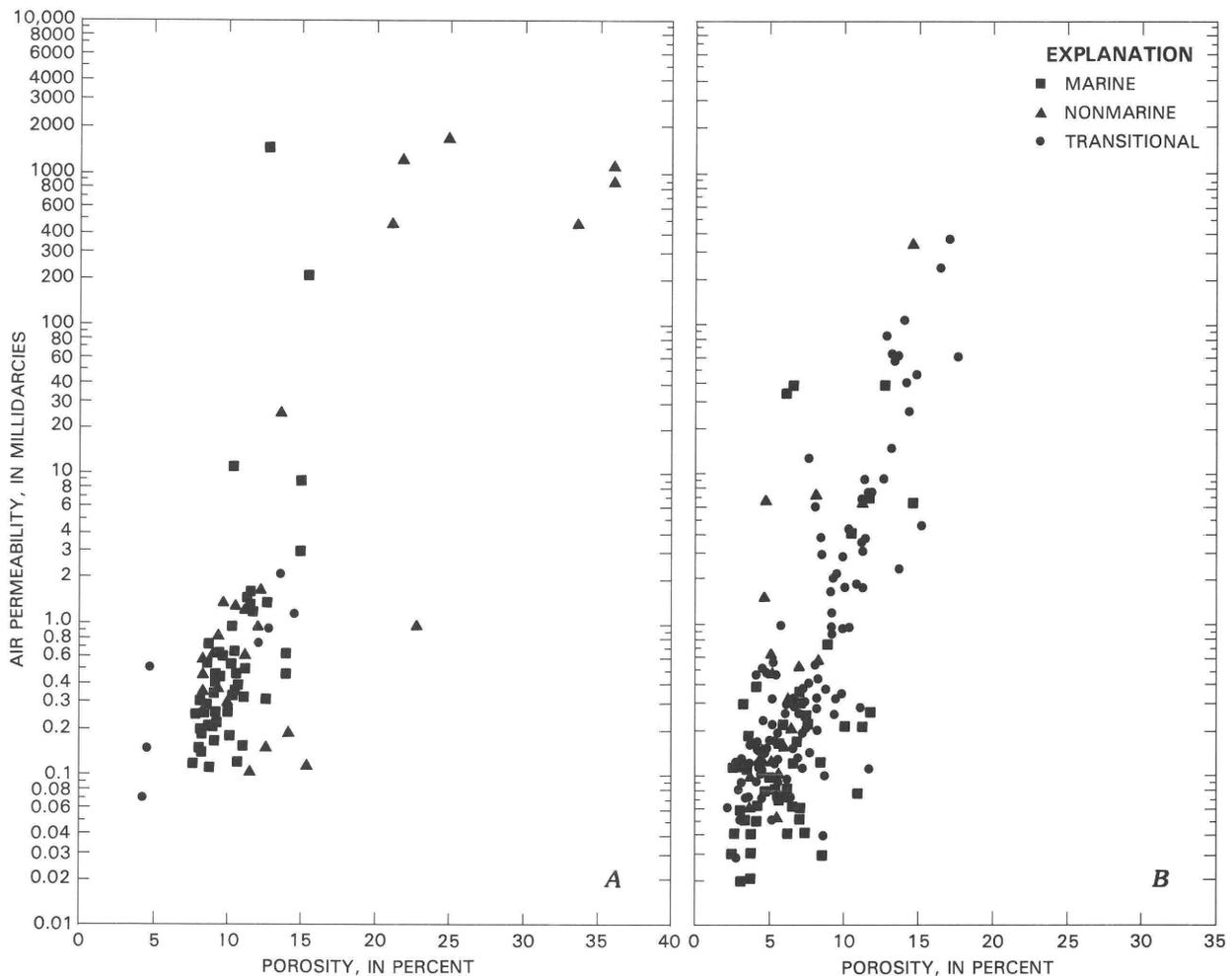


Figure 29. Porosity versus permeability plots for outcrop samples from *A*, Corwin delta (western); *B*, Umiat delta (eastern). Permeability measurements were generally not made on samples from the Corwin delta having less than 8 percent porosity.

average 7.6 percent, and permeability values range from 0.02 to 245 mD (millidarcies) and average 6.3 mD. Several 10–15-m-thick intervals of nearly unconsolidated sand in the Kurupa anticline and Killik type sections are interpreted as stacked foreshore and upper distributary mouth bar deposits. In both of these sections, the unconsolidated intervals are near the top of the transitional part of the section. Fluvial-channel sandstones average 8.1 percent porosity, ranging from 2.5 to 17.7 percent, and average 19.2 mD permeability, ranging from 0.03 to 374 mD.

The interdistributary bays between channels on a prograding lobe are filled with mudstone and shale deposits interbedded with crevasse-splay sandstones. Although individual sandstone beds average only 4.5 m thick, they are commonly stacked on top of each other for aggregate thicknesses of as much as 30 m. The average porosity and permeability of these sandstones are less than those of the higher energy deposits but locally were found to be as high as 14.2 percent and 64 mD, respectively. Crevasse-splay deposits occur in the interdeltic

subembayments as well as on the lobes, although not in such thick accumulations.

Distal-bar deposits, though widespread, are commonly thin and silty, although aggregate thicknesses of as much as 25 m are not rare. Porosity and permeability of these deposits are generally low, averaging 5.6 percent and 0.06 mD respectively, and most deposits contain abundant intergranular silt and clay. No porosity of more than 9.4 percent or permeability of more than 0.33 mD were found in these sandstones in any of the outcrop samples of the Umiat delta.

Along the outcrop belt of the Umiat delta, the higher energy environments are concentrated in the transitional and upper parts of the marine part of the Nanushuk section. This part of the section contains as much as 70 percent of the total sandstone content of the Nanushuk and ranges in thickness from 200–1,000 m. In the subsurface the same relationship is apparent in electric logs northward to the vicinity of Umiat. From Umiat to the vicinity of the South Simpson–1 well, sandstones are con-

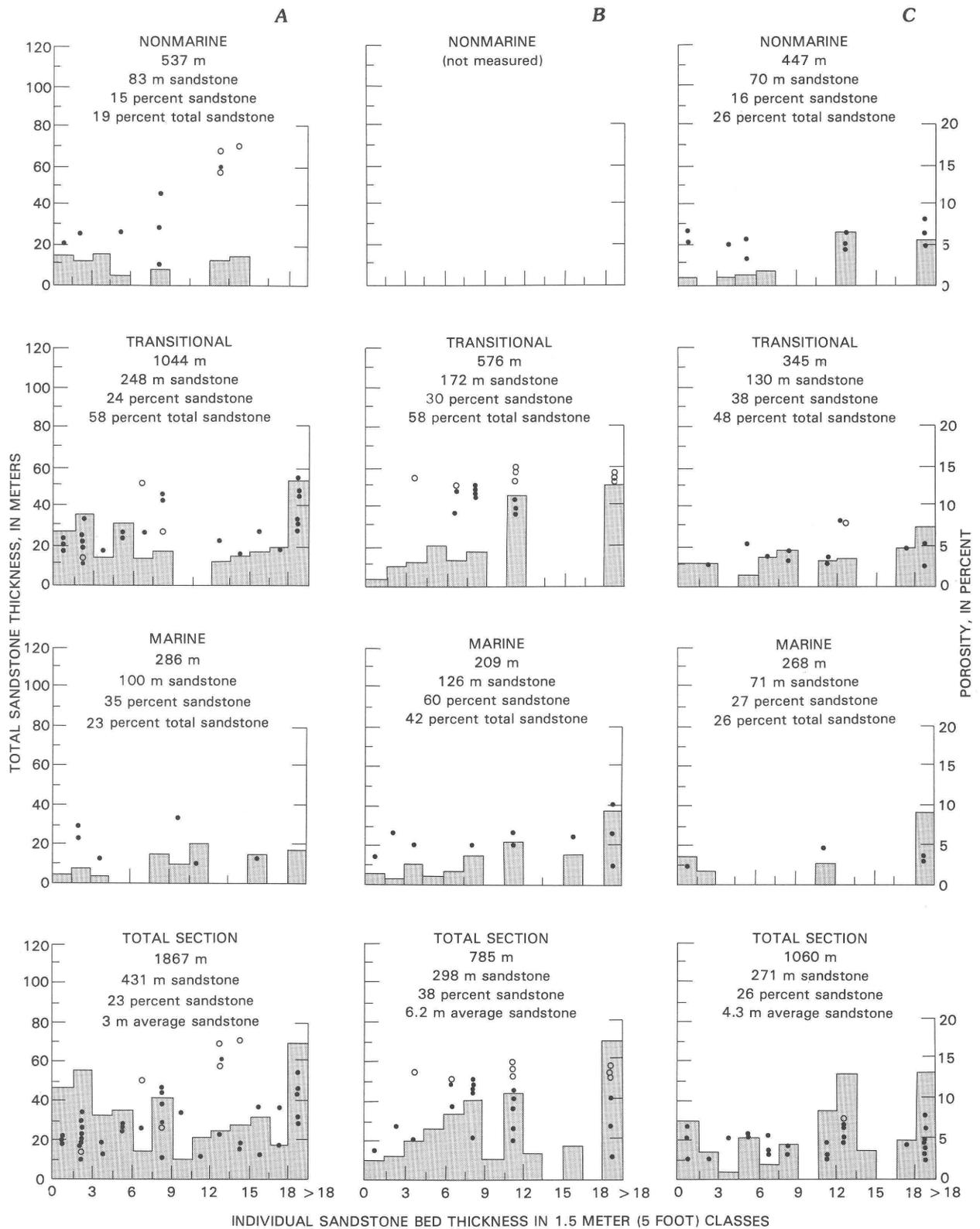


Figure 30. Distribution of sandstone within 1.5-m-thickness classes from four sections measured in the Umiat delta deposits, central North Slope. *A*, Kurupa anticline; *B*, Grandstand type; *C*, Marmot syncline; *D*, Tuktu Bluff. Dots, porosity values by thickness class; open circles, sample has a permeability in excess of 10 mD. For each facies of the Nanushuk Group present (marine, transitional, and nonmarine) and for the total measured section, values are given for total thickness, net sandstone, percent sandstone in that facies or section, percent of sandstone in total section contained in that facies (percent total sandstone), and average bed thickness of sandstone in total section (average sandstone).

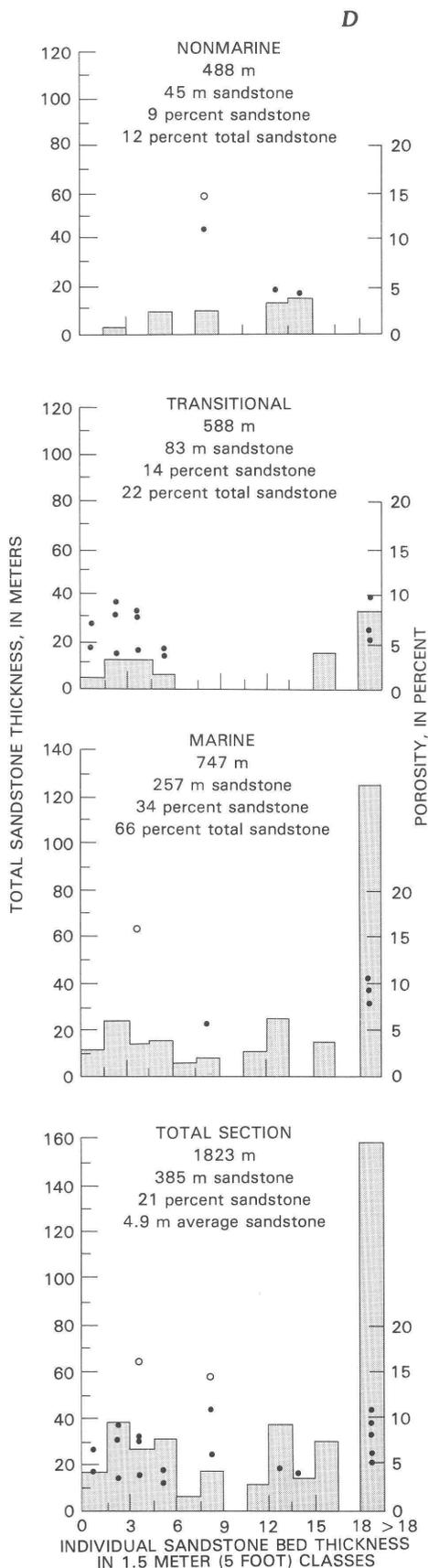


Figure 30. Continued

centrated in the upper part of the marine part of the section in what are apparently coastal-barrier deposits. Porosity and permeability values are high in these sandstones, averaging 28 percent and 203 mD, respectively, further indicating deposition in high-energy environments.

The general relationship of porosity and permeability to depositional environment is apparent on a plot of porosity versus permeability as shown in figure 29. Because of the low marine energy acting on the Corwin delta (fig. 29A), the higher energy deposits and thus generally better porosities and permeabilities are found in the fluvial sandstones, whereas in the Umiat delta (fig. 29B) with its greater marine influence, better porosities and permeabilities occur in the transitional and marine parts of the section. These relationships are also demonstrated on figure 30, which indicates that the best reservoir development in the Umiat delta is in the transitional part of the section on depositional lobes as at the Kurupa, Grandstand, and Marmot measured sections (fig. 1) and in the marine part of the section away from the lobes (Tuktu Bluff). Along the high-sandstone-percentage belt between Umiat and the Ikpikpuk well, the same relationship would be expected, with the best reservoir capacity in the coastal-barrier sandstone bodies within the marine part of the section.

DEPOSITIONAL HISTORY

The following interpretation of Nanushuk depositional history is intended as a generalized representation only. Although ideas and data are drawn liberally from various chapters in this volume and Ahlbrandt (1979), only a few specific references are included.

Deposition of the Nanushuk Group began in the area that is now the far western and southwestern North Slope during early Albian or perhaps late Aptian time (Scott and Smiley, 1979). The Nanushuk was deposited as a fine-grained, elongate, river-dominated delta system onto a broad, shallow shelf of prodelta Torok mud, silt, and clay (fig. 31A), which was prograding into the Colville basin from west to east. The sources of both the Nanushuk and much of the Torok were probably the De Long Mountains, Tigara uplift, and Herald arch (Huffman, 1979; Mull, 1979). Both wave and current energies acting on the Corwin delta were apparently low due to the elongate nature of the Colville basin, the wide, shallow shelf, and possibly the sill effect of the Barrow and Meade arches. Because of the low wave activity and the general structural stability, the available sand was concentrated in long, narrow distributary mouth bar and fluvial-channel deposits. Much of the delta was apparently bay and marsh, resulting in extensive thin coal and crevasse-splay deposits.

The Corwin delta prograded in several major lobes

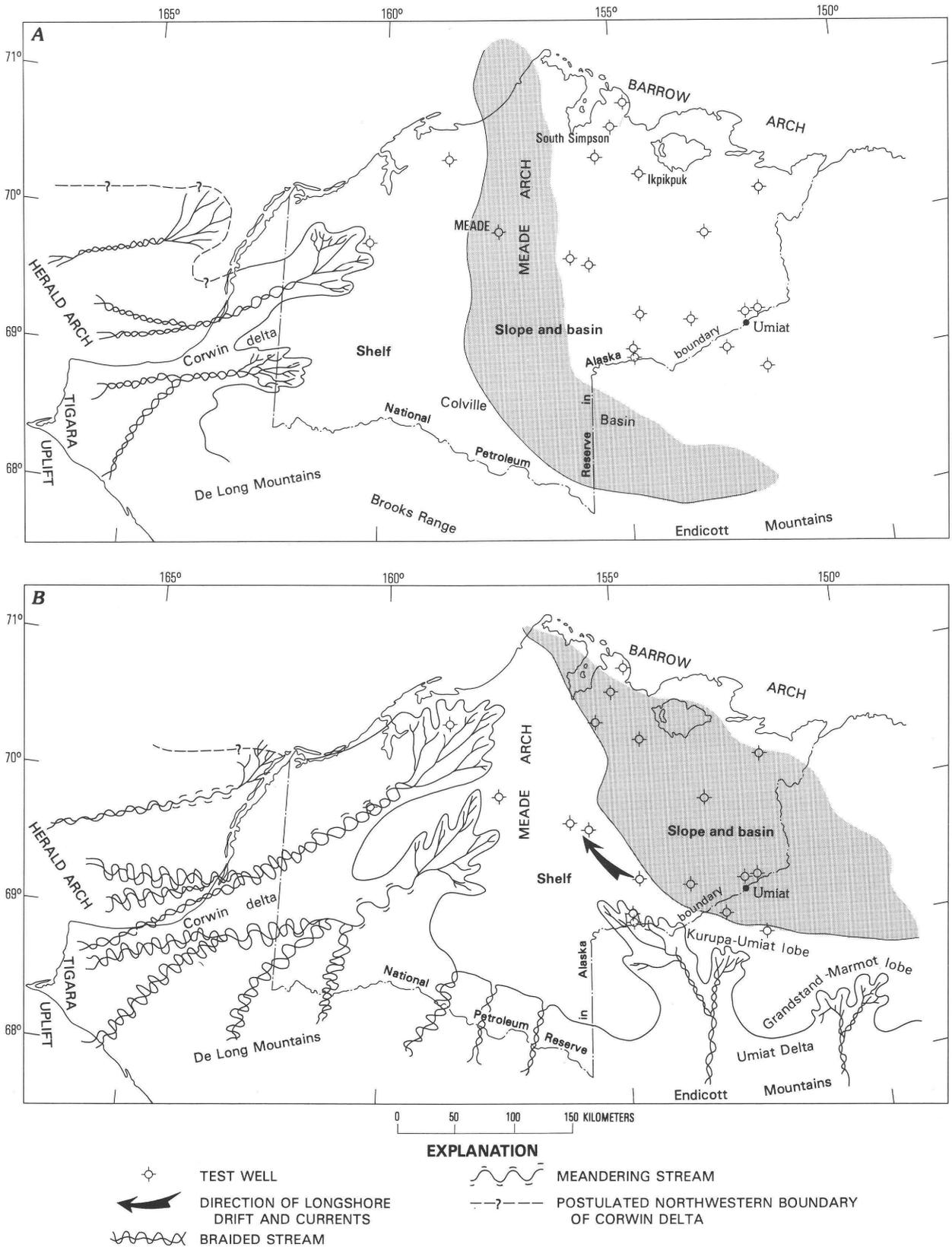


Figure 31. Paleogeographic maps depicting the depositional history of the Nanushuk Group, central North Slope. *A*, Early-mid Albian time; *B*, mid-late Albian time; *C*, late Albian-Cenomanian(?) time; *D*, Cenomanian time (at time of maximum regression).

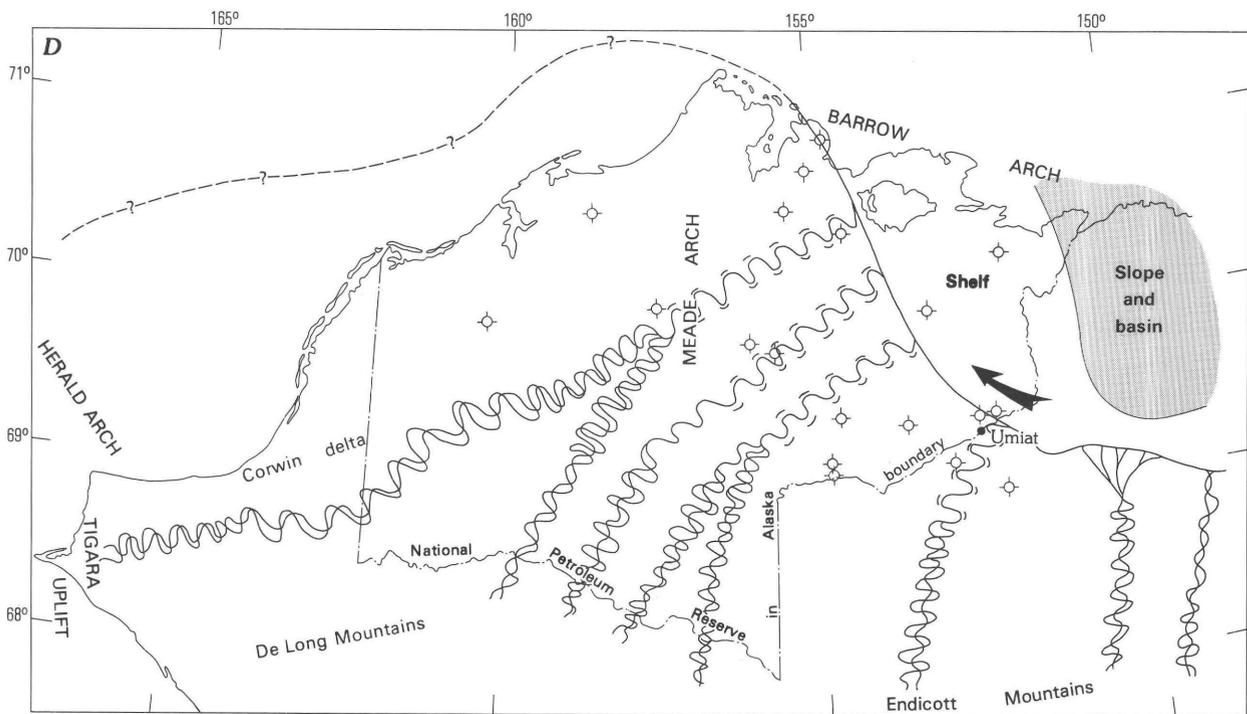
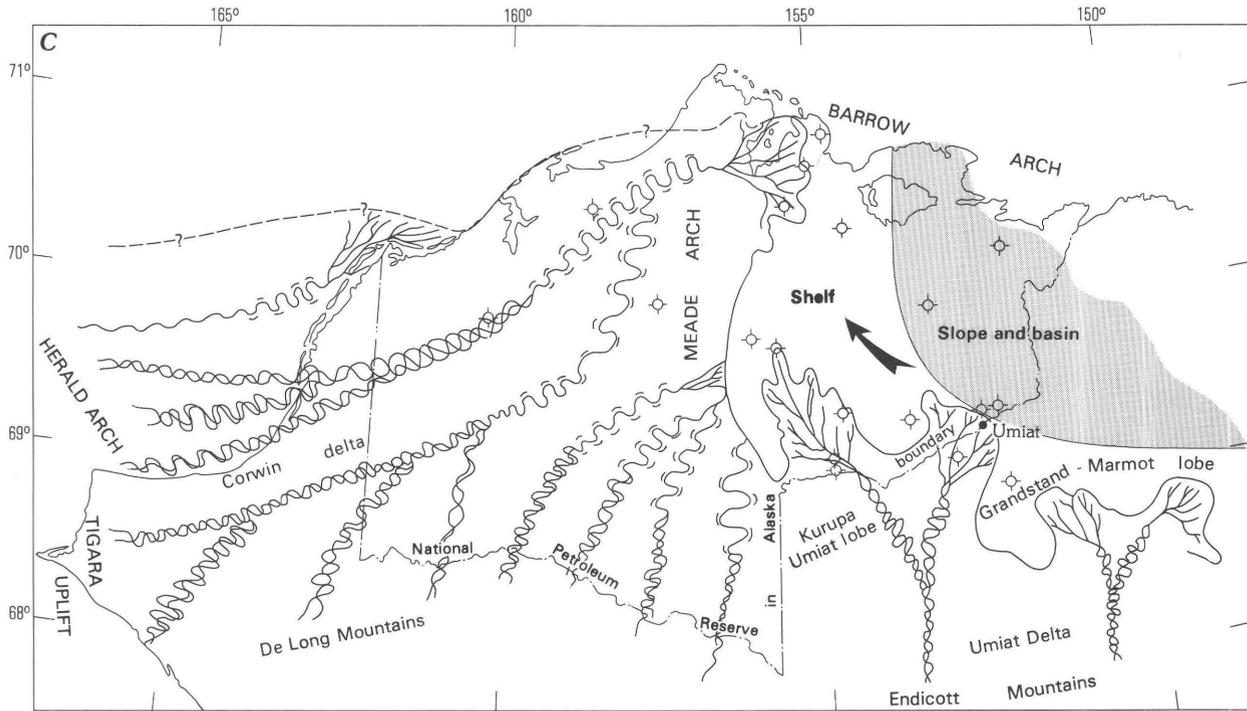


Figure 31. Continued

to the northeast and east with large deltaic subembayments between them (fig. 31B and C). The southern lobe did not extend east of long 159° W. as a recognizable entity. Between long 159° W. and 157° W., deposition was pre-

dominantly interdeltic, with little sandstone deposition but thick delta-plain and coastal-plain deposits (fig. 31B and C). This environment existed as far north as the Meade-1 test well. The northern lobe of the Corwin delta

apparently swung to the north of the Meade-1 well and continued around the northern end of the ancestral Meade arch.

As the Corwin delta prograded northeast and east, the shelf and slope migrated generally eastward. During mid-Albian time the Umiat delta began building northward from the Endicott Mountains onto a shelf constructed of material derived from the south and west (fig. 31B). Because of the narrow shelf and the proximity to the open end of the Colville basin, wave and current activity was greater than that which affected the construction of the Corwin delta. The Umiat delta began as an elongate river-dominated system (fig. 31B), but as the effects of waves and currents increased, the delta assumed a more lobate character (fig. 31C).

Material supplied to the Umiat delta was both coarser and more quartzose than that of the Corwin delta. As the delta prograded generally northward, clastics were carried northwestward by longshore drift and current activity. These sediments were deposited along a north- to northwest-trending strandline that slowly prograded eastward (fig. 31C). Streams from the Corwin delta continued to transport and deposit sediment in deltaic environments

in the vicinity of the Topagoruk and South Simpson-1 test wells. Mixing of the Corwin and Umiat sediment types occurred throughout much of the marine and transitional parts of Nanushuk deposition from the Umiat delta northward.

Faunal evidence suggests that the Kurupa-Umiat lobe of the Umiat delta was initiated prior to the Grandstand-Marmot lobe (F. E. May, oral commun., 1979). Initiation of delta construction was probably determined more by the presence of a shelf that was prograding from west to east than by activity within the source area. The presence of coarse conglomerates at the base of and interspersed through the lower nonmarine part of the section suggests renewed uplift in the Endicott Mountains accompanied by rapid progradation of the delta northward.

Delta progradation was followed by a marine transgression in Late Cretaceous time (fig. 31D). Intertonguing of marine and nonmarine deposits and thin transgressive sandstones record transgressive pulses followed by still stands or regression. This transitional phase was followed by deposition of the marine Colville Group in what appears to be a normal transgressive relationship.

Petrography of Sandstones of the Nanushuk Group From Four Measured Sections, Central North Slope, Alaska

By Susan Bartsch-Winkler

INTRODUCTION

Ahlbrandt (1979) includes a reconnaissance petrographic examination of the Lower and Upper Cretaceous Nanushuk Group (Bartsch-Winkler, 1979, p. 61) and a detailed examination of the Barabara syncline section in the western outcrop belt (Huffman, 1979, p. 77). This report, a study of the eastern outcrop belt north of the central and east-central Brooks Range, is a continuation of the earlier study. Included are descriptions of the Kurupa anticline, Tuktu Bluff, Arc Mountain, and Marmot syncline sections, all south and east of the National Petroleum Reserve in Alaska (NPRA), and the Colville River (fig. 32). Modal analyses were performed on a total of 94 thin sections, and many more slides were examined for textural details. The stratigraphic sections range in depositional setting from fluvial to deltaic to shallow marine and show variations in texture, composition, and diagenetic alteration.

DESCRIPTION OF MEASURED SECTIONS

Stratigraphic sections were measured using a combination of tape and Jacob-staff techniques and described in Huffman and others (1981b). The sandstone intervals were measured and described on a meter-by-meter basis; the shale intervals were described in less detail. Sampling for porosity, permeability, and petrographic studies was not systematic, but instead concentrated on the coarser grained sandstones that would be most favorable as petroleum reservoirs. The thicker, coarser beds were sampled at several horizons. All of the sections grade from marine at the base to nonmarine at the top (fig. 33).

Kurupa Anticline Section, Killik River Quadrangle

The base of the Kurupa anticline section forms bluffs at the junction of Heather Creek and the Kurupa River north of the Tuktu escarpment. The Kurupa anticline section, the westernmost described here, extends for 4 km and totals 1,867 m in thickness. About 672 m (36

percent) of section is exposed, and approximately 413 m (22 percent) of the section is sandstone. The basal part consists of prodelta mudstone; it is overlain by estuarine and intertidal mudstone and siltstone and beach sandstone deposits. Braided and meandering stream deposits of sandstone and conglomerate cap the section.

Tuktu Bluff Section, Chandler Lake Quadrangle

The Tuktu Bluff section crops out just south of the Chandler River as part of the Tuktu escarpment between Tuktu Bluff on the west and Gunsight Pass on the east. The section is 5 km long, and about 1,823 m of strata was measured. Approximately 22 percent of the interval is exposed, and 21 percent (385 m) is sandstone. The sequence of depositional environment is lower shoreface at the base, succeeded by upper shoreface, delta front, tidal delta and tidal channels, and river-mouth bar and braided stream at the top (fig. 33).

Arc Mountain Section, Chandler Lake Quadrangle

The Arc Mountain section, north of the Tuktu escarpment, is 3 km long and comprises 516 m of strata. About 97 percent of the section is exposed, and 40 percent is sandstone (205 m). Foreshore and shoreface sandstones, interpreted as the base of the section, grade upward into prodelta and delta-front sandstones that are capped by fluvial and interdistributary bay-fill deposits (fig. 33).

