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DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

THE PETROLEUM GEOLOGY AND HYDROCARBON POTENTIAL OF NAVAL PETROLEUM RESERVE NO. 4 NORTH SLOPE, ALASKA

By
R. D. Carter, C. G. Mull, K. J. Bird, and R. B. Powers

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THE PETROLEUM GEOLOGY AND HYDROCARBON POTENTIAL OF NAVAL PETROLEUM RESERVE NO. 4 NORTH SLOPE, ALASKA

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SUMMARY

The Naval Petroleum Reserves Production Act of 1976 provides for the transfer of jurisdiction of Naval Petroleum Reserve No. 4 from the Department of the Navy to the Department of the Interior on June 1, 1977. In anticipation of the enactment of the law, the U.S. Geological Survey prepared an administrative report in 1976 to provide background information, to describe the state of knowledge of the geology of NPR-4, and to recommend studies necessary for an evaluation of the hydrocarbon potential of the Reserve.

This paper is based on the above administrative report which in turn depended upon published literature, unpublished U. S. Geological Survey data, and the background knowledge of Survey geologists with extensive experience in the regional geology and petroleum geology of the North Slope of Alaska. In addition, results of the ongoing Navy exploration of NPR-4 were made available to the Geological Survey following the signing of the Act by the President on April 5, 1976. These results were reviewed for possible conflicts with interpretations and conclusions reached in this report and no incompatibilities of significance were found.

Surface geology exploration by the USGS in the NPR-4 area began in 1904 and has continued sporadically to the present. The PET-4 program 1944-1953, designed "to appraise the oil possibilities of Naval Petroleum Reserve No. 4 and surrounding areas," produced the first subsurface information and resulted in the discovery of several minor oil and gas deposits. There was little exploration activity following the termination of the PET-4 program until 1974 when the Navy initiated a vigorous program of geophysical and drilling exploration.

Naval Petroleum Reserve No. 4 includes parts of the three major tectonic elements of the North Slope; the Brooks Range, the Barrow Arch which underlies the Beaufort Sea coast, and the Colville Trough which lies between them. Basement rocks slope from shallow depths along the Barrow Arch southward into the Colville Trough, reaching a depth of about 30,000 feet near the front of the east-west-trending Brooks Range. Rocks of the North Slope range in age from Precambrian to Holocene and have been grouped into three sequences on the basis of sediment provenance. The Franklinian (pre-Mississippian) and Ellesmerian (Mississippian to Jurassic) rock sequences were derived from a northern source, and Brookian (Late Jurassic, Cretaceous, Tertiary) sequence rocks were derived from a southern source, the Brooks Range. Franklinian rocks constitute economic basement whereas Ellesmerian rocks contain the oil reservoirs of the Prudhoe Bay field. Brookian rocks include the richest source beds on the North Slope and comprise most of the presently known reservoirs of the NPR-4 oil and gas fields.

The requirements for a petroleum province--source rocks, reservoir rocks, traps, and a favorable geologic history-- are amply met on the North Slope. The oil and gas fields discovered in the PET-4 program and the presence of the supergiant Prudhoe Bay field certify its qualification as a major petroliferous basin.

Geochemical data indicate the most important source rocks known at present are Cretaceous and Jurassic shales. Cretaceous beds are probably the source for most of the oil in the Prudhoe Bay field. The few geochemical analyses in NPR-4 indicate a low source potential for Jurassic shale at Barrow, but the small oil and gas accumulations and numerous surface and subsurface shows in the Reserve indicate probable Middle and Upper Cretaceous source rocks.

The best reservoir rocks found to date are the pre-Middle Cretaceous clastic and carbonate rocks related to a northern provenance. These are the Lisburne, Sadlerochit, Shublik, Sag River, and Kuparuk River beds, and all are present in NPR-4 with the possible exception of the Kuparuk River sand. Two of the most important reservoirs, the Lisburne and Sadlerochit, apparently pinch out along the south flank of the Barrow Arch. Cretaceous sandstones, varying in porosity and permeability depending upon their source area and burial history, provide potential reservoirs throughout most of the Reserve.

The presently known oil and gas fields of the North Slope have proved the existence of structural and combination structural-stratigraphic traps. Additional structural traps should be present in the foothills folded belts and possibly on the Barrow Arch. Stratigraphic traps related to updip pinch-outs and truncations in pre-Lower Cretaceous rocks may be present along the Barrow Arch, and in shaled-out sands of the foreset and bottomset beds in Cretaceous clastic wedges. Sealing beds, usually shale, have been demonstrated between and within major reservoir units.

In evaluating the potential of NPR-4, it is profitable to compare the geology of the Prudhoe Bay area with that of the Reserve. Hydrocarbon reservoirs have been found in Ellesmerian and early Brookian rock sequences on the North Slope. Late Cretaceous and Tertiary beds are also potential reservoirs, but, with the exceptions of limited areas along the north coast and the eastern boundary, they are very thin or absent from NPR-4. Geochemical data indicate that Cretaceous, Jurassic, and Upper Triassic shales have source-rock potential. Mississippian and Lower Triassic rocks are low in source-rock potential probably because of low organic content and thermal over-maturity in deeper parts of the basin. The supergiant Prudhoe Bay field is the result of rich, thermally mature Cretaceous source beds superposed on the truncated edges of a series of good reservoir beds. Unfortunately, this juxtaposition will probably not be found in most of NPR-4. Within the Reserve the unconformity accounting for this superposition is apparently present onshore only in very limited areas along the north coast. Two of the most important Prudhoe Bay reservoirs, the Lisburne and Sadlerochit, may be present in a favorable structural-stratigraphic position only in the extreme northeastern part of NPR-4. Regional dips would seem to preclude oil migration from the Prudhoe Bay area westward into the Reserve. Known oil and gas occurrences in NPR-4 are found in Upper Triassic, Jurassic, and Cretaceous rocks whereas older beds have had no reported shows. Cretaceous or Jurassic rocks containing the richer source beds, or reservoir beds of any age within fluid migration distance of them, would appear to be the major objectives in NPR-4.

Three broad exploration trends with a number of plays can be predicted for NPR-4. The Coastal Plain trend is prospective for oil and gas in structural, stratigraphic, and combination traps in pre-Middle Cretaceous rocks. The Northern Foothills trend might find oil and gas in shallow structural traps in Middle Cretaceous and in limited Upper Cretaceous reservoirs. Deeper structural and stratigraphic traps in Lower Cretaceous formations are prospective for gas. A major play in both the above trends is the Nanushuk Group of Middle Cretaceous age, a coarse clastic wedge present over much of the northern Brooks Range Foothills and the southern coastal plain area. Stratigraphic relationships are analogous to the Cretaceous Mesa Verde Group of the Rocky Mountains. Intertonguing of marine and non-marine sediments combined with structural features may result in potential traps. Coal is abundant and suggests a probable gas play. Many of the sediments are medium- to coarse-grained sandstones, but a clay matrix inhibits porosity and permeability, and the prediction of porosity trends will be a major concern.

In the Southern Foothills trend gas may be found in complex structural traps in Mississippian allochthons, and in Triassic and Lower Cretaceous rocks. Estimated depths of over 25,000 feet to autochthonous Paleozoic rocks may preclude them from exploration. Experience in similar thrust belts suggests that total reserves are likely to be smaller than in less deformed areas. A known prospect in the Lisburne Group in the southeastern corner of the Reserve exhibits several hundred feet of porous dolomite, some of which contains pyrobitumen. The rocks dip northward into the basin and could be a drilling objective.

Current knowledge of North Slope geology suggests several hydrocarbon plays that might be considered in assessing the potential of the Reserve. Analysis of the plays indicates slight likelihood of Prudhoe Bay-type accumulations.

INTRODUCTION

The Naval Petroleum Reserves Production Act of 1976, which was signed into law on April 5, 1976, provides for the transfer of jurisdiction of Naval Petroleum Reserve No. 4 on the North Slope of Alaska from the Department of the Navy to the Department of the Interior effective June 1, 1977. Upon the date of transfer the area shall be redesignated as the National Petroleum Reserve in Alaska (NPRA).

In anticipation of the enactment of the law the U. S. Geological Survey of the United States Department of the Interior, which has been active for many years in mapping and other research activities in northern Alaska, began preparation early in 1976 for the transfer. As part of this effort a project that was conducting a study of the regional petroleum geology of the North Slope was asked to prepare a report furnishing background information and the present state of knowledge of the geology of NPR-4, and to recommend additional studies necessary for a detailed evaluation of the hydrocarbon potential of the Reserve.

The study was initiated in January 1976, and drew upon the published literature, unpublished U. S. Geological Survey data, and the first-hand knowledge of Survey geologists with many years of experience in both the regional and petroleum geology of the North Slope. Proprietary data gathered by the on-going Navy exploration program inaugurated in 1974 became available to the Geological Survey shortly after the transfer Act was signed. By no means all of this considerable mass of information has been assimilated, but well and seismic results have been reviewed. No confidential or proprietary Navy data are included in this report. However, significant facts pertinent to a description of the geology and an assessment of the hydrocarbon potential of NPR-4 were carefully considered for their effect on statements and conclusions put forward in this paper, and no inconsistencies were noted. Geological interpretations will undoubtedly be modified in the future as more of this geophysical, geochemical, and well information is digested, and as additional material becomes available.

This paper describes the history of exploration of NPR-4 and documents the information base presently available for hydrocarbon-resource assessment. From this data base and first-hand knowledge the framework and petroleum geology are described, and a comparison made between NPR-4 and the Prudhoe Bay area. A discussion of the three apparent exploration trends is followed by a detailed description of the types of plays possible in NPR-4.

HISTORY OF EXPLORATION

Naval Petroleum Reserve No. 4, an area of 37,000 square miles in northern Alaska, was established by Executive Order on February 27, 1923. The Reserve is bounded on the south and east by the Brooks Range and the Colville River; on the north by the Arctic Ocean; and on the west by long 161°52'31" (fig. 1). NPR-4 is slightly larger than the state of Indiana and occupies more than half the Alaska North Slope.

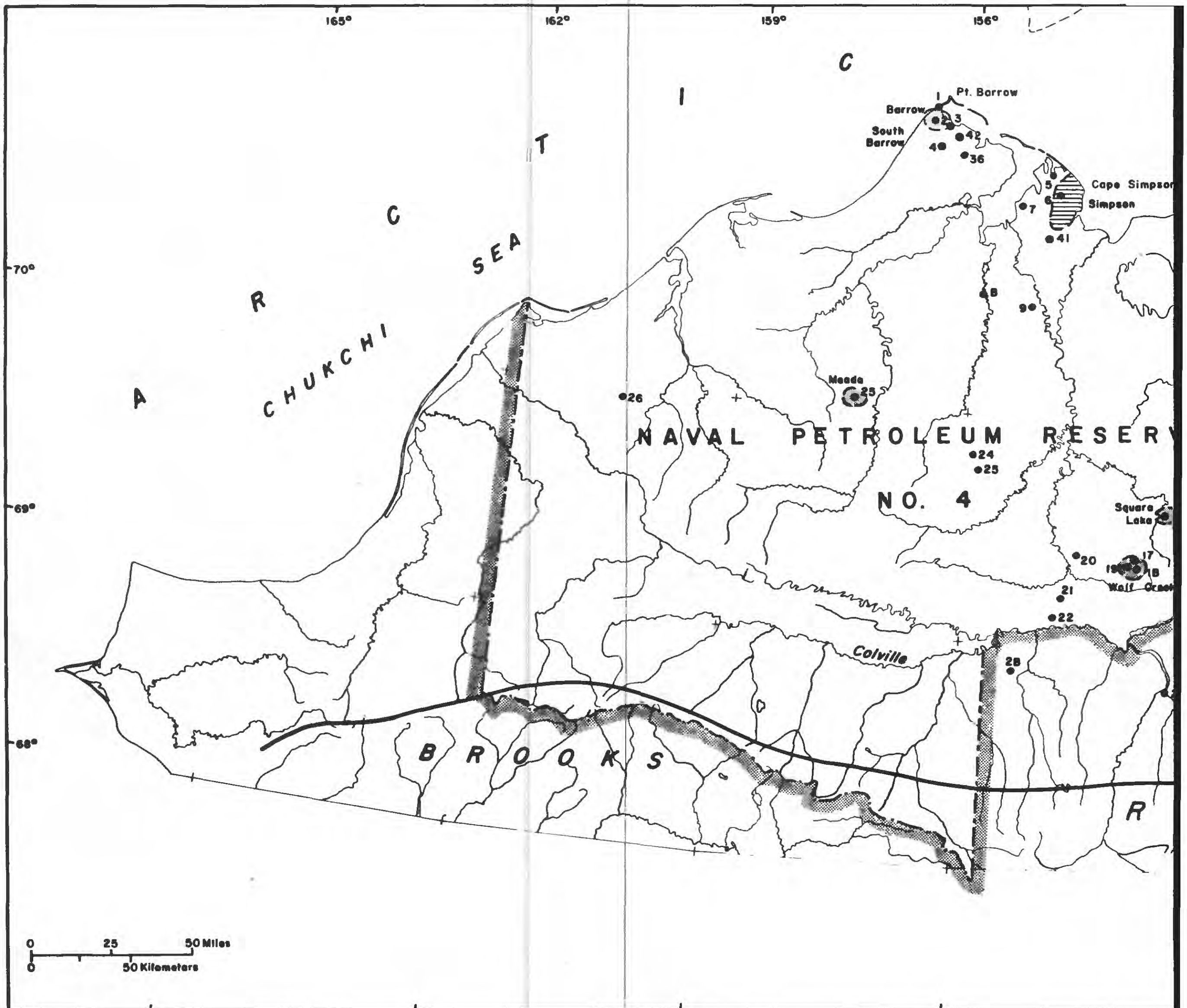
Geologic exploration in the NPR-4 area was first reported on in 1904 in U.S.G.S. Professional Paper 20 (Schrader and Peters, 1904), and exploration continued on a sporadic basis until the Reserve was created in 1923. From 1923 through 1926 U.S.G.S. parties, at the request of the Navy, traversed NPR-4 along major rivers and mapped at reconnaissance scales. The results of this work were published by Smith and Mertie (1930) in U.S.G.S. Bulletin 815.

