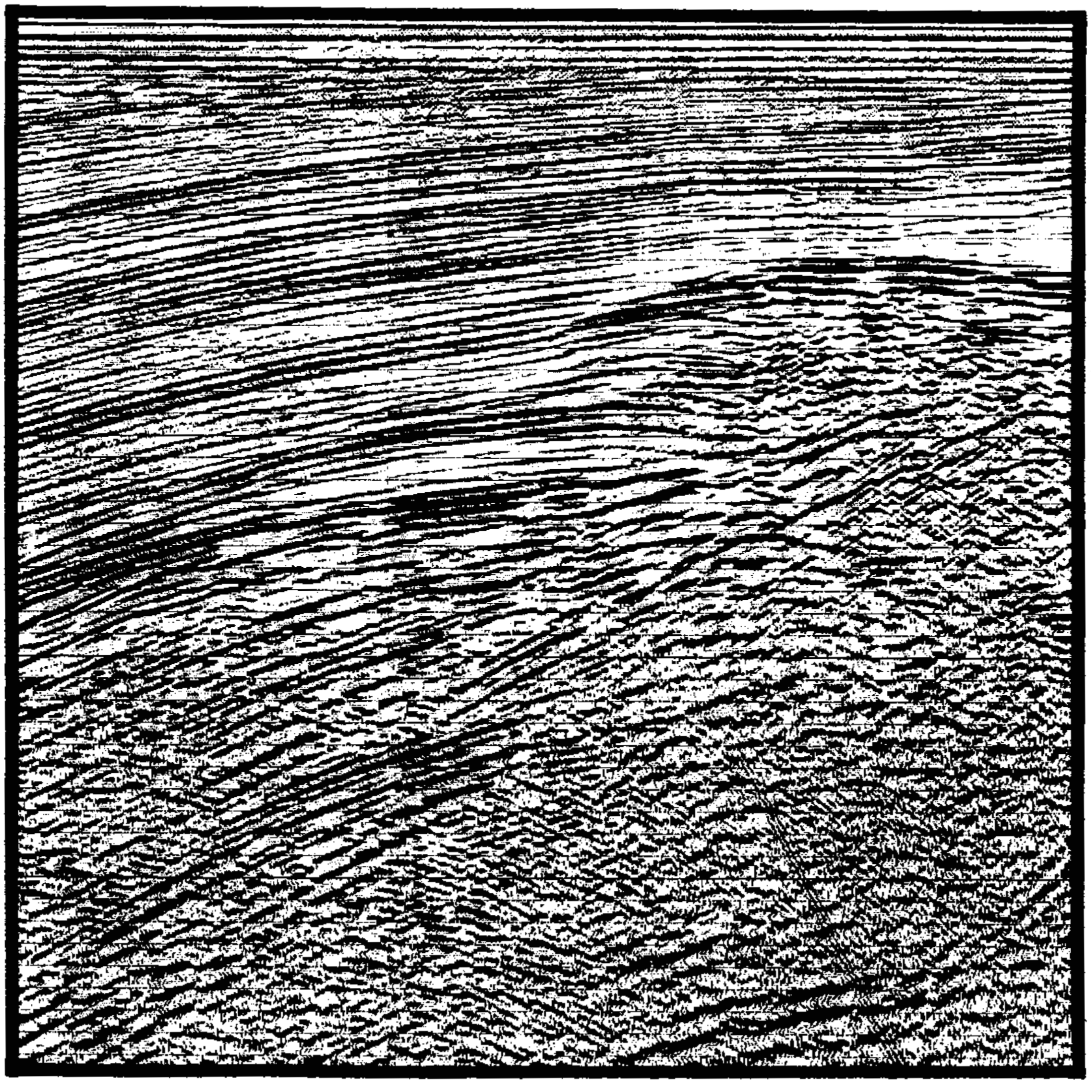
OCS Report
MMS 85-0111

Geologic Report for the
BEAUFORT SEA
Planning Area

Alaska



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GEOLOGIC REPORT FOR THE BEAUFORT SEA PLANNING AREA, ALASKA:

Regional Geology, Petroleum Geology, Environmental Geology

by

JAMES D. CRAIG
KIRK W. SHERWOOD
PETER P. JOHNSON

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Alaska OCS Region
Anchorage, Alaska

Contents

Part 1 Regional Geology

Part 2 Petroleum Geology

Page

Part 3 Environmental Geology

Figures

Plates

Tables

English-Metric Conversion

(The following table gives the factors used to convert English units to metric units.)

multiply English units	by	to obtain metric units
inches	2.5400	centimeters
feet	0.3048	meters
miles (statute)	1.6093	kilometers
square miles	2.5899	square kilometers
acres	0.4047	hectares
barrels (U.S. petroleum)	158.9828	liters
	0.1589	cubic meters
cubic feet	0.0283	cubic meters
knots	1.8520	kilometers per hour

To convert from Fahrenheit (°F) to Celsius (°C), subtract 32 then divide by 1.8.

Abstract

The Federal Outer Continental Shelf (OCS) Beaufort Sea Planning Area extends approximately 500 miles along the northern continental margin of Alaska from the Canadian border to 162° west longitude, where it meets the Chukchi Sea OCS Planning Area. The planning area includes continental shelf, slope, and abyssal plain physiographic provinces. The Beaufort continental shelf is relatively narrow, and most of the planning area lies in the abyssal plain of the Arctic Ocean. For geological and logistical reasons, only the continental shelf is thought to have any realistic potential for economic accumulations of hydrocarbons. Lease blocks on the shelf are tentatively scheduled for public offering at lease Sale 97.

Northern Alaska is divisible into two major geologic provinces: (1) a landward province containing Paleozoic and Mesozoic rocks underlain by continental crust and (2) an offshore province containing a thick clastic wedge of Cretaceous and Tertiary sediments deposited on the subsiding continental margin underlain by transitional to oceanic crust. The gently southward-dipping surface of the continental basement complex, termed the "Arctic Platform," is separated from the post-Jurassic continental margin along a highly faulted flexure termed the "Hinge Line."

Acoustic and economic basement of the Arctic Platform consists of a metamorphic complex (the Franklinian sequence) formed by a regional orogeny in Devonian time. The basement complex is overlain by Middle(?) Devonian to Lower Cretaceous strata (the Ellesmerian sequence) deposited in a stable shelf setting. The Ellesmerian sequence generally thins northward toward the orogenic terrane which existed before the rifting of the Beaufort continental margin in Early Cretaceous time. A structurally anomalous basin (informally termed the "Northeast Chukchi Basin") containing greater than 30,000 feet of Paleozoic sediments underlies the northeastern Chukchi shelf. These lower Ellesmerian sedimentary deposits are juxtaposed with the basement complex of the Arctic Platform across a poorly resolved fault zone termed the "Barrow fault." Ellesmerian sedimentation terminated in Early Cretaceous time with the uplift of an incipient rift zone in the vicinity of the present continental margin. This uplift and associated erosion produced a regionally extensive unconformity that truncated the Ellesmerian sequence on

some onshore and most offshore parts of the Arctic Platform. Extensional tectonics early in the rifting episode produced grabens which were filled with Lower Cretaceous sediments (the Rift sequence) derived from nearby uplifted blocks. A broad, SE-plunging structural high, the "Barrow Arch," was created by the subsidence of flanking basins (Colville and Nuwuk) following continental breakup. Subsidence of the offshore continental margin in Cretaceous and Tertiary time created deep structural basins (Nuwuk and Kaktovik Basins) beneath the present Beaufort shelf. An immense clastic wedge (the Brookian sequence) prograded northward from the Brooks Range orogenic belt into these depocenters.

All North Slope producing oil fields occur within the Ellesmerian sequence, and any area of northern Alaska where these rocks occur is considered highly prospective. The northernmost parts of the Arctic Platform are considered to be less prospective because Ellesmerian rocks are absent as a result of northward pinch-out by onlap and erosion at overlying unconformities. Paleozoic strata in the Northeast Chukchi Basin are involved in numerous fault and fold structures, and the potential for significant hydrocarbon accumulations is accordingly high. Untested Rift sequence rocks deposited in infrarift grabens on the northern Arctic Platform have good reservoir and source rock potential. Numerous structural and stratigraphic traps may exist within the deep basins seaward of the Hinge Line filled with Brookian clastic units. Potential reservoirs in this prograding clastic wedge are likely to be deltaic or basinal sandstones, which suggests that individual reservoirs may be thin and lenticular. Rotational folds associated with listric faulting near the basin margins are the most attractive exploration objectives in the western Beaufort (Nuwuk Basin); compressional folds and fault traps form the most prevalent plays in the eastern Beaufort (Kaktovik Basin).

Geologic features and processes which may affect petroleum-related activities in the planning area include a mobile and pervasive ice cover, active seabed scouring by ice and currents, unstable seafloor sediments, massive slumps on the outer shelf, subsea permafrost, shallow gas accumulations, abnormal formation pressure, near-seafloor faults, and modern seismicity. Ice movement may exert great stresses on platforms as well as on the seabed. Ice gouging on the shelf may necessitate burial of pipelines and wellheads. Strudel scouring of the seafloor near the mouths of rivers is active during spring flood periods. Subsea permafrost has been confirmed in several nearshore areas and presents unique engineering problems for foundations, gravel excavation, and pipeline routing. Shallow gas may be trapped in several ways and presents a serious drilling hazard, particularly in areas dissected by near-seafloor faults. Abnormally high formation pressures have been encountered in Cenozoic sedimentary basins in eastern Alaska and the Beaufort Sea. Earthquake activity has been documented on the eastern Beaufort shelf and may be related to ongoing tectonism in the northeastern Brooks Range. Surface fault displacements and massive slumps on the outer Beaufort shelf may be triggered by these shallow-focus, moderate-magnitude earthquakes.

Introduction

This report is a summary of the geologic framework, hydrocarbon potential, and environmental conditions in the Beaufort Sea Planning Area. It was prepared as part of the support documentation related to Federal OCS Lease Sale 97, tentatively scheduled for 1987. The report focuses specifically on the petroleum geology of this highly prospective area. The discussion of offshore geology is based largely on seismic reflection data collected during regional surveys by Western Geophysical Company (WGC), which has generously allowed us to use selected seismic lines to illustrate the regional geology discussed in this report. WGC and other industry-acquired seismic data generally display higher resolution, are more accurately navigated, and are far denser in coverage than existing, publicly available surveys used in previous geologic reports for this planning area (Grantz and others, 1982b). Publicly released exploration wells are fairly abundant on the North Slope and offshore in Canadian waters, and these wells provide regional stratigraphic control for our seismic interpretation. However, the Beaufort Sea Planning Area is truly a frontier exploration province. Seismic data coverage is sparse in some areas, and onshore stratigraphy may vary considerably from that offshore. The few offshore exploratory wells drilled in previous sale areas are proprietary at the present time, and there are no deep stratigraphic test wells (referred to as COST wells) on the Beaufort shelf. Our geologic analysis, based almost entirely on seismic data, is therefore somewhat speculative and will surely be modified as offshore well information is released.

The Beaufort Sea Planning Area encompasses the entire continental margin of northern Alaska and part of the abyssal Canada Basin (plate 11). It stretches in longitude for approximately 500 miles from just east of 141° west, the disputed border with Canada, to 162° west, where it meets the Chukchi Sea Planning Area. On the basis of projected industry interest, future technology development, and economic feasibility, the National Petroleum Council (1981) concluded that offshore exploration in the Arctic will be confined, in the foreseeable future, to the continental shelf where water depths are less than about 200 feet. The serious logistical difficulties associated with the Arctic ice pack, which covers the area most of the year, are of primary concern. Since geological and logistical considerations suggest that only the continental shelf has economic hydrocarbon potential, most of this report will focus on the geology of the shelf area. In the Chukchi Sea, approximately 60 percent of the total planning area lies on the continental shelf; in the Beaufort Sea, only 25 percent of the planning area is located on the shelf. The potential occurrence and economic significance of nonenergy minerals (gravel and metal placers) are not addressed.

Despite its remote setting, hostile climate, and politically sensitive environmental issues, northern Alaska has experienced a great deal of petroleum-related activity for several decades. The largest and second largest oil fields in North America (Prudhoe Bay and Kuparuk, respectively) are currently producing over 1.5 million barrels of oil per day through the Trans-Alaska Pipeline System (TAPS). Several peripheral fields (Endicott and Seal Island) are considered to be of commercial size and may be developed in the near future. There have been three Federal OCS lease sales which have received over $4 billion in bonus bids. At the present time, there are approximately 376 Federal leases in the Beaufort Sea Planning Area.

Part 1

Regional Geology

1

Geological Framework

The northern Alaska region, including the offshore continental margin, can be divided into two main petroleum provinces: an older southern province containing strata deposited on a continental basement complex (Arctic Platform, province I), and a younger northern province containing strata deposited in deep basins on the continental margin (Brookian basins, province II) (fig. 1). The dividing line between these main provinces lies offshore along a zone of down-to-the-north basement faults termed the "Hinge Line" by Grantz and others (1982b). The Hinge Line marks the southern edge of a major rift zone that developed in Late Jurassic to Early Cretaceous time. South of the Hinge Line, the basement surface forms a broad platform (the "Arctic Platform") that dips southward away from northern tectonic highlands which existed before continental rifting. The present structural relief of this continental basement complex (fig. 2) is largely the result of coeval compressional tectonics in the Brooks Range and rifting of the Arctic Platform since Late Jurassic or Early Cretaceous time. A prominent structural ridge (the "Barrow Arch") trends NW-SE along the Beaufort coastline and across the eastern Chukchi shelf (fig. 1). This regional feature, formed after Mesozoic continental rifting, separates a continental foredeep (the Colville Basin) from basins on the subsiding continental margin (Nuwuk and Kaktovik Basins). A third petroleum province is located seaward of the present continental shelf (Canada Basin, province III). This modern oceanic basin contains a relatively young sedimentary fill and is thought to have little economic potential for hydrocarbons in the foreseeable future. The general characteristics of these petroleum provinces are summarized in table 1.

The stratigraphy of northern Alaska can be divided into four main sequences by prominent unconformities which mark regional tectonic episodes. From oldest to youngest, these are the Franklinian, Ellesmerian, Rift, and Brookian sequences. Each of these sedimentary sequences has a unique source area, depositional environment, and structural character. Additional angular unconformities were identified in the seismic data; however, because they represent local tectonic movements or sea-level fluctuation events, a further subdivision of the main regional tectonostratigraphic sequences is not warranted. The most prominent of these unconformities

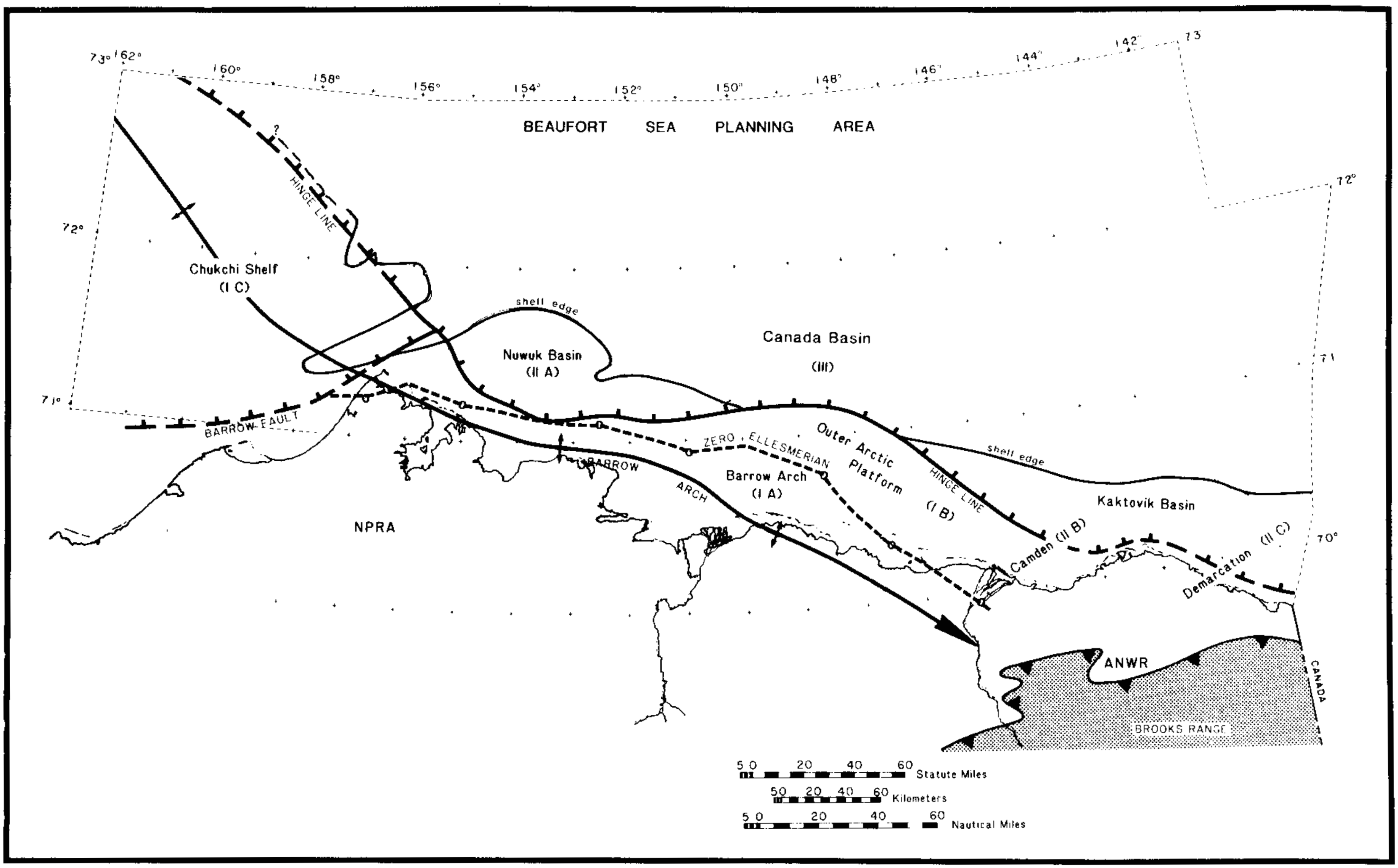


Figure 1.

Petroleum provinces in the Beaufort Sea Planning Area. Arctic Platform provinces (Chukchi shelf, Barrow Arch, and Outer Arctic Platform--province I) are geologic basins formed in mid-Paleozoic to mid-Mesozoic time on a continental basement complex. The Hinge Line is the crustal flexure along the continental margin formed after mid-Mesozoic rifting. Post-breakup basins along the subsiding continental margin (Nuwuk and Kaktovik Basins--province II) contain thick sections of Cretaceous to Tertiary clastic sediments beneath the present Beaufort shelf. The Canada Basin (province III) is an oceanic basin north of the Beaufort shelf edge. These petroleum provinces are also described in table 1.

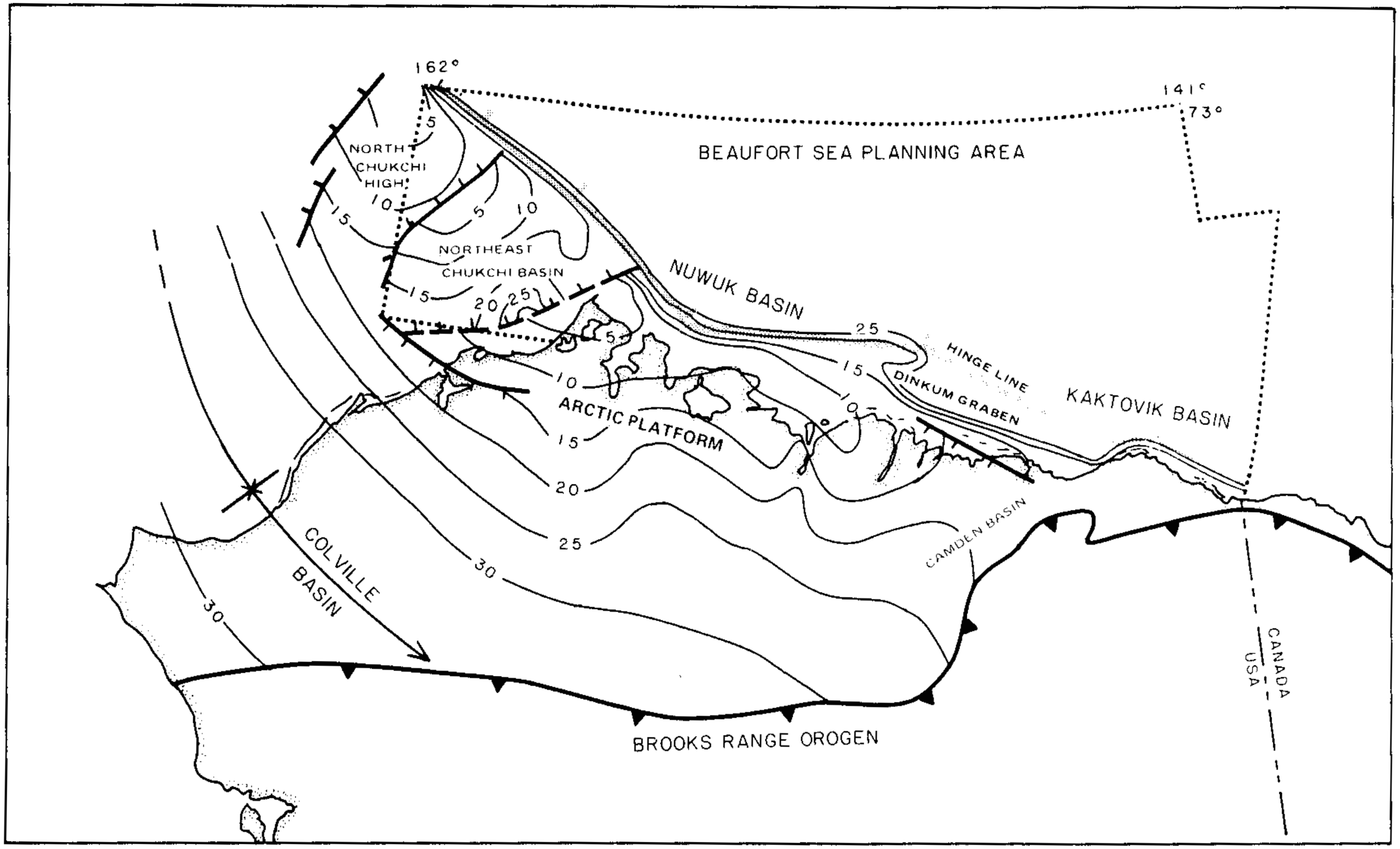


Figure 2.

Structure contours on acoustic basement, representing the top of the Franklinian sequence. This basement complex is composed of Middle Devonian and older strata that were structurally deformed and metamorphosed during several early Paleozoic tectonic episodes. The basement rocks are separated from overlying Paleozoic through Tertiary strata by a regional angular unconformity. Onshore contours were taken, in part, from a similar map presented in Jackson and others (1981). Offshore contours were derived from seismic data. Contour lines are labeled in thousands of feet below sea level. Major fault zones are shown, with hachures toward the downthrown block.

Table 1. Petroleum provinces in the Beaufort Sea Planning Area.

Petroleum Provinces	Geologic Setting	Physiographic Setting	Most Prospective Sequence
I. ARCTIC PLATFORM			
A. Barrow Arch	Northern Arctic Platform south of zero Ellesmerian line.	Inner Beaufort shelf; water depth <20 m.	Ellesmerian
B. Outer Arctic Platform	Between zero Ellesmerian line (south) and Hinge Line (north).	Middle to outer Beaufort shelf; water depths 20-100 m.	Rift
C. Chukchi Shelf	South of Hinge Line and west of Barrow fault.	Chukchi shelf; water depths 20-100 m.	Ellesmerian
II. BROOKIAN BASINS			
A. Nuwuk Basin	North of Hinge Line and south of present shelf edge in western Beaufort Sea.	Middle to outer Beaufort shelf; water depths 20-100 m.	Brookian
B. Kaktovik Basin-Camden Sector	North of Hinge Line and south of present shelf edge in eastern Beaufort Sea.	Middle to outer Beaufort shelf; water depths 20-100 m.	Brookian
C. Kaktovik Basin-Demarcation Sector	South of present shelf edge and east of Barter Island.	Entire continental shelf; water depths 10-100 m.	Brookian
III. CANADA BASIN	North of present shelf edge.	Continental slope, rise, abyssal plain; water depths 100-3,800 m.	Unknown

are a Permian unconformity (PU) in the western Beaufort and Chukchi sectors, a Miocene unconformity (MU) in the eastern Beaufort, and a shelf-wide Pleistocene unconformity (QU). A generalized stratigraphic column of the major rock units found onshore and their relationship to offshore seismic sequences is shown in figure 3. The following descriptions of rock unit age and lithology are drawn from numerous previous studies and publicly available North Slope wells (Brosgé and Tailleur, 1971; Brosgé and Dutro, 1973; Detterman and others, 1975; Carter and others, 1977; Tetra Tech, Inc., 1982; Molenaar, 1983).

In Arctic North America, an early Paleozoic sedimentary sequence (the Franklinian sequence) was severely deformed and mildly metamorphosed during a regional orogeny in Middle(?) to Late Devonian time. This metamorphic complex forms the present-day basement. The Ellesmerian sequence (Middle(?) Devonian to Early Cretaceous) unconformably overlies the Franklinian basement complex and represents deposition on a stable epicontinental shelf that persisted until the onset of continental rifting which began in latest Jurassic time (Grantz and May, 1982). The post-Jurassic development of the Beaufort continental margin generally followed the rift evolution model proposed by Falvey (1974). The "intracratonic basin" (Ellesmerian sequence) was uplifted in the incipient rift zone prior to continental breakup and truncated by a "rift-onset unconformity" (the Lower Cretaceous unconformity, or LCU). Initial graben formation and deposition of "rift valley" sediments (the Rift sequence) before continental fragmentation was followed by the progradation of a thick clastic wedge (the Brookian sequence) into basins along the newly formed continental margin. The Rift sequence (Early Cretaceous) and erosional remnants of infrarift highlands are separated from the overlying Brookian clastic wedge by a "breakup unconformity" (BU, fig. 3). The Brookian sequence (Early Cretaceous through Cenozoic) on the North Slope consists of clastic sediments derived from a contemporaneous orogenic belt (the Brooks Range) to the south. These evolutionary stages and their associated sedimentary deposits are illustrated by figure 4.

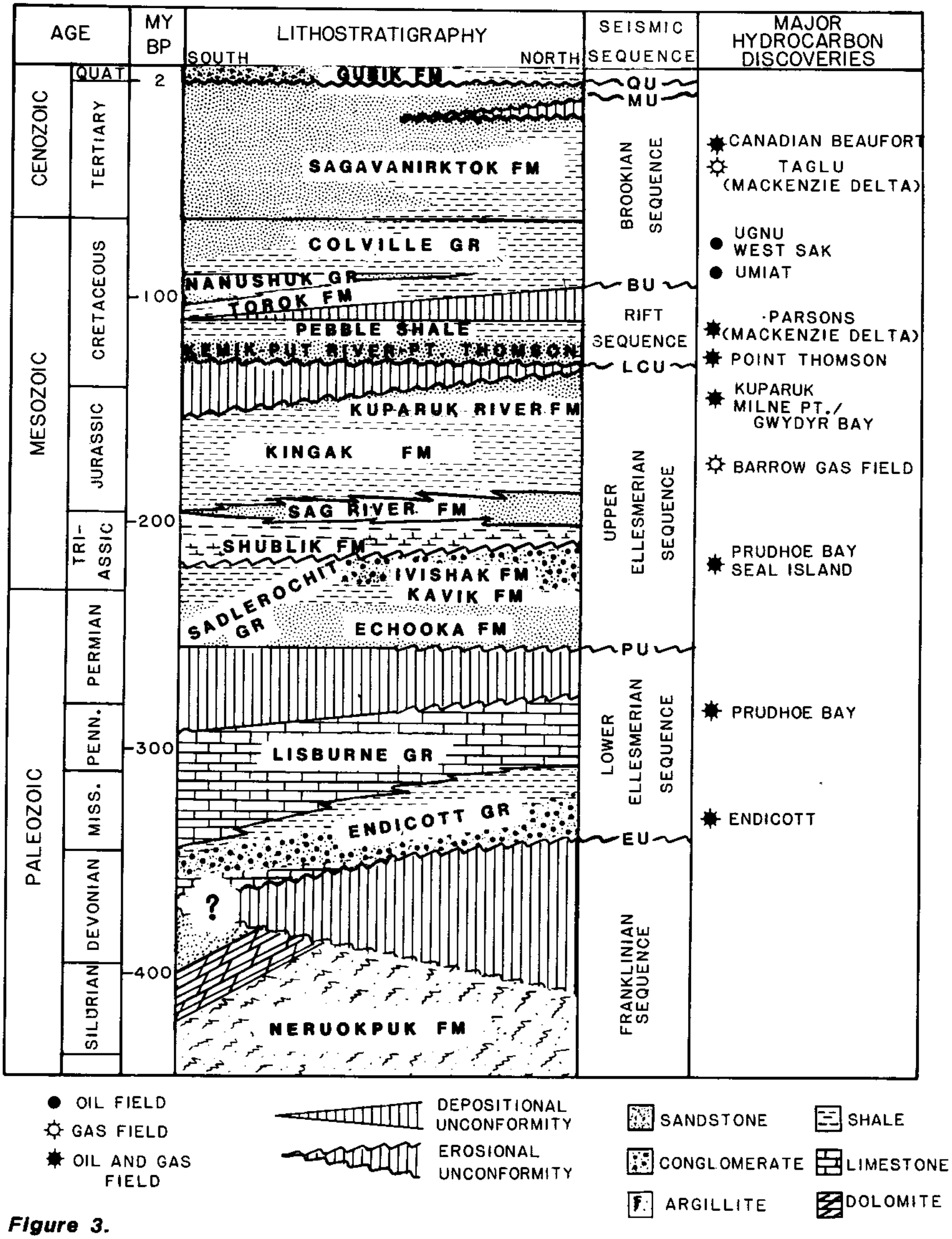


Figure 3.

Generalized lithostratigraphic column showing the relationship of onshore rock units in northern Alaska to offshore seismic sequences in the Beaufort Sea Planning Area. Significant hydrocarbon discoveries in northern Alaska and Canada are shown by their reservoir formations.

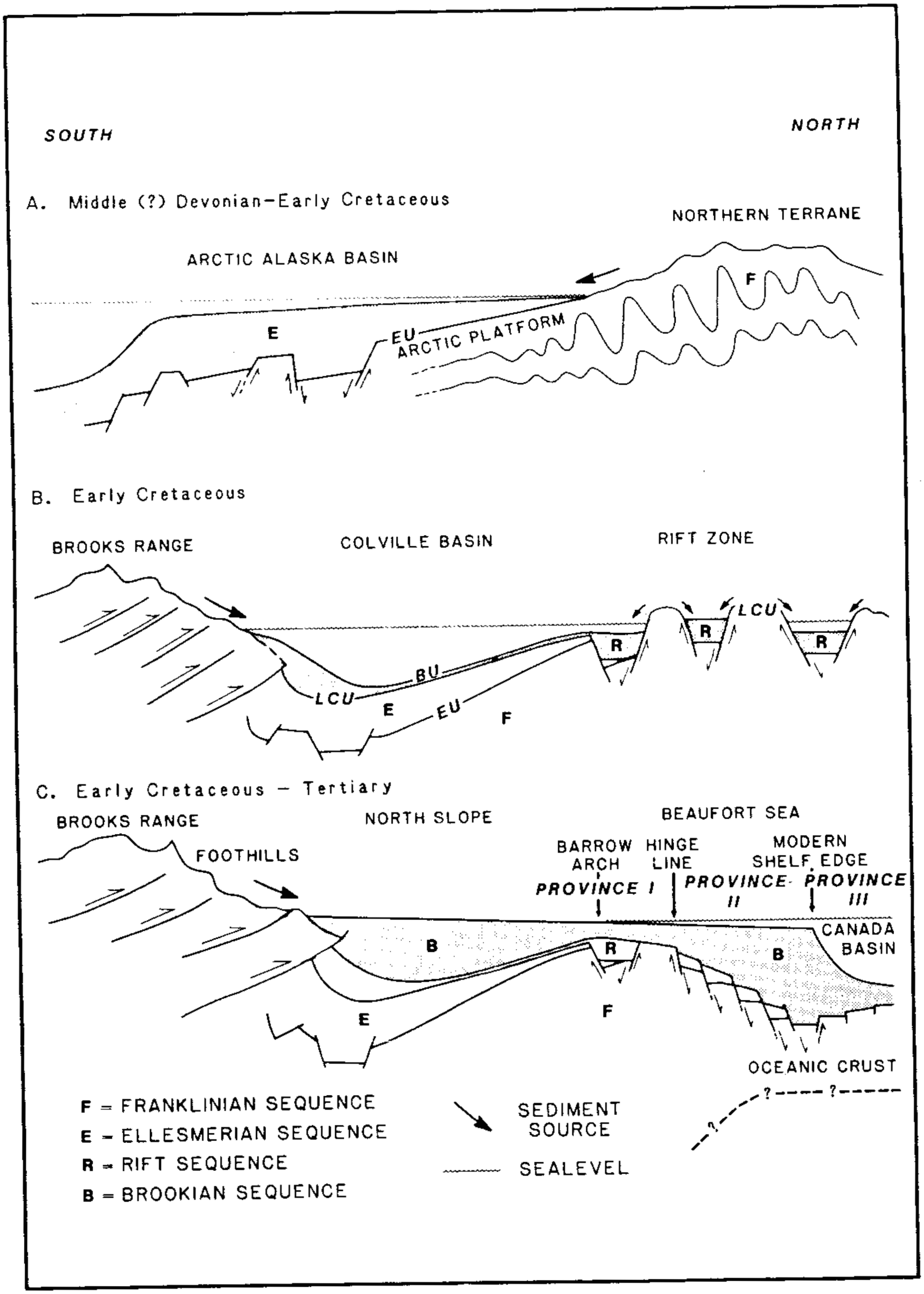


Figure 4.

Generalized geologic evolution of northern Alaska. Paleogeographic relief is diagrammatically shown during the time periods represented by the Ellesmerian, Rift, and Brookian stratigraphic sequences. Active depocenters are indicated by shading.

2

Stratigraphy

FRANKLINIAN SEQUENCE

A diverse assemblage of highly deformed, low-grade metamorphic rocks, predominantly sedimentary and carbonate lithologies, generally constitutes acoustic basement in northern Alaska. This basement complex is composed of steeply dipping Middle Devonian and older rocks beneath a regional angular unconformity (EU, fig. 3). Lower Paleozoic rocks in northern Alaska are thought to represent sedimentation in a circum-Arctic basin (referred to as the Franklinian Geosyncline) that generally deepened to the north and had broad shelf areas to the south (Churkin, 1973). These deposits have been referred to as the Neruokpuk Formation in the Brooks Range (Dutro and others, 1972) as well as the Franklinian sequence in the Canadian Arctic Archipelago (Lerand, 1973). We will refer to the basement complex as the Franklinian sequence in conformance with prior usage for the Alaskan Beaufort area (Grantz and others, 1982a, 1982b; Grantz and May, 1982, 1984).

The internal stratigraphy of the Franklinian sequence in northern Alaska is partially known both from outcrops in the Brooks Range and from well localities throughout the North Slope (Brosgé and Dutro, 1973; Churkin, 1973). Original depositional relationships are usually obscured by later tectonic overprinting, and Franklinian rocks are better known in areas in northern Canada outside the influence of Cordilleran tectonics (Cook and Aitken, 1973; Churkin, 1973; Trettin, 1973). Typically, fossiliferous lower Paleozoic strata lie unconformably on Precambrian quartzite and schist in the northeastern Brooks Range (Dutro and others, 1972). The Cambrian and Ordovician rocks, particularly in the northernmost parts of Canada and Alaska, are characterized by basinal deposits, including graptolitic shale and chert. Silurian to Middle Devonian rocks typically consist of platform carbonates, particularly to the south (Brosgé and Dutro, 1973). Middle to Upper Devonian rocks reflect a major tectonic episode (perhaps correlative to the Ellesmerian orogeny) and are composed of coarse clastic deposits and intrusive plutons (Dutro, 1981). Sedimentation in the Franklinian geosyncline was terminated by this orogeny, and these lower Paleozoic deposits were subsequently deformed and uplifted. The tectonic highland formed by this mid-Paleozoic episode served as the source province for succeeding Ellesmerian deposits until Early Cretaceous time.

Due to similarities of lithology and regional variations in tectonic alteration caused by the mid-Paleozoic orogeny, the relationship of Devonian rock units to the Franklinian or Ellesmerian seismic sequences is ambiguous. Our broad division of seismic units is intended to separate the highly deformed metamorphic basement rock (the Franklinian sequence) from unconformably overlying miogeosynclinal strata (the Ellesmerian sequence) without implying strict provincial age definitions. Grantz and others (1982b) assigned all pre-Mississippian rock to the Franklinian sequence, following the stratigraphic nomenclature developed in the Canadian Arctic by Lerand (1973). This is clearly valid for the North Slope of Alaska where a Mississippian clastic unit (the Kekiktuk Conglomerate) unconformably overlies metamorphic argillite of Ordovician to Silurian age (Carter and Laufeld, 1975). On the northern Arctic Platform, acoustic basement in seismic data closely coincides with highly deformed argillite encountered in coastal wells. However, in the central and southwestern Brooks Range, an allochthonous section of Upper Devonian marine and fluvial rocks (Hunt Fork Shale and Kanayut Conglomerate, respectively) lies with angular unconformity on Middle Devonian and older strata (Brosgé and Dutro, 1973, fig. 10). These allochthonous clastic deposits are conformably overlain by parautochthonous Mississippian strata of the Endicott Group (Brosgé and Tailleur, 1971; Nilsen and Moore, 1982b). Clearly, the effects of the mid-Paleozoic orogeny are less pronounced on Devonian and older rocks farther to the south, away from the northern foldbelt, in Canada and Alaska (Bell, 1973). Consequently, the distinction between the Franklinian and Ellesmerian sequences, based on a criterion of deformed versus undeformed character, becomes less apparent in these southern areas. In the Brooks Range, this distinction is further obscured by Mesozoic to Cenozoic orogenic thrusting.

Our preliminary conclusion is that the unconformity separating the Franklinian basement complex and the Ellesmerian miogeosynclinal sequence is diachronous, ranging in possible age from Middle Devonian to Early Mississippian. This is based on the following observations in northern Alaska: (1) the youngest reported age for tectonized rock below the regional basement unconformity (EU) is Middle Devonian or older from the metasedimentary strata in the Topagoruk well (Collins, 1961); and (2) the oldest reported age for strata unconformably overlying highly deformed lower Paleozoic rock is Middle(?) to Late Devonian in the Endicott Group (Dutro, 1981). The hiatus represented by this unconformity (EU) and the tectonic alteration of underlying rock units generally increase towards the northern foldbelt. The diachronous nature of the basement unconformity is further enhanced by younger unconformities which have exhumed basement surface in northern parts of the Arctic Platform. In many places, strata ranging in age from Mississippian to Tertiary lie directly on the lower Paleozoic basement complex. Our broad division of tectonostratigraphic sequences is based on seismically recognizable characteristics, and the bounding unconformities of these units are recognized to be time transgressive. The seismic sequences, therefore, may not coincide with strict formational definitions based on stratigraphic age.

ELLESMERIAN SEQUENCE

The Ellesmerian sequence (Middle(?) Devonian to Early Cretaceous) is bounded at its base by an angular unconformity on the Franklinian basement complex (EU) and at its top by the rift-onset unconformity (LCU, fig. 3). Ellesmerian sediments were derived from a terrane composed of deformed Franklinian rocks that existed north of the present Beaufort coastline. Coarse-grained, proximal sediments deposited on an epicontinental shelf (the Arctic Platform) adjacent to the northern source terrane generally grade southward into fine-grained basinal facies. The Ellesmerian depocenter (also termed the "Arctic Alaska Basin") deepened to the south beneath the present location of the Brooks Range (Brosgé and Tailleur, 1971) (fig. 4). Sedimentation throughout this period followed a general pattern of progressive marine onlap (transgression) to the north interrupted by brief regressive pulses which prograded south. Tectonic activity on the Arctic Platform was largely restricted to post-orogenic block faulting in Late Devonian to Late Mississippian time (Tetra Tech, 1982). Ellesmerian sedimentation terminated in Early Cretaceous time as the northern source terrane was rifted away from northern Alaska during the formation of the modern Canada Basin (Grantz and May, 1982). In common with rifting episodes on other continental margins (Falvey, 1974), a regional uplift of the incipient rift zone is marked by an extensive erosional unconformity (the LCU) which truncated southward-dipping Ellesmerian formations. The present distribution of Ellesmerian units is controlled by northward depositional thinning as well as erosional truncation. Ellesmerian-unit zero-lines generally trend northwest-southeast along the coastal and inner shelf areas of the Beaufort Sea (fig. 1).

Ellesmerian formations contain much of the known hydrocarbon reserves on the North Slope and are consequently the most thoroughly studied part of the geologic section in northern Alaska (Brosgé and Tailleur, 1971; Morgridge and Smith, 1972; Detterman and others, 1975; Carter and others, 1977; Jamison and others, 1980; Tetra Tech, 1982). Our brief description of the lithology and depositional setting of these formations is based largely on these previous studies.