Marmot Syncline Section, Phillip Smith Mountains Quadrangle

The Marmot syncline section, the easternmost section studied, is west of the junction of the Sagavanirktok River and Accomplishment Creek, is about 2 km long, and had a total thickness of 1,060 m. About 496 m (47

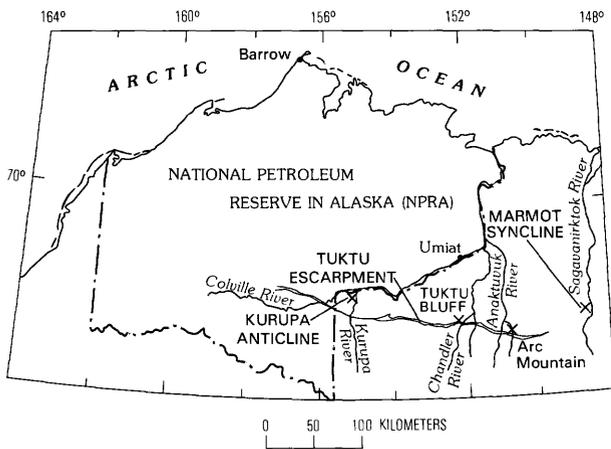
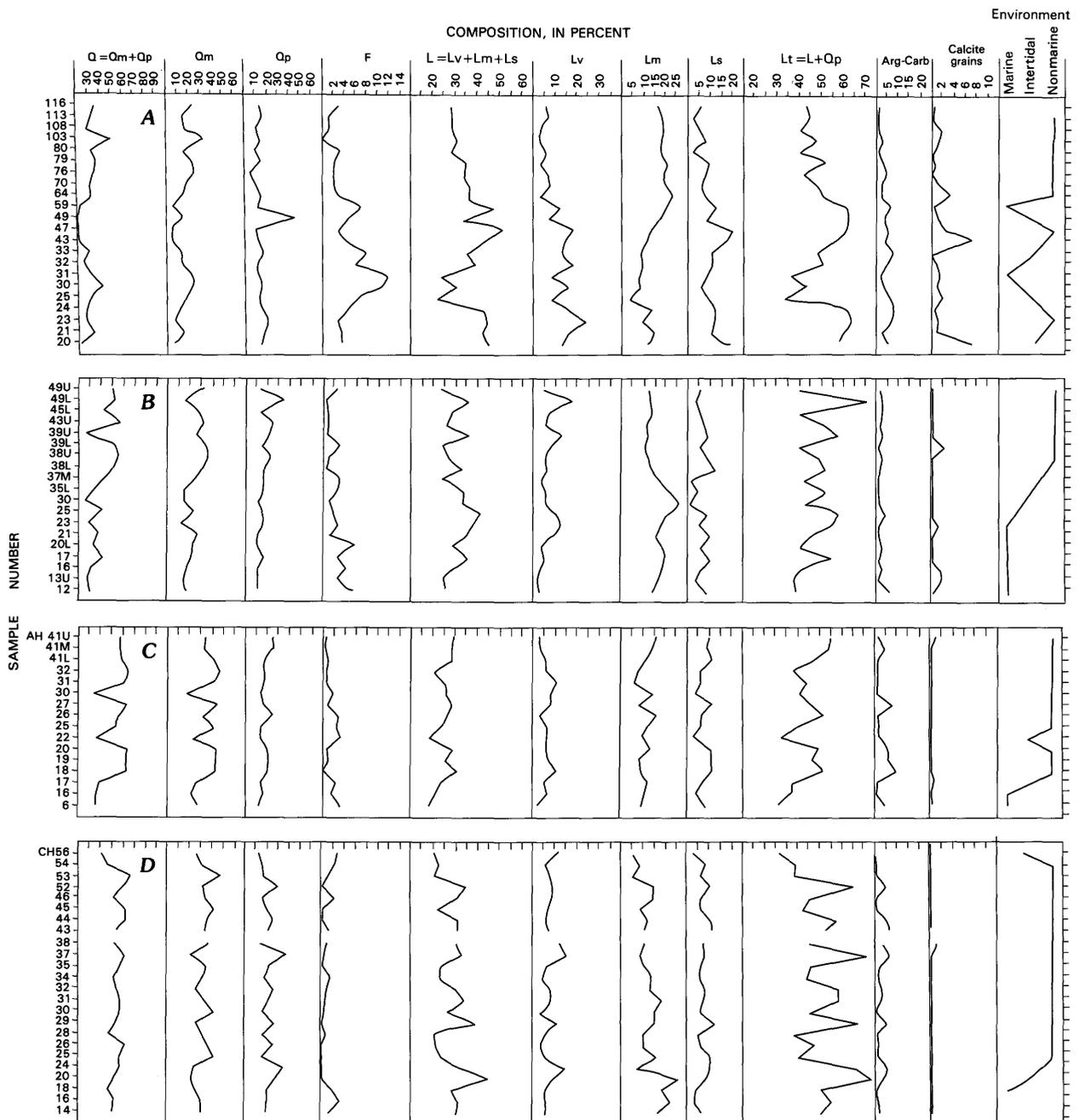


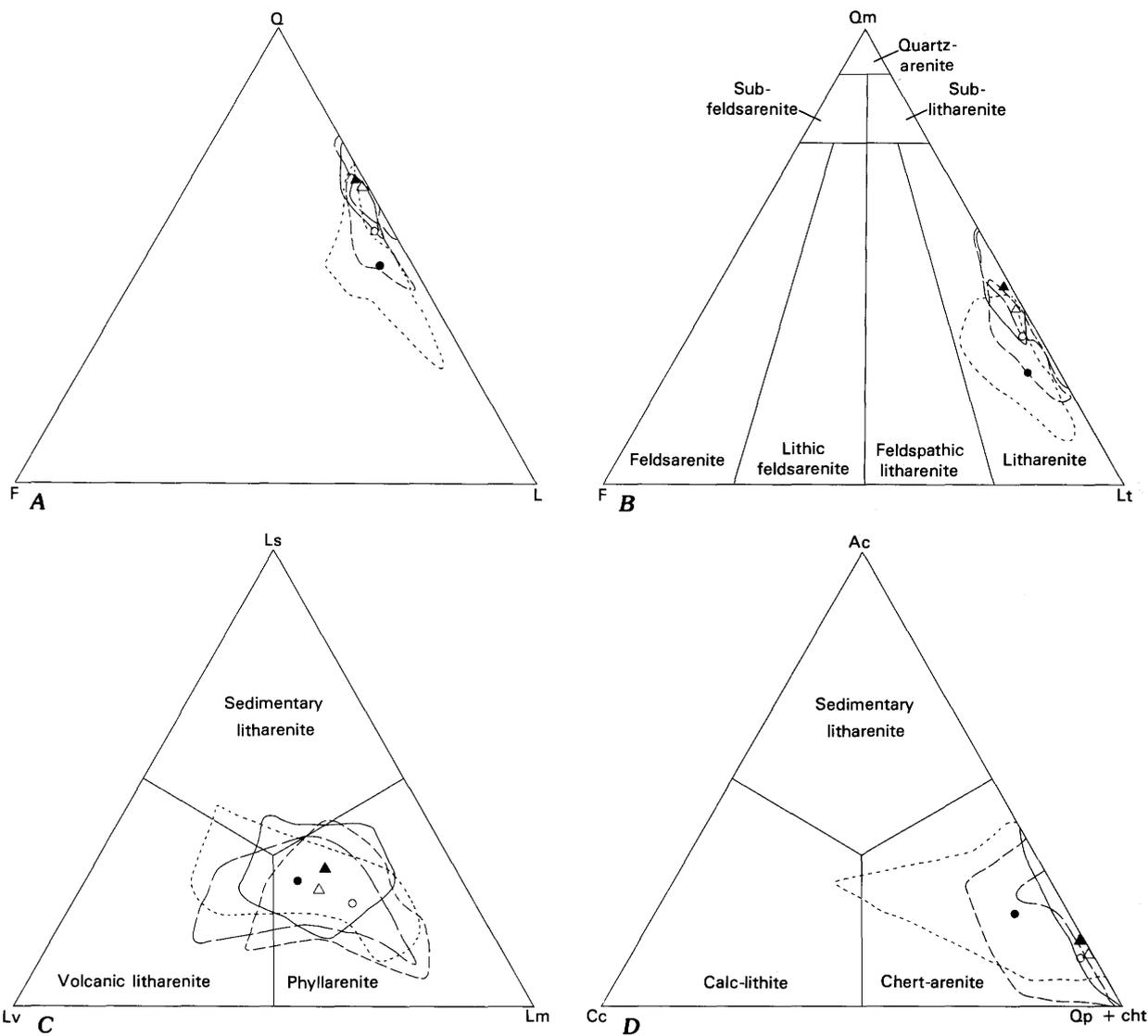
Figure 32. Location of the four measured sections discussed in this study.

percent) of the section is exposed, and about 271 m (26 percent) of the section is sandstone. The lower 270 m is interpreted as being deposited in lower shoreface and foreshore environments and is succeeded by about 20 m of intertidal sedimentary rocks, overlain by 770 m of fluvial (braided and meandering stream) deposits (fig. 33).

PETROGRAPHY

The thin sections were stained with sodium cobalt-nitrite to aid in identification of potassium feldspar, and with alizarin red S to aid in identification of dolomite. Owing to the poor quality of the thin sections, especially





EXPLANATION

Measured section	Average modal composition	Outer limit of modal plots
Kurupa Anticline	●	-----
Tuktu Bluff	○	-----
Arc Mountain	▲	-----
Marmot syncline	△	-----

Figure 34. Triangular plots showing outer limits of modal plots for each measured section discussed in this report and the average modal composition of each. Q, monocrystalline and polycrystalline quartz, quartzite, and chert; Qm, monocrystalline quartz; F, feldspar grains; L, volcanic, metamorphic, and sedimentary lithic fragments; Lt, total lithic fragments and polycrystalline quartz; Lt, total lithic grains; Lv, volcanic lithic fragments; Lm, metamorphic lithic fragments; Ls, sedimentary lithic fragments; Qp + cht, polycrystalline quartz, quartzite, and chert; Ac, argillaceous and carbonaceous grains; Cc, calcareous grains.

Figure 33 (facing page). Graphs showing environment of deposition and compositions of sandstones as determined from modal analyses of samples from four measured sections, Nanushuk Group, North Slope, Alaska. A, Kurupa anticline. B, Tuktu Bluff. C, Arc Mountain. D, Marmot syncline. Q, monocrystalline and polycrystalline quartz, quartzite, and chert; Qm, monocrystalline quartz; Qp, polycrystalline quartz, quartzite, and chert; F, feldspars; L, volcanic, metamorphic, and sedimentary lithic fragments; Lv, volcanic lithic fragments; Lm, metamorphic lithic fragments; Ls, sedimentary lithic fragments; Lt, total lithic fragments and polycrystalline quartz; Arg-Carb, argillaceous and carbonaceous grains. All samples have less than 30 percent matrix and less than 30 percent cement by volume. Total matrix and cement may not exceed 35 percent.

Table 6. Modal analyses of surface samples of sandstone from four measured sections in the Lower and Upper Cretaceous Nanushuk Group, central North Slope, Alaska

[Q, monocrystalline and polycrystalline quartz, quartzite, and chert; Qm, monocrystalline quartz; Qp, polycrystalline quartz, chert, and quartzite; F, feldspars; L, volcanic, metamorphic, and sedimentary lithic fragments; Lv, volcanic lithic fragments; Lm, metamorphic lithic fragments; Ls, sedimentary lithic fragments; Lt, total lithic fragments and polycrystalline quartz; Ac, argillaceous and carbonaceous grains; Cc, calcareous grains. All values in percent; all samples listed have less than 30 percent matrix and less than 30 percent cement, by volume. Total matrix and cement do not exceed 35 percent. Modal data not recalculated to 100 percent but is percentage of total point counts for each sample. Grain size classes, measured petrographically, are: fs, fine sand; ms, medium sand; cs, coarse sand; vcs, very coarse sand]

Sample No.	Grain-size class	Grain type													Matrix	Cement
		Q	Qm	Qp	F	L	Lv	Lm	Ls	Lt	Ac	Cc	Mica			
Kurupa anticline section																
20	fs----	22.3	9.3	13.0	3.7	45.0	14.7	12.3	18.0	58.0	5.0	7.0	0.3	4.7	25.6	
21	ms----	34.3	15.3	19.0	3.7	42.0	15.7	15.0	11.3	61.0	2.7	.3	.0	7.0	7.3	
23	cs----	29.0	9.0	20.0	3.0	44.7	24.0	9.0	11.7	64.7	7.0	.7	.0	11.6	3.7	
24	cs----	29.9	12.0	17.0	2.7	43.3	16.6	14.4	12.3	60.3	7.3	.3	.0	6.3	20.3	
25	fs----	38.8	27.4	11.4	6.0	22.9	9.0	4.0	9.9	34.3	6.6	2.0	1.3	12.1	20.0	
30	fs----	31.6	18.3	13.3	11.7	30.6	15.7	8.6	6.3	43.9	3.3	1.0	.3	17.0	6.7	
31	fs----	34.0	21.7	12.3	12.0	24.9	9.6	8.0	7.3	37.2	2.3	1.7	.0	9.7	11.3	
32	fs----	28.7	16.0	12.7	6.3	39.3	18.4	10.0	10.9	52.0	5.3	1.3	1.3	8.0	9.9	
33	ms----	31.3	13.3	18.0	8.0	35.8	14.7	9.7	11.4	53.8	7.7	.0	.7	11.0	2.0	
43	fs----	21.0	7.7	13.3	4.3	43.4	14.7	12.0	16.7	56.7	4.7	7.7	1.0	6.0	28.3	
47	ms----	18.9	8.3	10.6	3.7	51.4	18.0	13.3	20.1	62.0	5.7	8.7	.3	6.6	22.7	
49	fs----	32.2	17.9	14.3	5.0	36.4	9.3	17.9	9.2	50.7	4.3	1.3	1.3	21.9	7.2	
59	ms----	23.4	8.7	14.7	6.7	47.0	14.4	20.0	12.6	61.7	6.0	.3	.3	11.0	8.7	
64	fs----	32.3	17.3	15.0	3.7	36.0	4.3	24.0	7.7	51.0	3.3	3.7	.3	5.7	25.7	
70	fs----	32.0	20.0	12.0	2.3	36.4	9.4	20.3	6.7	48.4	2.7	1.7	.7	24.3	4.9	
74	ms----	29.6	19.3	10.3	2.3	27.0	6.7	15.6	4.7	37.3	3.7	.0	1.3	1.7	39.7	
76	cs----	38.0	28.7	9.3	2.3	35.0	7.3	20.0	7.7	44.3	5.0	.0	.0	16.0	4.7	
79	ms----	39.6	23.3	16.3	2.3	35.4	4.7	20.7	10.0	51.7	3.3	.7	2.7	17.0	3.7	
80	fs----	31.3	19.0	12.2	3.7	28.4	6.7	18.7	3.0	40.7	1.0	.3	15.3	19.3	.7	
103	cs----	50.6	34.3	16.3	.0	31.6	4.0	18.0	9.6	47.9	3.0	1.3	4.3	11.3	4.3	
108	cs----	31.7	19.0	12.7	1.7	29.7	4.3	19.7	5.7	42.4	.7	1.7	14.3	16.0	7.0	
113	fs----	33.3	16.3	17.0	1.7	28.7	7.3	18.7	2.7	45.7	1.0	.0	21.7	18.7	1.6	
116	fs----	38.3	23.0	15.3	3.3	27.7	6.7	15.7	5.3	44.6	1.3	.3	10.3	18.3	1.6	
Average-----		32.2	18.0	14.7	4.4	36.5	11.7	15.0	10.0	51.4	4.3	1.8	3.4	12.4	10.1	
Tuktu Bluff section																
12	fs----	31.3	19.0	12.3	5.3	26.9	3.7	14.6	8.6	39.2	5.3	0.3	9.3	26.0	3.0	
13U	fs----	29.0	16.0	13.0	2.7	25.0	3.0	17.4	4.6	38.0	.3	2.0	17.7	19.7	8.3	
16	fs----	30.0	18.0	12.0	4.3	29.2	4.0	18.6	6.6	41.2	3.3	2.0	17.7	14.6	9.0	
17	ms----	42.0	23.0	19.0	2.7	36.6	6.0	20.0	10.6	55.6	1.3	.0	2.1	18.4	5.0	
20L	fs----	34.1	22.7	11.4	6.0	29.7	4.6	18.4	6.7	41.1	2.7	.0	28.7	25.7	3.0	
21	cs----	39.0	27.3	11.7	1.7	35.6	9.0	16.3	10.3	47.3	1.0	.0	4.7	14.3	6.4	
23	fs----	30.0	12.7	17.3	2.7	38.0	13.0	19.3	5.7	55.3	1.7	1.7	5.7	9.7	15.7	
25	ms----	41.0	24.0	17.0	2.0	41.7	10.3	21.7	9.7	58.7	4.7	.0	3.3	9.3	10.0	
30	fs----	26.0	15.0	11.0	1.3	33.4	6.0	25.4	2.0	44.4	.7	.3	8.0	28.0	5.0	
35L	fs----	34.6	15.8	18.8	2.6	33.1	5.3	22.8	5.0	51.9	.7	.3	14.5	17.1	3.0	
37M	fs----	43.9	25.3	18.6	3.2	24.9	4.8	17.9	2.2	43.5	.3	.0	10.9	14.4	7.1	
38L	ms----	51.5	33.1	18.4	.3	33.7	6.8	13.3	13.6	52.1	2.0	.0	1.4	15.9	.6	
38U	ms----	58.7	36.7	22.0	1.3	27.6	5.7	12.2	9.7	49.6	2.8	.0	4.1	11.0	1.1	
39L	fs----	51.3	35.2	16.1	3.2	24.3	8.1	10.6	5.6	40.4	1.0	2.3	5.8	13.6	4.3	
39U	cs----	51.2	28.7	22.5	.7	35.4	13.3	12.4	9.7	57.9	2.9	.0	2.0	12.7	2.0	
43U	cs----	59.0	33.0	26.0	1.0	26.0	6.6	12.0	7.4	52.0	1.7	.0	.3	17.4	.0	
45L	fs----	42.1	28.7	13.4	1.0	28.0	7.6	14.7	5.7	41.4	2.7	.0	8.3	21.0	1.0	
49U	cs----	50.3	34.3	16.0	2.7	24.6	5.6	13.0	6.0	40.6	1.3	.0	4.3	19.0	1.0	
49L	fs----	53.6	17.3	36.3	.3	36.7	18.3	14.0	4.4	73.0	2.7	.0	.0	2.3	1.3	
Average-----		42.0	24.5	17.5	2.4	31.1	7.5	16.6	7.1	48.6	2.1	.5	7.8	16.3	4.6	

Table 6. Continued

Sample No.	Grain-size class	Grain type													
		Q	Qm	Qp	F	L	Lv	Lm	Ls	Lt	Ac	Cc	Mica	Matrix	Cement
Arc Mountain section															
6	fs----	38.7	25.7	13.0	3.0	17.4	2.0	8.4	7.0	30.4	4.7	0.3	14.7	25.3	3.3
16	fs----	36.9	21.0	15.9	1.9	21.3	6.1	11.1	4.1	37.2	.0	.0	18.2	19.7	2.2
17	fs----	39.4	26.0	13.4	2.3	23.3	5.0	12.0	6.3	36.7	1.7	.3	10.0	23.0	1.6
18	vcs----	62.9	42.7	20.2	.0	31.5	10.9	9.3	11.3	51.7	9.6	.0	.3	5.3	1.0
19	ms----	62.6	42.3	20.3	1.0	26.0	7.0	8.6	10.4	46.3	5.7	.0	1.3	10.0	1.6
20	ms----	63.3	43.3	20.0	.3	29.3	6.3	12.7	10.3	49.3	5.0	.0	2.7	7.3	.6
22	fs----	38.3	23.3	15.0	3.7	18.7	6.0	10.0	2.7	33.7	1.7	.0	16.0	18.7	4.7
25	ms----	55.1	40.7	14.4	2.3	24.8	6.7	12.4	5.7	39.2	1.7	.0	4.3	16.4	.6
26	ms----	56.3	31.3	25.0	2.3	26.6	3.6	16.0	7.0	51.6	1.0	.0	7.3	12.0	.3
27	cs----	62.3	45.0	17.3	.7	28.7	8.7	8.0	12.0	46.0	7.3	.0	.0	2.7	2.0
30	ms----	34.3	19.7	14.6	2.0	26.7	8.0	14.0	4.7	41.3	.7	.0	9.0	22.0	.7
31	cs----	61.6	42.3	19.3	.7	25.2	11.3	7.6	6.3	44.5	1.3	.0	.7	6.3	4.4
32	ms----	64.7	47.3	17.4	.7	21.1	6.7	8.4	6.0	38.5	1.3	.0	.7	10.7	.6
41L	ms----	59.9	41.2	18.7	1.0	28.6	6.6	11.7	10.3	47.3	1.7	.0	2.0	9.0	1.0
41M	cs----	58.7	32.3	26.4	.3	28.4	4.3	14.7	9.4	54.8	4.7	.0	3.3	12.3	1.6
41U	cs----	58.6	33.0	25.6	.3	29.3	.3	16.0	10.0	54.9	1.3	.7	3.3	12.7	.3
Average	-----	53.4	34.8	18.5	1.4	25.4	6.4	11.3	7.7	44.0	3.1	.1	5.9	13.3	1.7
Marmot syncline section															
14	fs----	51.4	31.0	20.4	1.7	31.3	7.3	17.4	6.6	51.7	1.3	.0	6.0	13.6	2.3
16	cs----	52.9	30.3	22.6	3.3	32.0	6.0	23.0	3.0	55.6	1.0	.0	6.3	10.0	2.7
18	fs----	48.0	26.7	21.3	2.0	29.3	6.3	18.7	4.3	50.6	1.3	.0	7.0	13.0	3.0
20	cs----	52.3	23.3	29.0	.0	45.4	9.0	26.7	9.7	74.4	3.7	.0	1.3	10.3	.3
24	vcs----	59.3	25.3	34.0	.0	33.3	15.0	8.0	10.3	67.3	5.3	.0	.0	2.7	1.4
25	cs----	58.3	41.0	17.3	.0	24.4	6.4	16.3	11.7	41.7	2.0	.0	.7	8.3	2.1
26	ms----	62.7	37.0	25.7	.0	22.1	4.4	11.0	6.7	47.8	2.0	.0	4.0	9.4	2.0
28	fs----	49.0	31.0	18.0	.7	21.7	6.4	10.3	5.0	39.7	.7	.0	3.3	23.7	2.3
29	ms----	54.7	27.0	27.7	.0	39.7	12.0	15.4	12.3	67.4	5.3	.0	2.3	7.4	2.9
30	cs----	59.3	41.0	18.3	.3	27.0	4.7	15.3	7.0	45.3	1.0	.0	6.0	12.3	1.0
31	vcs----	59.0	35.3	23.7	.7	34.4	8.3	18.7	7.4	58.1	3.7	.0	1.0	8.4	.3
32	ms----	55.6	27.3	28.3	1.0	30.6	8.0	14.3	8.3	58.9	4.3	.0	4.7	9.0	.2
34	fs----	52.4	32.7	19.7	1.7	24.8	5.0	14.4	5.4	44.5	1.7	.0	8.7	13.4	.3
35	cs----	58.0	35.7	22.3	.0	24.3	7.0	11.0	6.3	46.6	2.3	.0	4.7	14.0	.3
37	cs----	60.9	21.3	39.6	.3	33.3	15.7	9.3	8.3	72.9	7.0	.0	.3	5.0	2.6
38	cs----	53.3	39.0	14.3	1.3	31.0	13.4	10.3	7.3	45.3	3.7	1.3	.3	8.7	8.3
43	cs----	54.0	33.2	20.8	1.5	31.1	8.8	10.4	11.0	51.9	7.0	.0	.0	14.9	1.8
44	cs----	63.0	37.0	26.0	.0	31.4	7.0	12.7	11.7	57.4	5.7	.0	.7	6.6	.3
45	ms----	62.0	41.7	20.3	.3	23.3	7.4	9.3	6.6	43.6	.3	.0	3.3	11.3	2.3
46	fs----	53.3	35.7	17.6	2.3	30.0	9.7	15.0	5.3	47.6	1.0	.0	4.3	11.0	.6
52	vcs----	62.7	32.7	30.0	.0	35.0	9.7	15.0	10.3	65.0	5.0	.0	1.7	3.6	.3
53	ms----	67.7	49.7	18.0	1.3	21.0	8.3	6.3	6.4	39.0	.7	.0	1.7	9.0	.6
54	fs----	47.3	31.3	16.0	2.3	23.3	7.0	9.0	7.3	39.3	1.3	.0	6.7	21.0	1.7
56	fs----	40.4	28.7	11.7	2.7	21.0	12.3	5.7	3.0	32.7	.3	.0	12.7	24.4	2.3
Average	-----	55.7	33.1	22.6	1.0	29.2	8.5	13.5	7.6	51.8	2.8	.1	3.7	11.3	1.8

in staining and impregnation, modal data on visible porosity and potassium feldspar content are considered tentative. For modal analyses, 300 grains were counted per thin section, according to the methods described by Dickenson (1970).

Compositional Data

Compositionally, sandstones of the Nanushuk Group from the eastern outcrop belt are classified as litharenites (Folk, 1968). The sandstones making up the

easternmost Arc Mountain and Marmot syncline sections have more chert and monocrystalline and polycrystalline quartz grains than do the more micaceous sandstones rich in lithic grains to the west, which compose the Kurupa anticline and Tuktuk Bluff sections.

Mineralogy and Grain Types

Quartzose grains include monocrystalline quartz, polycrystalline quartz, chert, and quartzite. The monocrystalline grains include undulose types as well as those

with straight extinction angles. Quartzite grains are those with elongated crystallite morphologies, lacking any mica. Polycrystalline quartz grains may have a wide range in crystallite dimensions, even in a single grain. For this reason, grains with crystallites smaller than 0.03 mm, which most workers would classify as chert, 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 is not a significant component in sandstones of the Nanushuk Group, and where it is present, it is significantly altered. Most feldspar grains are blocky and show albite and Carlsbad twinning. Perthitic and myrmekitic feldspar types are also present.

Lithic grains are typically altered by compaction and (or) replacement. Sedimentary lithic grain types include calcareous, argillaceous or carbonaceous grains, and unfoliated quartz-mica grains. Metamorphic lithic grains include quartzite and foliated quartz-mica grains. Volcanic lithic grain types include felsite, microlitic volcanic, and microgranular-hypabyssal grains. Trends in lithic grain compositions may be questionable due to their generally smaller grain size and their apparent susceptibility to alteration and recrystallization. Also, microcrystalline felsite grains and quartzite grains having only slightly elongate crystallites may be difficult to distinguish from polycrystalline quartz grains.

More detailed descriptions of grain types in sandstones of the Nanushuk Group may be found in Huffman (1979, p. 80–83) and Fox (1979, p. 50–52).

Modal Distribution

Compositional data for each of the measured sections are shown graphically in figure 33. No consistent vertical compositional trends were found in a comparison of all four sections. Tuktuk Bluff and Arc Mountain sections are the most comparable in that both show an upwardly decreasing content of feldspar and increasing content of total quartzose grains, polycrystalline quartz grains, and total lithic grains. The Kurupa anticline section has a decreasing amount of volcanic lithic grains and feldspars and an increasing amount of metamorphic lithic grains. In contrast, the plot of the Marmot syncline section indicates a decreasing amount of metamorphic lithic grains upward.

Ternary plots (figs. 34A–D) of the data shown in figure 33 show that the sandstones of the Nanushuk Group from the eastern outcrop belt are compositionally litharenite (Folk, 1968). On the triangular plot with quartzose grains, feldspar grains, and lithic grains (fig. 34A), an eastward trend from Kurupa anticline to Marmot syncline is clearly shown by increasing quartzose grains and decreasing lithic and feldspar grains. Total percentages of quartz, monocrystalline quartz, and polycrystalline quartz

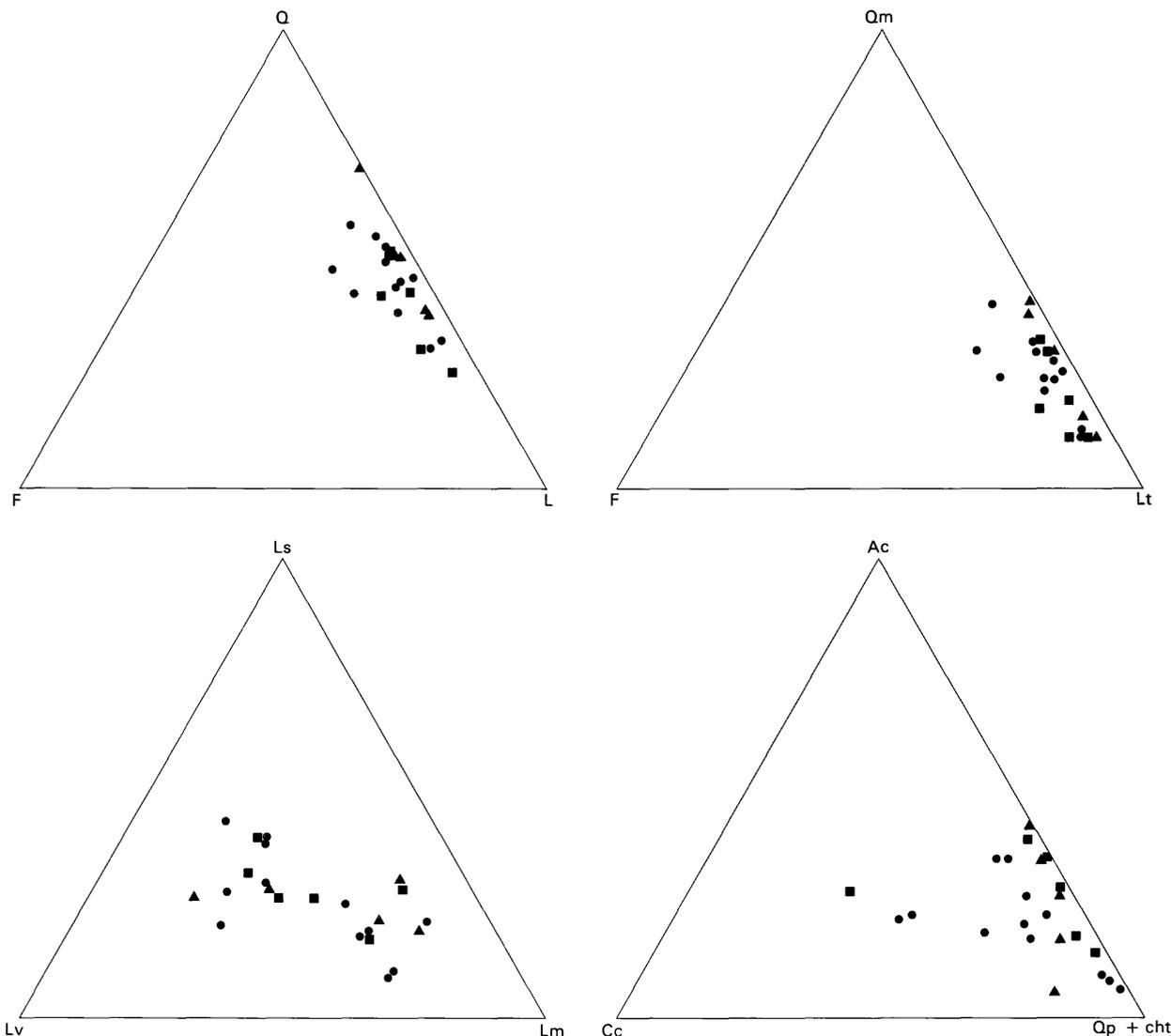
increase eastward by 13, 3, and 11 percent, respectively (table 6). The ternary plot having lithic grains as end members (fig. 34C) shows the average composition of the sandstones to be phyllarenite, although some samples of sandstones of the Nanushuk Group may fall into volcanic and sedimentary litharenite categories as well. Characteristic lithic types (argillaceous/carbonaceous, calcareous, and chert/polycrystalline quartz) plotted on a ternary diagram (fig. 34D) show an eastward trend of increasing chert and polycrystalline quartz grains with a reduction in both argillaceous/carbonaceous grains and calcareous grains; the sandstones are classified as chert arenites. Percentages of calcareous grains in sandstones decrease rapidly eastward from the Kurupa anticline section. Only trace amounts (less than 1 percent) of calcareous grains may be found in the Arc Mountain, Marmot syncline, and Tuktuk Bluff sections (table 6).

Textural Data

Maximum and mean grain size was measured under the petrographic microscope and estimated in the field using the American Stratigraphic Company grain-size chart. Roundness was estimated petrographically by comparison with the Krumbein (1941) visual estimator. Rock chips were mounted in Lakeside¹ cement, coated with gold-palladium, and examined using a Cambridge-180¹ scanning electron microscope (SEM) with an attached energy-dispersive X-ray analyzer in order to further disclose the relation between grains, pores, and cements.

Using the petrographic microscope, textural parameters were determined by estimation of sorting and packing density. Sorting was estimated by referring to sorting images illustrated by Pettijohn and others, (1972, p. 585). Estimated packing density was determined visually using these criteria: high, framework grains tightly packed with abundant penetration involving squeezing of relatively soft lithic fragments between and around more resistant grains such as quartz and feldspar; moderate, closely packed framework with minor grain interpenetration and little or no deformation of lithic fragments; and low, framework separated by or floating in matrix (including highly deformed material without recognizable grain boundaries) or authigenic cement with no observable grain interpenetration. Type of grain contacts (Taylor, 1950) include (1) sutured grains, mutual stylolitic interpenetration of two or more grains (which must be carefully distinguished from grains of polycrystalline quartz); (2) concavo-convex grain contacts; (3) long or straight contacts; (4) point or tangential contacts; and (5) floating grains that are not in contact with other framework constituents. Most sam-

¹Use of trade names is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey



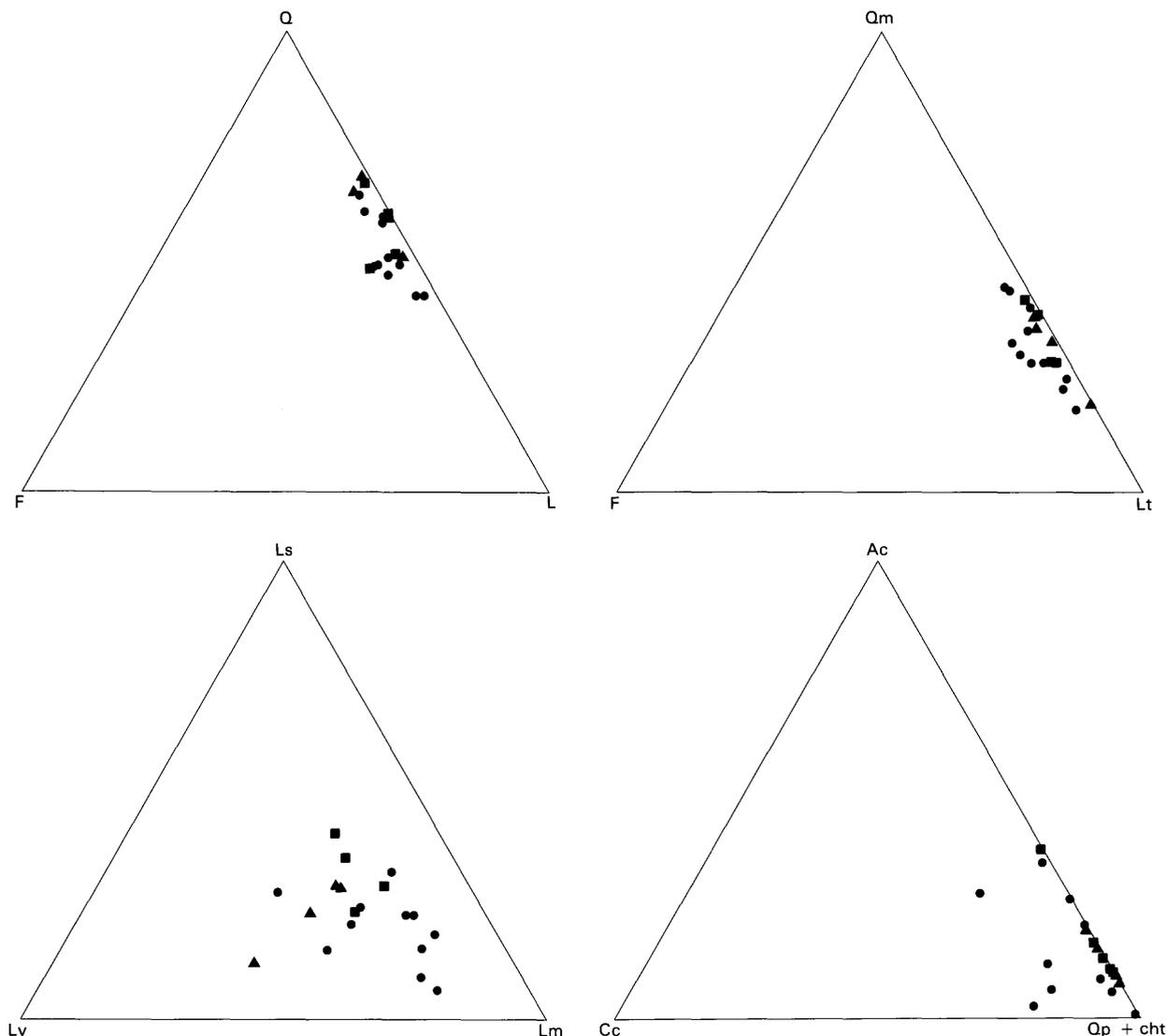
Symbol	Class	n	Amount (percent)	Q	F	L	Qm	Lt	Lv	Lm	Ls	Qp+ cht	Ac	Cc
●	Fine sand-----	12	52	45	8	47	26	67	32	43	25	67	21	13
■	Medium sand---	6	26	40	6	54	20	74	30	42	28	65	27	8
▲	Coarse sand---	5	22	50	3	47	28	70	28	47	25	70	25	5
	Total-----	23	100											
	Average-----			45	6	49	25	70	31	44	26	67	23	10

Figure 35. Triangular diagrams showing modal analyses plotted according to grain size, and table showing average modal composition for each grain-size class, Kurupa anticline section, North Slope, Alaska. n, number of samples; Q, quartzose grains (including monocrystalline and polycrystalline quartz, chert, and quartzite); F, feldspar grains; L, lithic grains; Qm, monocrystalline quartz; Lt, total lithic grains; Lv, volcanic lithic fragments; Lm, metamorphic lithic fragments; Ls, sedimentary lithic fragments; Qp + cht, polycrystalline quartz, quartzite, and chert; Ac, argillaceous and carbonaceous grains; Cc, calcareous grains.

ples show more than one type of grain contact. Textural components and cement plus matrix were determined from the modal analysis of each thin section. Matrix (as discussed by Dickinson, 1970) may be high in samples having significant amounts of phyllosilicate coatings and (or)

squeezed or compacted lithic fragments. Results of porosity and permeability tests are discussed by Huffman and others (this volume).

