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PETROLEUM EXPLORATION OF THE NORTH SLOPE IN ALASKA, U.S.A.

By

Kenneth J. Bird

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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PETROLEUM EXPLORATION OF THE NORTH SLOPE IN ALASKA, U.S.A.

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Abstract

Petroleum exploration on the North Slope in Alaska has been conducted intermittently for 40 of the last 60 years. The role of Government in these ventures is unique in U.S. petroleum exploration history. Exploration activity has been strongly influenced by the world political situation and exploration activity in other parts of Alaska, as well as by Government regulations. An outline of this history shows nearly equal time spent by industry and Government in exploration, which may be considered in three phases: (1) early Government exploration, 1923-53; (2) industry exploration, 1958-78; and (3) recent Government exploration, 1974-78.

Early Government exploration (1923-53) was a pioneering undertaking for Arctic region operations and established the geologic framework of the basin. Exploration involved Naval Petroleum Reserve No. 4 (NPR-4), about one-half of the North Slope area. Activity was recessed in 1953 after the discovery of three oil and five gas accumulations, all subeconomic.

Industry exploration dates from 1958 and has largely been restricted to the central third of the region. This effort, which remains indebted to the early Government work, is responsible for the discovery of five gas fields and five oil fields, including the largest accumulation in North America--the Prudhoe Bay field.

Recent Government investigations of the National Petroleum Reserve in Alaska (NPRA) (1974-78) constitute an assessment program emphasizing land-use decisions. This continuing program has resulted in the discovery of one small

gas field and several promising shows of oil and gas that may lead to significant future discoveries. Resource estimates by a novel "play" approach suggest that substantial undiscovered resources are also present. In conclusion, because the basin is only lightly explored, much remains to be done in evaluating its petroleum resource potential.

INTRODUCTION

Intermittent petroleum exploration of the North Slope in Alaska can be documented for 40 of the last 60 years, and the role of Government in these efforts makes this region unique. Nearly equal amounts of time have been spent in North Slope exploration by Government and by private industry. A tabulation of this history suggests that the interval from initial exploration to first commercial discovery has been lengthened because of the remoteness of the region, its harsh arctic climate, and, in later years, by Government policies.

About one-half of the prospective area of the North Slope was secured by the U.S. Government in 1923, under the jurisdiction of the Navy, as Naval Petroleum Reserve No. 4 (NPR-4). Exploration was conducted here for four consecutive seasons by geologic-topographic parties from the U.S. Geological Survey. Between 1926 and 1943, no further exploration of this area or of adjacent areas was undertaken either by Government or by private industry.

During World War II (1944), the U.S. Government showed renewed interest in petroleum exploration of the North Slope. The ensuing 10 year program, concentrated in NPR-4, resulted in the discovery of several subcommercial oil and gas accumulations. A second hiatus in exploration was between 1954 and 1958.

When, in 1958, the Government lifted a "land freeze" and offered acreage for lease, this announcement marked the beginning of 21 years of exploration by private industry on the North Slope--exploration distinguished by the discovery of the Prudhoe Bay field. For most of these 21 years, industry exploration has been restricted to the central third of the region, although additional acreage has lately been made available through a native corporation and an offshore joint State-Federal lease sale.

The Government recommenced exploration of NPR-4 in 1974, during the Arab Oil Embargo, and in 1977 the Naval Petroleum Reserve Production Act transferred jurisdiction of this program from the Department of the Navy to the Department of the Interior (Geological Survey); at the same time NPR-4 was redesignated the National Petroleum Reserve in Alaska (NPRA). Now in its seventh year, this Government effort has resulted in the discovery of one small gas field (East Barrow) and several promising shows of oil and gas that may lead to significant future discoveries. Resource estimates based on the latest information also suggest that substantial undiscovered resources are present in the North Slope area.

GEOLOGIC SETTING

Introduction

Viewed from a polar perspective, the North Slope of Alaska is one of several petroleum-bearing areas bordering the Arctic Ocean (fig. 1). The North Slope, which encompasses all the land north of the Brooks Range drainage divide, is generally subdivided into three physiographic provinces, from south to north: the Brooks Range, the Foothills (generally subdivided into Northern and Southern Foothills), and the Coastal Plain (fig. 2). Trending in a subparallel easterly direction, these provinces reflect underlying geologic trends. The North Slope is composed of three main structural elements: the Brooks Range orogen, the Colville trough, and the Barrow arch, which correspond generally to the respective physiographic provinces (fig. 3).

The Barrow arch is a broad regional basement high that separates the Colville trough from the present Arctic Ocean basin. The basement, at relatively shallow depths along the Barrow arch, slopes gently southward into the Colville trough, where it reaches a depth of about 10,000 m. The southern

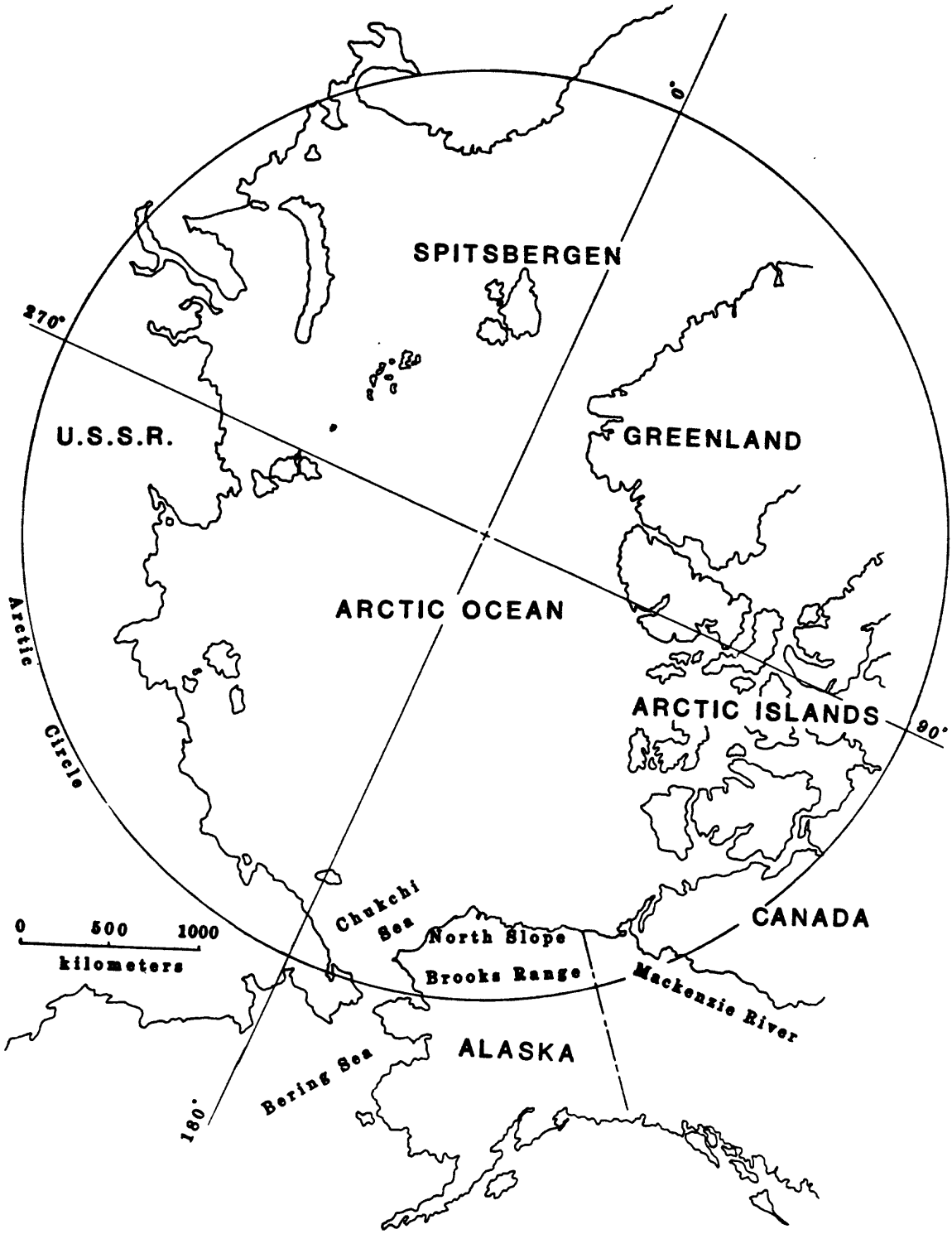

Figure 1.--Location of North Slope in relation to other circum-Arctic lands. Other petroleum-bearing areas include Arctic U.S.S.R., Mackenzie Delta, and Canadian Arctic Islands.