The PET-4 program, with the defined objective "to appraise the oil possibilities of Naval Petroleum Reserve No. 4 and surrounding areas" (Reed, 1958, p. 1), was begun in 1944, and the U.S.G.S. was asked to undertake the geologic aspects of the exploration program. From 1944 to 1953 extensive geological and geophysical surveys were carried out and 45 shallow core tests and 36 test wells were drilled in and adjacent to NPR-4 (Gryc, 1970, p. c2-c3; fig. 1).

Test well drilling resulted in the discovery of an oil field at Umiat; a gas field at Gubik; a small gas field at Barrow; three possible gas fields at Meade, Square Lake, and Wolf Creek; and two minor oil deposits at Simpson and Fish Creek (Gryc, 1970, p. c3; fig. 1). The Pet-4 program was recessed in March 1953.

Since 1953 the Air Force has drilled a well at Barrow to replace a Navy well destroyed by fire (Porterfield, 1974), and the Navy has drilled South Barrow wells Nos. 6 through 13 in order to assure a continuing supply of gas for the natives and the government facilities at Barrow. South Barrow well 12 (1974) was drilled 6 miles east of the field and completed as a marginal gas well (fig. 1). Recent Navy exploratory wells include the Iko No. 1 (gas well?) and the Cape Halkett No. 1 (standing), both drilled in 1975; the East Teshekpuk No. 1 (abandoned) drilled in 1976; and six wells proposed for fiscal year 1977. Of the latter, the South Harrison Bay No. 1 and the Atigaru Point No. 1 have been drilled and plugged; the South Barrow No. 14, drilled about 1 mile southeast of South Barrow No. 12, has been completed as a gas well; and the West Fish Creek No. 1, the W. T. Foran No. 1, and the South Simpson No. 1 are presently drilling (March, 1977, fig. 1).

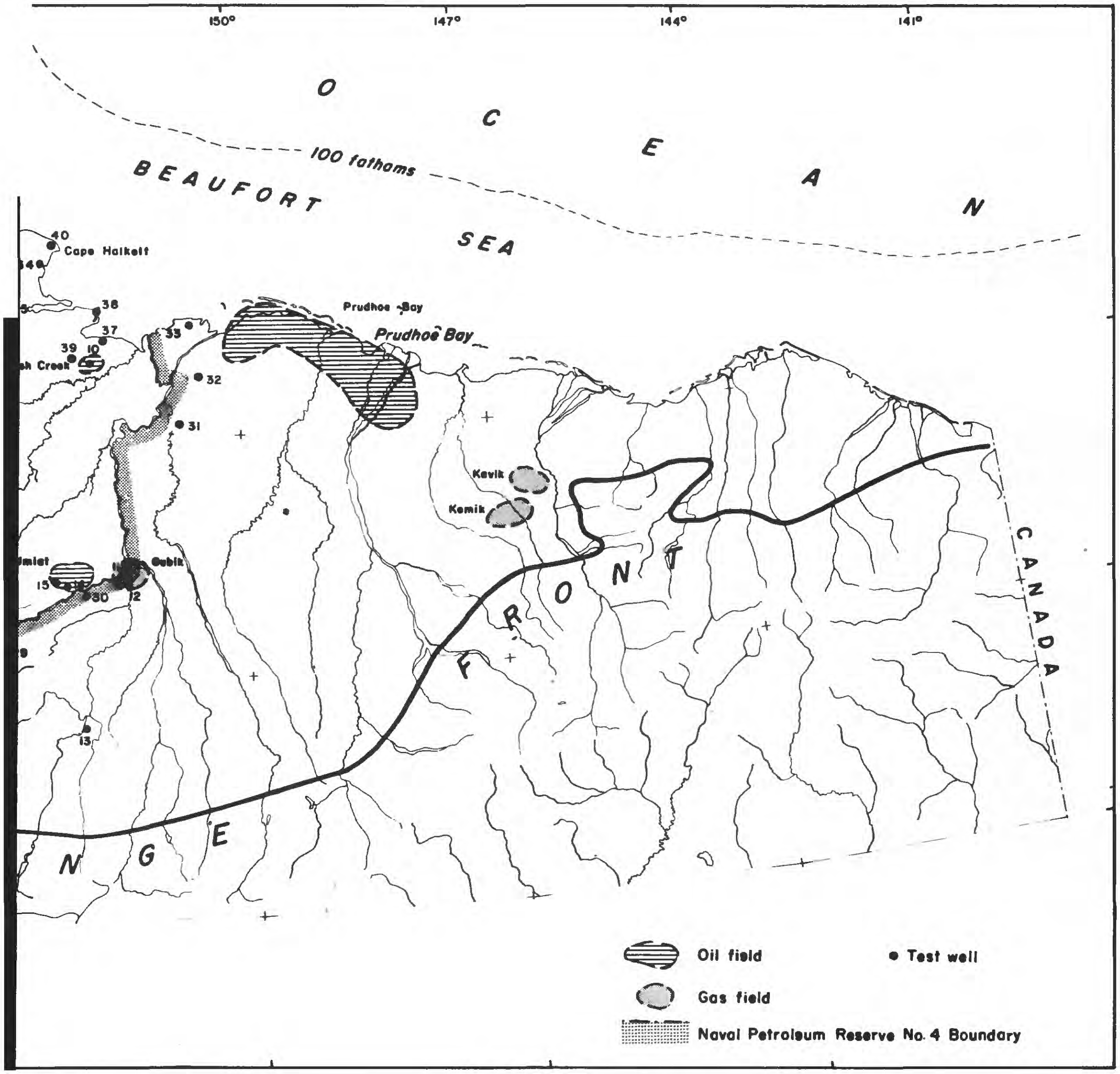
The increase in fiscal year 1974 funding for NPR-4 allowed the Navy to embark on a vigorous exploration program of seismic-and gravity-data collection in addition



TEST WELL

1. South Barrow	1	8. Topagoruk	1	14. Umiat	2-11	21. Knifeblade
2. South Barrow Gas Field		9. East Topagoruk	1	15. Umiat	1	22. Knifeblade
3. Avak	1	10. Fish Creek	1	16. Square Lake	1	23. East Oumalik
4. South Barrow	3	11. Gubik	1	17. Wolf Creek	2	24. Oumalik
5. North Simpson	1	Colorado Oil & Gas	1	18. Wolf Creek	1	25. Meade
6. Minga (velocity test)	1	12. Gubik	2	19. Wolf Creek	3	26. Kaolak
7. Simpson	1	13. Grandstand	1	20. Titaluk	1	27. Texaco E. Kurupa

Figure 1. Index map: NPR-4, test wells, oil and gas fields, north slope Alaska



1	28.	Texaco W. Kurupa	1	33.	Gulf Colville Delta	1	40. W. T. Foran	1
2-2A	29.	Arco Schrader	1	34.	Cape Halkett	1	41. South Simpson	1
1	30.	McCulloch Colville	1,2	35.	East Teshekpuk	1	42. South Barrow	12,14
1		McCulloch E. Umiat	2	36.	Iko	1		
1		Brit. Pet. E. Umiat		37.	South Harrison Bay	1		
1	31.	Arco Itkillik	1	38.	Atigaru Point	1		
1	32.	Union Kookpuk	1	39.	West Fish Creek	1		

to the test well drilling. According to a recent Federal Energy Administration report (1976), recent Navy activity includes the acquisition of about 5,000 line miles of high-quality seismic data through May 1976 with about 3,000 line miles scheduled for fiscal year 1977. Considerable gravity data have also been collected in the course of the seismic work.

Surface geologic studies in northern Alaska were continued by the U.S. Geological Survey following the termination of the Pet-4 program. Although not focused on NPR-4, considerable work in the Brooks Range and northern foothills and offshore in the Beaufort and Chukchi Seas has direct bearing on geologic interpretations within the Reserve. As a result of the energy crisis a project was initiated in 1974 by the Geological Survey aimed at more fully evaluating the petroleum potential of the entire North Slope by means of surface, subsurface, and geophysical studies.

Immediately adjacent to the Reserve, oil companies have drilled six wells south and east of Umiat, two wells in the Kurupa and Killik Rivers areas (southwest of Umiat), and three wells in the lower Colville River area (fig. 1). The results of the intensive development in the Prudhoe Bay field and other exploratory drilling east of NPR-4 have added immeasurably to the understanding of regional structure and stratigraphy. Much of the seismic data generated, however, while relevant to exploration on the Reserve, is proprietary and not available to the Government.

EXISTING DATA BASE

Publications

Early geologic exploration of NPR-4 through 1926 was reported on by the U.S.G.S. (Schrader and Peters, 1904; Smith and Mertie, 1930). The results of the PET-4 program were discussed at length in U.S.G.S. Professional Papers 301, 302 A-D, 303 A-H, 304 A, and 305 A-L. A comprehensive report on the subsurface, stratigraphic, structural, and economic geology of NPR-4 was published by Collins and Robinson (1967). Papers and reports on NPR-4, and the North Slope in general, by the Geological Survey and others are listed in two recent bibliographies by Maher and Trollman (1970) and by Carter, Denman, and Pierpoint (1975). Subsequent significant papers include those by Detterman and others (1975), Grantz, Holmes, and Kososki (1975), Bird and Jordan (1976), Blean (1976), and Jones and Speers (1976). Unpublished data in March, 1977 include a folio of subsurface mapping of the eastern North Slope area, gravity mapping and rock-density tabulation in the northern portion of the Arctic National Wildlife Range, and a northern Alaska paleomagnetism-plate tectonics study. Geologic mapping coverage is shown on fig. 2.

Test wells

Test well data in NPR-4 are shown in fig. 1 and in table 1. The 45 core tests (page 10) are shown neither on fig. 1 nor in table 1. A few were drilled in widely scattered areas,

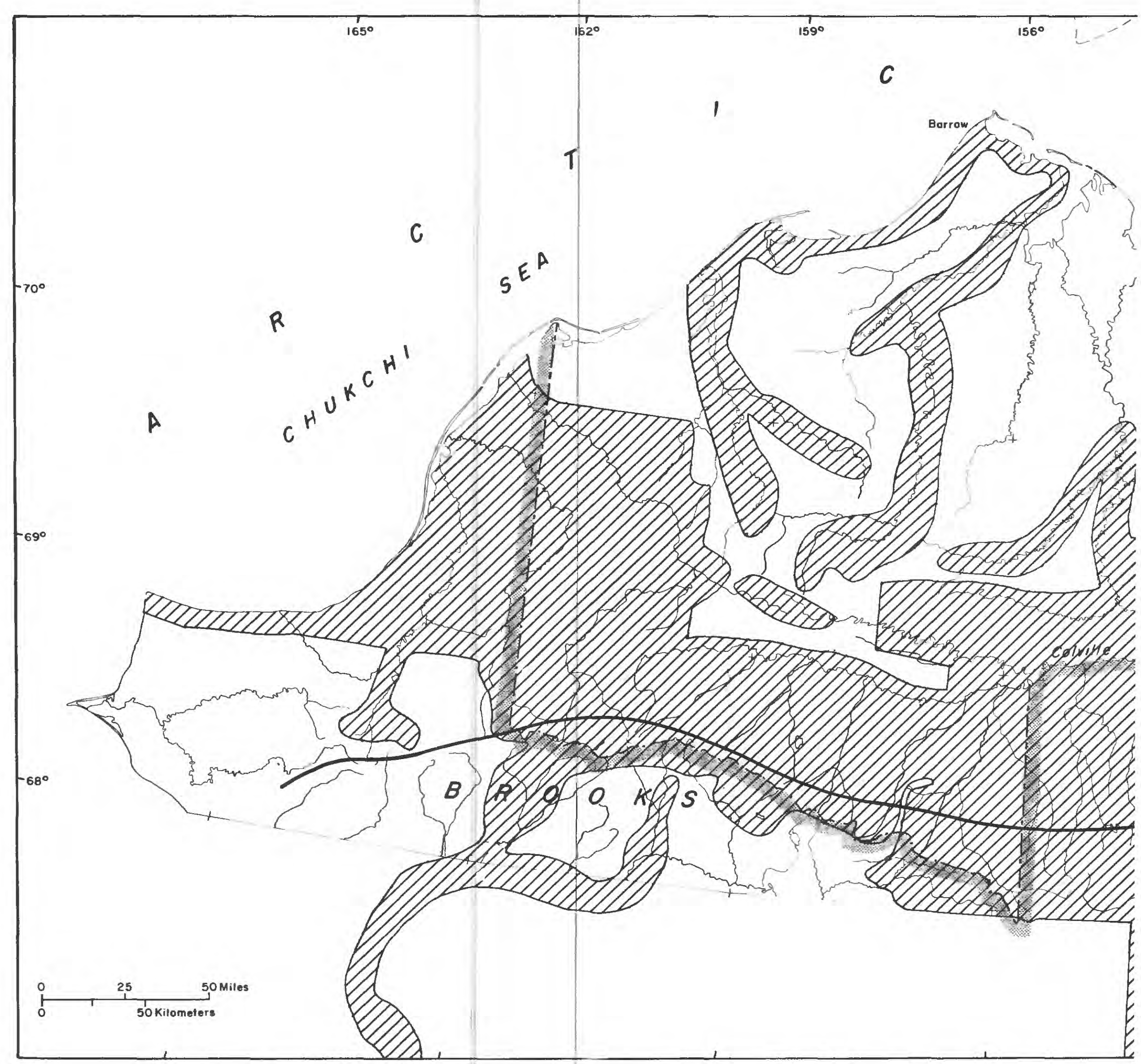
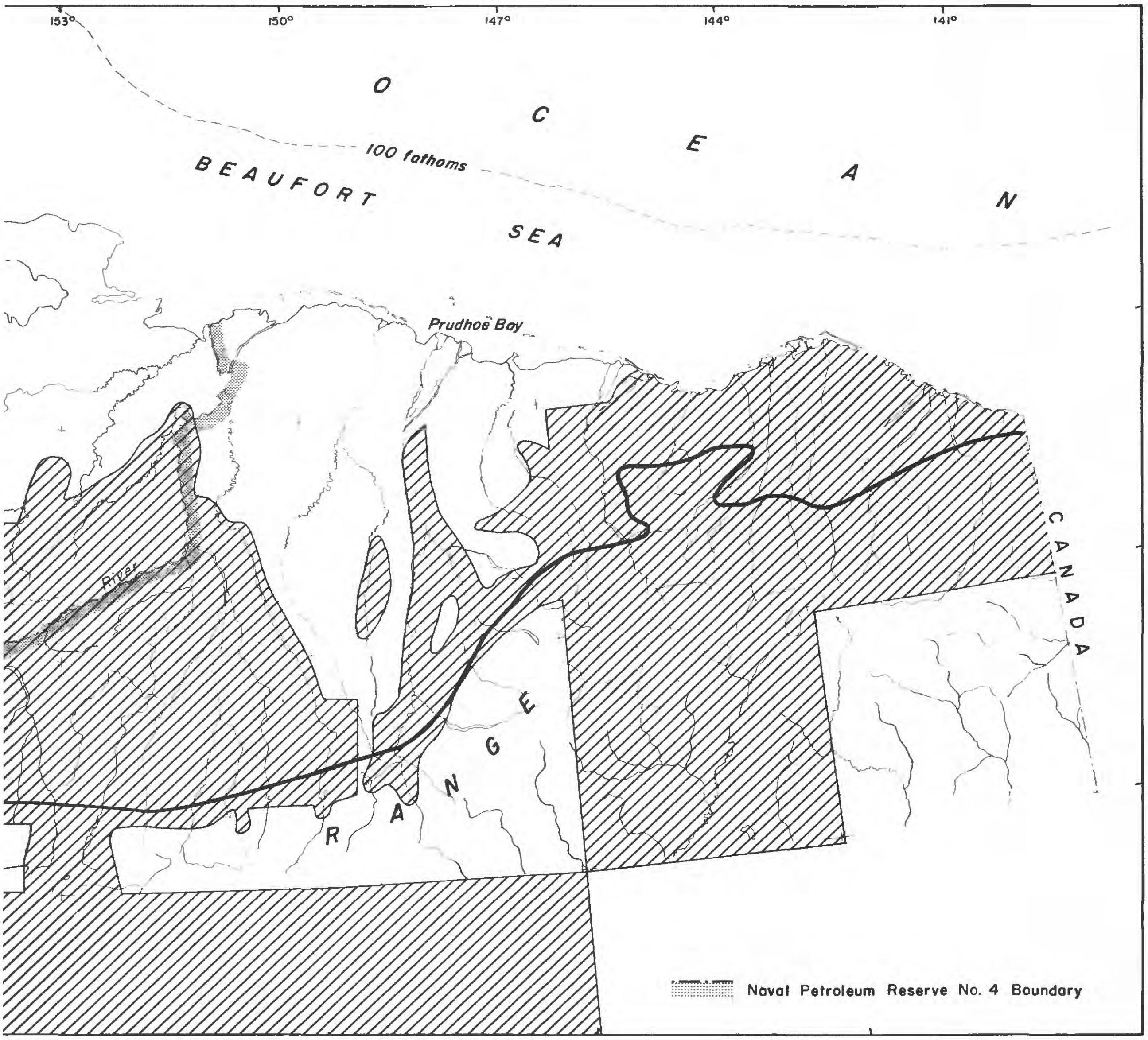