The first Ellesmerian depositional cycle occurred in Late Devonian to Late Mississippian time, when coarse clastic sediment was shed from the orogenic foldbelt which lay to the north (fig. 4). Fault-bounded basins, such as the Northeast Chukchi and Ikpikpuk Basins, contain thick accumulations of these coarse clastic deposits. As a consequence of the active tectonic setting, the thickness and regional distribution of these lower Ellesmerian rocks are more irregular than those of Mesozoic-age upper Ellesmerian units. The post-orogenic clastic deposits include both marine units (for example, Hunt Fork and Kayak Shales) and fluvial units (Kanayut and Kekiktuk Conglomerates) assigned to the Endicott Group (Brosgé and Tailleur, 1971). Although somewhat obscured by later northward thrusting in the Brooks Range, the deposition of Endicott clastic units seems to follow a general time-transgressive trend in which older (Late Devonian) and thicker units occur to the south, whereas younger (Mississippian) and thinner units occur on the northern Arctic Platform.

An exception to this regional stratigraphic trend is observed in seismic data from the Chukchi shelf area. There, a thick clastic wedge, tentatively correlated to the Endicott Group, is underlain by a seismic unit inferred from interval velocity data to be composed of carbonate rock. This is the only known occurrence of a thick carbonate unit stratigraphically interposed between the Endicott Group and acoustic (presumably metamorphic) basement north of the Brooks Range. The stratigraphic relationship to the underlying basement complex (assumed to be Middle Devonian or older) and overlying Endicott-equivalent clastic wedge (Late Devonian to Late Mississippian) suggests that this locally restricted carbonate unit may be age-equivalent to carbonate rocks of the Baird Group described in the southwestern Brooks Range (Tailleur and Brosgé, 1970). We include this carbonate unit in the lower Ellesmerian sequence because it is relatively undeformed and is closely associated with inferred Endicott-equivalent strata. It must be emphasized that the lower Ellesmerian sequence observed in the Northeast Chukchi Basin is anomalous with respect to thickness and apparent age as compared with traditional Ellesmerian units on the Arctic Platform to the east.

Deposition of the Endicott Group was followed by a slow marine transgression and subsequent accumulation of platform carbonates assigned to the Lisburne Group. A diverse assortment of shallow marine carbonate facies progressively onlapped existing basement highs, with time-transgressive deposition progressing northward from Late Mississippian to Pennsylvanian time (Armstrong and Bird, 1976). Although the Lisburne Group is wider in regional distribution than the underlying Endicott Group, its overall thickness increases significantly in fault-bounded basins that continued to subside through Late Mississippian time (Tetra Tech, 1982).

In Late Pennsylvanian to Early Permian time, erosion of Carboniferous and older strata occurred in response to sea-level lowering or epeirogenic elevation of the Arctic Platform. The effects of this episode are particularly pronounced on positive basement features (Armstrong and Bird, 1976; Carter and others, 1977; Dutro, 1981; Tetra Tech, 1982) and on the northern Chukchi shelf, where it divides the Ellesmerian section into distinct upper (Permian to Early Cretaceous) and lower (Middle(?) Devonian to Permian) seismic sequences. We refer to this unconformity as the Permian unconformity (PU, fig. 3) and believe it is correlative to the "Echooka unconformity" as defined by Tetra Tech (1982) in NPRA. Grantz and others (1982a) also recognized this unconformity in the Chukchi shelf region and termed the underlying, pre-Permian section "Eo-Ellesmerian."

The upper Ellesmerian transgressive cycle began in Late Permian time, with marine sandstones and shales assigned to the Sadlerochit Group onlapping structural highs from south to north. The basal transgressive sandstones of the Echooka Formation (Late Permian) are overlain by the deepwater shales of the Kavik Formation (Early Triassic). In the upper Sadlerochit Group, fluvial-deltaic deposits of the Ivishak Formation (Early to Middle Triassic) represent a progradational pulse from the source terrane to the northeast. In the southern distal portions of the basin, time-equivalent rocks are composed of a deepwater facies known as the Siksikpuk Formation.

In Middle to Late Triassic time, a second marine transgression extended north of the present Beaufort coastline. Limestone, mudstone, sandstone, and phosphatic beds assigned to the Shublik Formation were deposited in a low-energy, moderately deepwater environment (Detterman and others, 1975).

The Shublik Formation is overlain by well-sorted, fine-grained, glauconitic sandstones and interbedded marine shales of the Sag River Formation (Late Triassic to Early Jurassic). Sag River sandstone lenses probably represent a barrier beach complex that prograded to the south over deeper water Shublik sediments (Jones and Speers, 1976).

The upper Ellesmerian transgression reached its maximum extent in Jurassic time when the Kingak Formation was deposited in a moderately deepwater setting throughout northern Alaska and Canada (Poulton, 1982). Lithologic studies and organic chemistry analyses suggest that the Kingak shelf shoaled to the northwest in Alaska, resulting in an overall thinner and more sand-prone facies, while to the southeast a thick, organic-rich shale facies accumulated (Magoon and Claypool, 1984). In western NPRA, transgressive marine shelf sandstones are interbedded with Kingak shales. These lenses are shingled above one another, progressively shifting localized sandstone deposition to the northwest in the Lower to Middle Jurassic section (Tetra Tech, 1982).

In Late Jurassic to Early Cretaceous time, the northern part of the Arctic Platform began to shoal, probably in response to thermal uplift of the incipient rift zone (by analogy to the Falvey model). Locally derived, shallow marine sandstone lenses are locally common in the uppermost Kingak Formation, particularly above basement highs. These discontinuous sandstone bodies have been informally referred to as "Kuparuk River sands." In the type area (the Kuparuk oil field), sandstone beds assigned to the Kuparuk Formation (Carman and Hardwick, 1983) lie above and below the regional rift-onset unconformity (LCU). In the present report, the usage of "Kuparuk River sands" is restricted to sandstones immediately below the LCU in the upper Ellesmerian sequence. Lower Cretaceous sandstones above the regional unconformity are included in our Rift sequence.

RIFT SEQUENCE

Previous geologic studies of northern Alaska have usually divided the Phanerozoic section into three main sequences (Franklinian, Ellesmerian, and Brookian). However, these studies have often disagreed on the boundary between the Ellesmerian and Brookian sequences as well as the placement of Lower Cretaceous (generally Neocomian) strata. The Neocomian section, often referred to as the "Pebble Shale unit," has been included in the Ellesmerian sequence (Grantz and others, 1982b), the Brookian sequence (Tetra Tech, 1982), or considered as a separate "Barrovian" sequence (Carman and Hardwick, 1983). Because the Neocomian section is distinctly bracketed by regional unconformities and, in the offshore area, its thickness and depositional setting are uniquely related to the rift zone which was located on this part of the Arctic Platform, we have decided to distinguish these sediments as a separate seismic sequence informally termed the "Rift sequence" (fig. 3). We have not adopted the Carman and Hardwick (1983) terminology for several reasons: (1) their infrarift "Barrovian sequence" includes Kuparuk River sandstones and some upper Kingak shales which are clearly beneath the regional rift-onset unconformity (LCU); (2) the depositional setting for Kuparuk River sediments on the Barrow Arch is very different from that of the deep infrarift grabens to the north; and (3) there may be some confusion between a prior usage of "Barrovia" (Brosgé and Tailleur, 1971) as the northern source terrane for Ellesmerian sediments and "Barrovian" (Carman and Hardwick, 1983) for sediments derived from Ellesmerian highlands in the rift zone.

Two time-transgressive regional unconformities form the boundaries of the Rift sequence. The lower unconformity is a southward-dipping erosional surface that progressively truncates underlying Ellesmerian rocks until it eventually reaches Franklinian basement on northern portions of the Arctic Platform. This angular unconformity has been termed the "Lower Cretaceous unconformity" (LCU) by Jamison and others (1980) and the "Pebble Shale unconformity" by Bird (1982). The LCU forms part of the trap for petroleum pooled in Ellesmerian strata at the Prudhoe Bay field. The upper unconformity forms a southward-dipping seismic couplet with the LCU in the Colville Basin but diverges from the LCU on the Beaufort shelf, becoming a gently northward-dipping depositional disconformity that is downlapped by prograding Brookian horizons. This unconformity has been termed the "breakup unconformity" (BU) by Grantz and others (1982b) and corresponds to the top of the Pebble Shale unit (Bird, 1982).

As the name implies, the depositional setting for the Rift sequence is closely related to the locality, time interval, and structural character of the Mesozoic rift zone which developed on the northern Arctic Platform in latest Jurassic to Early Cretaceous time (fig. 4). During the early rift stage, Ellesmerian units were extensively eroded on uplifted blocks, and clastic sediments shed into local fault-bounded basins. The largest of the infrarift basins is the Dinkum graben (Grantz and May, 1982), which contains a sedimentary section at least 10,000 feet thick. Several smaller, but genetically related, infrarift basins are identified farther to the west (fig. 9). As the rift zone evolved through Neocomian time, it subsided and the supply of clastic material from highlands to infrarift basins was eliminated. The upper facies of the Rift sequence may be characterized as relatively deepwater, starved-basin deposits lithologically similar and age-equivalent to the Pebble Shale unit onshore. During this time tectonic activity began in the Brooks Range to the south, and thick flysch deposits of the Okpikruak or Kongakut Formations were shed northward into the Colville foreland basin from the orogenic belt.

BROOKIAN SEQUENCE

The Brookian sequence (Early Cretaceous to Pliocene) is the thickest and most widespread sedimentary sequence in the planning area as well as the most complex stratigraphically and structurally. It is essentially a huge wedge of clastic sedimentary rock which prograded northward from the Brooks Range orogenic belt (fig. 4). This wedge initially filled the Colville Basin and then prograded north across the newly formed continental margin into the Nuwuk and Kaktovik Basins. The Brookian sequence is bounded at its base by the breakup unconformity (BU), which is typically a depositional discontinuity, and at its top by a low-angle unconformity (QU) at the base of the Pleistocene sequence (fig. 3). The thickness of the Brookian section varies from less than 3,000 feet on the Barrow Arch (fig. 2) to greater than 35,000 feet (6-second seismic record length) in the Nuwuk Basin north of the Hinge Line. In the Kaktovik Basin the Brookian sequence is over 8 seconds thick (CDP record length). The lower portion (approximately half) of this clastic wedge is composed of sigmoidal clinoform and hummocky (foreset) reflectors indicative of deepwater, prodelta marine shales (Brown and Fisher, 1977). Lithologic descriptions of numerous North Slope wells confirm this interpretation. The lower Brookian shale facies is overlain by a series of parallel, high-amplitude (topset) reflectors that gently dip into the main depocenters. This seismic facies is typical of depositional environments ranging from coastal plain to marine shelf (Brown and Fisher, 1977). Well data confirm that the upper Brookian facies includes fluvial (nonmarine) as well as neritic (marine shelf) deposits, with a high proportion of sandstone and abundant coal beds.

Although a very detailed lithostratigraphic nomenclature has been developed for Brookian strata (Brosgé and Tailleur, 1971; Molenaar, 1983), an abbreviated nomenclature is sufficient for our purposes (fig. 3). In the western part of the North Slope and adjacent offshore areas, the lower, prodelta shale facies is referred to as the Torok Formation (Aptian to Albian) and the upper, fluvial-deltaic facies is referred to as the Nanushuk Group

(Albian to Cenomanian). In the central part of the North Slope and adjacent offshore areas, prograding Brookian strata are identified as the Colville Group (Cenomanian to Maestrichtian age) and the Sagavanirktok Formation (Tertiary).

Beginning in Late Cretaceous to early Tertiary time, Brookian sedimentation was focused in the Kaktovik Basin (fig. 1). West of Barter Island (the Camden sector), the Brookian sequence consists of a single major progradational cycle, where Paleocene to Eocene marine shales are overstepped by Oligocene and Miocene fluvial-deltaic beds. East of Barter Island (the Demarcation sector), the Brookian sequence contains numerous major transgressive and regressive cycles more analogous to the Mackenzie Delta region of Canada than to the North Slope of Alaska. Fluvial-deltaic sediments deposited during regressive cycles in the Paleocene (equivalent to Moose Channel/Reindeer Formation), Oligocene to middle Miocene (equivalent to Kugmallit/Pullen sequence), and late Miocene to Pliocene (Beaufort Formation) are separated by local unconformities and transgressive marine shales (Young and others, 1981; Willumsen and Cote, 1982). The complex stratigraphy in the eastern Beaufort area is apparently related to contemporary tectonics in the northeastern Brooks Range as well as syndepositional tectonics within the eastern Kaktovik Basin. The Brookian depositional cycle was terminated by sea-level lowering associated with Pleistocene glacial periods.

PLEISTOCENE SEQUENCE

The Pleistocene section is identified as a separate seismic sequence because it is bounded by regional unconformities and it accumulated in a distinctly different depositional environment than the underlying Brookian wedge. It can be argued, however, that these coastal plain and glaciomarine deposits should be included in the Brookian sequence because they were also partially derived from the Brooks Range. A low-angle, regional unconformity (QU) separates the progradational Brookian sequence from an overlying sequence of Pleistocene age (Craig and Thrasher, 1982). This sequence is correlative with the Gubik Formation of the Arctic coastal plain and consists of a laterally discontinuous group of marine and nonmarine rocks deposited during numerous glacial and interglacial periods (further discussion in Part 3, Environmental Geology). The Pleistocene section may be several hundred feet thick on the outer Beaufort shelf, but is conspicuously absent on the crests of shallow folds in the Kaktovik Basin (Dinter, 1982) as well as on much of the Chukchi shelf (Grantz and others, 1982a). Lithologies recovered from shallow boreholes on the inner shelf vary from massive siltstone to coarse-bedded gravels with peat layers (Harding-Lawson, 1979). Onshore, the Pleistocene section and upper portions of the Brookian sequence typically contain a permafrost layer up to 1,500 feet thick. This permafrost zone is projected (by refraction velocity studies) northward beneath the present Beaufort shelf where it grades laterally into unfrozen strata (Neave and Sellmann, 1983). The permafrost layer apparently does not occur on the Chukchi shelf (Grantz and others, 1982a).

HOLOCENE SEQUENCE

The Holocene sequence lies above a strong, often irregular reflector at the top of the Pleistocene sequence and is generally recognized as a seaward-thickening, acoustically transparent layer (Craig and Thrasher, 1982). Its relatively uniform composition (sandy silt) and unconsolidated state are probably responsible for its acoustic transparency. The surface of the Holocene sequence, the seafloor, is covered by ice gouges and small-scale bed forms, creating a very irregular microrelief. The overall thickness of this unit is uncertain (Briggs, 1983), although the thickness of the acoustically transparent layer ranges from zero nearshore, or above shallow folds, to several tens of meters on the outer shelf (Dinter, 1982; Craig and Thrasher, 1982).

3

Seismic Stratigraphy

This section presents seismic profiles which represent the general stratigraphy and structural character of the Beaufort Sea Planning Area. Western Geophysical Company (WGC) has generously allowed MMS to release these data for our general regional analysis. The nonexclusive WGC data base in the Beaufort Sea Planning Area is shown in figure 5. Where possible, seismic profiles were tied to onshore, publicly available wells providing direct correlations into offshore provinces. Formation tops and regional unconformities as tabulated for North Slope wells by Witmer and others (1981) and Bird (1982) were used in conjunction with numerous Husky-NPR Geologic Reports. These datums were tied to seismic horizons using synthetic seismograms that were generated from digitized 5-inch, long-spaced sonic logs. We derived the depth conversion scales given on the seismic profiles from the Dix Equation using typical Root Mean Square (RMS) velocities picked from WGC Velans. The regional time-depth conversions shown on the seismic plates are only approximations because of the complex structure and stratigraphy of the geologic provinces. Significant local velocity variations can be expected within each geologic province. A regional time-depth curve, although perhaps practical in a report of regional scope, may not be an applicable tool for detailed mapping.

Our seismic interpretation focuses on the stratigraphy and structural evolution of the major tectonostratigraphic sequences bounded by regional unconformities. Maps of seismic horizons representing prospective rock units will not be presented in order to protect the proprietary interests of lease-holders of Federal OCS tracts.

In order to describe the complex geologic history of this very large region, we found it necessary to divide the planning area into three geographic sectors (fig. 6). The sectors may each contain one or more petroleum provinces (fig. 1) which are distinct stratigraphically as well as structurally.

NORTHEASTERN CHUKCHI SHELF

The Chukchi shelf sector is quite different in structural character and Paleozoic stratigraphy from contiguous areas of the Arctic Platform on the North Slope. The well control in adjacent

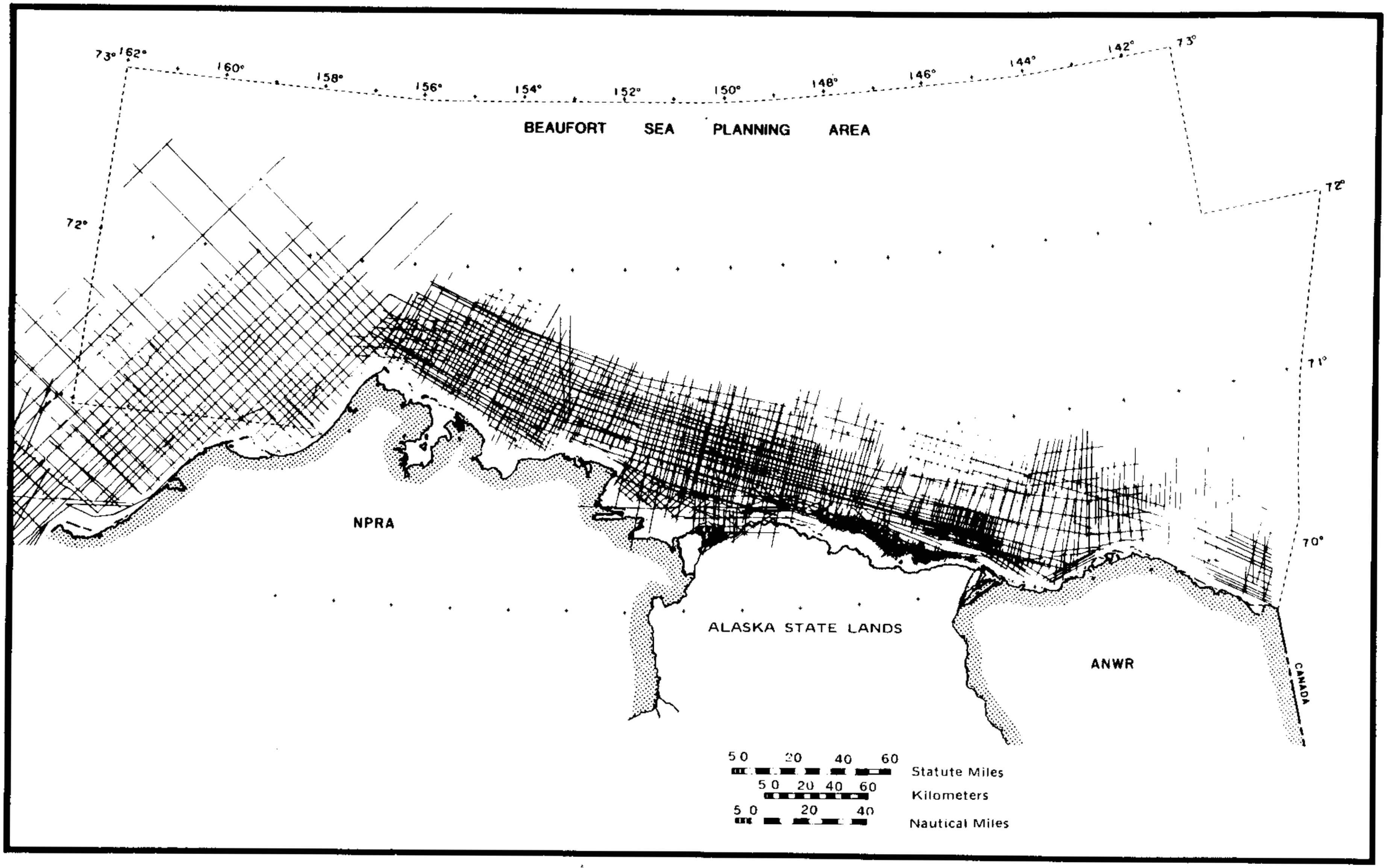


Figure 5.

Regional nonexclusive seismic data coverage in the Beaufort Sea Planning Area acquired by Western Geophysical Company from 1977 through 1984.

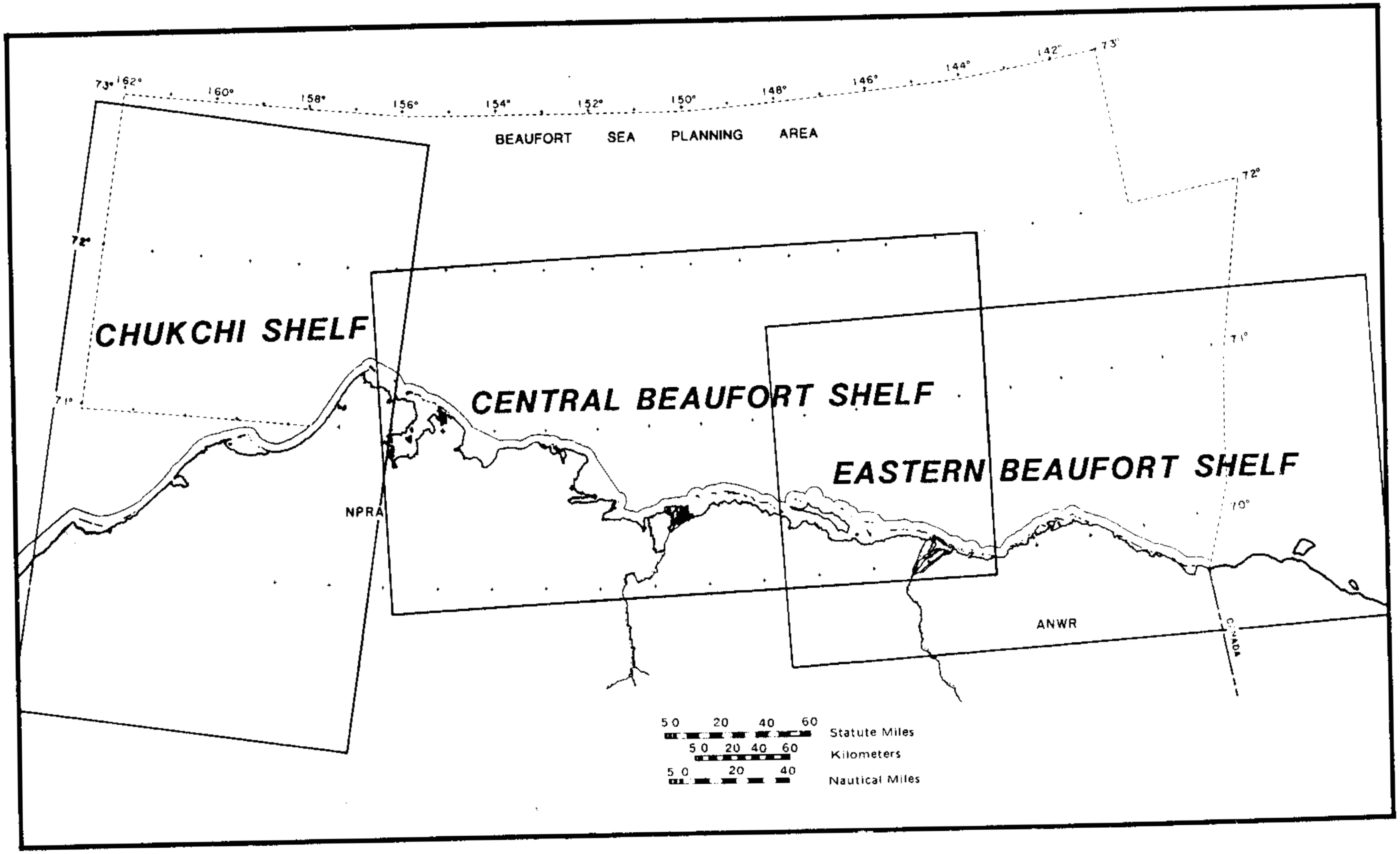


Figure 6.
Geographic subdivision of the Beaufort Sea Planning Area. The Chukchi shelf, central Beaufort shelf, and eastern Beaufort shelf sectors contain one or more petroleum provinces. These provinces are shown in figure 1.

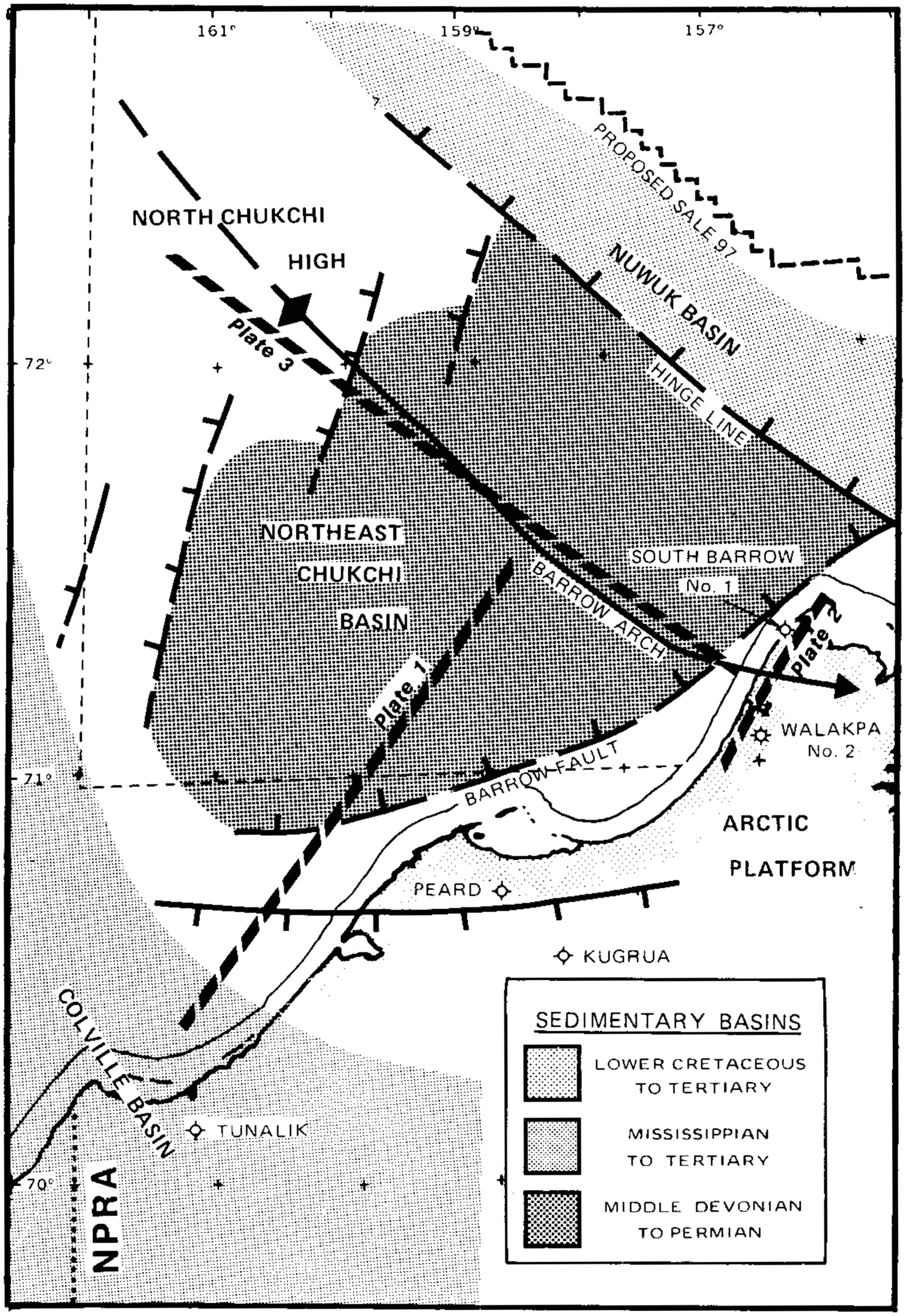


Figure 7.

Geologic framework of the Chukchi sector. Our geologic interpretation is illustrated by three regionally compressed seismic profiles (plate 1, 2, and 3) controlled by jump-ties to onshore exploration wells in western NPRA. Basement blocks, major fault zones, and sedimentary basins are labeled.

onshore areas is isolated from a relatively sparse seismic grid on the northeastern Chukchi shelf (fig. 5) by complex structural zones developed in Paleozoic time. Direct seismic correlation of the Paleozoic stratigraphy across these structural discontinuities is impossible, thereby rendering our analysis of the lower parts of the seismic profiles somewhat uncertain.

The structural framework and sedimentary basins in the northeastern Chukchi Sea are shown in figure 7. In contrast to the gently southward-dipping surface of the Arctic Platform to the east, the Chukchi sector has an irregular northeast-trending "basin and range" structural character, where deep sedimentary basins are bounded by complex fault zones. The largest of these basins, which we informally term the "Northeast Chukchi Basin," is structurally isolated from the Arctic Platform to the east by a poorly resolved, NE-SW-trending fault zone (informally termed the "Barrow fault"). The Northeast Chukchi Basin is a deep half-graben filled with a clastic wedge of Paleozoic age. The deepest part of this Paleozoic basin lies along the Barrow fault, and the basin floor rises towards the northwest where it is deformed across a highly faulted structural uplift referred to as the "North Chukchi high" (fig. 2). This structural uplift is characterized by a dense array of extensional block faults that offset and tilt the Brookian sequence in the shallow subsurface. The broad, unfaulted crest of the Barrow Arch plunges to the southeast over the older Northeast Chukchi Basin and is disrupted at its northwestern crest by the faulted uplift of the North Chukchi high. The northeastern part of the Chukchi sector contains the Hinge Line, which trends beneath the outer continental shelf. The Nuwuk Basin lies north of the Hinge Line. The Chukchi sector is flanked to the south by the Colville Basin, which contains over 30,000 feet of sedimentary rocks assigned to the Ellesmerian and Brookian sequences (fig. 2). The Northeast Chukchi Basin is structurally isolated from the Colville Basin by a complexly structured basement ridge.

Plate 1 is a seismic "dip" line which illustrates the stratigraphy of the Colville and Northeast Chukchi Basins, and the structural character of the Barrow Arch (fig. 7 shows seismic profile locations). Stratigraphic control for this seismic interpretation is provided by jump-ties to coastal exploration wells in western NPRA, in particular the Tunalik No. 1 well. This deep well (TD at 20,335 feet) penetrated a nearly complete section of Ellesmerian and Brookian strata, representing deposition from late Paleozoic to Mesozoic time. However, the Tunalik No. 1 well bottomed in Pennsylvanian carbonates of the Lisburne Group and does not provide direct control for older (Endicott Group or Franklinian basement) seismic horizons. The correlation of pre-Lisburne stratigraphy from the Colville Basin northward into the Northeast Chukchi Basin is also obscured by an intervening structural zone which effectively isolates these two major basins. As shown in figure 7, this structural zone occurs at the projected intersection of several major fault trends and may represent a complexly faulted basement ridge of pre-Lisburne age.

The interpretation of the upper Ellesmerian and Brookian seismic sequences on plate 1 is relatively simple because of direct well control and uncomplicated structure. The PU, picked at the base of the Sadlerochit Group, is a smooth, unfaulted, angular unconformity which dips southward from the Barrow Arch. This unconformity represents the contact between the upper Ellesmerian and lower Ellesmerian seismic sequences (fig. 3). The Permian and Triassic units (Sadlerochit Group and Shublik Formation) in the upper Ellesmerian sequence progressively onlap the PU and thin northward. The overlying Triassic and Jurassic units (Sag River and Kingak Formations), which depositionally overstep the older units, are progressively truncated at the LCU northward onto the Barrow Arch. On the broad crest of the Barrow Arch, all upper Ellesmerian and Pebble Shale (Rift sequence equivalent) strata have been removed by erosion at the LCU and BU, and a thin layer of Brookian strata lies directly on lower Ellesmerian deposits. The Pebble Shale unit (age equivalent to the Rift sequence) is easily identified in the Colville Basin and on the southern flank of the Barrow Arch as a distinctive seismic couplet formed by the LCU and BU. The Brookian sequence thins considerably northward from the Colville Basin over the Barrow Arch, and is reduced to a thickness of less than 3,000 feet on the crest of the arch. Brookian foreset and bottomset beds, correlative to the Torok Formation, downlap the BU. Brookian topset beds, correlative to the Nanushuk Group which originally prograded northward, are progressively truncated at a shallow unconformity related to post-Albian uplift of the Barrow Arch in the Chukchi sector.

The structural character of the northern Arctic Platform in the Barrow area is illustrated by the seismic profile presented in plate 2. Well control for this seismic interpretation is provided by the Walakpa No. 2 and the South Barrow No. 1 wells (fig. 7). At the Walakpa No. 2 well, the upper Ellesmerian and Brookian sequences have thinned considerably, and the Shublik Formation (Middle to Late Triassic) lies directly on Franklinian argillite of Ordovician to Silurian age (Carter and Laufeld, 1975). The lower Ellesmerian sequence (Endicott and Lisburne Groups) is absent on this part of the Arctic Platform as a result of depositional onlap (on the EU) and perhaps some erosional truncation (at the PU). Similarly, the upper Ellesmerian sequence is considerably reduced in thickness as a consequence of depositional onlap (on the PU) and erosional truncation (at the LCU). Between the Walakpa No. 2 and the South Barrow No. 1 wells, the upper Ellesmerian section is completely truncated at the LCU, and the Lower Cretaceous Pebble Shale unit lies directly on the basement complex (Haga and Mickey, 1982). The Pebble Shale unit (Rift sequence equivalent) remains fairly constant in overall thickness south of the Barrow Arch and then abruptly thickens on the north flank of the basement ridge (right side of plate 2). Plate 2 illustrates that the crest of the Barrow Arch defined by a Cretaceous horizon (the BU) lies south of the basement high in the Barrow area. The Brookian sequence thins to approximately 2,000 feet on the Barrow Arch from over 10,000 feet in the Colville Basin (Bird, 1982) largely as the result of erosion on the Barrow high. North of the Hinge Line, these Cretaceous Brookian strata thicken to greater than 35,000 feet (6-second CDP record length) in the Nuwuk Basin beneath the Beaufort shelf.

It is important to inspect the seismic character of the Franklinian sequence in plate 2 which is typical of acoustic basement observed elsewhere on the Arctic Platform. The reflection from the top of the basement complex is usually moderate to high amplitude, and internal reflectors generally lack any lateral continuity. Consequently, few attempts have been made to resolve the seismic stratigraphy of the Franklinian sequence beneath the Arctic Platform.

The seismic profile shown in plate 3 extends from the Arctic Platform, across the Northeast Chukchi Basin, and onto the eastern flank of the North Chukchi high (fig. 7). Subsurface control for this interpretation is provided by a jump-tie to the Walakpa No. 2 well. This seismic profile generally parallels the SE-plunging axis of the Barrow Arch. In marked contrast to the acoustic basement beneath the PU on the Arctic Platform to the east (plate 2), pre-Permian rocks in the Northeast Chukchi Basin exhibit laterally continuous horizons with a distinctly bedded appearance. Primary depositional features, such as sigmoidal prograding clinoforms, are common, as are structural features, such as faults and folds. Two distinct seismic units can be recognized within the lower Ellesmerian sequence: an upper clastic wedge characterized by numerous detached folds, and a lower unit, relatively uniform in thickness, characterized by parallel, high-amplitude, laterally continuous horizons. These apparent sedimentary units lie unconformably on acoustic basement, presumably correlative to the Franklinian sequence.

The rocks which we have identified as lower Ellesmerian in plates 1 and 3 are enigmatic: they clearly have not experienced the same degree of tectonic alteration as lower Paleozoic (Franklinian sequence) basement rocks of the Arctic Platform, but they also are quite different from Ellesmerian strata distributed throughout Arctic Alaska. Grantz and Eittriem (1979) first recognized these rocks and identified them as "lower Ellesmerian or Franklinian and Pre-Cambrian(?)." Grantz and May (1982) later proposed that these strata (their unit "SOf," p. 84) are correlative to the Ordovician to Silurian argillite of the basement complex in the Barrow area. Subsequent maps depict a shallow Franklinian basement high on the eastern Chukchi shelf overlain by a thin Brookian section (Ehm, 1983). However, a comparison of plates 1 and 3 (on the Chukchi shelf) with plate 2 (in the Barrow area) shows that it is unlikely that the metamorphic complex of the Arctic Platform is correlative to the sedimentary strata in the Northeast Chukchi Basin. We believe that a major fault zone (the "Barrow fault," fig. 7) must juxtapose the younger sedimentary deposits in the basin with the basement rock of the Arctic Platform. The seismic expression of this fault zone is poorly resolved because of its high (perhaps reverse) angle and the lack of available seismic data in state waters. A later publication by Grantz and May (1984) abandoned the Franklinian correlation to these Paleozoic sedimentary rocks and provisionally assigned them to an informal group termed the "Eo-Ellesmerian sequence." Our work essentially agrees with this conclusion; however, we refer to these sedimentary units as the lower Ellesmerian sequence.

Overlying the lower Ellesmerian sequence on this seismic profile is a highly abbreviated section of Mesozoic rocks. The upper Ellesmerian, Rift, and Brookian sequences occur at shallow subsurface depths (3,000 feet or less) and are truncated at several erosional unconformities related to uplift of the Barrow Arch. On the eastern flank of the North Chukchi high, the upper Ellesmerian sequence and Pebble Shale are entirely truncated, and Lower Cretaceous Brookian strata lie unconformably on Paleozoic rock.

On the northwest end of this seismic line, the broad, extensively faulted North Chukchi high dissects the crestal portion of the Barrow Arch. This structural uplift extends into the adjacent Chukchi Sea Planning Area (D. Thurston, personal commun.). In this interpretation, we show Brookian strata lying unconformably on the lower Ellesmerian sequence. It is also possible that Franklinian basement rocks occur at shallow subsurface depths beneath the thin, highly faulted Brookian section. An accurate delineation of individual fault traces is difficult because seismic data coverage is sparse, but the structural character is one of high-angle, basement-involved block faulting on a north-to-northeast trend. The timing and origin of the tectonic activity on the North Chukchi high is uncertain; however, large near-surface fault displacements of Brookian beds suggest that it occurred in Late Cretaceous to Tertiary time. The block-fault pattern clearly deforms the NW-SE-trending Barrow Arch.

These seismic profiles clearly illustrate that the "Barrow Arch" in the Chukchi sector is not coincident with a regional basement ridge. The Barrow Arch, which trends roughly parallel to the Hinge Line, is a structural flexure between two major post-rifting basins (Nuwuk and Colville; fig. 2). Early Cretaceous and younger strata exhibit the broad, unfaulted symmetry typical of an arch, whereas the structural relief of the basement rock has a highly irregular, block-faulted configuration. On the Arctic Platform (east of the Barrow fault), the Barrow Arch coincides approximately with a SE-plunging basement ridge (fig. 2). West of the Barrow fault, however, the Northeast Chukchi Basin and North Chukchi high trend obliquely to the Barrow Arch and represent entirely different tectonic episodes.

These seismic data have illustrated that Mesozoic and younger strata lie at shallow depths over large portions of the eastern Chukchi shelf. The geology of the underlying section is, therefore, of primary consideration for the petroleum potential of the Chukchi sector. By tracing seismic horizons, it can be demonstrated that the lower Ellesmerian sequence in the Northeast Chukchi Basin is pre-Permian in age. A lower age limit cannot be as accurately defined, although these sedimentary rocks are apparently younger than the Upper Ordovician to Silurian argillites of the Arctic Platform. These middle to upper Paleozoic deposits are separated into two distinct seismic units which unconformably overlie acoustic basement (presumably representing lower Paleozoic metamorphic rock). The lower seismic unit consists of parallel, high-amplitude, laterally continuous horizons and has a constant overall thickness throughout the basin (approximately 10,000 feet). The upper seismic unit appears to be a clastic wedge which has been deformed into a series of folds that roughly parallel the Barrow fault zone. These folds are thousands of feet in amplitude and are detached across a décollement from the underlying seismic unit. Restoration of azimuths (by removal of regional dip) for prograding clinoform horizons yields a primary depositional strike of 45 degrees and an initial dip (before basin tilting) of 2 degrees to the southeast. The southeastward accretion of sigmoidal seismic horizons also suggests that this basin received clastic sediment from the northwest.

The lithology of these seismic units can be inferred from their acoustic velocity. Figure 8 summarizes a velocity analysis of the two lower Ellesmerian seismic units and the Brookian sequence which unconformably overlies these deposits (plate 3). Interval velocities calculated by using WGC Velan data are plotted with sonic velocities of known rock units from various North Slope wells. Group A (Brookian sequence) velocities are comparable to those obtained for Lower Cretaceous rocks (Torok Formation) at shallow burial depths. Group B (lower Ellesmerian clastic wedge) velocities are similar to interval velocities for Endicott Group rocks. The interval velocity for Group B is somewhat higher than that of the Torok Formation at equivalent subsurface depths. This difference could be explained by a greater abundance of sandstone in this clastic wedge (compared to the Torok Shale) or a considerable amount of post-depositional uplift. The acoustic velocity of Group C (basal lower Ellesmerian unit) is typical of carbonate rocks characterized by the Lisburne Group. The seismic velocities of the Lisburne Group are shown for comparative purposes only.