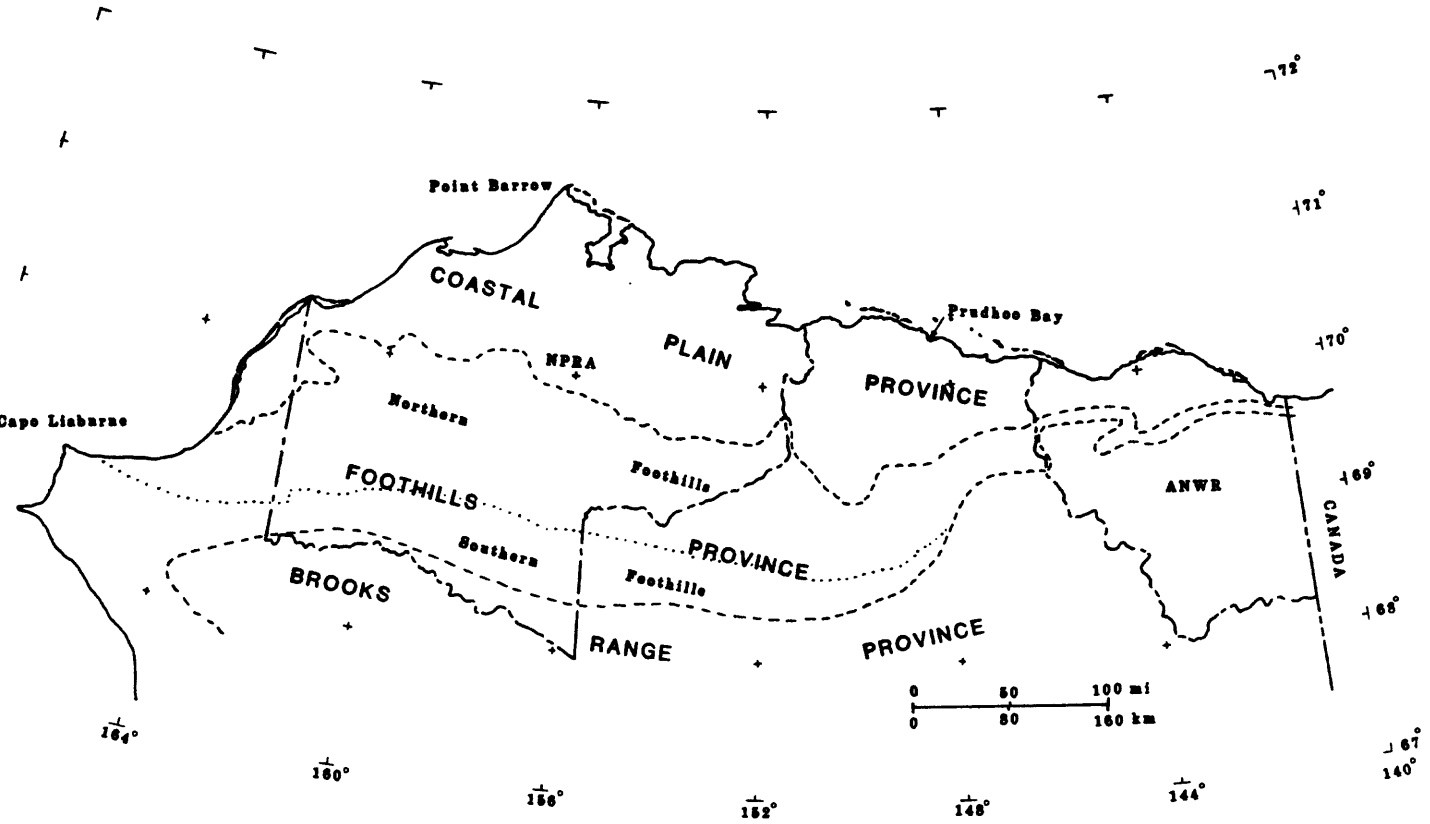

Figure 2.--Physiographic provinces of North Slope, showing locations of National Petroleum Reserve in Alaska (NPRA) (formerly Naval Petroleum Reserve No. 4 [NPR-4]) and Arctic National Wildlife Range (ANWR).

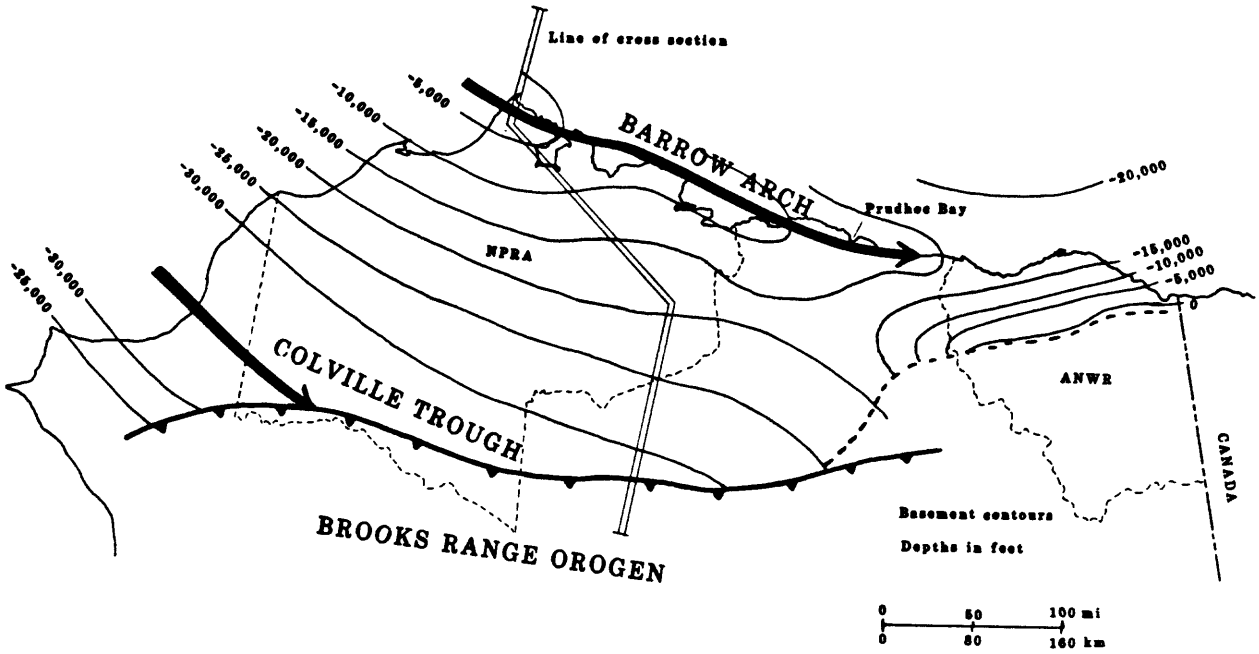

Figure 3.--Major tectonic features of North Slope in Alaska.

part of the trough is overridden by the Brooks Range orogen, which contains basement and younger rocks. These structural relations are diagrammatically illustrated in a cross section trending north through Point Barrow (fig. 4). Other published cross sections include those in the reports by Morgridge and Smith (1972) (Prudhoe Bay area), Roeder and Mull (1978) (central Brooks Range), and Grantz and others (1979) (Chukchi Sea shelf and Arctic National Wildlife Range area).

Much new information on the stratigraphy and petroleum geology of the North Slope has been published since the summary by Brosge and Tailleur (1971). This new information includes publications on the NPRA by Carter and others (1977), Bird (1978), Bird and others (1978), Ahlbrandt (1979) and Magoon and Claypool (1979); on the Prudhoe Bay area by the Alaska Geological Society (1971, 1972, 1977), Morgridge and Smith (1972), Jones and Speers (1976), Bird and Jordan (1977), and the U.S. Geological Survey (1978); and on the Arctic National Wildlife Range (ANWR) area by Reiser and others (1971, 1978), Armstrong and Mamet (1975), Detterman and others (1975), Sable (1977), Grantz and Mull (1978), Kososki and others (1978), and Palmer and others (1979). The tectonic setting of the North Slope in relation to adjacent offshore areas has been summarized most recently by Grantz and others (1979).

The bedded rocks of the North Slope can be conveniently grouped into three sequences that reflect major episodes in the tectonic development of the region and, to a degree, its lithologic character. Defined on the basis of source area, these sequences, proposed by Lerand (1973) and applied to northern Alaska by Grantz and others (1975), are, in ascending order: (1) the Franklinian (Cambrian through Devonian), (2) the Ellesmerian (Mississippian through Jurassic), and (3) the Brookian (Cretaceous to Holocene). The areal distribution of these sequences and significant structural trends on the North

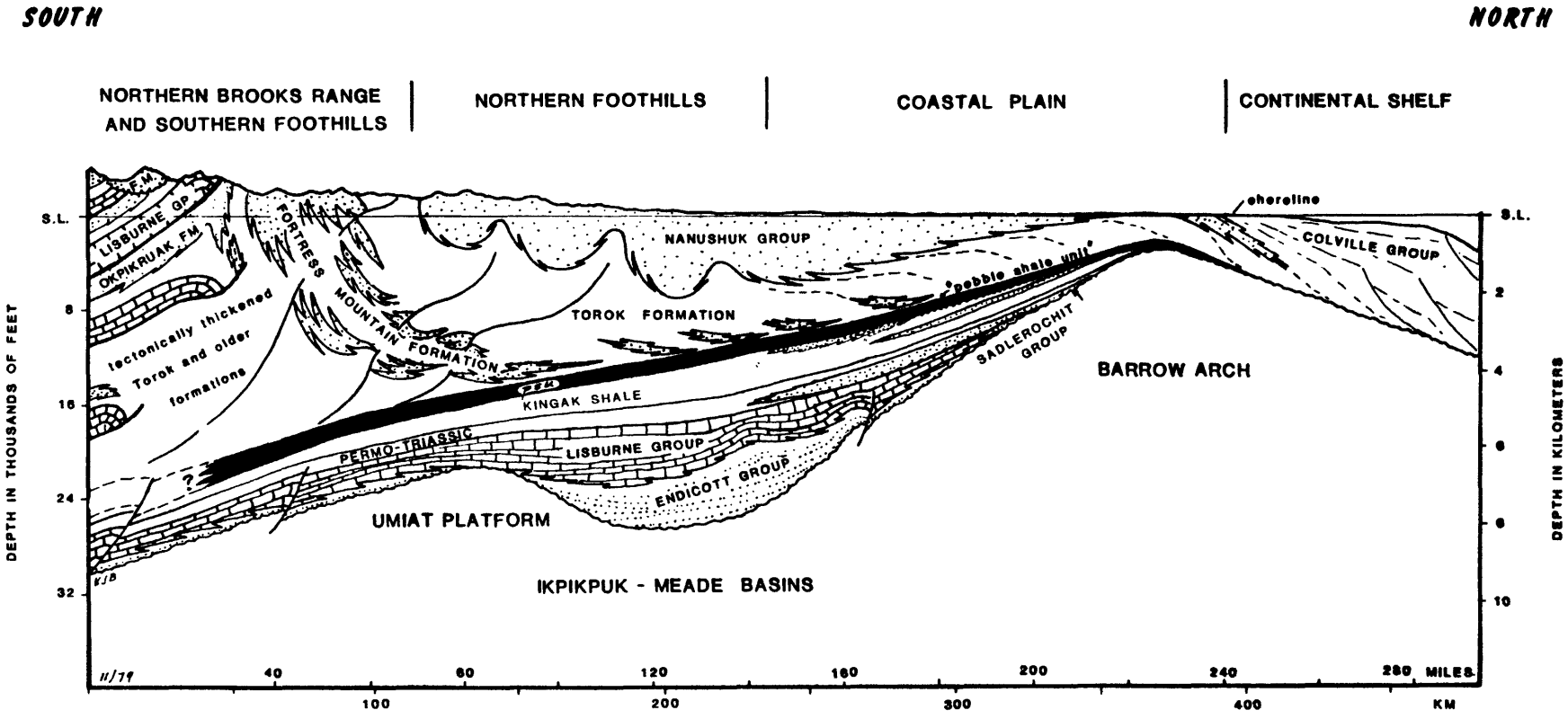

Figure 4.--Diagrammatic cross section in NPRA; see figure 3 for location.