Estimates of average grain size measured with the petrographic microscope show that the sandstones of the

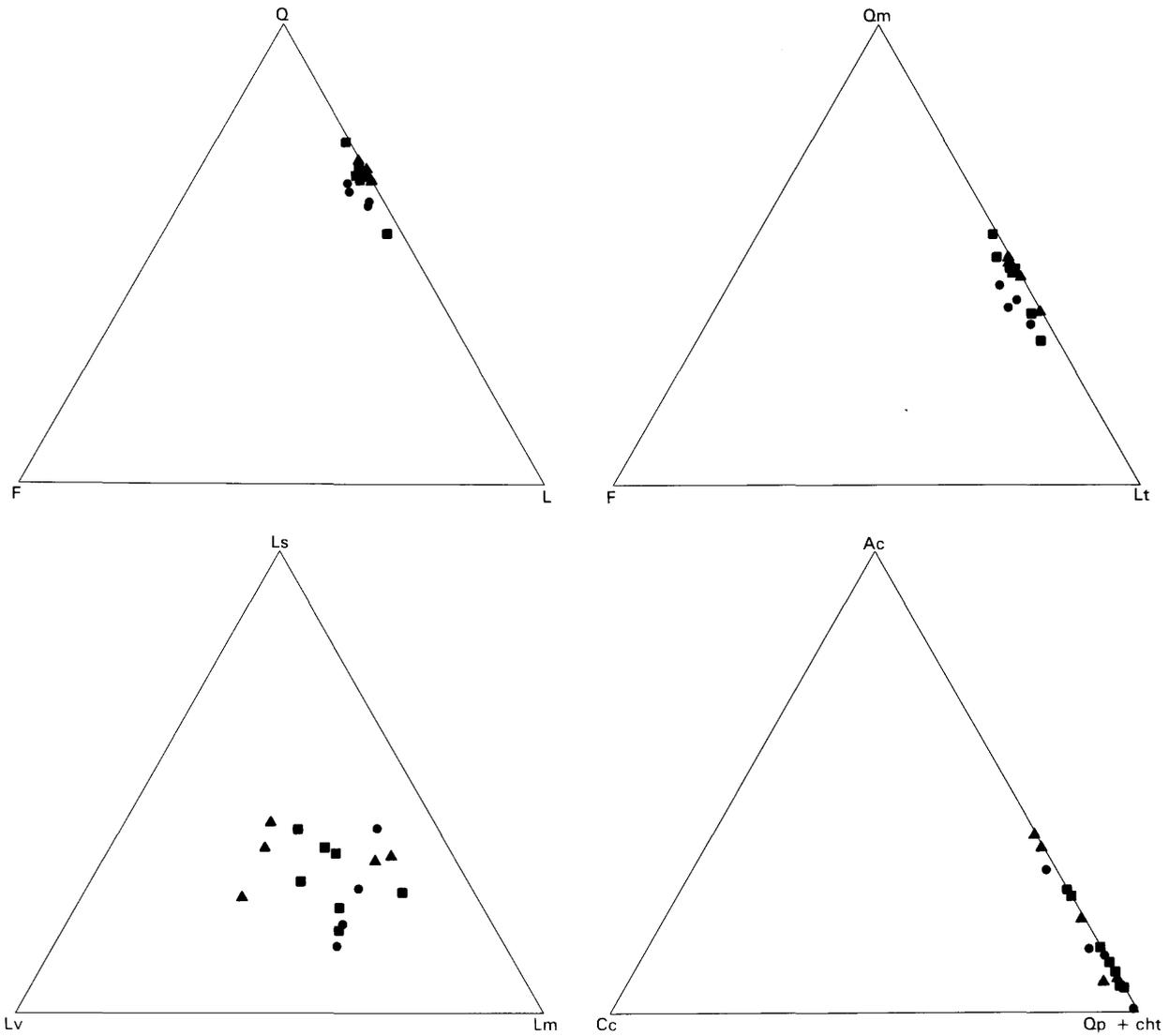


Symbol	Class	n	Amount (percent)	Q	F	L	Qm	Lt	Lv	Lm	Ls	Qp+ cht	Ac	Cc
•	Fine sand-----	11	58	53	5	43	32	64	21	61	19	80	14	6
■	Medium sand---	4	21	57	2	41	34	64	21	48	32	81	19	0
▲	Coarse sand---	4	21	59	1	40	32	67	35	41	24	89	11	0
	Total-----	19	100											
	Average-----			55	3	42	32	64	24	54	23	82	14	4

Figure 36. Triangular diagrams showing modal analyses plotted according to grain size, and table showing average modal composition for each grain-size class, Tuktu Bluff section, North Slope, Alaska. n, number of samples; Q, quartzose grains (including monocrystalline and polycrystalline quartz, chert, and quartzite); F, feldspar grains; L, lithic grains; Qm, monocrystalline quartz; Lt, total lithic grains; Lv, volcanic lithic fragments; Lm, metamorphic lithic fragments; Ls, sedimentary lithic fragments; Qp+cht, polycrystalline quartz, quartzite, and chert; Ac, argillaceous and carbonaceous grains; Cc, calcareous grains.

Nanushuk Group sampled are progressively coarser eastward (figs. 35–38). Sorting changes eastward from moderate to well sorted (fig. 40). Grain size determines the composition of these sandstones (figs. 35–39) and, in gen-

eral, the coarser sandstones are more quartzose, containing fewer feldspathic, micaceous, and calcareous components. Therefore, the coarsest sandstones to the east probably have the most favorable values of porosity and,



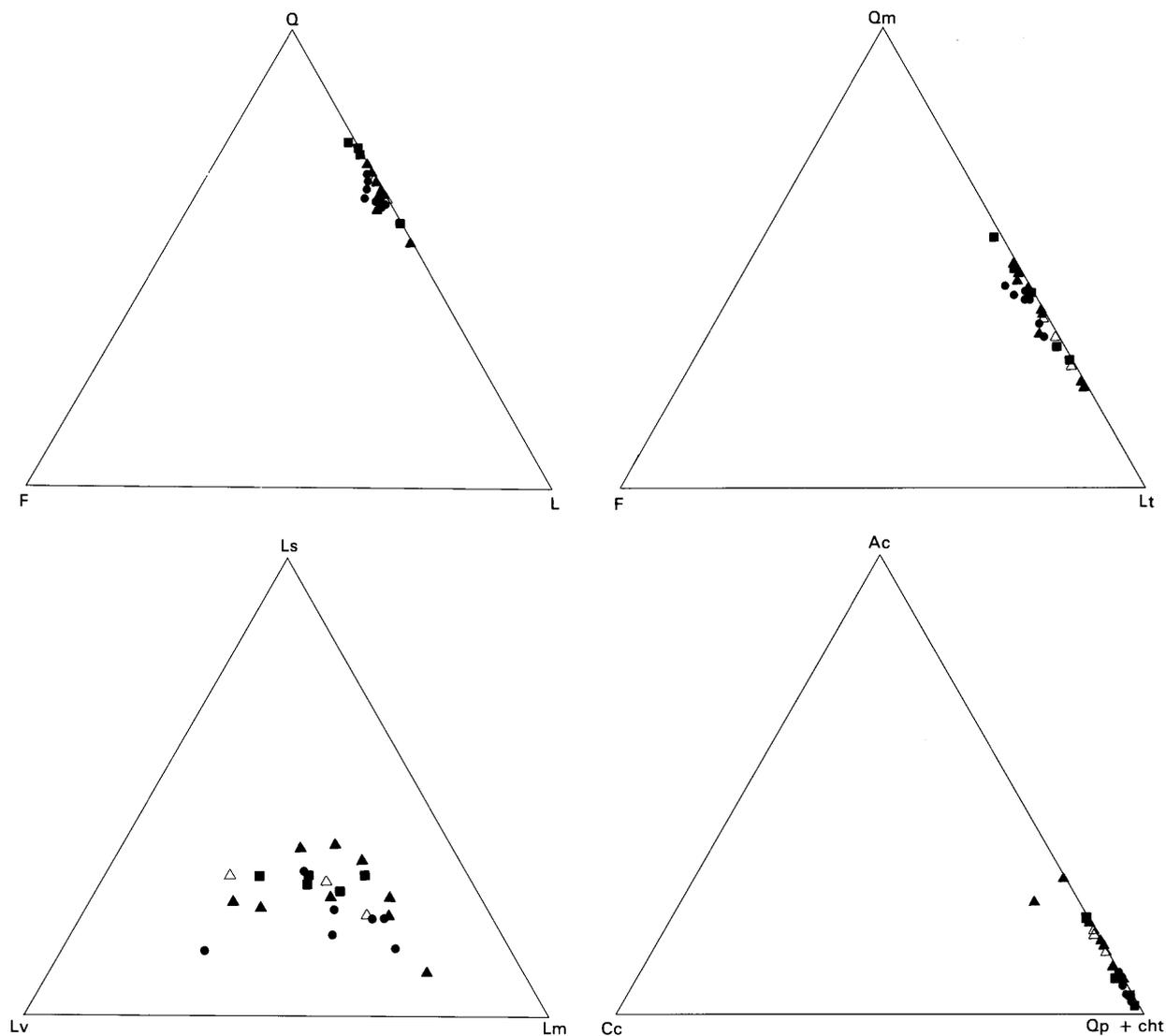
Symbol	Class	n	Amount (percent)	Q	F	L	Qm	Lt	Lv	Lm	Ls	Qp+ cht	Ac	Cc
•	Fine sand-----	4	25	63	5	33	39	56	21	51	25	85	14	1
■	Medium sand---	7	44	67	2	32	45	54	25	46	30	87	13	0
▲	Coarse sand--	5	31	68	0	32	43	56	27	39	34	78	22	1
	Total-----	16	100											
	Average-----			66	2	32	42	55	25	45	30	83	16	1

Figure 37. Triangular diagrams showing modal analyses plotted according to grain size, and table showing average modal composition for each grain-size class. Arc Mountain section, North Slope, Alaska. n, number of samples; Q, quartzose grains (including monocrystalline and polycrystalline quartz, chert and quartzite); F, feldspar grains; L, lithic grains; Qm, monocrystalline quartz; Lt, total lithic grains; Lv, volcanic lithic fragments; Lm, metamorphic lithic fragments; Ls, sedimentary lithic fragments; Qp+cht, polycrystalline quartz, quartzite, and chert; Ac, argillaceous and carbonaceous grains; Cc, calcareous grains.

owing to these mechanically and chemically more stable quartzose grains, have the least visible alteration by compaction. Lithic grains show no significant compositional variation with grain size. Vectorial analyses of grain size

and compositional trends in these sandstones are shown in figure 39.

The sandstones of the Nanushuk Group have undergone considerable alteration by compaction and are typi-



Symbol	Class	n	Amount (percent)	Q	F	L	Qm	Lt	Lv	Lm	Ls	Qp+cht	Ac	Cc
•	Fine sand-----	7	29	64	3	34	41	59	31	49	21	93	7	0
■	Medium sand-----	5	21	69	1	31	42	58	30	41	29	90	10	0
▲	Coarse sand-----	9	38	64	1	35	38	61	27	46	27	83	16	1
△	Very coarse sand---	3	12	64	0	36	33	67	32	40	27	83	17	0
	Total-----	24	100											
	Average-----			65	1	34	38	61	30	44	26	87	12	0

Figure 38. Modal analyses plotted on triangular diagrams according to grain size, and table showing average modal composition for each grain size class, Marmot syncline section, North Slope, Alaska. n, number of samples; Q, quartzose grains (including monocristalline and polycristalline quartz, chert and quartzite); F, feldspar grains; L, lithic grains; Qm, monocristalline quartz; Lt, total lithic grains; Lv, volcanic lithic fragments; Lm, metamorphic lithic fragments; Ls, sedimentary lithic fragments; Qp + cht, polycristalline quartz, quartzite, and chert; Ac, argillaceous and carbonaceous grains; Cc, calcareous grains.

cally well compacted. The degree of compaction is a function of grain size, sorting, and composition. Estimates of packing densities of the sandstones of the Nanushuk

Group show them to be highly compacted (fig. 40) with intergrain boundaries that are sutured, concavo-convex, or long and straight (fig. 41). Sandstones having high pack-

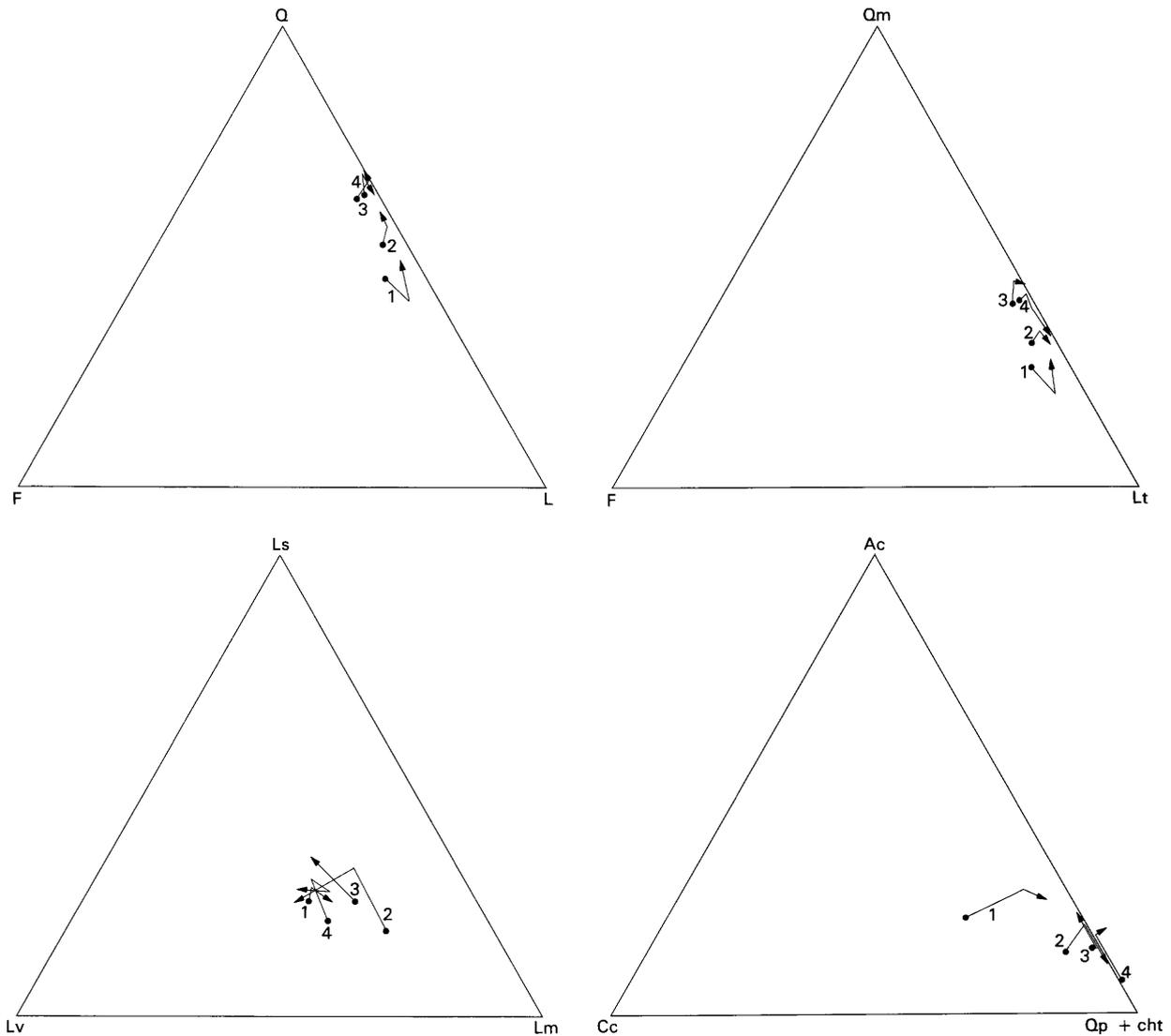


Figure 39. Vectoral analyses showing compositional trends according to grain size of samples from four measured sections, North Slope, Alaska. 1, Kurupa anticline section. 2, Tuktu Bluff section. 3, Arc Mountain section. 4, Marmot syncline section. Vectors begin at fine-grained mean and end at coarse-grained mean. Q, quartzose grains (including monocrystalline and polycrystalline quartz, chert, and quartzite); F, feldspar grains; L, lithic grains; Lt, total lithic grains; Qm, monocrystalline quartz; Lv, volcanic lithic fragments; Ls, sedimentary lithic fragments; Lm, metamorphic lithic fragments; Cc, calcareous grains; Ac, argillaceous and carbonaceous grains; Qp + cht, polycrystalline quartz, quartzite, and chert.

ing densities may also contain large percentages of pseudomatrix, which is thought to result from less competent (lithic?) grains being squeezed into pore spaces and molded around adjacent grains until the original grain is indistinguishable (fig. 42). Pseudomatrix may also be included in the low packing density category, because abundant pseudomatrix may result in floating grains or separated grains with no interpenetration along grain boundaries. Rocks of the Tuktu Bluff and Kurupa anticline sections have higher percentages of low packing density, probably because pseudomatrix is the predominant form of matrix material in finer grained sandstones containing

a higher lithic grain component or in sandstones with abundant mica.

Alteration by Cementation

Cementation by carbonate, silica, and various clays is a major contributor to reduction and filling of the intergranular pores in Nanushuk rocks. Grain size, thickness of the sandstone beds, the amount of burrowing and mixing of sediment layers, and composition of the framework grains probably help to determine the amount and type

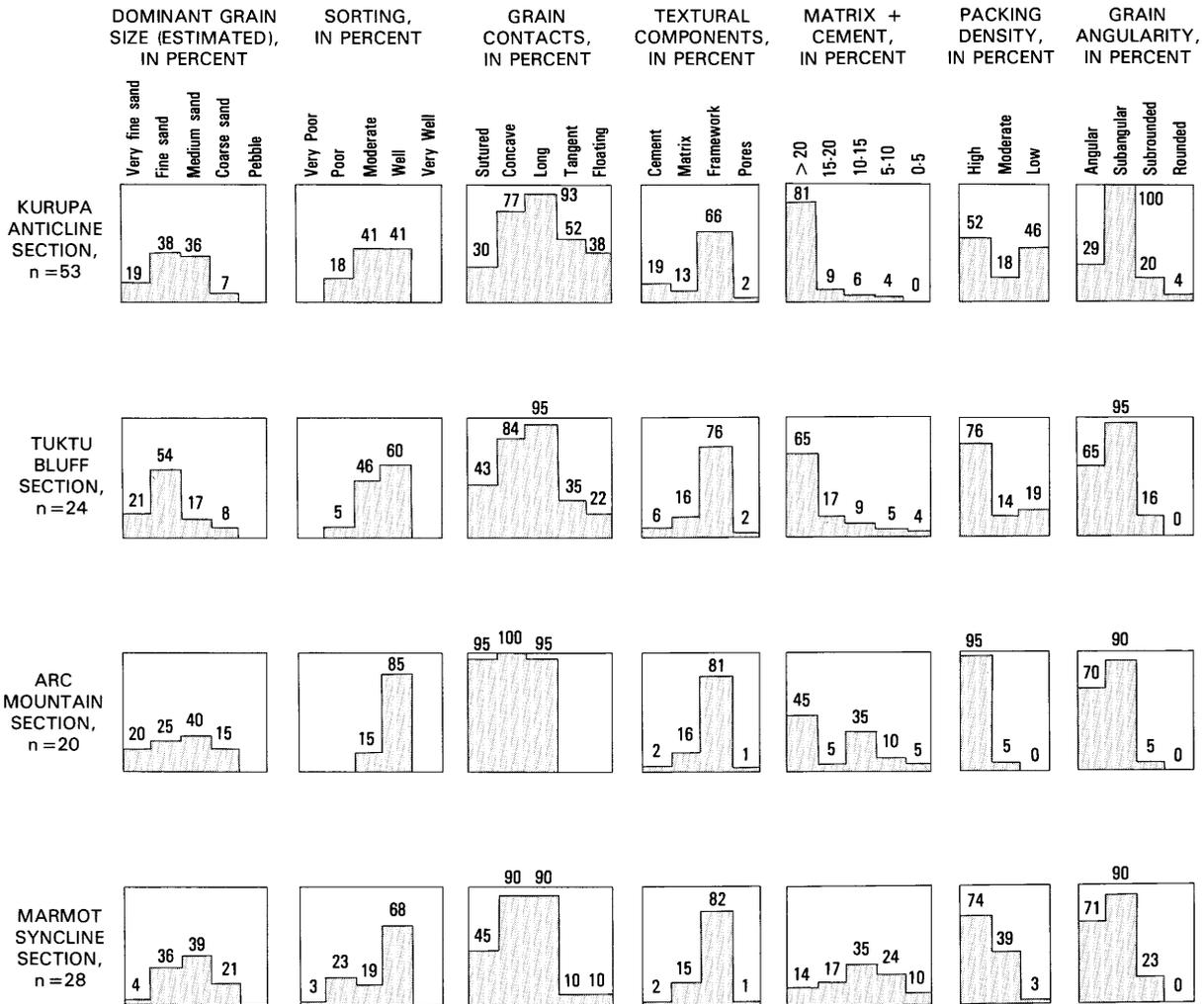


Figure 40. Histograms of textural characteristics shown in thin sections for measured sections discussed in this report, North Slope, Alaska. Generally, the most favorable reservoir characteristics are shown on the right side of each histogram. n, number of samples.

of cement present. Other workers have shown that cementation increases with proximity to shale contacts (Fothergill, 1955; Fuchtbauer, 1974). The cementation is attributed to the process of ion diffusion as connate water is released from the shales (Jonas and McBride, 1977). Cements may also originate from internal sandstone sources by dissolution and recrystallization of the framework grains (such as quartz, lithic, feldspar, and carbonate grains) as pressures and temperatures increase in the sandstone during the compaction process.

The most cemented rocks are found in the westmost measured section, Kurupa anticline (table 6). Of the samples from Kurupa anticline section, 81 percent have values of matrix plus cement exceeding 20 percent (fig. 40). The amounts of cement and cement plus matrix decrease significantly eastward; for example, the Marmot syncline samples average only 2 percent cement and between 10 and 15 percent when matrix is added.

Carbonate cement is a major component in some

of the sandstones of the Nanushuk Group. In some samples, the amount of carbonate cementation is related to the abundance of detrital calcareous grains in the sandstones (Bartsch-Winkler, 1979; Huffman, 1979). Outlines of original (calcareous?) grains replaced by calcite cement may be visible (fig. 43A). Replaced framework grains, such as quartz, may appear to be floating in carbonate cement (fig. 43B). The carbonate cement apparently replaces clay and siliceous cements in sandstones of the Nanushuk Group and commonly appears as the last stage of alteration.

Early diagenetic clay cements, which probably formed at intermediate depths of burial (Jonas and McBride, 1977), include chlorite, kaolinite, and illite and are common in samples of the Nanushuk (Bartsch-Winkler, 1979). The clay is typically authigenic rather than detrital (that is, it develops in place rather than having been transported and deposited contemporaneously with the grains) and forms by alteration and (or) compaction

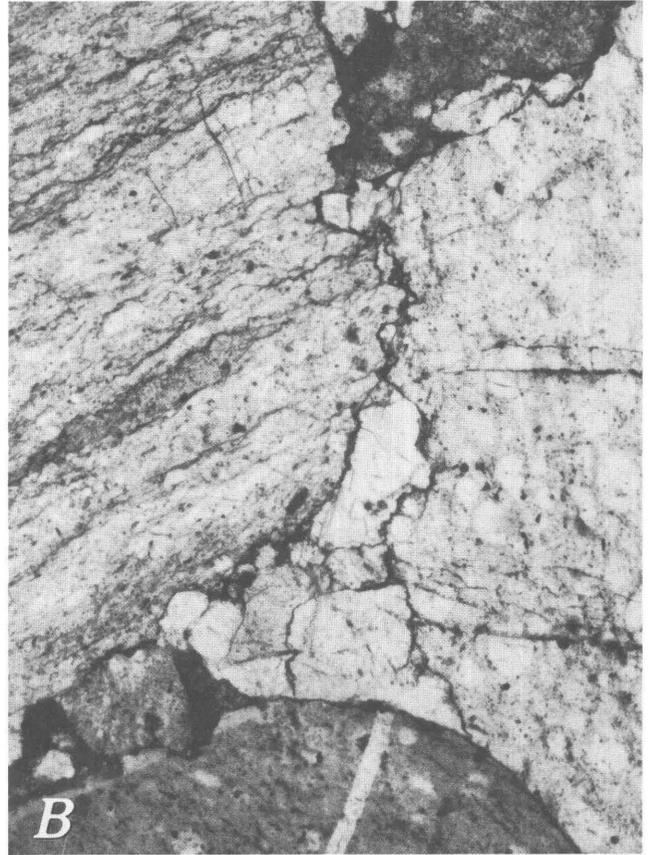


Figure 41. Intergrain boundaries in sandstone from the Nanushuk Group. *A*, Displacement of pebble boundary and extensive cracking as a result of compaction pressure. *B*, Stylolitic interpretation of rounded quartzose

pebbles, probably resulting from high compaction pressures at grain boundaries. Sample 78AAh47L, Tuktu Bluff, magnification, 2.5×10 , photomicrograph.

of framework grains. The clay cement may be oriented fibers growing in and around grains and pores (figs. 44, 45, and 46) or, in some places, may grow secondarily after partial dissolution or replacement of detrital grains (figs. 44 and 45). Other workers have shown that clay cement that coats quartz-grain surfaces may prevent development of quartz overgrowths (Fuchtbauer, 1967; Pitman, 1972; Heald and Larese, 1974) and this relationship may apply to Nanushuk sandstones (fig. 46). Clay cements, because of their stacked or platy morphology (such as kaolinite), may give the impression of better porosity in laboratory tests that measure porosity and permeability (fig. 44). According to Sarkisyan (1971), regularly stacked plates of kaolinite may retain as much as 20 percent porosity and a permeability of 8.8 millidarcies.

Silica is mobilized for cementation by compaction pressures and temperatures of sandstones; 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 are thought to provide silica for cementation (Jonas and McBride, 1977). Siliceous cementation in sandstones of the Nanushuk

Group may result from a combination of these factors. Higher pressures along resistant quartz-grain boundaries cause silica to dissolve (seen as sutured, concavo-convex, and long or straightgrain boundaries) and to be redeposited as quartz overgrowths (figs. 47 and 48). Typically, quartz overgrowths in samples of the Nanushuk occur after formation of clays. However, where framework grains do not have clay rims, or where siliceous cementation is abundant, overgrowths and areas with significant siliceous cement may be sometimes difficult to distinguish from the angular detrital grains. The amount of siliceous cementation in these sandstones may, therefore, have been underestimated. Chalcedony and feldspar, in rare instances, may also be present as cement.

POROSITY

Because of unsatisfactory impregnation of original pore spaces by blue plastic dye before thin-section preparation and because of abundant grain plucking, conclusions on the type and amount of pores retained by these

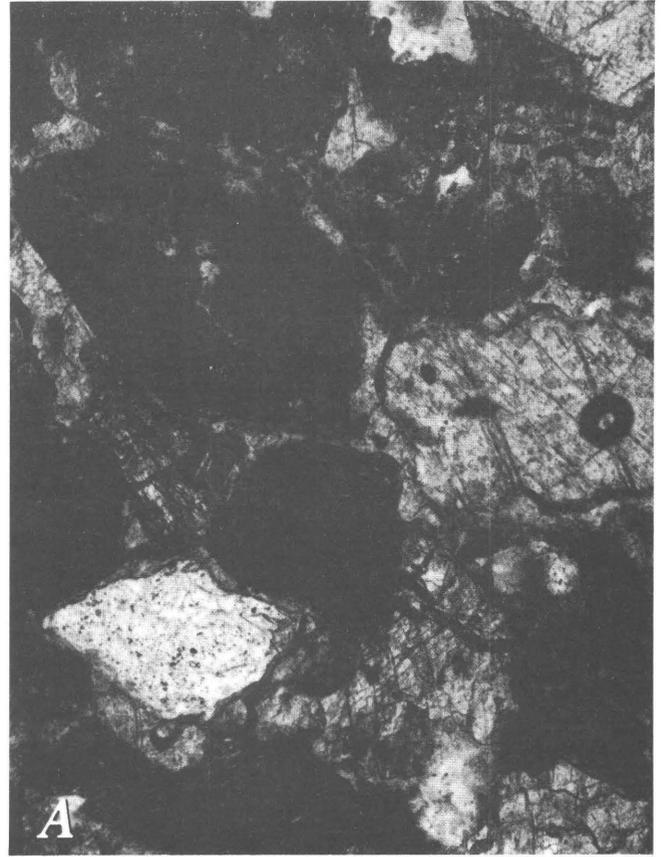


Figure 42. Tightly appressed sandstone from the Nanushuk Group, showing squeezing and contortion of less competent framework grains around more resistant grains and into intergranular spaces. Some cracking of resistant grains has also taken place. Sample 77AAh21, Tuktu Bluff; magnification, 6.3×10 , photomicrograph.

sandstones and the relation between pores and cements are only tentative. Further study is warranted if details are to be ascertained.

Average visible porosity, calculated from questionable point-count data, is not encouraging from a reservoir standpoint. Visible porosity values are highest in the Tuktu Bluff samples (average 2 percent) and lowest in the Arc Mountain samples (average 1 percent). Significant values (as much as 16 percent) of visible porosity are sporadic. The data suggest that the coarser sandstones have a higher incidence of visible porosity and that the



Figure 43 (at right). Replacement by calcite cement in sandstone from the Nanushuk Group. *A*, Calcite replacement of detrital grains, leaving a clay rim around original (calcareous?) grain. Sample 78ACh35, Kurupa anticline; magnification, 6.3×10 . *B*, Framework quartz grain appears to float in calcite cement after partial replacement, but relict grain boundary is still visible. Sample 78ACh16, Kurupa anticline; magnification, 16×10 , photomicrograph.

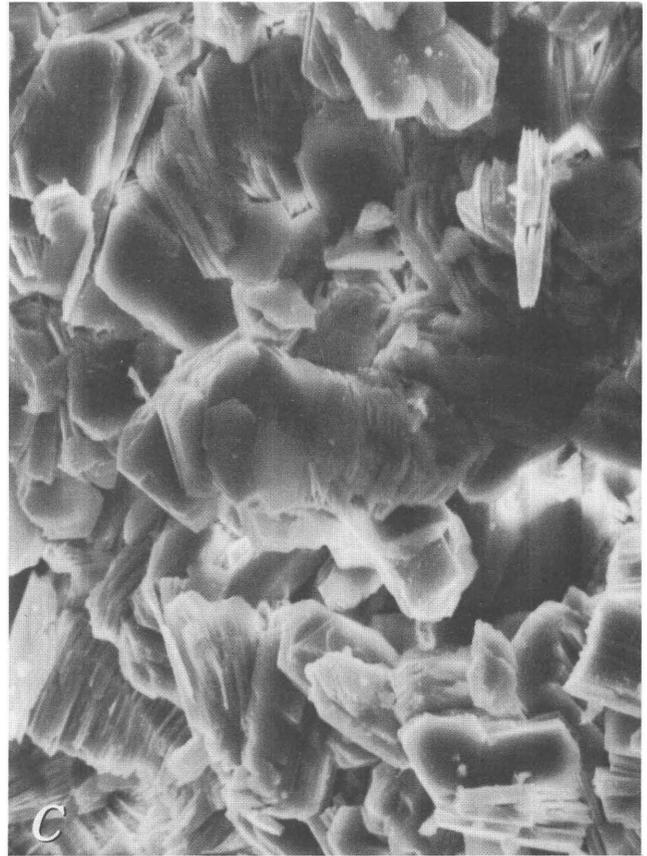


Figure 44. Kaolinite fills pore spaces created by dissolution and (or) replacement of framework grains, in sandstone from the Nanushuk Group. *A*, Sample 78ACh54, Kurupa anticline. *B*, Sample 78ACh67, Kurupa anticline. Magnification, 16×10 , photomicrographs. *C*, Books of hexagonal kaolinite crystals growing in pore space. Sample 78ACh41, Marmot syncline; magnification, $\times 1,340$, SEM.

porosity is localized. The medium- and coarse-grained sandstones have a larger percentage of quartzose grains, and original intergranular pore spaces are more likely to be preserved in these rocks than in the finer grained sandstones that are composed of less resistant, squeezed grains. The grains in the coarser, quartz-rich sandstones apparently have more exposure to dissolving fluids that move through the rock creating secondary porosity. The diagenetic processes that result in grain dissolution are complex; two factors thought to contribute to the development of secondary porosity, pressure and temperature, were discussed by Jonas and McBride (1977, p. 91–95A).