Figure 2. U.S. Geological Survey surface mapping coverage, north slope of Alaska.



153°
150°
147°
144°
141°
O C E A N
100 fathoms
BEAUFORT
SEA
Prudhoe Bay
River
CANADA
RANGE
Naval Petroleum Reserve No. 4 Boundary

WELL	NO.	TOTAL DEPTH IN FEET	FORMATION AT TOTAL DEPTH	COMPLETED	
Test Wells					
Umiat	1	6,005	Lower Cret.-Oumalik	Dry	10/46
	2	6,212	Lower Cret.-Topagoruk	Dry	12/47
(Core test 1)	3	572	Lower Cret.-Grandstand	Oil (ab'd)	12/46
	4	840	Lower Cret.-Grandstand	Oil	7/50
	5	1,077	Lower Cret.-Topagoruk	Oil	10/51
	6	825	Lower Cret.-Grandstand	Oil (ab'd)	12/50
	7	1,384	Lower Cret.-Grandstand	Dry	4/51
	8	1,327	Lower Cret.-Grandstand	Oil	8/51
	9	1,257	Lower Cret.-Topagoruk	Oil (ab'd)	1/52
	10	1,573	Lower Cret.-Grandstand	Oil	1/52
	11	3,303	Lower Cret.-Topagoruk	Dry	8/52
South Barrow	1	3,553	Basement, pre-Miss.	Dry	11/48
	2	2,505	Basement, pre-Miss.	Gas (ab'd)	4/49
	3	2,900	Basement, pre-Miss.	Dry	8/49
	4	2,538	Basement, pre-Miss.	Gas	5/50
Avak	1	4,020	Basement, pre-Miss.	Dry	1/52
Topagoruk	1	10,503	Basement, Devonian	Dry	9/51
East Topagoruk	1	3,589	Lower Cret.-Topagoruk	Dry	4/51
Kaolak	1	6,952	Lower Cret.-Topagoruk	Dry	11/51
Oumalik	1	11,872	Lower Cret.-Oumalik	Gas (ab'd)	4/50
East Oumalik	1	6,035	Lower Cret.-Oumalik	Dry	1/51
[1]Simpson	1	7,002	Basement, pre-Miss.	Dry	6/48
North Simpson	1	3,774	Lower Cret.-Oumalik	Dry	6/50
Square Lake	1	3,987	Lower Cret.-Grandstand	Gas (ab'd)	4/52
Titaluk	1	4,020	Lower Cret.-Topagoruk	Dry	7/51
Wolf Creek	1	1,500	Lower Cret.-Grandstand	Gas (ab'd)	6/51
	2	1,618	Lower Cret.-Grandstand	Dry	7/51
	3	3,760	Lower Cret.-Topagoruk	Dry	11/52
Knifeblade	1	1,805	Lower Cret.-Grandstand	Dry	12/51
	2	373	Lower Cret.-Grandstand	Dry	8/51
	2A	1,805	Lower Cret.-Grandstand	Dry	10/51
[2]Gubik	1	6,000	Lower Cret.-Topagoruk	Gas (ab'd)	8/51
	2	4,620	Lower Cret.-Topagoruk	Dry	12/51
Fish Creek	1	7,020	Lower Cret.-Topagoruk	Oil (ab'd)	9/49
Meade	1	5,305	Lower Cret.-Topagoruk	Gas (ab'd)	8/50
[2]Grandstand	1	3,939	Lower Cret.-Torok	Dry	8/52
Iko	1	2,731	? ?	Dry	3/75
Cape Halkett	1	9,900	Basement, pre-Miss.	Dry	5/75
East Teshekpuk	1	10,664	Rept'd. Lisburne penetration	Dry	5/76
South Harrison Bay	1	11,290	Mississippian	Dry	2/77
Atigaru Point	1	11,535	?	Dry	3/77
West Fish Creek	1	Drilling March 1977			
W. T. Foran	1	" " "			
South Simpson	1	" " "			

1. Simpson field discovered by shallow core tests.
2. Navy wells outside NPR-4.

Table 1: Test and development wells, NPR-4.

WELL	NO.	TOTAL DEPTH IN FEET	FORMATION AT TOTAL DEPTH	COMPLETED	
Development Wells					
South Barrow	5	2,456	Jurassic	Gas	6/55
	6	2,363	Jurassic	Gas	3/64
	7	2,351	Jurassic	Gas	4/68
	8	2,359	Jurassic	Gas	5/69
	9	2,450	Jurassic	Gas	4/70
	10	2,349	Jurassic	Gas	3/73
	11	2,350±	?	?	3/74
	12	2,287	Jurassic	Gas	5/74
	13	2,534	Pre-Dev. argillite	Gas (Susp.)	1/77
	14	2,257	Jurassic	Gas	2/77

Sources: U.S.G.S. Prof. Papers 301, 305-A-K; Alaska Div. of Oil and Gas; The Alaska Scouting Service, May 19, 1976; Navy press release, Jan. 21, 1977; Petroleum Information, Feb. 16, 23, Mar. 23, 1977.

Table 1 (Cont): Test and development wells, NPR-4.

but the majority were near the Simpson oil seeps and most of these reached only shallow depths. Considerable core and other rock material from all the wells is stored in U.S.G.S. warehouses in Anchorage, Alaska, and Menlo Park, California. Records and logs of industry wells drilled along the east side of the Reserve are available commercially, and samples are available for inspection in the Alaska Division of Oil and Gas in Anchorage. Data from the 1975-1977 Navy drilling programs are proprietary and not presently available for public inspection.

Oil and gas fields

Oil and gas fields are shown on fig. 1, and reserve estimates and producing horizons are included in table 2.

Geophysical data

Coverage and other data of the 1944-1953 PET-4 geophysical program are shown on fig. 3 and table 3. All of the original seismic records are stored and available from the U.S.G.S. Alaska Technical Data Section, Menlo Park, California. The original seismic data have been digitized and reprocessed by industry contractors using modern techniques and their quality has been considerably enhanced. The Navy has acquired the reprocessed data, and they are available commercially. Seismic coverage acquired by the Navy in its current program is not plotted.

Table 2. Oil and gas fields, Alaska north slope.

Field	Production	Producing Formation		Reservoir Lithology	Approximate Depth of Production in feet	Identified Resources (Econ. & Subecon.) Million bbls. oil Billion c.f. gas
Umiat NPR-4	Oil	Lower Cret.	Nanushuk Group	Sandstone	250-1,350	70
Gubik	Gas	Upper Cret.	Prince Creek Fm.	Sandstone	1,450-1,750	22-295 (Gubik, both rows)
		Upper Cret.	Chandler-Ninuluk Fms. undiff.	Sandstone	3,550	
South Barrow NPR-4	Gas	Jurassic	?	Sandstone	2,500	18
Meade NPR-4	Gas	Lower Cret.	Nanushuk Group	Sandstone	4,200	10
Square Lake NPR-4	Gas	Upper Cret.	Seabee Fm.	Sandstone	1,650-1,850	33-58
Wolf Creek NPR-4	Gas	Lower Cret.	Nanushuk Group	Sandstone	1,500	No est.
Simpson NPR-4	Oil	Upper Cret.	Nanushuk-Seabee Fms.	Sandstone	300	30 (Simpson NPR-4 and Fish Creek NPR-4)
Fish Creek NPR-4	Oil	Lower Cret.	Topagoruk Fm.	Sandstone	3,000	
Prudhoe Bay	Oil	Jurassic	Kuparuk River	Sandstone	8,000	No est.
	Oil & Gas	Jurassic	Sag River Fm.	Sandstone	10,000	No est.
	Oil & Gas	U. Triassic	Shublik Fm.	Sandstone/Limestone	10,000	No est.
	Oil & Gas	L. Triassic-Perm.	Sadlerochit Grp.	Sandstone	10,500	*9.6 bill. bbls. oil 26.5 trillion cfg
	Oil & Gas	Miss. & Penn.	Lisburne Grp.	Carbonates	11,500	No est.
Kavik	Gas	Triassic	Sag River Fm.	Sandstone	4,250	No est.
	Gas	Triassic	Sadlerochit Grp.	Sandstone	4,600	No est.
Kemik	Gas	Triassic	Shublik Fm.	Limestone	8,700	No est.

Sources: Harrison and others (1973); American Petroleum Institute and others (1974); Morgridge and Smith (1972)