Slope are shown on the map in figure 5; figures 6 and 7 summarize these sequences and their component formations.

Franklinian Sequence

The Franklinian (pre-Mississppian) sequence is generally considered nonprospective for petroleum. This sequence is best known in the northeastern Brooks Range, where it consists of a variety of deformed and mildly metamorphosed clastic and carbonate geosynclinal rocks (Reiser and others, 1971, 1978). Most wells into this sequence have penetrated argillite. Ordovician and Silurian graptolites and chitinozoans have been recovered from this argillite at Point Barrow and Prudhoe Bay (Carter and Laufeld, 1975). Late Devonian orogenic uplift in what is now northern Alaska shed large amounts of clastic debris southward. Thick clastic wedges, composed mainly of quartz and chert (the Kanayut Conglomerate and its marine equivalent, the Hunt Fork Shale), are presently in the Brooks Range. Subsequent erosion and subsidence of the Devonian orogen provided a platform for deposition of the Ellesmerian sequence.

Ellesmerian Sequence

The Ellesmerian (Mississippian through Jurassic) sequence records a major northward advance of the sea. The sequence consists of shallow-marine and nonmarine clastic rocks, composed predominantly of quartz and chert, and of platform carbonate rocks. Such features in the rocks as northward onlap, increasing grain size, decreasing stratigraphic thickness, and numerous unconformities suggest that the ancient shoreline lay near the present coast and that the open ocean was to the south. Periods of mild tectonic activity and local volcanism are represented in the lower part of the sequence (Reiser and others, 1979). Differential subsidence accompanied by faulting created local basins (for example, the Ikpikpuk-Meade basins, fig. 4) containing as much as

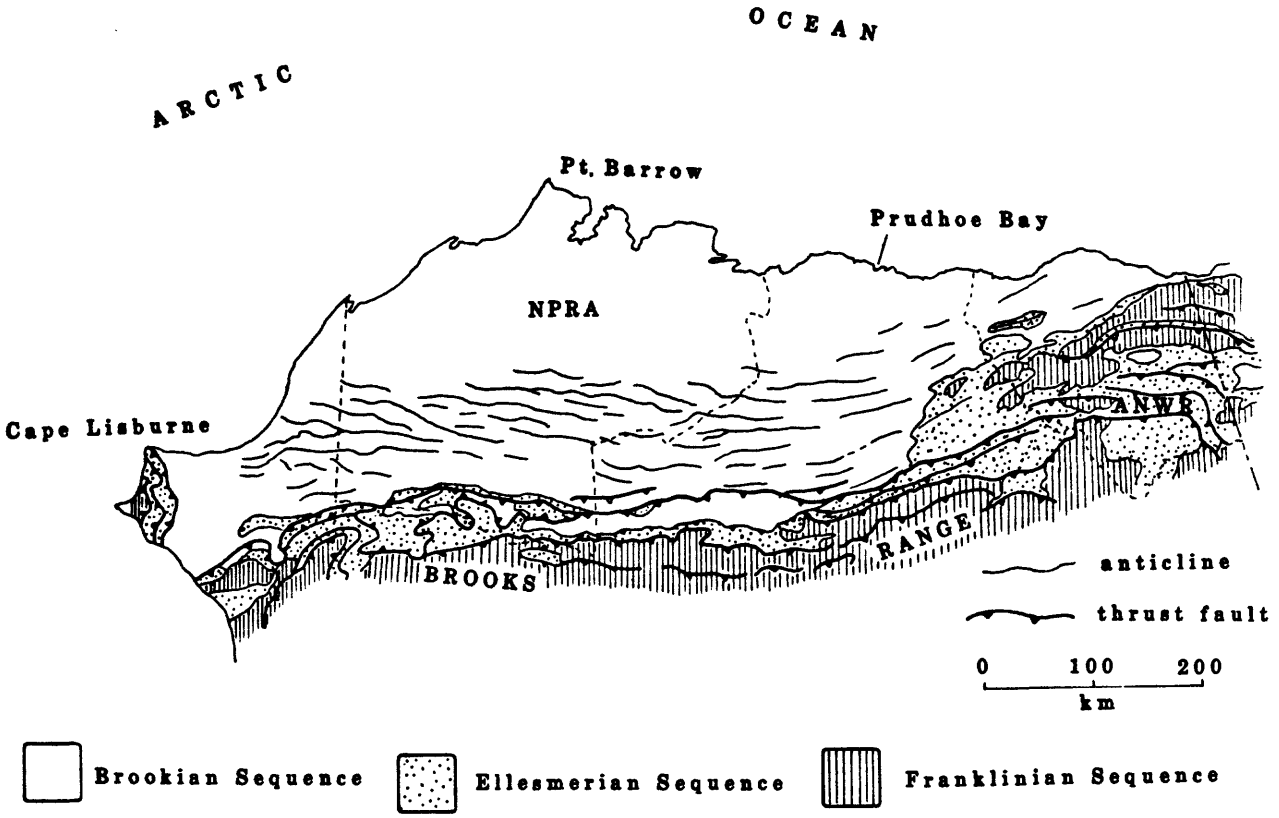

Figure 5.--Generalized geologic map of North Slope, showing distribution of major rock sequences, thrust faults, and anticlines.

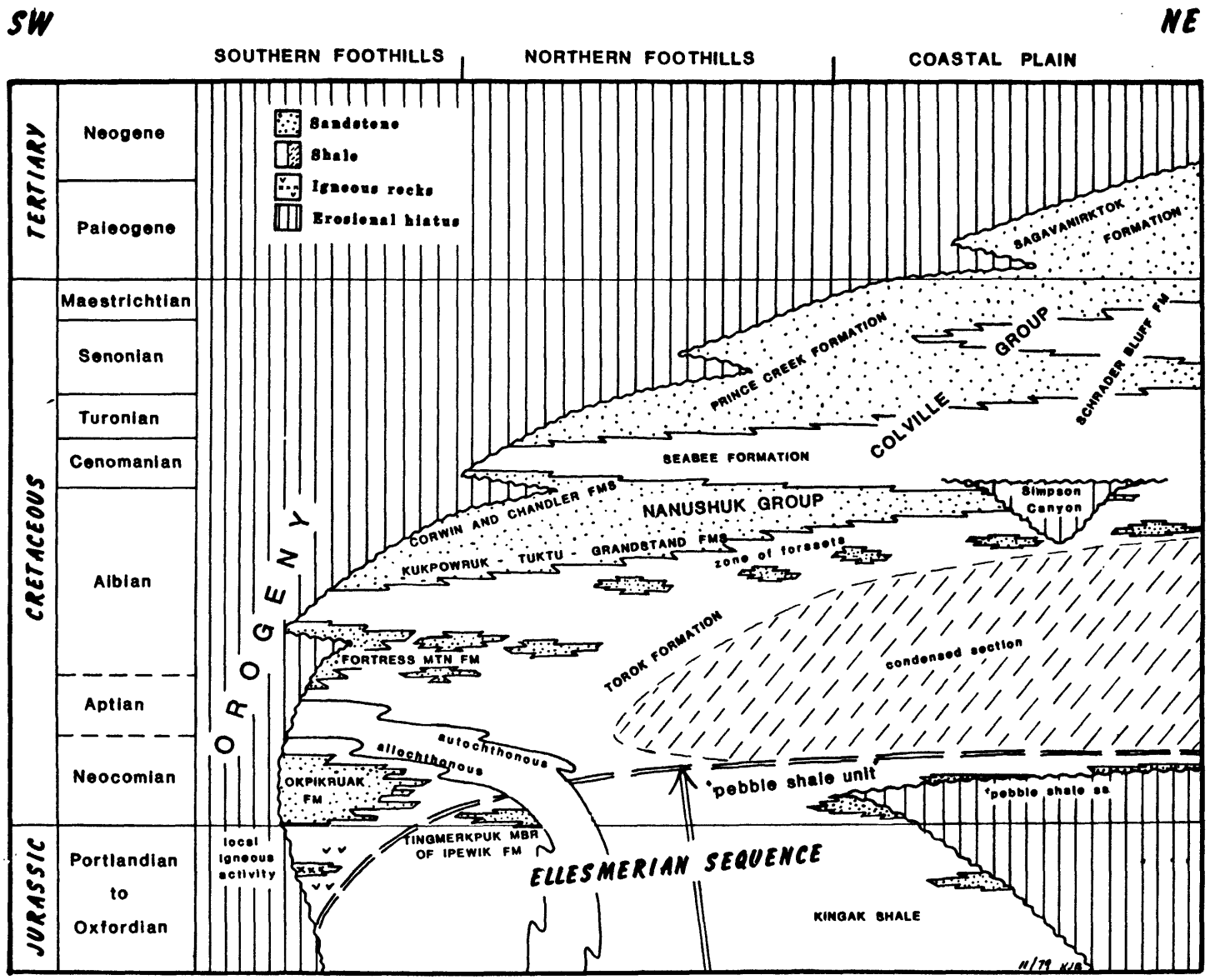

Figure 6.--Time-stratigraphic diagram of Brookian sequence of North Slope in Alaska.