Although the porosity values in the Nanushuk Group are generally not significant, leaching and corrosion of siliceous framework grains apparently help to create secondary porosity in these rocks (fig. 49; Bartsch-Winkler, 1979). Secondary porosity was recognized using a petrographic microscope and the criteria listed in Scholle (1979, p. 171). Such features as partial dissolution and



Figure 45. Original porosity is still retained in this sandstone sample from the Nanushuk Group, but some reduction in porosity probably took place during compaction. Quartzose grains were dissolved at grain contacts and welded. At some later stage, minor secondary porosity was created by dissolution of quartzose grains (arrow). Growth of chlorite in pore spaces completes diagenetic cycle. Sample 78ACh32, Kurupa anticline; magnification, 6.3×10 , photomicrograph.

corroded grains and cements, inhomogeneity of packing, oversize pore spaces, floating grains, and fractured or cracked grains were observed (fig. 50). Secondary porosity may subsequently be totally or partly destroyed by infilling of diagenetic clays and cements.

Very small quantities of black to dark-brown, slightly translucent material in some samples was suspected to be oil, though no hydrocarbon tests were con-

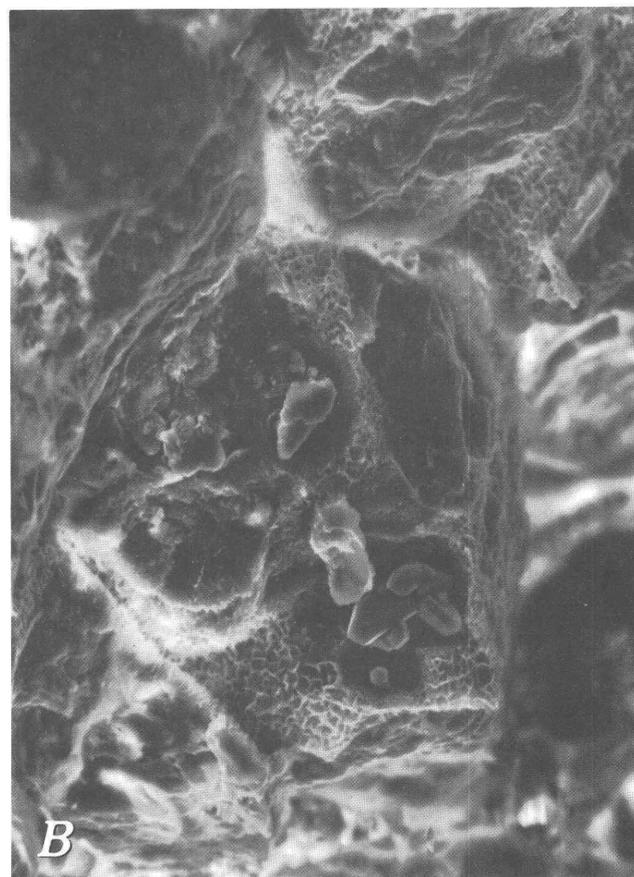
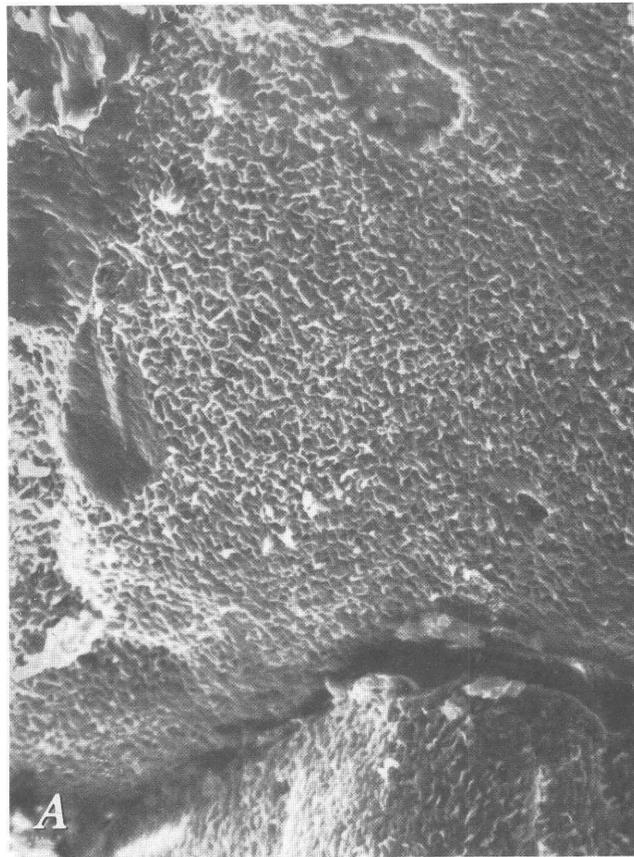


Figure 46 (at right). Quartz-grain surfaces are coated with chlorite in sandstone from the Nanushuk Group, which may inhibit development of quartz overgrowths. *A*, chlorite cement might facilitate retention of primary porosity by reducing siliceous cementation (presolution). Sample 78ACh17, Kurupa anticline; magnification, $\times 370$, SEM. *B*, Quartz overgrowth is surrounded by a halo in which no chlorite cement exists. It is uncertain which cement is inhibiting growth of the other. Sample 78ACh32, Kurupa anticline; magnification, $\times 319$, SEM.

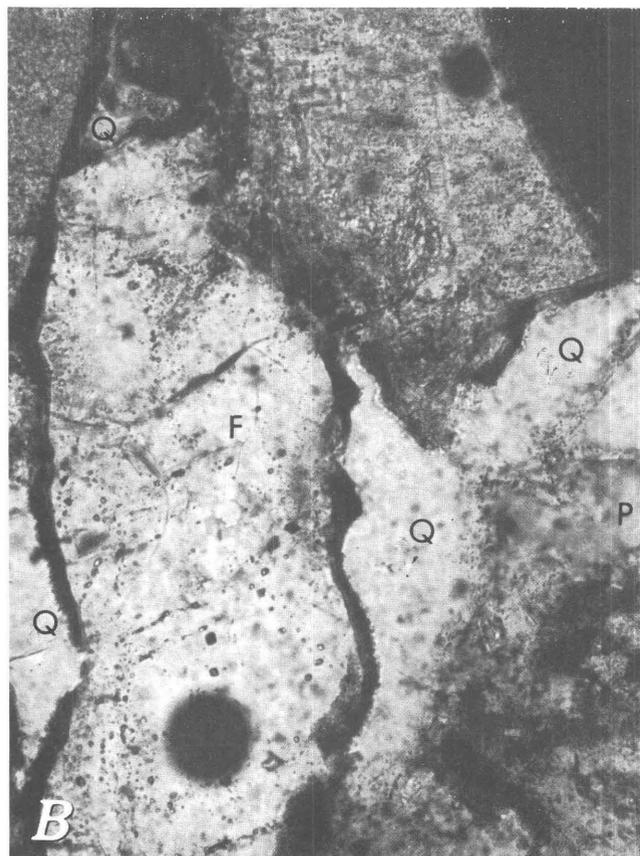
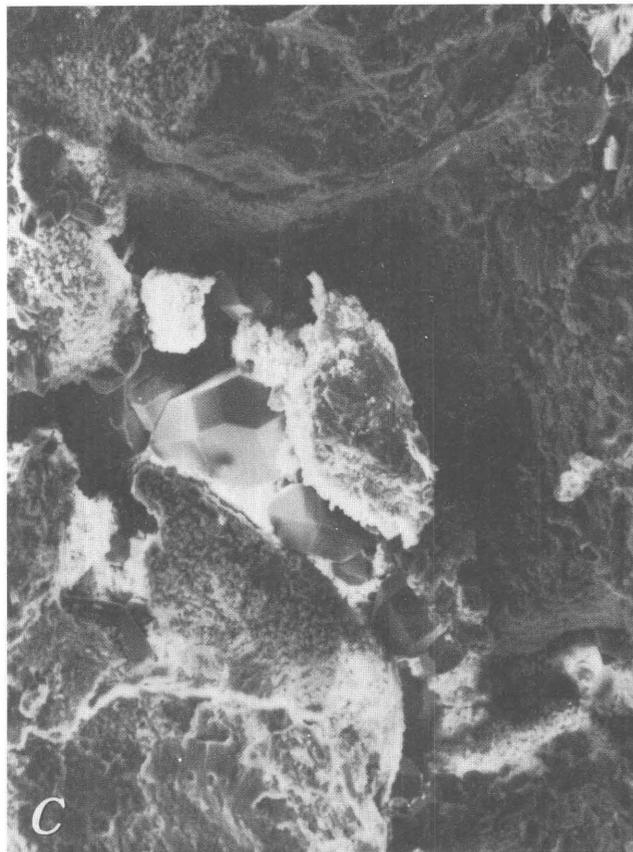
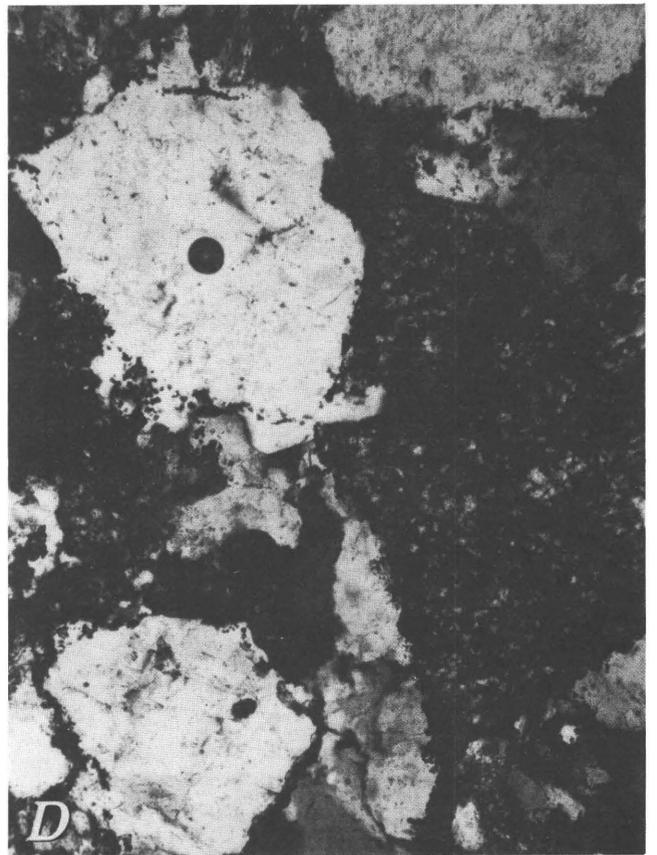
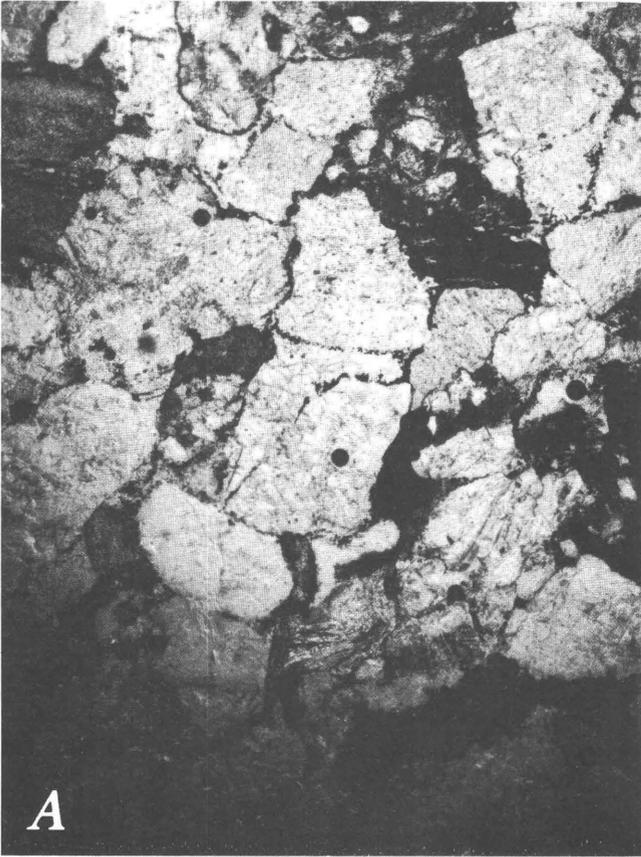


Figure 47. Quartz overgrowths on sandstone grains after clay formation, Nanushuk Group. *A*, Quartzose grains have overgrowths at points of low pressure (pore space) adjacent to areas that were probably under high pressure (grain contacts). Overgrowths probably develop where clay coatings are absent. A polycrystalline quartz grain (upper left) has a pod of kaolinite growing on its surface. Sample 78ACh23, Kurupa anticline; magnification, 6.3×10 , photomicrograph. *B*, Framework quartz grain with vacuoles (F) is outlined by diagenetic clay. Clear areas of quartz-overgrowth development (Q) are probably initiated where clay rim is absent. Secondary porosity (P) may be created by leaching of siliceous cement; no clay development is taking place in the secondary pore space. Sample 78ACh32, Kurupa anticline; magnification, 6.3×10 , photomicrograph. *C*, Chlorite cement and quartz overgrowths clog intergranular pore spaces. Sample 78ACh32, Kurupa anticline; magnification, $\times 234$, SEM.

ducted. The hydrocarbons(?) appear to have migrated into the sandstone during or after the compaction process (fig. 51).

PROVENANCE

The sandstone compositions of the Nanushuk Group from the eastern outcrop belt are high in quartzose and metamorphic lithic grains and low in feldspar grains (table



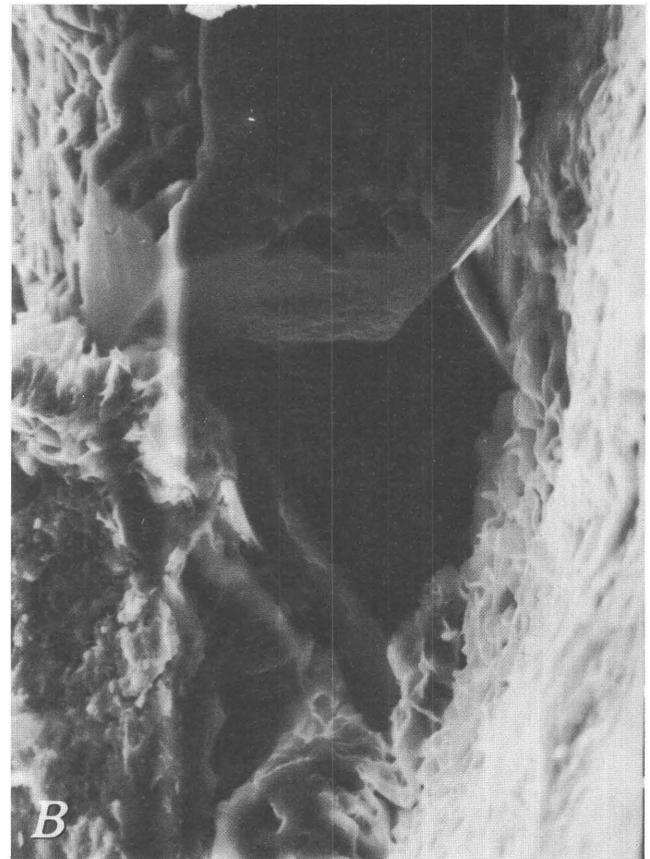
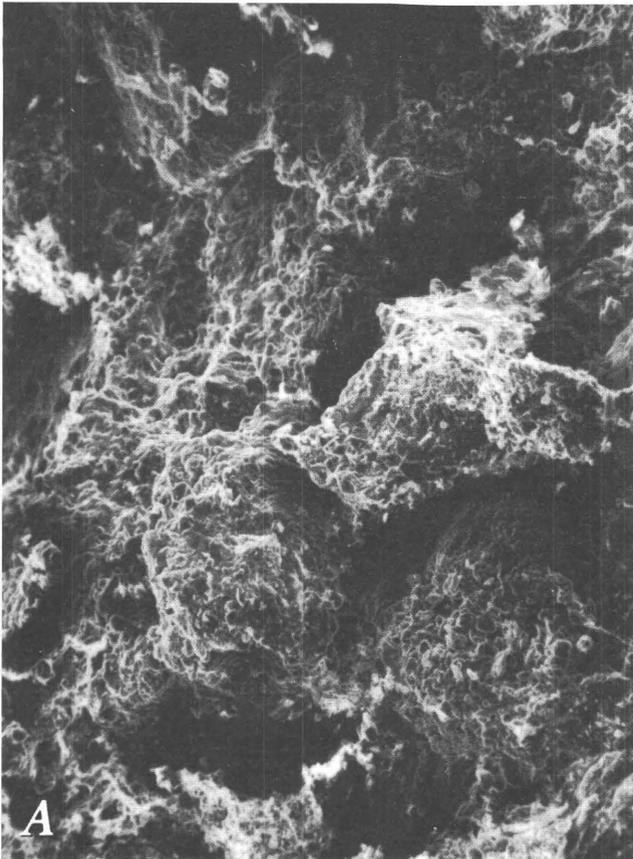


Figure 49. Secondary porosity in Nanushuk Group sandstones. *A*, Scanning electron microscope shows leaching, corrosion, and honeycombing of framework grains. Sample 78ACh76, Kurupa anticline; magnification, $\times 143$,

SEM. *B*, Irregular surface on quartz-overgrowth crystal indicates possible dissolution of siliceous cement. Sample 78ACh17, Kurupa anticline; magnification, $\times 1220$, SEM.

6). The average sandstone contains about 45 percent quartzose grains (27 percent monocrystalline quartz grains) and about 30 percent lithic grains (14 percent metamorphic lithic grains). Feldspars, almost exclusively plagioclase grains, make up from 1 to 5 percent. According to Dickinson (1970) and Folk (1968), sandstones of this composition originate in a tectonically active terrane, and this origin is borne out for the Nanushuk sequence by geologic mapping in the North Slope and Brooks Range regions (Grybeck and others, 1977). Thrust sequences active in the Brooks Range during Cretaceous

time provided a structural and probably a topographic high that shed sediments northward into the Colville basin (Detterman, 1973; Mull, this volume). In the Brooks Range, clastic rocks of the Upper Devonian Kanayut Conglomerate and Hunt Fork Shale, both of the Endicott Group, may have been the source of the quartzose component in the sandstones of the Nanushuk. Chloritic phyllite and graywacke sequences of the Hunt Fork Shale and related sedimentary rocks probably contributed metamorphic detritus to the Nanushuk Group. Shale clasts containing sponge spiculites similar to those pictured in Mamet and Armstrong (1972, figs. 5C and 5D, p. C134) from the Early Mississippian Kayak(?) Shale and also present in the Lisburne Group (A. K. Armstrong, oral commun., 1979) are abundant in sandstones of the Marmot syncline section.

Figure 48 (facing page). Quartzose sandstone from the Nanushuk Group, having abundant quartz-overgrowth development. Sample 78ACh25, Marmot syncline. *A* and *B*, iron-rich(?) clay outlines original grain boundaries and overgrowths from adjacent quartz grains in optical continuity with parent grain. *A*, plain light; *B*, polarized light. Magnification, 2.5×10 . *C* and *D*, quartz cement migrated from the monocrystalline quartz grain into the adjacent polycrystalline quartz grain, which has been corroded. *C*, plain light; *D*, polarized light. Magnification, 6.3×10 , photomicrographs.

PETROLEUM POTENTIAL

The results of this study indicate that the sandstones of the Nanushuk Group are borderline petroleum reservoirs. Sandstone comprises only 20 percent of the mea-

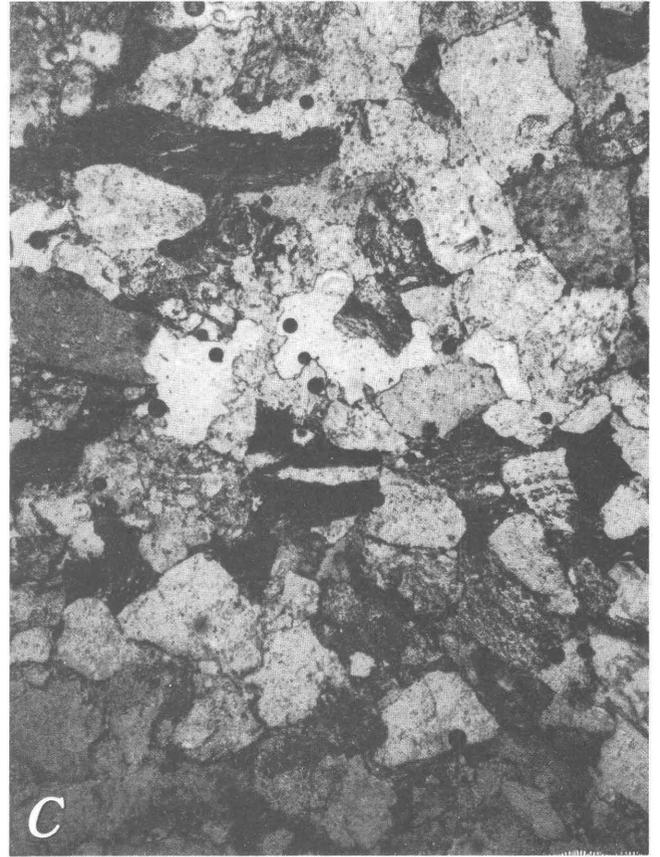
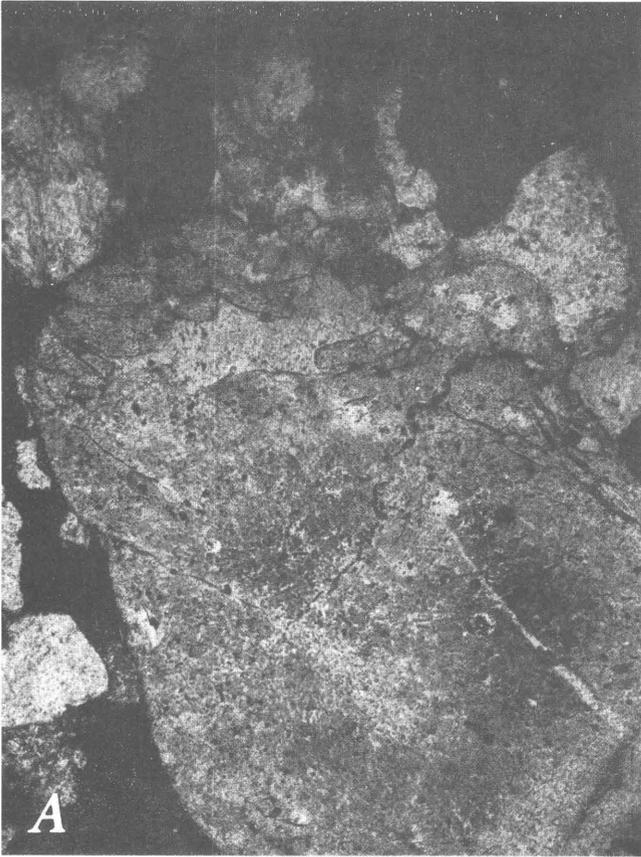


Figure 50. Secondary porosity features in sandstone from the Nanushuk Group. *A*, Apparent partial dissolution of a rounded polycrystalline quartz grain creates secondary porosity in a highly compacted sandstone. Sample 78ACh72, Kurupa anticline; magnification, 6.3×10 , photomicrograph. *B*, Abundant partial dissolution of grains results in elongate and oversize pores and floating grains. Sample 78ACh72, Kurupa anticline; magnification, 6.3×10 , photomicrograph. *C*, Embayed grains give secondary pores rounded borders. Pores are oversize and may have resulted from complete dissolution of a framework grain or from dissolution of cement that replaced a framework grain. Sample 78ACh79, Kurupa anticline; magnification, 2.5×10 , photomicrograph.

sured sections, on the average, and most of this is in lenticular bodies containing extensive shale interbeds. Many sandstones are shaly or muddy because of mixing by burrowing organisms. The sandstones, classified as phyllarenites or litharenites, are mostly fine to medium grained and are moderately to well sorted. Porosity has been destroyed by compaction and cementation, and permeability values are expected to be correspondingly low. Where visible porosity is present, it is localized and occurs probably as a result of depositional environment of the sandstones, which influences the grain size, or of post-depositional processes, which create secondary porosity.

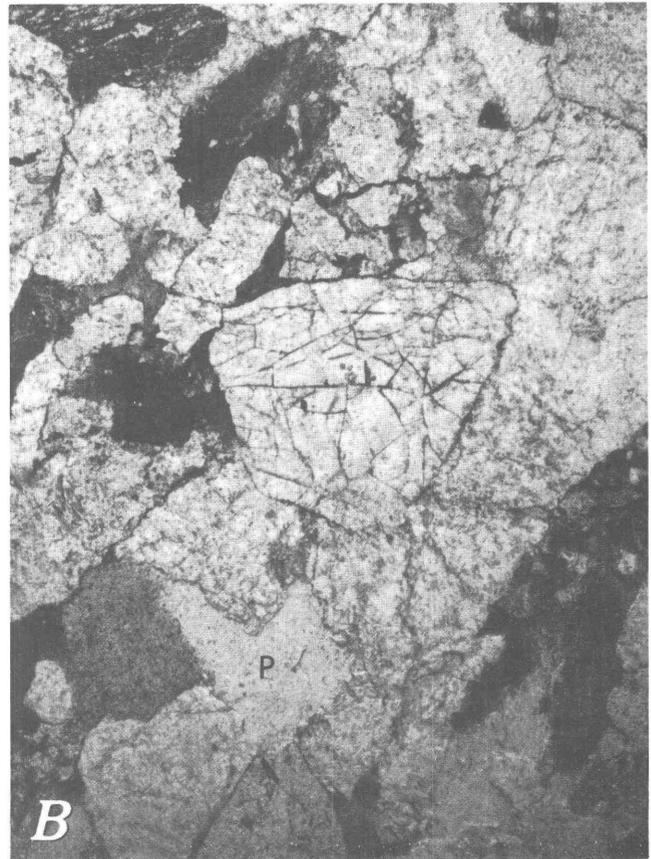
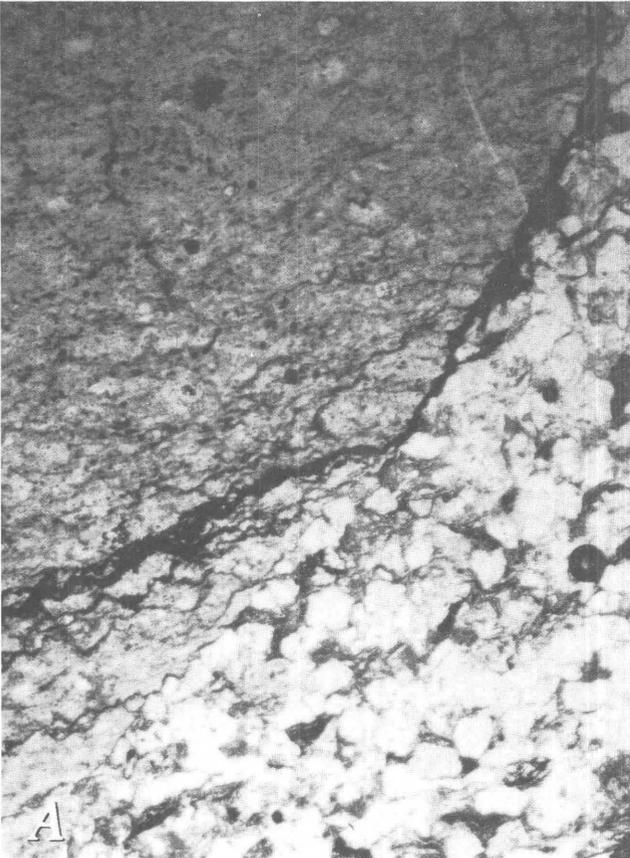


Figure 51. Possible presence of hydrocarbons(?) in Nanushuk Group rocks. Migration apparently occurred during or after compaction of the sandstones. *A*, Possible hydrocarbon(?) migration is facilitated along solution seams probably formed during compaction. Sample 78ACh34, Marmot syncline; magnification, 2.5×10 , photomicrograph. *B*, Possible hydrocarbon(?) migration

into intergranular pore spaces and into a grain cracked by compaction. Dissolution pore (P) unfilled by hydrocarbon indicates that migration may have occurred prior to creation of dissolution porosity. Sample 78ACh25, Marmot syncline; magnification, 2.5×10 , photomicrograph.

An Analysis of the Umiat Delta Using Palynologic and Other Data, North Slope, Alaska

By Fred E. May¹ and John D. Shane²

INTRODUCTION

Fieldwork on the northern Alaska Nanushuk Group (Albian-Cenomanian) in the eastern National Petroleum Reserve in Alaska (NPRA) yielded sedimentological evidence of a northward prograding delta herein referred to as the Umiat delta (fig. 52). This delta is different from the northeastward prograding Corwin delta, which is generally considered to be the result of most of the Albian-Cenomanian deposition in the NPRA (Ahlbrandt and others, 1979). Evidence of the Umiat delta was observed in many detailed measured sections of the Nanushuk, and consists of paleotransport-direction measurements and sedimentary structures. Sand-percentage contours and sand-isopach maps plotted from data from wells within the area (Bird and Andrews, 1979; Huffman and others, this volume) show the general shape of the delta.

Because palyniferous assemblages occur in wells within the area of the proposed Umiat delta, this study was undertaken to determine the geologic history of the Umiat delta using palynology. These wells are within the boundaries of the western part of the delta. Although the eastern boundary of the delta is in the area of the Marmot syncline, no wells have been drilled there. Outcrop samples in this eastern area, between the Grandstand-1 well and the Marmot syncline, yielded poor pollen, spore, and dinoflagellate-acritarch assemblages and are not reported here.

Palynological counts were made on 164 core samples from the Nanushuk Group from 10 test wells on the North Slope of Alaska. Pollen groups counted were gymnosperms, spores, angiosperms, dinoflagellates, and acritarchs; approximately 25,000 grains were counted. These count data are presented here as composite relative-frequency graphs, and a preliminary paleoecological interpretation is made for each well.

Also evaluated were the general characteristics of the relative abundances of pollen groups in each well and the coal occurrence. This report illustrates and discusses the data, but the meaning of the data is left to the reader to interpret. Some of the data may yield direct

paleoecological information, whereas other data may yield information about the hydrodynamics of the delta and associated marine systems responsible for the deposition of the sediments.

Some conclusions are presented as preliminary hypotheses. For example, the paleoecological interpretations are based on the assumption that most of the pollen and spores observed originated from near the well site. This assumption is probably more accurate for the spores and angiosperm and nonconiferous gymnosperm pollen than for the conifer, dinoflagellate, and acritarch pollen, but until detailed work is completed on the distribution of individual taxa, we treated all major groups counted as having been deposited near their localities of origin. There is reason to assume that nearby deposition was possible, and this possibility is discussed.

Field localities for invertebrate megafossils reported by Imlay (1961) are noted to show what types of mollusks and other animals have been found at particular points within the Umiat delta. These data help to determine the range of paleoenvironments for the formations at certain localities within the delta. Paleobotanical data (Smiley, 1967, Lowther, 1957) has aided in suggesting the type of climate during the time of deposition.

STUDY AREA

The proposed Umiat delta is in an area between lat 68°50' and 69°50' N. and long 156°00' and 151°20' W. on the North Slope (fig. 52). In general, the area lies in the southeast corner of the NPRA, and also slightly south and east of it. It is called the "Umiat delta" because one of its proposed main central lobes moved over the Umiat area. Palynological count data were gathered from the following wells: Grandstand-1; Umiat-1 and -11; Square Lake-1; Wolf Creek-2 and -3; Titaluk-1; Knifeblade-1; Oumalik-1; and East Oumalik-1. Some observations are used from Gubik-1 and -2, and Umiat-2.

GEOLOGIC UNITS

The Nanushuk Group in this area was deposited by the prograding Umiat delta. Formations in the Nanushuk are the Grandstand and Tuktu Formations (delta-front de-

¹Presently with Idaho State University, Pocatello.

² Presently with Exxon Co., U.S.A., Houston, Tex.