Our preliminary conclusions, based entirely on seismic data, are that the lower Ellesmerian sequence in the Northeast Chukchi Basin consists of a lower carbonate unit and an upper clastic unit of middle to late Paleozoic age. However, these units are not similar in thickness or in lithologic succession to the lower Ellesmerian units known from the central and eastern North Slope. There, the Endicott Group of Mississippian age (Kekiktuk and Kayak Formations) is conformably overlain by Mississippian to Pennsylvanian platform carbonates of the Lisburne Group (fig. 3). In the Northeast Chukchi Basin, the clastic wedge and basal carbonate units are much thicker, and the carbonate-clastic succession is reversed from the Endicott-

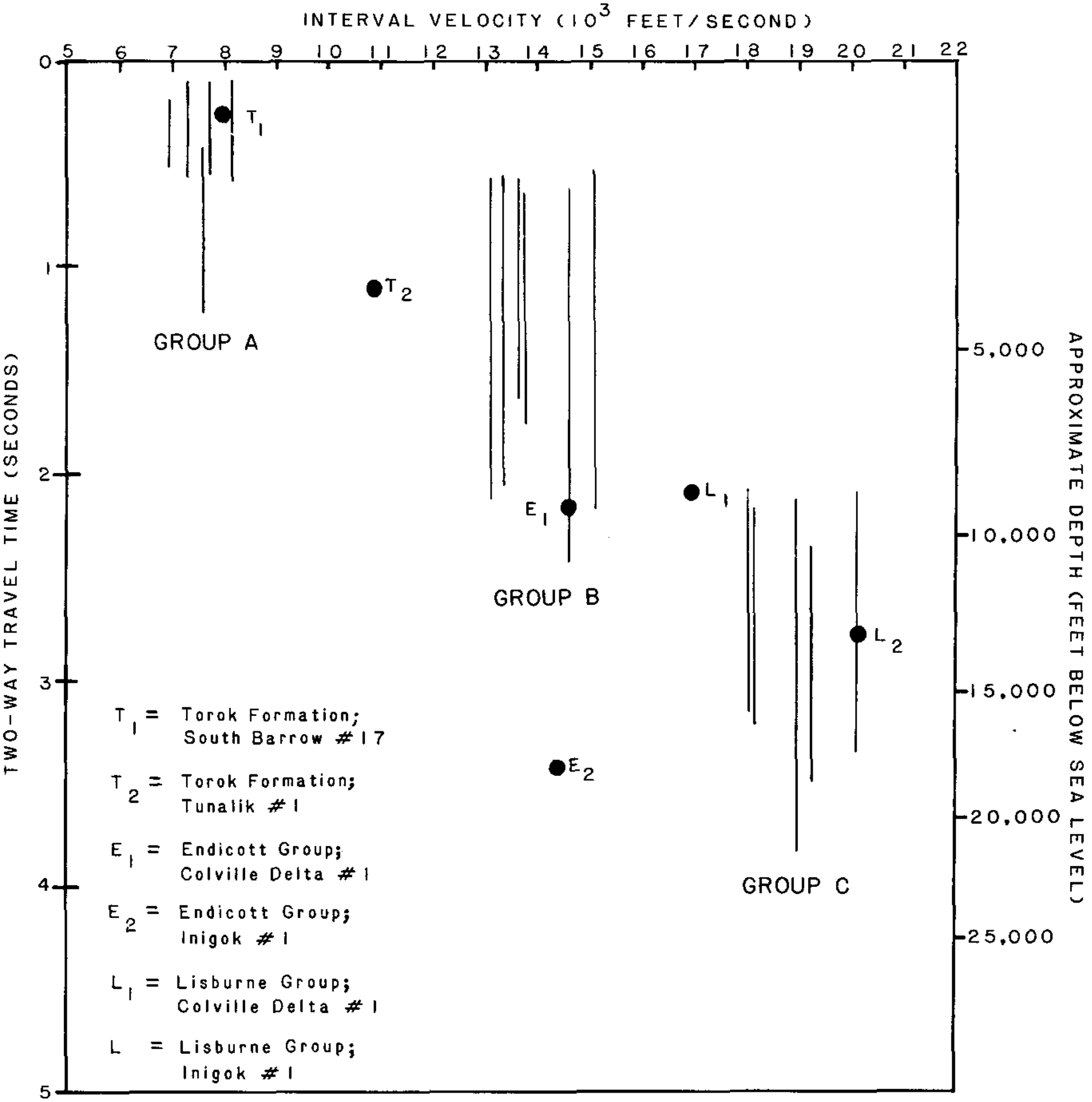


Figure 8.
Acoustic velocity analysis of seismic sequences identified beneath the Chukchi shelf. Dix interval velocities (shown as lines) were calculated by using RMS picks from Western Geophysical Company Velans. Typical acoustic velocities (solid dots) were computed as the inverse of interval transit times in sonic logs from onshore wells. Representative rock units in onshore wells are listed. Groups A, B, and C correspond to the seismic sequences labeled in the box on plate 3.

Lisburne relationship. The lower Ellesmerian seismic units in the Northeast Chukchi Basin are more similar to the stratigraphic succession of the Middle to Upper Devonian Baird Group (carbonates) and the Upper Devonian Endicott Group (clastics) exposed in allochthonous thrust sheets in the west-central Brooks Range (refer to Brosgé and Dutro, 1973; Nilsen and Moore, 1982a).

An alternative hypothesis is that the Paleozoic deposits in the Northeast Chukchi Basin are age equivalent to the Franklinian rocks of the North Slope basement complex, but were not tectonically altered by the mid-Paleozoic orogeny. Unaltered Franklinian rocks could have been juxtaposed against metamorphosed Franklinian rocks of the orogenic foldbelt along a shear zone represented by the Barrow fault. We find it unlikely that a regional orogenic belt would contain such sharp transitions along strike from highly tectonized to moderately deformed coeval strata without large horizontal displacements along a major fault. Regional depositional patterns, such as the progressive northward onlap of the Lisburne Group, suggest that this allochthonous Franklinian block may have "docked" against the Arctic Platform before Pennsylvanian time.

In the absence of direct (well bore) information, our preferred conclusion is that the lower Ellesmerian deposits in the Northeast Chukchi Basin are age equivalent to the allochthonous Middle to Upper Devonian rocks of the Baird and Endicott Groups in the west-central Brooks Range. We include these deposits in the lower Ellesmerian seismic sequence because they were not tectonically altered by the mid-Paleozoic orogeny which produced the basement complex of the Arctic Platform.

CENTRAL BEAUFORT SHELF

The central Beaufort shelf, between Point Barrow and Camden Bay, contains three petroleum provinces: (1) the Barrow Arch (province IA) on the Arctic Platform south of the Ellesmerian pinch-out, (2) the Outer Arctic Platform (province IB) south of the Hinge Line, and (3) the Nuwuk Basin (province IIA) north of the Hinge Line (fig. 1). Figure 9 locates regional basement features, two representative seismic lines, and pertinent control wells in the central Beaufort sector.

A representative seismic profile extending from the Husky J.W. Dalton well on the Arctic Platform into the Nuwuk Basin is presented in plate 4. On the Arctic Platform, the Ellesmerian sequence is characterized in seismic data as a relatively thin wedge of continuous, high-amplitude reflectors which dip gently southward. This sequence depositionally thins to the north and is progressively truncated at the LCU. Beneath the Barrow Arch, the PU lies on Franklinian basement, and lower Ellesmerian strata are absent farther north. The thickness of the upper Ellesmerian sequence is reduced considerably over the basement ridge as a result of depositional thinning and truncation at

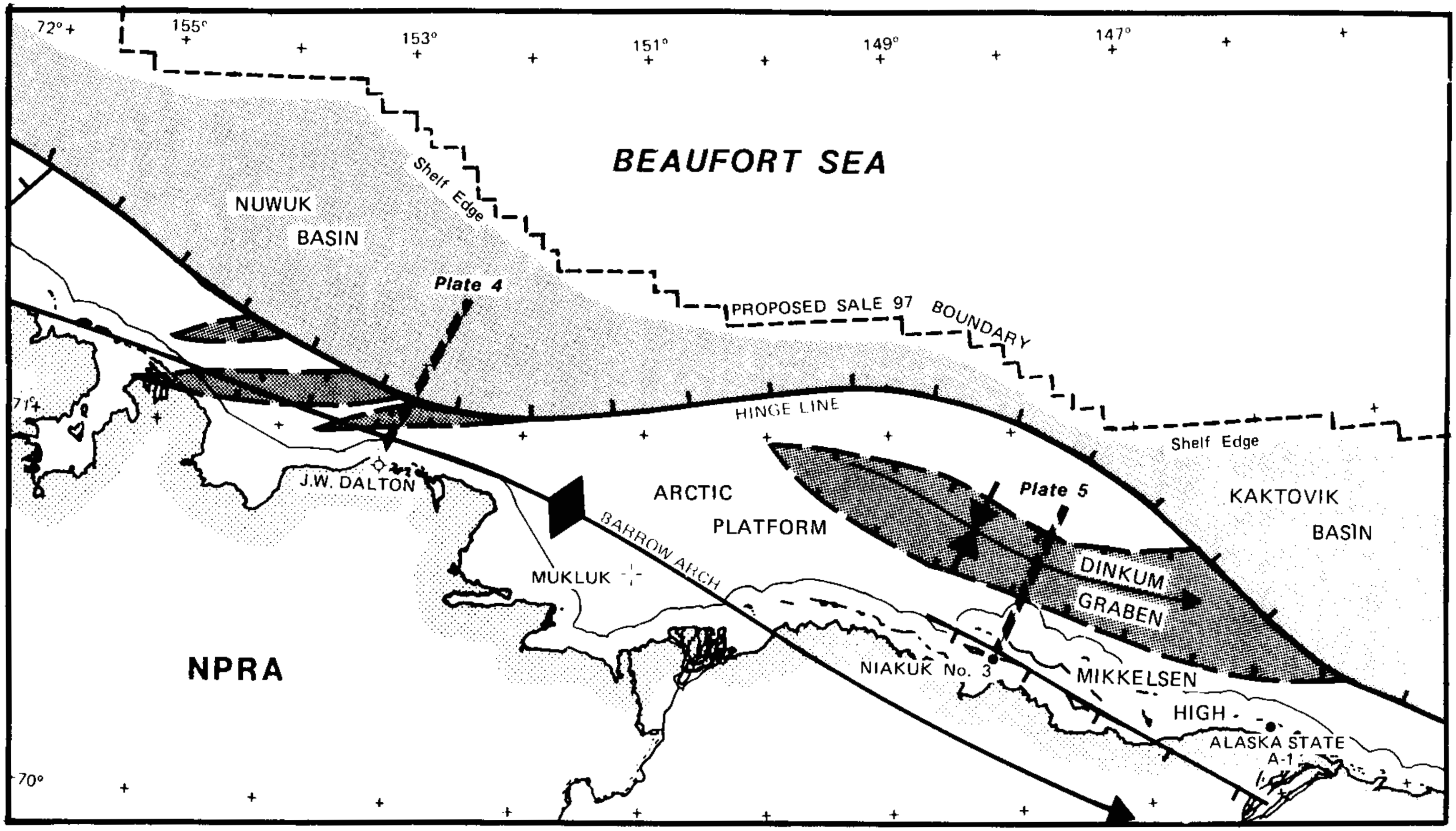


Figure 9.
Geologic framework of the central Beaufort shelf. The structure and stratigraphy of the Arctic Platform and Nuwuk Basin are illustrated by plate 4, extending offshore from the Husky J. W. Dalton well. The structure and stratigraphy of the Outer Arctic Platform are illustrated by plate 5, extending northward from the Sohio Niakuk No. 3 well into the Dinkum graben.

the LCU. The overlying Rift sequence (Pebble Shale unit) and Brookian sequence (Torok Formation-Nanushuk Group) are relatively constant in thickness and unfaulted over the Barrow Arch.

On the northernmost part of the Arctic Platform, the stratigraphy and structural character change rapidly. Remnants of the northward-thinning upper Ellesmerian sequence may be preserved locally in downdropped blocks beneath the LCU. Block faulting in the rift zone prior to the erosion at the LCU influenced the present distribution of upper Ellesmerian units on the northern Arctic Platform. The overlying Rift sequence thickens greatly into a graben typical of the Outer Arctic Platform. This infrarift depocenter is filled with several thousands of feet of well-stratified, high-amplitude horizons.

The Hinge Line (center of plate 4) marks an abrupt thickening of the Brookian sequence into the Nuwuk Basin and is identified by large-displacement, down-to-the-north basement faults and a listric fault system in overlying Brookian strata. The Hinge Line faults characteristically postdate basement faults that bound the infrarift grabens; that is, Brookian horizons are not usually faulted above the infrarift grabens as they are along the Hinge Line and in the basins farther to the north. The Hinge Line marks the northern edge of the Cretaceous continental margin. Post-rift subsidence along the continental margin is marked by the system of listric growth faults. These growth faults are not necessarily connected with the underlying basement faults; they seem to be detached from the underlying, pre-Brookian sequences along a décollement in the lower Brookian shale. The extensive growth fault system can be used to trace the approximate southern margin of post-rifting depocenters beneath the Beaufort shelf where the basement complex lies below the 6-second seismic records.

The Nuwuk Basin is located north of the Hinge Line and contains over 6 seconds (approximately 35,000 feet) of Brookian sediment. This Cretaceous to Tertiary depocenter is cut by numerous listric growth faults traceable from shallow subsurface depths to the base of coherent seismic data. The upper Brookian seismic facies, consisting of parallel to slightly divergent, high-amplitude, laterally continuous, "topset" horizons, is a facies-equivalent to the fluvial-deltaic strata of the Nanushuk (Lower Cretaceous) and Colville (Upper Cretaceous) Groups. The lower Brookian seismic facies, consisting of variable-amplitude, discontinuous to sigmoidal "foreset" horizons, is a facies-equivalent to the deepwater, prodelta shales of the Torok (Lower Cretaceous) and Seabee (Upper Cretaceous) Formations. The Rift sequence may be present at great subsurface depths (below 20,000 feet) beneath the Brookian fill of the Nuwuk Basin.

Plate 5 is a representative seismic line across the Mikkelsen basement high and the Dinkum graben. Well control is provided by the Sohio Niakuk No. 3 well, which contains a complete, but reduced, section of Ellesmerian units, the Pebble Shale, and the Brookian sequence. The lower Ellesmerian sequence (the Endicott and Lisburne

Groups) is present at the well but thins abruptly on the southern flank of the Mikkelsen high. The abrupt thickness change in the lower Ellesmerian section occurs as a result of depositional onlap (on the EU) and possible erosion at the PU. The northern flank of this local basement high was formed by faulting associated with the Mesozoic rift episode. Upper Ellesmerian strata (Sadlerochit Group through Kingak Formation) overstepped lower Ellesmerian units on the Arctic Platform but were subsequently truncated at the LCU. Near the crest of the Mikkelsen high, the LCU lies directly on Franklinian basement rock and Ellesmerian units are probably absent farther north.

In the Dinkum graben, two seismic facies can be distinguished in the Rift sequence. The lower facies is characterized by discontinuous, hummocky, high-amplitude reflectors and attains a thickness of over 10,000 feet on this profile. It is inferred to represent Lower Cretaceous clastic deposits composed of reworked Ellesmerian and Franklinian rocks which rapidly accumulated in infrarift depocenters. A possible analog for these clastic deposits may be the Point Thomson sandstones found south of the Mikkelsen high. The upper Rift facies consists of a relatively thin series of laterally continuous, high-amplitude reflectors which onlap to the south on the lower Rift facies (plate 5). We infer that these horizons represent deep basinal shales which are age equivalent to the Pebble Shale unit in onshore North Slope wells. In contrast to the relatively thin Pebble Shale onshore, the upper Rift facies reaches over 1,000 feet in thickness in the Dinkum graben. The thickness of the entire Rift sequence in the Dinkum graben cannot be accurately determined because Franklinian basement is difficult to resolve below about 4 seconds (approximately 20,000 feet). Similarly, the interpretation of the north wall of the Dinkum graben and the block-faulted basement relief along the Hinge Line is also very subjective at these subsurface depths, perhaps because of the low acoustic impedance contrast between deeply buried sedimentary (Rift sequence) and metasedimentary (Franklinian sequence) rocks.

The Brookian sequence (plate 5) lies above the BU and represents a northward-prograding clastic wedge of Cretaceous to Tertiary age. On the Mikkelsen high, local erosion at the BU occasionally truncates the Pebble Shale unit and upper Ellesmerian sequence. In these areas, the Brookian prodelta shale lies directly on Franklinian basement rock. Typically, however, the BU is a depositional unconformity between the starved-basin shale of the upper Rift facies and the more rapidly deposited prodelta shale of the prograding Brookian sequence.

As described in the previous plates, the Brookian sequence consists of two seismic facies: a lower "prodelta facies" composed of variable-amplitude, sigmoidal clinoform reflectors; and an upper "fluvial-deltaic facies" consisting of parallel, high-amplitude, laterally continuous seismic horizons. The lithology of the lower

Brookian facies is inferred to be deepwater shales, whereas the upper Brookian facies is inferred to represent fluvial, delta plain, and shallow marine shelf deposits with high proportions of sand to shale (Brown and Fisher, 1977). The Brookian sequence in south-central parts of the Beaufort shelf is probably age equivalent to the Colville Group (Late Cretaceous) and Sagavanirktok Formation (Tertiary) (fig. 3). The toplap contact between the fluvial-deltaic facies and prodelta facies probably represents a depositional disconformity where the sediment supply exceeded basin subsidence and clastic material bypassed nearshore shelf areas to deepwater depocenters farther north. On the northern end of this seismic profile, the interfingering of high-amplitude "topset" horizons with low-amplitude clinoform (shale) intervals suggests temporary variations in the rate of basin subsidence or sediment supply from the Brooks Range. Decreasing the rate of sediment supply (or increasing the basin capacity by subsidence) could result in local marine transgressions between shifting delta lobes on a regionally stationary shoreline.

EASTERN BEAUFORT SHELF

The geologic framework of the eastern Beaufort sector is shown in figure 10. This part of the planning area contains the Kaktovik Basin, north of the Hinge Line, and a narrow portion of the Arctic Platform. Onshore, the active tectonic front of the Brooks Range orogen and the southeastward-plunging Barrow Arch form prominent structural elements. The eastern Beaufort sector may be further subdivided into two geologically distinct sub-provinces: a western, or Camden, sector (province IIB) and an eastern, or Demarcation, sector (province IIC) (Grantz and others, 1982b). As shown in figures 2 and 10, the Arctic Platform extends only a short distance offshore beneath the present Beaufort shelf before it is intersected by the Hinge Line and is abruptly faulted below the 6-second CDP records (plate 6). The Kaktovik Basin is younger than the Nuwuk Basin in that it is filled largely with Tertiary sediment, whereas the Nuwuk Basin is filled primarily with Cretaceous sediment. The time-transgressive progradation of the Brookian delta system towards the northeast across the Beaufort continental margin is responsible for this age distribution. Both of these post-breakup depocenters contain over 6 seconds (approximately 35,000 feet) of Brookian strata and an extensive NW-SE-trending growth fault system related to active basinal subsidence north of the Hinge Line. In the Kaktovik Basin, the growth fault system which formed contemporaneously with early Tertiary basin subsidence is obliquely intersected by a series of NE-SW-trending compressional folds of late Tertiary to Quaternary age. These structures postdate the deposition of the Brookian clastic wedge.

Well control for the Camden sector is provided by the Exxon Alaska State A-1 well on the eastern end of the Mikkelsen high. This well discovered oil in Paleocene turbidite sands at the base of the Brookian sequence (Wharton, 1981). These oil sands are siliceous

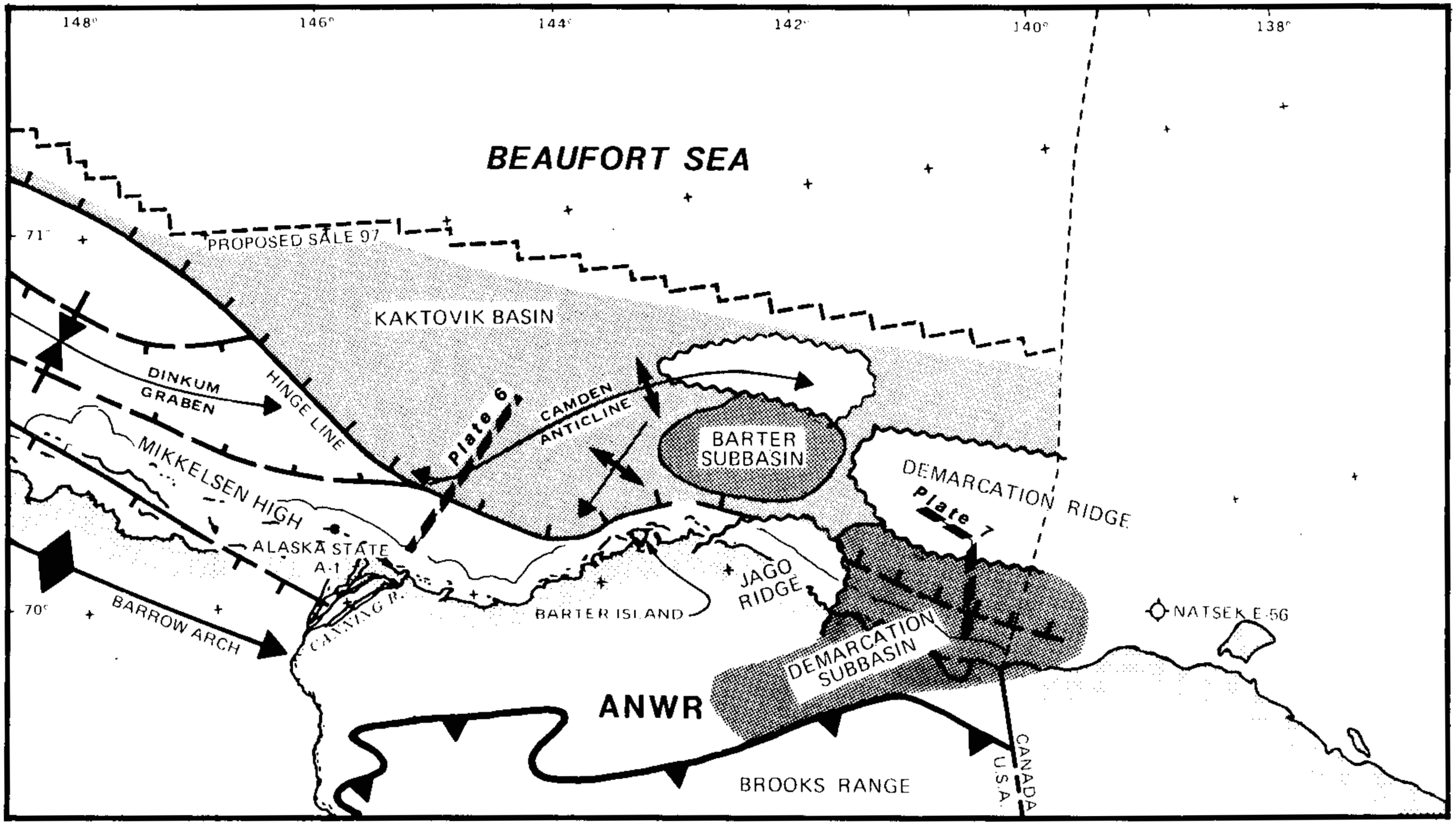


Figure 10.
Geologic framework of the eastern Beaufort shelf and adjacent onshore areas. Major fault zones, prominent anticlines, ridge uplifts, subbasins, and the Brooks Range foldbelt are labeled. The Exxon Alaska State A-1 exploration well on Flaxman Island provides stratigraphic control for the seismic profile in the Camden sector (plate 6). The Dome Natsek E-56 offshore test well provides stratigraphic control for the seismic profiles in the Demarcation sector (plate 7).

in composition and clearly not an extension of the Lower Cretaceous Point Thomson carbonate sands found in wells on the south side of the Mikkelsen high (discussed further in chapter 7, Potential Reservoir Formations). The Franklinian basement complex on the eastern end of the Mikkelsen high is not the massive argillite usually encountered in most wells on the Arctic Platform; instead, basement rock consists of interbedded quartzite, marble, and phyllitic shale. Oil shows in these fractured metasedimentary rocks suggest that migration has occurred from overlying (Brookian) sources into the basement complex.

Plate 6 is a representative seismic "dip" line illustrating the stratigraphy and structural features found in the Camden sector (subprovince IIB). The Brookian sequence in the Camden sector is similar to areas of the Beaufort margin farther west in that it consists of a lower seismic facies of prograding "foreset" clinoforms and an upper seismic facies of continuous, high-amplitude "topset" horizons. At the Alaska State A-1 well, the lower seismic facies is correlated to a massive shale interval of Paleocene to Eocene age (Wharton, 1981) inferred to represent deposition in a prodelta marine environment. The upper seismic facies is correlated to a predominantly sandy interval inferred to represent a nonmarine to marginal marine shelf environment.

South of the Hinge Line, the Brookian sequence is approximately 12,000 to 15,000 feet thick on the nearly flat-lying Arctic Platform; large faults offsetting both Brookian and Franklinian rocks are rare. On this portion of the Arctic Platform, the Ellesmerian sequence is absent as a result of extensive erosion, and the breakup unconformity lies directly on Franklinian basement, representing a hiatus between early Paleozoic and early Cenozoic time. Local outliers of the Rift sequence may occur in small infrarift grabens.

North of the Hinge Line, Franklinian basement blocks are abruptly downfaulted into the Kaktovik Basin. At the base of the Brookian sequence, we identify a group of high-amplitude horizons possibly correlated to the Rift sequence. The Rift sequence may occur elsewhere beneath the thick Brookian wedge in fault-bounded basins genetically related to the Dinkum graben. A NW-trending growth fault system is recognized parallel to and north of the basement Hinge Line, and listric faults often offset strata throughout the entire Brookian sequence to shallow depths in the subsurface. These large growth faults apparently have influenced deltaic sedimentation in Tertiary time, as evidenced by significant thickening of the Tertiary topset beds in downthrown fault blocks.

The Camden anticline rises as a large-amplitude compressional fold that is apparently detached from the extensional basement structure north of the Hinge Line. The NE-SW trend of this anticline is structurally anomalous in that it is oblique to the regional NW-SE-trending margin of the western Kaktovik Basin (fig. 10). Rollover anticlines formed contemporaneously with growth faults along a passive basin margin should generally trend parallel to the basin margin. The lateral continuity and constant overall thickness of the upper Brookian facies across the Camden anticline indicate that these fluvial-deltaic strata were deposited prior to the formation of this compressional fold. Seismic evidence suggests that the Camden anticline is a late Tertiary, possibly Quaternary, feature whose origin is related to external or deep-seated tectonic mechanisms and not to growth faulting within the western Kaktovik Basin. On the crest of the Camden anticline many of the listric faults extend upward into Pleistocene and perhaps Holocene strata. The extensive unconformity which truncates the top of the Camden anticline and other shallow anticlines in the Camden sector is probably Pleistocene in age.

The regional structure of the Demarcation sector (subprovince IIC) is illustrated in figure 10. The Beaufort shelf east of Barter Island contains two large structural uplifts (the Jago and Demarcation ridges) and two intervening depressions (the Barter and Demarcation subbasins). The NW-SE-trending growth fault system that typically occurs seaward of and parallel to the Hinge Line is obscured by the structural complexity beneath the eastern Beaufort shelf. The Brookian sequence in the Demarcation sector is composed of several distinct transgressive and regressive depositional cycles, and attains a thickness of greater than 8 seconds on seismic profiles. Prominent unconformities are recognized within and between these cycles. This is in contrast to the Camden sector and areas to the west, where a single major regressive cycle characterizes the Brookian sequence. The contemporaneous tectonic activity in the Demarcation sector has obviously modified the general northeastward progradation of the Brookian clastic wedge. The nearest publicly available well control for this area is the Dome Natsek E-56 well drilled northwest of Herschel Island on a structural high which may be an eastern extension of the Demarcation ridge. The stratigraphy of this control well is summarized in figure 31.

The seismic interpretation shown in plate 7 illustrates the stratigraphy and structural features of the Demarcation sector (subprovince IIC). Acoustic basement probably consists of a lower Paleozoic metasedimentary complex identified as the Franklinian sequence. In contrast to the flat-lying Arctic Platform of the Camden sector (plate 6), the Franklinian basement complex is tilted steeply to the north. The Demarcation subbasin is floored by Franklinian basement rock and apparently formed as a structural sag between a major basement uplift to the south (onshore) and the Demarcation ridge to the north (offshore). Ellesmerian units were not identified in this offshore area beneath an extremely thick Brookian section, but some Ellesmerian formations may occur south of the Hinge Line in the eastern Arctic National Wildlife Refuge (ANWR) (discussed further in chapter 8, Play Concepts). Likewise, the Rift sequence was not identified in seismic data in the Demarcation sector.

The stratigraphy of the Brookian sequence is inferred from published reports on Canadian geology and on the surface geology of ANWR (Palmer and others, 1979; Molenaar, 1983). The oldest Brookian unit is inferred to be a thick shale of Cretaceous age. This unit is represented as a seismically homogeneous interval, and it is identified only in the cores of deep folds or as possible diapiric spines within the Demarcation ridge (plate 7). An overlying stratified unit is provisionally correlated with the Cretaceous to Paleocene fluvial-deltaic rocks which were penetrated by the Natsek well. The parallel, high-amplitude horizons which comprise this unit are most apparent in deep, possibly thrust-cored folds within the structural ridges. We tentatively correlate this seismic unit to the Moose Channel and Reindeer Formations (Young and others, 1981) in the Mackenzie Delta or to the Sabbath Creek Formation (Molenaar, 1983) in ANWR. The "Cretaceous to Paleocene(?) deltaic unit" (plate 7) is overlain by a second seismically homogeneous interval inferred to represent a massive shale. This seismic unit varies greatly in thickness over the deep folds and possible diapiric spines within the structural ridges. This "Eocene(?) mobile shale unit" (plate 7) is thought to be age equivalent to the Brookian prodelta shale in the Camden sector and to a massive Paleocene to Eocene shale penetrated by the Natsek well. We tentatively correlate it to the Richards Formation in the Mackenzie Delta area (Young and others, 1981).

A prominent local unconformity separates the lower Tertiary seismic units, which form the structural ridges, from the middle to upper Tertiary strata, which onlap the ridges and fill the Barter and Demarcation subbasins. Strata which fill the Demarcation subbasin are represented by divergent, high-amplitude seismic horizons presumably deposited in a shelf environment (Brown and Fisher, 1977). These horizons are downwarped into the Demarcation subbasin and thin by onlap, as well as by erosional truncation, onto the Demarcation ridge. Numerous local unconformities on the flanks of the Demarcation ridge suggest episodic uplift through mid-Tertiary time. Continuous, high-amplitude horizons were traced between these local subbasins and westward into the upper Brookian fluvial-deltaic facies in the Camden sector. We tentatively correlate these inferred Oligocene to Miocene strata to the Kugmallit and Mackenzie Bay Formations (Young and others, 1981) or the Pullen and Akpak Formations (Willumsen and Cote, 1982) in the Mackenzie Delta area.

An upper Tertiary seismic unit lies above a prominent erosional unconformity that has been dated in the Mackenzie Delta as middle to late Miocene (Young and others, 1981). Inferred fluvial-deltaic strata overlying this regional unconformity (designated MU in plate 7) are tentatively correlated to the Beaufort and Nuktak Formations (Young and others, 1981; Willumsen and Cote, 1982) of late Miocene to Pliocene age.

The internal structure of the Demarcation ridge, although highly deformed, can be partially resolved in some seismic profiles which cross this feature. We offer the interpretation shown in plate 7 to illustrate a possible model for the complex internal structure. According to our preliminary interpretation, parts of the Demarcation ridge may be composed of en echelon (possibly thrust-cored) folds which involve Cretaceous to Paleocene strata and which generally trend NE-SW, nearly orthogonal to the NW-SE trend of the composite ridge mass (fig. 28). Deep-seated thrust faults (if present) trend parallel to these en echelon folds, with fault planes dipping to the southeast. The "Eocene mobile shale unit" (plate 7) was apparently mobilized by flowage above the deeper folds. The Demarcation ridge, including thrust-cored(?) anticlines and diapiric intrusions (if present), was welded together and uplifted as a NW-SE-trending structural mass roughly parallel to the margin of the eastern Kaktovik Basin. The shallow, highly faulted crest of the Demarcation ridge covers a wide area of the eastern Beaufort shelf (fig. 10), and the low relief of shallow unconformities contrasts greatly with the underlying structural complexity within the ridge.

Although the mechanism responsible for this uplift is uncertain, we believe the timing for the event is contemporaneous with the local subsidence and deposition of strata in the adjacent Demarcation and Barter subbasins. Assuming that our age correlations are approximately correct, this structural event is bracketed between early Oligocene (depositional onlap on the "Eocene mobile shale unit") and late Miocene time (extensive erosion represented by the MU). We hypothesize that the structural mechanisms responsible for the uplift of the Demarcation ridge are related to, but do not extend from, the thrust tectonics of the northeastern Brooks Range. This preliminary conclusion is based on the following observations:

1. The internal folds within the offshore ridge were formed in middle Tertiary time, with the massive uplift ending by late Miocene time. In contrast, thrust-fold tectonism onshore in ANWR has apparently been active throughout Cenozoic time. We believe that it is unlikely that the effects of a relatively localized, older thrusting episode would be preserved beyond the presently active tectonic front.

2. The axial traces of the internal folds in the offshore ridge are oriented NE-SW, oblique to the more easterly trends in the thrust belt onshore. The orientation of the internal folds and associated thrust faults within the Demarcation ridge suggest a more northwestward-directed compression offshore compared to the northward thrusting onshore in ANWR.

We do, however, clearly favor a tectonic mechanism over a syndepositional (diapiric) model as proposed for the genesis of these ridges by Willumsen and Cote (1982). The structural features within the Demarcation ridge clearly trend orthogonally to the margin of the eastern Kaktovik Basin (fig. 28). Growth fault systems along basin margins typically control the orientation of local diapiric spines and usually trend parallel to the basin margin. A wrench fault mechanism may explain the en echelon compressional fold assemblage within the Demarcation ridge. However, the exact location of hypothetical wrench zones and their structural relationship to the thrust belt in ANWR or the Kaltag shear zone which trends into this area from the Canadian continental margin (Jones, 1982) have yet to be defined. Substantially more mapping, both onshore and offshore, coupled with biostratigraphic control, is required before a comprehensive model for the structural evolution of the Beaufort margin can be developed.

Part 2

Petroleum Geology

4

Exploration History

The following section on petroleum exploration in the northern Alaska and Beaufort Sea regions is extracted from summaries by Jamison and others (1980), Lynch and others (1985), Young and others (1981), Meyerhoff (1982), Tetra Tech (1982), Husky Oil NPR Operations, Inc. (1983c), and numerous issues of Petroleum Information's "Alaska Report."

Geologic investigations of northern Alaska were first conducted in the early 1900's by USGS-sponsored field parties. The first description of oil occurrence along the northern Alaska coast was made by Leffingwell, of the USGS, who reported oil seeps in the Cape Simpson area in 1917. Based on the presence of these seeps and conjectured estimates of resource potential, President Harding established the Naval Petroleum Reserve No. 4 (NPR-4) in 1923. Detailed field mapping by the USGS was begun at the request of the Navy Department and continues in NPR-4 (now termed the National Petroleum Reserve in Alaska, or NPRA) to the present time. In 1944, the Navy, in cooperation with the USGS, launched a major exploratory drilling program and by 1953 had drilled 81 holes (45 core tests and 36 test wells). Oil fields were discovered at Umiat, Simpson, and Fish Creek, and gas fields were found at Gubik, South Barrow, Meade, Square Lake, Oumalik, and Wolf Creek. The largest of these discoveries, 30 to 100 million barrels of oil at Umiat and 370 to 900 billion cubic feet of gas at Gubik were, and still are, uneconomic to produce. The gas field at Barrow was used to supply the Naval Arctic Research Laboratory and village of Barrow. In 1953, the Federal Government ceased funding the exploration of NPR-4.

In 1959, Alaska changed from territorial status to statehood and, under provisions of the statehood act, selected as state land the central portion of the North Slope between NPR-4 and the Arctic National Wildlife Refuge (ANWR). Exploration activity was centered in this "corridor" for the next few years. By the mid-1960's exploration activity had largely shifted from surface mapping in the foothills of the Brooks Range to seismic surveys on the coastal plain. In 1964, the State of Alaska held the first competitive lease sale on the North Slope. A second competitive lease sale was held in 1965, with interest focused on a large anticlinal

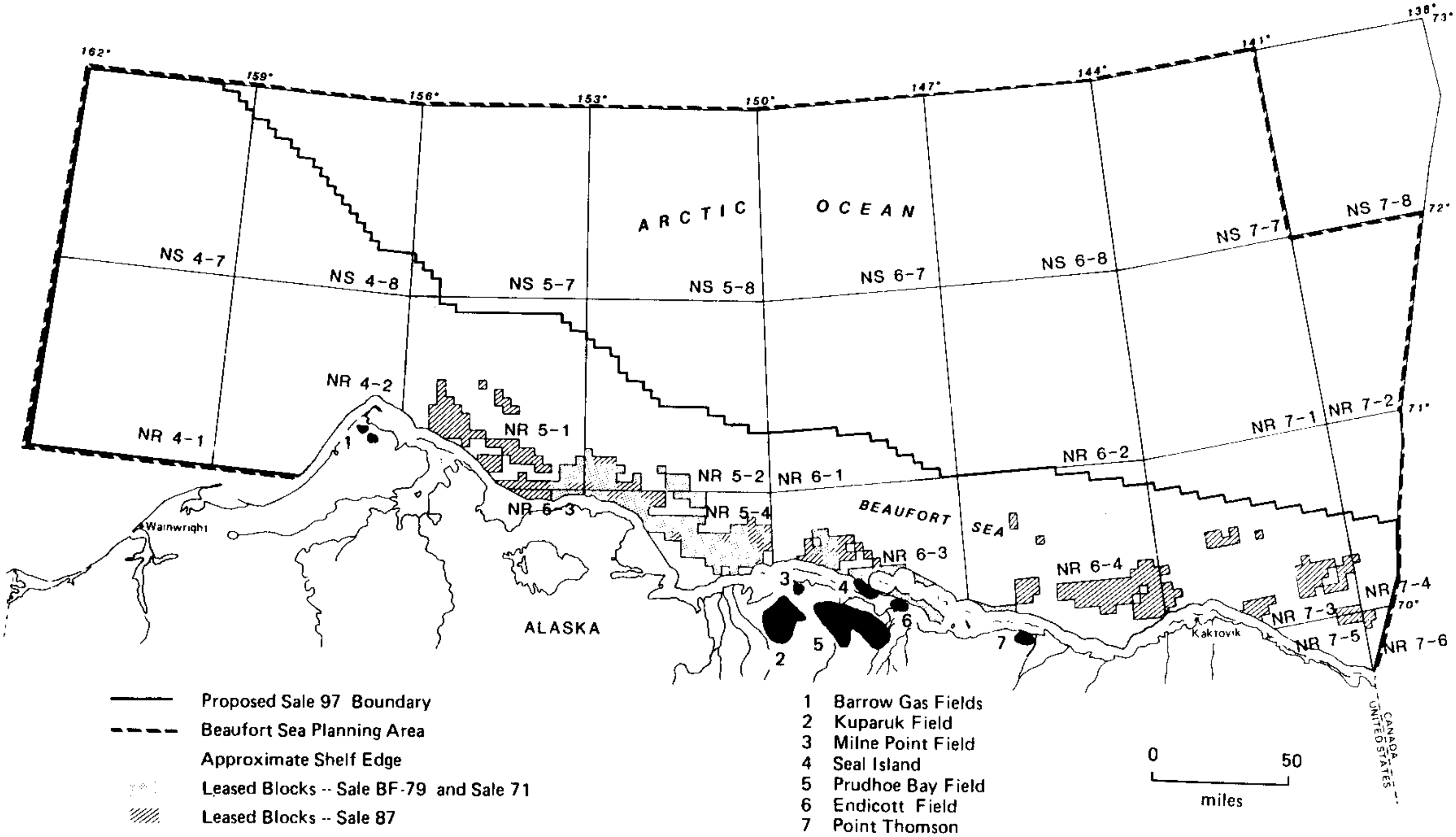


Figure 11.

Area proposed for inclusion in Sale 97 (tentatively scheduled for 1987). Also shown are the tracts leased previously in Sale BF-79 (December 1979), Sale 71 (October 1982), and Sale 87 (August 1984). The producing fields and major hydrocarbon discoveries along the Beaufort coastline are identified by numbered key. The continental shelf edge marks the probable limit of offshore exploration and development in the foreseeable future.

structure south of Prudhoe Bay. In 1968, Atlantic Richfield Company and Humble Oil drilled the Prudhoe Bay State No. 1 well and, after drilling an additional confirmation well, announced the discovery of what soon proved to be the largest oil and gas field found in North America. Recoverable reserves from the Ivishak Formation (Triassic) and Lisburne Group (Carboniferous) range upwards of 10 billion barrels of oil and 26 trillion cubic feet of gas.

A period of intense drilling activity and seismic exploration in the coastal area after the Prudhoe discovery led to discoveries of oil, gas, and condensate in adjacent fields (fig. 11). Possible commercial fields were delineated at Kuparuk (1969; 1.5 billion barrels recoverable), Milne Point and Gwydyr Bay (1970; 120 million barrels recoverable), and Point Thomson (1977; 350 million barrels, 5 trillion cubic feet gas) fields. Construction of the Trans-Alaska Pipeline System (TAPS) from Prudhoe Bay to a tanker terminal in Valdez allowed production to begin from the Triassic reservoirs in the Prudhoe Bay field in 1977, with Lower Cretaceous reservoirs in the Kuparuk field brought on line in 1981.