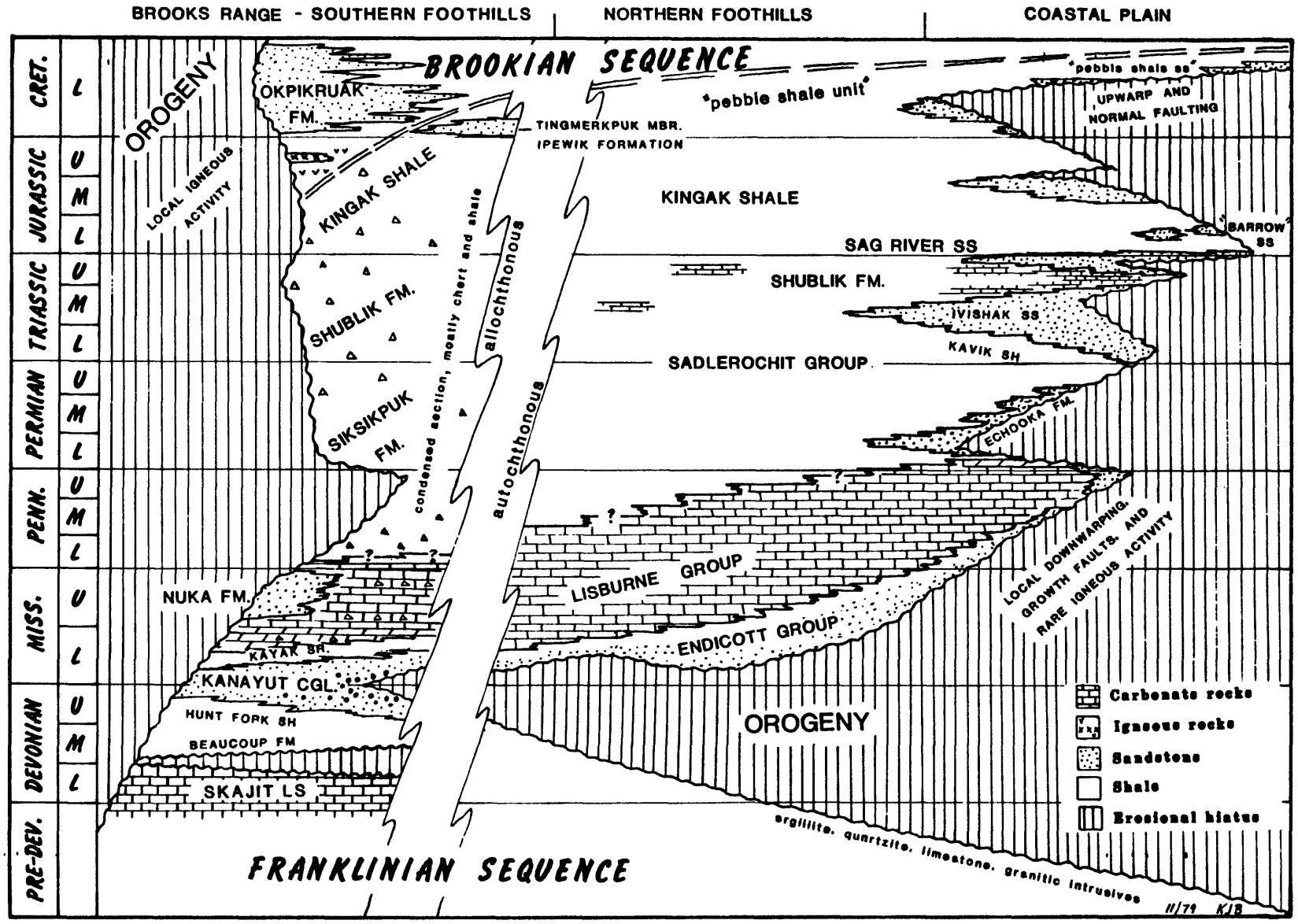

Figure 7.--Time-stratigraphic diagram of Ellesmerian sequence of North Slope in Alaska.

5000 m of Carboniferous and Permian rocks. By Triassic time most deformation ended and consequent local variations in sedimentary thickness were eliminated.

Mississippian clastic rocks and coal of the Endicott Group unconformably overlie steeply dipping mildly metamorphosed basement rocks of the Franklinian sequence. The clastic rocks grade upward and laterally into shallow-marine carbonate rocks of Carboniferous and Permian age (the Lisburne Group). Southward retreat of the sea during Permian time terminated carbonate deposition and created a regional unconformity that truncates older sedimentary deposits in the north. After the northward readvance of the sea, clastic sedimentation predominated. Important sandstone reservoir rocks were deposited during the Permian and Triassic (the Sadlerochit Group), Late Triassic (the Sag River Sandstone), Middle Jurassic (unnamed sandstone), and Late Jurassic - Early Cretaceous (the Kuparuk River Sandstone). All sandstone units are of limited areal extent and grade southward (downdip) into siltstone and shale that are potential source rocks. Important petroleum-source-quality shale was deposited during transgressions in the Late Triassic (the Shublik Formation), Jurassic (the Kingak Shale) and Early Cretaceous (pebble shale unit).

The following differences in the Ellesmerian sequence on the Barrow arch between the NPRA and the Prudhoe Bay area are noteworthy. In the NPRA the Ellesmerian sequence displays successively northward onlapping rock units. In contrast, at Prudhoe Bay and eastward, very little onlap is evident; instead, the entire sequence is truncated and overlapped by Cretaceous marine shale. This truncation, by Late Jurassic-Early Cretaceous subaerial erosion, is postulated to have improved the porosity of exposed Ellesmerian reservoir rocks by leaching (van de Kamp, unpublished data 1979). Overlap of the truncated sequence by Cretaceous seas juxtaposed potential (Cretaceous) source rocks and

reservoir rocks. This relation of rich Cretaceous source to porosity-enhanced reservoir occurs only locally and on a small scale in the NPRA.

In the Brooks Range, the Ellesmerian sequence consists of a variety of rock types juxtaposed by faulting that include Mississippian shallow-marine clastic rocks (the Endicott Group and the Nuka Formation) and shallow- to deep-marine carbonate rocks (the Lisburne Group). The Pennsylvanian through Jurassic rocks consist primarily of siliceous shale, chert, and minor amounts of limestone. Oil shale is known locally from Mississippian, Triassic, and Jurassic rocks (Tailleur, 1964). Intrusive and extrusive basic igneous rocks are known from the Mississippian, Permian, and Jurassic periods (Ellersieck and others, 1979; Reiser and others, 1979).

Brookian Sequence

The Brooks Range orogeny drastically changed the paleogeography of Arctic Alaska. Northern sources were replaced by southern sources--the ancestral Brooks Range. Initially, however, sediment was supplied from both northern (Ellesmerian) and southern (Brookian) sources. As the Brooks Range was uplifted, regional subsidence immediately to the north formed the Colville trough. Subsidence of the northern land area was accomplished by northward downwarping and by normal faulting concentrated along a linear zone approximately parallel to the present shoreline. The resulting structure, the Barrow arch, is a linear basement ridge plunging to the southeast. Numerous oil and gas fields, including the Prudhoe Bay field, are situated along the crest of this feature. Recently, Grantz and others (1979) postulated that the Barrow arch is but one of three segments of contrasting structure and stratigraphy that make up the continental margin north of Alaska.

Present-day landforms and most structures on the North Slope are related to the Brooks Range orogeny. The driving force for that widespread and long-

lasting period of deformation is considered by many investigators to be rifting and rotation of northern Alaska away from the continental margin of northern Canada. A recent comprehensive review of this hypothesis and its supporting data was presented by Grantz and others (1979). Deformation in much of the Brooks Range is characterized by east-trending low-angle northward-yielding thrust faults. Aggregate shortening by 100 to 500 km is postulated for those faults in the western part of the range (Snelson and Tailleur, 1968; Tailleur, 1969; Martin, 1970). In the northeastern part of the range, however, deformation is characterized more by vertical uplift--folding and high-angle reverse faulting. In the Southern Foothills, immediately north of the Brooks Range, structural style resembles that of the range itself; deformation diminishes northward in a series of linear detachment folds (fig. 5).

Throughout the orogeny, large volumes of clastic debris were shed from the rising Brooks Range northward (and probably southward as well) into a foredeep. Older uplifted sedimentary rocks to the southwest and younger deeply buried sedimentary deposits to the northeast indicate that the orogen and foredeep migrated northeastward. The oldest Brookian orogenic deposit (Neocomian) is a flyschlike sequence of turbidites (the Okpikruak Formation) exposed in the Brooks Range and Southern Foothills. To the north, in the subsurface, its equivalent is the pebble shale unit, rich in organic material. This black marine shale, part of northern derivation, forms part of a sequence of Cretaceous shale units postulated to be a major source for Prudhoe Bay petroleum (Morgridge and Smith, 1972).

Throughout the remainder of Cretaceous and Tertiary time, periodic influxes of coarse terrigenous debris accumulated in thick clastic wedges in the Colville trough. Prominent among these deposits are the Early Cretaceous Fortress Mountain Formation, the middle Cretaceous Nanushuk Group, the Late

Cretaceous Colville Group, and the Tertiary Sagavanirktok Formation (fig. 7). Periods of relative basin subsidence separated these wedges by thick marine shale sections; the depocenter of each wedge is successively farther northeast. The middle Cretaceous depocenter is southwest of the NPRA, whereas Late Cretaceous and Tertiary depocenters lie near Prudhoe Bay and partly offshore. Most oil and gas fields in the NPRA and several of the latest discoveries east of Prudhoe Bay are in Brookian rocks.

Certain generalizations that can be made about drilling objectives (age of reservoir and type of trap) in each physiographic province are summarized in table 1. By using this tabulation, some insight can be gained into drilling objectives merely by knowing the general location of the well.