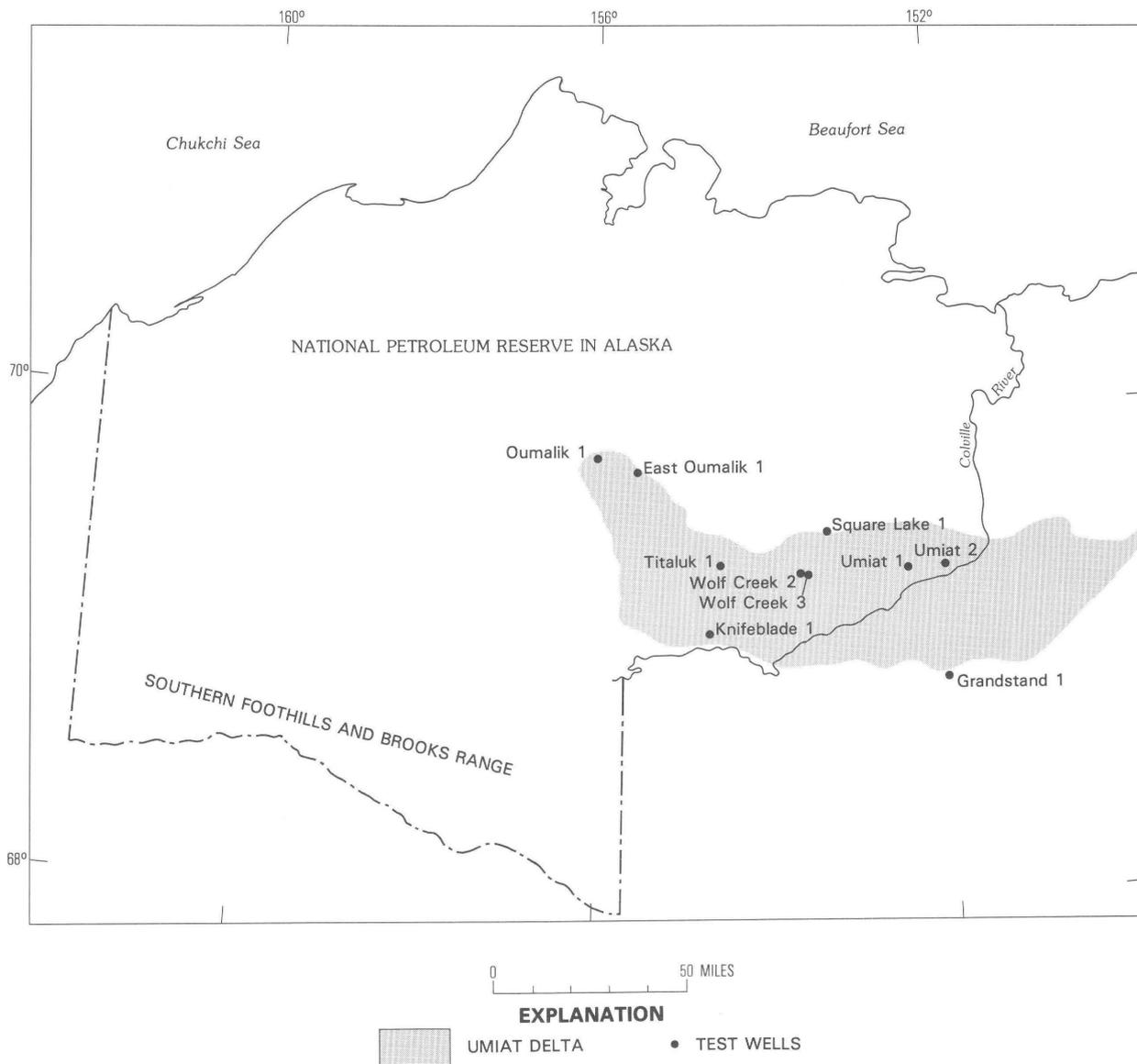


Figure 52. Index map showing the general Umiat delta area (Huffman and others, this volume) and test-well locations, North Slope, Alaska.

posits of middle to late Albian age), the Killik Tongue of the Chandler Formation (delta deposits of probable late Albian to early Cenomanian age), and the Ninuluk Formation (mixed delta and marginal-marine facies deposited as a result of the Seabee marine transgression into the Umiat delta; this unit is early Cenomanian in age).

All formational units referred to in this report are based on the work of Collins (1958, 1959) and Robinson (1956, 1958, 1959) of the U.S. Geological Survey.

METHODS

All samples were processed by standard palynological maceration procedures; samples were not sieved.

Palynomorphs were mounted in AYAF¹ plastic mounting medium on microscope slides. Palynomorphs were examined with Nomarski interference contrast. Counts were made on representative samples from each core; counts of as many as 200 specimens (angiosperms, gymnosperms, spores, and dinoflagellates-acritarchs) were made on each sample, depending upon the quality and quantity of grains present on a slide. Relative frequencies of these palynomorph groups were calculated and plotted as composite relative-frequency diagrams for purposes of comparing the fossil groups.

Dominant fern-spore frequencies are considered to

¹Use of trade names does not imply endorsement by the U.S. Geological Survey.

represent wetter parts of the delta; dominant gymnosperm pollen (primarily bisaccates) are considered to represent drier or better drained parts of the delta; dinoflagellate and acritarch frequencies are considered to represent marine areas, or encroaching marine areas that were likely often brackish.

Coal is considered to represent periods of subaerial deposition or exposure. Leaf impressions and carbonaceous material in the strata are generally considered to represent subaqueous deposition within the delta or near the delta front. The presence of marine dinoflagellates and various marine megafossils indicates intervals of marine deposition. The presence of brackish-water dinoflagellates indicates intervals of brackish-water deposition.

PHYSIOGRAPHY AND PLANT ECOLOGY OF MODERN DELTAS IN WARM, HUMID CLIMATES

Although the specific kinds of vegetation growing on modern deltas are different from those of the Albian-Cenomanian, it is still reasonable to expect that the physical environments in the deltas have remained much the same. It also seems possible that these physical environments supported vegetation that was structurally similar to vegetation that grows in similar environments today.

Modern deltaic environments can be grouped under the following headings (from Fosberg, 1964):

1. Water

- a. Distributaries.—Main branches through which the river empties into the sea. These tend to be the larger channels in the delta, and are arranged fanwise, forking and spreading out, and often becoming very wide in their lower reaches.
- b. Delta channels and tidal channels.—Channels that originate within the delta itself, draining the lakes, ponds, swamps, and marshlands. They tend to be closely meandering and intricately branched. This pattern is striking, very uniform, and immediately recognizable from the air. The origin of the pattern is not clear, though it is undoubtedly related to the near lack of any slope and consequent low cutting or scouring power of the tidal currents. The water escaping through the delta and tidal channels is primarily from rain floods and that which entered at high tides.
- c. Lakes and ponds.—Bodies of still water ranging from extensive basins to small ponds and pools. Some have outlets; others do not. All have a tendency to fill with sediment and plant remains and to change gradually to marshes or swamps.

- (1) Interconnecting basins.—These originate as areas of shallow sea cut off by sediments deposited, as the delta builds

outward, as natural levees, sand bars, and ridges. At first they may be practically open to the sea, merely deeper areas in the shallow water over the extensive silt deposits of the extending delta.

- (2) Levee flank depressions.—The sediments that make up deltas normally contain a large component of water and much organic matter. Organic matter may be especially abundant in the swampy strips along the outer slopes of natural levees. During periods of low water, both decomposition of organic matter and loss of water from the sediments by evaporation and gravity flow take place at greater than normal rates. Compaction and settling, both from the above processes and from slow but continuous action of gravity, tend to produce long narrow ponds aligned along the outer edges of the natural levees.

- (3) Abandoned channels or oxbow lakes.—As channels, especially distributaries, fill up with silt, they tend to cut through their enclosing natural levees and assume new courses, especially when floods occur. This commonly takes place on the seaward side of a seaward loop of a meander, and the new channel, being straighter at first, takes most of the water. The old channel is soon cut off by newly formed natural levees and is left as a lake, often a C-shaped lake called an oxbow.

2. Wetlands

- a. As lakes, ponds, and channels fill with silt and organic debris, they gradually change from areas of permanent standing water to land that, although still wet, is firm enough to support emergent vegetation. In the tropics the vegetation of such land tends to be woody, trees or shrubs, and the ecosystem is called a swamp. Marshes and wet savannahs are, however, not completely lacking in woody plants. There trees become dominant in wet sandy areas, peat accumulates, and a peat swamp results. Wet savannahs and peat swamps are generally well away from the strongly salty end of the salinity gradient, toward the head of the delta. They are also confined to areas where the water supply is principally rain and ground-water seepage rather than floods.

3. Drylands

- a. Delta terraces.—On many deltas, there are ero-

sional remnants of former delta land surfaces that formed during times of higher sea-level stands. They are flat or very gently sloping platforms, found near the head of or the landward margins of the present-day deltas. They are normally drier than the rest of the delta. The soil is older and more weathered, often severely leached if the delta is in a rainy region. In very humid regions the vegetation may be the normal lowland rain forest of the region.

- b. Natural levees.—In the distributaries, the water in the center of the channel flows faster than at its sides. Consequently, more sediment is dropped at the sides than in the center, and the bottom tends to build up along the sides while the center is kept scoured clean, and even deepens. As the incipient natural levees thus formed are left dry during low water in the dry season, the propagules of mangroves and other plants gain a foothold. At high water the resulting vegetation, though small and sparse, slows the water still more and causes the deposition of more silt, building up the levee. Further silt deposition takes place during each flood season, and further establishment of vegetation occurs during each dry season. As the level of the strip of land becomes higher, flooding may become less frequent. The composition of the vegetation changes as dryland conditions become more prevalent. Swamp species give way to terrestrial plants. A riparian forest is formed, made up of trees well adapted to land having a rather high permanent water table.
- c. Sand ridges and flats.—Along the seaward margins of deltas, beaches are formed in proportion to the roughness of the sea, and sand is piled up in ridges. Offshore bars may form and move shoreward under normal storm-wave action until they are piled against the beach ridges, forming a broader ridge or a parallel series of ridges. Eventually, narrow sand flats are formed, parallel with the shore. These ridges and flats tend to invade and cover marshes or swamps or to protect them in some measure from wave erosion, or both. The sand is soon covered by a considerable assortment of beach plants: grasses with deep rhizomes and roots, various creepers that root at the nodes and form mats anchored to the sand, and firmly rooted herbs and shrubs that tend to form a low shrub vegetation, often dense. Trees in the Old World, especially *Casuarina equisetifolia*, tend to grow on these ridges, usually starting while there is still bare sand and only grass; although slow growing,

they gradually overtop the scrub and form a characteristic strand forest.

A COMPARISON OF TEMPERATE AND TROPICAL DELTAS

Because the Umiat delta appears to have formed under humid, warm-temperate to subtropical conditions, indicated by the palynoflora (see the section on "Paleoecology"), comparison of temperate and tropical deltas is of interest. Two main differences between temperate and tropical deltas are that tropical deltas are flooded to greater depths than are temperate ones, and tropical deltas tend to have woodier vegetation. These two factors seem to go together, as deep flood waters likely reduce photosynthesis for smaller herbaceous vegetation, whereas taller woody vegetation would grow better in such conditions. Woody vegetation also creates peat bogs, which are characteristic of tropical deltas. Temperate deltas have fewer peat bogs; they seem to be replaced by freshwater marshlands (Fosberg, 1964, p. 229).

PALEOECOLOGY

Paleobotanical information was interpreted by Smiley (1967, p. 853) as indicating that the climate of northern Alaska during Albian-Cenomanian time was warm and humid, and that similar vegetation today grows south of lat 30° N. During the present palynological study, as many as 65 genera of fern and other spores have been observed, suggesting a diverse fern-lycopod-bryophyte flora within the wetter parts of the Umiat delta. The approximately 10 genera of bisaccate gymnosperm pollen are interpreted as having originated partly from within better drained parts of the delta. Angiosperm pollen make up a minor component of the overall palynoflora. Thus, the vegetation consisted mainly of ferns, lycopods, some bryophytes, and a variety of gymnosperms existing within an actively building delta system in a warm, humid environment. No doubt much of the gymnosperm flora existed in the uplands.

Coastal waters are thought to have been temperate, not warm, due to the presence of peccens and abundant burrowing pelecypods. Pelecypods that lived in and near the Umiat delta are ones common to shallow Albian Age seas of northwest Europe (Imlay, 1961, p. 16–17; Nicol, 1955, p. 122).

The relatively small amount of coal formed within the Umiat delta, as compared to the large amount formed within the Corwin delta, is likely related to higher energy within the shifting Umiat fluvial system and to biogenic degradation of organic material. Relative frequencies de-

terminated in this study for spores, gymnosperms, angiosperms, and dinoflagellates and acritarchs for 10 test wells within the confines of the Umiat delta area suggest that adjacent areas of vegetation were nearly always undergoing change. This change is reflected in the alternation of dominance and the widely fluctuating frequencies. Although dinoflagellate and acritarch percentages are generally lower than those of gymnosperms and spores, rapid increases in percentages of dinoflagellates and acritarchs suggest frequent marine inundation of large areas within the delta, and such inundations too would be detrimental to coal formation, both in the cleaning out of peat deposits as well as increasing the salinity in large areas of freshwater that supported coal-producing vegetation. The widespread presence of dinoflagellates and acritarchs in samples examined from these 10 wells suggests that the delta was deposited primarily at sea level. Mollusks collected within the Umiat delta (discussed later) also indicate a wide range of environments, from freshwater to inner shelf.

The lush vegetation suggested by the diverse pollen and spore assemblages in the Nanushuk Group is difficult to reconcile with a long Arctic night during Albian-Cenomanian time. Today, the Arctic winter months are dark due to the $23\frac{1}{2}^{\circ}$ angle of inclination of the Earth's rotational axis. Other than small wobbles through time, the Earth's rotational axis has been considered to have remained essentially in its present orientation. Because of this, continental plate movements, based on paleopole estimates, have provided one of the main tools for continental-drift and sea-floor-spreading reconstructions. The highly diverse vegetation found in the Arctic Albian-Cenomanian strata suggests a warm, humid climate somewhat similar to present-day climates at lower latitudes. It is difficult to visualize such a climatic setting with a long Arctic night.

If the long Arctic night did not exist during Albian-Cenomanian time, then only a few explanations are possible. Either the angular inclination of the Earth's axis has changed considerably, or the Arctic-Alaskan plate has been much more south due to continental drift.

The present understanding of plate tectonics suggests that North America has rotated counter-clockwise to its present position. During Albian-Cenomanian time, Alaska appears to have been north of its present position (Irving, 1979, p. 684), suggesting that such an Arctic night would have been even more of a factor than today. Thus, continental drift does not appear to explain the rich and diverse flora in this time and location.

The other explanation of why there was such a diverse flora in the Arctic during Albian-Cenomanian time is a change in the inclination of the Earth's rotational axis relative to the plane of the ecliptic. Wolfe (1978, p. 701-702) provided an interesting discussion of this

idea, using paleobotanical evidence. His studies of Tertiary Arctic vegetation suggest that the Earth's axis inclined from about 10° during the Paleocene to about 5° during the middle Eocene, thus nearly negating the Arctic night. Although the lower to middle Cretaceous floras of the same region are more difficult to equate with modern ones than were these reported by Wolfe from the Tertiary, a change in axis inclination could still have occurred during the Cretaceous. No new evidence is furnished here, but the high numbers of fern, bryophyte, and lycopod spore taxa, some 65 genera, combined with cycad pollen suggest a flora that would not have survived the yearly dark period.

Another possibility suspected by Smiley (1967, p. 861) is that the Albian-Cenomanian forests of the Arctic had adapted to extended periods of darkness and had survived in spite of it. Smiley's argument revolves around deciduous plants, and he suggests that this kind of vegetation would have been dormant during the prolonged winter darkness and have not needed daylight. Therefore, Smiley thought that no change in axial inclination was necessary. He pointed out some possibilities that could have helped cause warmer climates in the Arctic, such as periods of extreme volcanism. He also mentioned the possibility of changes in extraterrestrial influences on the Earth. Such factors have been reported by Gribbin (1979), who discussed climatic change in terms of fluctuations in solar radiation, solar flares, cosmic seasons, the effect of passing through the spiral arms of the galaxy or through galactic dust lanes, and variations in eccentricity of the Earth's orbit.

It seems reasonable that Alaska was either farther south during Albian time, or that the Earth's axial inclination was different, or else that a combination of both factors reduced considerably the effect of the prolonged Arctic darkness.

Paleofloral Components

Delta-Front Colonizers

One consideration in the development of deltaic vegetation is what kind of vegetation constitutes the delta-front colonizers. Typically, in temperate deltas, herbaceous forms colonize new areas, but in tropical areas several species of trees, called mangroves, grow in newly built areas due to their viviparous dispersal mechanism and their ability to trap sediment and withstand high salinities. Mangrove species today are angiosperms, a group of plants that did not appear in the fossil record until Albian time, but it appears unlikely that angiosperm mangroves existed then. The earliest angiosperms on the North Slope, such as the few primitive forms in the Umiat

delta, were most likely small herbaceous forms that occupied disturbed areas within the delta. Perhaps, though, nonangiospermous Albian mangroves did exist, and may be identified through palynological and paleobotanical work in ancient deltas. These might be trees that could tolerate the high salinity, fluctuating depth from tides, and rather high energy that exists in the area where the delta meets the sea. (We have no idea what Arctic tidal and wave energies would have been. Today, wave energies are low due to ice cover). Angiosperms probably did not form the colonizing vegetation, as they appear to have been a new and minor component during the Albian-early Cenomanian in the Arctic areas. The colonizers probably would have been gymnosperms (conifers), lycopods, or ferns. If they were trees, they could be called mangroves. If they were herbaceous, then the seaward margin of the delta would likely have appeared similar to some modern temperate deltas, lacking mangroves. It is noteworthy that robust and complex root systems that characterize mangroves have not been reported among the fossil plant remains of the Albian of the North Slope. This lack of record would be unusual, because if mangroves had been present they would likely have formed substantial root mats with aerial structures acting as silt catchers.

Any fossil mangrove roots should have been buried in fine-grained sediment that would have allowed preservation. A considerable amount of paleobotanical work has been done on the North Slope deposits of Albian-early Cenomanian age, and many well cores and measured sections have been examined with no apparent observation of such root systems. It seems likely then that such mangrove root systems were not present, and that the most probable delta-front colonizer was not like present mangroves, at least in its root systems. It seems at present that the most likely colonizers would have been euryhaline herbaceous plants. These could have been gymnosperms, lycopods, or ferns. The gymnosperm pollen observed is primarily coniferous. It is difficult to imagine conifers as mangroves or as euryhaline colonizers. Except for Cypress, conifers are not known to inhabit modern euryhaline environments. Lycopod spores are not nearly as diverse as the ferns. Therefore, the most likely delta-front colonizers appear to be ferns.

Although few modern ferns favor aquatic, brackish environments, one genus, *Acrostichum*, does favor terrestrial brackish-marsh conditions (Copeland, 1947, p. 64). In Lake Maracaibo, Venezuela, *Acrostichum* grows in a swampy delta-front region of brackish water in areas of dense vegetation that are difficult to walk through (Tschudy, 1969, p. 81; Tschudy, oral commun., 1979). Similar fern overgrowths could have been successful colonizers in the Albian-Cenomanian Umiat delta because tide ranges were likely low, as they are today, and there would have been little destruction at the delta front. For

example, a spring tide, measured 130 km northwest of Point Barrow in 1962, was only about 18 cm. In the Chukchi Sea, sea level has been noted to change by only about 1 m in 1 week, and in general, tide range in the Chukchi Sea is about 20 cm (Coachman and Aagard, 1974, p. 31), due to local wind and (or) atmospheric pressure fields. In such conditions, herbaceous colonizers would have had little difficulty in becoming established. The main tolerance they would have had to develop was to higher salinities, and, therefore, such fern types as the modern *Acrostichum* would be very likely to have been colonizers in the Umiat delta.

Mixed Swamp-Forest Vegetation

Behind the delta-front colonizers, we postulate a mixed swamp-forest vegetation occupying primarily the wetlands and water areas described previously. Leveed distributaries and delta channels likely meandered through these areas. Because these areas probably contributed most of the spores and pollen counted in this study, dominances of particular groups, such as fern spores, probably represent these areas. It is suggested that as fern, lycopod, and bryophyte spore trends increased to dominance in the count data for a particular well, that areas near the well site were becoming wetter, suggesting development of these water and wetland areas. Suspected taxodiaceous pollen observed in the wells possibly represent the conifer vegetation within such areas. *Elatides*, a suspected taxodiaceous plant megafossil (Lowther, 1957, p. 16), has been identified from Oumalik-1 well (Robinson, 1956, p. 27). The rare angiosperm pollen observed likely represent the newly appearing angiosperms as they occupied disturbed areas, such as along cuts in river banks, breached levees, or other areas affected by crevasse splays. Otherwise, most of the representative palynomorphs probably come from the highly diverse ferns and the less diverse lycopods and bryophytes.

Highland Forest Vegetation

Behind the delta system, southward in the highlands, which may have been a few tens of kilometers away based on the nearest persistent granular or conglomeratic sediments, in the foothills of the ancestral Brooks Range, we postulate a primarily coniferous forest. This upland area probably yielded pollen such as *Pinuspollenites*, *Vitreisporites*, *Podocarpus*, *Araucariacites*, and possibly *Sequoiapollenites*. As drylands developed within the delta system, we believe that the conifer vegetation, represented by their pollen types, colonized these areas, creating the source for some of the coniferous pollen that influenced the trends in the illustrated counts (figs. 54-62) for the gymnosperm group. Most of the fossil wood collected within the boundaries of the adjacent

Corwin delta system is coniferous, and petrified coniferous tree trunks have been observed there in probable growth position (R. A. Scott, oral commun., 1979) in the Corwin Formation, which is considered to have been environmentally similar to the Umiat delta Killik Tongue of the Chandler Formation discussed here. Fossil conifer leaves possibly of the fossil genus *Elatocladus* have been observed by May (unpub. data) in great numbers in the Killik Tongue of the Chandler Formation on the Anaktuvuk River at the type locality of the Grandstand Formation. Other conifer remains have been observed by us in Titaluk-1 well. Robinson (1956, p. 27) reported *Elatides* in the Grandstand of Oumalik-1 well. Collins (1959) reported *Cephalotaopsis* from Square Lake-1 well. These occurrences suggest the presence of conifers within the delta system. Dominances of bisaccate conifer pollen have been observed in the Grandstand Formation in the westernmost part of the Umiat delta from Titaluk-1 and East Oumalik-1 wells. These dominances may reflect the development of better drained land areas near there. These dominances are discussed specifically later.

An argument can be made that these pollen and leaves have washed in along distributaries, or that the pollen have been transported by wind or water currents for considerable distances. Such interpretations can be readily determined by the reader, and we feel that some degree of the count data represents this amount of transport. Based on a few published criteria, we also think that it is possible that most of the palynomorphs counted originated within a few kilometers of the well sites (this is even more true of spores). Traverse and Ginzberg (1966, p. 428) stated that "it must be pointed out that the great bulk of pine pollen, or any other pollen, is dropped within a few miles of the tree of origin, unless the air is very turbulent." They also indicated that pine-pollen deposition is generally greater near the source, and that it decreases away from the source. Tschudy (1969, p. 80) stated that "experiments on modern pollen rains suggest that probably most pollen that occur as fossils have been transported relatively short distances before becoming incorporated into sedimentary deposits." He further stated that the "plants growing within a basin or an area of deposition may drop their pollen and spores in situ. The pollen will then be moved about only by such currents as may be active within the area" (Tschudy, 1969, p. 80-81). An example provided by Tschudy shows that fern spores mainly of the genus *Acrostichum* growing near the mouth of the Rio Catatumbo at Lake Maracaibo, Venezuela, are deposited in greatest percentages directly off the mouth of that river. We apply these criteria solely as a preliminary approach to the areas within and immediately in front of the Umiat delta, anticipating that some unknown amount of the pollen and spores counted originated from greater distances.

Marine and Brackish-Water Palynomorphs

Dinoflagellates and acritarchs occur in most samples examined and counted. Although often in low percentages, their presence indicates that the Umiat delta was frequently inundated by seawater, which indicates a low delta relief, near sea level. Some assemblages in the Killik Tongue of the Chandler Formation and the Ninuluk Formation are unique in having small deflandreoid and ceratioid complexes not previously described, which probably represent brackish-water environments (May, 1979). Some of these forms illustrated in May (1979) are identified as:

Deflandrea species A through H

Muderongia species A and B

Other assemblages in the Grandstand Formation and the Killik Tongue of the Chandler Formation appear to be more characteristically marine and are represented by the following (May 1979; May and Stein, 1979):

Apteodinium granulatum

Batioladinium jaegeri

Callaiosphaeridium asymmetricum

Chlamydomphorella nyei

Cribroperidinium edwardsi

Gardodinium elongatum

Hystrichosphaeridium arundum

Lithodinia stoveri

Luxadinium propatulum

Muderongia asymmetrica

New Genus A

Oligosphaeridium albertense

Ovoidinium verrucosum

Pseudoceratium expositum

Spinidinium vestitum

The study of these probably brackish versus marine associations appears to be extremely useful in paleogeographical reconstructions of the Umiat delta.

CONDITION OF PLANT MATERIAL PRESERVED IN TEST WELLS STUDIED

Fossil plant remains found during logging of the test wells in this study were described, for the most part, in general terms by Collins (1958, 1959) and Robinson (1956, 1958, and 1959). Plant remains seem to be more complete and better preserved in two of the westernmost wells, Titaluk-1 and Oumalik-1, where nearly complete leaves, plant-leaf coquina, numerous black plant impressions, abundant black plant fragments, *Elatides* sp., and *Ginkgo digitata* were found. In the remaining wells, rather nondescript terms were used by Collins and Robinson to describe the plant remains, such as plant impressions, carbonaceous plant fragments, coaly plant remains, and car-

bonaceous partings, which suggests that plant material east of the Titaluk-Oumalik area is more degraded. One reason for the difference in preservation may be because sedimentological data suggest that a delta lobe with natural levees extended from the Titaluk area to the Oumalik area (fig. 1; Huffman and others, this volume). Natural levees are one of the longer lasting features of modern deltas because leaf litter protects them from erosion by rain. This leaf litter comes from riparian forests that develop on the levees as dryland conditions become more prevalent (Fosberg, 1964, p. 230). One hypothesis, then, is that the apparently better preservation of plant megafossils in the Titaluk-Oumalik area resulted from leaf litter on levees that were built out from the Titaluk area to the Oumalik area. The apparently poorer condition of fossil-plant remains east of there may have resulted from the influence of more destructive marine and (or) fluvial systems, and the plant material became quite degraded before final deposition.

One curious aspect of the Umiat delta is its small amount of coal as compared to that of the Corwin delta system to the west. For example, the Nanushuk Group of the Corwin delta system at Kaolak-1 well appears to have about 60 m of coal (Ira Pasternack, U.S. Geological Survey, oral commun.), whereas Titaluk-1 and all of the other Umiat delta test wells appear to have less than 6 m of coal each. The high diversity in the palynomorphs (more than 100 genera), especially the spores, suggests a lush vegetation within or near the Umiat delta. Apparently the relative lack of coal resulted from biodegradation of plant material within the swamps. Nutrients in the water probably were abundant, and biological agents could have caused deterioration of the organic material. This deterioration may account for the carbonaceous shales described from some of the eastern wells. At any rate, both fluvial and paludal processes appear to have degraded the organic material in the east.

COAL AND SHORELINES

The presence or absence of coal in parts of the wells studied was helpful in determining the general positions of shorelines. The presence of coal indicates periods of terrestrial deposition, interpreted here as indicating that at times the shoreline was somewhat seaward, or north of the wells. Intervals containing marine fossils and lacking coal suggest marine deposition and that at times the shoreline lay landward, or to the south of the wells. The relative direction of the shoreline from each well site, based on coal or marine fossils, is one of the main tools used here in the reconstruction through time of the Umiat delta.

PALEOECOLOGY OF INVERTEBRATE MEGAFOSSILS

Invertebrate megafossils collected from the Nanushuk Group within the Umiat delta are listed below with associated environments (N. F. Sohl and D. L. Jones, U.S. Geological Survey, Washington, D.C., and Menlo Park, Calif., respectively, oral commun., 1979. See fig. 53 for general localities by formation based on Imlay, 1961):

Grandstand Formation (fig. 53A and B)

Arctica. Slightly brackish water, sluggish, shallow burrower.

Entolium. Bysally attached pectinoid. Can be ambulatory into bays. Definitely marine, but may extend into lower estuaries. Shallow water.

Corbula. Brackish water.

Lingula. Muddy sand and fine-grained sediments. Also found in Gulf Coast chalks. Sometimes brackish water but not freshwater.

Inoceramus. Almost completely marine. Nearly any water depth.

Nucula. Likely deepest part of shelf, fully marine.

Psilomya. Marine shore to shelf; more common at shallow ends. Burrows about 6 in. Bottom dweller. Nonturbid. Sluggish.

Panope. Similar to *Psilomya*.

Tancredia. Possibly brackish water, extremely shallow. Hard substrate.

Thracia. Mainly marine. Thin shelled. Good burrower. Shallow mud and silt.

Killik Tongue of the Chandler Formation (figs. 53C and D)

Entolium. See *Entolium* above.

Leptosolen. Razor clam. Deposit feeder. Deep burrower. Can be shallow marine.

Lingula. See *Lingula* above.

Panope. See *Panope* above.

Psilomya. See *Psilomya* above.

Thracia. See *Thracia* above.

Veniella. Fully marine. Muddy sand.

Unio. Freshwater.

Also reported were fish teeth, fish scales, and starfish.

ANALYSIS OF PALYNOFLORAS

The palynological history of each well is described below in terms of the floras inferred to have existed in the vicinity of each well. As a preliminary approach, we assume that most pollen and spores were deposited within a few kilometers of their vegetation, but we also acknowl-

edge that some pollen and spores were carried greater distances (for example, bisaccate conifer pollen) (Traverse and Ginzberg, 1966).

Knifeblade-1 Well (Robinson, 1959) (Fig. 54)

Well information.—Knifeblade-1 well contains about 243 m of the Killik Tongue of the Chandler Formation (from surface to about 250-m depth) and about 305 m of the Grandstand Formation (250 m to 550 m). It is not known how much Grandstand Formation lies beneath the bottom of the well, but at nearby Titaluk-1 well there is about 488 m of Grandstand Formation, suggesting that about 183 m of Killik has been eroded at Knifeblade. Sandstone and shale alternate through the Nanushuk, and coals are present in the Killik and upper Grandstand Formation.

General palynology.—Samples are lacking for much of the Grandstand Formation between 305 and 518 m, but were available in the bottom 30 m and the top 61 m. Adequate samples were available through the Killik.

Dinoflagellates are numerous in the bottom 30 m of the Grandstand Formation (15–36 percent), which indicates marine conditions. Gymnosperms dominate in this interval (36 to 40 percent) over dinoflagellates and acritarchs, but alternate in dominance with spores. In the upper 61 m of the Grandstand, where samples are again available, spores dominate strongly, reaching peaks of 68 percent, gymnosperms have decreased slightly, having peaks of 33 to 40 percent, and dinoflagellates-acritarchs have decreased markedly to 3 to 10 percent.

Percentages remain about the same for each group passing from the Grandstand Formation into and through the Killik Tongue of the Chandler Formation. However, spores increase slightly, gymnosperms decrease slightly, and dinoflagellates-acritarchs remain about the same, having very low percentages of 2–9 percent.

Trends.—Although little data are available for the Grandstand Formation, trends exist in the Killik and can be inferred in the lower Grandstand. Spores increase from the base of the Grandstand up and through the Killik; gymnosperms remain about the same in the Grandstand but decrease through the Killik, being intermediate between spores and dinoflagellates; and dinoflagellates and acritarchs decrease from the lower Grandstand into the upper Grandstand where they are greatly dominated by both gymnosperms and spores, and they remain about the same, in very low percentages, through the Killik.

Coal.—Coal is not present in the lower two-thirds of the Grandstand Formation, but it is fairly common from 350 m up through the remaining Grandstand and Killik Tongue of the Chandler Formation.

Paleoenvironmental interpretation.—The presence of dinoflagellates and acritarchs throughout the well, although generally in small percentages (less than 10 percent), suggests a continual marine influence. The abundance of terrestrial palynomorphs indicates a close proximity to shoreline in the lower half of the Grandstand Formation, but the lack of coal and presence of dinoflagellates in the lower Grandstand suggest marine near-shore deposition. Higher in the Grandstand, the repeated presence of coal suggests frequent subaerial exposure along an oscillating shoreline. The high concentration of spores in the upper Grandstand and all of the Killik suggests wet conditions within the delta. The continual increase in spores and decrease in gymnosperm pollen indicate that conditions were becoming continually wetter. Thus, in this area, the adjacent delta was initially dry enough to sustain occasionally dominant gymnosperm floras (base of Grandstand Formation), but it became wetter, and spore-producing vegetation became dominant. At the well locality, subaqueous deposition persisted until upper Grandstand time when the first coals formed. After this time, an oscillating shoreline controlled deposition, allowing coal to form on marginally marine shales and siltstones. The continual increase in spores suggests shoaling or continual establishment of the delta in the area, and that the general paleoenvironment was wet.

Titaluk-1 Well (Robinson, 1959) (Fig. 55)

Well information.—The Titaluk-1 well penetrated the Ninuluk Formation, the Killik Tongue of the Chandler Formation, and the Grandstand Formation. The Ninuluk occurs at the surface, and it is not known how much of the upper part is missing. Because more Ninuluk is present here than in any of the other wells, probably most of it is present. Samples were available for the lower 122 m of the Ninuluk. All of the Killik is present (disconformities are not suspected), and several samples were available for analysis throughout this unit. The underlying Grandstand Formation was also completely penetrated, and adequate sampling was done throughout the Grandstand Formation.