Federally funded exploration in NPR-4 was resumed in 1975 under the direction of the Navy. This responsibility was later transferred to the Department of the Interior, which renamed it the National Petroleum Reserve in Alaska (NPRA) in 1977. A total of 28 exploratory wells were drilled by the USGS contractor, Husky Oil, and 14,770 miles of seismic data were collected over the 7-year life of the program. The structural and stratigraphic anomalies mapped by the USGS and their contractor, Tetra Tech, Inc., yielded some oil shows but no commercial-size discoveries. In 1979, the USGS reduced its estimate of recoverable oil in NPRA from 10 billion barrels to 3 billion barrels. The first of a series of competitive oil and gas lease sales in the NPRA was held in 1981, and three additional lease offerings followed. The most recent lease offering (1984) received no industry bids, and future lease sales are not scheduled at the present time. Only one exploration well was drilled by industry on Federal NPRA acreage, and this well (ARCO's Brontosaurus No. 1) was plugged and abandoned in early 1985.

Exploration in the offshore area of Arctic Alaska began in the early 1960's, and during the period of 1964 through 1984, over 65,000 line-miles of deep-penetration, multichannel CDP seismic data were collected under permit in Federal offshore areas. Government-sponsored exploration included a reconnaissance survey by the USGS in 1977 (Grantz and others, 1982b) which collected over 5,600 km of 24-channel CDP seismic data on the Beaufort and Chukchi shelves.

The first offshore lease sale (Sale BF-79) was held jointly by the State of Alaska and the Federal Government in December 1979 (fig. 11). A total of $1.056 billion was collected in high bids for 86 of the 117 tracts offered, with the highest bid of $143 million for a tract in the Sag Delta-Duck Island area. Sixteen wells were drilled from natural and artificial gravel islands in the next 3 years to test several prospects. Potentially commercial discoveries were announced at Sag Delta-Duck Island (1980; approximately 350 million barrels recoverable from the Kekiktuk Formation) and at Seal Island (1984; approximately 300 million barrels recoverable from the Ivishak Formation) (fig. 11).

In the Alaskan OCS, the Minerals Management Service (MMS) held its first lease sale (Sale 71) in the Beaufort Sea in October 1982. Twenty-four companies participated in active bidding for 125 of the 338 tracts offered (fig. 11). High bonus bids totaled $2.067 billion, with the two highest bids of $227 and $219 million for tracts on the Mukluk structure in Harrison Bay. This large subunconformity trap on the Barrow Arch resembles the supergiant Prudhoe Bay field just to the east (fig. 23). The most expensive well in OCS history (over $140 million) was drilled from an artificial gravel island to test a group of tracts receiving over a billion dollars in bonus bids. In early 1984, the drilling partners, led by Sohio, announced that the Mukluk well was a dry hole and they would plug and abandon the well. Additional wells on the Mukluk structure have not been proposed. Two test wells were drilled farther to the northwest by Exxon from a concrete island drilling system (Global Marine's CIDS) during the 1984-1985 winter. These wells on Exxon's Antares Prospect were also plugged and abandoned in early 1985.

The most recent OCS lease offering in the Beaufort Sea (Sale 87) was held in August 1984 (fig. 11). In contrast to the selected areas included in previous lease sales, Sale 87 offered 1,477 tracts covering the entire continental shelf from Point Barrow to the Canadian border. Twenty-seven companies were awarded 232 tracts with high bids of $877 million. The highest bids ($55 and $53 million) and most competitive bidding were concentrated on faulted anticline structures in Camden Bay in water depths less than 120 feet. New designs of mobile gravity platforms or arctic drillships will probably be used to test these structures in waters beyond the depth limitation for gravel islands (approximately 50 feet). Site-specific shallow-hazards surveys for these high-bid tracts in Camden Bay were conducted in the fall of 1984, and a series of exploratory wells using the Canmar drillship Explorer II began to test these prospects during the summer of 1985.

The results of exploration activity in the Mackenzie Delta region of Canada are relevant to the petroleum potential of the Alaskan Beaufort shelf because both regions contain thick sequences of Brookian strata equivalent in age, lithofacies, and structural style. Although the large fields presently producing oil on the North Slope occur in the Ellesmerian sequence, the discovery of oil in turbidite sands at Flaxman Island (Alaska State A-1, 1975), the vast heavy oil deposits in the West Sak and Ugnu sands (Jamison and others, 1980), and well-known oil seeps along the Alaskan coast indicate that hydrocarbons do occur in the Brookian sequence as well.

After over a decade of onshore and offshore seismic mapping in the Canadian Beaufort region, the first well was spudded on the Mackenzie Delta in 1965. Drilling continued for 5 years until oil was discovered onshore in Lower Cretaceous sands at Atkinson (1970). The discovery of large onshore gas fields in Eocene rocks at Taglu (1971) and in Lower Cretaceous rocks at Parsons Lake (1972) followed shortly thereafter. Exploratory drilling moved progressively offshore through the 1970's, and at the present time, over 50 wells have tested a variety of structural and stratigraphic traps in Brookian strata beneath the Canadian Beaufort shelf. Of these offshore wells, about half were drilled from bottom-founded platforms in shallow water (gravel islands and caisson structures) and half from drillships with icebreaker support vessels. By 1982, several major discoveries had been announced (the largest being the Koakoak, Kopanoar, Nektoralik, Issungnak, and Tarsuit fields; Meyerhoff, 1982), but delineation drilling indicated that none of these fields could individually support commercial production from this remote province. Since then, discoveries at Amauligak J-44 and Pitsiulak A-05 in 1984 (Oil and Gas Journal, 1984) and at Nipterk L-19 and Amerk O-09 in 1985 (Oil and Gas Journal, 1985a) have been added to the list of potential oil and gas production from Brookian strata. To date, however, no commercial production has occurred in the Mackenzie region, onshore or offshore. The lack of an existing transportation system to market and the marginal economics for this remote region require that fields with a recoverable reserve base larger than 300 million barrels be found to spark development (Oil and Gas Journal, 1985e).

In conclusion, after decades of field work, seismic surveys, and exploratory drilling in the northern Alaskan and Canadian Beaufort region, numerous oil and gas fields have been discovered. However, it was the discovery of the multi-billion barrel Prudhoe Bay field (with a production capability over 1.5 million barrels per day) which prompted the construction of a $7.7 billion pipeline to transport the oil to outside markets. The associated gas produced in the Prudhoe field is currently reinjected into the gas cap to maintain reservoir pressure. The estimated 26 trillion cubic feet of gas in the Prudhoe field probably will not be produced until a gas pipeline is constructed. With the Prudhoe Bay field infrastructure in place, large adjacent oil fields such as Kuparuk (production capacity over 250 thousand barrels per day) were brought into commercial production. Reserves in known commercial-size fields (greater than 300 million barrels of oil) in northern Alaska total over 12 billion barrels of oil and 30 trillion cubic feet of gas. Estimated oil in place on the North Slope is thought to exceed 60 billion barrels. Future production from marginal-size fields such as Milne Point, Endicott, Seal Island, and Point Thomson hinges on the price of oil, the marketability of gas, and environmental constraints. In the Canadian Beaufort region, the fields discovered are not large enough individually to initiate production at present, and all hydrocarbon reserves, onshore and offshore, are shut-in.

Given the long lead time required for drilling platform design and construction, exploratory and delineation drilling, environmental studies, regulatory and production permits, and infrastructure development, it is estimated that 10 years will elapse between a lease sale and first production from the sale area--assuming that discoveries of giant oil fields can be found by a limited number of very expensive exploration wells. However, the Beaufort Sea Planning Area is highly complex structurally and stratigraphically. Although it may frustrate preliminary geologic analyses, the polycyclic tectonic history of this region may eventually prove to be favorable for large hydrocarbon fields. Exploration plays are abundant, and offshore provinces contain untested potential reservoir and source rocks ranging in age from Devonian to Tertiary. All of the offshore petroleum provinces contain hydrocarbon plays which differ from those tested by previous exploration onshore. Subsequent sections of this report will summarize what is presently known about potential source and reservoir rocks on the North Slope and their relationship to significant plays and recognized trap types in the offshore petroleum provinces.

5

Source Rocks on the Beaufort Shelf

ELLESMERIAN AND RIFT SEQUENCES

The hydrocarbons which occur in the Prudhoe Bay and adjacent fields are generally regarded as having been derived from organic-rich shales in the Ellesmerian sequence or Rift sequence (the Pebble Shale) or both (fig. 12). The Lower Cretaceous Pebble Shale contains an average total organic carbon content (TOC) of 5.4 percent, with C_{15+} hydrocarbon content in excess of 3,000 parts per million (ppm) (Morgridge and Smith, 1972). It is therefore considered a very rich, oil-prone, potential source bed. The Jurassic Kingak Formation is considered to be a very good potential source rock, containing an average TOC of 1.9 percent and 650 ppm of C_{15+} (Morgridge and Smith, 1972, fig. 16; Magoon and Claypool, 1984). The dark-colored, phosphatic, highly organic shales and limestones of the Triassic Shublik Formation are also regarded as rich potential oil source beds (Seifert and others, 1980, table II). The Triassic Sadlerochit Group (Kavik Formation) shales, Carboniferous Lisburne Group shales, and Mississippian Endicott Group shales are regarded as somewhat "lean" (low organic carbon content) and gas prone (Morgridge and Smith, 1972, p. 500). Seifert and others (1980, p. 428) provide data which suggest potential sources within certain dark-colored Endicott Group shales (Kayak Formation), although they do not correlate any Prudhoe oils to this source.

Jones and Speers (1976) suggested from crude oil analyses that all oils in the Prudhoe area accumulations are geochemically alike and were derived from a common source or common set of multiple sources. Young and others (1977, p. 594, table 10; p. 596, table 12) obtained a set of calculated ages for Prudhoe oils which varied depending on the reservoir horizon from which they were extracted. Oil samples obtained from Triassic and Pennsylvanian reservoirs yielded generation ages of 218 million years (m.y.), while oil obtained from an Upper Cretaceous reservoir was found to have an apparent generation age of 87 m.y. Magoon and Claypool (1981, p. 644) interpreted this data as indicating that the Prudhoe oils were derived from both Cretaceous and Triassic sources.

Magoon and Claypool (1981) identified two principal families of oils on the North Slope: (1) a "Barrow-Prudhoe" type found in accumulations along the Barrow Arch and (2) a "Simpson-Umiat" type found in the Cape Simpson area and the Umiat area in the northern

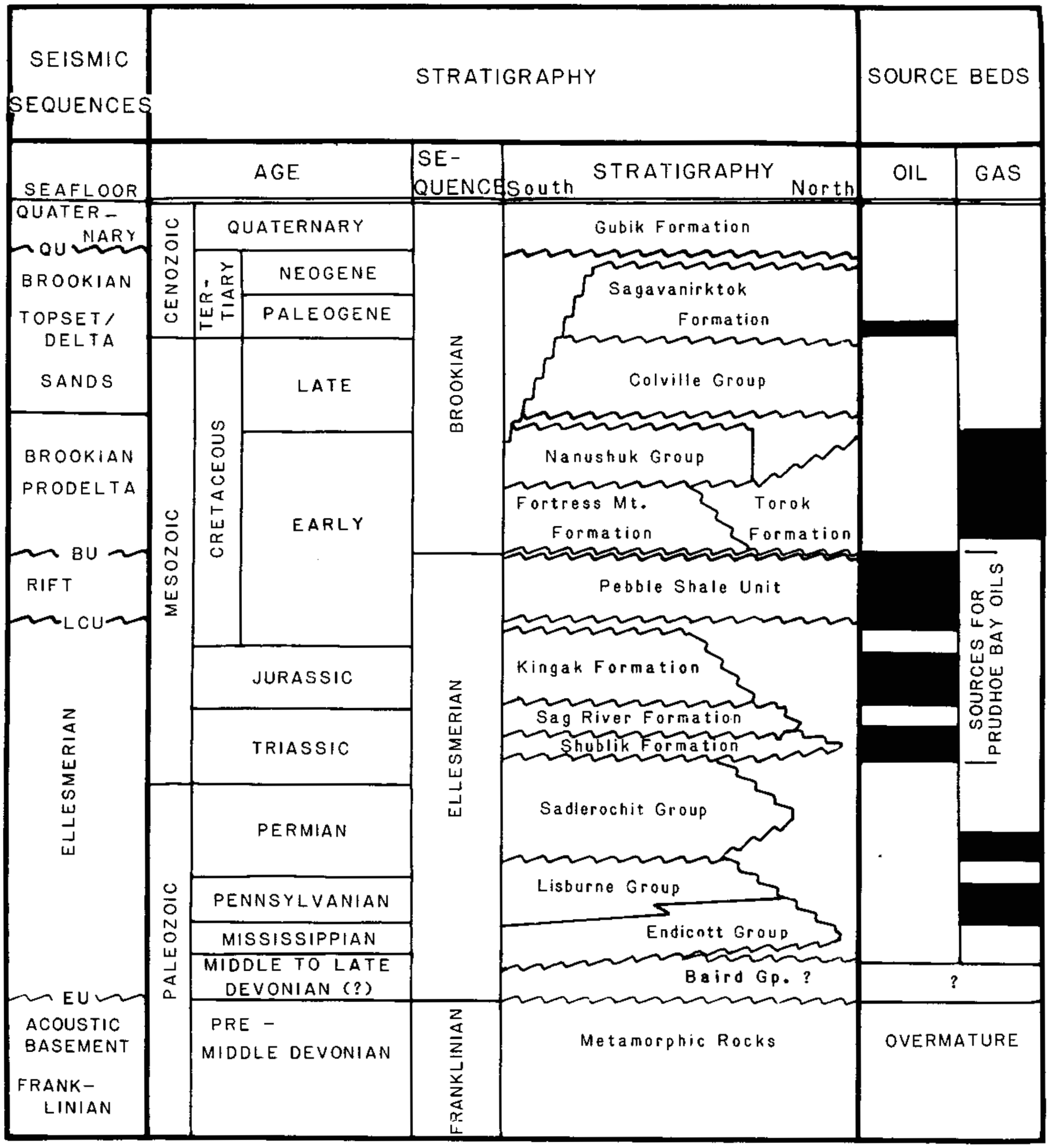


Figure 12.

Stratigraphic relationships of significant source beds on the North Slope of Alaska. Shaded areas in source bed column indicate presence and type of source beds. The source potential of the lower Ellesmerian strata thought to occupy the Northeast Chukchi Basin is unknown. The metamorphosed Franklinian sequence on the North Slope locally contains organic-rich rocks, but is thermally overmature.

foothills of the Brooks Range. An informal research consortium conference recently concluded (McCloy, 1983, p. 14) that the "Prudhoe" oils were derived principally from Triassic and Jurassic sources, whereas the "Umiat" oils were sourced from the Lower Cretaceous Pebble Shale or younger Brookian sequence rocks. The concept of a Pebble Shale source for Prudhoe oils was discarded by some participants at the conference on the basis of the apparent thermal immaturity of these rocks in the vicinity of the Prudhoe area accumulations. However, Morgridge and Smith (1972, p. 500) have forcefully argued from geochemical and geological data that the Lower Cretaceous Pebble Shale forms the most probable major source for the Prudhoe Bay oils.

Few of the traditionally recognized Prudhoe-province source rocks are considered to be present in the offshore areas north of the Barrow Arch province (IA, fig. 1). All Ellesmerian sequence source beds are probably absent as a consequence of depositional onlap or erosional truncation from areas north of the zero-Ellesmerian line traced on figure 1, and, therefore, do not form potential sources over much of the OCS planning area. Jurassic and Lower Cretaceous potential source beds are present beneath the Arctic coastal plain of ANWR (Reiser and others, 1980), and may extend offshore into that part of the Demarcation sector which is south of the Hinge Line (Norris and Yorath, 1981, fig. 3). Jurassic shales of the Kingak Formation increase in organic carbon content to the east (Magoon and Claypool, 1984, fig. 6) and may form an excellent petroleum source bed in ANWR and adjacent offshore areas.

The Pebble Shale, or its stratigraphic equivalent, probably extends offshore (fig. 13) as the upper part of the Rift sequence. The geochemical character of the Rift sequence shales within offshore grabens may differ from that of time-equivalent rocks to the south, which accumulated in the open marine environment of the Colville Basin. The Rift sequence shales in offshore areas may have accumulated in a more restricted environment within contemporaneously subsiding infrarift grabens. Kerogen compositions of shales within the infrarift grabens may be similar to the geologically analogous North Sea grabens, where highly sapropelic (oil-prone) shales in the central parts of the grabens are ringed by leaner, nonsapropelic shales along basin margins (Reeder and Scotchman, 1985, p. 142). The recently announced discovery at Seal Island (Petroleum Information, 1984) is particularly interesting because the oil is much lighter (40° API) than typical "Barrow-Prudhoe" oils (27° API). These oils may have been derived from more mature or geochemically distinct Rift sequence source beds to the north.

Over much of the Nuwuk and Kaktovik Basins, Rift sequence strata lie at depths exceeding 23,000 feet and therefore are probably overmature. In these remote offshore basins, potential source beds must be sought within the Brookian sequence.

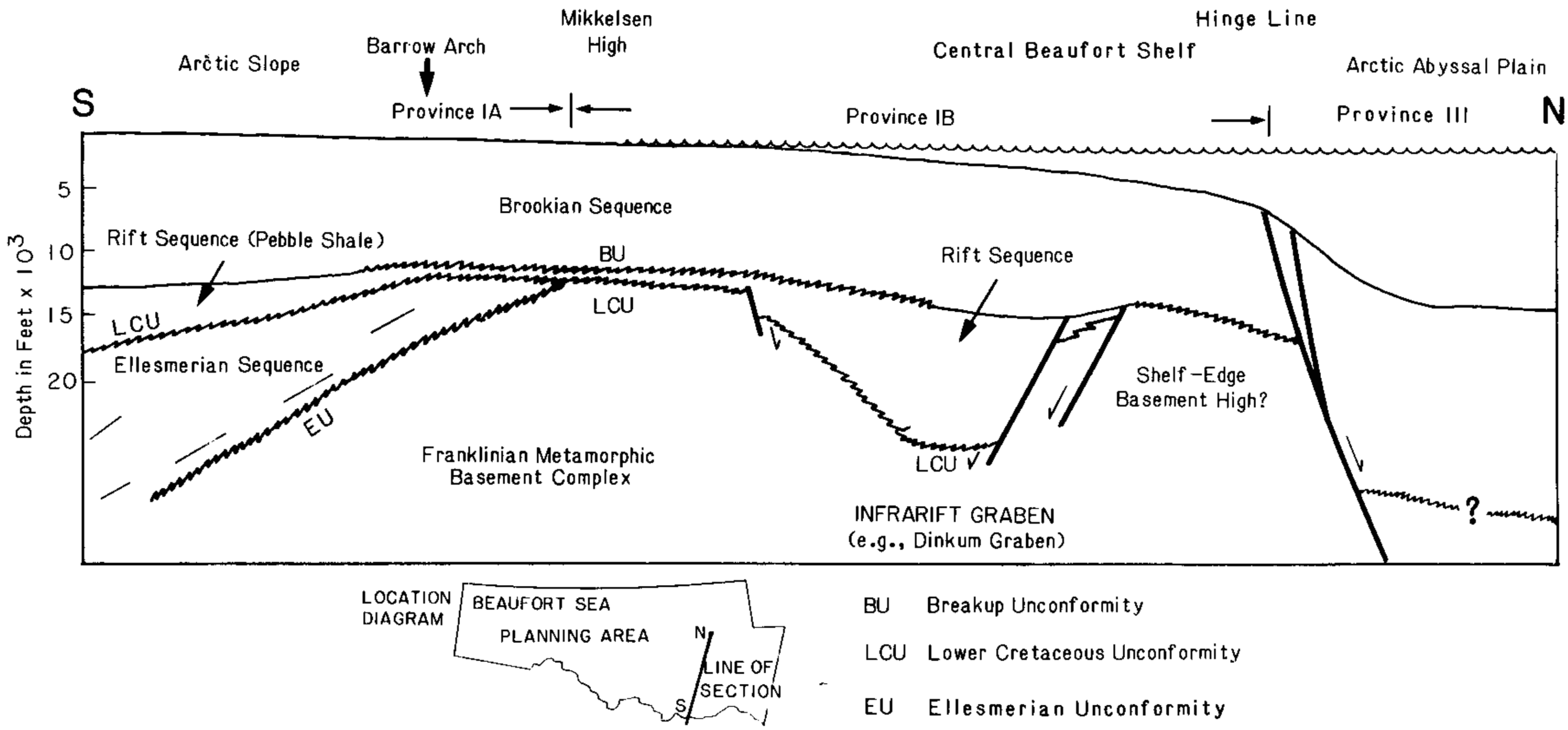


Figure 13.

Schematic geological cross section across Beaufort shelf showing stratigraphic relationships which preclude most traditionally recognized Ellesmerian source rocks from offshore shelf provinces. The Rift sequence shales, which form very rich potential oil source rocks onshore (Pebble Shale), are thought to extend into offshore rift basins. The offshore Rift sequence shales, however, may be geochemically distinct from the time-equivalent sediments which accumulated in the Colville Basin south of the Barrow Arch. Shales within the Brookian sequence may also form potential sources for liquid hydrocarbons in offshore areas.

BROOKIAN SEQUENCE

Early Cretaceous and younger shales have typically been found to be nonsource or gas prone, although the Albian Torok shales (fig. 12) have been invoked as a potential source for the Umiat-type oil (McCloy, 1983, p. 14). In the Prudhoe Bay area, an organic-rich, tuffaceous, radioactive shale of Coniacian-Turonian age (Carman and Hardwick, 1983, fig. 4) disconformably overlies the Pebble Shale. An analysis published by Seifert and others (1980, table II, p. 428) indicates that this Upper Cretaceous shale may be a rich (TOC=3.44 percent), oil-prone, potential source rock. These rocks apparently extend northward at the base of the Brookian sequence into offshore areas and may there form an important potential source bed.

Upper Cretaceous shales of the Brookian prodelta facies disconformably overlie Coniacian-Turonian shales above the breakup unconformity (BU) in the central part of the Arctic Platform. However, Brookian prodelta shales of Albian age (Torok Formation) directly overlie the Pebble Shale in the western part of the Arctic Platform. In contrast, the Brookian sequence in the eastern Arctic Platform consists almost entirely of Tertiary strata which overlie a relatively thin sequence of Upper Cretaceous rocks. The Tertiary Brookian sequence in the eastern Arctic Platform, unlike the much older Brookian strata found in more western parts of the platform, is probably the most representative of the largely Tertiary Brookian sequence anticipated offshore in the Beaufort Sea Planning Area. The following discussion will therefore focus upon the geochemistry of Brookian strata in the eastern Arctic Platform. The Brookian sequence in this area has been penetrated by several exploration wells. These wells form the data base for our speculations about the source rock potential of the Brookian sequence in offshore areas.

Geochemical analyses of the Upper Cretaceous to Tertiary strata of the Brookian sequence in the Camden Bay area (Union Oil, 1983; Harwood, 1983) are summarized in a graphical format in plates 8, 9, and 10. These analyses were performed on cuttings from three wells in the Camden Basin (fig. 18): the Exxon Point Thomson No. 2, the Exxon Point Thomson No. 3, and the Mobil West Staines No. 2 wells. The geochemical data show that the Brookian shales in this area range from nonsource to fair source potential (based upon TOC) and yield a low hydrogen index consistent with a dominant population of gas-prone kerogens. However, in two of the three wells, analyses of certain sample intervals near the contact between the marine prodelta and marginal marine deltaic facies indicate the presence of organic rich beds with hydrogen indices in excess of 200 (plates 9 and 10). This suggests the presence of liquid-prone potential source beds. At present burial depths of 5,000 to 7,000 feet and vitrinite reflectance levels of 0.30 to 0.55, these potential source beds are thermally immature or lie just within the lower limit

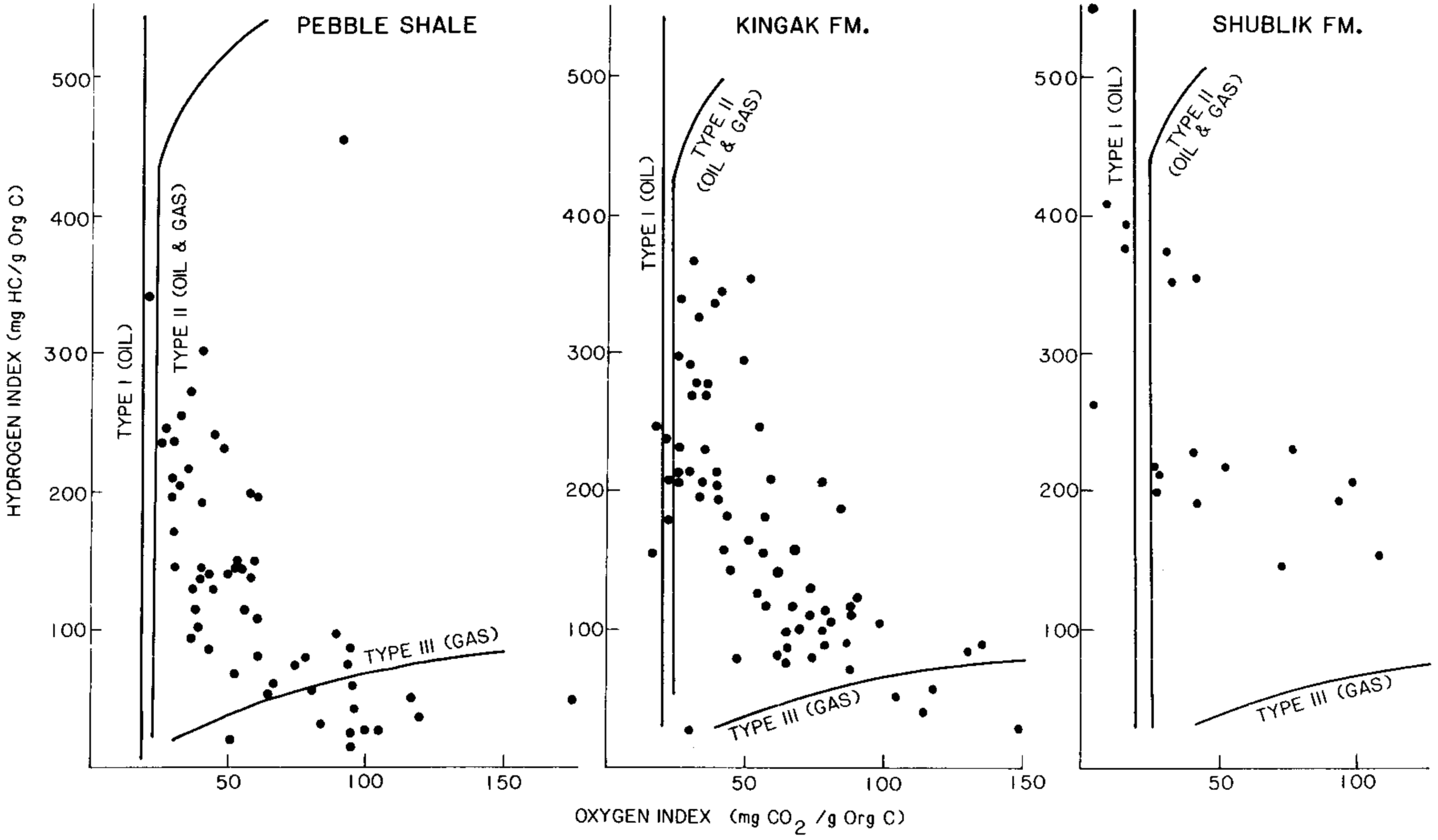


Figure 14.
Van Krevelen diagrams for compositions of the major source beds for the Prudhoe Bay oils. All three formations exhibit a wide spectrum of compositions, ranging from Type III (gas prone) to Type I (oil prone) in kerogen content. These data were compiled from Ruth (1982) and include analyses from the Gulf Colville Delta St. No. 1, Placid Beechy Pt. No. 1, BP Ugnu No. 1, Socal Simpson Lagoon 32-14, ARCO Placid St. No. 1, Union Kookpuk St. No. 1, and Sinclair Colville St. No. 1 wells. All wells are in the vicinity of the Prudhoe Bay field. Diagram modified from Tissot and Welte (1978, p. 446, fig. V.1.12).

for oil generation. However, at appropriate burial depths offshore in the Kaktovik and Nuwuk Basins, these beds or younger facies-equivalent beds could have undergone sufficient thermal maturation to have formed important sources for liquid hydrocarbons. The discovery of potential oil source beds at this stratigraphic level is very significant because the Brookian sequence is generally regarded as gas prone, and over most of the planning area north of the Hinge Line, the potential oil source beds in the deeper Ellesmerian and Rift sequences are either absent or so deeply buried that they are probably overmature.

Figure 14 presents a series of modified Van Krevelen diagrams which illustrate the variation in kerogen composition for the three formations believed to constitute the principal sources for the hydrocarbons in the Prudhoe Bay field (Morgridge and Smith, 1972; Magoon and Claypool, 1981). All three formations, including the Pebble Shale, exhibit a broad spectrum of kerogen compositions, ranging from Type III (gas prone) to Type I (oil prone). For comparison, Van Krevelen plots for Brookian strata in the Point Thomson No. 2 and West Staines No. 2 wells are presented in figure 15. The compositional field of the "Prudhoe Bay" oil source beds synopsized from figure 14 is superimposed as a stippled area upon the Brookian data sets in figure 15. Several analyses in the Point Thomson No. 2 well appear to document a strong Type I/II kerogen component that is quite comparable to the kerogen makeup of the Prudhoe oil source beds. The depths of occurrence of these liquid-prone strata are annotated on the plot. Most range between 6,030 and 6,570 feet, straddling the fluvial-deltaic to prodelta facies boundary in the Point Thomson No. 2 well. In both wells, the bulk of the Brookian strata above and below this facies boundary are compositionally dominated by Type III kerogens and are therefore considered to be unlikely potential sources for liquid petroleum.

Sample logs for the intervals which contain these apparent oil source beds indicate the presence of live, heavy hydrocarbons in sandstone cuttings. It is therefore possible that the geochemical data reflect the presence of migrated oil rather than the presence of actual oil-prone source beds. Contamination of this kind is further suggested by high bitumen/TOC ratios in the interval of interest in the Point Thomson No. 3 well (plate 10). With only the geochemical data at hand, it is difficult to assess the extent and impact of a possible contamination problem in these data. Therefore, as a means of independently evaluating the presence of potential source beds in this interval, the three wells were analyzed by using a wireline log method devised by Meyer and Nederlof (1984) for source bed identification. This method is based upon the observation that source shales typically exhibit lower acoustic velocity, lower density, and higher resistivity than mineralogically similar nonsource shales. The Meyer and Nederlof technique employs bivariate plots of these properties as a means of discriminating between conventional nonsource shales and potential source shales.

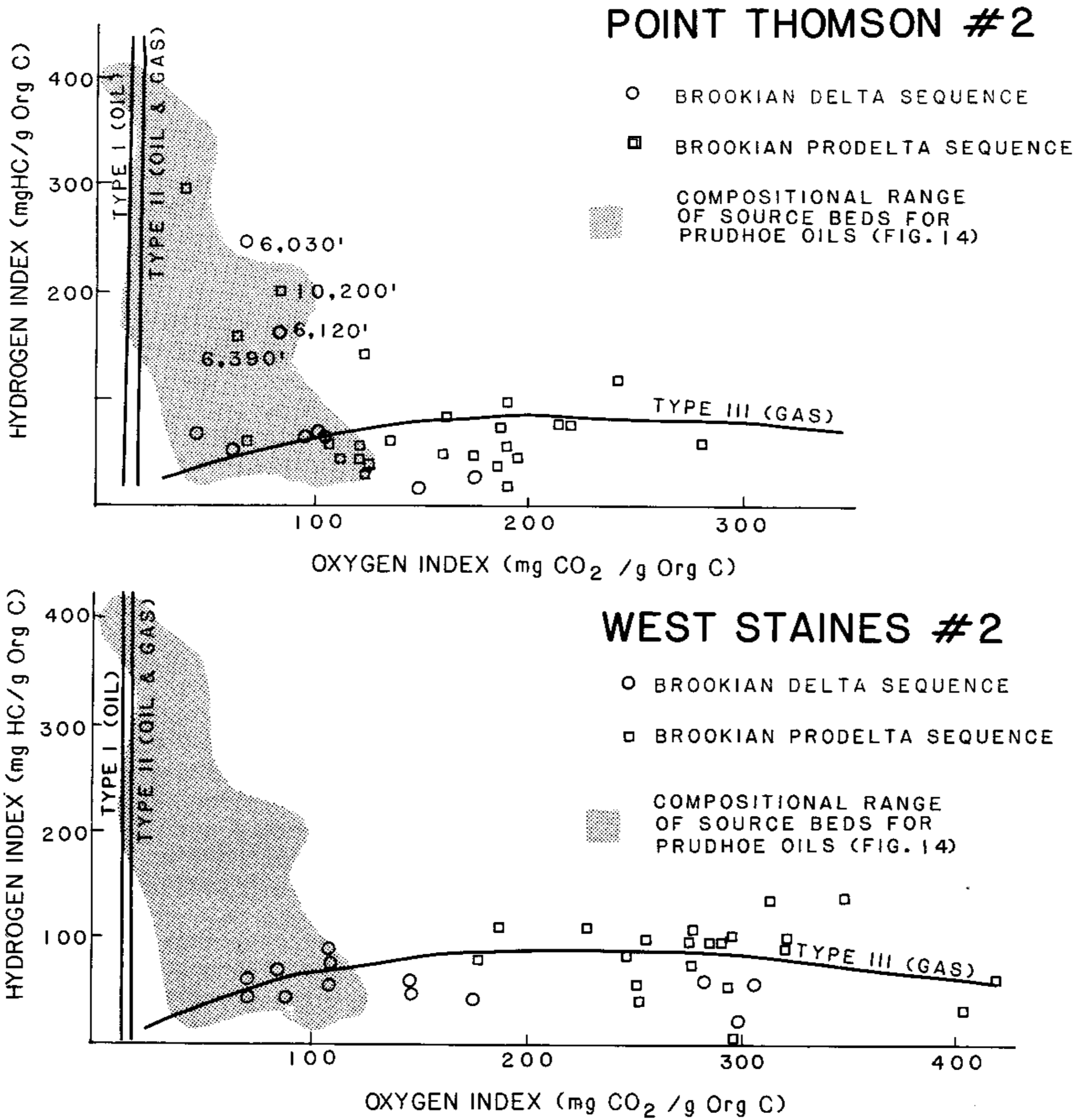


Figure 15.

Van Krevelen diagrams for potential source beds in the Brookian delta and prodelta facies in the Point Thomson No. 2 and the Mobil West Staines No. 2 wells. The compositional range of source beds for Prudhoe Bay oils, as obtained from figure 14, is superimposed on both data sets. These data suggest that source beds containing Type I/II kerogens in quantities comparable to the Prudhoe source beds are present in the Brookian sequence at the Point Thomson No. 2 location. The depths of occurrence of apparent oil-prone potential source beds in the Point Thomson No. 2 well are annotated on the plot. Most of these potential source beds lie between 6,000 and 6,600 feet, corresponding to the prodelta/delta facies boundary. Diagrams adapted from Tissot and Welte (1978, p. 446, fig. V.1.12).

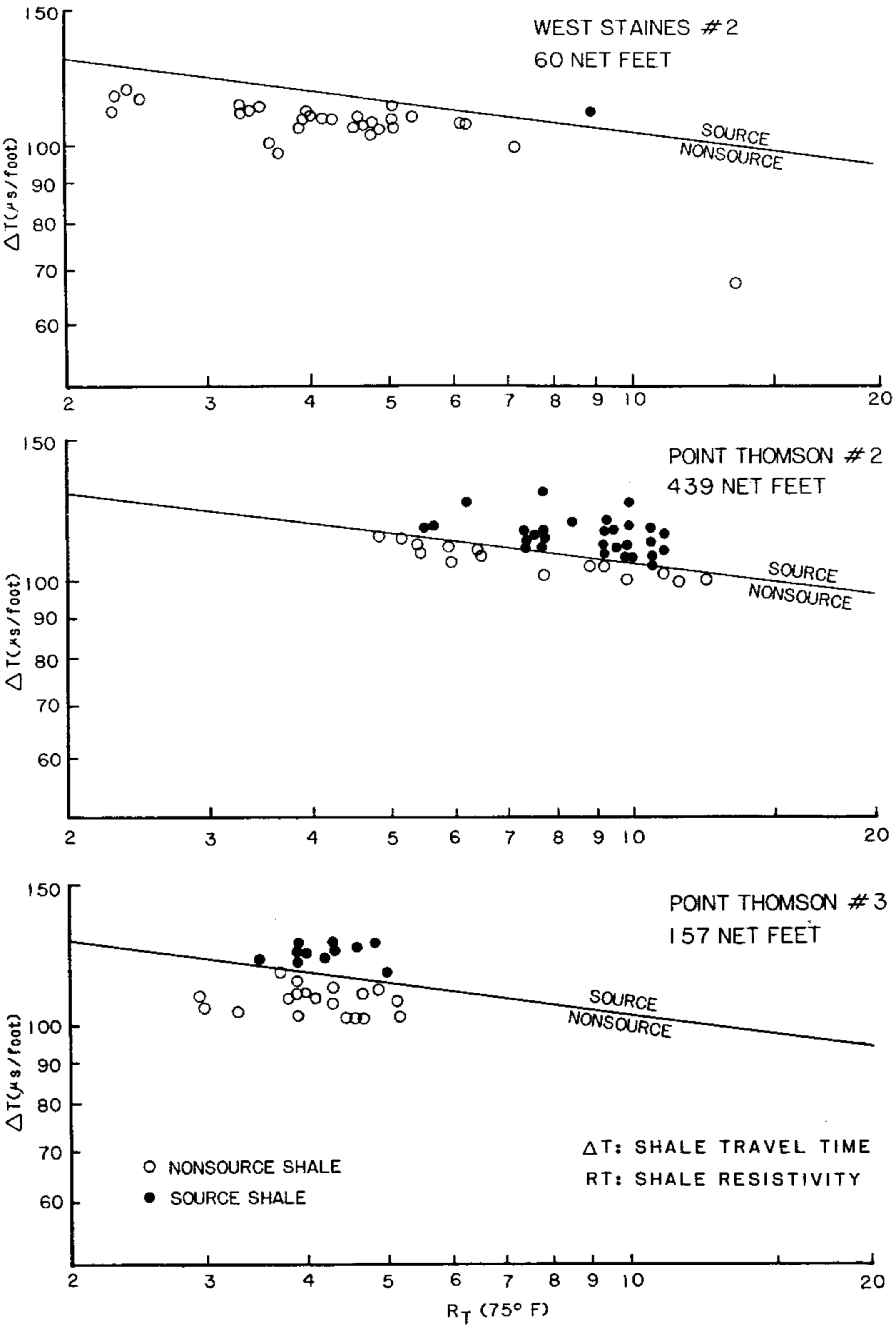


Figure 16.
Cross plots for source bed identification in the West Staines No. 2, Point Thomson No. 2, and Point Thomson No. 3 wells. Line separating source and nonsource fields after Meyer and Nederlof (1984, fig. 11). Normalization of shale resistivity to 75 °F was done by use of Arp's formula (after Schlumberger, 1972, p. 9).

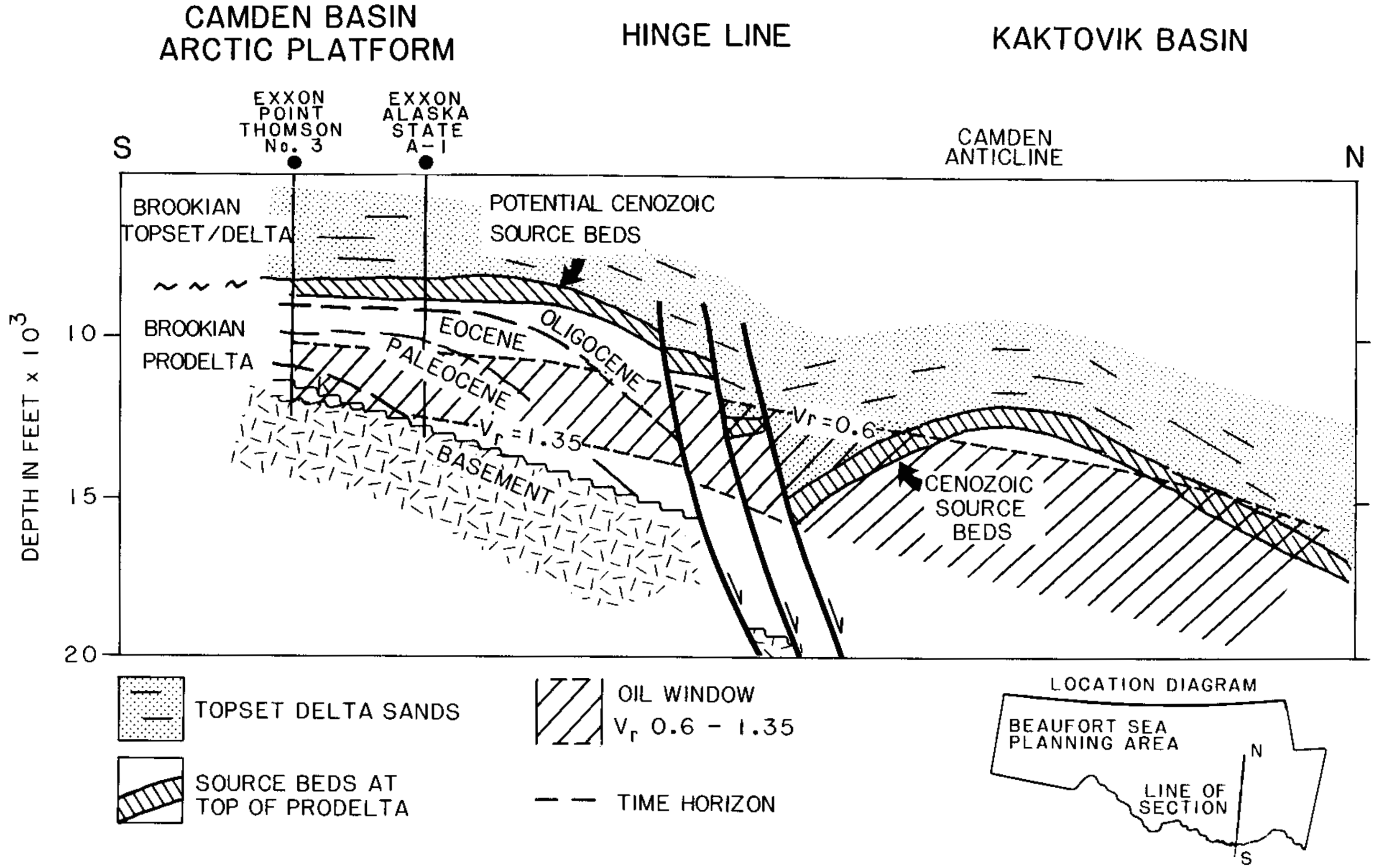


Figure 17.