EXPLORATION HISTORY

Introduction

The territory of Alaska became an American possession in 1867, when it was purchased from Russia for a total of $7.2 million. The North Slope of Alaska was first viewed by Captain James Cook sailing for Britain in 1778, and the first geologic traverse of this area was by Frank Charles Schrader in 1901. The history of petroleum exploration on the North Slope certainly dates back to earliest times, to include the common place search by native Alaskans for oil seeps and oil shale to use as fuel. In 1921, A. M. Smith guided the Adams Expedition, sent out in the interests of a group of California bankers to stake claims on the oil seepages near Cape Simpson (Collins and Robinson, 1967, p. 171). For purposes of discussion here, however, the beginning of petroleum exploration on the North Slope is identified as 1923, when Naval Petroleum Reserve No. 4 (NPR-4) came into existence and the U.S. Geological Survey was invited by the Navy to examine the area and report their findings.

Table 1.-Drilling objectives by physiographic province, Alaskan North Slope

PROVINCE	TRAP TYPE		RESERVOIR UNIT	
	STRUCTURAL	STRATIGRAPHIC	CARBONATE	CLASTIC
Coastal Plain	Broad anticlines Normal faults	Onlap Updip pinchout Truncation	Shublik Fm. Lisburne Gp.	Sagavanirktok Fm. Colville Gp. Nanushuk Gp. Kuparuk River Ss Unnamed Jurassic ss Sag River Ss Sadlerochit Gp. Endicott Gp.
Northern Foothills	Faulted anticlines	Updip pinchout	Shublik Fm. Lisburne Gp.	Colville Gp. Nanushuk Gp. Fortress Mountain Fm. Kuparuk River equivalents Endicott Gp.
Southern Foothills and Brooks Range	Faulted anticlines	---	Shublik Fm. Lisburne Gp. Skajit Fm.	Fortress Mountain Fm. Okpikruak Fm. Nuka Fm. Endicott Gp. Fractured siliceous shale

Exploration history was previously reported by Reed (1958) and Gryc (1970), who emphasized the Government role in exploration, and by Jamison (1978), who detailed industry efforts.

This report updates the exploration history of the region since the discovery of the Prudhoe Bay field and attempts to quantify and compare the exploratory efforts and outcome for both Government and industry. Exploratory activities (geology, geophysics, and drilling) in the onshore North Slope area during the last 60 years are displayed graphically in figure 8; information is current through 1978, the date of the latest complete statistics. Data are not uniformly available for specific field activities--for example, line-miles of seismic surveys--and the only consistently reported unit of measure is the crew-month, a term of limited value because it reflects neither crew size nor variability of crew efficiency over the years. Figure 8 plots data on three phases of exploration history: (1) Government exploration, 1923-53; (2) industry exploration, 1958-78; and (3) Government exploration, 1974-78. The following sections discuss these phases individually.

Government Exploration (1923-53)

Early Government exploration on the North Slope was motivated by concern for national security. World War I had demonstrated that the U.S. Navy would require enormous quantities of petroleum products. For a few years after World War I the United States, normally a leading world exporter of petroleum, was a net importer of oil. The Government was concerned over oil supplies: "The U.S. position can best be described as precarious," stated the Director of the Geological Survey in 1920. "The best technical authorities seem to believe that the peak of petroleum production in the United States will soon be reached," wrote the Secretary of State in 1919 (Stobaugh and Yergin, 1979, p. 19). Against this background, NPR-4 (see fig. 2) was established by

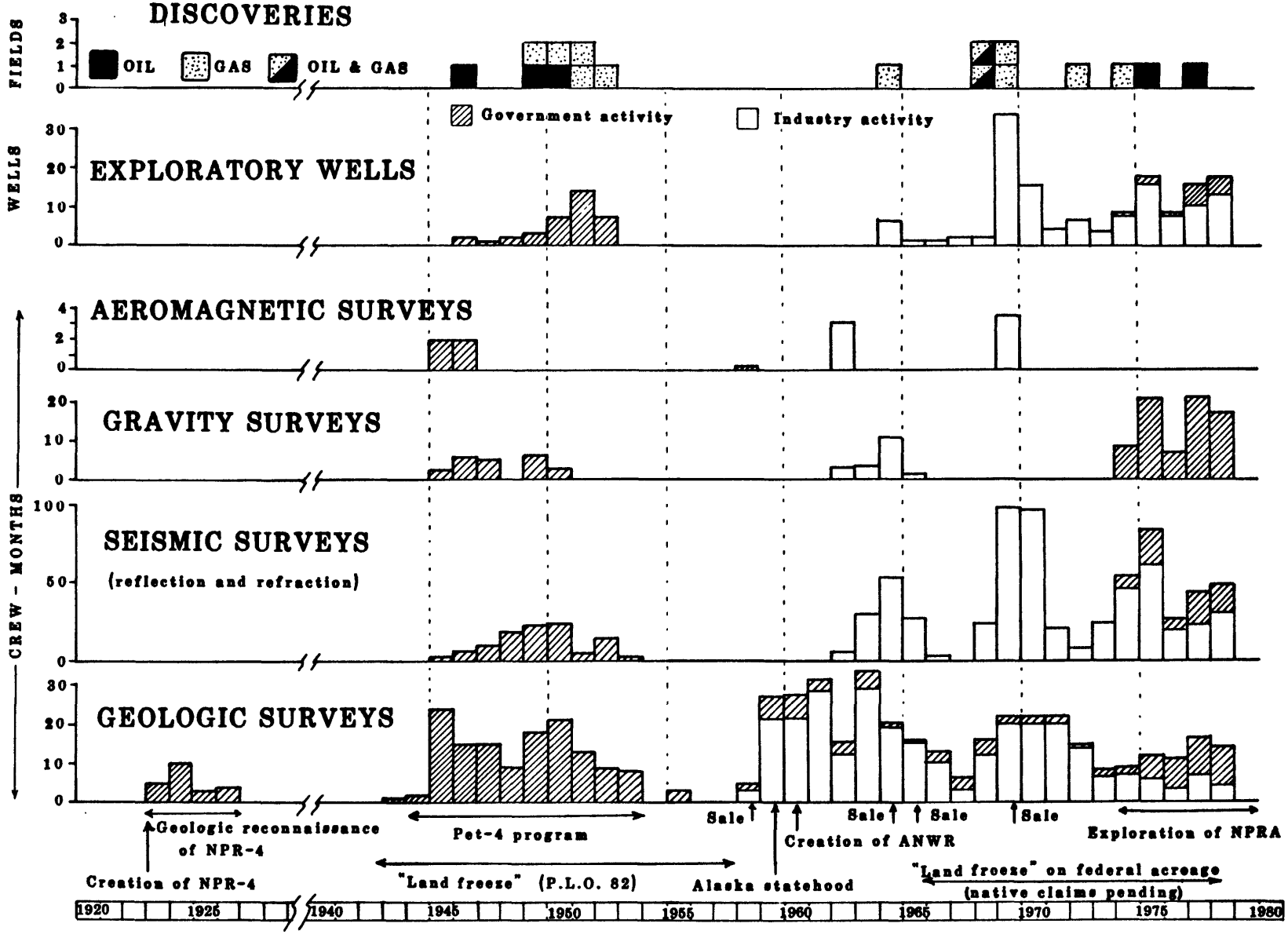

Figure 8.--Summary of petroleum exploration elements on North Slope in Alaska. See figure 9 and table 2 for additional information.

Executive order in 1923 to insure an adequate supply of petroleum for the Navy.

The area designated NPR-4 was selected because of known oil seeps in the coastal area and because geologic field parties had traversed this area, but little was known of the area east of the Colville River. The Geological Survey, invited by the Navy to investigate and report on this area, began field studies in 1923 that were continued through 1926.

For the 1923 Geological Survey field parties, transportation to the field was a formidable problem: reaching the North Slope by ship in midsummer with half the field season gone was unproductive. During the next three years, investigators endured unheard-of rigors just to reach the area; they departed from the end of the railroad in interior Alaska during midwinter and traveled with all necessary gear by dogsled nearly 1600 km. By spring breakup they reached the field area, and transportation in the field was on foot or by small boat; the return trip was generally by ship. The compilation of crew-months of geologic work on the graphs in figure 8 includes only the time spent by each crew on the North Slope, not the travel time to and from the field. Therefore, these data reflect an unfair diminishment of the intrepid efforts of these first field parties.

Smith and Mertie (1930) summarized these earliest field studies, which demonstrated that anticlines apparently favorable for the accumulation of petroleum were numerous and fairly widespread, and that one likely petroleum source was oil shale believed to occur near the base of the Lower Cretaceous. By 1926, however, crude-oil production was nearly double what it had been in 1920, and during the period 1920-26 oil was being discovered at the rate of one and one-half barrels for every barrel consumed (Williamson and others, 1959, p. 304). Not surprisingly, no further exploration was conducted between 1926 and 1943.

The unprecedented use of petroleum during World War II, and a general tightening of supplies, prompted a renewal of interest in Alaska's petroleum potential. In 1943, Public Land Order 82 withdrew from public entry all generally recognized possibly petroliferous parts of Alaska, including all of the North Slope. In the same year, the Bureau of Mines sponsored a field investigation of all known and rumored petroleum seeps on the North Slope. This investigation was reported by Ebbley (1944), who described multiple seeps in six localities, mainly in the coastal area from Simpson Peninsula to near the U.S.-Canadian border. The most inland point examined was a seepage of oil and gas near Umiat--a "leak" from what was later determined to be the Umiat field.

In 1944 the Navy initiated the Pet-4 program to "assess the petroleum potential of the Reserve". This program was a full-scale exploration, a pioneering effort in the Arctic region that utilized all the then currently available petroleum exploration techniques and introduced new ones. The history of this program was detailed by Reed (1958). Although exploration was concentrated in NPR-4, it was not restricted to its boundaries. Extensive and far-ranging geologic investigations, conducted by the Geological Survey, included geologic mapping, detailed studies of well data, paleontologic and lithologic studies, and, finally, the integration of these results with geophysical data. Gravity coverage of the region was extensive; reflection and refraction seismic surveys were undertaken, and aeromagnetic surveys, the first ever, were conducted.