*Measured Reserves

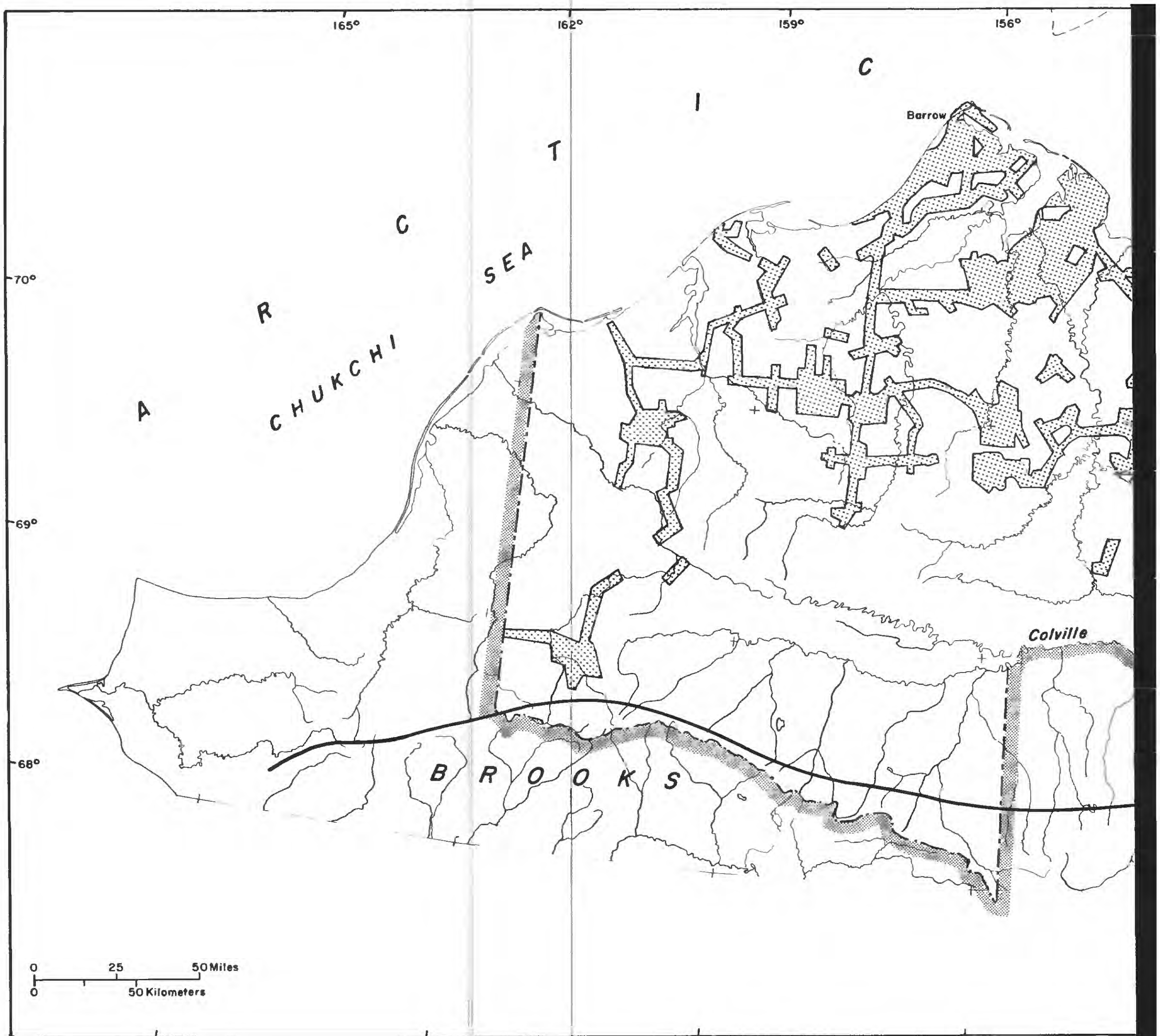
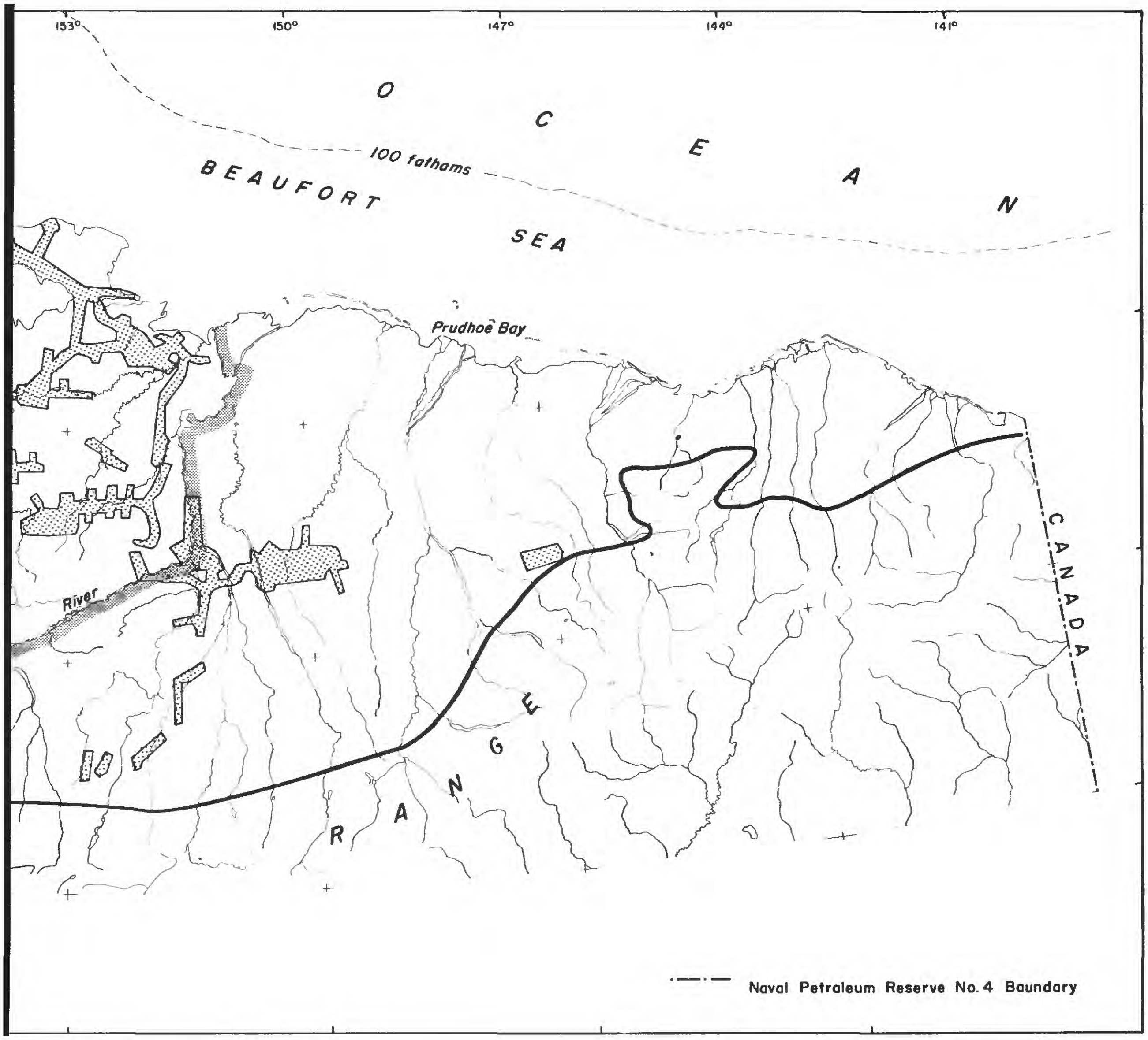


Figure 3. PET 4 Program seismic coverage 1945-1953, north slope of Alaska


153°
150°
147°
144°
141°
O C E A N
100 fathoms
BEAUFORT
SEA
Prudhoe Bay
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CANADA
RANGE
Naval Petroleum Reserve No. 4 Boundary

Gravity Data

Source	No. of Stations	Year Completed
U.S. Navy	636	1945
U.S. Navy	2,804	1946
U.S. Navy	594	1947
U.S. Navy	296	1949
U.S. Navy	1,788	1950

Total Navy coverage available: 6,118 Stations/37,000sq. mi. +1 sta/6 mi^2.

Aeromagnetic Data

Source	Flight-line miles	Flight-line spacing	Year Completed
U.S.G.S.	6,700	2 miles	1945
U.S.G.S.	5,900	2-4 miles	1946
Aero Service*	12,200	2-4 miles	1970

Total Navy coverage available: 12,600 flight-line miles covering an area of 36,000 square miles

*Commercial gradiometer survey available.

Note: Does not include gravity stations recently acquired by the Navy.

Table 3: Geophysical data, PET-4 program, NPR-4

SEISMIC REFLECTION DATA

(Single Fold Dynamite)

Source	No. of Profiles	Line Miles	Year Completed
U.S. Navy	297	74.25	1945
U.S. Navy	850	212.50	1946
U.S. Navy	1,412	353.00	1947
U.S. Navy	1,944	486.00	1948
U.S. Navy	3,191	797.75	1949
U.S. Navy	3,501	875.25	1950
U.S. Navy	790	197.50	1951
U.S. Navy	1,305	326.25	1952
U.S. Navy	141	35.25	1953
Totals:	13,431	3,357.75	

Mileage based on seismic profile spacing of 1,320 ft.

SEISMIC REFRACTION DATA

Source	No. of Profiles	Year Completed
U.S. Navy	21	1946
U.S. Navy	246	1948
U.S. Navy	77	1949
U.S. Navy	15	1950
U.S. Navy	32	1952
Total:	391	

Refraction profiles were usually shot with 8,000-ft spread lengths.

Note: Does not include 5,000± miles of seismic records recently acquired by the U. S. Navy.

Sources: Woolson and others (1962); Keller and Henderson (1947).

Table 3 (Cont): Geophysical Data, PET-4 program, NPR-4

FRAMEWORK GEOLOGY

Introduction

Naval Petroleum Reserve No. 4 includes parts of all three major east-trending tectonic elements that make up the North Slope of Alaska. These elements, 1) the Brooks Range orogen, 2) the Colville Trough, and 3) the Barrow Arch, correspond generally to the Brooks Range, Foothills, and Coastal Plain physiographic provinces, respectively (fig. 4). The basement, at relatively shallow depths along the Barrow Arch, slopes gently southward into the Colville Trough where it reaches a depth of about 30,000 feet. The southern part of the trough is overridden by the Brooks Range orogen, which contains basement and younger rocks. These structural relations are diagrammatically illustrated in the north-trending cross-section A'-A (fig. 5). In this cross-section, structure within the basin fill has been eliminated north of the Brooks Range in order to emphasize stratigraphic relations critical to the petroleum potential of this region.

The bedded rocks of the North Slope can be conveniently grouped into three sequences, which reflect the major stages in the tectonic development of the region. These sequences are defined on the basis of source-area location and have been named by Lerand (1973) and applied to northern Alaska by Grantz, Holmes, and Kososki (1975). In ascending order they are 1) Franklinian (Cambrian through Devonian),