Throughout the Nanushuk Group, sandstones alternate with shales and siltstones typical of a continually shifting delta. The Killik has much less sandstone per unit of section than does the Grandstand.

General palynology.—In the lower 152 m of the Grandstand Formation, spores and gymnosperm pollen are similar in relative frequencies, alternating in dominance. Through the next 244 m, gymnosperm pollen dominates markedly, reaching peaks of 66 to 75 percent. In the upper 122 m of the Grandstand, gymnosperm pollen and spores again are similar in numbers, but alternate, the

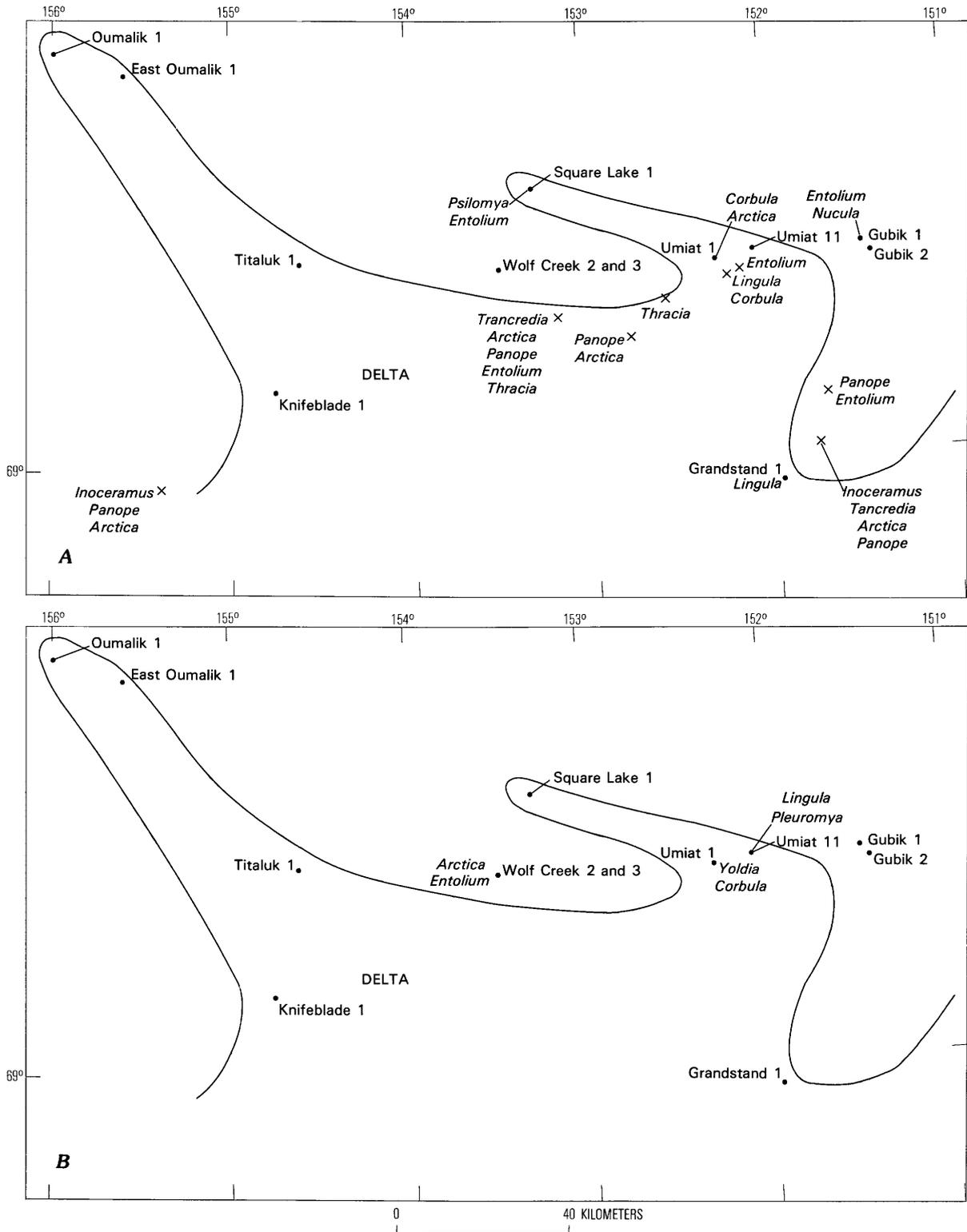


Figure 53. Invertebrate megafossils observed in Nanushuk Group rocks (Imlay, 1961). Shape of delta (heavy solid line) based on configuration of sand percentage contours (Huffman and others, this volume) and shows composite of features that developed over the lifetime of the delta. *A*, lower part of Grandstand Formation; *B*, upper part of Grandstand Formation; *C*, lower part of Killik Tongue of the Chandler Formation; *D*, upper part of Killik Tongue of the Chandler Formation.

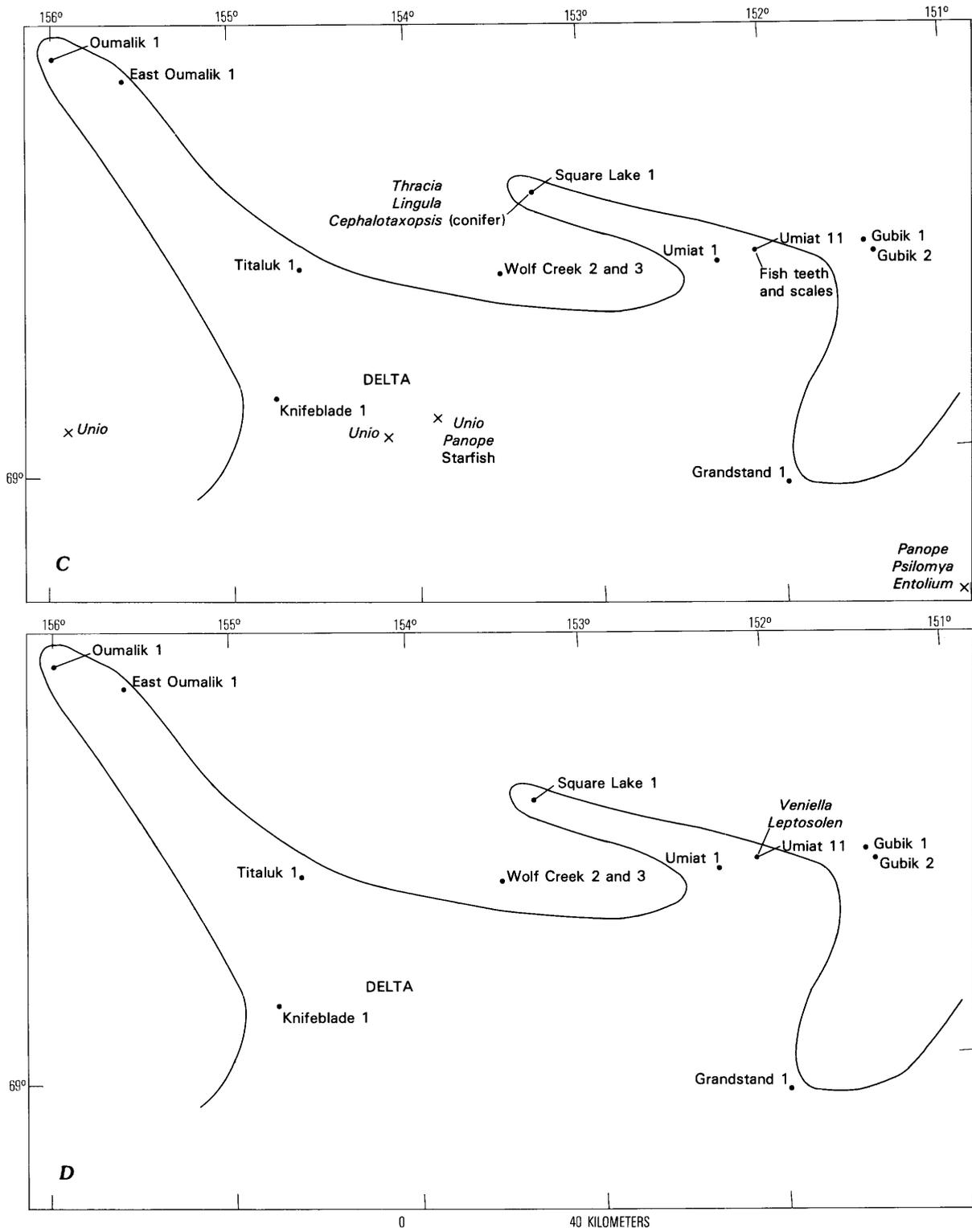


Figure 53. Continued

spores becoming dominant. Spores then dominate in the lower 122 m of the Killik, and reach peaks of 68 to 81 percent. Spores dominate in the remainder of the well.

Gymnosperm pollen appears to be dominant throughout most of the Grandstand, although alternating somewhat with spores at the base and top. In the Killik,

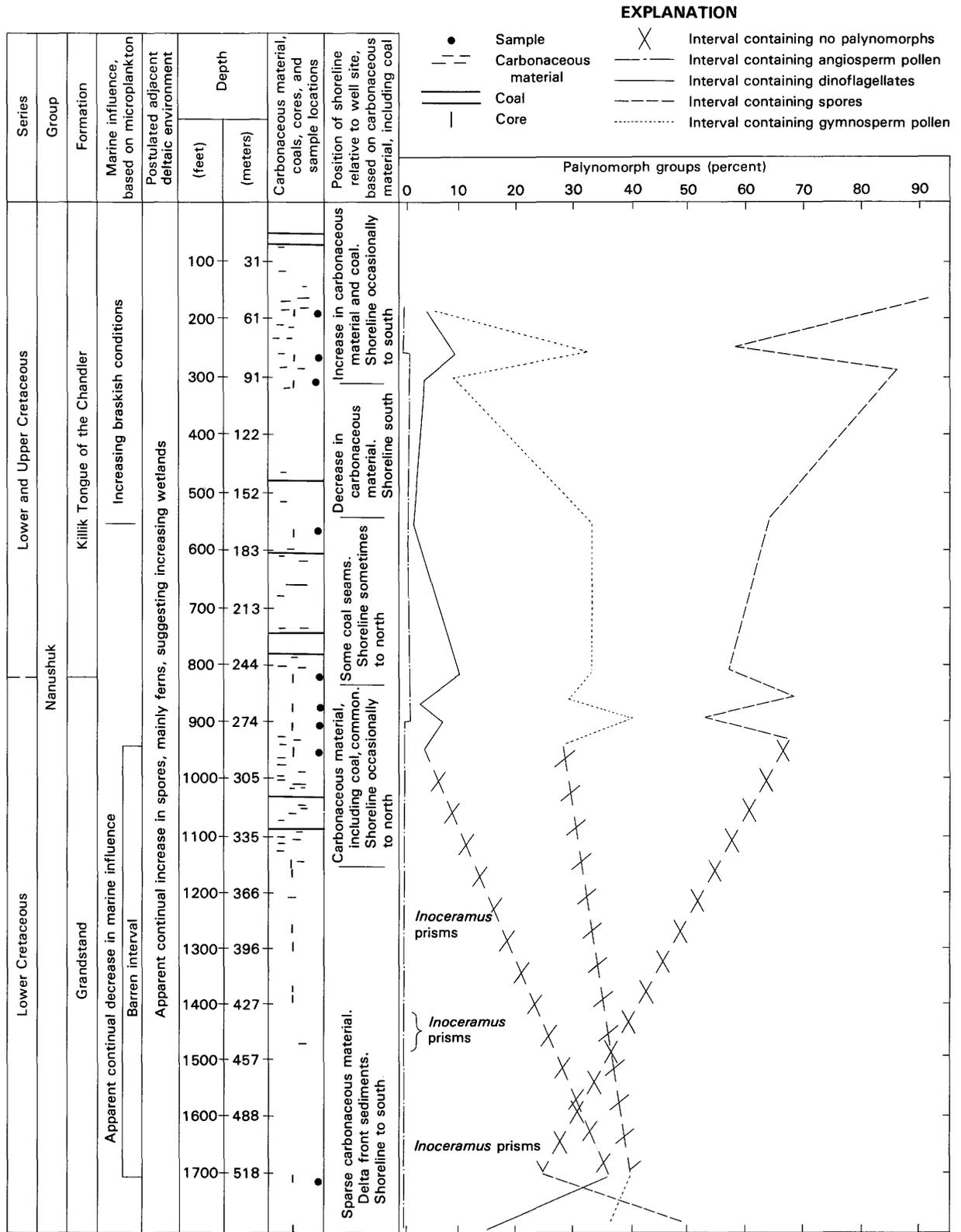


Figure 54. Composite relative-frequency diagram of main palynomorph groups and environmental data from Knifblade-1 well, Umiat delta area, North Slope.

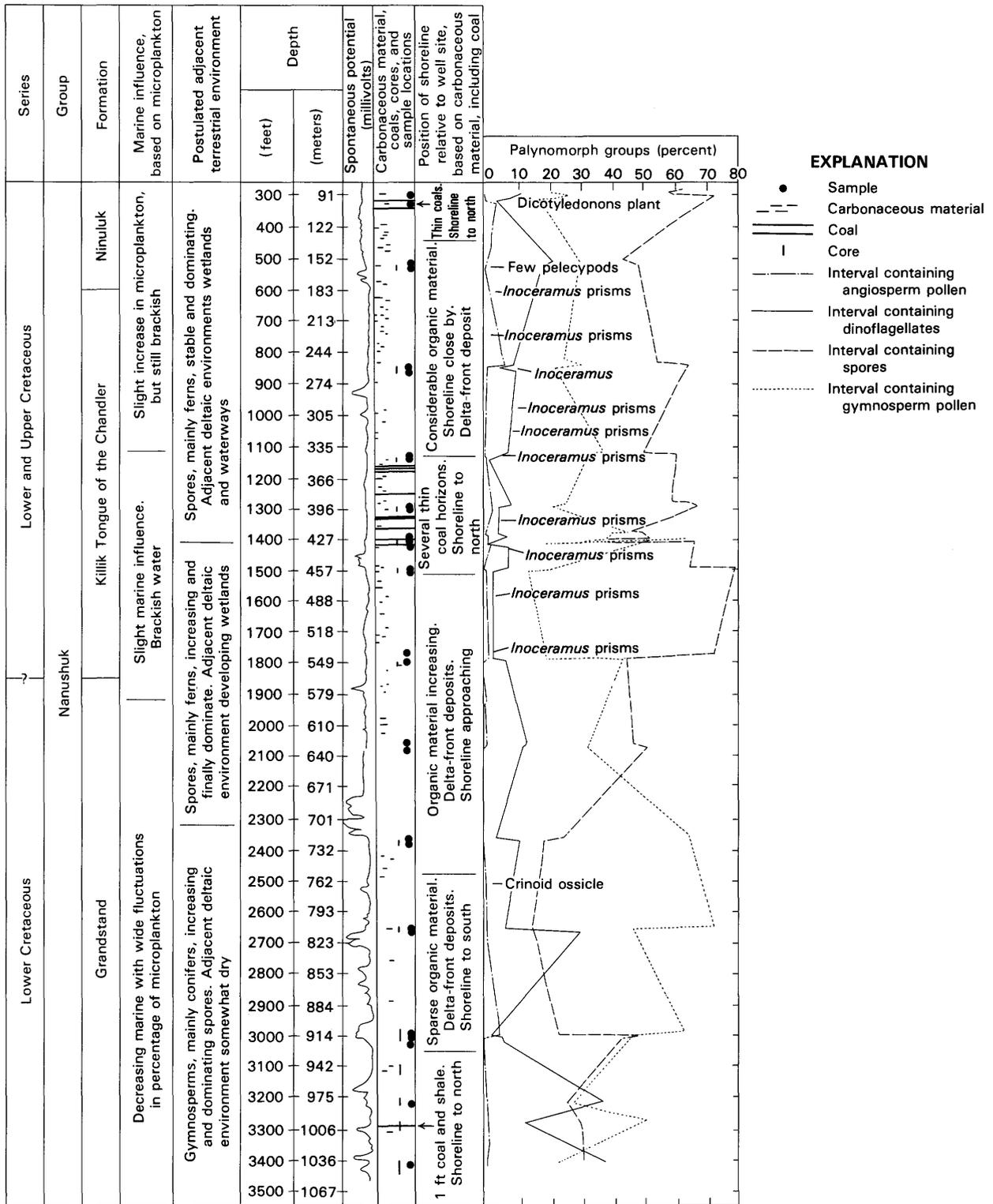


Figure 55. Composite relative-frequency diagram of main palynomorph groups, environmental data, and spontaneous-potential log from Titaluk-1 well, Umiat delta area, North Slope.

gymnosperm pollen are subordinate to spores, but amounts remain rather uniform to the top of the Ninuluk.

Dinoflagellates and acritarchs dominate in two samples at the base of the Grandstand, but are almost totally subordinate to both gymnosperm pollen and spores throughout the remainder of the well.

Angiosperms are present as a very minor component in several samples scattered throughout the well.

Trends.—Dinoflagellates and acritarchs generally decrease in numbers from the base to the top of the Grandstand (40–4 percent), but remain relatively uniform up through the Killik and Ninuluk, although increasing slightly upsection into the Ninuluk.

Gymnosperm pollen generally increases from the base of the Grandstand Formation for about 305 m (25–67 percent), and then generally decreases to the top of the Ninuluk (67–22 percent).

Spores generally decrease from the base of the Grandstand Formation upward for about 305 m. In the upper Grandstand, spores increase (20–47 percent) and remain rather uniform upward through the remaining Killik and Ninuluk.

Coal.—One thin coal seam occurs in the lower part of the Grandstand Formation. In the middle Killik, coal is common in thin layers. In the upper Killik and lower Ninuluk, coal is sparse but is present in somewhat thicker layers in the middle Ninuluk. It is sparse in the upper Ninuluk.

Paleoenvironmental interpretation.—The continual decrease in dinoflagellates and acritarchs upward in the Grandstand Formation suggests a lessening in marine conditions throughout that interval. This change suggests that deltaic buildup was reducing the marine influence more and more. The one thin coal seam in the lower part of the Grandstand Formation suggests rare subaerial exposure at that time. Subaerial exposure was common in middle Killik time. In the lower and upper Grandstand Formation gymnosperms (mainly conifers) become markedly dominant over spores, suggesting better drained conditions in adjacent deltaic areas. In the uppermost Grandstand, spores first begin to dominate over gymnosperm pollen, suggesting that deltaic conditions near the Titaluk well were becoming wetter. This environment becomes more striking in the lower Killik where spores dominate over gymnosperms by as much as 60 percent. At 122 m up into the Killik, spores and gymnosperms alternate several times, but spores dominate upward through the remainder of the section, which suggests general wet conditions.

The rare occurrence of coal in the Grandstand suggests that the Titaluk well area was generally submerged. The shoreline appears to have reached the area once in early Grandstand time, but not again until middle Killik time.

Lower Killik deposition was much the same as the upper Grandstand. Coal is sparse and sporadic. During

middle Killik time here, coal formation was more common, suggesting that the area was emergent more frequently and that the shoreline, therefore, was often to the north.

Coal formed occasionally during middle Ninuluk time. At this time the shoreline, though oscillating back and forth, was probably mostly to the south, due to the more common marine influence. Dinoflagellate occurrence tends to increase from the lower Killik upward through the Ninuluk, which suggests the establishment of estuarine conditions within the delta, possibly due to the Seabee transgression that ultimately covered the delta.

In general, in most of the Grandstand Formation, the pollen, spores, and dinoflagellates-acritarchs suggest an initial period of draining when gymnosperm vegetation dominated adjacent deltaic areas. This period was followed by wet conditions during latest Grandstand time and throughout the remainder of the time represented in the well, when spore-producing vegetation dominated. The shoreline appears to have remained to the south most of the time.

Oumalik-1 Well (Robinson, 1956) (Fig. 56)

Well information.—Oumalik 1 well penetrated the Grandstand Formation from the surface to a depth of 929 m. Therefore, no data are available for either the Killik or the Ninuluk, which typically overlie the Grandstand. Sandstones, shales, and siltstones alternate throughout the Grandstand, sandstone being less common in the upper half.

General palynology.—From the base of the Grandstand Formation upward, spores and gymnosperm pollen alternate in dominance through about 152- or 183-m intervals, implying slow changes in the wetness and dryness of the delta. In the bottom 152 m, spores reach peaks of 50 to 56 percent, dominating gymnosperm pollen by 10 to 25 percent. Through the next 152-m interval, gymnosperms reach a peak of 62 percent, dominating spores by as much as 32 percent. Through the next 183 m, spores and gymnosperm pollen remain relatively uniform, spores dominating gymnosperms by only 1 to 5 percent. Through the next 213 m of the Grandstand, gymnosperms increase continually from 43 to 77 percent, and spores drop continually from 45 to 19 percent. No samples were available for the upper 152 m of the well. Angiosperm pollen was not observed.

Dinoflagellates and acritarchs are present in each sample examined, but they dominate in only one sample from about 137 m above the base of the Grandstand. In all other samples they are subordinate to both spores and gymnosperm pollen throughout the section.

Trends.—Dinoflagellates and acritarchs decrease generally from the base of the Grandstand to the top.

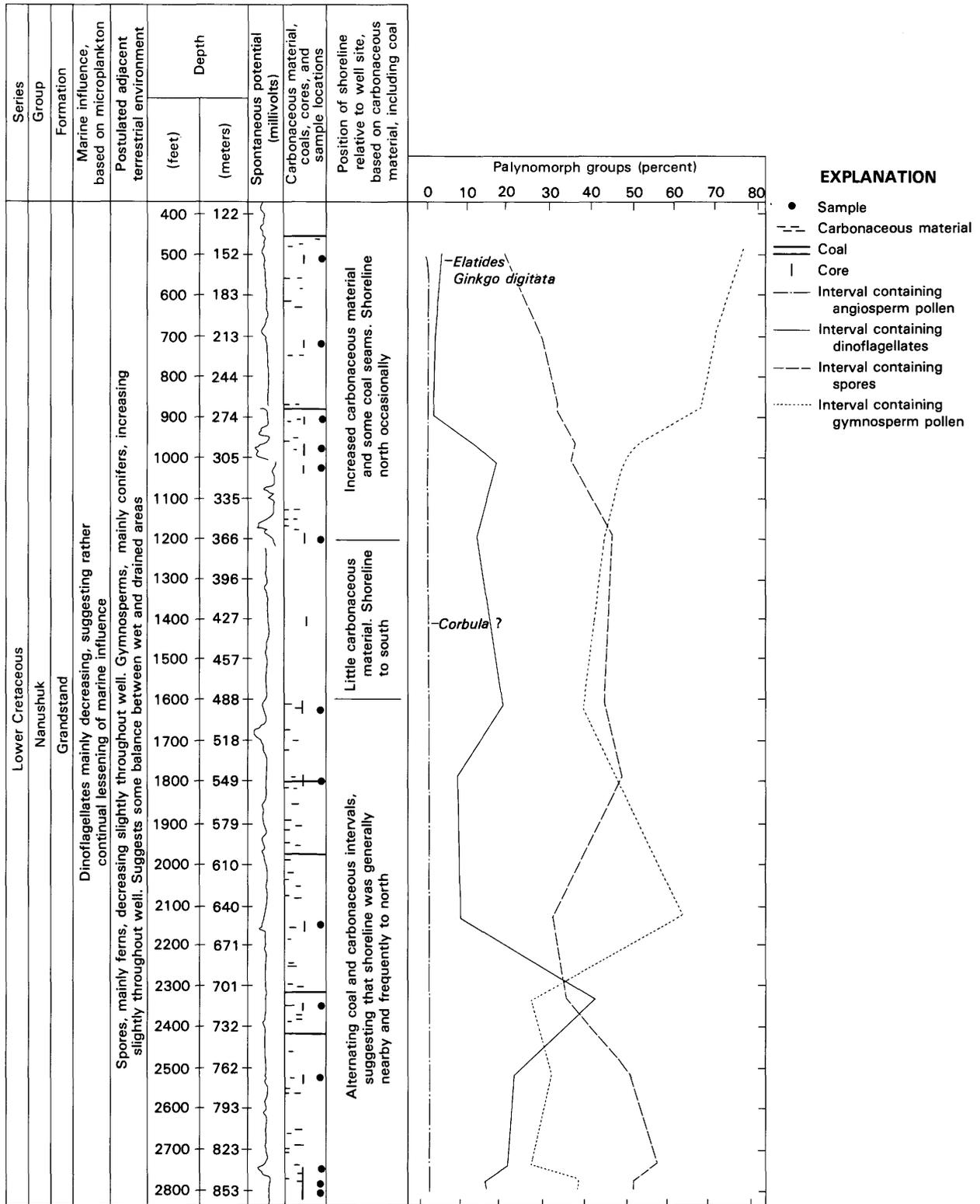


Figure 56. Composite relative-frequency diagram of main palynomorph groups, environmental data, and spontaneous-potential log from Oumalik-1 well, Umiat delta area, North Slope.

Gymnosperm pollen increase slightly up through the well, and spores decrease slightly up through the well.

Alternation of dominance between gymnosperm pol-

len and spores is almost rhythmic, changing over each 152 to 183 m.

Coal.—Coal occurs sparsely through the Grand-

stand Formation, but is more common in the Grandstand here than in any of the other wells examined.

Paleoenvironmental interpretation.—The general decreasing trend in dinoflagellates and acritarchs suggests growth of the delta and accompanying restriction of marine influences through time. The few occurrences of thin coal seams suggest some subaerial exposure and that the shoreline was occasionally to the north. However, the shoreline was oscillating, as dinoflagellates are also persistent, though in low percentages, most samples having less than 18 percent.

Dominant spores in the lower 152 m suggest that adjacent deltaic areas were wet. Drier conditions are suggested by dominant gymnosperm pollen in the next higher 152 m. For 183 m above this, fern spores dominate the gymnosperms slightly by a few percent. This relationship suggests some equivalence between areas of gymnosperm and spore floras in adjacent deltaic areas. In the upper 213 m, gymnosperms increase consistently in dominance, which suggests drying conditions in adjacent deltaic areas where gymnosperm floras became dominant.

The striking overall feature in the Oumalik well is that spores as well as dinoflagellates and acritarchs consistently decrease, and gymnosperms consistently increase even though spores and gymnosperms alternate in dominance. This relationship suggests that marine influence was continually decreasing and that better drained conditions were becoming more prevalent in the adjacent deltaic areas, or that nearby distributaries were bringing in more bisaccate pollen from the highlands.

East Oumalik-1 Well (Robinson, 1956) (Fig. 57)

Well information.—East Oumalik-1 well penetrated a complete section of Killik, 207 m thick, and Grandstand, 707 m thick. The entire section consists of alternating sandstone, shale, and siltstone.

General palynology.—Of all the wells examined, East Oumalik has the least variation in relative frequencies for each group of palynomorphs. Dinoflagellates are present in each sample examined, generally between 5 and 18 percent, and dominating the other two main groups (gymnosperm pollen and spores) only in the uppermost Killik in one sample. Spores fluctuate with the dinoflagellates, remaining uniform up through the Grandstand, always dominated by gymnosperm pollen. In two samples, at 289 and 518 m in the Grandstand, gymnosperm pollen dominate spores by only about 1 percent. In the Killik, however, spores dominate gymnosperm pollen by a considerable amount (3–41 percent). The relative frequencies of gymnosperm pollen are very uniform up through the

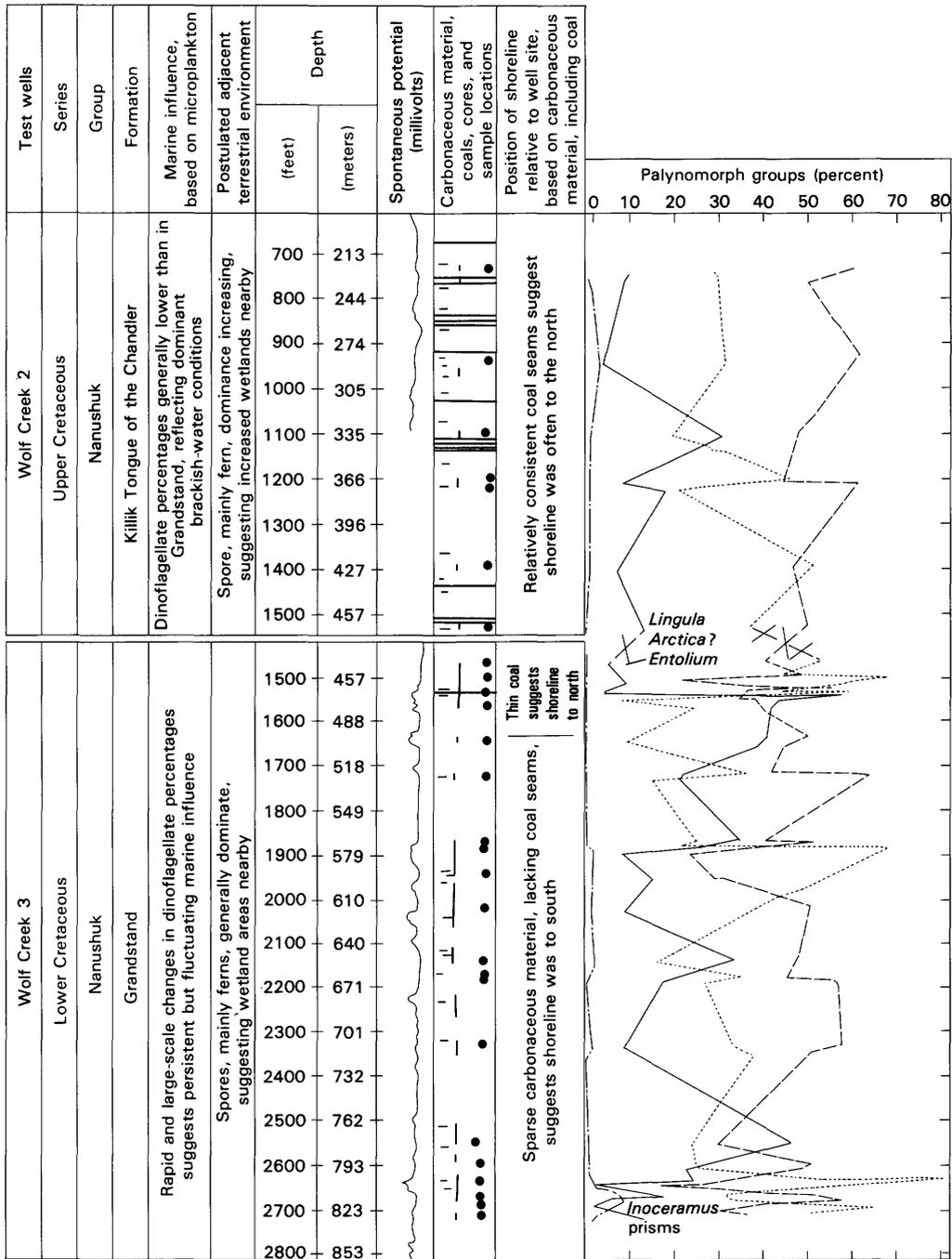
Grandstand, generally between 43 and 55 percent. In the Killik, however, gymnosperm pollen shows a rather continual decreasing trend, and is dominated by both dinoflagellates and spores near the top of the tongue.

Trends.—Relative frequencies are fairly uniform for each group throughout the Grandstand Formation. Gymnosperm pollen dominate at least slightly in almost every sample examined, spores are slightly subordinate to the gymnosperm pollen, and dinoflagellates and acritarchs are dominated by both. In the Killik Tongue of the Chandler, the trend of gymnosperm pollen amounts is to lower percentages, and these amounts are subordinate to spores throughout most of the tongue. The trend of dinoflagellates and acritarchs is to higher percentages, dominating both spores and gymnosperms near the top of the tongue. No angiosperm pollen were observed in any Grandstand or Killik samples.

Paleoenvironmental interpretation.—The presence of dinoflagellates and acritarchs in all samples examined suggests continuous marine influence throughout Nanushuk time, although the Killik assemblages appear more estuarine than those of the Grandstand. The almost continuous and uniform dominance of gymnosperm pollen throughout the Grandstand Formation suggests that better drained conditions existed for a long period in adjacent deltaic areas, or that deltaic distributaries were transporting bisaccates to this area. The decrease in numbers of gymnosperm pollen in the Killik and the resulting dominance by spores suggests that conditions became wetter in adjacent areas. This conclusion is substantiated by the increase in numbers of dinoflagellates, which suggests brackish water through Killik time. Bodies of standing water likely communicated with the sea by increased mixing with saltwater through tidal channels. Swamp conditions appear more prevalent in the basal Killik, as is indicated by increased coal amounts.

Wolf Creek-2 and -3 Wells (Collins, 1959) (Fig. 58)

Well information.—In the Wolf Creek-3 well, palynological samples were available only for the Grandstand Formation. For this reason, palynological data for the Killik Tongue of the Chandler Formation were gathered from Wolf Creek-2 well and were included with the Grandstand data from Wolf Creek-3 as a composite section. In Wolf Creek-3, a complete section of Grandstand Formation was penetrated from about 427 m to 841 m. In Wolf Creek-2, a complete section of Ninuluk Formation was penetrated, but no samples were available. Underlying the Ninuluk, a complete section of Killik was



EXPLANATION

- Sample
- Carbonaceous material
- ==== Coal
- | Core
- × Gap between parts of composite section
- Interval containing angiosperm pollen
- Interval containing dinoflagellates
- Interval containing spores
- Interval containing gymnosperm pollen

Figure 58. Composite relative-frequency diagram of main palynomorph groups, environmental data, and spontaneous-potential log from Wolf Creek-2 and -3 wells (composite section), Umiat delta area, North Slope.

penetrated between 198 and 472 m, for which samples were available.