A total of 36 test wells and 45 core tests were drilled on the North Slope. Core tests are herein distinguished from test wells on the basis of the type of drilling rig used: core tests were drilled with shallow-capacity rigs. NPR-4 core tests have not generally been included in compilations of

exploratory wells and therefore are not included on the graphs in figure 8--even though the Simpson field was "discovered" by a core test. Most core tests were shallower than 450 m and were drilled in the Simpson and Barrow areas.

Most of the 36 test wells evaluated mid-Cretaceous objectives in anticlines in the Northern Foothills: 26 wells tested 10 structures. Pre-Cretaceous (Ellesmerian) objectives were tested by seven wells in the Coastal Plain province; five of these wells were at Barrow. Three wells in the Coastal Plain province also tested Cretaceous (Brookian) objectives. The program was terminated before any pre-Cretaceous objectives could be drilled in the Southern Foothills.

The Pet-4 program yielded a wealth of information on the regional geologic framework and the tectonic history of the entire North Slope. Consequent discoveries were three oil fields (Umiat, Simpson, and Fish Creek) and five gas fields (Gubik, Square Lake, Meade, Wolf Creek, and South Barrow) (fig. 9, table 2). All these discoveries were uneconomic, although it is noteworthy that because of increasing world petroleum prices and the proximity of the Trans-Alaska Pipeline, the largest oil accumulation (Umiat) and the largest gas field (Gubik) currently may be nearing commercial status.

The Pet-4 program was terminated by Congress in 1953; regional geologic studies by the Geological Survey continued but were not petroleum specific. Although NPR-4 was accessible to geologic studies by industry during subsequent years, there was little incentive for exploration because land acquisition and drilling were not allowed.

Industry Exploration (1958-78)

After the termination of the Pet-4 program in 1953, the "land freeze" under Public Land Order 82 remained in effect for the North Slope, and there

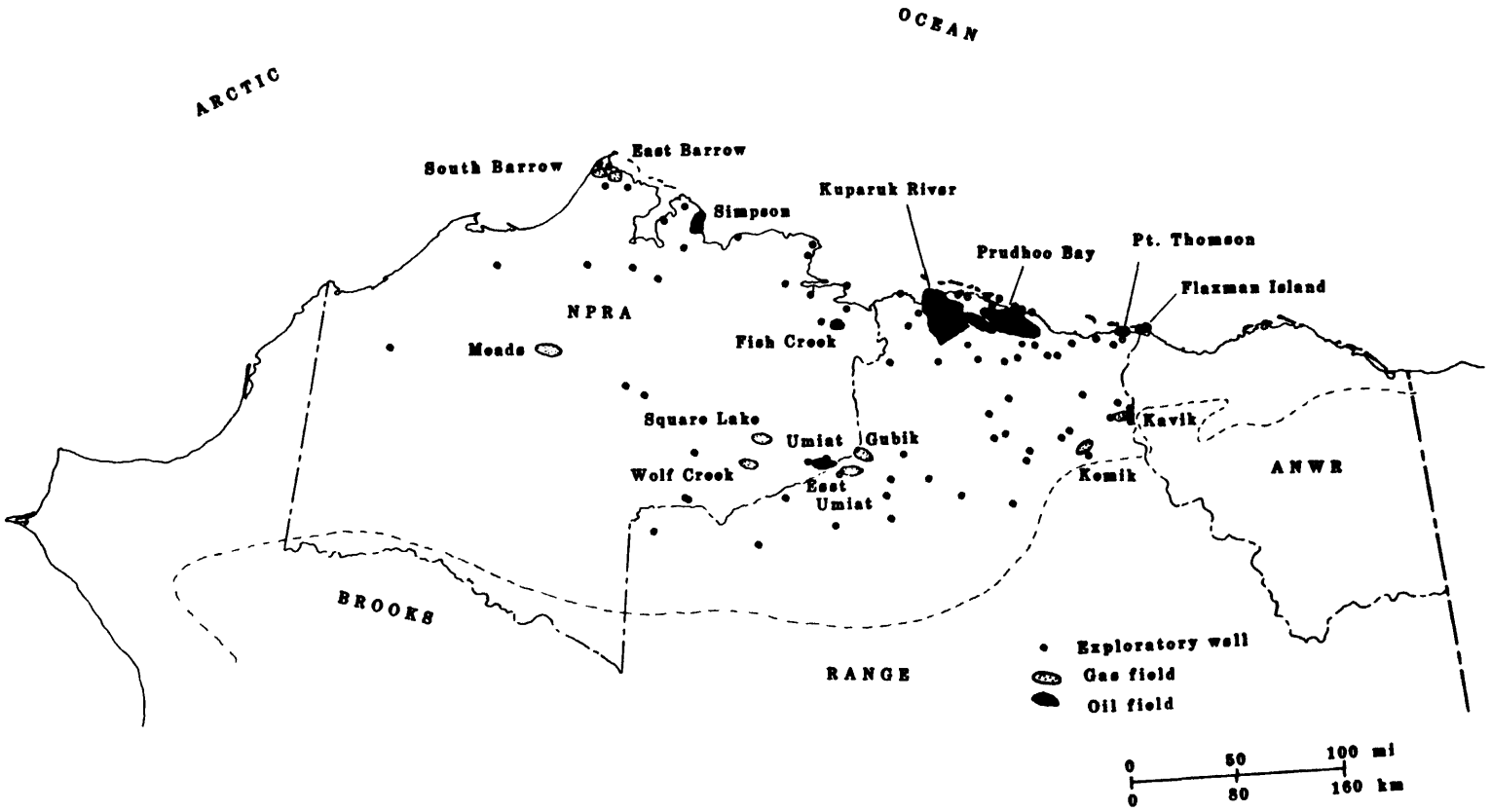

Figure 9.--Petroleum deposits and exploratory wells in North Slope, Alaska. Wells within outline of oil and gas fields are not shown and may be quite numerous, e.g., in Prudhoe Bay field. Data are current through 1978. See table 2 for details.

Table 2.-Oil and gas fields, Alaskan North Slope

FIELD	DISCOVERY DATE	PETROLEUM TYPE	PRODUCING FORMATION	RESERVOIR LITHOLOGY	TRAP	PRODUCTION DEPTH (in ft)	IDENTIFIED RESOURCES (economic & subeconomic) (oil x 10^6 bbl; gas x 10^9 ft^3)
Umiat	12-26-46	oil	Nanushuk Gp.	Sandstone	Structural	250-1350	19-122 recoverable [1]
South Barrow	4-15-49	gas	"Barrow ss"	"	"	2250	25.2 recoverable [2]
Fish Creek	9- 4-49	oil	Nanushuk Gp.	"	Stratigraphic	3000	No estimate
Simpson	5- 9-50	oil	"	"	"	300	2.5-12 recoverable [1, 3]
Meade	8-21-50	gas	"	"	Structural	4200	10-20 recoverable [4]
Wolf Creek	6- 4-51	gas	"	"	"	1500	No estimate
Gubik	8-11-51	gas	Colville Gp. Nanushuk Gp.	" "	"	1450-3550	22-295 recoverable [1]
Square Lake	4-18-52	gas	Colville Gp. Nanushuk Gp.	" "	"	1650-1850	33-58 recoverable [4]
East Umiat	3-28-63	gas	Nanushuk Gp.	"	"	1800-3000	No estimate
Prudhoe Bay	1- 1-68	oil and gas	"Put River ss" Sag River ss Shublik Fm. Sadlerochit Gp.	" " Carbonate Sandstone	Combination	8000-9000	9,600 recoverable oil 26,500 recoverable gas [5]
"	1- 1-68	oil and gas	Lisburne Gp.	Carbonate	"	8800-9500	650 recoverable oil 1,900 recoverable gas [8]
Kuparuk	5- 9-69	oil	Kuparuk River ss	Sandstone	Stratigraphic	6000-7000	3560 in-place [6]
Kavik	11- 5-69	gas	Shublik Fm. Sadlerochit Gp.	Carbonate Sandstone	Structural	4700-6200	No estimate
Kemik	6-17-72	gas	Shublik Fm.	Carbonate	"	8600-8800	No estimate
East Barrow	5- 4-74	gas	"Barrow ss"	Sandstone	"	1900-2100	19.1 recoverable [7]
Flaxman Island	9-11-75	oil and gas	unnamed Tertiary	"	Stratigraphic(?)	12,500	600 recoverable oil 4,500 recoverable gas [8]
Point Thomson	9- ?-77	oil and gas	"	"	"	13,000	

Sources:

[1] Arctic Contractors, 1953b, p. 89-91. [2] Gruy and Associates, 1976, table 1. [3] Miller and others, 1959, p. 100.

[4] Arctic Contractors, 1953a, p. 213-223. [5] Morgridge and Smith, 1972, p. 489. [6] van Poollen and Associates and State of Alaska Division of Oil and Gas, 1978, p. 1.

[7] Gruy and Associates, 1978, p. 1. [8] Van Dyke, 1980, table 1 (most likely values).

was little further stimulus to industry exploration. In 1958, however, the situation dramatically altered when commercial quantities of oil were discovered in southern Alaska (Cook Inlet), and interest in Alaskan exploration was thereby renewed. Also in 1958, Public Land Order 82 was rescinded and land was made available through lease sales; two sales were held in the area south and east of Umiat during the year. Industry petroleum exploration had begun.

Exploration was restricted by land availability. Initially, the Federal government was the sole landholder, and NPR-4 the only area unavailable for private exploration. In relatively quick succession, Alaska became a State and selected acreage on the North Slope; the Arctic National Wildlife Range (ANWR) was formed (1960), and approximately 10,000 km^2 of petroleum-prospective land was thereby defined as off-limits to industry. Present North Slope land ownership is approximately 80 percent Federal, 10 percent State, and 10 percent native corporation.