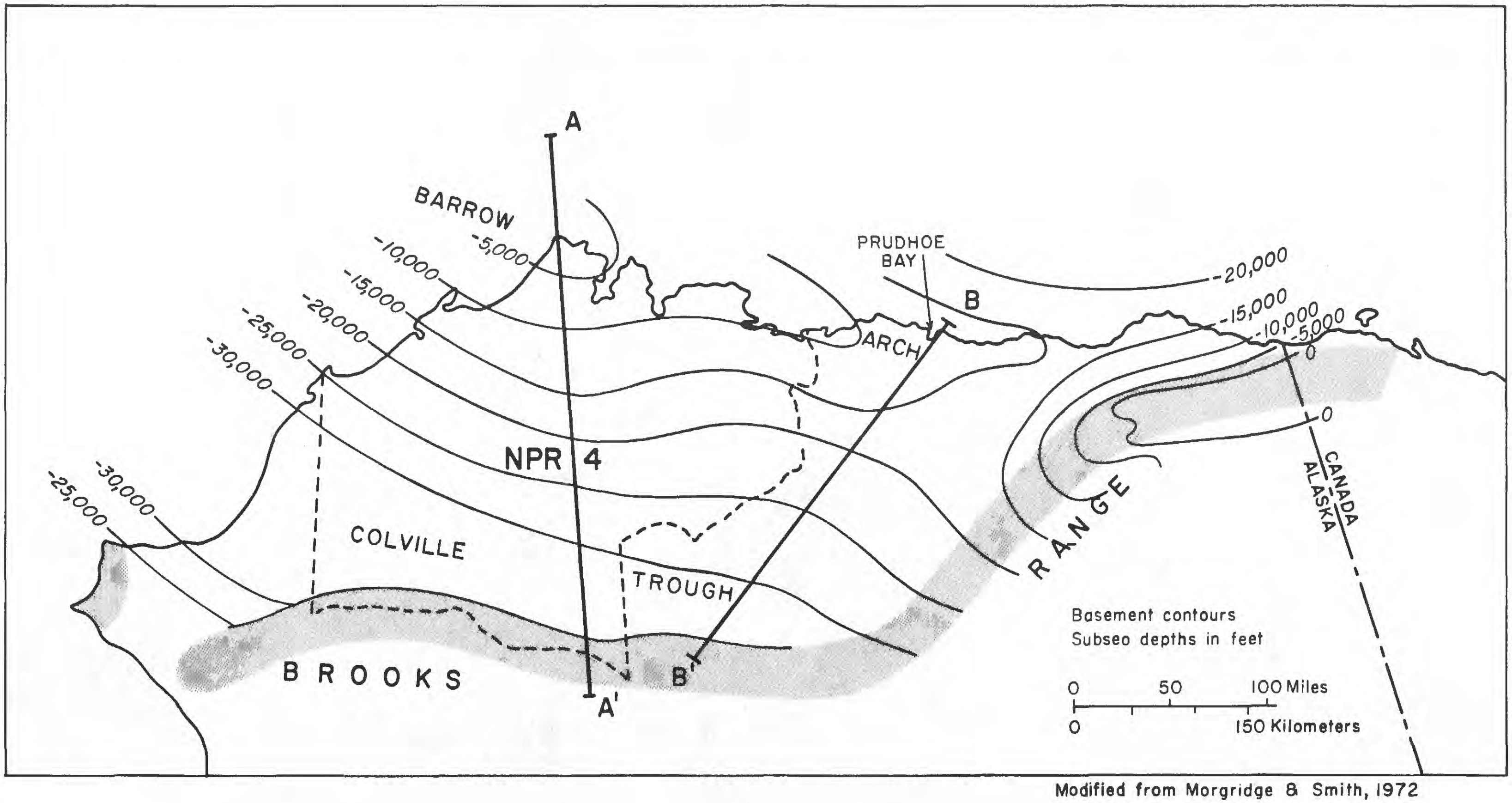


Figure 4. Tectonic elements of the north slope of Alaska

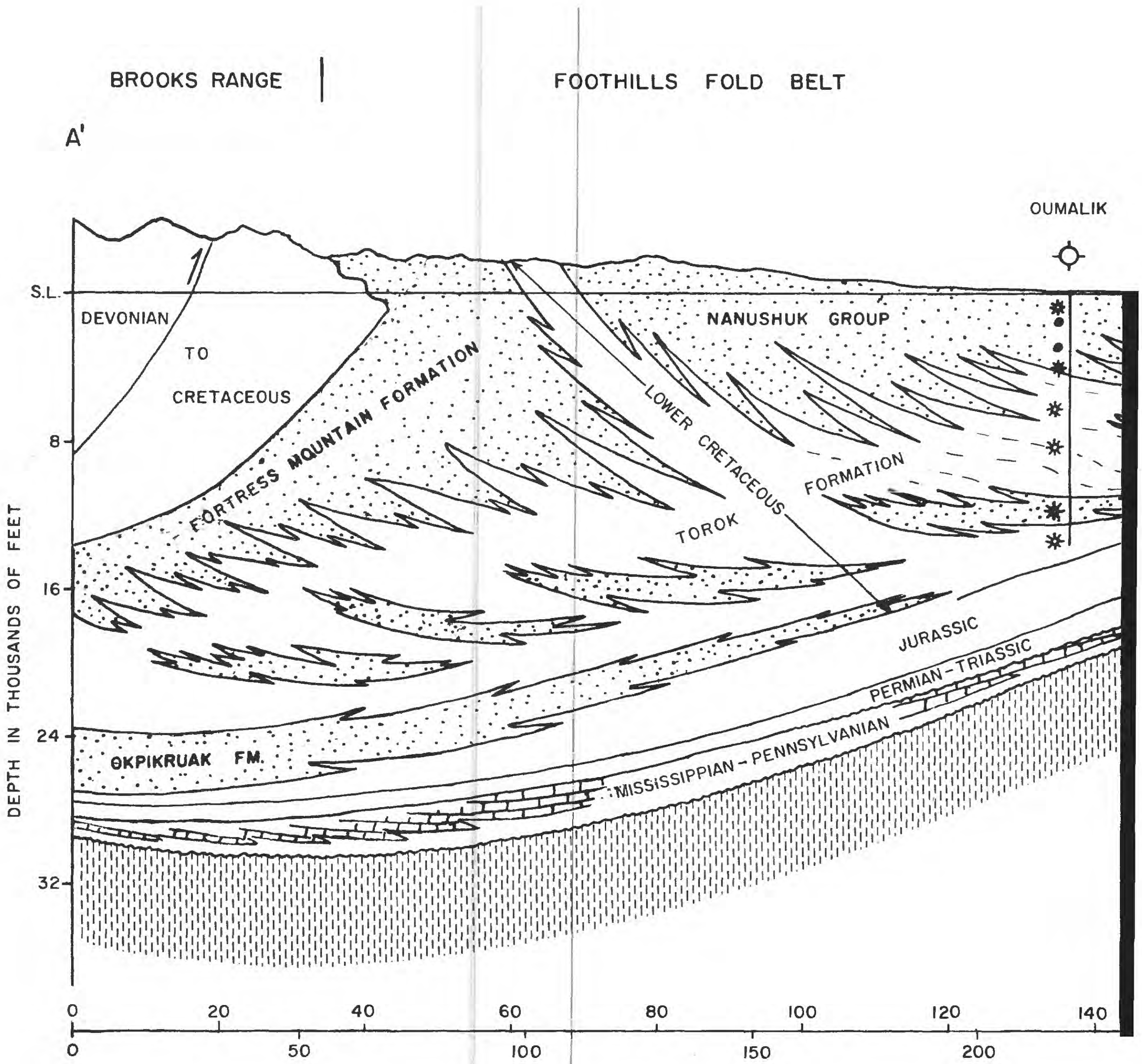
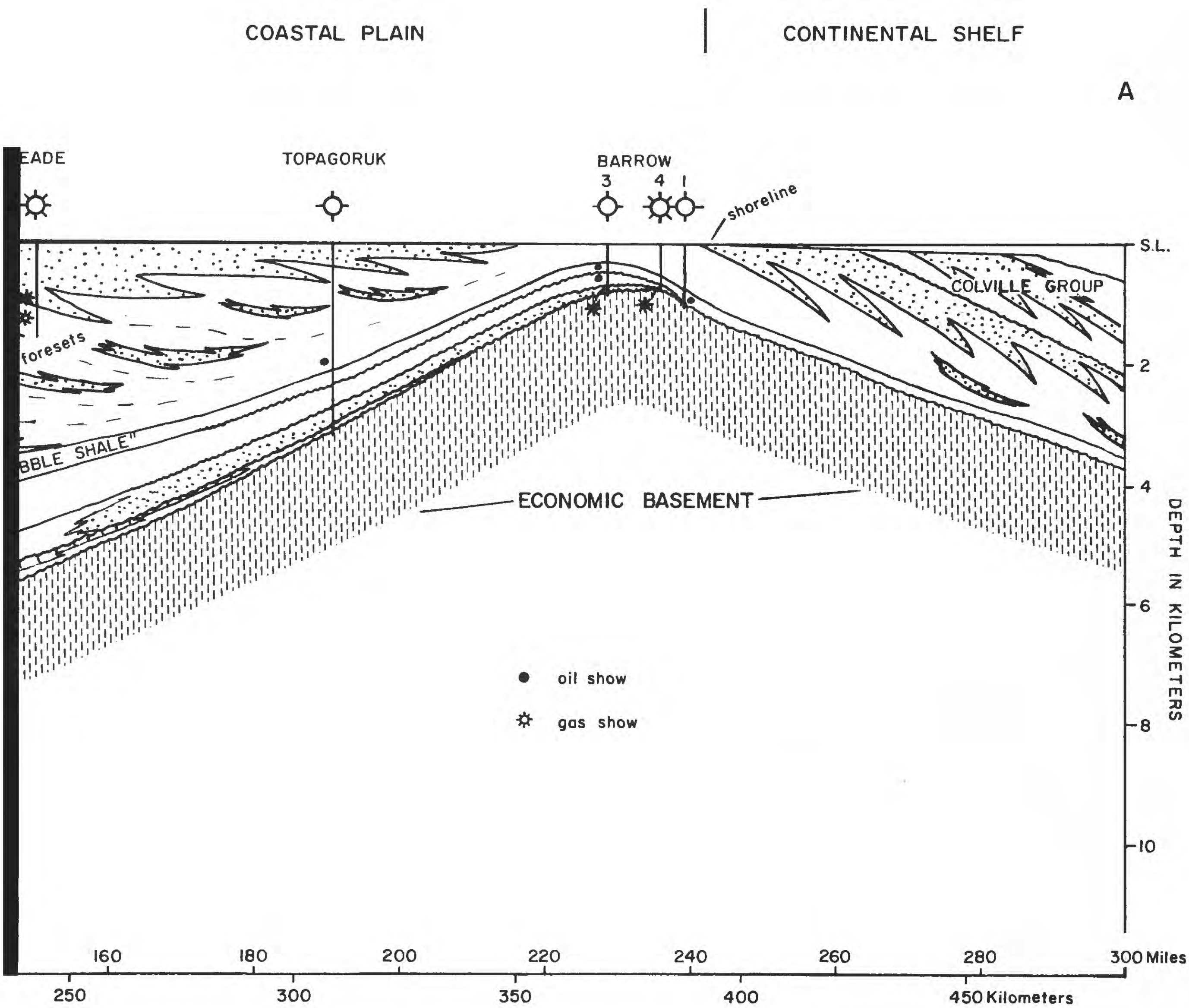


Fig 5. Diagrammatic structural-stratigraphic cross-section A'- A, NPR-4



COASTAL PLAIN
CONTINENTAL SHELF
A
EADE
TOPAGORUK
BARROW
3
4
1
shoreline
S.L.
COLVILLE GROUP
foresets
BBLE SHALE"
ECONOMIC BASEMENT
oil show
gas show
2
4
6
8
10
DEPTH IN KILOMETERS
160
180
200
220
240
260
280
300 Miles
250
300
350
400
450 Kilometers

2) Ellesmerian (Mississippian through Jurassic), and 3) Brookian (Cretaceous to Recent). The sequences and their component formations in NPR-4 are summarized in the accompanying stratigraphic sections (fig. 6).

The stratigraphy of the North Slope has been summarized by Brosge and Tailleur (1971) and that of the Prudhoe Bay area by Morgridge and Smith (1972), and Jones and Speers (1976). The tectonic setting of the North Slope and adjacent offshore areas has been summarized most recently by Grantz, Holmes, and Kososki (1975).

Franklinian Sequence

The Franklinian (pre-Mississippian) sequence constitutes economic basement for petroleum exploration on the North Slope. It consists of a variety of contorted and mildly metamorphosed clastic and carbonate geosynclinal rocks, and most wells penetrating this sequence have encountered argillite. Late Devonian orogenic uplift in what is now northern Alaska shed great volumes of clastic debris southward to form thick clastic wedges (Kanayut Conglomerate and Hunt Fork Shale). Subsequent erosion and subsidence of the Devonian orogen provided a platform for deposition of the following sequence.

Ellesmerian Sequence

The Ellesmerian (Mississippian to Jurassic) sequence contains some hydrocarbon source rock and the best reservoir found to date on the North Slope. It consists of a platform

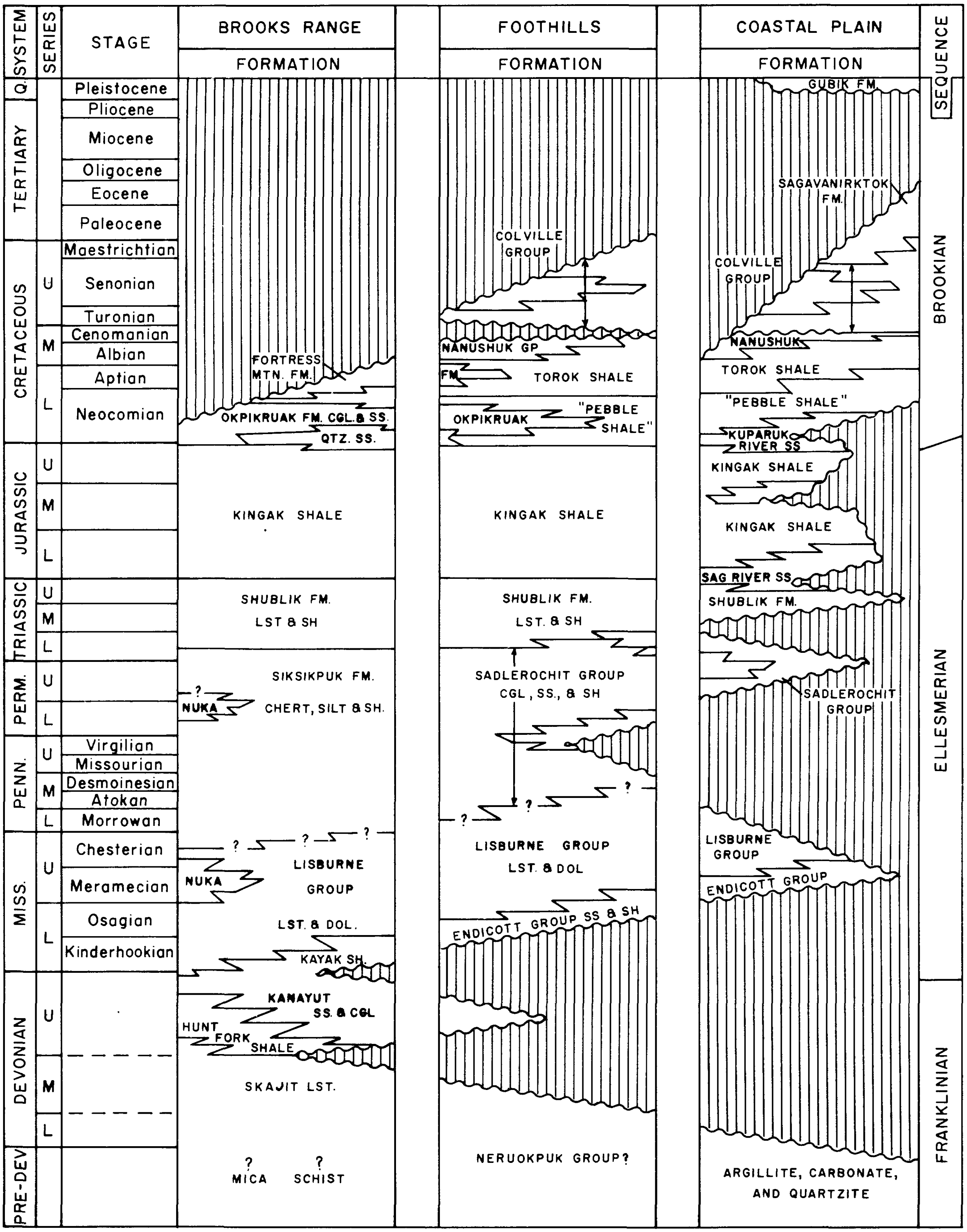


Figure 6. Generalized stratigraphic sections, NPR-4

sequence of marine and nonmarine clastic and carbonate rocks, which display increasing grain size, decreasing stratigraphic thickness, and numerous unconformities northward. These features suggest that the source area lay near the present shoreline.

Mississippian clastic rocks (Endicott Group) unconformably overlie steeply dipping and metamorphosed Franklinian-sequence basement rocks. They grade into Mississippian and Pennsylvanian shallow marine carbonate rocks (Lisburne Group). Late Pennsylvanian or Early Permian regression resulted in a regional unconformity and truncation of these sediments in the north. Subsequently important sandstone reservoir units were deposited during the Permian and Triassic (Sadlerochit Group), Late Triassic or Early Jurassic (Sag River Sandstone), and Late Jurassic or Early Cretaceous (Kuparuk River Sandstone). All of these units are of limited areal extent and they grade southward (downdip) into siltstone and shale. Important source-quality shale was deposited during transgressions in the Late Triassic (Shublik Formation) and Jurassic (Kingak Formation).

In the Brooks Range the Ellesmerian sequence consists of Mississippian shallow marine clastic rocks (Endicott Group and Nuka Formation) and shallow to deep marine carbonate rocks (Lisburne Group). Pennsylvanian through Jurassic age rocks consist of siliceous shale, chert, and minor limestone. Locally the Jurassic contains oil shale and volcanic rocks.

Brookian Sequence

The Brookian (Late Jurassic, Cretaceous, Tertiary) sequence consists of large amounts of greywacke sandstone and shale derived from an orogeny that began in Late Jurassic and continued into Late Cretaceous and perhaps Early Tertiary time in the western Brooks Range and apparently into the Neogene in the northeastern Brooks Range. This orogeny, a result of intense compression, caused large-scale relatively northward thrusting of Paleozoic to Cretaceous age rocks. Aggregate shortening in the western Brooks Range is estimated to be 100 km (62 mi) (Martin, 1970) or more than 240 km (149 mi) (Snelson and Tailleur, 1968).