Schematic geological cross section illustrating possible time-transgressive nature of Cenozoic potential source beds and relationship to the oil window in the Kaktovik Basin. The potential source beds encountered at the top of the Brookian prodelta facies in the Camden Basin may extend northward as a facies of the northward-prograding Brookian deltaic system. In the vicinity of the Camden anticline, these potential source beds probably lie within the oil window and there may become active sources for liquid hydrocarbons. Potential sources deeper within the prodelta shale sequence or in older Cretaceous-Jurassic strata may be overmature in the vicinity of Camden anticline.

The results of the analysis of the Camden Basin wells are presented in the cross plots of figure 16. The graphs display shale travel time plotted versus shale resistivity. The line which separates source shales from nonsource shales is the statistically derived discriminant line obtained from worldwide data by Meyer and Nederlof (1984, fig. 11). The plots show that a considerable number of shale beds, particularly in the Point Thomson No. 2 well, qualify as potential sources. The analysis appears to confirm that potential source beds are present in this interval, although it does not address whether these source beds are oil prone or gas prone. The aggregate thickness of all beds identified by the graphs in figure 16 as potential source beds is posted with each plot beneath the well name. The depth intervals of occurrence of all log-identified source beds are also posted in the "$S_1 + S_2$" columns of plates 8, 9, and 10. As suggested previously from geochemical data, the log-identified source beds are observed to span the transition zone between the Brookian prodelta and overlying fluvial-deltaic facies.

The coincidence of the potential source beds with the marine to marginal marine transition in the Brookian deltaic system suggests that the source beds represent a specific facies setting within this transition zone. Dow (1977, p. D6-D8) notes that areas of high marine organic productivity are typically associated with areas of high nutrient supply, such as upwelling zones and the mouths of major rivers. The source beds in the Camden Basin may have formed in interdistributary bays or estuarine settings where moderate sedimentation rates and high nutrient supply were coupled with quiet water and anoxic bottom conditions. If so, then this organic facies might have prograded northward with the delta complex as it spilled into offshore sedimentary basins. This model, summarized in figure 17, implies that the source bed facies is time transgressive and becomes progressively younger to the north in offshore areas.

As an alternative model, we also recognize that certain global conditions (e.g., climate, sea level, oceanic circulation) which can promote the formation of potential source beds may have prevailed at the specific time (discussed below) that the Brookian source shales were deposited in the Point Thomson area. It is possible that potential source beds may have accumulated simultaneously in various environments (e.g., interdistributary bay, delta front, prodelta, abyssal plain) where the chief sedimentary process was deposition of shale. If a specific interval of time and associated global conditions, rather than local facies settings, provided the dominant controls for source bed accumulation, then source beds in the Brookian sequence may be found to be paleogeographically widespread, but confined to a certain interval of geologic time.

The potential source bed zone in the Point Thomson area wells roughly coincides with an interval that may be early Oligocene in age, based upon palynological evidence (J. Larson, personal commun., June 1985). The mid-Oligocene (30 m.y.) is thought to coincide with the end of a worldwide cycle of maximum marine transgression (Vail and others, 1977, fig. 2) and relative global warmth (Keigwin and Keller, 1984, p. 16; Keigwin, 1980, p. 723). Early Oligocene time may thus represent a unique period in the depositional history of the Brookian sequence. Demaison and Moore (1980, p. 1204) have emphasized that known oil source bed systems in the stratigraphic record are not randomly distributed, but coincide with periods of worldwide transgression and oceanic anoxia. North of the control wells, facies-equivalent but younger strata may have been deposited in a climatic setting or sea-level stand much different from that which prevailed during early Oligocene time. Changing global conditions may have precluded the formation of source beds in the transition zone facies setting in younger Tertiary shales in more northern parts of the Brookian deltaic system. However, this hypothesis cannot be evaluated in the absence of offshore well data. For the present, we assume northward continuity of the source beds, either as facies-equivalent, younger strata, or as time-equivalent strata formed in different environmental settings. In either case, potential source beds are presumed to extend northward within the Brookian sequence into offshore areas of the Kaktovik and, possibly, Nuwuk Basins.

Source beds capable of generating liquid hydrocarbons may be present elsewhere in the Cenozoic Brookian sedimentary sequence, but remain largely undetected at present by conventional geochemical and visual kerogen analyses. Exploration wells on the Canadian Beaufort shelf have found apparently autochthonous light oil and gas condensate in Cenozoic sediments which exhibit insufficient levels of thermal maturity (less than 0.6% V_{Ro}) for oil generation. These liquid hydrocarbons are also anomalous because they appear to have been derived from sediments containing primarily Type III (humic) organic matter, generally associated with gas-phase hydrocarbons. Snowdon (1980) and Snowdon and Powell (1982) suggest that these anomalous light oils were derived from thermal maturation of resinite (a maceral derived from tree resins) or from dispersed resinous material. Resinite is a prominent constituent of the Eocene brown coals of Germany and the Tertiary coals of Japan (Stach and others, 1982, p. 118-119), but is also found in Carboniferous and Cretaceous coals. This organic component of the Brookian sediments may have been overlooked in routine geochemical studies. If it occurs in sufficient abundance in the Brookian sequence, Tertiary rocks at relatively shallow depths and low levels of thermal maturity may offer a much greater potential for generation of liquid hydrocarbons than previously thought.

6

Geothermal Gradients on the Beaufort Shelf

The geothermal gradients measured in wells across the Arctic coastal plain of northern Alaska vary widely, as illustrated in the geothermal map presented in figure 18. Between 148° and 154° west longitude, the areas of high heat flux generally follow the axis of the Barrow Arch. West of 154°, the highest geothermal gradients lie south of the Barrow Arch (which parallels the coastline) and extend through the Husky-NPRA South Meade No. 1 well. This well measured the highest reported geothermal gradient (47 °C/km) on the North Slope of Alaska (Blanchard and Tailleur, 1982a, p. 47). East of 148° west longitude, the northwest-trending axis of the Barrow Arch is overprinted by the northeast-trending Camden Basin. The Camden Basin is a Late Cretaceous to Tertiary foredeep developed north of the Sadlerochit Mountains that contains at least 13,000 feet of Tertiary sediments onshore. As a result of rapid subsidence and high sedimentation rates, geothermal gradients are somewhat lower in the Camden Basin. The composite average gradient from several wells in the Point Thomson area is 33 °C/km (fig. 18).

Geothermal gradients comparable to those measured along the present coastline are inferred to extend into the geologically similar nearshore areas of the Arctic Platform (fig. 18). An average gradient of approximately 36 °C/km probably characterizes these areas, with the possible exception of the easternmost parts of province IB in the Camden Basin, where, as noted above, the gradient may be as low as 33 °C/km. Lower geothermal gradients are anticipated north of the Hinge Line (fig. 18) in the Nuwuk and Kaktovik Basins. Both of these areas were sites of substantial basinal subsidence and sedimentation during Cretaceous and Cenozoic time. The only information on the thermal structure of these remote provinces is a well in Canadian waters a few tens of miles east of the U.S.-Canadian border. The Dome Natsek E-56 well measured an uncorrected geothermal gradient of 26.7 °C/km (fig. 18). Although insufficient data are available for the application of Horner-type corrections to the thermal data from this well, relatively long residence times for uncirculated mud (up to 20 hours) preceded most logging surveys. The temperature data obtained in routine logging runs in the Natsek well are therefore considered to approximate static (true) formation temperatures.

The geothermal gradients inferred above for the principal petroleum provinces of the Beaufort shelf can be used to estimate the minimum burial depths required to achieve sufficient thermal maturation of organic matter for hydrocarbon generation. These minimum depths for the top of the "oil window" are tabulated below. The thermal ranges for oil generation and destruction used here were obtained from an organic maturation chart published by Hunt (1979, figs. 7-42, 7-49) and time-temperature relationships described by Dow (1977, figs. 13, 15). Because of the effect of thermal exposure time on the maturation of kerogen, younger sediments must be heated to higher temperatures than older sediments in order to reach corresponding levels of thermal maturity, or equal values of vitrinite reflectance. Subsidence in the Arctic Platform, the Camden Basin, and southern parts of the Nuwuk Basin occurred primarily during Cretaceous time, whereas subsidence in the outer Nuwuk Basin and the Kaktovik Basin occurred primarily in Tertiary time. Thus, the maturation history of the Arctic Platform, Camden Basin, and perhaps the southernmost parts of the Nuwuk Basin is considered to resemble that of the Cretaceous trend of the Louisiana Gulf Coast, where the oil window is found to lie between 100 and 136 °C (0.6 to 1.35 percent vitrinite reflectance). In contrast, areas of Tertiary subsidence north of the Hinge Line are probably more analogous, for example, to the lower to middle Miocene Gulf Coast trend (Dow, 1977, fig. 13), where the oil window is projected to lie between 131 and 198 °C (0.6 to 1.35 percent vitrinite reflectance).

Province	Predicted Geothermal Gradient	Oil Generation	Oil Destruction
Arctic Platform (provinces IA, IB, IC)	36 °C/km	9,200 feet (100 °C)	12,300 feet (136 °C)
Camden Basin (eastern parts of provinces IA, IB)	33 °C/km	10,200 feet (100 °C)	13,700 feet (136 °C)
Kaktovik and outer Nuwuk Basins (provinces IIA, IIB, IIC)	27 °C/km	15,400 feet (131 °C)	23,500 feet (198 °C)
Southern Nuwuk Basin (province IIA)	27 °C/km	12,200 feet (100 °C)	16,500 feet (136 °C)

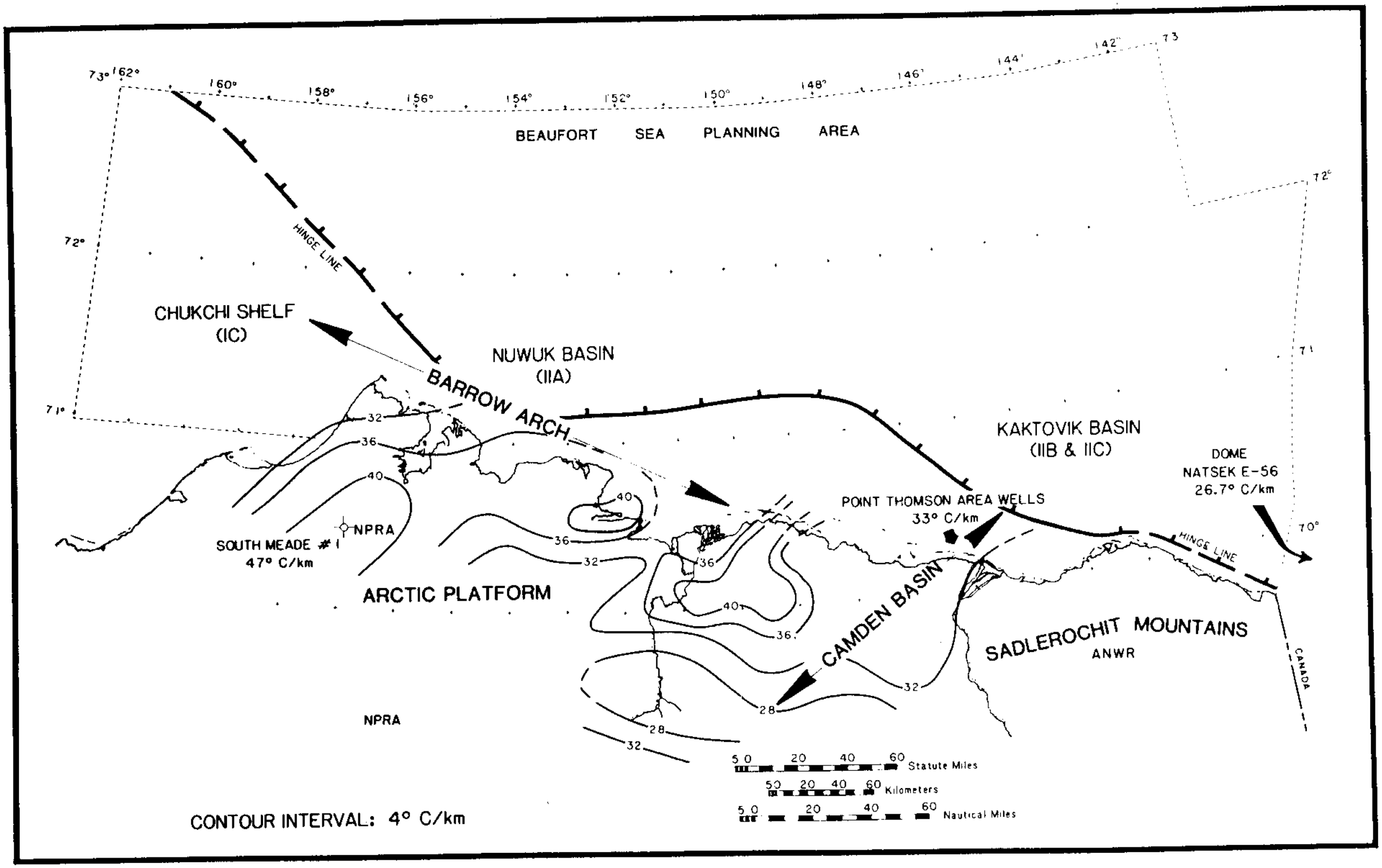


Figure 18.
Geothermal gradient map for the Arctic coastal plain, northern Alaska. Map compiled from interpreted data published by AAPG (1976) and Blanchard and Tailleur (1982a, p. 47, fig. 21; 1982b), and from unpublished well data.

The use of a temperature value to define maturity in the rocks of the Nuwuk and Kaktovik Basins is probably justified because maturation and oil generation are young and are probably related to equally young, rapid subsidence within the depocenters (Tissot and Welte, 1984, p. 619). This assumption may be less valid for older source beds within the Ellesmerian and Rift sequences of the Arctic Platform. In the Point Thomson area (Camden Basin), vitrinite reflectance values for Rift sequence beds compare favorably with maturity levels predicted from wellbore geothermal data (plates 8, 9, and 10). However, in wells in northwestern NPRA, Ellesmerian and Rift sequence source beds exhibit levels of thermal maturity (Magoon and Bird, 1986) which exceed those predicted by present burial depths and geothermal regimes. This suggests a prior history of deeper burial for these rocks.

Thermal models for rift zones (Falvey, 1974, p. 96) predict elevated geothermal gradients preceding and accompanying the actual rift event. Older sediments on the Arctic Platform may have accordingly been subjected to a thermal environment during the rift event which was much different than that which exists at present. Vitrinite reflectance data for the Inigok No. 1 well (Lerche and others, 1984, fig. 1), for example, suggest a past history of elevated heat flow. However, existing data (Magoon and Bird, 1986) from coastal wells along the southern margin of the planning area indicate thermal immaturity to early peak-oil levels of maturity for Rift sequence and older source beds (e.g., plates 8, 9, and 10). Isoreflectance maps published by Magoon and Bird (1986, figs. 12 and 18) for rock units in NPRA document a pattern of increasing thermal maturity to the south, away from the rift zone. This does not support an association of elevated heat flow with the rift axis during the rift event. However, this map pattern probably more closely reflects patterns of burial history, rather than areal variation in heat flow. Because pre-Brookian beds were at shallow burial depths near the rift zone at the time of rifting, threshold temperatures for the initiation of vitrinite maturation were probably not reached. The early history of high heat flow associated with the rift event probably had little or no effect on the present distribution of thermal maturity within Ellesmerian or Rift sequence source beds on the Arctic Platform.

7

Potential Reservoir Formations

In the following paragraphs, a synoptic description is presented for each potential reservoir formation which may occur in the Beaufort Sea Planning Area (fig. 3). The descriptions are obtained from an onshore data base, and the distribution, facies setting, and potential reservoir quality of these rocks in offshore areas can only be conjectured. Most of the formations described are not producing hydrocarbons at present, and in onshore areas, several do not occur in sufficient thickness or with adequate reservoir properties to be even considered capable of supporting a development facility. It is recognized, however, that the thickness and reservoir quality of these rock units may increase in different facies settings offshore.

The most prolific reservoir formation of the Ellesmerian sequence is the Ivishak sandstone, which is the principal reservoir in the Prudhoe Bay field (fig. 3). Development of less attractive reservoirs in other fields near Prudhoe Bay has only been made possible by the infrastructure which was constructed to develop the Ivishak reservoir in the Prudhoe Bay field. Clearly, the Ivishak Formation must be considered the primary reservoir objective within the Barrow Arch province, with all other units forming secondary, less attractive objectives.

Within the Nuwuk and Kaktovik Basins, Ellesmerian reservoir strata are either absent or lie at depths exceeding 20,000 feet. In these provinces, only sandstones of the Brookian fluvial-deltaic facies may occur in sufficient thicknesses and with adequate reservoir quality to be considered attractive exploration objectives. More deeply buried Brookian sandstones that accumulated in other facies settings, such as turbidites deposited in submarine fan complexes, are much more risky objectives, and can only be considered secondary exploration targets.

DEVONIAN CLASTIC ROCKS AND CARBONATES

Clastic rocks and carbonates of Devonian age are known only from surface outcrop studies of allochthonous thrust sheets in the Brooks Range far south of the Beaufort Sea Planning Area. No age-equivalent, undeformed rocks are known to occur in any wells which have penetrated basement near the Arctic coast. However, strata possibly equivalent to the allochthonous Devonian sequence exposed in the Brooks Range are inferred to occur in the Northeast Chukchi Basin beneath the Chukchi shelf province.

The Kanayut Conglomerate (Upper Devonian) ranges in thickness from 2,600 meters in the east-central Brooks Range to approximately 300 meters in the western Brooks Range (Nilsen and Moore, 1982b). In the western Brooks Range, the lower part of the Kanayut Conglomerate grades into the Noatak Sandstone (Nilsen and Moore, 1982b, p. 9), estimated to reach 1,000 meters in thickness (Tailleur and others, 1967). The Kanayut and Noatak sequences consist of sandstones, conglomerates, and shales deposited in a fluvial to nearshore marine setting which flanked a highland source terrane to the north and east (Nilsen and Moore, 1982b). Although these rocks are well indurated in surface exposures, their potential reservoir quality in the subsurface is unknown. No porosity or permeability data are presently available.

The Upper Devonian clastic sequence (Endicott Group) containing the Kanayut Conglomerate, Noatak Sandstone, and Hunt Fork Shale is underlain by platform carbonates of the Baird Group (Nilsen and Moore, 1982b, p. 1) of Middle to Late Devonian age (Tailleur and Brosgé, 1970, p. E4). We speculate that these Devonian carbonates may be equivalent to the basal carbonate unit identified in the Northeast Chukchi Basin. No information is presently available on the reservoir potential of the Baird Group rocks. Deformed sequences of lower Paleozoic carbonates (Katakturuk Dolomite and Nanook Limestone) are also known from surface exposures in the northeastern Brooks Range. Available data suggest that the reservoir quality of these rocks is poor, with porosities no greater than 1.9 percent reported for limestones and no greater than 5 percent reported for dolomites (Dutro, 1970, p. M2-M3). However, moderately deformed to undisturbed Devonian carbonates are known to contain numerous petroleum accumulations in central Alberta Province, Canada (Barss and others, 1970; Hemphill and others, 1970), and at the Norman Wells field, Northwest Territories, Canada (Meyerhoff, 1982, p. 525). Devonian carbonates may, therefore, be regarded as potential reservoir formations wherever they are thought to occur in subsurface traps.

KEKIKTUK FORMATION (MISSISSIPPIAN)

The Kekiktuk Formation, part of the Endicott Group, is widely exposed in the Brooks Range and is found in the subsurface across much of the Arctic coastal plain. Within the Beaufort Sea Planning Area east of Barrow, the Kekiktuk Formation is confined to the Barrow Arch province. West of Barrow, in the Northeast Chukchi Basin, many thousands of feet of strata inferred to be age equivalent to the Endicott Group are present (fig. 7). These strata may form the most important objective in the Chukchi shelf province.

At surface exposures and in most wells, the primary porosity of Kekiktuk sandstones and conglomerates is observed to be completely occluded by silica cement. For this reason, the formation was not regarded as a significant potential reservoir until the discovery of the Endicott field. At this location northeast of Prudhoe Bay, Kekiktuk sandstones are much less thoroughly cemented and form the principal reservoir within the field. Reservoir intervals in the Endicott field possess an average porosity of 20 percent (Alaska Oil and Gas Conservation Commission, 1984, p. 57) and the average permeability of some zones may range up to 1,100 millidarcys (Behrman and others, 1985, p. 656). The studies of Behrman and others (1985) suggest that the pore network in the Kekiktuk sandstones within the Endicott field has been enhanced by secondary leaching. However, even within the field, abrupt lateral changes in sandstone thickness and net sand content are observed within the Kekiktuk Formation. In most areas across the Arctic Platform the overall reservoir quality of the Kekiktuk Formation is quite poor. The reservoir potential of this formation (or its stratigraphic equivalent) in the Northeast Chukchi Basin remains unknown.

LISBURNE GROUP (MISSISSIPPIAN TO PENNSYLVANIAN)

The Lisburne Group is widely exposed at surface localities across the Brooks Range and has been penetrated by many wells along the coastal plain of northern Alaska. It is considered to be present over most of the Barrow Arch province, but it may pinch out in the southernmost part of the Chukchi shelf province. Beneath the Arctic coastal plain, the Lisburne Group ranges up to 4,000 feet in thickness and consists fundamentally of two informal limestone units separated by a dolomite unit (Bird and Jordan, 1977b). The dolomite unit has been considered to form the primary reservoir objective within the formation, exhibiting porosities averaging from 10 to 15 percent but ranging as high as 27 percent locally (Bird and Jordan, 1977b, table 1). The Lisburne Group contains only one known commercial accumulation and that is at the Prudhoe Bay field. There, the upper limestone unit lies mainly within the Prudhoe oil column, whereas the main dolomite unit lies below the oil-water contact. Nevertheless, the Lisburne pool in the Prudhoe Bay field is thought to contain 2 to 3 billion barrels of oil in place (Edrich, 1985). Tests of relatively thin dolomite beds in the upper limestone unit in the Prudhoe oil column have yielded flow rates of 1,000 to 1,500 barrels of oil per day (Bird and Jordan, 1977b, p. 93). Significant delineation and development drilling, however, has only occurred within the past few years, following development of the infrastructure for the Ivishak reservoir in the Prudhoe Bay field. Oil has been tested from Lisburne carbonates at other localities, but no additional commercial accumulations have been found. Because of its complex reservoir geology and generally poor reservoir quality, the Lisburne Group can only be considered a secondary objective in the Barrow Arch province.

ECHOOKA FORMATION (PERMIAN)

The Echooka Formation consists of very fine- to fine-grained, muddy, glauconitic sandstone. It is present in the subsurface across the Arctic coastal plain but thins depositionally to the north. It is probably absent over most of the Barrow Arch province. The formation reaches a thickness of at least 250 feet across central NPRA, but thins northward to a zero edge which projects offshore into the Chukchi shelf at Peard Bay. The Echooka Formation therefore may not extend northward into the Chukchi shelf province (IC). The formation is quite shaly to the south, but becomes more sandy to the north (Tetra Tech, 1982, fig. 46). At the USGS-Husky Peard No. 1 well, the formation consists of 160 feet of fine-grained sandstone exhibiting core porosities ranging from 10 to 21 percent. However, reservoir quality is quite poor: permeabilities range from 0.0 to a maximum of 2.5 millidarcys (Husky Oil NPR Operations, 1982, p. E-1). Poor reservoir quality typifies the Echooka Formation, and even where it lies within the hydrocarbon column at Prudhoe Bay, it does not constitute an attractive reservoir (Jones and Speers, 1976, p. 32). On the basis of these observations, the Echooka Formation is considered unlikely to form a potential reservoir horizon in any part of the Beaufort Sea Planning Area.

IVISHAK FORMATION (TRIASSIC)

Fluvial-deltaic sandstones and conglomerates of the Ivishak Formation form the most significant reservoir unit on the North Slope. The Ivishak Formation is the principal reservoir in the Prudhoe Bay field, where porosities can rise above 30 percent and permeabilities may exceed several darcys (Morgridge and Smith, 1972). These properties account in part for the exceptional reserves and productivity of this super-giant field.

The distribution of the Ivishak Formation on the North Slope is illustrated in figure 19. In the western part of the Barrow Arch province, the Ivishak Formation is absent north of a depositional limit shown as the "Zero Ivishak Formation" line in figure 19. Along the central Beaufort coast, the Ivishak depositional edge is truncated by the LCU. The Ivishak Formation truncation edge lies offshore and roughly parallel to the present coastline (fig. 19). In the vicinity of Prudhoe Bay, it passes southward onshore beneath the Arctic coastal plain. In northeastern Alaska, surface geology (Reiser and others, 1980) suggests a much more northern position (near the coastline) for this subcrop line. However, the distribution of the Ivishak Formation beneath the coastal plain of northeastern Alaska remains unknown. The map in figure 19 is drawn to suggest that northeastern Alaska is underlain by a subtle structural basin or outlier of Early Cretaceous age in which Ellesmerian strata, including the Ivishak Formation, have been preserved beneath the LCU. However, we recognize that the map distribution of the Ivishak

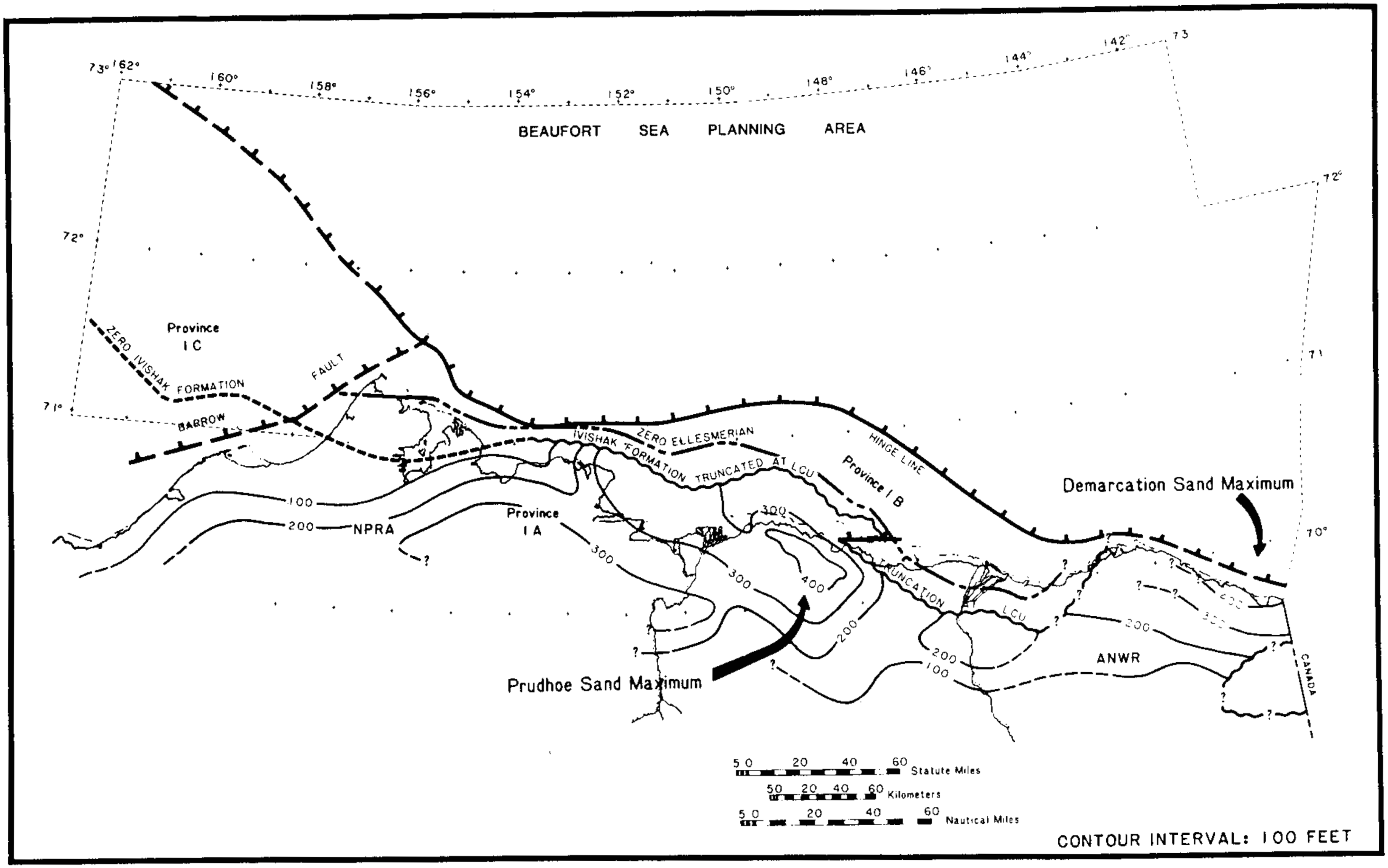


Figure 19.
Isopach map for net sand in the Triassic Ivishak Formation. Adapted from an unpublished map by J. Wills (MMS), 1985.

Formation and other units in northeastern Alaska may have been disturbed by northward-directed thrust faults of Cretaceous and younger age. The possible impact of such potentially significant structural displacements, however, cannot be evaluated with the limited data available at present.

Eckelmann and others (1976) and McGowen and Bloch (1985) have recognized the presence of a major lobe in the Ivishak deltaic system in the vicinity of the Prudhoe Bay field. Similar conclusions were reached by Jones and Speers (1976, figs. 14 and 16). Figure 19 presents a net sand isopach map for the Ivishak Formation. This map suggests that maximum sand deposition in the Ivishak system was focused at two principal localities on the North Slope. The westernmost depocenter (net sand greater than 400 feet) lies near Prudhoe Bay and is designated the "Prudhoe Sand Maximum" in figure 19. Finer grained, distal-facies sandstones and siltstones possessing poor reservoir characteristics generally dominate the Ivishak Formation at any significant distance from the Prudhoe Bay area. A second sand depocenter or deltaic lobe appears to be located in northeastern Alaska near Demarcation Bay, where surface outcrops contain 390 feet of sand in a stratigraphic section abbreviated by an overlying unconformity (Detterman, 1984, section 6). This exposure and other measured sections along the Egaksrak River published by Detterman (1974; 1984) show that the sandstones of the Ivishak Formation are thicker and more conglomeratic in those areas than in outcrops farther south and west, where a more distal facies appears to be dominated by fine-grained sandstone, siltstone, and shale. These observations prompted Detterman (1981, p. 39) to suggest the existence of a second major delta complex in the Ivishak depositional system in northeastern Alaska. This is designated the "Demarcation Sand Maximum" in figure 19. This eastern deltaic lobe may be time equivalent, as well as facies equivalent, to the depocenter near Prudhoe Bay. The existence of an eastern deltaic lobe which may have localized the accumulation of a reservoir sequence comparable to that found at Prudhoe Bay is very significant to the prospectiveness of northeastern Alaska (ANWR) as well as OCS waters in the eastern Beaufort Sea.

In the Kavik gas field, 80 miles southwest of Barter Island, Ivishak Formation porosities range from 5 to 12 percent (Mast and others, 1980, fig. 3). Porosities of only 2 to 10 percent are reported for outcrop specimens of Ivishak sandstone in the northeastern Brooks Range (Palmer and others, 1979). However, on the basis of the paleogeographic model presented above, we speculate that the reservoir quality of the Ivishak Formation in northeastern Alaska may improve to the north beneath the coastal plain concomitant with the development of a coarser grained fluvial-dominated facies as found at Prudhoe Bay.

Distal facies of the Ivishak Formation west and south of Prudhoe Bay are composed largely of fine-grained sandstone closely interbedded with siltstone and shale. Accordingly, the reservoir quality of the Ivishak Formation in the Beaufort Sea Planning Area is probably poor west of 154° west longitude. Because of the pattern of increasing shaliness to the west, the Ivishak Formation is not likely to form an attractive reservoir formation in the Chukchi shelf province of the Beaufort Sea Planning Area.

SAG RIVER FORMATION (TRIASSIC TO JURASSIC)

The Sag River Formation is inferred from geophysical mapping to be present beneath most of the Barrow Arch province. It is also thought to be present beneath much of the southern half of the Chukchi shelf province. The Sag River Formation contains highly bioturbated, glauconitic, muddy, very fine- to fine-grained sandstone (Jones and Speers, 1976, p. 41). The formation ranges in thickness along the Barrow Arch from approximately 50 feet at Prudhoe Bay to 70 feet near Point Barrow. The presence of abundant detrital matrix coupled with diagenetic cements and compaction have severely impacted the reservoir quality of the sandstones (Barnes, 1985). Jamison and others (1980, p. 304) report that an average porosity of 25 percent and permeabilities up to 270 millidarcys are observed where reservoir quality is best developed in the north part of the Prudhoe Bay field. The Sag River sandstone contains oil shows at numerous localities and has yielded oil in drill stem tests. However, because of the poor overall reservoir quality of the formation and because of its limited thickness, the Sag River Formation is not generally considered an attractive objective on the North Slope or in the Beaufort Sea Planning Area.

SIMPSON AND BARROW SANDSTONES (JURASSIC)

Sandstones interbedded with the shales of the Kingak Formation are found in the subsurface in the northwestern part of the North Slope. In contrast to the regionally widespread Sag River sandstone, these younger Jurassic sandstones are known only from wells in western NPRA. The uppermost of the two major sandstone bodies, informally termed the "Simpson" sand, is approximately 130 feet thick. The lower sandstone, termed the "Barrow" sand, is approximately 120 feet thick. The Simpson sand is found south and east of Barrow, but is truncated by the LCU in the vicinity of Barrow. The Barrow sands are found in the subsurface in the vicinity of Point Barrow. Similar facies-equivalent sandstones are probably present throughout the Jurassic section offshore southwest of Barrow in the Chukchi shelf province. Because of their limited eastward extent and because of the truncation of the entire Jurassic section to the north at the LCU, these sands are unlikely to be present offshore in the Barrow Arch province.

The Simpson sand is a silty, very fine- to medium-grained glauconitic sandstone. A core of the most well-developed part of the Simpson sand body in the USGS-Husky Peard No. 1 well yielded porosities ranging up to 25 percent but permeabilities no greater than 0.5 millidarcys (Husky Oil NPR Operations, 1982, p. E-1).

The Barrow sandstones are typically silty, argillaceous, very fine- to (locally) coarse-grained, and commonly glauconitic (Collins, 1961). In the South Barrow Test No. 2 well, cores recovered from the Barrow sand yielded an average porosity of 17 percent and permeabilities ranging from 8 to 20 millidarcys (Collins, 1961, p. 603). In the South Barrow Test No. 3 well, two specimens of cores recovered from the Barrow sand yielded porosities of 10 to 25 percent and permeabilities of 7.8 to 9.0 millidarcys (Collins, 1961). In the East Barrow gas field, a lower sandstone lens within the Barrow sandstones yielded an average core porosity of 21 percent and an average permeability of 552 millidarcys (Gruy and Associates, 1978, p. 7). However, the average porosity of the sands in the South Barrow field is 16.8 percent and the average permeability is only 24 millidarcys (Gruy and Associates, 1979, p. 5).

Gas is presently being produced from the Barrow sandstones as a source of energy for the village of Barrow and nearby government facilities. The production of this gas is not commercially viable, but is made possible through subsidies by the U.S. Government (Lantz, 1981, p. 199).

These data indicate that the overall reservoir quality of the Jurassic sandstones is poor, apparently as a consequence of fine grain size, high initial matrix content, and the introduction of diagenetic cements. Good reservoir quality is locally found in some minor sand bodies. Because of the limited thickness of these sandstones and their erratic reservoir quality, they are considered to represent only marginally attractive reservoir objectives, primarily confined to the Chukchi shelf province.

KUPARUK FORMATION (EARLY CRETACEOUS)

The Kuparuk Formation consists of a sequence of interbedded shales and very fine- to coarse-grained, quartzose, glauconitic sandstones which overlies the Kingak Shale (Carman and Hardwick, 1983). Sandstones occur in individual bodies up to 150 feet thick. The Kuparuk Formation occurs only in onshore areas and in nearshore parts of the Barrow Arch province west and north of Prudhoe Bay (Jamison and others, 1980, fig. 18). Because of northward stratigraphic thinning and truncation at the overlying LCU, the Kuparuk Formation probably does not extend far northward into offshore OCS waters. However, it may underlie some Federal OCS tracts south of the barrier islands between the deltas of the Colville and Sagavanirktok Rivers.

The Kuparuk Formation is generally divided into two members on the basis of distinctive lithologies, depositional settings, and reservoir properties (Carman and Hardwick, 1983, fig. 8). In the upper member, porosity (mostly of secondary origin) averages 23 percent and ranges locally up to 33 percent; permeabilities average 130 millidarcys, but range up to 1,500 millidarcys (Eggert, 1985).

In the sandstones of the lower member, porosity (chiefly primary) also averages 23 percent, but ranges up to 30 percent; permeabilities average 100 millidarcys, but may range up to 500 millidarcys (Eggert, 1985).

Oil has been recovered in formation tests from the Kuparuk Formation at numerous onshore localities north and west of the Prudhoe Bay field. However, current production is limited to an area 10 to 30 miles west of Prudhoe Bay. The presently mapped Kuparuk pool covers 300 square miles (an area approximately equal to 30 OCS tracts), with a vertical closure of about 1,100 feet (Carman and Hardwick, 1983, p. 1024). Ultimate recoverable reserves are estimated to be between 1.0 and 1.5 billion barrels (Carman and Hardwick, 1983, p. 1014), making the Kuparuk field the second largest in the United States. Additional production from Kuparuk Formation sandstones at the 100-million-barrel Milne Point field is scheduled to begin during the first quarter of 1986 (Oil and Gas Journal, 1985c, p. 55).

RIFT SEQUENCE SANDSTONES (EARLY CRETACEOUS)

At widely scattered localities on the northern Arctic Platform, exploration wells have encountered sandstones lying directly upon the LCU. A mixed nomenclature has been applied to these sandstones, generally reflecting the geographic locale or particular well in which the sandstones were encountered. Examples include the Walakpa, Kuyanak, Put River, Niakuk, and Point Thomson sandstones along the coast, and the Kemik sandstones in the Brooks Range foothills. These sandstones range in thickness from a few tens of feet at most localities up to 330 feet in the Point Thomson area.

A conceptual model for the paleogeographic setting of Point Thomson sandstone deposition, as developed in the following paragraphs, is important because it may provide an analog for depositional settings found along the margin(s) of infrarift grabens developed in the Outer Arctic Platform province during Early Cretaceous time. Structurally localized clastic facies, such as the Point Thomson sandstones, associated with the evolution of infrarift grabens and highlands may form the basis for the most significant play in the Outer Arctic Platform province.