The Grandstand Formation is composed of alternat-

ing sandstone and shale or siltstone. The Killik is primarily shale and siltstone, but thin sandstones are also present.

General palynology.—Spores tend to dominate through both the Grandstand and Killik, even though their relative frequencies fluctuate considerably from sample to sample, especially within the Grandstand Formation. Rare peak abundances of gymnosperm pollen or dinoflagellates and acritarchs occur. Whereas dinoflagellates and acritarchs are dominated by gymnosperm pollen at the base of the Grandstand, they alternate with the gymnosperm throughout the remainder of the Grandstand. In the Killik, where spores tend to dominate all groups, the dinoflagellates and acritarchs are subordinate to the gymnosperms, with one exception in the middle of the Killik.

Angiosperms are present in low percentages (0–4 percent) and form an almost negligible component, as in other wells.

The most striking feature of the relative frequencies from the Wolf Creek wells is the degree of fluctuation of each group from sample to sample within the Grandstand Formation; this fluctuation reflects unstable conditions near the well sites. Although hydrodynamic conditions could be involved, such as facies-controlled deposition of palynomorphs, we make a preliminary interpretation here of rapidly changing vegetational environments in adjacent deltaic areas.

Trends.—Dinoflagellates and acritarchs appear in low percentages (2–18 percent) at the base of the Grandstand, but they rise to 46 percent in the lower Grandstand before decreasing again to 9 percent. This decrease is followed by a relatively consistent rise through the rest of the Grandstand to 58 percent. Dinoflagellates and acritarchs then decline abruptly at the top of the Grandstand, followed by continuously increasing peaks into the Killik.

Spores dominate through most of the Nanushuk, but it was difficult to determine any particular trends. The consistent wide fluctuation in their percentages is striking, but peaks or lows do not seem to follow any particular pattern.

Gymnosperm pollen percentages appear to have rhythmically fluctuating patterns. At the base of the Grandstand, gymnosperm pollen percentages are high (two peaks of 65 and 92 percent), then they decrease to 24 percent, rise to 68 percent at the base of the upper Grandstand, then decrease to 8 to 21 percent in the upper Grandstand, then increase to 69 percent at the top of the Grandstand. In the Killik, gymnosperm pollen generally decrease from the 69 percent peak at the top of the Grandstand to 29 percent at the top of the Killik.

Coal.—Except for one thin coal seam at about 465 m (uppermost Grandstand), no coal is present throughout the Grandstand Formation, although carbonaceous partings and material were frequently recorded in the well description. A few thin coal seams appear in the base of the Killik at both Wolf Creek–2 and –3 wells and become more abundant through the middle Killik at Wolf

Creek–2. Coal is present in the upper Ninuluk at both Wolf Creek–2 and –3.

Paleoenvironmental interpretations.—The lack of coal in the Grandstand suggests continual subaqueous (marine to estuarine) deposition, but the presence of carbonaceous material throughout this interval indicates near-shore deposition. Dinoflagellates and acritarchs have several peaks between 25 and 59 percent in the Grandstand, which suggests relatively good marine conditions. The general dominance of spores throughout the Grandstand suggests wet conditions in adjacent deltaic areas; a few gymnosperm peaks suggest that better drained conditions existed somewhere nearby.

In the Killik, dinoflagellate and acritarch percentages are consistently lower than in the Grandstand, and the assemblages are assumed to be estuarine. The drop in dinoflagellates corresponds to coal development at the well site, which suggests shoaling and some subaerial deposition. The dominance of spores and the decreasing gymnosperm pollen in the Killik suggests increasingly wet conditions in adjacent deltaic areas.

The high degree of fluctuation of percentages for all groups in the Grandstand is interpreted as suggesting frequent changes in wetness in the nearby deltaic areas. On rare occasions, adjacent areas may have become dry enough to support dominant gymnosperm vegetation (primarily conifer), but this appears exceptional.

Square Lake–1 Well (Collins, 1959) (Fig. 59)

Well information.—Square Lake–1 well penetrated the Nanushuk Group from 576 to 1,215 m. The formations include Chandler-Ninuluk undifferentiated from 576 to 756 m and Grandstand Formation from 756 to 1,215 m. Although the well bottomed in the Grandstand Formation, we believe that most of the formation is present in the well.

Although the Killik Tongue of the Chandler and the Ninuluk are undifferentiated in the well, we believe that most of this interval is probably Killik because the thickness of the unit is only 183 m, which is not unreasonable for the Killik in this area.

The section consists of alternating sandstone, shale and siltstone, with shale predominant.

General palynology.—In the lower 152 m of the Grandstand Formation, gymnosperms dominate initially, but decrease from 60 to 38 percent, whereas the spore palynoflora increases through the same interval from 35 to 49 percent. The transition interval from gymnosperm dominance to spore dominance shows much alternation in the dominance of spores and gymnosperms. Although dinoflagellates and acritarchs are a minor component, they show one peak of 40 percent. Angiosperms are present, but they are always less than 3 percent.

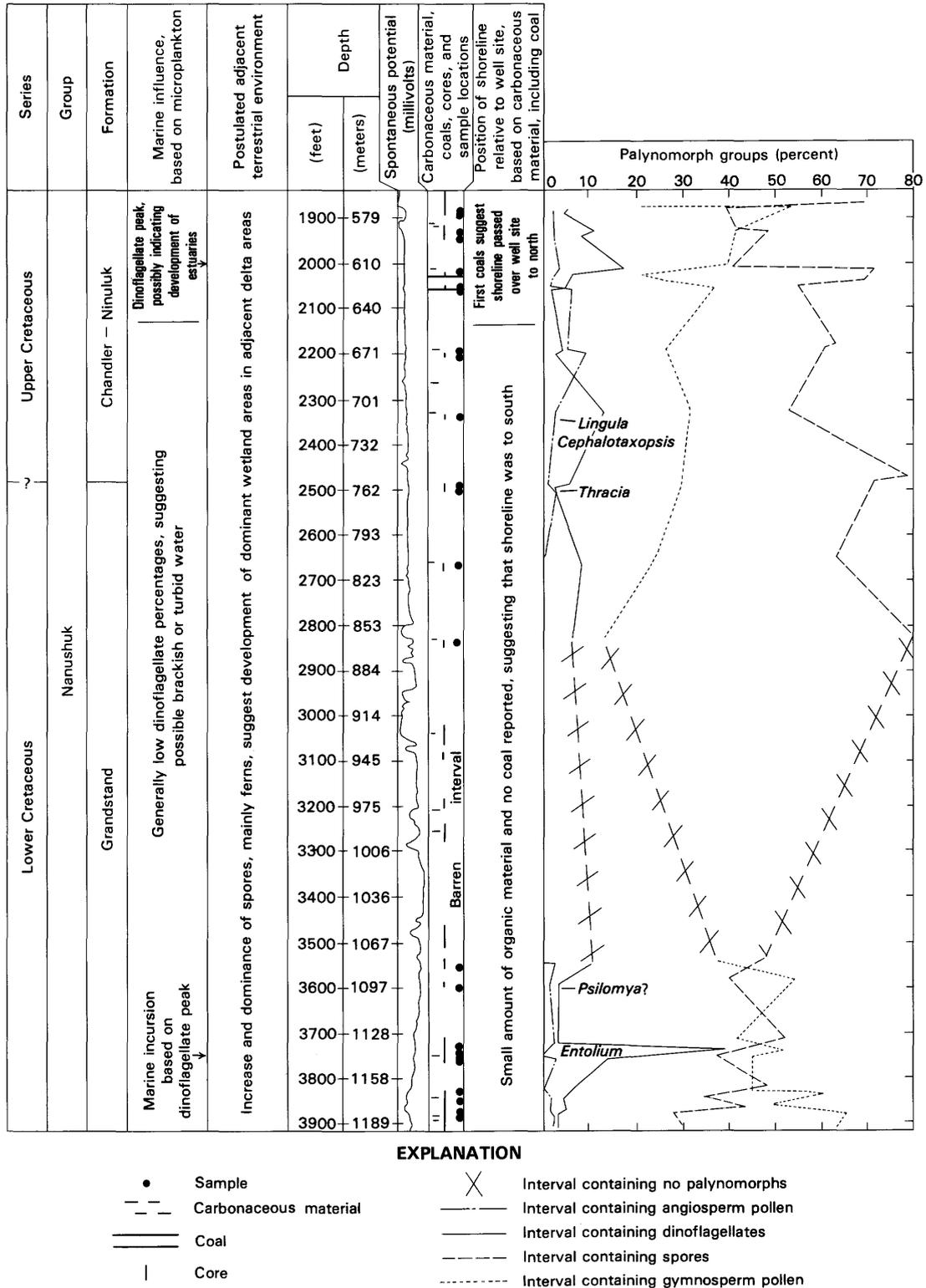


Figure 59. Composite relative-frequency diagram of main palynomorph groups, environmental data, and spontaneous-potential log from Square Lake-1 well, Umiat delta area, North Slope.

The overlying 213 m of the Grandstand Formation lacked samples. At the top of this interval, at 866 m, spores dominate markedly (81 percent) over gymnosperms

(13 percent). Dinoflagellates and acritarchs are present in low numbers (about 6 percent). Angiosperms are absent.

From 866 m (upper Grandstand Formation) to the

top of the Nanushuk Group (576 m), spores generally decrease from 80 to 40 percent, whereas the gymnosperm pollen generally increases from 13 to 53 percent. In the upper 15 m of the Chandler-Ninuluk undifferentiated sequence, gymnosperms and spores alternate briefly in dominance, but near the top of this interval spores dominate (71 percent) over gymnosperm pollen (22 percent).

Trends.—In a general way, spores and gymnosperm pollen vary inversely to each other in the well. As gymnosperms decrease in dominance from the base of the well in the lower Grandstand to the upper Grandstand, spores increase. From the upper Grandstand to the top of the Nanushuk, gymnosperm pollen increase in numbers and spores decrease. Spores, however, maintain a slight dominance at the top of the well in what is probably the Chandler Formation (Killik Tongue).

Dinoflagellates and acritarchs are relatively stable throughout the well with some peaks of less than 20 percent, and they do not appear to be affected by trends in either the spores or the gymnosperms.

Angiosperms are an insignificant part of the overall palynoflora, and trends are difficult to detect.

Coal.—Two occurrences of coal are indicated in the well description. These are thin layers in the upper Chandler-Ninuluk interval. A few carbonaceous partings and carbonaceous plant remains were also noted throughout the Nanushuk.

Paleoenvironmental interpretations.—The presence of dinoflagellates throughout the Nanushuk Group, although generally in small percentages (less than 18 percent), suggests a continuous marine influence. The dominance of terrestrial palynomorphs suggests a close proximity to shoreline. The general lack of coal suggests general subaqueous deposition. General dominance of spores suggests that adjacent deltaic areas were wet; the slight dominance of gymnosperm pollen at the bottom of the well (lower Grandstand), however, suggests somewhat better drained conditions nearby at that time, or that deltaic distributaries were draining into the area.

Umiat-1 Well (Collins, 1958) (Fig. 60)

Observations on the Umiat-1 well were made only in the Ninuluk Formation and Killik Tongue of the Chandler Formation for comparison with the same intervals in nearby Umiat-11 well. The unusually high amount of shale in Umiat-1 contrasts strongly with the higher concentrations of sand from the same interval at Umiat-11 and suggests dissimilar environments of deposition, probably an embayment versus a delta lobe.

Well information.—A complete section of the Ninuluk Formation, Killik Tongue of the Chandler Formation, and the Grandstand Formation was penetrated to a depth of 613 m.

General palynology.—Dinoflagellates and acritarchs in the Killik Tongue of the Chandler Formation range between 5 and 15 percent, suggesting some marine influence. Specific assemblages suggest estuarine conditions as well. Higher in the Ninuluk Formation, two samples show a range for dinoflagellates of 3 to 63 percent, probably indicating quiet or brackish-water areas possibly caused by the initial effects in the delta of the Seabee marine transgression.

Spores appear to dominate most of the Killik Tongue of the Chandler, suggesting relatively wet environments in adjacent deltaic areas. Gymnosperms appear to be intermediate between dinoflagellates and spores within this interval. In the upper part of the Killik Tongue of the Chandler and in the Ninuluk Formation, gymnosperms have relative frequencies similar to those of the spores, but with a slight dominance. Angiosperms are a minor part of the palynoflora, and occur in only two samples.

Trends.—Spores decrease generally up through the section. The limited data make it difficult to interpret trends for the gymnosperms and dinoflagellates and acritarchs.

Coal.—No coal was described in the well log. Carbonaceous partings are common.

Paleoenvironmental interpretations.—The overall lack of coal suggests general subaqueous deposition. Dinoflagellate occurrences suggest marine conditions with some brackish water. The presence and persistence of carbonaceous material indicates nearshore shallow water.

Umiat-11 Well (Collins, 1958) (Fig. 61)

Well information.—Umiat-11 well penetrated a complete section of the Ninuluk Formation, Killik Tongue of the Chandler Formation, and the Grandstand Formation to a depth of 937 m. The Grandstand is about 198 m thick, the Killik about 79 m thick, and the Ninuluk Formation is about 36 m thick. Lithologies are alternating sandstone and siltstone or shale.

General palynology.—Dinoflagellate and acritarch relative frequencies are generally higher in Umiat-11 than in most of the other wells examined, and range from 17 to 38 percent in the Grandstand Formation, 13 to 37 percent in the Killik Tongue of the Chandler Formation, and 24 to 40 percent in the Ninuluk Formation.

Gymnosperm pollen are generally intermediate in abundance between dinoflagellates-acritarchs and spores, except in the lower Grandstand and Ninuluk, in which they appear to be subordinate to both dinoflagellates-acritarchs and spores.

Spores dominate throughout the Grandstand interval, alternate in dominance with gymnosperms through much of the Killik, and then dominate through most of the Ninuluk.

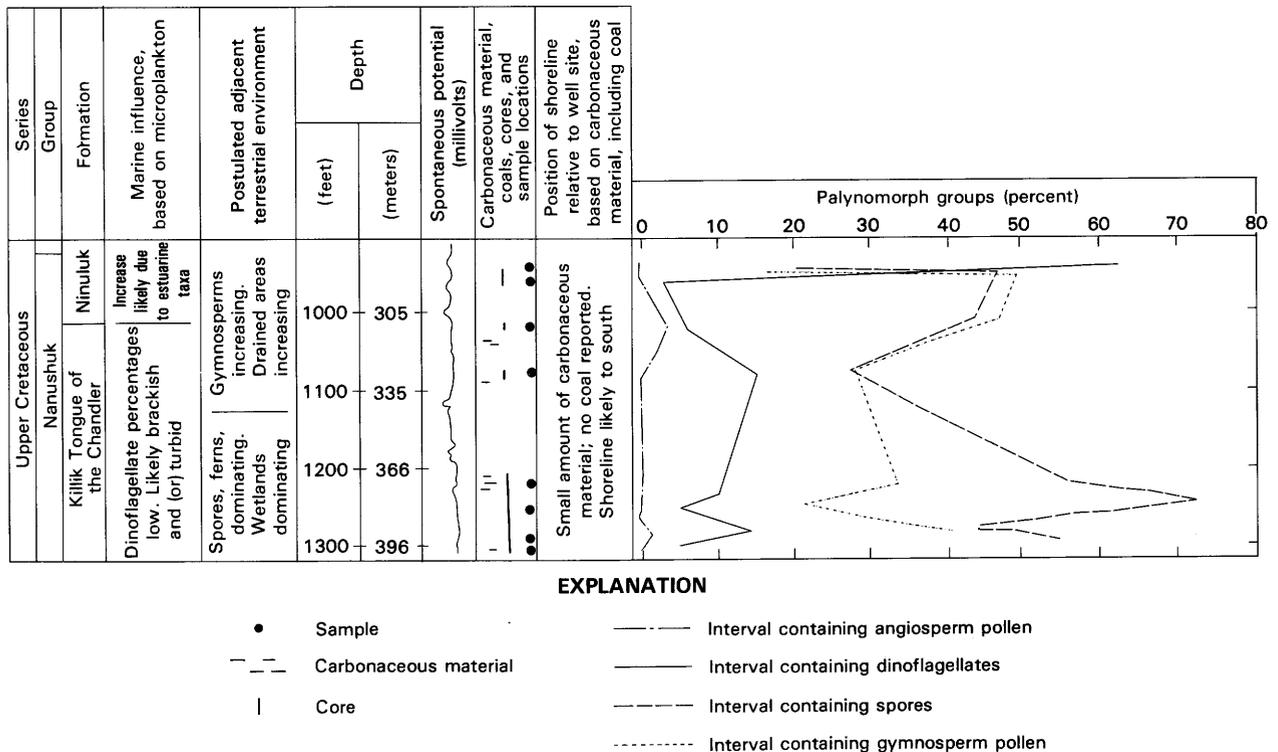


Figure 60. Composite relative-frequency diagram of main palynomorph groups, and environmental data and spontaneous-potential log from Umiat-1 well, Umiat delta area, North Slope. Megafossils reported from the underlying Grandstand Formation include: *Voldia* and *Corbula?* (1,635 ft, 498 m); *Corbula?* (1,693 ft, 516 m); and *Arctica* (1,712 ft, 522 m).

Angiosperm pollen are a minor component, generally less than about 3 percent, but they are persistent in most of the samples examined.

Trends.—Dinoflagellates-acritarchs decrease from 38 to 13 percent up through the Grandstand Formation and into the lower Killik, but they peak at 36 percent in the middle Killik. In the Ninuluk they have two peaks of 35 and 40 percent.

Gymnosperm pollen are somewhat stable in number in the Grandstand, but increase through the Killik, and then decline through the Ninuluk.

Spores fluctuate widely through the Grandstand Formation, and have high relative frequencies (35 to 62 percent), then decrease continuously into the middle part of the Killik. From the middle Killik to the upper Killik the spores generally increase, although they fluctuate in numbers, but they drop to 15 percent in the uppermost Killik. Through the Ninuluk the spores rise sharply.

Coal.—There is no coal reported from the Grandstand Formation. One thin seam occurs in the lower Ninuluk or uppermost Killik. No coal is reported from the remainder of the Ninuluk. Carbonaceous material is reported from the Killik and Ninuluk.

Paleoenvironmental interpretations.—Dinoflagellates and acritarchs range generally between 13 and 25 percent in the Nanushuk Group, which suggests a rather

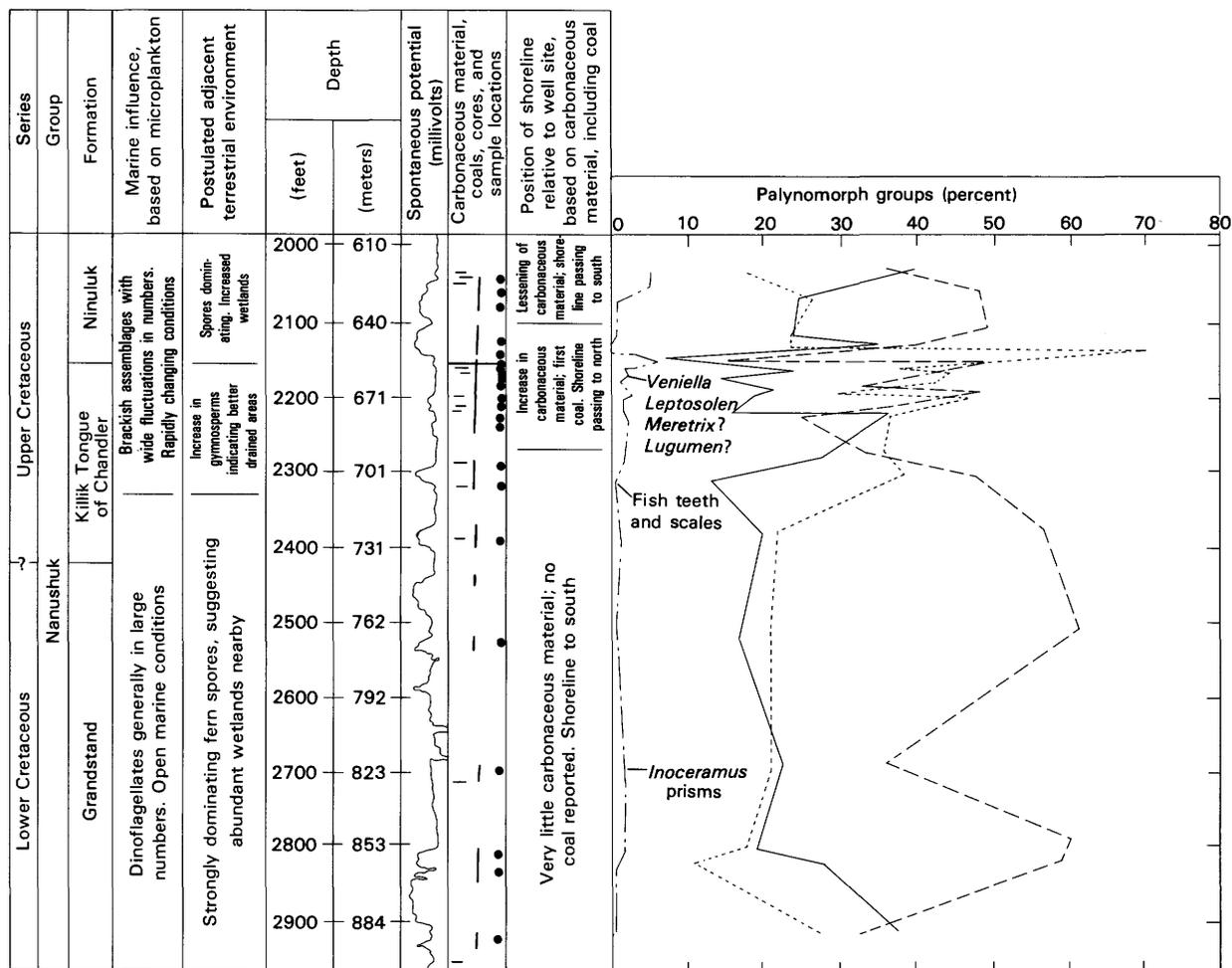
continual marine influence. A few peaks of more than 30 percent were observed.

The overall dominance of the terrestrial palynoflora suggests close proximity to shoreline. The spore dominance in the Grandstand and lower Killik indicates that adjacent deltaic areas were wet during that time interval. The low relative frequencies of dinoflagellates and acritarchs and high frequencies of gymnosperms in the upper Killik suggest that the area was becoming less marine and that better drained environments were developing within the adjacent delta. The decrease in both gymnosperms and spores through the Ninuluk and sharp increase of dinoflagellates and acritarchs suggests that the nearby areas were again coming under a marine influence, likely from the Seabee transgression.

Grandstand-1 Well (Robinson, 1958) (Fig. 62)

Well information.—The Grandstand-1 well penetrated the Nanushuk Group from 34 to 326 m. Formations penetrated include the Killik Tongue of the Chandler Formation from 36 to 64 m and the Grandstand Formation from 64 to 226 m. No samples were studied from the part considered to be Killik.

This section consists of alternating sandstone, shale and siltstone. Shales appear to dominate.



EXPLANATION

- Sample
- Carbonaceous material
- Coal
- | Core
- Interval containing angiosperm pollen
- Interval containing dinoflagellates
- Interval containing spores
- Interval containing gymnosperm pollen

Figure 61. Composite relative-frequency diagram of main palynomorph groups, environmental data, and spontaneous-potential log from Umiat-11 well, Umiat delta area, North Slope.

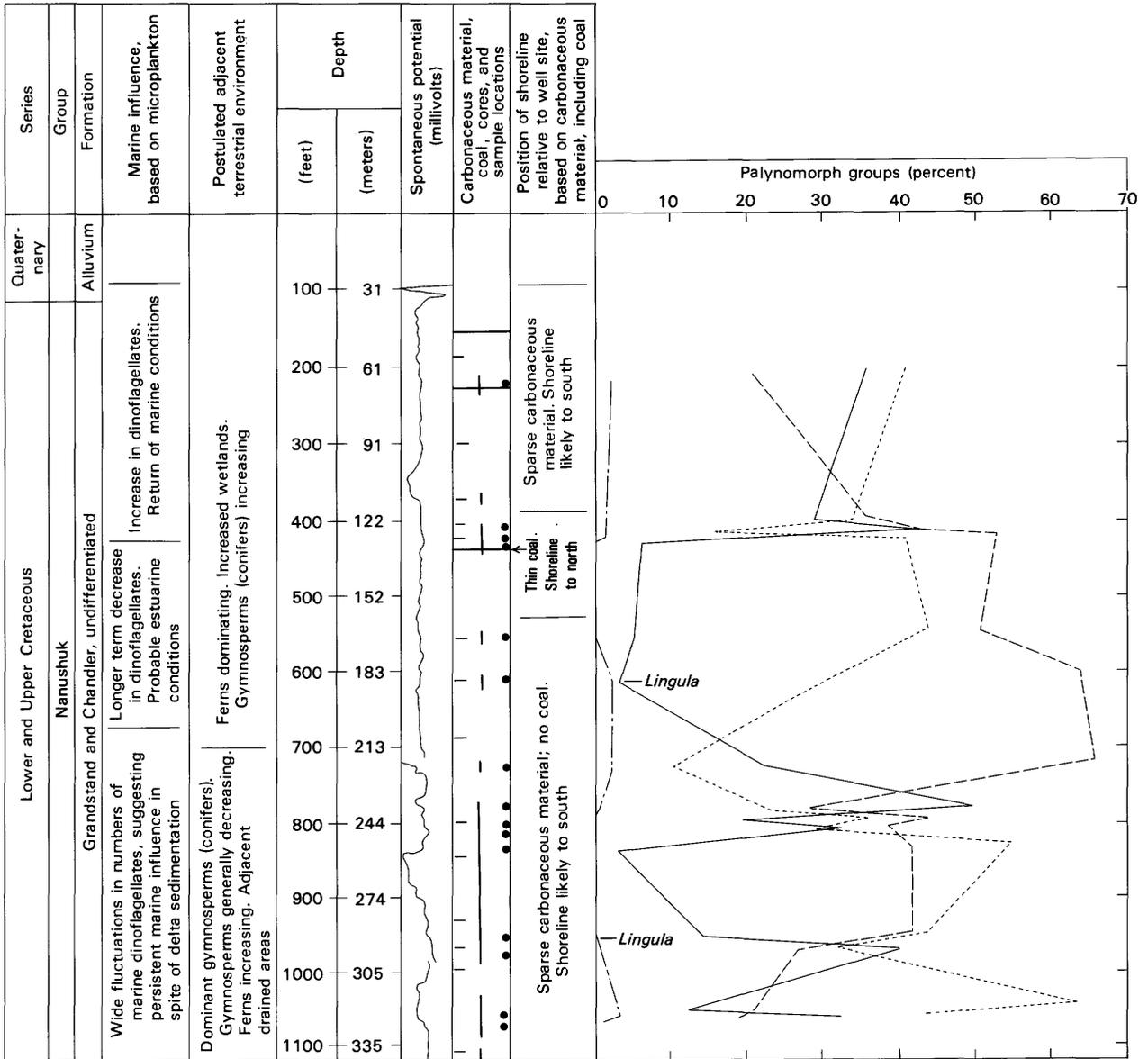
General palynology.—Dinoflagellate relative frequencies fluctuate widely throughout the Grandstand Formation (3 to 49 percent). Gymnosperm pollen dominate through the lower part of the Grandstand but become subordinate to spores in the middle Grandstand. At the top of the Grandstand (67 m), gymnosperms again dominate. Spores are intermediate between dinoflagellates-acritarchs and gymnosperm pollen in the lower Grandstand, but they dominate through the middle Grandstand. In the upper Grandstand the spores decline and are finally dominated by both gymnosperm pollen and dinoflagellates-acritarchs. Angiosperm pollen are present in many samples, but they are rare.

Trends.—Dinoflagellate relative abundances fluctuate widely throughout the Grandstand. Generally, per-

centages are low, but some high percentages occur as short-lived peak abundances. It is difficult to say whether dinoflagellates and acritarchs generally increase or decrease up through the section because of the wide fluctuations and the relatively short section. Spores generally appear to increase up through the section into the upper Grandstand, but they then decrease through about four samples. Gymnosperm pollen decrease generally through the lower Grandstand, but then appear to increase to the position of the upper sample. Angiosperms are too rare to indicate any trends.

Coals.—Carbonaceous partings generally occur throughout the Grandstand Formation. Sparce coal was reported in the upper Grandstand-Chandler interval.

Paleoenvironmental interpretations.—Marine dino-



EXPLANATION

- Sample
- Carbonaceous material
- ==== Coal
- | Core
- Interval containing angiosperm pollen
- Interval containing dinoflagellates
- Interval containing spores
- Interval containing gymnosperm pollen.

Figure 62. Composite relative-frequency diagram of main palynomorph groups, environmental data, and spontaneous-potential log from Grandstand-1 well, Umiat delta area, North Slope.

flagellates occur throughout the Grandstand Formation, indicating relatively continuous marine influence. Several samples have rather low percentages (less than 6 percent), but several peaks of more than 30 percent exist, indicating that marine conditions fluctuated to a large degree. This fluctuation is substantiated by some coal and carbonaceous partings in the well.

Gymnosperm pollen dominate in the lower Grandstand, which suggests better drained conditions than dur-

ing middle Grandstand time when spores dominated. The general increase in spores in the middle to upper part of the Grandstand suggests a relatively continuous increase in wet conditions in adjacent deltaic areas. In the upper Grandstand Formation, spores decrease in numbers, suggesting that the wetter conditions subsided. That better drained conditions developed is suggested somewhat by the dominance of gymnosperm pollen in the uppermost sample of the Grandstand.

Uranium Potential of the Cretaceous Nanushuk Group, North Slope, Alaska

By A. Curtis Huffman, Jr.

INTRODUCTION

The deltaic Nanushuk Group of Cretaceous age was evaluated as a uranium host rock at the same time that it was being evaluated as a hydrocarbon reservoir. Although no uranium occurrence has ever been reported in the Nanushuk, host-rock environments potentially favorable for sandstone-type deposits have been described by many investigators (for example, Chapman and Sable, 1960; Detterman and others, 1963; Chapman and others, 1964; Patton and Tailleux, 1964; Brosgé and Whittington, 1966; Roehler and Stricker, 1979).

Exposures of the Nanushuk Group were examined and described in detail at 32 localities (fig. 1; Huffman and others, 1981a, b) from Corwin Bluffs on the west coast to the Sagavanirktok River in the central North Slope (Ahlbrandt and others, 1979). Many more outcrops were visited during the course of this study but were described and sampled in less detail. Radioactivity measurements were made at each station and used for relative comparisons only; no attempt was made to convert values to absolute uranium content. However, approximately 700 samples of Nanushuk Group and related rocks were analyzed for uranium using the delayed-neutron counting method. A summary of these analyses is given in table 7.

SANDSTONE-TYPE URANIUM DEPOSITS

Sandstone-type uranium deposits can be loosely divided into peneconcordant deposits and vein deposits (Finch, 1967). The peneconcordant types are closely related to lithology and depositional environment, whereas vein deposits are controlled by structure and tectonics and occur in a wide variety of lithologies. Because the types of structures associated with vein deposits (high-angle fractures, collapse structures, and so forth) are very rare or absent in the Nanushuk Group, and because these types of deposits are not dependent on lithology, this discussion is concerned primarily with the favorability of the Nanushuk as a host for peneconcordant deposits.

Finch (1967) stated that most peneconcordant deposits "are in lenticular sandstone beds that accumulated

from fresh-water streams," and that "some uranium deposits are in sandstone beds deposited on deltaic coastal plains bordering shallow or deep seas." Fischer (1974) added that "Sedimentation on a low-lying terrane with a high water table, yielding nonoxidizing conditions of water-saturated beds, is indicated by the preservation of coalified fossil plants, which are present in almost all host beds." In addition to these two general characteristics, such criteria as attitude of the bedding, sandstone-mudstone ratio, percentage of stream deposits, and color have been frequently used to determine the favorability of a rock unit as a potential host for uranium deposits.

The possibility of suitable host rocks actually containing uranium deposits depends largely on an accessible source of the uranium. This source could either be within or adjacent to the host rocks, or connected to the host rocks by an aquifer. Sources within the host originate, together with the sediment itself, from uranium-rich rocks such as tuff, granite, black shale, phosphatic rocks, or from pre-existing uranium deposits. Adjacent sources and those connected to the host rock by aquifers include overlying or underlying units and the sediment source terrain itself. Fluids from intrusive bodies are another possible source (Page, 1960).

This assessment of the uranium potential of the Nanushuk Group is based on an evaluation of its suitability as a host rock, and includes factors such as depositional environments, hydrologic characteristics, texture, the presence of reductants, and the presence of possible uranium sources.