The orogeny drastically changed the paleogeography of Arctic Alaska. Northern sources were replaced by southern sources--the Brooks Range. Initially, however, sediments were supplied from both northern (Ellesmerian) and southern (Brookian) sources. The northern source subsided and was overlapped in Early Cretaceous (Neocomian) time. Subsidence of this source area is recorded by the overlapping sediments and subsequent northward downwarping and faulting along a linear zone approximately parallel to the present shoreline. The resultant structure, the Barrow Arch, is a linear basement ridge plunging to the southeast (fig. 4). The Prudhoe and South Barrow fields are located on the crest of this feature.

Throughout the orogeny large volumes of clastic debris were shed northward into a migrating foredeep. The Early

Cretaceous (Neocomian) rocks consist of a flysch-like sequence of turbidites (Okpikruak Formation) and its northward equivalent, the organically rich "pebble shale". This shale, in part of northern derivation, is believed to be a major source for petroleum at Prudhoe Bay (Morgridge and Smith, 1972). Locally present in the Brooks Range and foothills and equivalent in age to the Okpikruak is a thin quartzose sandstone (recently named the Tingmerkpuk Member of the Ipewik Formation by Crane and Wiggins, 1976) and maroon coquinoid shale. This unit, lithologically anomalous among the thick greywackes of the Brookian sequence, is similar to Ellesmerian sequence rocks and may record deposition on an intrabasin high or a southward extension of the lithologic and age equivalent Kuparuk River Sandstone. Throughout the remainder of Cretaceous and Tertiary time periodic influxes of coarse terriginous debris produced clastic wedges separated by thick shale units. The depocenter of each wedge is located successively further to the northeast. Seismic data indicate that some wedges consist internally of large-scale foreset beds. Prominent wedges formed in the Early Cretaceous (Fortress Mountain Formation), Middle Cretaceous (Nanushuk Group), Late Cretaceous (Colville Group), and Latest Cretaceous and Early Tertiary (Sagavanirktok Formation). The depocenters for the Late Cretaceous and Tertiary wedges lie to the east of NPR-4 and partly offshore.

PETROLEUM GEOLOGY

Introduction

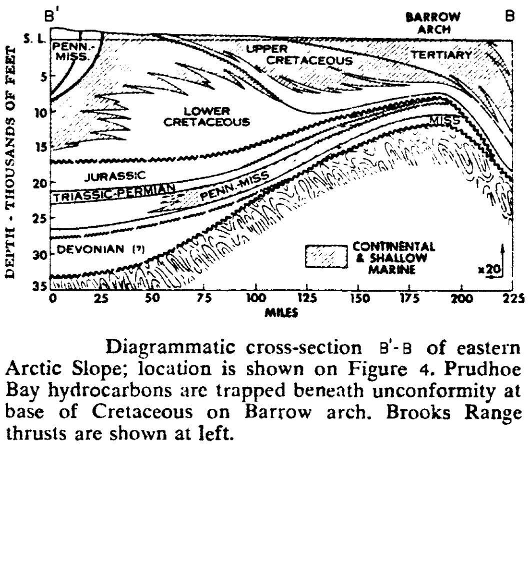
A petroleum province requires the relatively close association of petroleum source rock, porous reservoir rock, and sealing beds adjacent to the reservoir to form traps. An additional and most critical requirement is a favorable geologic history, generally referred to as "timing". A favorable history requires the following events: 1) burial of source rocks sufficiently deep for petroleum generation, 2) the presence of permeable rock to provide a migration path for the petroleum as it is generated and expelled from the source rock, and 3) the formation of traps in reservoirs updip from, or adjacent to, the source beds in order to entrap the migrating petroleum and to prevent its escape to the surface.

The petroleum potential of a province, therefore, depends on the quality of source and reservoir rock, the size of the traps, and the geologic history of the basin. The discovery initially of several oil and gas seeps and later several small oil and gas fields by the Navy confirmed the belief that the North Slope was an oil province. However, the potential of this province was not fully appreciated until the discovery of the Prudhoe Bay field. This field is an example of an unusual combination of favorable features.

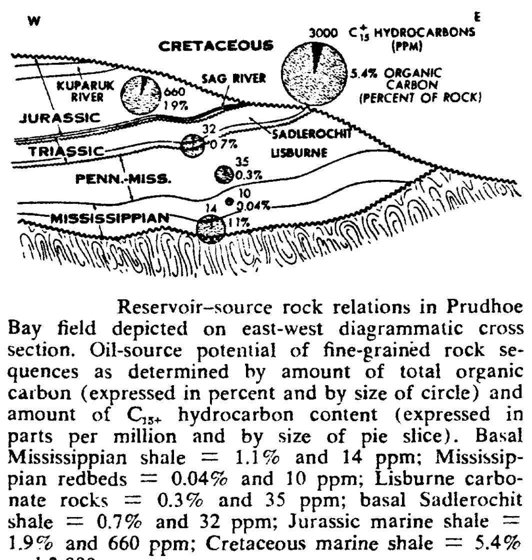
Briefly the Prudhoe Bay field consists of multiple stacked reservoirs, which reach their maximum development near the crest of the Barrow Arch. Along the north flank of the arch the reservoir rocks are truncated and are directly overlain and sealed by very rich source rocks. Subsequently these source rocks were buried to oil-generating depths and the oil thus produced migrated updip into a trap on the crest of a structure formed on the Barrow Arch. It is this fortuitous combination of highly favorable circumstances that resulted in the largest petroleum accumulation in North America. According to American Petroleum Institute and American Gas Association figures (1974), Prudhoe Bay proved reserves in the major reservoir are 9.6 billion barrels of oil and 26.5 trillion cubic feet of gas. Reserve figures for the other reservoirs are not available at present (table 2). The rare combination of these geological features suggests that hydrocarbon accumulations of similar magnitude may not exist anywhere else on the North Slope. Recent Navy wells drilled in the northeastern part of NPR-4, apparently in optimum locations for a Prudhoe Bay type accumulation, have been completed as dry holes (fig. 1, table 1).

Source rocks

Gray marine shales abound on the North Slope and all may be considered potential source rocks (Brosge and Tailleur, 1971). Few geochemical data are available from NPR-4, however, to actually measure the oil-generating potential of these rocks. In the Prudhoe Bay area geochemical data from industry have been summarized by Morgridge and Smith (1972) (fig. 7). They show that the Cretaceous and Jurassic (Kingak Formation)



Diagrammatic cross-section B'-B of eastern Arctic Slope; location is shown on Figure 4. Prudhoe Bay hydrocarbons are trapped beneath unconformity at base of Cretaceous on Barrow arch. Brooks Range thrusts are shown at left.



Reservoir–source rock relations in Prudhoe Bay field depicted on east-west diagrammatic cross section. Oil-source potential of fine-grained rock sequences as determined by amount of total organic carbon (expressed in percent and by size of circle) and amount of C_{15+} hydrocarbon content (expressed in parts per million and by size of pie slice). Basal Mississippian shale = 1.1% and 14 ppm; Mississippian redbeds = 0.04% and 10 ppm; Lisburne carbonate rocks = 0.3% and 35 ppm; basal Sadlerochit shale = 0.7% and 32 ppm; Jurassic marine shale = 1.9% and 660 ppm; Cretaceous marine shale = 5.4% and 3,000 ppm.

Figure 7. Diagrammatic cross-sections showing reservoir- source-rock relations and geochemical data in the Prudhoe Bay area (modified from Morgridge and Smith, 1972).

are good source rocks and that the Cretaceous is the probable source for most of the oil at Prudhoe Bay because it overlies the truncated edge of each of the main reservoirs. Their analyses indicate a low oil-generating potential for pre-Jurassic rocks. Coal, a potential source of gas, is locally abundant in the Mississippian (Endicott Group), Cretaceous (Nanushuk and Colville Groups), and Tertiary (Sagavanirktok Formation. Unpublished U. S. Geological Survey geochemical analyses from elsewhere in northern Alaska generally confirm the Prudhoe Bay data.

Within NPR-4 geochemical data are very sparse. Analyses indicate low oil-generating potential for Jurassic shale at Barrow. In the Brooks Range Tailleur (1964) reports the occurrences of oil shale in the Jurassic(?) yielding as much as 127 gallons of oil per ton, in the Shublik Formation yielding 6.7 gallons per ton. However, these rocks are allochthonous fault slivers and are probably not present in the subsurface. Several small accumulations of oil and gas and numerous surface and subsurface shows, separated by thousands of feet of shale from Jurassic and Lower Cretaceous source rocks, suggest that Middle and Upper Cretaceous strata in NPR-4 contain indigenous source rocks.

Extensive geochemical sampling and analyses in order to determine organic richness and thermal maturity will be essential for an accurate evaluation of the hydrocarbon potential of NPR-4.

Reservoir Rocks

Both clastic and carbonate reservoir rocks are present on the North Slope. The best reservoirs are the pre-Middle Cretaceous clastic and carbonate rocks along the Barrow Arch. However, these reservoirs are of limited thickness and areal extent. In contrast, the Cretaceous rocks in the foothills region are generally poorer quality reservoirs, but they are very thick and areally extensive. Reservoir data have been summarized for outcrop samples and Navy wells (Brosge and Tailleur, 1971), for the Sadlerochit Group at Prudhoe Bay (van Poolen and Associates, Inc., 1974; Jones and Speers, 1976), and for the Lisburne Group (Bird and Jordan, 1976).

The most attractive reservoir rocks are those related to a northern source area. Included are the Lisburne Group, Sadlerochit Group, Shublik Formation, Sag River Sandstone, and Kuparuk River Sandstone. All are productive at Prudhoe Bay and are best developed in the north. The Ellesmerian sequence in NPR-4 has been penetrated by the Topagoruk, Simpson, and Barrow wells and probably by the recent Navy wells, Cape Halkett and East Teshekpuk (table 1). Data from the available wells indicate that nearly all sandstone units at Prudhoe Bay are present in NPR-4. These data are insufficient to determine the most favorable reservoir facies and trends, but they do indicate that the basic stratigraphic pattern is progressive northward onlap onto the Franklinian basement complex. The southernmost well (Topagoruk) penetrated a lateral clastic equivalent of the Lisburne carbonates and indicates that the updip limit of the Lisburne lies to the south (fig. 8). The updip limit of the Sadlerochit lies to the north of the Topagoruk well but south of Simpson and Barrow (fig. 8). The Shublik Formation, Sag River Sandstone, and unnamed Lower and Middle Jurassic sandstones are also present in NPR-4. The Kuparuk River Sandstone of latest Jurassic or Early Cretaceous age does not appear to be present in the northern part of NPR-4. In the foothills, potential reservoirs in the pre-Cretaceous section include Shublik Formation limestone and Lisburne Group dolomite. Shublik limestone is productive in the foothills east of the Reserve in the Kemik gas field (fig. 1); and porous Lisburne dolomite with pyrobitumen occurs in the foothills in the southern part of the Reserve (Armstrong, 1970).

Cretaceous sandstone derived from the south generally has lower porosity and permeability than northern-source sandstone because of a relatively high percentage of clay minerals and soft-rock fragments. A trend of improving porosity and permeability up section is suggested by the data summary of Brosge and Tailleur (1971). The youngest reservoirs in NPR-4 are in the Upper Cretaceous Colville Group. This group is found primarily in the eastern one-third of the Reserve and at depths of less than 5,000 feet. The Colville Group is productive at the Gubik gas field. The most widely

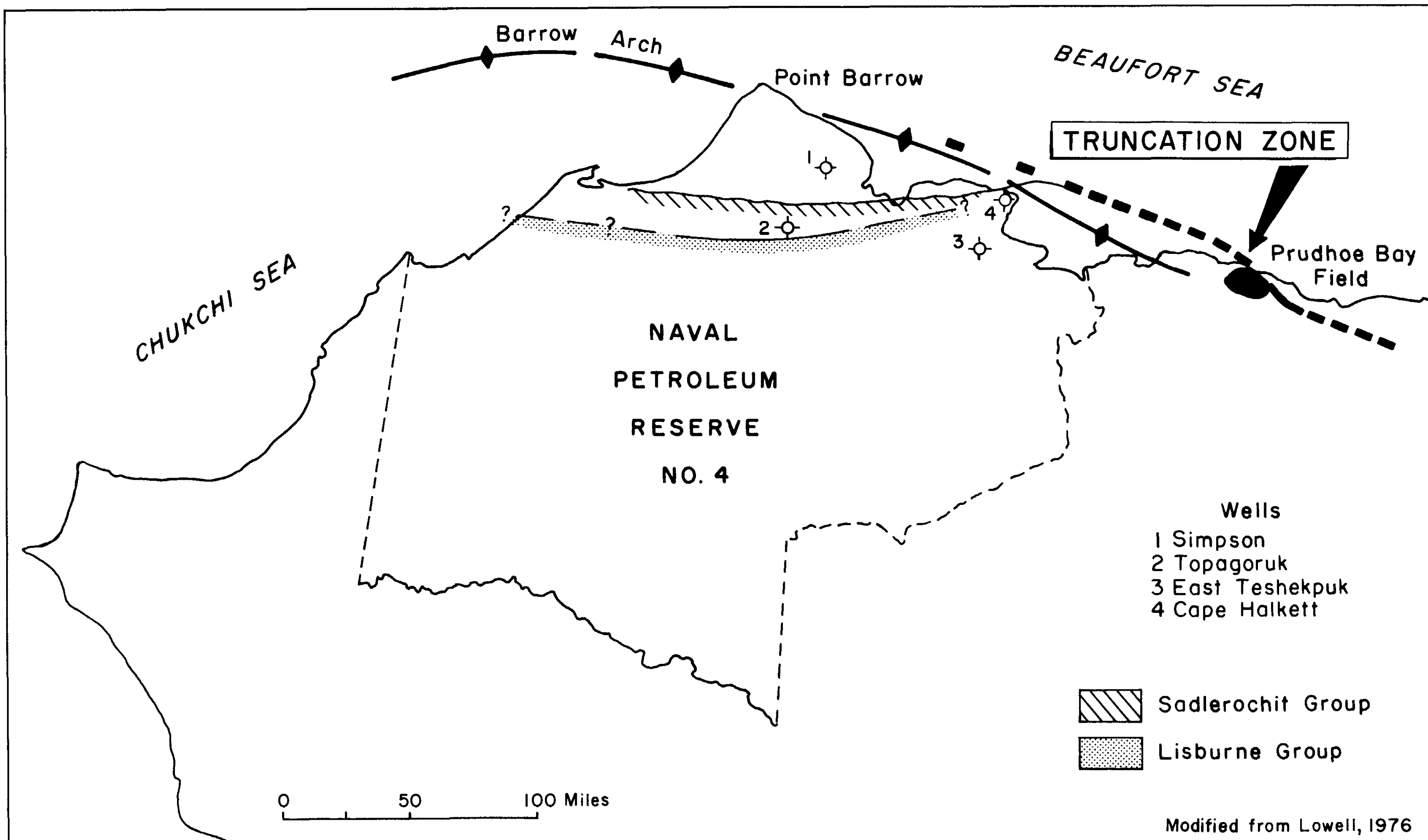


Figure 8. Approximate northern limits, Lisburne and Saddlerochit Groups

distributed reservoir unit in NPR-4 is the Middle Cretaceous Nanushuk Group, which is analogous to the Mesa Verde Group and related rocks of the Rocky Mountains. It underlies the northern-foothills foldbelt and is oil productive at Umiat. In the southern foothills the Okpikruak and Fortress Mountain Formations consist of many thousands of feet of low-porosity and low-permeability greywacke sandstone. In a favorable structural setting these rocks have the potential for very thick columns of oil or gas. An analog for the Okpikruak and Fortress Mountain Formations may be the Late Tertiary turbidites in the Ventura Basin, California. The Neocomian thin quartzose sandstone (Tingmerkpuk Member of the Ipewik Formation) in the foothills is a potential reservoir, although it is generally tightly cemented in outcrop.