The Point Thomson sandstones were first tested at Exxon's Point Thomson No. 1 well in 1977. At this locality, 330 feet of sandstone and conglomerate lie directly upon metamorphic basement (Franklinian) and are in turn overlain by the Lower Cretaceous Pebble Shale. Age inferences based solely upon the stratigraphic position of these coarse clastics are somewhat equivocal. The LCU in the Point Thomson area is commonly located at the base of the Pebble Shale sequence (fig. 3). This placement of the unconformity in the Point Thomson No. 1 well only constrains the stratigraphic age of the sandstones as

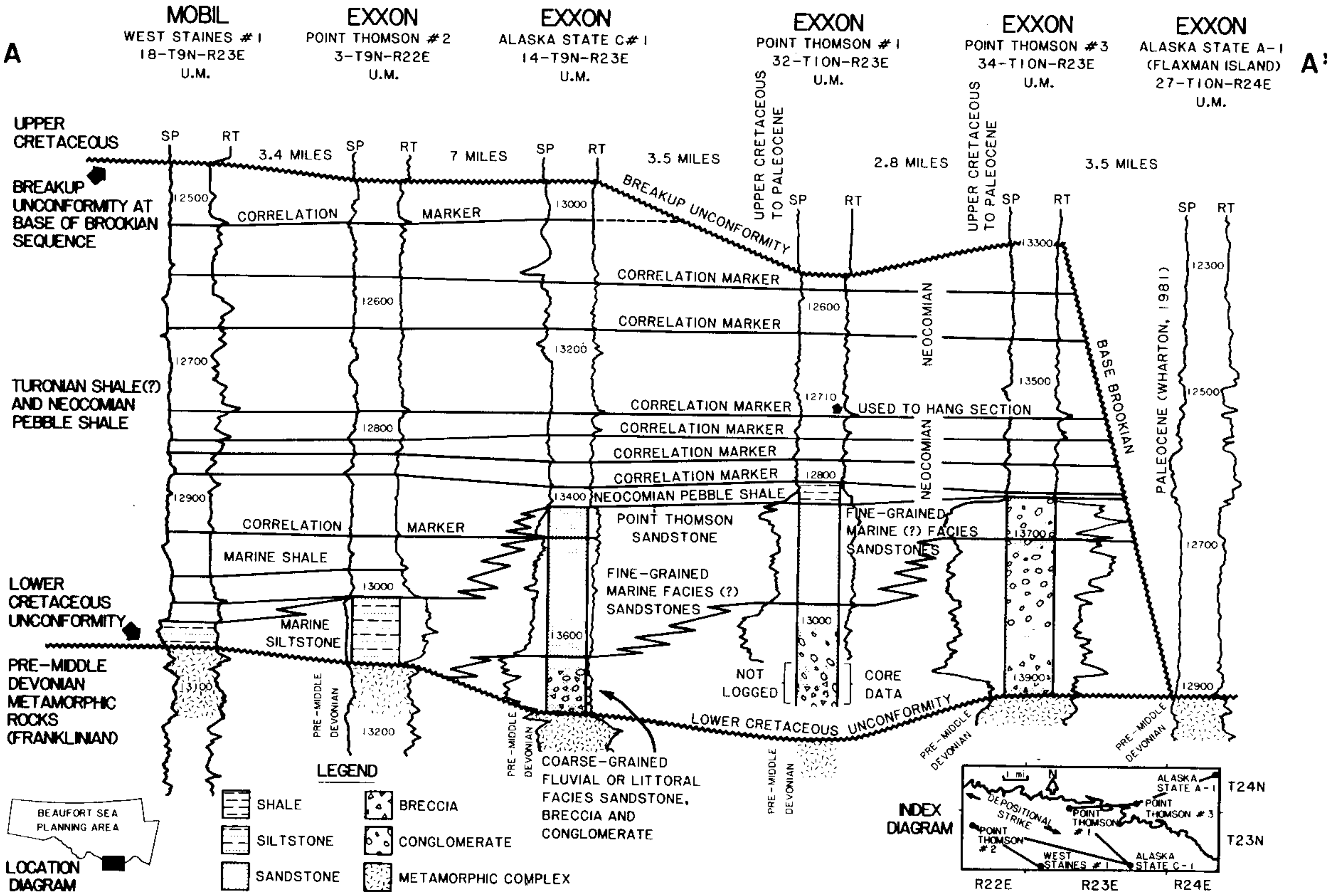


Figure 20.
Stratigraphic cross section illustrating facies relationships within the Lower Cretaceous Point Thomson sandstones. The wells are projected into a northeast-southwest line of cross section oriented roughly perpendicular to depositional strike. All posted depths are log-measured depths.

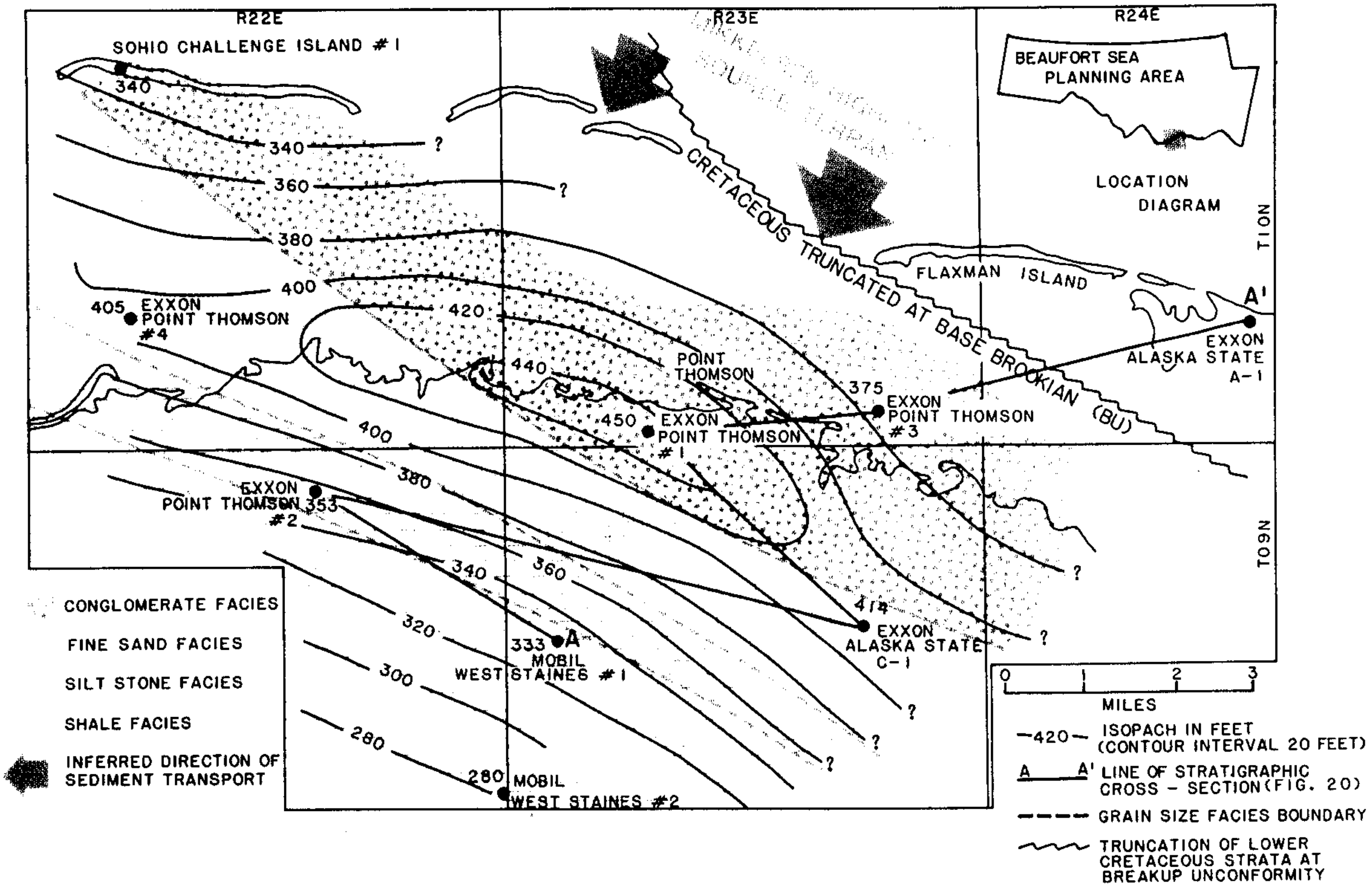


Figure 21.

Isopach and facies map for Lower Cretaceous depositional system in Point Thomson-Flaxman Island area, eastern Beaufort Sea Planning Area. Isopach lines show thickness of interval between prominent correlation marker in Pebble Shale (fig. 20) and the Lower Cretaceous unconformity (LCU). Grain size facies represent the lowermost 100 feet of Point Thomson sandstones or equivalent strata (Pebble Shale).

between Middle(?) Devonian (i.e., post-Franklinian) and Early Cretaceous. However, consideration of the regional geology and detailed correlations between a group of wells in the area (fig. 20) suggest that the LCU in the Point Thomson area lies instead at the base of the sandstone/conglomerate sequence. The top of the Point Thomson sand sequence is therefore probably not a major unconformity, but rather a conformable contact in a facies succession. The Early Cretaceous age assignment thus obtained for the Point Thomson sandstones suggests that they are equivalent to (but not necessarily continuous with) the Kemik sandstones exposed to the south in the Brooks Range (Detterman and others, 1975, fig. 21). The Point Thomson sandstones may then also be considered correlative with the "Put River" sandstones (Jamison and others, 1980, fig. 8) known from the subsurface in the Prudhoe Bay area, and the Walakpa and Kuyanak sandstones in NPRA. All of these rocks, as well as the Pebble Shale, are included within the Rift sequence.

Facies relationships within the Lower Cretaceous depositional system in the Point Thomson area are illustrated in the stratigraphic cross section presented in figure 20. The cross section is restored to paleohorizontal, or "hung," on a thin, high-resistivity bed with excellent lateral traceability which is found within the upper part of the Pebble Shale. Lithologic logs of the wells suggest that this distinctive marker bed is a well-cemented coquinoid limestone. This bed, for reference purposes, occurs at a log-measured depth of 12,710 feet in the Exxon Point Thomson No. 1 well. An isopach map for the stratigraphic interval between this marker bed and the LCU is presented in figure 21.

As shown in figure 21, Lower Cretaceous strata beneath the marker bed thicken into a basin with a northwest-trending axis which lies at or near the Point Thomson No. 1 well. The cross section in figure 20 shows that these strata thin southwestward by onlap onto a subtle structural high. The wells illustrated in figure 20 project into a line of cross section which is oriented northeast-southwest, roughly perpendicular to the axis of the basin in which the Point Thomson sandstones accumulated. Wells along the northeast margin of the Point Thomson basin have encountered abundant coarse-grained sandstones, conglomerates, and breccias. Detailed correlations (fig. 20) show that within a few miles across depositional strike to the southwest, these coarse-grained rocks grade abruptly into siltstones and shales more typical of the Pebble Shale sequence. Within the sand complex, a northern facies characterized by conglomerate and breccia can be separated from a southern facies dominated by fine-grained sandstone (fig. 20). The map distribution of grain size facies within the Lower Cretaceous depositional system in the Point Thomson area is superimposed upon the isopach map of figure 21. The facies distribution implies that the source terrane for the Point Thomson detritus lay to the north of the depositional basin.

Breccias and conglomerates in the Point Thomson area wells are composed of angular to rounded clasts of dolomitic marble and metaquartzite. Sandstones, and the sand matrix of conglomeratic rocks, are composed largely of lightly abraded, subangular, monocrystalline grains of dolomitic carbonate. Because such particles are highly susceptible to mechanical attrition and chemical dissolution, their presence implies rapid erosion, brief transport, and deposition in a setting very near the source area. Dolomitic marbles and metaquartzites which are mineralogically identical to the major clast types found within the Point Thomson sandstones have been encountered within the basement complex penetrated by several wells in the area. In concert with the map distribution of grain size facies within the Point Thomson sandstones, these observations seem to document the presence of a significant, northern source for Point Thomson detritus at subaerial exposures of the basement complex along the Mikkelsen high during Early Cretaceous time.

The Rift sequence sandstones typically exhibit fair to good reservoir properties. At its type locality, the average porosity of the Put River sandstone is about 12 percent. Permeabilities are typically less than 100 millidarcys, but may range up to 404 millidarcys (Jamison and others, 1980, p. 304). A core of a sandstone overlying the LCU in the Walakpa No. 1 well yielded an average porosity of 18 percent and an average permeability of 49 millidarcys, with maximum values of 25 percent and 157 millidarcys (Husky Oil NPR Operations, 1983a, p. D-1). No core data are presently available for the Point Thomson sandstones, but a flow test of 87 feet of perforations in the Exxon Point Thomson No. 1 well yielded 2,300 barrels of oil per day and 13 million cubic feet of gas per day (Jamison and others, 1980). The Point Thomson pool is estimated to contain recoverable reserves of 350 million barrels of condensate and 5 trillion cubic feet of gas (Smith, 1984, p. 4).

In conclusion, with the exception of the Point Thomson sandstones, the thin and discontinuous Rift sequence sandstones are not considered to form significant reservoir formations in most onshore areas or within offshore parts of the Barrow Arch or Chukchi shelf provinces. However, we speculate that a significantly thicker sand facies with attractive reservoir properties may have formed in the infrarift grabens offshore in the Outer Arctic Platform province. In these areas, Lower Cretaceous sandstones overlying the LCU may eventually form the primary target for exploratory drilling.

BROOKIAN PRODELTA SANDSTONES (CRETACEOUS TO TERTIARY)

Shales and siltstones are presumed on the basis of onshore data to compose the bulk of the Brookian prodelta facies throughout all provinces within the Beaufort Sea Planning Area. In onshore wells, sandstones, interpreted to represent turbidite deposits, occur locally within this primarily shale sequence. These sandstones occur in beds ranging from several feet to several tens of feet in thickness. The prodelta sandstones are fine to medium grained, silty, and commonly rich in detrital clay matrix. Log-derived porosities are typically high (25 to 35 percent) because of the combined effects of matrix clay and undercompaction. Flow tests of oil-bearing intervals generally report low flow rates, apparently a consequence of poor formation permeability. However, Brookian prodelta sandstones in Exxon's Alaska State A-1 well on Flaxman Island form a noteworthy exception to this general observation. In this well, sandstones near the base of the Brookian prodelta shale facies flowed oil with associated gas at the rate of 2,507 barrels per day (Jamison and others, 1980, p. 298).

Data from onshore wells indicate that Brookian prodelta sandstones are not likely to form prospective reservoirs within provinces which lie south of the Hinge Line. However, prodelta sands may have been deposited in thicker and more extensive bodies in submarine fan complexes developed at the mouths of submarine canyon systems where the northward-prograding Brookian deltaic systems met areas of major contemporary subsidence north of the Hinge Line. Stratigraphic traps associated with such sand accumulations could form significant exploration objectives.

BROOKIAN FLUVIAL-DELTAIC SANDSTONES (CRETACEOUS TO TERTIARY)

Sandstones, shales, and coals of the Brookian fluvial-deltaic facies are present throughout all provinces on the Beaufort shelf. Sandstones are very fine to coarse grained, and conglomerates are locally abundant. These clastic rocks are commonly friable in coastal wells, but are well indurated in surface exposures and in wells to the south. Marginal marine to marine sandstones near the base of the sequence in coastal wells are less conglomeratic and occur in beds ranging from several feet to 100 feet in thickness. Fluvial sandstone complexes higher in the sequence are typically more conglomeratic, and individual sandstone bodies may range up to 700 feet in thickness.

Poor to fair reservoir quality is typically observed in Brookian deltaic sandstones to the south near the Brooks Range. In the Umiat area, average porosities for Brookian sandstones range from 12 to 16 percent, and average permeabilities range from 10 to 167 millidarcys (Fox, 1979, p. 53). Diagenetic cements and deformation of ductile clasts during compaction have adversely impacted the reservoir quality of these rocks (Bartsch-Winkler, 1979, p. 69).

Reservoir quality generally appears to improve to the north and east in facies-equivalent but younger strata of the Brookian deltaic complex. Along the Arctic coast from Harrison Bay to the Canning River, sonic-log-derived porosities in the marginal marine to marine sandstones at the base of the deltaic facies range from 25 to 33 percent. In the oil-bearing nearshore-marine West Sak sands, which occur at the base of the fluvial-deltaic facies, cores have yielded an average porosity of 29 percent and an average permeability of 500 millidarcys (Jamison and others, 1980, p. 312). Log-derived porosities in the fluvial sandstones higher in the Brookian delta complex commonly exceed 30 percent, possibly due in part to undercompaction.

Oil shows have been encountered in Brookian fluvial-deltaic sandstones at numerous well localities. Most commonly, oil shows occur in the lower, marginal marine sands near the base of the fluvial-deltaic facies. At present, the only known potential production in Brookian deltaic sands is in small anticlinal traps in the Umiat area (northern foothills of the Brooks Range) and in the West Sak and Ugnu pools (west of Prudhoe Bay). The Umiat structure is estimated to contain 30 to 100 million barrels of oil (Jamison and others, 1980, p. 291) but is not considered to be a commercial accumulation. The known, potentially productive area of the West Sak and Ugnu sands is quite large. The total in-place oil contained within these accumulations is estimated to be as large as 40 billion barrels (Werner, 1985), approximately twice the in-place volume of the Prudhoe Bay field. However, the reservoir sands here are less than 100 feet thick (Jamison and others, 1980, fig. 22) and contain a heavy oil ranging from 8° to 22° in API gravity (Werner, 1985). Because of these unfavorable reservoir and fluid properties, oil recovery, should production actually occur, is anticipated to be low.

Sandstones of the Brookian fluvial-deltaic facies are regarded as the primary reservoir objectives in the Nuwuk and Kaktovik Basins. Thick sequences of porous sandstone and conglomerate with favorable reservoir properties have been encountered in this interval by many coastal wells. Significant local thickening of these deltaic sands may be anticipated on the downthrown blocks of growth faults in actively subsiding depocenters directly north of the Hinge Line. This setting is therefore not only favorable for the structural entrapment of migrating hydrocarbons, but is also a likely area for the localization of thick sandstone reservoir sequences.

8

Play Concepts and Hydrocarbon Trap Configurations

The great diversity of structural styles and stratigraphic histories of the various geological provinces in the Beaufort Sea Planning Area offers a diverse array of potential hydrocarbon play concepts. Although it may frustrate geological analysis, this complexity is viewed as favorable for the occurrence of commercial accumulations of hydrocarbons. Complexity and diversity increase the opportunities for the occurrence of the unique combination of geological events necessary for the formation of a major hydrocarbon accumulation.

The discussion of potential play concepts in the planning area is organized primarily around the major tectonostratigraphic provinces outlined in figure 1. The discussion of the petroleum geology of the Camden and Demarcation sectors, however, departs from this format in that it is extended to include areas which lie both north and south of the Hinge Line. Although, as in other parts of the planning area, the Hinge Line separates areas of contrasting geology, the importance of these distinctions is diminished in the eastern Beaufort Sea. In the Camden and Demarcation sectors, many important stratigraphic and tectonic elements overlap or merge across the Hinge Line. In these sectors, the key aspects of the petroleum geology are more concisely addressed within an organizational format based upon geographic sectors. Synoptic descriptions of the play concepts and potential trap types associated with each of these major provinces or sectors are given in tables 2 through 7.

BARROW ARCH (IA)

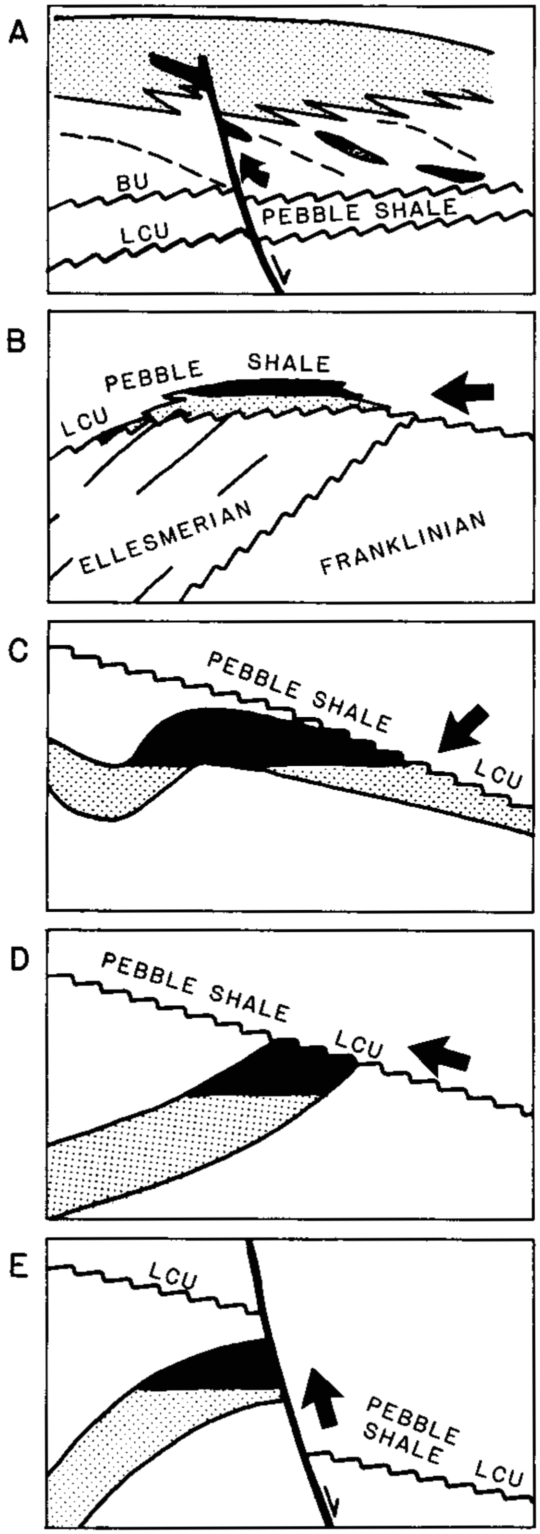
Within this part of the Beaufort shelf, Ellesmerian rocks are preserved, at least in part, beneath the Lower Cretaceous unconformity (LCU). The onshore extension of province IA includes most of the major fields discovered to date on the North Slope. Our concepts concerning potential plays offshore (fig. 22) extend chiefly from our knowledge of the geology of these onshore fields.

Oil and gas contained in onshore fields are pooled in a variety of trap configurations involving numerous reservoir formations. However, most share one common feature in that they directly or indirectly lie in contact with the Pebble Shale, a long-recognized

Table 2. Barrow Arch (province IA): Summary and play analysis.

SEISMIC SEQUENCE	TYPE OF TRAP	RESERVOIR	PROBABLE SOURCE BEDS	AGE OF TRAP	SIZE OF TRAP	PROBABLE OIL/GAS	REMARKS
Brookian	Stratigraphic	Upper Cretaceous	Lower to Upper Cretaceous	Late Cretaceous	Areally large. Potential pay <100'.	50/50	Lenticular bodies of Brookian sandstone (e.g., Ugnu, West Sak sands) charged with hydrocarbons migrating along faults from deeper seated sources.
Rift	Stratigraphic	Lower Cretaceous	Lower Cretaceous	Early Cretaceous	Areally small. Potential pay <200'.	60/40	Locally developed, relatively thin sands in apparent shoal areas on Lower Cretaceous unconformity. Examples in onshore wells include Walakpa, Kuyanak, Put River, and Niakuk sandstones.
Ellesmerian (Prudhoe style)	Gentle folds, closure at faults, and subunconformity wedge-outs on Barrow Arch	Carboniferous (Endicott and Lisburne), Triassic (Ivishak), Jurassic (Sag River), Cretaceous (Kuparuk River)	Triassic to Lower Cretaceous	Early Cretaceous	Areally large. Potential pay >100' depending upon reservoir involved.	40/60	Principal reservoir units at Prudhoe Bay and Kuparuk fields have pinched out or thinned significantly over much of the offshore areas in the Barrow Arch province.

BARROW ARCH (IA)



A. Brookian deltaic sandstones or prodelta turbidite sands charged with hydrocarbons which migrated up faults from deeper seated sources in Rift or Ellesmerian sequences. Diagram adapted from Carman and Hardwick (1983, p. 1029).

B. Laterally sealed Rift sequence sandstones developed locally on the Lower Cretaceous unconformity (LCU) over shoals possibly related to structural highs.

C. Simple anticline in Ellesmerian strata with hydraulic access to source bed at the LCU.

D. Tilted Ellesmerian reservoir formation truncated updip at the LCU and overlain by the Pebble Shale.

E. Folded or tilted Ellesmerian reservoir formation truncated updip at fault in hydraulic communication at depth with potential source beds in Rift or Ellesmerian sequences.

Figure 22.

Play concepts and known or potential trap configurations developed in Ellesmerian, Rift, and Brookian strata in the Barrow Arch province (IA). Large arrows denote potential migration paths.

major source bed sequence. It was this nearly universal relationship which prompted Morgridge and Smith (1972, p. 500-501) to suggest that most of the oil in Prudhoe Bay and satellite accumulations was sourced from the Pebble Shale. Structures not in direct communication with the Pebble Shale, such as the immense Colville anticline, were found to be dry. This reinforced the concept of a genetic link between contact with the Pebble Shale and access to migrating hydrocarbons.

Known hydrocarbon accumulations on the Arctic coastal plain typically combine two or more trapping mechanisms. The Prudhoe Bay field, for example, is sealed along its north margin by a major normal fault. It is sealed to the south beneath south-dipping shales which overlie the reservoir sand. A structural saddle in the upper surface of the reservoir unit limits the western extent of the field. The crest and eastern flank of the field are sealed where the reservoir sandstones are unconformably truncated by the LCU and overlain by the Pebble Shale. An excellent summary of the geology of the Prudhoe Bay field is found in Morgridge and Smith (1972). Most of the smaller accumulations found near the Prudhoe Bay field are also composite traps which incorporate more than a single trapping mechanism.

Potential traps which share fundamental properties with the Prudhoe Bay field exist offshore in province IA. The areally immense Mukluk structure in Harrison Bay contains the same reservoir unit and partial assemblage of trapping mechanisms as found at Prudhoe Bay (fig. 23). However, the trap has been tested and found to contain only residual oil. The trap may have been breached by leakage along a system of post-Brookian faults which cross the Mukluk structure. Alternatively, a prior accumulation of hydrocarbons may have spilled into other structures during regional tilting in Cretaceous or Tertiary time.

The most significant reservoir unit within the Ellesmerian sequence is the Ivishak Formation, which is the principal reservoir at Prudhoe Bay. In the Prudhoe Bay field, Ivishak Formation porosities may exceed 30 percent and permeabilities are observed to rise above several darcys (Jones and Speers, 1976; Morgridge and Smith, 1972), accounting for the tremendous productivity of this field. Limestones and dolomites of the Lisburne Group and sandstones of the Endicott Group form less attractive secondary objectives. Therefore, the presence and reservoir quality of the Ivishak sandstones at localities within province IA are critical to the overall prospectiveness of structures in those areas.

As discussed previously, the deposition of Ivishak sandstones appears to have been focused at two major deltaic lobes, or depocenters, located near Prudhoe Bay and Demarcation Bay. Much of western NPRA, and presumably the Chukchi shelf (province IC), is underlain by a shaly facies of the Ivishak Formation. Within the Barrow Arch province, the Ivishak Formation occurs along a narrow strip of OCS tracts between Smith Bay and the Sagavanirktok Delta (fig. 19). Although potential trapping structures are present within this area, including the recently discovered Seal Island field, the largest and most promising feature, the Mukluk structure, has been tested and found to be dry.

MUKLUK STRUCTURE

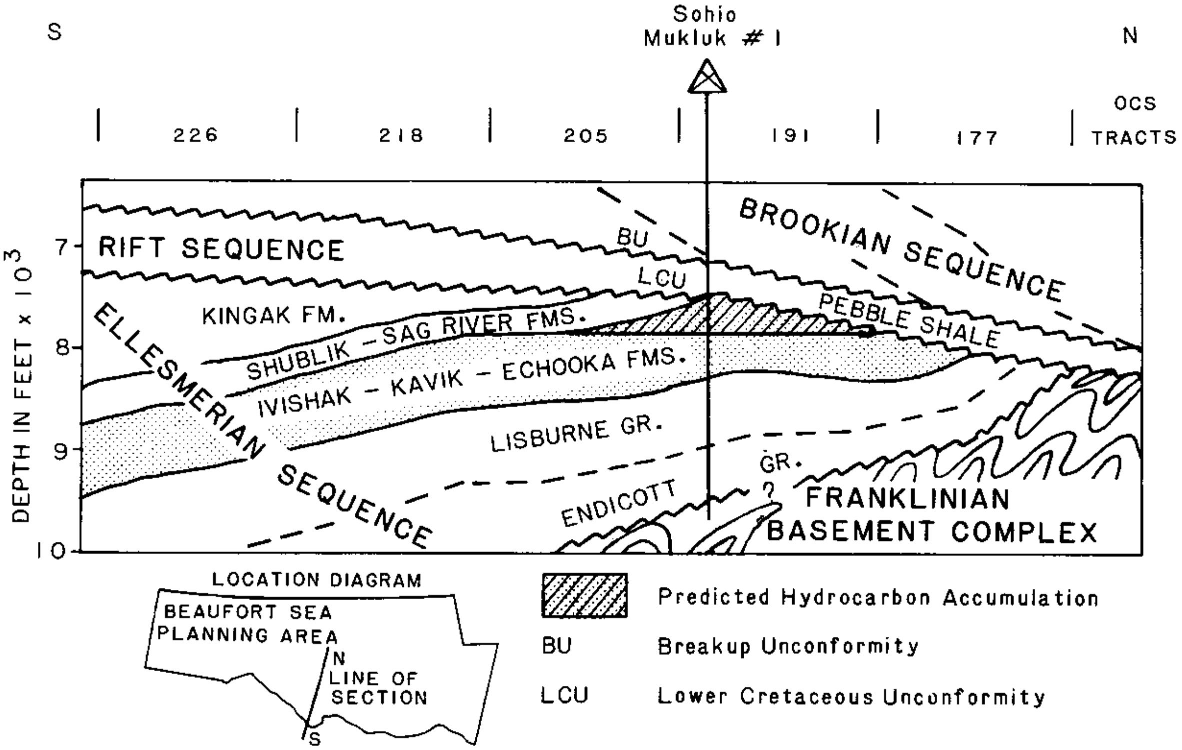


Figure 23.

Schematic geological cross section through Mukluk structure in the Barrow Arch (IA) province. A $140 million exploratory test well drilled by Sohio and partners in 1983 demonstrated conclusively that no significant hydrocarbon accumulation exists within the structure. The Mukluk structure is formed by a similar composite of sealing surfaces and trapping configuration as found at the neighboring Prudhoe Bay field. Diagram adapted from an illustration published by Cony (1983, p. A-2).

OUTER ARCTIC PLATFORM (IB)

This province is geologically separated from other Arctic Platform provinces (IA and IC) on the basis of the apparent absence of all Ellesmerian strata due to a combination of stratigraphic onlap and erosional truncation. The basic geology of the Outer Arctic Platform province is illustrated in plates 4 and 5 and the schematic geological cross section of figure 24. Although structurally part of the Arctic Platform, province IB possesses a distinct stratigraphy and consequently a somewhat reduced petroleum potential relative to provinces IA and IC.

The major structural feature of province IB is the Dinkum graben, first identified by Grantz and others (1982b). This structure, as illustrated in plate 5 and schematically portrayed in figure 24, is an asymmetric simple graben. The graben was formed by northward tilting and faulting on its south flank and by major normal faulting on its north flank, where it apparently abuts a shelf-edge basement high. Fault movement on the margins of the graben appears to have terminated during Early Cretaceous time, and the breakup unconformity (BU), which separates the overlying Brookian sequence from the underlying structural complex, is unfaulted over this feature (plate 5).

Grantz and May (1982, fig. 11) suggested that the LCU extends across the top of the Dinkum graben and caps a Jurassic to Cretaceous graben fill more or less coeval to the Ellesmerian Kingak and Kuparuk Formations. We offer an alternative interpretation (fig. 24) which assumes that the formation of the graben postdates the regional erosional event on the LCU. This model implies that the graben is filled with sediments of the Rift sequence which are time equivalent to the Pebble Shale and to basal sand units that overlie the LCU onshore. This interpretation is more consistent with our seismic mapping and with the rift model advocated in this report for the development of the Beaufort continental margin. In accordance with concepts for rift evolution proposed by Falvey (1974), the LCU ("rift onset unconformity") is thought to have formed in response to regional thermal elevation of the crust in the vicinity of the incipient rift. The subsequent onset of actual divergent movement (Falvey's "rift valley stage") apparently produced brittle fracturing and development of infrarift grabens and horsts within the Arctic Platform adjacent to the major rift. The structurally negative areas were subsequently filled with sediment derived from flanking highlands.

The Mikkelsen high is an infrarift positive structural block which intervenes between the Dinkum graben and the Arctic Platform to the south (fig. 24). The Mikkelsen high is flanked along parts of its southern margin by a thick apron of coarse-grained sandstones and conglomerates of Early Cretaceous age, informally termed the Point Thomson sands. These sands have been tested by Exxon as hydrocarbon productive at several wells and may contain a commercial accumulation.

Table 3. Outer Arctic Platform (province IB): Summary and play analysis.

SEISMIC SEQUENCE	TYPE OF TRAP	RESERVOIR	PROBABLE SOURCE BEDS	AGE OF TRAP	SIZE OF TRAP	PROBABLE OIL/GAS	REMARKS
Brookian	Stratigraphic	Upper Cretaceous	Lower to Upper Cretaceous	Late Cretaceous	Areally large. Potential pay <100'.	40/60	Lenticular bodies of Brookian sandstones in deltaic and prodeltaic settings.
Rift	A. Stratigraphic	Lower Cretaceous	Lower Cretaceous	Early Cretaceous	Areally small. Potential pay <200'.	60/40	Locally developed, relatively thin sands in apparent shoal areas on Lower Cretaceous unconformity. Examples on the Arctic Platform include Walakpa, Kuyanak, and Put River sandstones.
	B. Closure at faults	Lower Cretaceous	Lower Cretaceous	Early Cretaceous	Areally small. Potential pay >200'.	60/40	Clastic wedges, possibly analogous to the Point Thomson Sands, developed along the margins of Lower Cretaceous infrarift grabens. The largest example of these depocenters is the Dinkum graben.

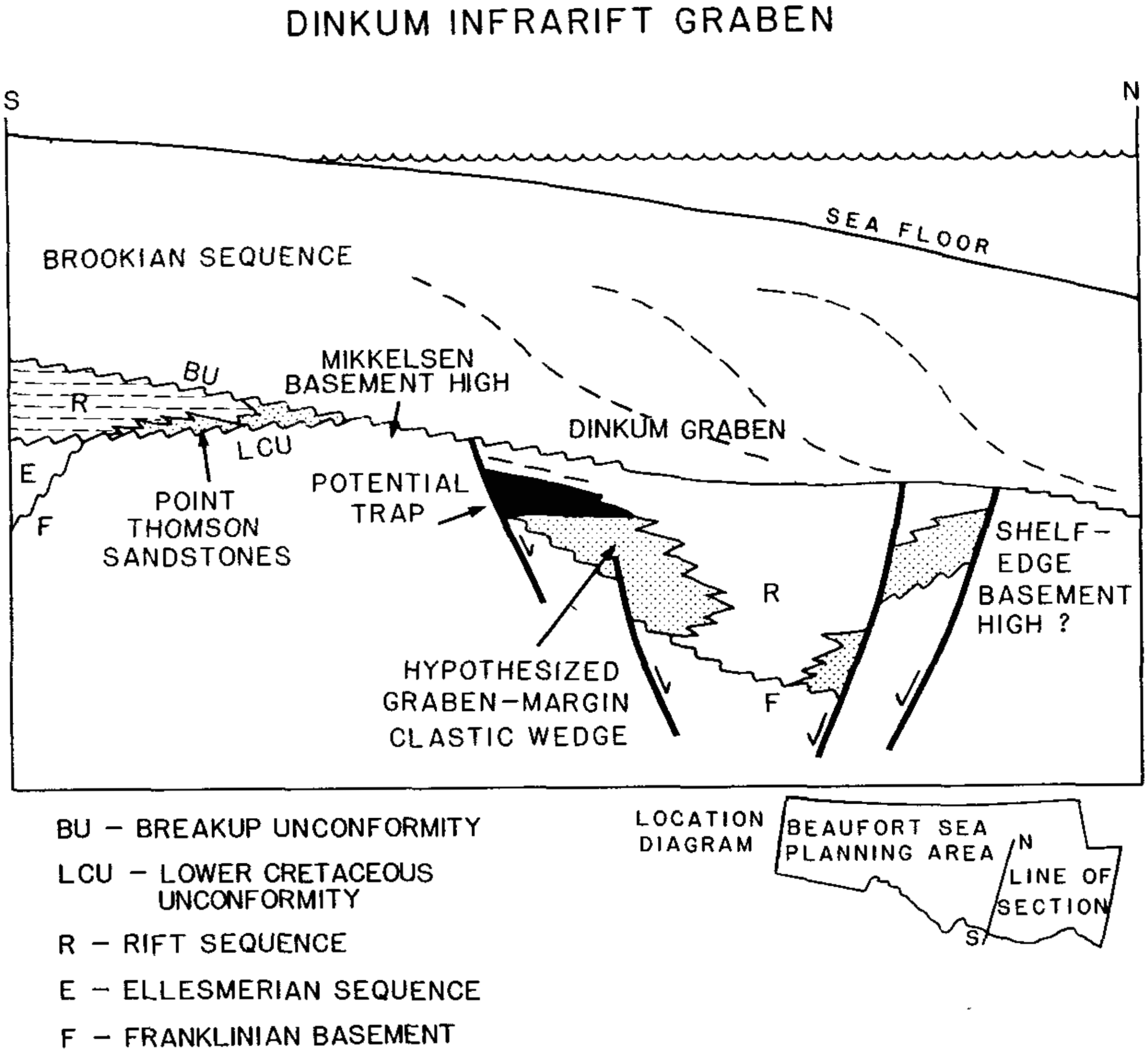


Figure 24.
Schematic geological cross section across the Mikkelsen basement high and Dinkum graben. This diagram is presented to illustrate how stratigraphic relationships observed within the Point Thomson sandstones may be extended into a broader paleogeographic model for sedimentation along the margins of the Dinkum graben, a major infrarift basin underlying the Beaufort shelf. The model suggests that coarse-grained clastic deposits may have been localized along the margins of the Dinkum graben and contemporaneous features adjacent to highland source terranes. Hydrocarbon traps may occur where these potential reservoir rocks lie within structural closures against basin margin faults, as illustrated above. Interior parts of the graben may contain highly organic shales similar to the equivalent Pebble Shale, known from onshore localities. Fault traps along the edge of the Dinkum graben may have been charged with hydrocarbons sourced from such shales.

As articulated in a preceding section, we suggest that Point Thomson sand deposition may form an analog for Early Cretaceous sedimentation along the margins of the Dinkum graben as well as other infrarift grabens. This is schematically illustrated in figure 24. The essential feature of the model is the development of a highland-flanking clastic wedge along the faulted margins of the Dinkum graben. Reservoir sands and traps developed along these structural features could have easy access to hydrocarbons generated by thermally mature shales in the interior parts of the graben or by onlapping shales facies equivalent to the Pebble Shale. As noted by Grantz and others (1982b, p. 17), most of the sedimentary fill in the Dinkum graben lies at or beneath the oil window, estimated in this report to lie in the depth interval from 9,200 to 12,300 feet in the west and from 10,200 to 13,700 feet in the east. Strata within the deeper northern and eastern parts of the graben are probably thermally overmature.

The model outlined above forms the basis for the most attractive play within the Outer Arctic Platform province. The structural setting of this play is somewhat similar to that of the highly faulted Hibernia field, which is lodged in Lower Cretaceous strata along the southwest flank of the Avalon Basin on the continental shelf off Newfoundland (McKenzie, 1981). The Hibernia field is less than 4 OCS tracts (24,000 acres) in areal extent (McKenzie, 1981) but is estimated to contain between 1.0 and 1.5 billion barrels of recoverable oil in multiple pay zones (Oil and Gas Journal, 1985b). It is also possible that sandstones of the Lower Cretaceous Rift sequence along the margin(s) of the Dinkum graben were deposited in a submarine fan setting analogous to fan systems which lie along the western margin of the Viking graben of the North Sea (Heritier and others, 1980, figs. 14, 15). Closure on these latter features is provided by inherited depositional topography or by faulting and dip reversal (Heritier and others, 1980, fig. 18). The Forties field of the North Sea is sited in a Paleocene fan system and contains recoverable reserves of 1.8 billion barrels of oil (Hill and Wood, 1980, p. 81) in a productive area of 90 square kilometers (3.9 OCS tracts).

Grabens similar to the Dinkum structure, but much smaller in size, are found in more western parts of the Arctic Platform near the Hinge Line (fig. 9 and plate 4). Northwest of the Dinkum graben, other Early Cretaceous infrarift basins may have been overprinted by the subsequent phase of faulting and post-rift subsidence along the Hinge Line in the Nuwuk Basin (fig. 26). There, disrupted infrarift grabens may occur north of the Hinge Line and perhaps beneath the deep parts of the Nuwuk Basin. Studies of seismic data suggest that these disrupted grabens may locally preserve thin outliers of Ellesmerian sequence rocks which were not removed from these parts of the Arctic Platform during the erosional event represented by the Lower Cretaceous unconformity.

CHUKCHI SHELF (IC)

The eastern Chukchi shelf is in some ways a geological extension of the Barrow Arch province, and some of the plays described for the Barrow Arch province involving Mesozoic and Cenozoic rocks also occur in province IC. However, the structural and stratigraphic evolution of the Paleozoic rocks of the Chukchi shelf province appears to differ in several significant ways from that of the Barrow Arch province. The structural block west of the Barrow fault zone contains a deep basin, informally termed the Northeast Chukchi Basin, which contains stratified sediments up to 30,000 feet in thickness beneath the axis of the Barrow Arch (fig. 2). Our work suggests that this stratified sequence ranges in possible age from Middle(?) Devonian to Mississippian and may be correlative, at least in part, with rocks of the Endicott Group and Baird(?) Group exposed in the western Brooks Range. This interpretation contrasts with previously published models for the geology of the Chukchi shelf province (Grantz and others, 1982b; Ehm, 1983) which portray the area as a large structural high where "Franklinian" basement is mantled by a thin veneer of Mesozoic strata. The fact that the Chukchi shelf province is underlain by a thick sequence of modestly deformed Paleozoic strata makes this province one of the more attractive parts of the Beaufort Sea Planning Area in terms of overall hydrocarbon potential.