SUITABILITY OF THE NANUSHUK GROUP AS A HOST ROCK

The Nanushuk Group contains more than 1,500 m of nonmarine and fluvial sediments deposited on a low-lying deltaic plain, as has been documented elsewhere in this volume and in previous work. The abundance of carbonized plant debris throughout the Nanushuk has also been documented by many workers, most notably by Smiley (1966, 1969a, b). Because of the preservation of the fossil plant material, the general gray to greenish-gray color of a fresh surface, and the widespread occurrence of pyrite, it appears that the Nanushuk has never been

Table 7. Sedimentologic data and uranium content from the transitional and nonmarine parts of

[NA, not applicable; uranium determination by delayed neutron activation; analyses by H. T. Millard, C. McFee, C. M. Ellis, C. A.

Sample No.	Measured section	Transitional and nonmarine facies thickness (m)	Sandstone (percent)	Fluvial channel sandstone (percent)	Sandstone-mudstone ratio
33	Barabara syncline-----	1,295	14.7	6.1	0.172
8	Pitmegea syncline-----	451	3.2	1.5	.033
14	Tupikchak syncline-----	814	7.6	6.4	.083
26	Tupikchak Mountain-----	808	13.0	8.1	.151
18	Kokolik warp-----	1,551	5.9	3.4	.063
14	Folsom Point-----	540	10.9	2.5	.123
12	Lookout Ridge-----	214	4.2	2.4	.045
15	Carbon Creek anticline-----	432	3.5	.8	.036
140	Average Corwin delta-----	NA	7.9	3.9	.088
60	Kurupa anticline-----	1,516	21.8	6.7	.279
45	Tuktu Bluff-----	1,075	11.9	5.4	.135
30	Type Grandstand-----	576	29.7	3.1	.424
20	Arc Mountain-----	226	52.7	25.4	1.120
32	Marmot syncline-----	792	25.2	21.5	.337
187	Average Umiat delta-----	NA	28.6	12.4	.459

strongly oxidized and contains abundant material to act as a reductant for uranium-bearing solutions.

Table 7 lists values of several sedimentologic factors for 13 measured sections in the transitional and nonmarine parts of the Nanushuk Group. The most obvious conclusion to be drawn from this compilation is that the Corwin delta of the western North Slope (Ahlbrandt and others, 1979) was a muddy system containing a low percentage of sandstone, and of fluvial-channel sandstone in particular. The Umiat delta of the central North Slope (Huffman and others, this volume) contains more sandstone but little fluvial-channel sandstone. Low sandstone content, and especially the lack of long, continuous, and coalesced fluvial-channel sandstone bodies, is thought to be unfavorable for uranium mineralization in that the lack of such deposits impedes migration of the mineralizing fluids that form uranium deposits of minable size.

Along the southern margin of the North Slope the Nanushuk Group is folded into large open folds having limbs that dip as steeply as 70°. The folds die out to the north, however, and beneath the coastal plain dips range from 1 to 5°. Dips less than 5° are thought to be favorable for the development of peneconcordant sandstone-type uranium deposits, whereas intense deformation is generally considered unfavorable.

Based on these criteria, the Nanushuk Group of the western North Slope would be unsuitable as a potential host rock for uranium deposits, and would be only slightly

more suitable in the central region because of the increased sandstone and fluvial-channel sandstone content, particularly in the upper part. The nonmarine deposits along Sabbath Creek in the eastern North Slope (fig. 26) (correlated with the Nanushuk by Detterman and others, 1975) are also considered marginally suitable because of the presence of fluvial-channel sandstones and organic debris.

POSSIBLE URANIUM SOURCES

The Nanushuk Group is composed of sediments derived primarily from preexisting sedimentary rocks with a variable contribution from mafic to ultramafic rocks, metamorphic rocks, and volcanic detritus (Huffman, 1979; Mull, 1979; Bartsch-Winkler, 1979, and this volume). None of the sedimentary source rocks are known to contain uranium and none were found to be anomalously radioactive during this study. The mafic and ultramafic rocks in the source terrain are low in uranium (0.13–0.65 ppm) and fall in the gabbroic to ultramafic range documented by Z. E. Peterman (unpub. data, 1963) and Rogers and Adams (1969).

Anomalous radioactivity has been reported from phyllitic carbonaceous shales that contain sulfide deposits in the southwestern Brooks Range (Curtis and others, 1979), but it is doubtful that these distant rocks con-

selected measured sections in the Nanushuk Group of the western and central North Slope, Alaska

Bliss, M. F. Coughlin, R. B. Vaughn, M. N. Schneider, and W. R. Stang, U. S. Geological Survey. Locations of sections shown on figure 1]

Average sandstone thickness (m)	Alternations of sandstone to mudstone per 3.05 m (10 ft)	Average uranium (ppm)	High uranium (ppm)	Average uranium + 2 standard deviations (ppm)	No. samples greater than average uranium + 2 standard deviations
1.86	0.24	1.58	3.17	2.42	3
2.08	.04	1.18	1.62	1.30	2
3.69	.06	1.12	1.56	1.43	2
4.05	.10	1.45	1.99	1.63	6
1.86	.10	1.20	2.14	1.92	1
4.54	.07	1.41	2.59	2.11	2
2.29	.05	1.14	2.23	1.72	2
1.68	.06	2.21	2.82	2.72	1
2.76	.09	1.41	3.17	1.91	None
2.80	.24	1.58	4.19	3.60	2
5.58	.06	1.91	2.89	2.74	3
6.13	.15	1.73	3.59	2.78	1
7.43	.21	1.81	2.94	2.89	1
4.63	.17	1.73	2.76	2.38	4
5.31	.17	1.75	4.19	2.88	None

tributed significant amounts of sediment to the Nanushuk Group, and they are not connected to the Nanushuk by an aquifer.

The uppermost Nanushuk contains thin bentonitic beds as does the overlying Colville Group of Late Cretaceous age (Chapman and Sable, 1960; Smiley, 1969b; Detterman and others, 1963). The bentonites of the upper part of the Nanushuk in the western North Slope are associated with a thick shale section, so it is problematical whether any uranium released from these source beds could find its way to the host sandstones in sufficient quantities to form economic deposits. In the central North Slope, the upper part of the Nanushuk is more favorable, as it contains both bentonite and suitable host rocks and is overlain by the bentonite-rich Seabee Formation of the Colville Group. The source of the bentonites is not known, but possible sources include the granitic centers of east and west-central Alaska, some of which contain anomalous concentrations of uranium (Miller, 1970; Miller and Johnson, 1978).

The nonmarine deposits along Sabbath Creek in the eastern North Slope (fig. 26) do not contain bentonite beds but are close to the Romanzof Mountains, which are composed of granitic plutons reported to contain as much as 80 ppm uranium (Brosge and Reiser, 1976). The same authors also reported 20 to 30 ppm uranium in the Jurassic Kingak Shale and 30 to 80 ppm in phosphatic beds of the Triassic Shublik Formation in the same area.

SUMMARY

The Nanushuk Group of the central and eastern North Slope contains marginally suitable host rocks for peneconcordant sandstone-type uranium deposits. Host rocks that were deposited in favorable environments are present in the nonmarine and transitional parts of the Nanushuk Group throughout the North Slope, but the generally low sandstone content and the limited extent of sandstone bodies that do exist severely limit its overall favorability, particularly in the west.

Potential sources of uranium are present in the bentonitic clays of the uppermost Nanushuk and in the bentonitic and tuffaceous beds of the overlying Colville Group. Because of the high mudstone content of the upper part of the Nanushuk in the west, it is problematical whether any uranium released from these source beds could accumulate in the host sandstones in sufficient quantities to form economic deposits. Suitable host rocks exist in the upper part of the Nanushuk Group in close proximity to the tuffaceous sediments in the central North Slope, but no evidence of mineralization was found during this study.

The easternmost North Slope appears to have somewhat more potential for economic uranium deposits, based primarily on the presence of possible sources of uranium in the source terrain of the host rocks. This area is currently being evaluated.

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, p. 163.
- Ahlbrandt, T. S., and Huffman, A. C., 1978, Cretaceous Nanushuk Group, North Slope, Alaska, in K. M. Johnson, 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., Fox, J. E., and Pasternack, Ira, 1979, Depositional framework and reservoir-quality studies of selected Nanushuk Group outcrops, North Slope, Alaska, in T. S. Ahlbrandt, 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.
- Alaska Geological Society, 1978, North Slope stratigraphic nomenclature: Anchorage, Alaska, Newsletter, May issue, p. 1.
- Armstrong, A. K., Mamet, B. L., Brosgé, W. P., and Reiser, H. N., 1976, Carboniferous section and unconformity at Mount Doonerak, Brooks Range, northern Alaska: *American Association of Petroleum Geologists Bulletin*, v. 60, no. 6, p. 962-972.
- Bartsch-Winkler, Susan, 1979, Textural and mineralogical study of some surface and subsurface sandstones from the Nanushuk Group, western North Slope, Alaska, in T. S. Ahlbrandt, 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.
- Bates, R. L., and Jackson, J. A., eds., 1980, *Glossary of geology* [2d ed.]: Falls Church, Va., American Geological Institute, 749 p.
- Beikman, H. M., 1978, Preliminary geologic map of Alaska: U.S. Geological Survey Map, scale 1:2,500,000.
- Beikman, H. M., and Lathram, E. H., 1976, Preliminary geologic map of northern Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-789, scale 1:1,000,000, 2 sheets.
- Bird, K. J., and Andrews, Jack, 1979, Subsurface studies of the Nanushuk Group, North Slope, Alaska, in T. S. Ahlbrandt, 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 Pessel, G. H., 1977, Preliminary reconnaissance geologic map of Survey Pass quadrangle, Alaska: U.S. Geological Survey Open-File Report OF-77-27, scale 1:250,000.
- Brosgé, W. P., and Reiser, H. N., 1965, Preliminary geologic map of the Arctic quadrangle, Alaska: U.S. Geological Survey Open-file report, scale 1:250,000.
- 1971, Preliminary bedrock geologic map of the Wiseman and eastern Survey Pass quadrangles, Alaska: U.S. Geological Survey Open-file report, scale 1:250,000, 2 sheets.
- 1976, Preliminary geologic and mineral resource maps (excluding petroleum), Arctic National Wildlife Range, Alaska: U.S. Geological Survey Open-file report 76-539, scale 1:500,000, 4 sheets.
- Brosgé, W. P., Reiser, H. N., Dutro, J. T., Jr., and Detterman, R. L., 1979, Bedrock geologic map of the Philip Smith Mountain quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-879-B, scale 1:250,000, 2 sheets.
- Brosgé, W. P., and Tailleux, I. L., 1969, Isopach maps of upper Paleozoic and Mesozoic rocks, northern Alaska: U.S. Geological Survey Open-file report, 13 p., maps, scale 1:2,500,000.
- 1970, Depositional history of northern Alaska, in W. L. Adkison and M. M. Brosgé, eds., *Geological seminar on the North Slope of Alaska*, Palo Alto, Calif., 1970: Los Angeles, Calif., American Association of Petroleum Geologists, Pacific Section Meeting, Proceedings, p. D1-D18.
- 1971, Northern Alaska petroleum province, in I. H. Cram, 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, with a section on Heavy-mineral studies of the Umiat-Maybe Creek region, by R. H. Morris: U.S. Geological Survey Professional Paper 303-H, p. 501-638.
- 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., 1954, Stratigraphy and structure of the Kokilik and Kukpowruk Rivers area, Alaska: U.S. Geological Survey Open-file report, p. 71.
- 1960, Geology of the Utukok-Corwin region, northwestern Alaska: U.S. Geological Survey Professional Paper 303-C, p. 47-167.
- Coachman, L. K., and Aagaard, K., 1974, Physical oceanography of Arctic and subarctic seas, in Y. Herman, ed., *Marine geology and oceanography of the Arctic seas*: New York, Springer-Verlag, p. 1-72.
- Coleman, J. M., 1976, *Deltas—Processes of deposition and models for exploration*: Champaign, Ill., Continuing Education Publication Co., Inc., p. 102.
- Coleman, J. M., and Gagliano, S. M., 1964, Cyclic sedimentation in the Mississippi River deltaic plain: *Gulf Coast Association of Geological Societies Transactions*, v. 14, p. 67-80.
- Collins, F. R., 1958, 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.
- 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.
- Copeland, E. B., 1947, Genera *Filicum*, the genera of ferns: Waltham, Mass., Chronica Botanica Co., p. 247, 10 pls.

- Curtis, S. M., Rossiter, R., Ellersieck, I. F., Mayfield, C. F., and Tailleir, I. L., 1979, Gamma-ray values in the Misheguk Mountain region, northwestern Alaska: U.S. Geological Survey Open-File Report 79-1086, 2 sheets.
- Detterman, R. L., 1953, Northern Alaska (Sagavanirktok-Anaktuvuk region), in T. L. Pewe and others, Multiple glaciation in Alaska: U.S. Geological Survey Circular 289, p. 11-13.
- 1956, New and redefined nomenclature of Nanushuk group, in George Gryc and others, Mesozoic sequence in Colville River region, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 40, no. 2, p. 233-244.
- 1973, Mesozoic sequence in Arctic Alaska, in M. G. Pitcher, ed., Arctic geology: American Association of Petroleum Geologists Memoir 19, p. 376-395.
- Detterman, R. L., Bickel, R. S., and Gryc, George, 1963, Geology of the Chandler River region, Alaska—Exploration of Naval Petroleum Reserve No. 4 and adjacent areas, northern Alaska, 1944-53—Pt. 3, Aerial geology: U.S. Geological Survey Professional Paper 303-E, p. 233-324.
- Detterman, R. L., Bowsher, A. L., and Dutro, J. T., Jr., 1958, Glaciation on the Arctic Slope of the Brooks Range, northern Alaska: Arctic, v. 11, no. 1, p. 43-61.
- 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.
- Dickinson, W. R., 1970, Interpreting detrital modes of graywacke and arkose: Journal of Sedimentary Petrology, v. 40, no. 2, p. 695-707.
- Dillon, J. T., Pessel, G. H., Chen, J. H., and Yeach, N. C., 1980, Middle Paleozoic magmatism and orogenesis in the Brooks Range, Alaska: Geology, v. 8, no. 7, p. 338-343.
- Dutro, J. T., Jr., Brosgé, W. P., Lanphere, M. A., and Reiser, H. N., 1976, Geologic significance of the Doonerak structural high, central Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 60, no. 6, p. 952-961.
- Emery, K. O., 1965, Characteristics of continental shelves and slopes: American Association of Petroleum Geologists Bulletin, v. 49, no. 9, p. 1379-1384.
- 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.
- Finch, W. I., 1967, Geology of epigenetic uranium deposits in sandstone in the United States: U.S. Geological Survey Professional Paper 538, p. 121.
- Fischer, R. P., 1974, Exploration guides to new uranium districts and belts: Economic Geology, v. 69, no. 3, p. 362-376.
- Fisher, W. L., 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, 1969, Syllabus [1]: Austin, University of Texas, Bureau of Economic Geology, 78 p.
- Fisher, W. L., and McGowen, J. H., 1967, Depositional systems in the Wilcox Group of Texas and their relationship to occurrence of oil and gas: Gulf Coast Association of Geological Societies Transactions, v. 17, p. 105-125.
- Folk, R. L., 1968, Petrology of sedimentary rocks: Austin, Texas, Hemphill's, 170 p.
- Fosberg, F. R., 1964, Vegetation as a geological agent in tropical deltas, in Scientific problems of the humid tropical zone deltas and their implications: United Nations Educational, Scientific, and Cultural Organization, Proceedings of the Dacca Symposium, Paris, p. 227-233.
- Fothergill, C. A., 1955, The cementation of oil reservoir sands and its origin: World Petroleum Congress, 4th, Rome, 1955, Proceedings, Section 1B, Paper 1, p. 310-314.
- Fox, J. E., 1979, A summary of reservoir characteristics of the Nanushuk Group, Umiat test well 11, National Petroleum Reserve in Alaska, in T. S. Ahlbrandt, 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. 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, and Eittreim, S. L., 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.
- 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.
- Grantz, Arthur, and Mull, C. G., 1978, Preliminary analyses of the petroleum potential of the Arctic National Wildlife Range, Alaska: U.S. Geological Survey Open-File Report 78-489, 20 p.
- Grantz, Arthur, Wolf, S. C., Breslau, Lloyd, Johnson, T. C., and Hanna, W. F., 1970, Reconnaissance geology of the Chukchi Sea as determined by acoustic and magnetic profiling, in W. L. Adkison and M. M. Brosgé, eds., Geological seminar on the North Slope of Alaska, Palo Alto, Calif., 1970: Los Angeles, Calif., American Association of Petroleum Geologists, Pacific Section Meeting, Proceedings, p. F1-F28.
- Gribbin, J., 1979, Climatic change: Cambridge, England, Cambridge University Press, 191 p.
- Grybeck, Donald, Beikman, H. M., Brosgé, W. P., Tailleir, I. L., and Mull, C. G., 1977, Geologic map of the Brooks Range, Alaska: U.S. Geological Survey Open-File Report 77-166-B, scale 1:1,000,000, 2 sheets.
- Grybeck, Donald, and Nelson, S. W., 1981, Map and interpretation of the structural geology of the Survey Pass quadrangle, Brooks Range, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1176-B, scale 1:250,000.
- Gryc, George, and others, 1956, Mesozoic sequence in Colville River region, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 40, no. 2, p. 209-254.
- Hamilton, T. D., and Porter, S. C., 1975, Itkillik glaciation in the Brooks Range, northern Alaska: Quaternary Research, v. 5, no. 4, p. 471-497.

- Heald, M. T., and Larese, R. E., 1974, Influence of coatings on quartz cementation: *Journal of Sedimentary Petrology*, v. 44, no. 4, p. 1269–1274.
- Heezen, B. C., 1974, Atlantic type continental margins, in C. A. Burk and C. L. Drake, eds., *The geology of continental margins*: New York, Springer-Verlag, p. 13–24.
- Huffman, A. C., Jr., 1979, Stratigraphy and petrography of a measured section on the south limb of Barabara Syncline, North Slope, Alaska, in T. S. Ahlbrandt, 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., and Ahlbrandt, T. S., 1979, The Cretaceous Nanushuk Group of the western and central North Slope, Alaska, in K. M. Johnson and J. R. Williams, eds., *The U.S. Geological Survey in Alaska—Accomplishments in 1978*: U.S. Geological Survey Circular 804–B, p. 46–50.
- Huffman, A. C., Jr., and others, 1981a, Measured sections of the Cretaceous Nanushuk Group undivided, western North Slope, Alaska: U.S. Geological Survey Open-File Report 81–176.
- 1981b, Measured sections of the Cretaceous Nanushuk and Colville Groups undivided, central North Slope, Alaska: U.S. Geological Survey Open-File Report 81–177.
- Hunter, R. E., and Fox, J. E., 1976, Interpretation of depositional environments in the Fortress Mountain Formation, central Arctic Slope, in E. H. Cobb, ed., *The United States Geological Survey in Alaska—Accomplishments during 1975*: U.S. Geological Survey Circular 733, p. 30–31.
- Imlay, R. W., 1959, Succession and speciation of the pelecypod *Aucella*: U.S. Geological Survey Professional Paper 314–G, p. 155–169.
- 1961, Characteristic Lower Cretaceous megafossils from northern Alaska: U.S. Geological Survey Professional Paper 335, 73 p., 20 pls.
- Irving, E., 1979, Paleopoles and paleolatitudes of North America and speculations about displaced terrains, in R. A. Price, coord., *Geodynamics Canada: Canadian Journal of Earth Sciences*, v. 16, no. 3, pt. 2, p. 669–694.
- Jamison, H. C., Brockett, L. D., and McIntosh, R. A., 1981, Prudhoe Bay—A ten-year perspective, in M. T. Holbouty, ed., *Giant oil and gas fields of the decade 1968–1978*: American Association of Petroleum Geologists Memoir 30, p. 289–314.
- 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.
- 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.
- Krumbein, W. C., 1941, Measurement and geological significance of shape and roundness of sedimentary particles: *Journal of Sedimentary Petrology*, v. 11, no. 2, p. 64–92.
- Lathram, E. H., 1965, Preliminary geologic map of northern Alaska: U.S. Geological Survey Open-file report, scale 1:1,000,000, 2 sheets.
- LeBlanc, R. J., 1972, Geometry of sandstone bodies, in *Underground waste management and environment implications*: American Association of Petroleum Geologists Memoir 18, p. 133–190.
- Lowther, J. S., 1957, A Cretaceous flora from northern Alaska: University of Michigan unpublished Ph.D. dissertation, 184 p, 19 pls.
- Magoon, L. B., and Claypool, G. E., 1979, Hydrocarbon source potential of the Nanushuk Group and the Torok Formation, a preliminary report, in T. S. Ahlbrandt, 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.
- Mamet, G. L., and Armstrong, A. K., 1972, Lisburne Group, Franklin and Romanzof Mountains, northeastern Alaska, in *Geological Survey research, 1972*: U.S. Geological Survey Professional Paper 800–C, p. C127–C144.
- Mangus, M. D., Detterman, R. L., Lachenbruch, M. C., Jr. and Lachenbruch, A. H., 1954, Stratigraphy and structure of the Etivluk and Kuna Rivers area, Alaska: U.S. Geological Survey Open-file report, 15 p.
- 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. 3605–3622.
- May, F. E., 1979, Dinoflagellate and acritarch assemblages from the Nanushuk Group (Albian-Cenomanian) and the Torok Formation (Albian), Umiat test well 11, National Petroleum Reserve in Alaska, northern Alaska, in T. S. Ahlbrandt, ed., *Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska*: U.S. Geological Survey Circular 794, p. 113–127.
- 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 T. S. Ahlbrandt, ed., *Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska*: U.S. Geological Survey Circular 794, p. 128–146, 5 pls.
- Mayfield, C. F., and Tailleir, I. L., 1978, Bedrock geology map of the Ambler River quadrangle, Alaska: U.S. Geological Survey Open-File Report 78–120A, scale 1:250,000.
- Mayfield, C. F., Tailleir, 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.
- McIntosh, R. A., 1977, Prudhoe Bay operating plan, reservoir description—geologic: Testimony at conservation hearing on Prudhoe Bay Unit operating plan, May 5, 1977, 33 p.; transcript on file at Alaska Oil and Gas Conservation Committee, Anchorage.
- Miller, C. C., Pickard, J. E., Taber, E. C., and Rogers, R. B., 1981, Summary geophysical report—FY 1979: NPRA Summary Report, 18 p. Available from National Oceanographic and Atmospheric Administration (E.D.S.), Mail Code D621, Boulder, CO 80303.

- Miller, T. P., 1970, Petrology of the plutonic rocks of west-central Alaska: U.S. Geological Survey Open-File Report 1511, 132 p.
- Miller, T. P., and Johnson, B. R., 1978, An occurrence of parsonite, a secondary uranium mineral, in alaskite of the Wheeler Creek pluton, in K. M. Johnson, ed., *The United States Geological Survey in Alaska—Accomplishments during 1977*: U.S. Geological Survey Circular 772-B, p. 42-44.
- Mitchum, R. M., Jr., 1977, Seismic stratigraphy and global changes of sea level, Part II—Glossary of terms used in seismic stratigraphy, in C. E. Payton, ed., *Seismic stratigraphy—Applications to hydrocarbon exploration*: American Association of Petroleum Geologists Memoir 26, p. 205-212.
- Morgridge, D. L., and Smith, W. B., Jr., 1972, Geology and discovery of Prudhoe Bay field, eastern Arctic Slope, Alaska, in R. E. King, ed., *Stratigraphic oil and gas fields—classification, exploration, methods, and case histories*: American Association of Petroleum Geologists Memoir 16, p. 489-501.
- Mull, C. G., 1977, Apparent south vergent folding and possible nappes in Schwatka Mountains, in K. M. Blean, ed., *The United States Geological Survey in Alaska—Accomplishments during 1976*: U.S. Geological Survey Circular 751-B, p. B29-B31.
- 1979, Nanushuk Group deposition and the late Mesozoic structural evolution of the central and western Brooks Range and Arctic Slope, in T. S. Ahlbrandt, 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.
- 1982 [1983], 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, Colo., Rocky Mountain Association of Geologists*, V. 1, p. 1-45.
- Mull, C. G., and Kososki, B. A., 1977, Hydrocarbon assessment of the Arctic National Wildlife Range, eastern Arctic Slope, Alaska, in K. M. Blean, ed., *The United States Geological Survey in Alaska—Accomplishments during 1976*: U.S. Geological Survey Circular 751-B, p. B20-B22.
- Mull, C. G., and Tailleur, I. L., 1977, Sadlerochit(?) Group in the Schwatka Mountains, south-central Brooks Range, in K. M. Blean, 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., 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 E. H. Cobb, 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, 1979, Tectonic significance of metamorphic grade distribution, Survey Pass quadrangle, Alaska, in K. M. Johnson, ed., *The United States Geological Survey in Alaska—Accomplishments during 1978*: U.S. Geological Survey Circular 804-B, p. B16-B17.
- 1980, Geologic map of the Survey Pass quadrangle, Brooks Range, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map 1176-A, scale 1:250,000, 2 sheets.
- Newman, G. W., Mull, C. G., and Watkins, N. D., 1979, Northern Alaska paleomagnetism, plate rotation, and tectonics, in Alexander Sisson, ed., *The relationship of plate tectonics to Alaskan geology and resources*: Alaska Geological Society, 6th symposium, Anchorage 1977, Proceedings, p. C1-C7.
- Nicol, David, 1955, An analysis of the Arctic marine pelecypod fauna: *Nautilus*, v. 68, no. 4, p. 115-122.
- Page, L. R., 1960, The source of uranium in ore deposits, in *Genetic problems of uranium and thorium deposits*: International Geological Congress, 21st, Copenhagen 1960, sec. 15, pt. 15, p. 149-164.
- Pasternack, Ira, 1981, The depositional factors affecting the reservoir potential of the lower Cretaceous Nanushuk Group, northwestern Alaska: Golden, Colorado School of Mines M.S. thesis 2384.
- 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., 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, text.
- 1955, Mesozoic and Cenozoic tectonic elements of Alaska: U.S. Geological Survey Miscellaneous Geological Investigations Map I-84, scale 1:5,000,000.
- 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, scale 1:250,000.
- Pessel, G. H., Garland, R. E., Tailleur, I. L., and Eakins, G. R., 1973, Preliminary geologic map of southeastern Ambler River and part of Survey Pass quadrangles, Alaska: Alaska Division of Geological and Geophysical Surveys Open-File Report 28, scale 1:63,360.
- Pessel, G. H., Tailleur, I. L., and Bird, K. J., 1978a, 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.
- 1978b, Generalized isopach map of the sandstones within the Colville Group, eastern North Slope petroleum province, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-928-D, scale 1:500,000.
- 1978c, Generalized isopach map of shale in the Colville Group, eastern North Slope petroleum province, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-928-E, scale 1:500,000.
- 1978d, 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.
- Pettijohn, F. J., Potter, P. E., and Siever, Raymond, 1972, *Sand and sandstone*: New York, Springer-Verlag, 618 p.

- Pitman, E. D., 1972, Diagenesis of quartz in sandstones as revealed by scanning electron microscopy: *Journal of Sedimentary Petrology*, v. 42, no. 3, p. 507–519.
- Pitman, W. C., III, 1978, Relationship between eustasy and stratigraphic sequences of passive margins: *Geological Society of America Bulletin*, v. 89, no. 9, p. 1389–1403.
- Reiser, H. N., Brosgé, W. P., Detterman, R. L., and Dutro, J. T., Jr., 1978, Geologic map of the Demarcation Point quadrangle, Alaska: U.S. Geological Survey Open-File Report 78–526, scale 1:250,000.
- Reiser, H. N., Brosgé, W. P., Dutro, J. T., Jr., and Detterman, R. L., 1971, Preliminary geologic map, Mount Michelson quadrangle, Alaska: U.S. Geological Survey Open-file report, scale 1:200,000, 2 sheets.
- Rickwood, F. K., 1970, The Prudhoe Bay field, in *Geological seminar on the North Slope of Alaska*, Palo Alto, Calif., 1970: Los Angeles, Calif., American Association of Petroleum Geologists, Pacific Section meeting, Proceedings, 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.
- 1958, Test well, Grandstand area, Alaska: U.S. Geological Survey Professional Paper 305–E, p. 317–339.
- 1959, Test wells, Titaluk and Knifblade areas, Alaska: U.S. Geological Survey Professional Paper 305–G, p. 377–421.
- 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.
- Roehler, H. W., and Stricker, G. D., 1979, Stratigraphy and sedimentation of the Torok, Kukupwruk, 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.
- Rogers, J. J. W., and Adams, J. A. S., 1969, Uranium, chap. 92, in K. H. Wedepohl, ed., *Handbook of geochemistry*: Berlin, Springer-Verlag, v. II–4.
- Rona, P. A., 1973, Relations between rates of sediment accumulation on continental shelves, sea-floor spreading, and eustasy inferred from the central north Atlantic: *Geological Society of America Bulletin*, v. 84, no. 9, p. 2851–2872.
- 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.
- 1977, Geology of the western Romanzof Mountains, Brooks Range, northeastern Alaska: U.S. Geological Survey Professional Paper 897, 84 p.
- 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 Open-file report, 28 p.
- Sable, E. G., and Mangus, M. D., 1951, Stratigraphy and structure of the upper Utukok–Kokolik Rivers area, Alaska: U.S. Geological Survey Open-file report, 19 p.
- 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, texture, cements, and porosities of sandstones and associated rocks: *American Association of Petroleum Geologists Memoir* 28, 201 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 T. S. Ahlbrandt, 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.
- Seely, D. R., Vail, P. R., and Walton, G. C., 1974, Trench slope model, in C. A. Burk, and C. L. Drake, eds., *The geology of continental margins*: New York, Springer-Verlag, Inc., p. 249–260.
- Shepard, F. P., 1963, *Submarine geology* [2nd ed.]: New York, Harper and Row, 557 p.
- Silberman, M. L., Brookins, D. G., Nelson, S. W., and Grybeck, Donald, 1979, Rubidium-strontium and potassium-argon dating of emplacement and metamorphism of the Arrigetch Peaks and Mount Igikpak plutons, Survey Pass quadrangle, Alaska, in K. M. Johnson and J. R. Williams, eds., *The United States Geological Survey in Alaska—Accomplishments during 1978*: U.S. Geological Survey Circular 804–B, p. B18, B19.
- Sliter, W. V., 1979, Cretaceous foraminifers from the North Slope of Alaska, in T. S. Ahlbrandt, 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.
- 1967, Paleoclimatic interpretations of some Mesozoic floral sequences: *American Association of Petroleum Geologists Bulletin*, v. 51, no. 6, p. 849–863.
- 1969a, Cretaceous floras of Chandler-Colville region, Alaska—stratigraphy and preliminary floristics: *American Association of Petroleum Geologists Bulletin*, v. 53, no. 3, p. 482–502.
- 1969b, Floral zones and correlations of Cretaceous Kukupwruk and Corwin Formations, northwestern Alaska: *American Association of Petroleum Geologists Bulletin*, v. 53, no. 10, p. 2079–2093.
- 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.
- 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: *American Association of Petroleum Geologists Memoir* 19, p. 526–535.
- Tailleur, I. L., and Brosgé, W. P., 1970, Tectonic history of northern Alaska, in W. L. Adkison and M. M. Brosgé, eds., *Geological seminar on the North Slope of Alaska*, Palo Alto, California, 1970: Los Angeles, Calif., American Association of Petroleum Geologists, Pacific Section Meeting, Proceedings, p. E1–E19.

- Tailleur, I. L., Brosgé, W. P., and Reiser, H. N., 1967, Palinspastic analysis of Devonian rocks in northwestern Alaska, *in* D. H. Oswald, ed., International symposium on the Devonian system, Calgary, 1967: Alberta Society of Petroleum Geologists Proceedings, v. 1, p. 703–716; 1968, v. 2, p. 1345–1361.
- Tailleur, I. L., Kent, B. H., and Reiser, H. N., 1966, Outcrop geologic maps of the Nuka-Etiviluk region, northern Alaska: U.S. Geological Survey Open-file report, scale 1:63,360, 5 sheets.
- [Tailleur, I. L., Mull, C. G., and Pessel, G. H.] 1976, Geologist calls Prudhoe one of a kind: *Oil and Gas Journal*, v. 74, no. 44, p. 32.
- 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-928A, scale 1:500,000, 5 sheets.
- 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.
- Taylor, J. M., 1950, Pore-space reduction in sandstones: *American Association of Petroleum Geologists Bulletin*, v. 34, no. 4, p. 701–716.
- Traverse, Alfred, and Ginsburg, R. N., 1966, Palynology of the surface sediments of Great Bahama Bank, as related to water movement and sedimentation: *Marine Geology*, v. 4, no. 6, p. 417–459.
- Tschudy, R. H., 1969, Relationship of palynomorphs to sedimentation, *in* R. H. Tschudy and R. A. Scott, eds., *Aspects of palynology*: New York, Wiley-Interscience, p. 79–96.
- 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.
- Vail, P. R., Mitchum, R. M., Jr., and Thompson, S., III, 1977, Seismic stratigraphy and global changes of sea level—Part 4, Global cycles of relative changes of sea level, *in* C. E. Payton, ed., *seismic stratigraphy—applications to hydrocarbon exploration*: American Association of Petroleum Geologists Memoir 26, p. 83–97.
- Wolfe, J. A., 1978, A paleobotanical interpretation of Tertiary climates in the northern hemisphere: *American Scientist*, v. 66, p. 694–703.
- Young, F. G., Myhr, D. W., and Yorath, C. J., 1976, *Geology of the Beaufort–Mackenzie Basin*: Geological Society of Canada Paper 76–11, 65 p.