Additional well data, field work, laboratory measurements of porosity and permeability, and petrophysical log analyses all directed toward determining the relationship of reservoir quality to environments of deposition will be necessary in an evaluation of the hydrocarbon potential of NPR-4.

Trapping mechanism

Structural traps in NPR-4 are known from geologic mapping, seismic data, and well data. The presence of stratigraphic and combination structural and stratigraphic traps is inferred. Sealing beds, predominantly shale, are present between and often within each major reservoir unit (figs. 5 and 6).

Adequate seals are expected to be present in most structural and stratigraphic trapping situations.

The potential for structural traps is greatest in the foothills belt in folds associated with thrusting. These traps may be of limited areal extent and difficult to explore for, especially in the more geologically complex southern foothills. Accumulations in structural traps include the oil field at Umiat and the Gubik, Kemik, and Kavik gas fields. Structural traps related to broad gentle folding and associated normal faulting may also be present on the Barrow Arch. The South Barrow gas field may be an example of this type of trap.

Stratigraphic traps may be related to updip pinch-outs and truncations in the pre-Lower Cretaceous rocks along the Barrow Arch. However, the extremely favorable source-to-reservoir relationships at Prudhoe Bay may not be present. An additional trapping mechanism may be updip shaling-out of sands deposited on the foreset and bottomset beds in Cretaceous clastic wedges. Thin isolated sands within the thick Torok Shale may be an example of this type.

Combination structural and stratigraphic traps such as Prudhoe Bay may be present. They may be small, however, compared to Prudhoe Bay because of less favorable combinations of reservoir, source, and structure.

Geology of the Prudhoe Bay area compared with NPR-4

The regional geology of northern Alaska indicates that rocks of pre-Late Devonian age can be considered economic basement for hydrocarbons. Rocks of Early Mississippian to earliest Cretaceous age onlap onto, or were derived from erosion of, a continental platform area located generally north of the present coastline, but extending onshore in the Barrow area. Late Devonian deposits may be present locally in the subsurface of the Arctic Slope, but they are probably overmature and at best would contain only gas. During Late Devonian time the entire Arctic Slope area seems to have been an uplifted area acting as a source terrain, shedding sediment generally southward. The platform area has been called the Barrow Arch (fig. 4) in the literature, although the term is somewhat of a misnomer. Economic basement and the overlying Late Paleozoic to earliest Cretaceous rocks regionally dip southward toward the Brooks Range orogenic belt. Depths to basement range from about 3,000 feet in the Barrow area to an estimated 30,000 feet or more in the axis of the foredeep (Colville Trough, fig. 4) north of the Brooks Range thrust belt. This foredeep is filled with thick Lower Cretaceous flysch deposits (fig. 5) that record the progressive filling of the basin and the development of a coarse-clastic (molasse type) sedimentary wedge prograding northward onto the Barrow "arch".

Regionally in northern Alaska, hydrocarbon reservoir horizons have been found in the Ellesmerian sequence, consisting of Mississippian to Middle Pennsylvanian shallow water carbonates (Lisburne Group), a major Early Triassic sandstone and conglomerate horizon (Sadlerochit Group), thin carbonates in the Late Triassic (Shublik Formation), a thin late Triassic sandstone (Sag River Sandstone), and Early Cretaceous and/or Jurassic sandstone (Kuparuk River Sandstone) (fig. 6). All these horizons are related to the northern platform area. In addition, Early Cretaceous sandstones (Brookian sequence) derived from the south are reservoir horizons in some areas. Late Cretaceous and Tertiary beds are also potential reservoirs on the Arctic Slope, but available information indicates that rocks of this age are very thin or absent from most of the Reserve. With the exception of limited areas along the northern coastline, and the eastern boundary, Late Cretaceous and Tertiary rocks may be precluded from consideration as exploration objectives in NPR-4.

The Prudhoe Bay hydrocarbon accumulation is contained in reservoirs of the Lisburne Group, the Sadlerochit Group, the Shublik Formation, the Sag River Sandstone, and Kuparuk River Sandstone. The major reservoir is the Lower Triassic Ivishak Formation of the Sadlerochit Group. Published geochemical data, in combination with the structural and stratigraphic relationships (Morgridge and Smith, 1972) indicate that extremely rich organic shales of Cretaceous age unconformably overlying the reservoir horizons provide part of the seal and are the source of most, if not all, of the hydrocarbons at Prudhoe Bay (fig. 7, p. 33). These data also indicate that Jurassic shales also have hydrocarbon source-rock potential, although this potential is considerably lower than that of the Cretaceous shales and may tend more toward gas potential because of the advanced maturation of the sediments. The Mississippian and Early Triassic rocks are reported to be surprisingly low in source rock potential.

Regionally the data seem to suggest that the organic material contained in the Early Triassic and older sediments of northern Alaska may be overmature: i.e. that the organic material has been thermally matured past the point of optimum oil generation, although it may still be in the range of dry gas generation. Part of the reason for this advanced state of maturity may be found in the geothermal gradient, which is above 2°F per 100 feet of depth for most of northern Alaska (Am. Assoc. Petroleum Geologists, 1973). Based upon fairly extensive data from the Prudhoe Bay field, a gradient of at least 2.4 and perhaps as high as 2.8°F per 100 feet is indicated for the Sadlerochit reservoir in the field (van Poolen and others, 1974, p. 14-16). In northern Alaska, a gradient of this magnitude probably results from lower conductivity of the sedimentary section rather than from higher than average heat flow from the crust (A. H. Lachenbruch, oral commun., 1976; Gold and Lachenbruch, 1973). In either case, regardless of the cause of the high gradient, the result may be higher than average temperatures affecting the sedimentary section and the organic matter contained within the sediments. Older rocks with longer burial histories may thus have had greater residence times at elevated temperatures and therefore may have been more greatly affected by eometamorphic processes while younger beds may only be reaching the point of optimum oil generation and migration. At Prudhoe Bay, the Sadlerochit reservoir temperature ranges from 192° to 216°F at a depth of 8,650 feet, and an average of 200°F is being used in reservoir calculations (van Poolen and others, 1974, p. 15). Calculations by Bird and Jordan (1976) on burial history and geothermal gradient indicate that Mississippian coals in the Prudhoe Bay area are probably within the gas generating regime below 13,000 feet.

In summary, the supergiant Prudhoe Bay oil and gas accumulation appears to be the result of the fortuitous juxtaposition of organically rich, thermally mature, Cretaceous source beds with older reservoir beds containing good to excellent porosity and permeability. The importance of these geological, geochemical, and thermal history relationships cannot be overemphasized in an analysis of the hydrocarbon potential of any part of northern Alaska.

Unfortunately, analysis of the regional geology of northern Alaska suggests that Prudhoe Bay type accumulations are unlikely to be present in NPR-4 for the following reasons:

1. The Cretaceous unconformity that controls the Prudhoe Bay accumulation is probably present in only very limited areas onshore west of Prudhoe Bay. If present onshore in NPR-4, it will probably be confined to the immediate coastal area in Cape Halkett, Cape Simpson, and Point Barrow areas.
2. The northern portion of NPR-4 from at least Cape Simpson to Point Barrow is north of the northern onlap limit of both the Lisburne and Sadlerochit Groups (potential reservoirs) (fig. 8). These groups may be present in the Cape Halkett area, but to be productive they would have to be within hydrocarbon communication range of the Cretaceous truncation and in a favorable structural configuration to form a trap.
3. Regional dip in the pre-Cretaceous rocks of NPR-4 is southward; based on available data, it is difficult to envision hydrocarbon migration into these rocks in NPR-4 from the truncation zone in the Prudhoe Bay area to the east.

4. As a result of the above factors, the probability of juxtaposition of Cretaceous source beds with late Paleozoic and early Mesozoic reservoir horizons in most of NPR-4 is slight. Long distance hydrocarbon migration from Cretaceous source beds into these horizons appears unlikely.

Substantiation of the Prudhoe Bay area geochemical data seems to be found in the results of some of the Navy well data from the PET-4 program of exploration, and from industry drilling in northern Alaska other than in the Prudhoe Bay area. Discoveries of gas and some oil have been made from thin Jurassic and Upper Triassic beds in the Barrow area. An active oil seep and shows in wells in the Cape Simpson area are probably derived from Upper Cretaceous beds. Varying small amounts of oil and gas were recovered from Lower Cretaceous rocks at various locations in NPR-4. Almost every well that has penetrated Cretaceous beds on the Arctic Slope has had some hydrocarbon shows. In contrast, Permian and probable Lower Triassic and Mississippian beds had no reported shows in the only publicly available well (Topagoruk #1) that penetrated them in NPR-4. East of Prudhoe Bay, only gas has been recovered from Triassic reservoir beds in two areas distantly removed from communication with the rich Cretaceous source beds (Kemik and Kavik fields, fig. 1).

These data suggest that the major objectives in NPR-4 will be in the Cretaceous or Jurassic rocks, which contain the richer source beds. The data do not preclude consideration of an indigenous source for hydrocarbons in Early Triassic or older beds, but seem to decrease their overall potential. The data clearly suggest that the most prospective areas will be those in which reservoir beds of any age are in juxtaposition with, or within fluid migration distance of, the rich Cretaceous organic shales.

NPR-4 Exploration trends

With presently available data, three broad trends or subprovinces prospective for accumulations with similar source, reservoir, and trap characteristics can be outlined. Figure 9 shows the location and proposed names of these trends, and summarizes for each one the well density, hydrocarbon accumulations and active seeps, and the surface anticlines.

The northermost trend, referred to here as the Coastal Plain subprovince, is prospective for oil and gas in structural, stratigraphic, and combination structural-stratigraphic traps in pre-Middle Cretaceous rocks. The southern edge of this trend would be limited by drilling depths of 20,000 feet to Lisburne carbonate rocks. Shallow objectives in this trend may include Cretaceous stratigraphic traps in foreset sandstone bodies.

The Northern Foothills subprovince, lying to the south of the Coastal Plain trend, is prospective throughout the

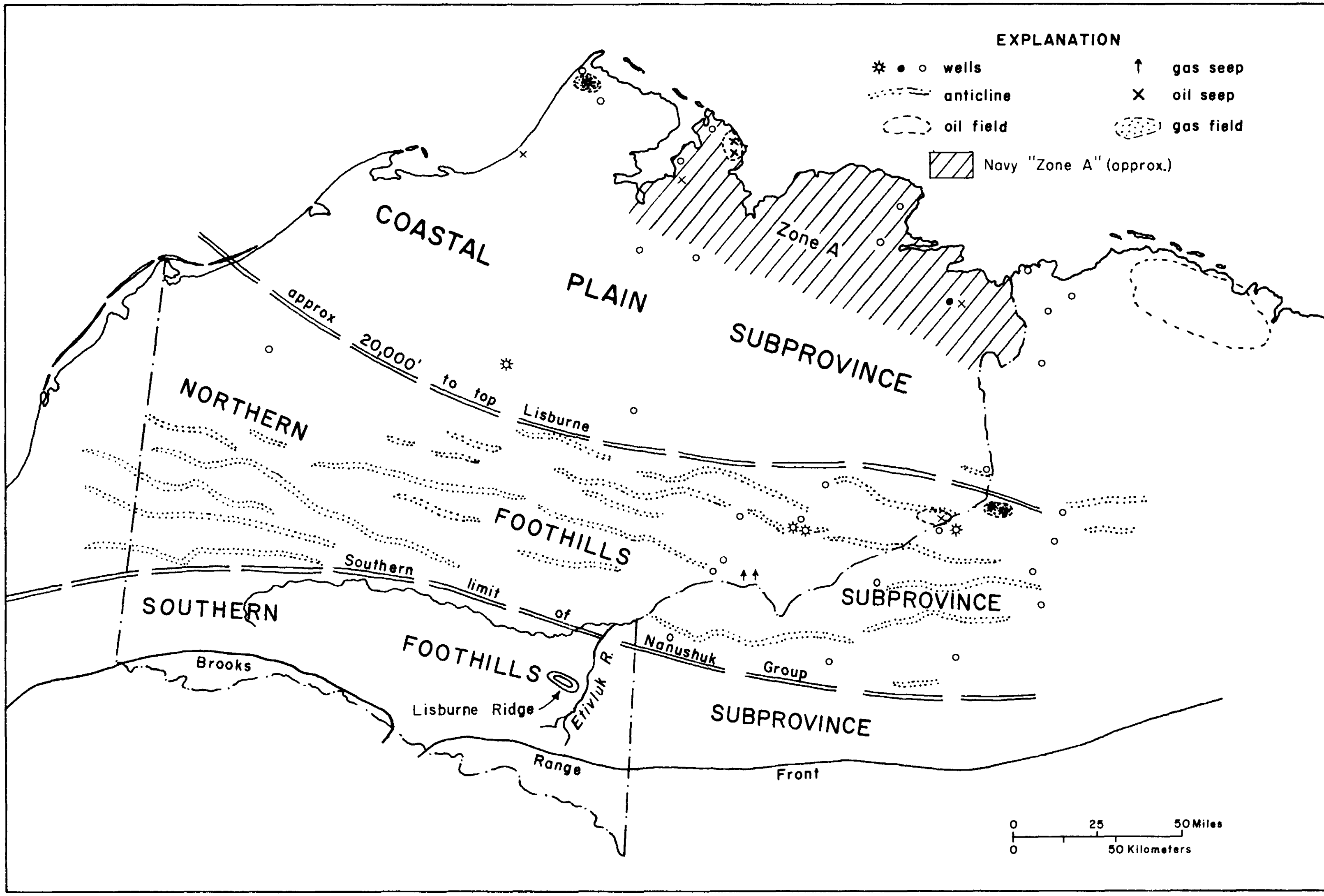


Figure 9. Exploration trends, NPR-4

entire area for oil and gas in shallow structural traps in the Middle Cretaceous Nanushuk Group and along the east edge of the Reserve in the Upper Cretaceous Colville Group. Stratigraphic traps in foreset sandstone bodies may also be present. Deeper objectives, primarily for gas, may be present in structural and foreset stratigraphic traps in the Lower Cretaceous Fortress Mountain and Okpikruak Formations. The southern edge of this trend is arbitrarily drawn along the southern limit of outcrop of the Nanushuk Group.