Seismic character and interval velocities (discussed previously in chapter 3, Seismic Stratigraphy) suggest that two distinct seismic units are present within the Northeast Chukchi Basin beneath the Permian unconformity (PU). The seismic sequence is composed of a lower carbonate unit and an upper unit consisting of clastic sedimentary rocks. The two seismic units are structurally detached in some parts of the basin where the upper clastic unit contains large folds which do not persist downward into the underlying carbonate unit (plates 1 and 3). The pre-Permian (lower Ellesmerian) sequence is truncated at major fault-bounded basement highs along the eastern and southern margins of the Northeast Chukchi Basin. Potential trap configurations in these Paleozoic strata are found in the following settings:

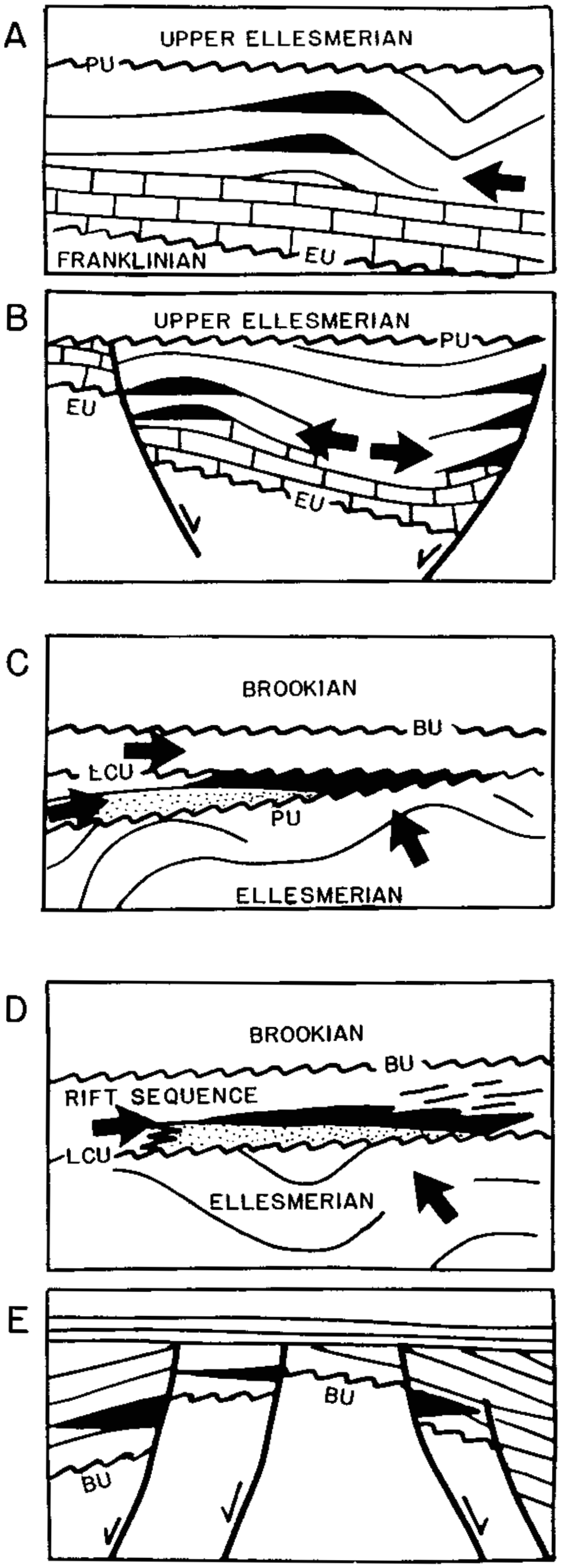
1. folds in the upper detached clastic unit of the lower Ellesmerian sequence (plates 1 and 3);
2. fault traps along the northwestern flank of the basement ridge (plate 1) that separates the Northeast Chukchi and Colville Basins (fig. 7), where lower Ellesmerian strata are juxtaposed against basement;
3. fault traps or drape structures in lower Ellesmerian rocks in the downthrown block along the Barrow fault (plate 3);
4. fault traps and anticlines in lower Ellesmerian strata along the crest and southeast flank of the North Chukchi high (plate 3).

Play concepts and potential trap configurations in the Northeast Chukchi Basin are schematically illustrated in the cross sections of figure 25a and 25b.

Table 4. Chukchi shelf (province IC): Summary and play analysis

SEISMIC SEQUENCE	TYPE OF TRAP	RESERVOIR	PROBABLE SOURCE BEDS	AGE OF TRAP	SIZE OF TRAP	PROBABLE OIL/GAS	REMARKS
Brookian	Closure at faults	Upper Cretaceous to Tertiary	Middle(?) Devonian to Lower Cretaceous	Tertiary	Areally small. Potential pay <100'.	40/60	Brookian sandstones in fault traps associated with deformation on the North Chukchi high.
Rift	Stratigraphic	Lower Cretaceous	Middle(?) Devonian to Lower Cretaceous	Early Cretaceous	Areally large. Potential pay <100'.	50/50?	Locally developed, relatively thin sandstones on Lower Cretaceous unconformity. Examples include Walakpa and Kuyanak sandstones.
Upper Ellesmerian	Stratigraphic	Triassic to Jurassic	Middle(?) Devonian to Lower Cretaceous	Early Cretaceous	May be areally large. Potential pay <200'.	50/50?	Stratigraphic traps within Permian to Jurassic strata where truncated at Lower Cretaceous unconformity on flank of Barrow Arch.
Lower Ellesmerian	Detached anticlines	Middle(?) Devonian to Permian	Middle(?) Devonian to Lower Cretaceous	Pre-Permian	Areally small. Potential pay >200'.	50/50?	Confined to detached folds in Endicott(?)-equivalent clastic wedge.
Lower Ellesmerian	Closure at faults	Middle(?) Devonian to Permian	Middle(?) Devonian to Lower Cretaceous	Pre-Permian	May be areally large. Potential pay >200'.	50/50?	Traps within Endicott(?)-equivalent clastic wedge and Baird(?)-equivalent basal carbonate unit at fault systems bordering Northeast Chukchi Basin.

CHUKCHI SHELF (IC)



NORTHEAST CHUKCHI BASIN: LOWER ELLESMERIAN STRATA

Anticlinal closures in detached folds within clastic wedge unit above basal carbonate unit in Northeast Chukchi Basin.

Fault traps and anticlinal closures associated with fault-bounded basement highs which enclose the Northeast Chukchi Basin.

BARROW ARCH: UPPER ELLESMERIAN STRATA

Stratigraphic traps within upper Ellesmerian (Permian to Jurassic) strata where truncated at the LCU on the south flank of the Barrow Arch.

RIFT AND BROOKIAN SEQUENCES

Laterally sealed sandstone lenses in the Rift sequence (e.g., Put River or Walakpa sandstones) developed locally on the LCU.

Fault traps in Cretaceous to Tertiary(?) Brookian strata in crestal areas of the North Chukchi high.

Figure 25.
Play concepts and trap configurations developed in lower Ellesmerian, upper Ellesmerian, Rift, and Brookian strata of the Chukchi shelf (province IC). Large arrows denote potential migration paths.

Across the southern parts of the Chukchi shelf province, upper Ellesmerian (Permian to Jurassic) strata are preserved beneath the LCU. These strata are successively truncated northward (plate 1) at the overlying LCU with increasing proximity to the crest of the Barrow Arch. Where potential reservoir units, such as the Ivishak sandstones, Sag River sandstones, or younger Jurassic sandstones (such as the Barrow and Simpson sands), are sealed updip at the LCU, potential stratigraphic traps may be found (fig. 25c).

Discontinuous sand bodies which grade laterally into shale are known to occur within the Rift sequence in onshore wells to the east of the Chukchi shelf province. Examples include the Walakpa and Kuyanak sandstones. These sandstones are typically less than 100 feet thick, however, and are unlikely to house hydrocarbon accumulations of commercial size on the Chukchi shelf. Nevertheless, we recognize that these sandstones could thicken westward and form widespread stratigraphic traps for hydrocarbons in the Chukchi shelf province (fig. 25d).

The folding and faulting of lower Ellesmerian strata in the Northeast Chukchi Basin and along flanking structural highs took place in most areas prior to erosion on the Permian unconformity (PU). Except for broad warping on the Barrow Arch, younger strata of the upper Ellesmerian, Rift, and Brookian sequences are virtually undeformed across most of the Chukchi shelf province. However, a younger (Late Cretaceous to Tertiary) phase of uplift and faulting has affected broad areas of the North Chukchi high in the northwestern part of the Chukchi shelf province (plate 3). In this area, Brookian and older strata are cut by a dense array of northeast-trending normal faults. Where these faults juxtapose Brookian reservoir beds updip against impermeable strata or basement-complex rock, a potential trap configuration is formed (fig. 25e). Although found at relatively shallow depths and perhaps areally small because of the close spacing of faults, many such traps appear to be present, and form the most conspicuous exploration objective in the northwestern part of the Chukchi shelf province.

Potential source beds in the upper Ellesmerian sequence (Kingak and Shublik Formations) are preserved beneath the LCU only in the southern part of the Chukchi shelf province. Rift sequence source beds (Pebble Shale) are present over much of the Chukchi shelf province. However, all of these units lie at depths no greater than 6,000 feet within the planning area. On the basis of geothermal data from adjacent onshore areas, the oil window in this area is estimated to now lie between 9,200 and 12,300 feet. However, upper Ellesmerian and Rift sequence source beds in this area appear to have been previously buried to much greater subsurface depths than at present. Despite their relatively shallow depths of burial (2,000 to 7,000 feet), in nearby wells in NPRA these strata yield vitrinite reflectance values ranging from 0.6 to 0.8 (Magoon and Bird, 1986, figs. 12 and 18), corresponding to the top of the oil window. Offshore (westward) projections of isoreflectance contours mapped in NPRA by Magoon and Bird (1986) indicate that these source beds should enter the oil window at the southern boundary of the Beaufort Sea Planning Area on the Chukchi shelf. Onshore data show that the thermal maturity and depth of burial of these beds increase to the south. Liquid hydrocarbons generated by these strata south of the planning area could have readily migrated updip to the north into stratigraphic traps in the Chukchi shelf province. Potential source beds may also occur within the deeper (lower Ellesmerian) sequence within the Chukchi shelf province. Hydrocarbons generated from these rocks could have migrated vertically into structural traps within the sequence or into stratigraphic traps in the overlying upper Ellesmerian and Rift sequences. However, the complex history of deep burial, folding, tilting, and repeated periods of uplift and exhumation at multiple unconformities probably has adversely affected the source potential of the lower Ellesmerian sequence. In addition, little is known about the stratigraphy of the lower Ellesmerian sequence aside from the observation that it apparently consists of a sequence of carbonate rocks overlain by a thick clastic unit. We speculate that potential source beds may be found within the lower Ellesmerian sequence if it contains marine shales (equivalent to the Hunt Fork Shale?) with compositions and maturity levels appropriate for hydrocarbon generation.

NUWUK BASIN (IIA)

The Nuwuk Basin began to develop in late Early Cretaceous time as a consequence of the fragmentation of the Arctic Platform and the subsidence of the newly formed continental margin toward the expanding Canada Basin. Subsidence of the outer parts of the continental margin occurred along a system of major, northward-dipping, listric growth faults which occur within or parallel to the Hinge Line (plate 4). The structural style of the Nuwuk Basin resembles that of other passive margins, such as the North American margin of the Gulf of Mexico. The Nuwuk Basin is filled with Cretaceous and Cenozoic deposits of the Brookian sequence. Potential reservoir formations in the Nuwuk Basin include: (1) fluvial-deltaic sands in the upper Brookian sequence; (2) prodelta slope and base-of-slope turbidites or submarine fan complexes in the lower Brookian sequence; and (3) Rift sequence sands in pre-Nuwuk grabens (analogous to the Dinkum graben) which may locally floor the Nuwuk Basin.

The principal mappable trap types within the Nuwuk Basin are fault truncations of inclined strata or gentle folds associated with northward-dipping listric faults along and north of the Hinge Line. The disrupted pre-Nuwuk grabens which may floor parts of the basin may be sealed beneath overlying lower Brookian prodeltaic shales. Potential stratigraphic traps in the Brookian sequence may be very common, but are difficult to recognize in seismic data without well control. The principal types of stratigraphic traps should consist of updip pinch-outs of deltaic and prodeltaic sands. Turbidite sandstones deposited in the prodelta setting may locally

Table 5. Nuwuk Basin (province IIA): Summary and play analysis.

SEISMIC SEQUENCE	TYPE OF TRAP	RESERVOIR	PROBABLE SOURCE BEDS	AGE OF TRAP	SIZE OF TRAP	PROBABLE OIL/GAS	REMARKS
Brookian	A. Rollover anticlines and closure at faults	Upper Cretaceous to Tertiary	Cretaceous	Late Cretaceous to Tertiary	Areally large. Potential pay >100'.	40/60	Rollover anticlines and fault traps in Brookian fluvial-deltaic strata along southern margin of Nuwuk Basin.
	B. Stratigraphic	Lower Cretaceous to Tertiary	Cretaceous	Early Cretaceous to Tertiary	Areally large. Potential pay <100'.	40/60	Lenticular prodeltaic and deltaic bodies of Brookian sandstones. May include submarine fan systems at mouths of major northeast-trending paleocanyons.
Rift	Closure at faults	Lower Cretaceous	Lower Cretaceous	Early Cretaceous to Tertiary	Areally small. Potential pay >200'.	50/50	Infrarift grabens along southern margin of Nuwuk Basin beneath thick Brookian wedge.
Ellesmerian	Closure at faults	Triassic to Jurassic	Lower Cretaceous to Triassic	Early Cretaceous to Tertiary	Areally small. Potential pay <200'.	50/50	Upper Ellesmerian rocks may be locally preserved within infrarift grabens along southern margin of Nuwuk Basin.

NUWUK BASIN

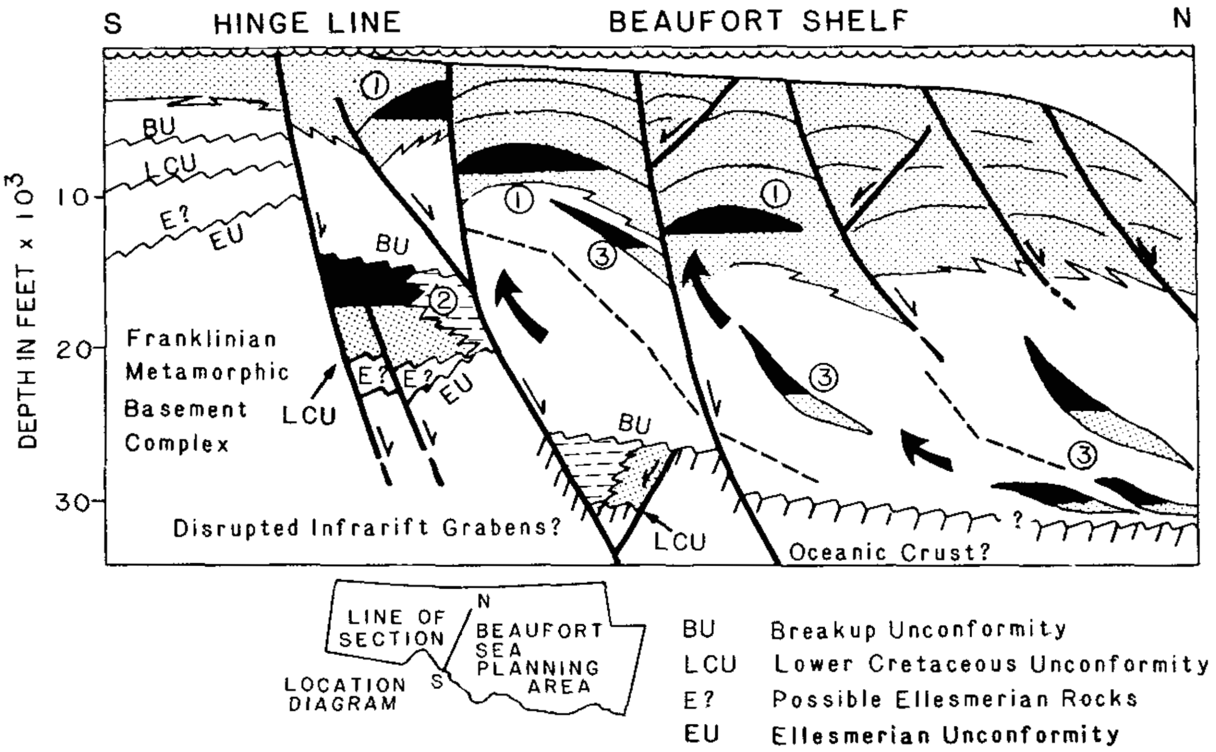


Figure 26.

Schematic geological cross section summarizing potential play concepts and trap configurations in the Nuwuk Basin. Shown are: (1) traps developed in fluvial-deltaic sands deformed by rotational folds associated with listric faults; (2) traps within reservoir sands deposited in Early Cretaceous infrarift grabens now disrupted by faulting associated with Nuwuk Basin subsidence; (3) a variety of stratigraphic traps involving lenticular bodies of sandstone deposited in deltaic, prodelta slope, or abyssal plain settings. Ellesmerian sequence rocks (shown as "E?") may be locally preserved in the southern parts of infrarift grabens and may form potential reservoir objectives. Large arrows denote possible migration paths for hydrocarbons, primarily along faults.

composite into major submarine fan complexes. Major northeast-trending canyon systems incised into Lower Cretaceous rocks and filled with Upper Cretaceous rocks have been identified in seismic data near Barrow and Dease Inlet south of the Hinge Line. These canyons probably formed major submarine(?) sediment transport systems into the Nuwuk Basin, and may have localized the deposition of major submarine fan complexes. In general, however, most stratigraphic traps in the Nuwuk Basin may be expected to be small in areal extent and volume. Rotational folds associated with listric faults which displace upper Brookian fluvial-deltaic sandstones remain the most conspicuous exploration objective in the Nuwuk Basin. Play concepts and potential traps within the Nuwuk Basin are summarized in the schematic geological cross section of figure 26.

The structural geology of the Hinge Line fault system along the southern margin of the Nuwuk Basin is outwardly similar to the Vicksburg trend of Texas. The Vicksburg fault zone is a complex system of listric faults up to 300 miles in length which trends parallel to the modern Gulf Coast of Texas. Displacements resulting in several thousand feet of stratigraphic throw have occurred across the Vicksburg fault system. A host of hydrocarbon accumulations are localized in rotational folds and fault traps on the downdropped (southeast) side of this fault system (Stanley, 1970). Several giant fields are present in this structural province, and total known recoverable reserves for Oligocene and Miocene strata in the Vicksburg trend are estimated to be 3 billion barrels of oil and 20 trillion cubic feet of gas (Stanley, 1970, p. 301). The largest field, the Tom O'Connor field, contains 500 million barrels (Mills, 1970, p. 292) within 15,000 productive acres (2.5 OCS tracts).

The inferred geothermal structure of the outer (northern) part of the Nuwuk Basin suggests a depth range of 15,400 to 23,500 feet for the oil window. The oil window may rise to shallower depths (12,200 to 16,500 feet) in the older, primarily Cretaceous, sedimentary wedge which fills the southernmost parts of the Nuwuk Basin. A large volume of Brookian strata in the Nuwuk Basin lies within either depth interval, but much of the basin fill also lies deeper than 23,000 feet and is probably overmature. As discussed in a previous chapter, Brookian prodelta shales typically contain insufficient quantities of appropriate kerogens to be considered important potential sources for liquid hydrocarbons. However, geochemical studies of well samples from the Point Thomson area have identified potentially important source beds near the top of the Tertiary Brookian prodelta sequence. If comparably rich source beds occur at a similar stratigraphic position in Cretaceous or Tertiary rocks in the Nuwuk Basin, they would now be buried at relatively moderate depths where temperatures are suitable for liquid hydrocarbon generation. The subsidence of these potential source beds into the oil window may have more or less coincided with the development of structural traps in the overlying Brookian fluvial-deltaic facies. This suggests that the most attractive potential traps were formed before or at the same time as significant quantities of liquid hydrocarbons might have been generated in underlying source beds. As shown in figure 26, listric faults probably formed the primary migration paths for hydrocarbons moving from deep source beds into shallower structural traps.

KAKTOVIK BASIN: CAMDEN SECTOR (IIB) AND DEMARCATION SECTOR (IIC)

In Camden Bay, the Hinge Line (figs. 1 and 2) trends southeast and then swings eastward in a sigmoidal configuration, passing north of Barter Island. Seaward of the Hinge Line, over 35,000 feet of Cretaceous(?) and Tertiary sediments have accumulated. This great accumulation has been termed the Kaktovik Basin by Grantz and others (1982b, fig. 4). As did Grantz and others (1982b, fig. 16), we further subdivide the basin and contiguous areas of the Arctic Platform to the south of the Hinge Line into two sectors (fig. 1) on the basis of fundamental differences in stratigraphic and structural histories. We informally term these geographic provinces the Camden and Demarcation sectors (fig. 28).

The stratigraphy of the Camden sector is inferred to be similar to that of the Camden Basin, as known from exploratory drilling in the Point Thomson area. In contrast, the Demarcation sector is hypothesized to be underlain by a stratigraphic section more directly analogous to the polycyclic Cenozoic sequence known from exploratory drilling in the contiguous Canadian Beaufort. Furthermore, unlike the Camden sector, the part of the Demarcation sector south of the Hinge Line may contain potential source and reservoir rocks of the Ellesmerian sequence. In the Camden sector, the Ellesmerian sequence on the Arctic Platform has been completely removed by erosion at the LCU and BU.

Camden Sector (IIB)

The principal structural feature of the Camden sector (IIB) is the Camden anticline. This immense fold (illustrated in fig. 27 and plate 6) can be traced for nearly 60 miles along its northeast-trending axis and exhibits up to several seconds (two-way travel time) of structural relief on some seismic dip lines. Detailed examination of seismic data reveals that the Camden anticline is not a simple feature. Seismic panels (plate 6) show that the fold is cut by numerous faults, which in some cases extend to the seafloor. The majority of these faults are part of the Hinge Line fault system and trend northwest, or nearly orthogonal to the axis of the Camden anticline. Middle Tertiary strata do not thin toward the crest of the structure and are truncated at or near the seafloor around the perimeter of the fold. This suggests that the Camden anticline is a very youthful structure. Modern shallow-crustal seismic activity suggests that the fold is still growing (Biswas and Gedney, 1978). The Brookian sequence deformed by the fold contains two seismic facies as recognized onshore: a lower interval of marine prodelta

Table 6. Kaktovik Basin, Camden Sector (province 118): Summary and play analysis.

SEISMIC SEQUENCE	TYPE OF TRAP	RESERVOIR	PROBABLE SOURCE BEDS	AGE OF TRAP	SIZE OF TRAP	PROBABLE OIL/GAS	REMARKS
Brookian	A. Compressional anticlines	Oligocene to Pliocene	Tertiary	Late Miocene to Pleistocene	Areally large. Potential pay >100'.	40/60	Faulted anticlines (e.g., Camden anticline) which involve Brookian fluvial-deltaic sandstones.
	B. Stratigraphic	Oligocene to Pliocene	Tertiary	Oligocene to Pliocene	Areally small. Potential pay <100'.	40/60	Lenticular prodeltaic and deltaic bodies of Brookian sandstones.

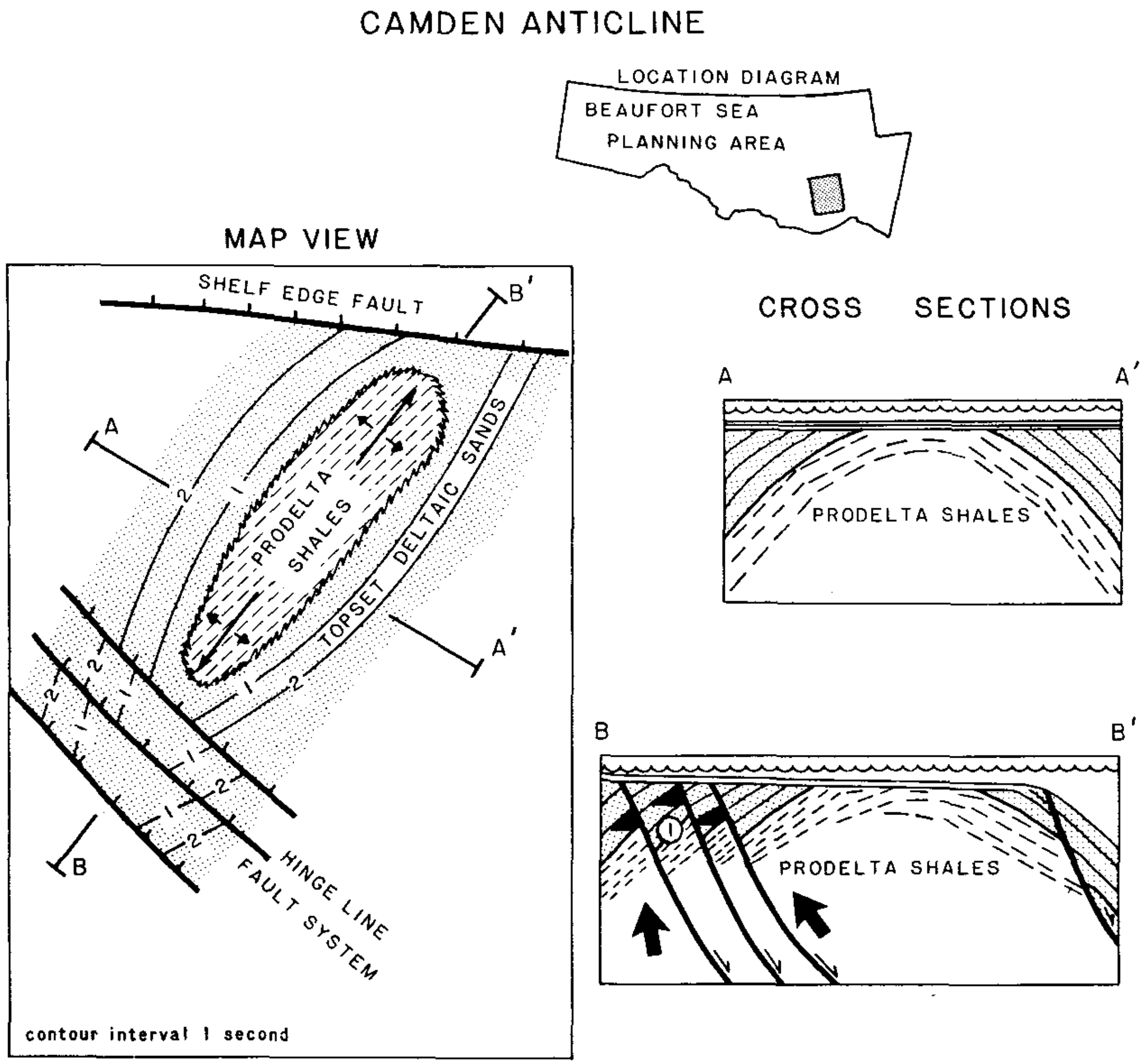


Figure 27.
Schematic structure-contour map and geological cross sections illustrating the fundamental geology of the Camden anticline. The prodelta shales which appear to core the anticline are breached at a shallow Pleistocene(?) unconformity over much of the crestal area of the structure. Traps developed along the northwest and southeast flanks of the fold, where potential reservoir sediments are truncated at the shallow unconformity, are probably too shallow for economic production. The most attractive potential traps (area 1 in section B-B') are probably found along the southwestern faulted nose of the Camden anticline, where the axis of the fold intersects the northwest-trending Hinge Line fault system. Large arrows suggest potential migration paths along faults for hydrocarbons mobilized out of prodelta shales into fluvial-deltaic reservoir sands. Many faults appear to be active at present, and may not form effective seals in some traps.

shales and an upper interval of fluvial-deltaic sediments. The upper fluvial-deltaic facies, which probably contains most of the prospective reservoir rocks, is breached at the seafloor over most of the axial region of the fold. At the crest of the fold, far offshore to the northeast, the prodelta shale lies near the seafloor, as illustrated in figure 27. On the southwestern nose of the Camden anticline, contemporary faults of the Hinge Line fault system structurally isolate numerous blocks of Brookian fluvial-deltaic sediments. Potential reservoir sands in this sequence may be involved in fault closures along the faulted nose of the anticline (fig. 27). Many of the faults extend to the seafloor, and their ability to act as seals at shallow subsurface depths may be poor. Nevertheless, the faulted southwestern nose of the Camden anticline is probably the most prospective part of the structure.

Grantz and others (1982b, p. 18) have stated that the youthful age (late Tertiary to Quaternary) of the Camden structure increases the risk that it may not have been present as a potential trap when hydrocarbons were generated and expelled from deeper strata. As noted in preceding sections, rich potential source beds apparently occur near the boundary between the prodeltaic and fluvial-deltaic facies of the Tertiary Brookian sequence in the Point Thomson area. These potential source beds may extend offshore at the same stratigraphic level as a continuous, prograding facies within the delta complex. The approximate base of the fluvial-deltaic sequence, as identified on seismic data, lies at depths between 6,000 and 15,000 feet (fig. 17) along the flanks of the Camden fold north of the Hinge Line. It is possible that potential source beds near this stratigraphic level began to subside into the oil window (estimated to lie between 15,400 and 23,500 feet) only after significant uplift on the Camden structure had occurred. These potential source beds in areas flanking the fold continued to move into the oil window as the fold grew. If source beds are indeed present offshore near the base of the fluvial-deltaic sequence, as appears to be the case in onshore wells, their thermal evolution may have been ideally timed for expulsion of hydrocarbons into the Camden structure. Source beds occurring at much greater depths within the prodelta facies may have reached thermal overmaturity before the initial uplift of the Camden anticline, and hydrocarbons derived from them may have been lost.

The geology of Camden anticline is analogous in many ways to that of the Teak oil field of Trinidad, West Indies. The Teak accumulation occurs within a northeast-trending anticline of Pleistocene or younger age dissected by a system of listric normal faults which trend at right angles to the anticlinal axis. Numerous individual petroleum accumulations occur in small, isolated fault blocks. Deltaic sands in contact with the faults were charged with hydrocarbons that migrated upward along fault surfaces (Bane and Chanpong, 1980, p. 398). Although these faults, like those which cross Camden anticline, extend all the way to the surface, in the

Teak field they provide seals for hydrocarbon accumulations lying throughout the depth range from 1,000 to 14,000 feet. The Teak anticline is a much smaller feature than Camden anticline, with a known productive area (Bane and Chanpong, 1980, p. 387) of 900 acres (one sixth of an OCS tract) and a total area under closure of 10,000 acres (1.6 OCS tracts). Nevertheless, within the first 7 years of development, the Teak field has produced 101 million barrels of oil and 107 billion cubic feet of gas (Bane and Chanpong, 1980).

Demarcation Sector (IIC)

The Demarcation sector is divided into two dissimilar geological subprovinces by the Hinge Line fault system. At least several thousand feet of aggregate stratigraphic throw, down to the north, has occurred across the faults which constitute the Hinge Line. Pre-Brookian strata are generally considered to be absent or to lie below drillable depths north of the Hinge Line. Much of the Brookian sedimentary wedge in the Kaktovik Basin north of the Hinge Line may rest upon Mesozoic oceanic crust. In the eastern Beaufort Sea, the Hinge Line trends southeast across Camden Bay, crosses the Camden anticline, and projects toward the present coast of Alaska southwest of Kaktovik (fig. 28). However, maps of the surface geology (Reiser and others, 1980) of the Arctic National Wildlife Refuge (ANWR) do not support the existence of an onshore extension of the Hinge Line fault system. In addition, Kososki and others (1978, p. 19-20) argue that a gravity high centered 20 miles southeast of Kaktovik along the trend of Marsh anticline (fig. 29) stems from a structural elevation of dense Arctic Platform basement rocks in that area. The Hinge Line must therefore lie north of this gravity anomaly and north of the present coast of Alaska near Kaktovik. These observations, coupled with studies of seismic data conducted by the present authors, suggest that the Hinge Line deflects eastward roughly 5 miles north of Kaktovik and does not extend onshore into ANWR. As shown in figure 28, the Hinge Line passes along the southern margin of the Barter subbasin and then turns southeast, trending parallel to the present Alaska coastline. The Hinge Line fault system appears to pass beneath unfaulted Oligocene to Miocene deposits (plate 7 and fig. 28) of the Demarcation subbasin.

The structure of the Demarcation sector south of the Hinge Line is dominated by two major anticlinorial features informally termed the "Marsh anticline" and the "Jago anticline." These structures, and a host of minor folds and faults, trend northeast, approximately parallel to the axis of the Camden anticline (fig. 28). Like the youthful Camden fold, these structures appear to deform late Tertiary to Quaternary sediments (Grantz and Mull, 1978, p. 9, 15; Reiser and others, 1980). The Marsh and Jago anticlinoria appear to be truncated to the northeast approximately 10 miles offshore, where they intersect the Hinge Line fault system (fig. 28).

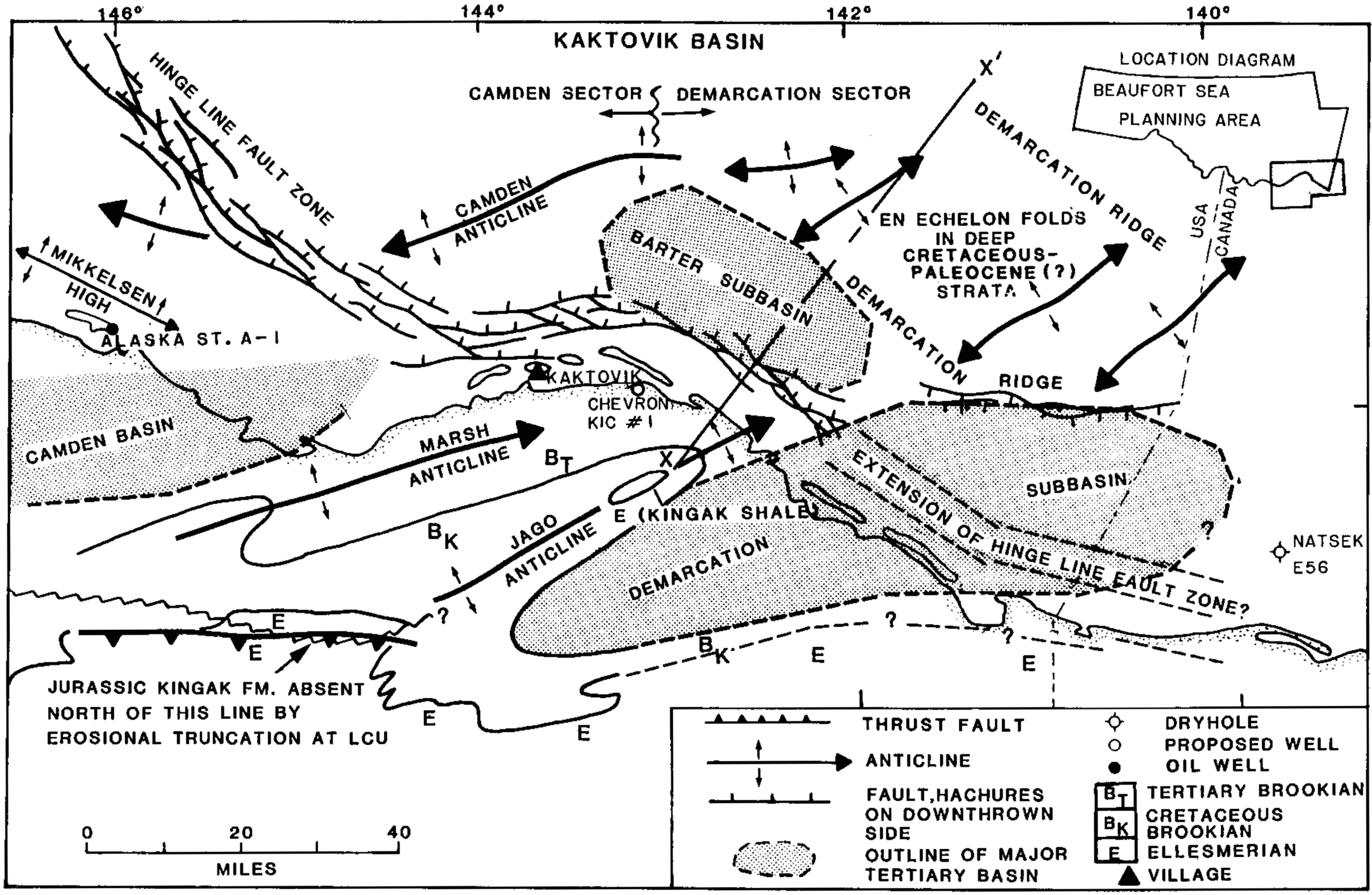


Figure 28.

Major structural features of Camden and Demarcation sectors of Kaktovik Basin and adjoining areas. Map adapted from Reiser and others (1980) and Grantz and Mull (1978). Line X-X' is cross section shown in figure 30.

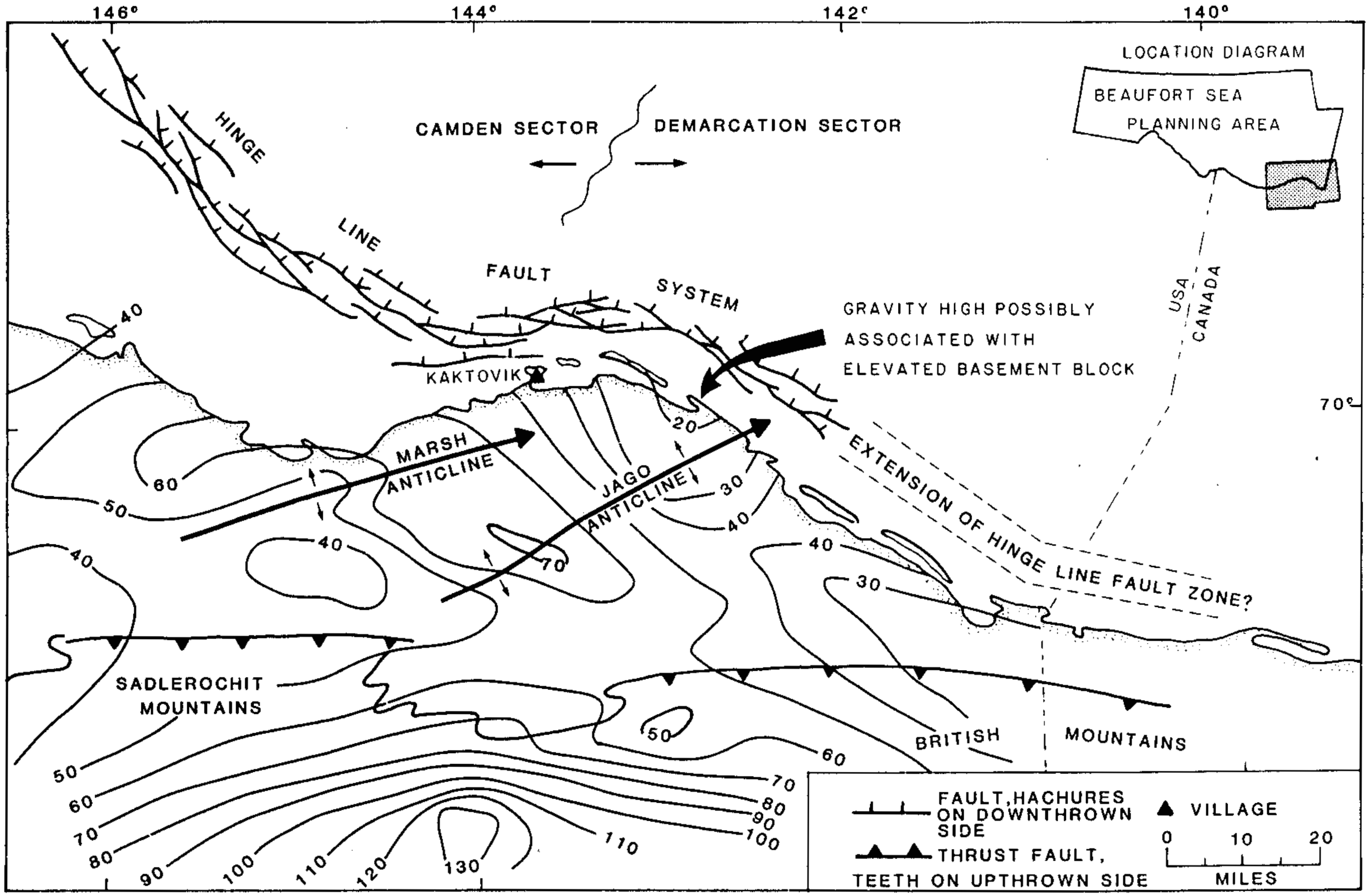


Figure 29.

Bouguer gravity map of the northern part of the Arctic National Wildlife Refuge, adapted from Kososki and others (1978, plate 1). The contour interval is 10 milligals, and all contoured gravity values are negative. Kososki and others (1978, p. 19-20) suggest that the gravity high near Kaktovik indicates an elevated basement platform in the shallow subsurface.