The frequency of lease sales is depicted on the graphs in figure 8. State leases were awarded on the basis of competitive cash-bonus bidding; Federal leases, on the basis of simultaneous filing and drawings. Sales were initially held in the Foothills, south and east of Umiat and later in areas farther north and east. Most recently, a joint State-Federal sale was held in December 1979 offshore Prudhoe Bay, and leases were awarded on the basis of cash-bonus bidding, profit-share bidding and sliding-scale royalties.

A prominent feature in the holding of Federal leases was the development contract, by which large groups of contiguous leases, held by various owners, were combined into a single unit. Leases so held were not counted against individual-company acreage limits. Development contracts stipulated work commitments to be satisfied or else acreage was to be relinquished. As many as

seven development contracts were concurrently in effect that covered a major part of the area between NPR-4 and the ANWR (Saunders, 1965, p. 861). The development contract, however is no longer a feature of North Slope land agreements.

A third and more recent landowner on the North Slope is the native corporation. The Alaska Native Claims Settlement Act of 1971 provided for native land ownership, with acreage in proportion to the number of native Alaskans from the corporation area. Land selection is from areas designated by the Federal Government within respective native corporation boundaries. At present, the North Slope lies entirely within the bounds of a single corporation area, the Arctic Slope Regional Corporation.

During the years 1966 to 1977, while legislation for the act was being written--and afterwards, while land selections were being made--Federal land on the North Slope was unavailable for leasing. With respect to oil exploration, this period constituted another "land freeze" (fig. 8). Although final figures are unavailable and conveyance of title remains incomplete, the Arctic Slope Regional Corporation is expected to assume ownership of approximately 20,000 km^2 mainly in the Foothills province south and west of the NPRA. Exploration agreements between the native corporation and private companies have been made, and exploration of these lands is underway.

Industry drilling began in the foothills near Umiat to test Cretaceous objectives similar to those tested by the Navy in NPR-4; eight wells were drilled during the period 1964 to 1967. Although only one, subcommercial gas field (East Umiat) was discovered, shows were encountered in every well. After most of these wells were drilled, exploration activity shifted northward to the Coastal Plain, where pre-Cretaceous (Ellesmerian) objectives could be tested at more reasonable depths than in the Foothills. Additional motivation

for this northward shift, according to Morgridge and Smith (1973, p. 494), was better opportunity to acquire solid leasing blocks on State acreage through competitive lease sales.

The first two wells penetrated attractive pre-Cretaceous reservoirs that yielded hydrocarbon shows and a more complete stratigraphic section than the Navy wells in NPR-4. The third Coastal Plain well was drilled when exploration activity had come to a virtual standstill. It was this well, the eleventh industry attempt, that resulted in the discovery of the largest petroleum accumulation in North America, the Prudhoe Bay field. This field actually consists of two oil pools with separate gas caps--the upper, Sadlerochit pool, and the lower, Lisburne pool. In the two years after this discovery, exploration activity reached record proportions in all categories. This activity included the evaluation of existing leases, partly in preparation for the 1969 State Lease Sale, and, after the sale, the evaluation of newly acquired leases. Shortly after the discovery of the Prudhoe Bay field, two additional discoveries were made (Kuparuk River and Kavik); exploration activity then declined for several years. An offshore sale, initially scheduled for 1975, was preceded by a gradual increase in seismic surveys and drilling activity; the sale was postponed, and activity again waned. The most recent trend is a gradual increase in drilling and seismic surveys in the coastal area. Records of drilling results during 1978-79 are incomplete because of Government regulations allowing this information to be held confidential for a period of 25 months; this period of confidentiality enables companies to maintain any competitive advantage resulting from drilling.

Industry results (probably incomplete) from 1958 through 1978 indicate five gas fields (East Umiat, Kavik, Kemik, Prudhoe-Sadlerochit pool, and

Prudhoe-Lisburne pool) and five oil fields (Prudhoe-Sadlerochit pool, Prudhoe-Lisburne pool, Kuparuk, Flaxman Island, and Point Thomson) (fig. 9, table 2).

Government Exploration (1974-78)

The discovery of the Prudhoe Bay field revived Government interest in exploration of NPR-4. Beginning in 1969, Tetra Tech, Inc., conducted a series of regional studies for the Navy to evaluate existing geologic-geophysical data in NPR-4. On the basis of these regional studies a "new major effort exploration plan was formulated" (Patterson and Harris, 1978). The Arab Oil Embargo of late 1973 prompted Congress to reestablish an exploration program in NPR-4 in January 1974, under the direction of the Navy. This program was projected to continue for 7 years, to include the drilling of 26 exploratory wells and the acquisition of approximately 10,000 line-miles of seismic and gravity data. Husky Oil NPR Operations, Inc., a consortium of Husky Oil Company, Alaska General Contractors, Inc., and Geophysical Services, Inc., was selected by competitive bid to be the prime contractor. This Navy program prevailed from 1974 to mid-1977, when jurisdiction of the program and of NPR-4 was transferred by congressional directive to the Department of the Interior in the Naval Petroleum Reserves Production Act, which directed the Department of the Interior to continue the Navy program of hydrocarbon resource evaluation in NPR-4. The act also provided that the name be changed from Naval Petroleum Reserve No. 4 to National Petroleum Reserve in Alaska (NPRA). Other stipulations provided for environmental restoration, production and development of gas reserves for the Barrow community, a study of management alternatives including economic and environmental analyses of estimated hydrocarbon resources, and an inventory of all other resources.

Just as early Government work in NPR-4 greatly aided the industry exploratory effort outside of the reserve, so the Government program in 1974 was in

turn indebted to industry exploration for much new geologic information that could be projected into the NPRA (U.S. Geological Survey, 1978). Thus, the Navy concentrated efforts in the northeast quarter of the NPRA--an area most likely to contain Prudhoe-type accumulations. Exploration activity was also restricted to this part of the NPRA because the necessary environmental assessment (Environmental Impact Statement) had not yet been completed for the remainder of the NPRA. The National Environmental Policy Act precludes drilling until such an assessment is provided.

The Navy program (1974-77) acquired about 7600 line-miles of seismic and gravity data and drilled 7 exploratory wells: all were dry holes in the northeast quarter of the NPRA, drilled for pre-Cretaceous (Ellesmerian) objectives on the Barrow arch. In the Barrow program, to insure adequate supplies of natural gas to the Government and civilian population, five wells were drilled: three were dry, and two were producers. A new gas field (East Barrow) was discovered about 10 km east of the South Barrow field. Testing of the Iko Bay well, 16 km southeast of the South Barrow field, indicates that it may be a produceable gas well for local use, although it is not recorded as a discovery, pending further analysis.

The Department of the Interior program is overseen by the Geological Survey. As in the Navy program, Husky Oil NPR Operations, Inc., is the prime contractor. Drilling, geophysical-data collection, and processing are subcontracted, as before. Interpretation of the geophysical and geologic data is subcontracted but also provided by Survey personnel. All facets of the program are coordinated by the Geological Survey.

In addition to the usual geologic-geophysical exploratory work, several special projects have been initiated to explore the basin more effectively, including multidiscipline studies of the different reservoir units and basin-

wide studies of paleontology and source-rock geochemistry. Experimental methods in direct hydrocarbon detection are being tried, including helium "sniffing" and low-level aeromagnetic surveys.

To make the best possible assessment of the petroleum resource potential of the NPRA within the time and drilling constraints of the original program (7 years and 26 wells), a strategy of assessing "plays" is being pursued. A play is defined as a group of geologically similar prospects. Initially, 12 plays were recognized; now, with additional data, there are 17. A minimum-assessment strategy would consist of testing one or more prospects in each play.

The Government program under the Department of the Interior (1977-78) has acquired, through 1978, 1844 line-miles of gravity and seismic data, and has drilled 4 exploratory wells on the Coastal Plain for pre-Cretaceous (Ellesmerian) objectives. All the wells are dry holes, although shows appeared in every well. Through 1978, 7 of 17 plays had been tested.

RESOURCE ESTIMATE OF NPRA

The Naval Petroleum Reserves Production Act called for a study to determine optimum alternative-management procedures for petroleum development of the NPRA (U.S. Department of the Interior, 1979). The act mandated that this study should consider the economic and environmental consequences of the procedures used in developing, producing, transporting, and distributing the petroleum resources. Fundamental to the study would be an estimate of the total petroleum resource in the NPRA; this assessment, to be most useful, would not only refer to the amount of petroleum present but also take into account its location, the size of the accumulations, and the certainty of the estimates. The method that most nearly satisfied all these requirements was the "play" approach.

The Office of Minerals Policy and Research Analysis, Department of the Interior, in cooperation with the Geological Survey, developed a method using the "play" as a basic unit of analysis (White, 1979). This method is a modification of that used by the Canadian Government in estimating Canada's petroleum resources (Roy and others, 1975; Canada Department of Energy, Mines and Resources, 1977). The play approach divides the geologic characteristics of potential hydrocarbon accumulations into three categories: play specific, prospect specific, and reservoir specific. Subjective probability judgments are made for each of these three categories, by experts familiar with the local geology, and these probabilities are then combined by a Monte Carlo method to give probability distributions of pool size and inplace hydrocarbon volumes for each play. Further use of the Monte Carlo method provides an aggregation of the probabilities for all plays to give a total resource estimate for NPRA.

A total of 10 people were organized into 2 committees to provide the inputs for this process. Committee members included, in nearly equal numbers, experts on the petroleum geology of the NPRA and experts in petroleum geology and resource appraisal. The first committee made subjective probability judgments on each category for each play; the second committee was responsible for reviewing the work of the first committee to ensure adherence to established procedures and definitions of terms. A sample data form for recording judgments on a particular play is presented in figure 10.