One of the major prospective hydrocarbon plays in the Coastal Plain and Northern Foothills subprovinces is the Nanushuk Group of Albian age. This group consists of a wedge of coarse clastic sediments prograding northward and eastward from the Brooks Range, which was its provenance. The unit ranges from marine shale at its base to nonmarine delta plain sediments with associated coals at the top. These sediments are present as a broad sheet over much of the northern Brooks Range foothills and southern coastal plain area.

The general stratigraphic relationships of the Nanushuk Group are analogous to the Mesa Verde Group of the Cretaceous of the Rocky Mountains. In terms of areal extent, this prospective unit covers by far the largest area of any of the plays in NPR-4. The complex intertonguing stratigraphic relationships of marine and nonmarine sediments, in combination with structural features may result in many potential traps. The abundance of coal in this wedge, and comparison with the similar Rocky Mountain Cretaceous section suggests that the play will be dominantly a gas play with small oil accumulations. This is somewhat substantiated by the numerous gas shows in many of the Navy wells in NPR-4. One of the main controlling factors in the play may be reservoir quality; although many of the sediments are medium- to coarse-grained sandstones, a pervasive clay matrix inhibits porosity and permeability. This clay probably consists of primary depositional material plus clays from diagenetic alteration of mafic igneous detritus derived from an extensive source terrain in the Brooks Range. As a result, one of the major problems in the Albian play will be prediction of porosity trends. One of the major controls on distribution of clay matrix and therefore porosity may be the environments of deposition. Winnowing of the clays may be much more efficient in some environments, whereas diagenetic alterations of igneous detritus may have a greater inhibiting effect in other environments. Only limited study has been devoted to these relationships in northern Alaska.

The southernmost trend, the Southern Foothills subprovince, is believed prospective for gas in complex structural traps. Possible objectives are carbonate reservoirs in the Mississippian (Lisburne Group) and Triassic (Shublik Formation) and sandstone reservoirs in the Cretaceous (Okpikruak, Fortress Mountain, and Ipewik Formations).

Possible hydrocarbon plays in the Southern Foothills should include those in allochthonous Mississippian carbonates. Estimated depths of more than 25,000 feet to the top of autochthonous Paleozoic rocks near the mountain front will probably preclude exploration of this deep section. Foothills plays of the type characteristic of the Canadian or Wyoming Rocky Mountains are found only in the area of the northeastern Brooks Range and are not likely to be found along the Brooks Range front in the area of NPR-4. In the allochthonous sections, clean quartzose sandstones of early Cretaceous age may also be a potential reservoir in part of the foothills, but the distribution of this facies is unknown. A possible play in Lower Cretaceous turbidites in association with organically rich Jurassic shales may also exist, but this play is also very speculative.

Industry experience in similar thrust belts elsewhere in the world suggests that total resources in such areas are likely to be much smaller than in less deformed areas of comparable size. Exploration is much more difficult; fields generally are small and likely to be gas rather than oil productive. In spite of these negative factors, a program of exploration is justified by the possibility of locating hydrocarbon accumulation and by the need for data to be added to the regional geologic framework.

One known prospect can be suggested currently, based upon information from surface mapping (Tailleur and others, 1966; Chapman and others, 1964), and on carbonate facies studies (Armstrong, 1970). The Lisburne Group in the area of Lisburne Ridge, near the Etivluk River at the southeastern corner of NPR-4 (fig. 9), contains approximately 500 feet of dolomite with observable intergranular and vugular porosity, some of which contains pyrobitumen. Although allochthonous, and tightly folded, the rocks dip northward into the basin. The possibility of a drilling objective to this allochthonous horizon should be studied by additional field work and seismic studies.

Hydrocarbon play analysis

Current experience on the Arctic Slope suggests that several types of plays should be considered in assessing the hydrocarbon potential of NPR-4. These plays are summarized in table 4 in approximate order of relative importance. It should be emphasized, however, that this relative ranking is somewhat subjective; one of the purposes of an evaluation program should be to provide data for a more accurate assessment of the relative potential of these plays. The list of play types is not intended to be all-inclusive; it includes only those play types and major controls that have been observed or can be inferred as likely to be present.

Evaluation of the tabulated play parameters (table 4) suggests that the likelihood of Prudhoe Bay type fields of wide areal extent in NPR-4 is slight. Several stacked reservoirs on a structure are not likely. Stratigraphic

Table 4. Petroleum geology and play analysis of NPR-4

PLAY TYPE	AGE OF RESERVOIR BEDS	AGE OF HYDROCARBON SOURCE BEDS	PROBABLE TYPE OF TRAP	RESERVOIR THICKNESS AND QUALITY	PROBABLE MAJOR TYPE OF HYDROCARBON	POSSIBLE AREAL EXTENT OF TRAP AND ACCUMULATION	REMARKS
Prudhoe Bay type, with unconformity juxtaposing reservoir and source beds.	Mississippian-Pennsylvanian carbonates	Cretaceous	Structural-stratigraphic (unconformity)	Thick, possibly up to 500', quality good but may be quite variable.	Oil and gas	Possibly large, and filled to spill point.	If present in NPR4, probably limited to small area near the coastline in northeastern NPR4. If present onshore, the truncation zone is probably mostly north of the northern onlap limit of Mississippian beds.
	Permian-Lower Triassic clastics	do	do	Thick, possibly up to 400', fair to excellent porosity	do	do	If present in NPR4, probably limited to small area near the coastline in northeastern NPR4. If present onshore, the truncation zone is probably mostly north of the northern onlap limit of Permian-Lower Triassic clastics. Where the horizon is present, it may have excellent reservoir characteristics as at Prudhoe Bay. However, the horizon is silica cemented in most areas: Prudhoe Bay is an exception.
	Upper Triassic sandstones and dirty carbonates	do	do	Thin, less than 50', probably very fine grained marine sandstone with good to excellent porosity and permeability, low rate of lateral facies change.	do	do	If present onshore in NPR4, probably limited to small area near the coastline in northeastern NPR4. If present onshore, the truncation zone is probably largely ~~north of~~ the northern onlap limit of Upper Triassic beds. Potential play in somewhat larger area than above plays.
	Jurassic to Lower Cretaceous sandstones from northern source	do	do	Thin, probably less than 100' net sandstone, probably good to excellent porosity and permeability.	do	do	If present in NPR4, probably limited to extreme northern coastal area from Barrow to Colville River.
	Summary of "Prudhoe Bay type" play in NPR4: Potentially the richest play, but conditions for development of this type of play are probably present only in one geographical area of NPR4, if at all. Potential for Jurassic-Lower Cretaceous sands truncated by overlying Cretaceous source beds is higher offshore in the Beaufort Sea.						
	Mississippian-Pennsylvanian carbonates	Indigenous	Stratigraphic and/or structural	Thick, possibly up to 500', quality may be good, but with rapid lateral facies changes	Gas	Traps could be either small or large, but unlikely to be filled to spill point	Possible play over a large area south of Barrow, limited on the south by depths of over 20,000'. Indigenous hydrocarbons probably quite overmature and limited to dry gas.

	Permian-Lower Triassic clastics	do	do	Thick, possibly up to 400', fair to excellent porosity and permeability	Gas	do	Possible play in a narrow east-west band south of Barrow. Indigenous hydrocarbons probably quite over-mature and limited to dry gas.
	Upper Triassic sandstones and dirty carbonates	do	Structural	Thin, less than 50', probably very fine grained sandstone with good to excellent porosity and permeability, low rate of lateral facies change	Gas	do	"
Conventional plays with approximately coeval age reservoirs and source beds	Jurassic and Lower Cretaceous sands from a northern source	do	do	Thin, probably less than 100' net sandstone with fair to good porosity and permeability, fair lateral facies continuity	Gas possibly oil	Traps could be either large or small, could be filled to spill point	Probably present in a broad band from the Barrow area to the Colville River. Indigenous hydrocarbons probably some what over-mature and somewhat gas prone, but with some oil. This play probably represents the most prospective oil play in NPR-4. Other oil plays have greater oil potential but are likely to be present in only a limited area.
	Lower Cretaceous (Albian) sandstones derived from a southern source (Nanushuk Group, Umiat type play)	do	Stratigraphic and/or structural	Thin, probably less than 150' net porous sandstone in any one prospect, with fair to good porosity and permeability; thick stratigraphic unit with numerous sandstones that could have local potential	Gas possibly oil	Probably small fields; if gas, possibly filled to spill point; if oil, probably not filled to spill point	Present over a wide geographic area of the entire central portion of NPR-4. Sands are part of a broad northward prograding coal-bearing clastic wedge. Dominantly a gas play because of the abundant associated coal. Some oil potential in lower portion of sandstone interval in zone of interfingering with underlying marine shales, and toward distal end of wedge where sands become marine. Total reserves may be large but likely to be in numerous small stratigraphically controlled fields. Largest play on NPR-4 in terms of total hydrocarbon potential, second to coastal plain Jurassic-Lower Cretaceous play in oil potential.

Table 4. con't.

PLAY TYPE	AGE OF RESERVOIR BEDS	AGE OF HYDROCARBON SOURCE BEDS	PROBABLE TYPE OF TRAP	RESERVOIR THICKNESS AND QUALITY	PROBABLE MAJOR TYPE OF HYDROCARBON	POSSIBLE AREAL EXTENT OF TRAP AND ACCUMULATION	REMARKS
Conventional plays with approximately coeval age reservoirs and source beds	Upper Cretaceous (Colville Group, Gubik gas field type of play)	Indigenous	Structural	Thin, probably less than 100' net porous sandstone in any one prospect	Gas or oil	Traps probably small, possibly filled to spill point	Possibly present in a narrow roughly north-south trending belt roughly parallel the Colville River from the Gubik area north to the coast. Best reservoir potential in southern part of trend.
	Upper Cretaceous	do	Stratigraphic	Thin, probably less than 50', probably dirty and tight, rapid lateral facies changes, probably poor porosity and permeability	Oil	Small traps, probably filled to spill point	Possibly present in a narrow belt adjacent to present coastline. Sands associated with extremely rich organic shales, but potential limited by the thin discontinuous nature of the sands, which likely will be dirty and tight.
	Mississippian carbonates and possibly clastics; Triassic carbonates	Indigenous or Lower Cretaceous	Structural	Thick, possibly up to 500', possibly good carbonate porosity, fracture permeability	Gas	Probably small fields, possibly not filled to spill point	Plays in allochthonous sheets in an extremely complex structural zone. Very difficult exploration; reflection seismic data difficult to obtain and interpret; exploration will require close integration of surface geology, gravity surveys, refraction seismic surveys, and subsurface data when available. Highly organic and phosphatic beds in Mississippian may be a fair hydrocarbon source although likely to be over-mature and dominantly a gas play. Prospective play limited by outcrop belt on south; depths of over 20,000 feet to penetrate horizon on the north.
Foothills thrust belt	Lower Cretaceous quartzose sandstones	Indigenous	Structural	Thin, probably less than 50', silica cement, generally tight, with only fair porosity and permeability at best	Gas	If present, probably small fields, possibly filled to spill point	A very tenuous play; subsurface extent and origin of sandstones is unknown. Associated organic shales may have been oil source, but now probably over-mature due to dynamic eometamorphism.
	Lower Cretaceous greywacke sandstones	Indigenous or Jurassic	Structural	Thick, possibly 1,000' or more. Low porosity and permeability due to abundant clay and soft rock fragments	Gas	Probably small fields, possibly filled to spill point	A speculative play in allochthonous and autochthonous sheets in southern foothills. Indigenous source rocks may be very poor but underlying Jurassic shales are locally extremely rich oil shales. These shales are probably over-mature and hence a gas source. Very difficult exploration for reasons listed above, but prospective over a wider area than above because of both autochthonous and allochthonous objectives.

controls are likely to play a major role in any hydrocarbon accumulation. Present knowledge of the potential reservoir horizons suggest that facies variations may occur rapidly. Fields may be of small areal extent and exploration will require detailed seismic facies interpretations closely integrated with micropaleontologic studies, and with geologic studies that include the latest concepts of clastic and carbonate deposition and their control on reservoir porosity and permeability.

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