The play-specific category consists of those geologic characteristics common to the entire play, including hydrocarbon source, timing, and migration; reservoir rock and reservoir rock type; hydrocarbon mix (oil and gas); and number of prospects (fig. 10). A probability of favorable occurrence is estimated for each of the first four characteristics. Reservoir rock type is

OIL AND GAS APPRAISAL DATA FORM

EVALUATOR: Bird--committee composite PLAY NAME: Sag River

DATE EVALUATED: 9 Nov 78 REVISED: 15 Nov 78; 21 May 79; 25 Sep 79

	ATTRIBUTE									PROB. OF FAVORABLE	COMMENTS
PLAY ATTRIBUTES	HYDROCARBON SOURCE (S)									1.0	Oil shows in Barrow 12, 17, 19, and Iko
	TIMING (T)									1.0	
	MIGRATION (M)									1.0	
	POTENTIAL RESERVOIR FACIES (R)									.7	New core data shows low perm.
	PLAY PROBABILITY (SxTxMxR=MP)									.7	
PROSPECT ATTRIBUTES	TRAP OCCURRENCE (TM)									.3	
	EFFECTIVE POROSITY (≥3%) (P)									.9	
	HYDROCARBON ACCUMULATION (C)									.9	
	PROSPECT PROBABILITY (TMxPxC=CP)									.243	
HYDROCARBON VOLUME PARAMETERS	RESERVOIR LITHOLOGY	SAND								1.0	
		CARBONATE								0	
	HYDROCARBON MIX	GAS								.2	
		OIL								.8	
	FRACTILES / ATTRIBUTE	PROB. OF EQUAL TO OR GREATER THAN									
		100	95	75	50	25	5	0			
	AREA OF CLOSURE ($x10^3$ ACRES)	.6	1	3	6	8	10	25			
	RESERVOIR THICKNESS (FT)	5	30	60	90	120	140	170			
	EFFECTIVE POROSITY (%)	3	8	10	12	15	20	25			Glauconitic ss; standard porosity vs. permeability relations may not hold
	TRAP FILL (%)	1	15	30	45	55	70	95			
	RESERVOIR DEPTH ($x10^3$ FT)	2	5	8	9	10	11	13			
	NUMBER OF DRILLABLE PROSPECTS	4	5	6	8	12	15	20			
PROVED RESERVES ($x10^6$ BBLS; TCF)								0			

Figure 10.--Sample data form used in "play" method for estimating undiscovered hydrocarbon resources in NPRA.

determined to be either sandstone or carbonate rock throughout the play. Hydrocarbon mix is an estimate of the relative preponderance of gas or oil accumulations within the play. The number of prospects is estimated as a probability distribution, expressed by 7 fractiles, based on an actual count of seismically mapped prospects. Allowances are made for undetected prospects, that is, those structures smaller than the seismic grid or stratigraphic traps. The product of the first four probabilities is termed the marginal play probability--the joint probability that all of the regional geologic characteristics necessary for the accumulation of hydrocarbons in the play area are simultaneously favorable. The joint occurrence of these play-specific characteristics is a necessary but not a sufficient condition for the existence of hydrocarbon accumulations in the play.

The prospect-specific category consists of those geologic characteristics common to individual prospects within the play; these characteristics include the trap existence, minimum effective porosity, and hydrocarbon accumulation (fig. 10). The term "hydrocarbon accumulation" expresses the favorable relation of source rock to reservoir rock and of the time of hydrocarbon generation to trap formation. A probability of favorable occurrence is estimated for each characteristic, based on the condition that all the play-specific characteristics are favorable. The product of these three probabilities gives the joint probability that a prospect contains petroleum, defined as the conditional deposit probability (conditional, that is, on favorable play geology).

The product of the marginal play probability and the conditional deposit probability gives the probability that a given prospect will contain hydrocarbons. This probability of success (equivalent to one minus the "dry hole risk factor") was compared to the individual estimator's opinion of the uncertainty.

The reservoir-specific category consists of those geologic characteristics that determine the volume of petroleum present in an individual accumulation in the play. These characteristics include area of closure, reservoir thickness, effective porosity, and trap fill (fig. 10). Each characteristic is assessed according to a probability distribution, represented by fractiles using basic information derived from maps and well data.

Utilizing the three basic sets of probability judgments recorded on the data form, a resource assessment is made as follows. For each Monte Carlo pass, the distribution of the number of drillable prospects is sampled to determine the number of prospects that can be simulated as existing in the play during that particular pass. Then, the reservoir-volume distribution is sampled for each prospect to simulate the amount of hydrocarbons present if the play were productive and the prospect actually a deposit. Iteration of this procedure, generally several thousand times, gives a pool-size distribution conditional on the prospects being hydrocarbon accumulations. Play potential--the probability distribution of hydrocarbon volume in a play--is generated by jointly sampling the pool-size distribution, the number of prospects distribution and the conditional deposit probability. The resulting distribution is play potential conditional on the play being productive. The various play potentials are then stochastically accumulated by sampling the marginal play probability to estimate overall basin resource potential.

The Geological Survey has defined and made estimates for 17 plays in the NPRA. Since November 1978, four additional assessments have been made as additional information became available from the exploration program. For the latest (May 1980) assessment the estimated pool size and totals for undiscovered inplace oil and gas are plotted in figure 11. The estimated volumes generally resemble previous estimates using volumetric and Delphi methods but

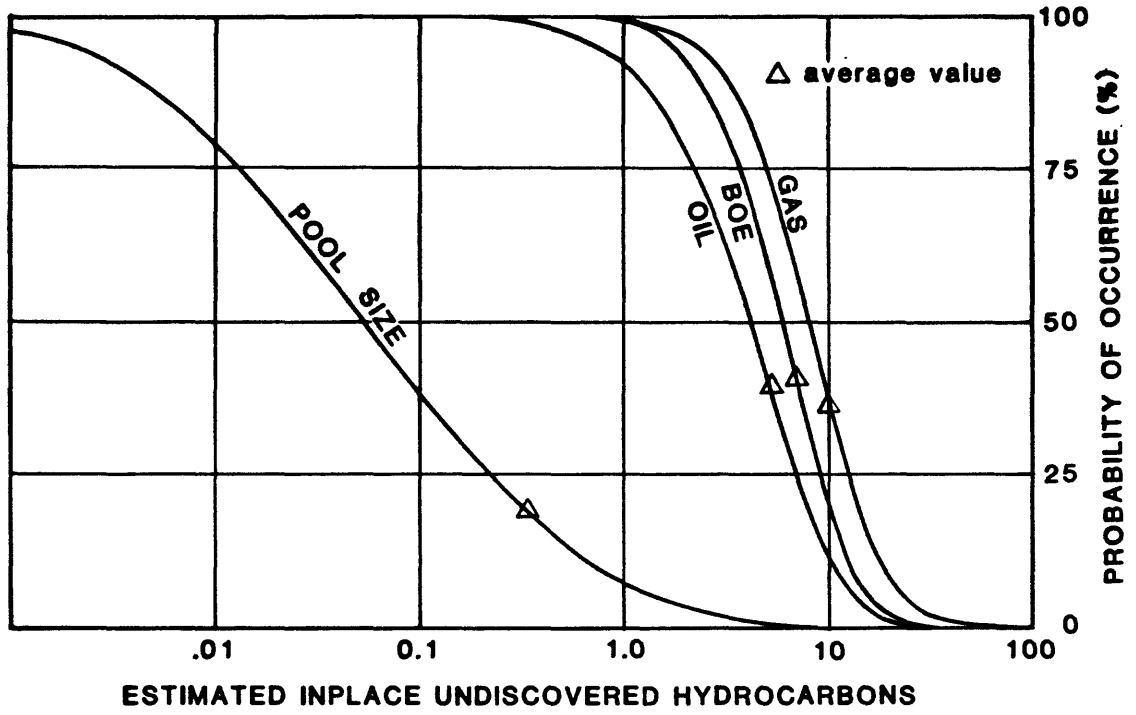

Figure 11.--Probability distributions for undiscovered inplace hydrocarbons in NPRA, including pool size, total oil, total gas, and barrels-of-oil equivalent (BOE) resulting from May 1980 assessment. All values are risked. Volumes: oil x 10^9 bbls; gas x 10^{12} ft^3.

are richer in important detail and, therefore, more useful. (For a concise review of these and other methods of estimating petroleum resources, see White and Gehman, 1979). The use of the play approach in resource estimation allows inclusion of all relevant geologic, geophysical, and engineering data and the best judgments of knowledgeable experts. In addition, the numerous components of this method permit each probability to be modified and updated as new or better data become available. As the exploration history unfolds, verification and further improvement of estimation techniques should become possible.

SUMMARY AND CONCLUSIONS

The exploration history of the North Slope in Alaska is unique in that both Government and private industry have spent approximately the same time in exploring this basin (about 20 years each). From 1944 to 1953, exploration was by Government to the exclusion of private industry. Industry exploration dates from 1958, and was originally restricted to the central third of the area. Only recently, through the native corporation, has the area of private exploration been significantly broadened.

All things being equal, industry has been obviously and spectacularly successful in its search for petroleum. All things, however, have not been equal in the North Slope area, and a strict comparison between industry and Government efforts is impossible for several reasons. The early Government program (4 seasons of geologic reconnaissance and 10 years of Pet-4) was a pioneering effort in terms of general Arctic operations and establishment of a broad geologic framework for the basin. Furthermore, the early program was focused on the area of NPR-4, and oil, as far as we know, is not uniformly distributed throughout the area under discussion. The later Government

program has been oriented toward assessment of all possible plays in the NPRA and not toward concentrating on the most promising plays. Industry exploratory efforts have benefited from demonstrated operational techniques and an established geologic framework, as well as the fortuitous occurrence of the Prudhoe Bay accumulation in the sector that they explored.

Basic to this report is the concept that not all the answers in petroleum exploration are presently known and that multiple hypotheses are therefore necessary to the most thorough exploration task. The exploration of the North Slope in Alaska has drawn the best efforts of both industry and Government, but much work remains to be done before the petroleum resource potential of the basin can be said to be fully explored.

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