The only available information on the stratigraphy of the Demarcation sector south of the Hinge Line is that obtained from surface outcrops in the northeastern Brooks Range and the Arctic coastal plain. Fossil-bearing Middle Jurassic shales (Reiser and others, 1980) of the Kingak Formation are exposed along the axis of Jago anticline at the locality annotated on figure 28. The Middle Jurassic shales appear to be disconformably overlain by Lower Cretaceous shales above the regionally widespread Lower Cretaceous unconformity (LCU). As recognized by previous authors (Grantz and Mull, 1978; Mast and others, 1980), the occurrence of Jurassic rocks at this locality is extremely significant. Regional stratigraphic relationships documented in nearby areas to the west imply that if Jurassic rocks have not been stripped from the northern coastal plain of ANWR by Early Cretaceous erosion, then the underlying Ivishak Formation (Triassic) logically should also be preserved at depth within or beneath the major fold systems south of the Hinge Line.

However, we recognize that several processes may have acted to preclude the important Ivishak strata from the Marsh-Jago fold province. The exposure of Jurassic rocks along the axis of the Jago structure is anomalous in that it lies 40 miles to the northeast (fig. 28) of the regionally mapped northwest-trending zero edge where the Kingak Shale is completely truncated by the LCU. We have interpreted this anomalous outcrop to indicate the presence of a subtle structural basin or outlier of pre-LCU age in which Ellesmerian strata have been preserved in northern ANWR. The northern extent of this hypothesized outlier is unknown. As recognized by Grantz and Mull (1978, p. 8), both the Kingak and older formations may have been stripped by the LCU from prospective areas a short distance north of the Jago outcrop. We also acknowledge that in northwestern Canada, pre-Kingak strata are regionally truncated by an unconformity at the base of the Kingak Formation (Norris and Yorath, 1981). It therefore remains possible that either Early Cretaceous or Early Jurassic erosional events may have removed the Ivishak Formation from parts of the Demarcation sector south of the Hinge Line, thereby greatly reducing the overall hydrocarbon potential of those areas. Lastly, it is not known to what extent the anomalous distribution of exposures of Ellesmerian rocks in northern ANWR may be the product of post-LCU large-scale tectonic transport and emplacement by thrust faults. For the present, however, we favor the most simple model, as outlined above, which maintains that Kingak shales exposed in northern ANWR represent the uppermost strata in an outlier of Ellesmerian rocks within which the potential reservoir strata of the Ivishak Formation are preserved.

The paleogeographic model for the Ivishak Formation presented in preceding sections and in figure 19 suggests that reservoir sands, perhaps deposited in a setting similar to that in which the excellent reservoir rocks at Prudhoe Bay accumulated, may be found in the subsurface beneath the Marsh and Jago anticlinoria and related offshore structures. At the most northeasterly point of control for Ivishak Formation thickness, 60 miles southeast of Kaktovik, the formation is 390 feet thick, although somewhat abbreviated by erosional truncation at its top (Detterman and others, 1975, p. 12). Thicker accumulations might be anticipated in the subsurface near Kaktovik.

The concept of the occurrence of a thick sequence of reservoir-quality Ivishak sandstone in structures in the part of the Demarcation sector south of the Hinge Line strongly affects the hydrocarbon potential of those structures. If sandstones possessing excellent reservoir properties could be shown to be present in the Jago and Marsh features, then this area must be regarded as one of the most prospective within the Kaktovik area. In OCS Sale 87, held in August 1984, industry obtained exploration rights to 9 tracts in the Demarcation sector south of the Hinge Line. Chevron is presently drilling at an onshore location (K.I.C. No. 1 well) on Kaktovik Village corporate lands 5 miles WSW of this group of offshore tracts (fig. 28). This well and the nearby offshore tracts appear to lie on the Marsh anticlinorial trend. The Chevron well will form a key evaluation of the geology and hydrocarbon potential of this area. However, the data obtained from this well are expected to remain confidential for the foreseeable future.

The fundamental structure of the Demarcation sector north of the Hinge Line was portrayed by Grantz and others (1982b, fig. 4) as a series of basins separated by northwest-trending structural highs, which they termed "diapiric shale ridges." Grantz and others (1982b) identified two principal basins, which they termed the Barter Island and Demarcation subbasins. These basins appear to be filled with shelf or deltaic sediments inferred to be Oligocene and younger in age. These strata are upturned or tilted at the basin margins, and deeper strata are truncated at faults which bound the basins (plate 7 and fig. 30). Shallow strata within the basins are gently upturned and truncated at a shallow unconformity inferred to be late Miocene(?) in age. The most attractive potential traps identified within these basins are fault traps associated with basin-margin faults (plate 7 and fig. 30). The sedimentary fill in the deep parts of these basins may exceed 20,000 feet in thickness. Geothermal data from wells in adjacent areas predict that sedimentary rocks below 15,400 feet in this province lie within the thermal window for oil generation. The structural and stratigraphic relationships depicted in plate 7 and figure 30 indicate that many basin-margin fault traps formed early in the subsidence history of the basins. These early-formed traps would have had natural access to migrating hydrocarbons expelled later from thermally mature sediments in the deep interiors of the basins. The seismic panel in plate 7 and a record published by Grantz and May (1982, fig. 14) show abundant amplitude anomalies, or "bright spots," and phase reversals along faults at the northern margin of the Demarcation subbasin. These amplitude anomalies suggest the presence of reservoir beds, possibly charged with gas. The gas may be associated with accumulations of liquid hydrocarbons.

Table 7. Kaktovik Basin, Demarcation Sector (province IIC): Summary and play analysis.

SEISMIC SEQUENCE	TYPE OF TRAP	RESERVOIR	PROBABLE SOURCE BEDS	AGE OF TRAP	SIZE OF TRAP	PROBABLE OIL/GAS	REMARKS
Brookian	A. Fault traps	Oligocene to Miocene	Upper Cretaceous to Miocene	Oligocene to Miocene	Areally large. Potential pay >100'.	40/60	Fault traps along margins of Demarcation and Barter subbasins.
	B. Compressional anticlines	Upper Cretaceous to Paleocene	Upper Cretaceous to Eocene	Eocene to Miocene	Areally large. Potential pay >400'.	40/60	En echelon, thrust-cored(?) anticlines in Cretaceous to Paleocene(?) fluvial-deltaic sediments within Demarcation Ridge.
	C. Stratigraphic	Oligocene to Miocene	Upper Cretaceous to Miocene	Oligocene to Miocene	Areally small. Potential pay <100'.	40/60	Lenticular prodeltaic and deltaic bodies of Brookian sandstones.
Ellesmerian	Compressional anticlines	Triassic(?)	Lower Cretaceous to Tertiary	Tertiary	Areally large. Potential pay >300'.	50/50	Folds in possible Ellesmerian strata on basement high south of the Hinge Line, on trend with onshore structures such as the Marsh and Jago anticlines.

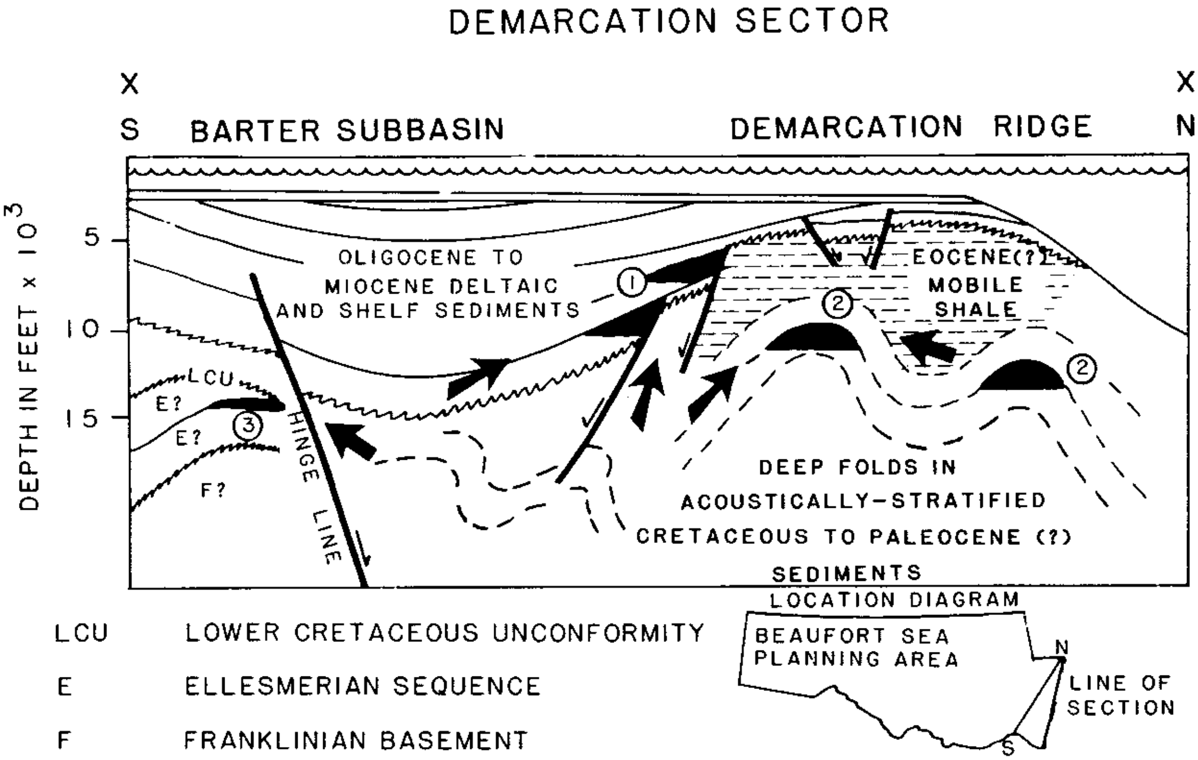


Figure 30.

Schematic geological cross section across the Demarcation sector (IIC) of the Kaktovik Basin illustrating the onlapping Oligocene and younger fill of the Barter subbasin and some internal features of adjacent structural highs, termed "diapiric shale ridges" by Grantz and others (1982b, fig. 4). Potential traps exist where basin fill sediments are truncated at basin margin faults in area 1 of the cross section. Deep folds involving a sequence with strong acoustic stratification (Cretaceous to Paleocene(?) fluvial-deltaic sandstone and shale(?)) are locally observed within the interior of Demarcation ridge, and potential hydrocarbon traps may occur at the crests of these folds (area 2). Onshore data from the Arctic National Wildlife Refuge suggest that some Ellesmerian sequence rocks may be preserved beneath the Lower Cretaceous unconformity in some offshore areas south of the Hinge Line. If so, potential traps may exist where these strata are involved in folds (area 3) which antedate the formation of the Barter subbasin. The location of the cross section is shown in figure 28. Large arrows suggest possible hydrocarbon migration paths.

Within the interiors of the major structural ridges which separate the Oligocene-Miocene subbasins, large, poorly defined anticlines and synclines are observed in seismic data. These structures involve a lower seismic unit of acoustically stratified sediments which is overlain by an interval of variable thickness characterized by discontinuous acoustic reflectors. These two seismic units are most clearly defined within the Demarcation ridge. At present, no direct well control is available for the internal stratigraphy of the Demarcation ridge. However, some indirect analogies may be drawn from stratigraphic relationships established by exploratory drilling in contiguous areas.

The closest point of offshore stratigraphic control for the Demarcation sector north of the Hinge Line is the Dome Natsek E-56 well, which was drilled at a site roughly 30 miles east of the U.S.-Canadian border (location shown in fig. 28). Two major stratigraphic sequences were penetrated by the Natsek well. The upper half of the well (fig. 31) encountered monotonous marine shales ranging in age from Paleocene to Eocene. These shales overlie a sequence of several thousand feet of nonmarine to marginal marine sandstone, conglomerate, shale, and coal ranging in age from Paleocene to Late Cretaceous. The overlying shale sequence might be expected to generate few coherent reflections, while the underlying sequence of interbedded sandstone, shale, and coal would probably form an acoustically well stratified interval on seismic records.

We hypothesize that the two major seismic sequences observed within the Demarcation ridge may be correlative to the two major sequences penetrated by the Natsek well. This correlation is significant, because it implies the possible presence of substantial thicknesses of reservoir rock within the lower, acoustically stratified, folded sequence within the Demarcation ridge. In the Natsek well, sandstone porosities in the lower sequence generally range from 10 to 15 percent, and although no shows were encountered, at least several hundred feet of potential reservoir sands are present (fig. 31). Hydrocarbon traps may be found along the crestal areas of folds in this presumed sandstone sequence, as illustrated in figure 30.

Geophysical mapping suggests that the folds within the Demarcation ridge trend northeasterly (fig. 28), subparallel to the somewhat younger Camden, Marsh, and Jago folds, but nearly perpendicular to the conspicuous northwesterly structural trend of the ridge (figs. 10, 28). Northeast-trending folds in deep Cretaceous and Paleocene(?) strata within the Demarcation ridge are concentric in style, linear in axial trend, and apparently largely unfaulted. Some folds may be thrust-cored or related to thrust fault deformation, as suggested by the interpretation in plate 7. Seismic reflectors do not persist updip into the axial regions of some anticlines within the Demarcation ridge. This may suggest extreme disruption of strata or diapiric intrusion in the

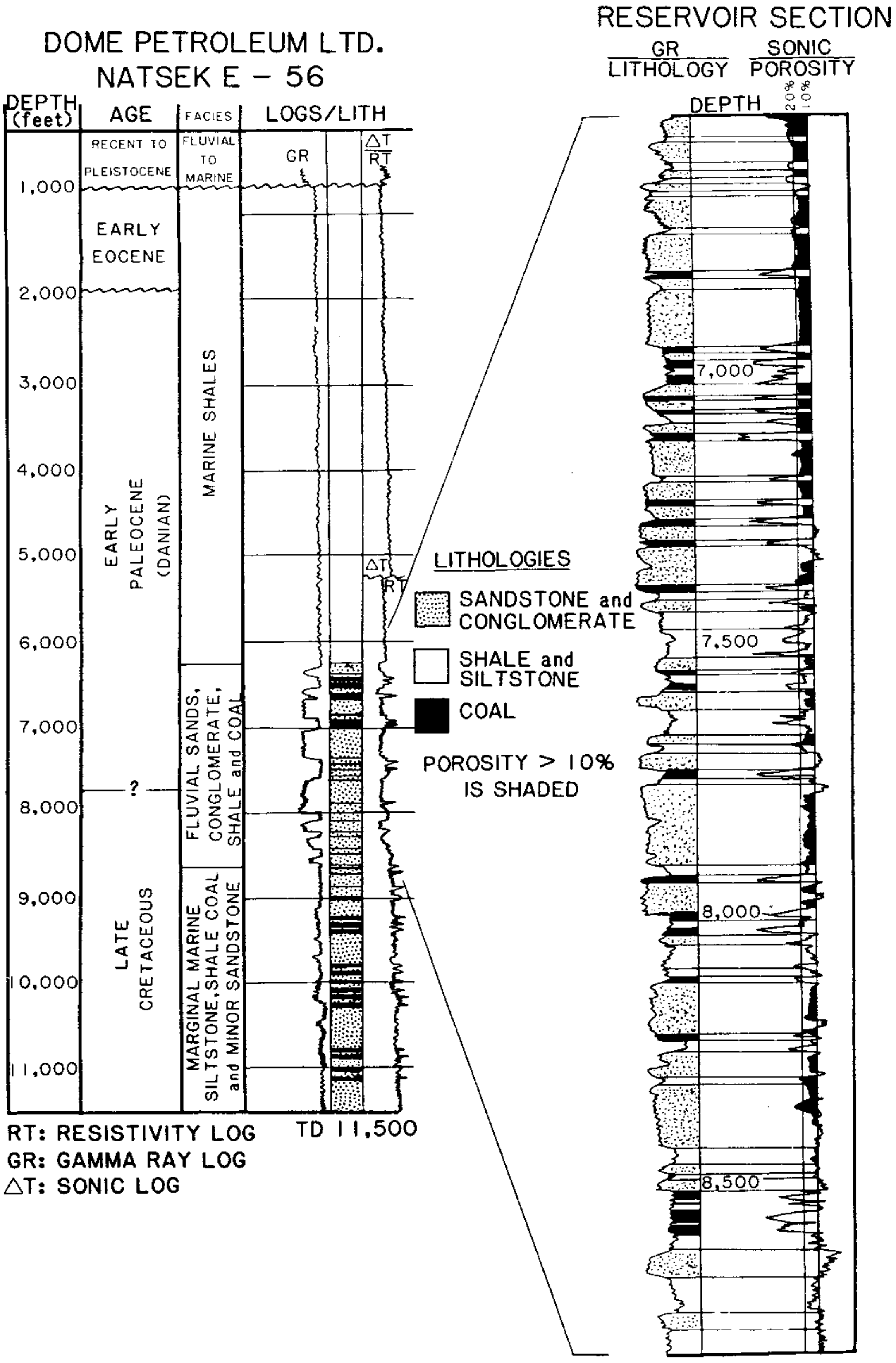


Figure 31.

Lithologic and wireline log profiles for Dome Natsek E-56 well drilled in Canadian waters 30 miles east of U.S.-Canadian border. Enlarged log of potential reservoir section with porosity profile to right.

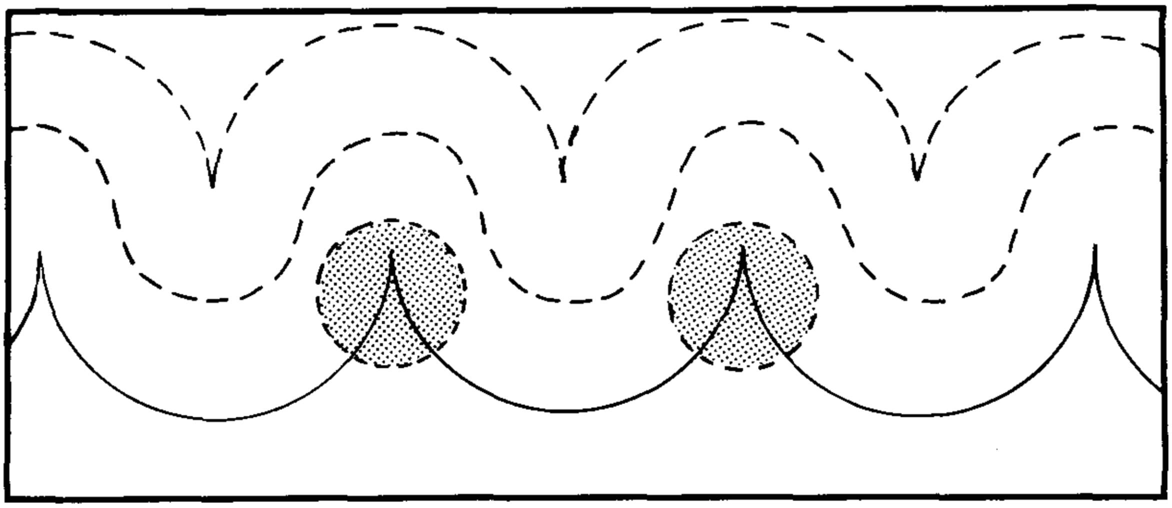
axial regions of these anticlines as a consequence of thrust faulting or liquefaction of an underlying shale unit. In the case of either structural disruption or diapiric intrusion, the prospectiveness of the crestal parts of these folds would be severely impacted. Intrusion of diapiric shales could confine reservoir beds (and trapped hydrocarbons) to the flanks of the anticlines. Severe deformation of strata in the axial regions could effectively eliminate porosity in potential reservoir beds in the crestal parts of the anticlines. Alternative mechanisms for crestal attenuation of reflectors, which may not alter the prospectiveness of the crests of the anticlines, include the following:

1. axial steep dips, possibly due to the existence of mappable reflectors in the fold only at the level where strata depart from open concentricity and develop a cuspate profile over anticlinal crests (e.g., fig. 32);

2. gas-charging or overpressuring of porous sediments in the crestal parts of the folds, thereby reducing the acoustic impedance contrast at sand-shale interfaces. A pulldown effect observed beneath the crests of some of these folds suggests crestal velocity anomalies.

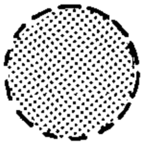
The Eocene(?) shale which overlies the deep folds appears to have responded in some areas to the folding of the substrate beneath it as a nonrigid or fluid material within which deformation patterns were governed by gravitational processes. The typical response of the shale to elevation of the crests of major substrate folds appears to have been listric detachment and mass movement toward flanking synclinal axes. The more cohesive Oligocene to Miocene shelf(?) sedimentary rocks which overlie the mobile shale on the Demarcation ridge responded to this movement by fracturing into discrete blocks which rotated and foundered along listric faults originating from the deeper shale section. Gravitational excavation of mobile shale from beneath the Oligocene to Miocene strata has produced a set of minor basins and graben structures which are superposed above the axial traces of deeper anticlines. Numerous and diverse potential trap configurations are thus associated with the crestal areas of these deep folds.

Hydrocarbons generated in shales underlying or overlying the Cretaceous to Paleocene(?) reservoir beds or in the Oligocene to Miocene basins flanking the major structural ridges may have migrated to the crests of the deep folds or overlying fault traps. The Brookian sequence of the nearby Canadian Beaufort has been regarded as somewhat gas prone. However, new concepts for organic content and necessary thermal maturity for liquid hydrocarbon sources (Snowdon, 1980), coupled with the recent significant discoveries of oil at Amauligak, Nipterk, and Pitsiulak (Oil and Gas Journal, 1984; 1985a; 1985d) in the Mackenzie Delta region, suggest that liquid hydrocarbons are equally likely to be present in the eastern part of the Beaufort Sea Planning Area.



- - - - - DASHED HORIZON – **not resolved in seismic data because of low acoustic impedance**

——— SOLID HORIZON – **stratigraphic surface with high acoustic impedance, well resolved on seismic data**



Area of no seismic signal return due to excessively steep dips

Figure 32.

Sketch of an ideal train of concentric or parallel folds. This illustration is presented to show one possible explanation for the cuspate and diapirically intruded appearance of anticlinal crests in some of the folds within the structural ridge complexes. In this model, the only horizons resolvable in seismic data are the strong reflectors at the base of the fold train below the sinusoidal surface of maximum shortening. These reflectors follow a cuspate profile, and anticlinal crests contain no reflectors because of excessively steep dips and possible diffraction effects. The more rounded anticlinal crests higher in the fold train (dashed) may not be observed because these strata contain reflectors with very low acoustic impedance contrast and therefore generate poor signal return. Shortening strain in parallel-fold systems decreases upward and downward from the sinusoidal surface, and the folded strata are generally detached from overlying and underlying undeformed strata across décollements.

Part 3

Environmental Geology

9

Physical Environment

PHYSIOGRAPHY

The Beaufort Sea Planning Area covers the entire Alaskan Beaufort continental shelf and slope, the northeastern Chukchi shelf, and part of the Arctic continental rise and abyssal plain. The Beaufort shelf is narrow, typically 70 to 120 km wide, with an average gradient of 1 m/km. Large-scale relief features on the surface of the Beaufort shelf are rare, although on the inner shelf, the seabed is interrupted by shoals a few to several meters high and three sets of barrier islands. The northeastern Chukchi shelf is a broad, flat-lying platform, generally 40 to 80 m deep. In the far northwestern end of the planning area, Hanna Shoal rises to depths of less than 20 m. This shoal overlies a structural high (the North Chukchi high, fig. 2) on which pre-Quaternary bedrock is exposed at the seafloor (Grantz and Eittreim, 1979).

The Beaufort and Chukchi shelves are separated by the Barrow Sea Valley, a relict Pleistocene feature which was incised by fluvial erosion during Pleistocene lowstands of sea level and by marine currents during interglacial highstands of sea level (Grantz and Eittreim, 1979). The valley is flat bottomed, 200 km long, 2 to 8 km wide, and 100 to 250 m deep. The Barrow Sea Valley leads seaward to the Barrow Sea Canyon, which is the largest of several modern submarine canyons that incise the continental slope off northern Alaska.

The Beaufort shelf-slope break is a complex zone of bedding-plane slides and slump blocks (Grantz and Eittreim, 1979). East of 147° west longitude, both an inner and an outer shelf break have been identified. The inner shelf break occurs at the 60-m water depth and marks a sharp boundary between the flat-lying shelf and the "Beaufort Ramp" (Grantz and Eittreim, 1979). The Beaufort Ramp is an area with a typical gradient of 16 m/km characterized by bedding-plane faults. The outer shelf break lies seaward of the Beaufort Ramp at depths of 600 to 800 meters. This break marks the top of a chaotic zone of large rotational slumps. West of the Beaufort Ramp (147° west longitude), the inner and outer shelf breaks merge to form a single steep escarpment which drops over 1,000 meters from the 60-m isobath (plate 11).

The Beaufort coast trends northwesterly from Demarcation Bay to Point Barrow (plate 11). It is punctuated by numerous shallow bays and barrier islands. The beaches are narrow and often backed by a low, steep bluff of frozen or partially thawed Quaternary sediments (Hopkins and Hartz, 1978a). The Chukchi coast trends north-northeast to Point Barrow and, unlike much of the Beaufort coast, is unprotected by islands or bays. The Chukchi beach cliffs are generally taller and contain more coarse sediment than the Beaufort cliffs (Lewbel, 1984).

Hopkins and Hartz (1978a) divided the islands along the Beaufort coast into three types: (1) emergent depositional shoals at the mouths of rivers; (2) erosional remnants of the coastal plain; and (3) recent constructional islands. Type 1 is associated with deltas and acts to protect the coast from wave erosion. Gull Island, off Prudhoe Bay, is an example of this type. Type 2 includes several large islands close to shore, such as Flaxman Island and Barter Island. The elevation of these erosional remnants is commonly more than 4 m above sea level and they are generally covered with peat, thaw lake deposits, and, in places, Pleistocene lag gravels. The constructional islands (type 3) rise generally less than 3 m above sea level and are only sparsely vegetated. These islands are frequently overridden by storm surges and are migrating landward and to the west.

Numerous rivers cross the coastal plain to the Beaufort shelf, the largest being the Colville River. West of Prudhoe Bay, the rivers are generally slow and meandering, with headwaters in the foothills of the Brooks Range. East of Prudhoe Bay the rivers are typically braided and flow from the Brooks Range itself. These rivers transport predominantly fine sand, silt, and clay to the shelf during spring runoff. Coarse sediment remains in the river channels and little reaches the coast (Hopkins and Hartz, 1978a). Large deltas at the mouths of the rivers may trap most of the fine sediment (Reimnitz and Bruder, 1972), although some is transported (usually to the west) from the deltas by longshore marine currents.

METEOROLOGY

The Beaufort Sea Planning Area lies within the Arctic climatic zone. The mean annual temperature along the Beaufort coast is -12 °C (10 °F). Typical summer temperatures range from -1 °C (30 °F) to 4 °C (40 °F) while winter temperatures are typically -23 to -30 °C (-10 to -22 °F) with extreme temperatures to -50 °C (-60 °F) (U.S. Bureau of Land Management, 1979). Cloudy weather prevails most of the year with clear conditions occurring more often during the winter months. Fog is common along the coast and offshore from May to September. Arctic Alaska is very dry. The average annual precipitation at Barrow is 12.6 cm/yr (4.9 in/yr). Most of this precipitation occurs as rain in August and snow in September (U.S. Bureau of Land Management, 1979). In the western Beaufort, the prevailing winds are persistent in both direction and speed. There, the wind blows from the east at an average velocity of 19 to 21 km/hr (12 to 13 mph) (U.S. Bureau of Land Management, 1979). In the eastern Beaufort, the prevailing wind blows from either the east-northeast or the west-southwest (Aagaard, 1981). Winds usually blow from the west during fall storms.

ICE ZONATION

The Beaufort continental shelf is ice covered much of the year, with a typical ice-free period occurring in August and September only. In the fall, sea ice first forms in late September to early October and becomes continuous nearshore by mid-October. The shelf remains ice covered throughout the winter (October through June). The first movements and openings in the ice pack occur in late June and only by early August is the nearshore area largely ice free (Barry, 1979, table 1).

During the winter months, the offshore ice can be divided into three main zones: the landfast zone, the shear zone (or Stamukhi zone), and the pack ice zone (Reimnitz and Barnes, 1974) (fig. 33). The landfast ice is seasonal, forming along the shore and developing seaward in the early fall. It remains relatively undisturbed through the winter until it begins to melt in late June. Small movements related to storm fronts cause narrow leads and rubble fields in this zone. In late winter, the fast ice frequently extends out to the 25- to 30-m isobath.

The stamukhi zone is located between the landfast ice and the pack ice zone, generally in 18 to 30 m of water (fig. 33). It is a transition zone between the relatively stationary landfast ice and the highly mobile pack ice. Fragments of seasonal ice, multiyear ice, and ice ridges tens of meters high (fig. 34) are typically found in this zone. In the stamukhi zone there is an intense interaction between the ice and the seabed as ice-ridge keels plow the seabed to depths of several meters (Reimnitz and Barnes, 1974). During the brief summer, this is an area of open leads in the ice pack and serves both as a shipping lane and as a pathway for seasonal whale migrations. On the Beaufort shelf, the constructional islands and their associated shoals appear to be important in controlling the location of the stamukhi zone and the shoreward advance of the pack ice.

The pack ice zone, seaward of the stamukhi zone, is the shoreward edge of the permanent polar ice cap. It consists of multiyear ice, ice ridges, and ice island fragments that migrate westward in response to the clockwise circumpolar gyre (Reimnitz and Barnes, 1974). During the summer, ice movements in excess of 20 km/day are common (Weeks, 1978). Most of the Beaufort Sea Planning Area is covered by the ice pack year-round, although the location of the inner edge of the summer ice pack varies greatly from year to year (fig. 33). During an atypical summer it may occur tens to hundreds of kilometers offshore, but it generally occurs inside the shelf break (Barnes and Reimnitz, 1974).

On the Chukchi shelf, ice forms between the middle of October and early November. In contrast to the Beaufort Sea, which remains largely ice covered after freezeup, the Chukchi Sea has a persistent lead, or "polynya," which forms just seaward of the fast ice in the late winter and spring. This annual lead is thought to form in response to the prevailing easterly (offshore) winds. The polynya is generally wider south of the Beaufort Sea Planning Area, although it persists as far north as Point Barrow. At any time of the year, however, it can close rapidly either by freezing or as a result of ice movement in response to changing wind directions (Stringer, 1982a). The polynya acts as a spring pathway for migrating whales and waterfowl (Lewbel, 1984).

Ice motion in the Chukchi Sea is generally to the northwest in response to prevailing easterly winds and north-flowing currents (Pritchard, 1978). However, in the eastern Chukchi Sea, approximately four times a year, a tongue of ice, sometimes extending the length of the Chukchi Sea, moves in mass south through the Bering Strait. This occurs in response to several poorly understood physical conditions which include current reversals, ice damming at the Bering Strait, and weakening of the ice along the Chukchi coast (Reimer and others, 1981). In the planning area, large-scale ice movement and tremendous rubble flows along the coast may result from these events. These ice "breakout events" generally last for about 4 days (Lewbel, 1984).

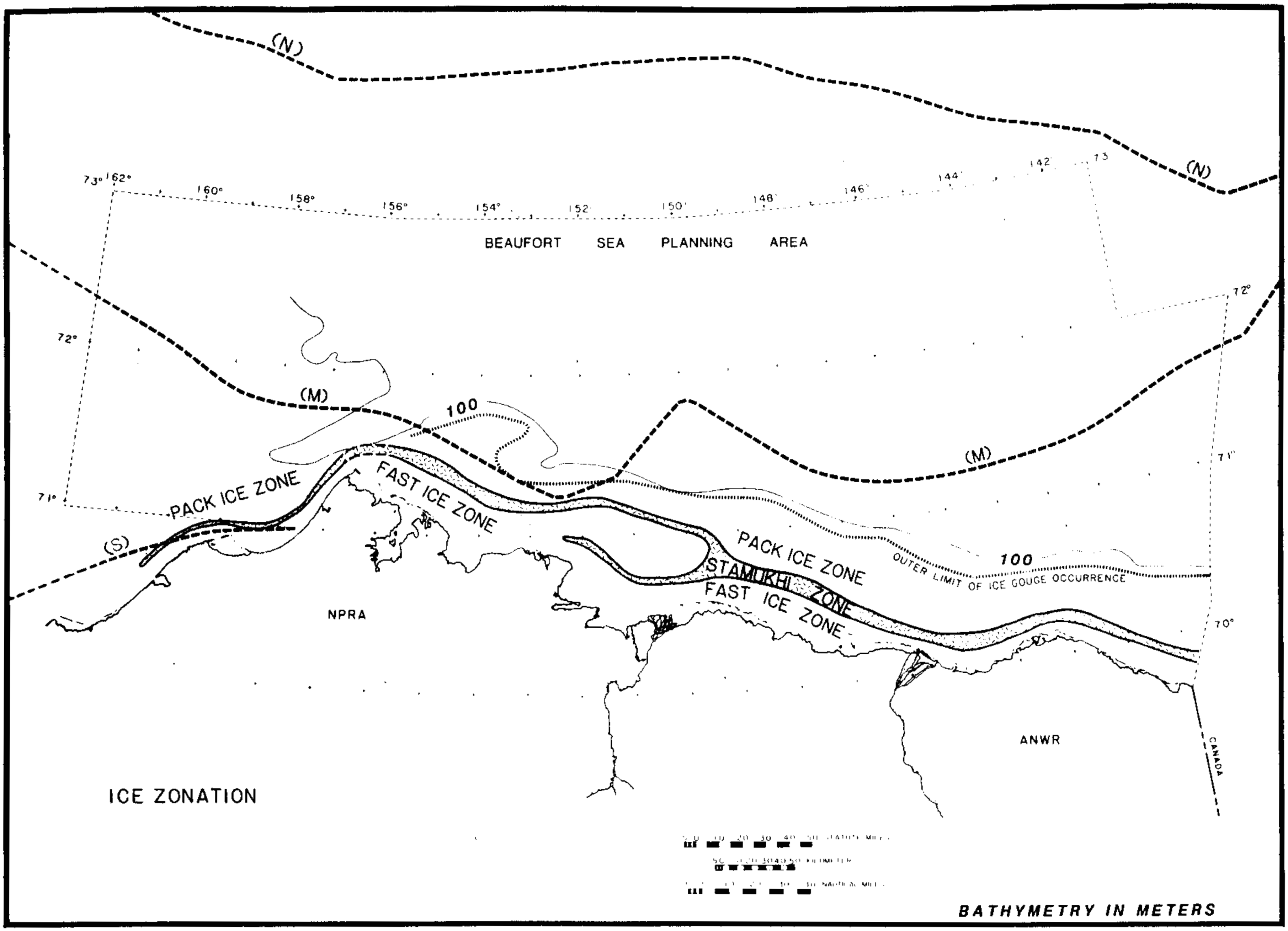


Figure 33.

Ice zonation in the Beaufort Sea Planning Area showing the location of the stamukhi zone (stippled). Dashed lines indicate the northernmost (N), southernmost (S), and median (M) position of the southern edge of the Arctic pack ice during the period of maximum retreat (September 16 to 30). Based on data collected from 1954 through 1970 (after Grantz and others, 1982b, and Brower and others, 1977).

10

Surficial Geologic Processes

ICE GOUGING

Ice gouging is one of the most important agents of sediment reworking on Arctic continental shelves. It is particularly important at mid-shelf and inner-shelf water depths. On the mid-shelf, ice ridges with deep keels intensely scour the seafloor to depths of several meters (figs. 34 and 35). Reimnitz and Barnes (1974) found gouges as deep as 5.5 m, with ridges 2.7 m high (total relief of 8.2 m), in 39 m of water off Smith Bay. The average ice gouge on the Beaufort shelf is 50 cm deep, plows a ridge 40 cm high, and is 7.5 m wide (Barnes, 1981). For planning purposes, ice gouges of between 1 and 10 m of relief may be expected. The maximum incision depth of ice gouges tends to increase with increasing water depth, at least to a water depth of 45 m.

The distribution of ice gouge density is shown in fig. 36. Although ice gouges are found across the entire shelf, they are concentrated in the stamukhi zone, generally between the 18- and 30-m isobaths. The highest intensity gouging occurs on the up-drift side of shoals and islands bordering the stamukhi zone. The shoals often show little or no evidence of ice gouging on their down-drift side (Reimnitz and others, 1982). Off Prudhoe Bay, the inner boundary of high-intensity ice gouging is controlled by the location of the island chains, generally 15 to 20 km from the coast. In Harrison Bay, where there are no barrier islands, two zones of high-intensity ice gouging occur: one near the 10-m isobath and the other in 20 m of water seaward of Weller Bank (Reimnitz and others, 1978). These zones correspond to areas of abundant ice ridge formation (fig. 34B).

Inshore of the stamukhi zone (water depth less than 18 m), ice gouging is much less severe. An average of 1 or 2 percent of the seafloor per year is gouged (Barnes and others, 1978), and current-related hydraulic bedforms dominate over ice gouges (Barnes and Reimnitz, 1974). Any ice gouges which form are rapidly buried by sand waves or sediment sheets. In addition, nearshore sediments tend to be coarser grained than those farther offshore, and ice gouges degrade more rapidly in coarse sediments than in more cohesive, fine-grained sediments (Barnes and Reimnitz, 1979).

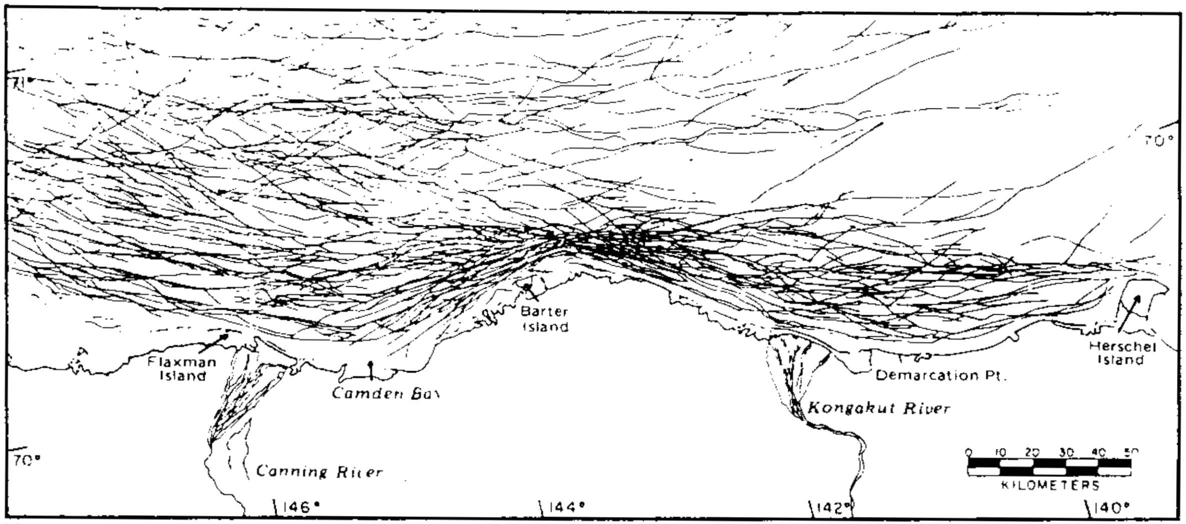


Figure 34A.
Composite map of all major ice ridges observed in the eastern Beaufort Sea (Herschel Island to Foggy Island) between 1973 and 1981. (Source: Stringer, 1982b.)

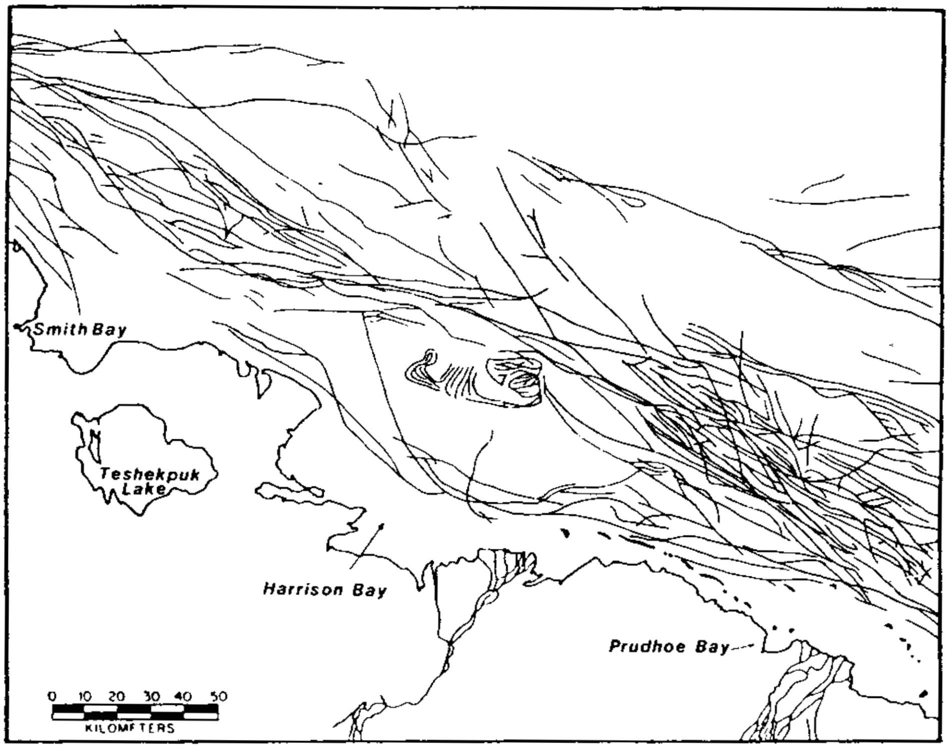
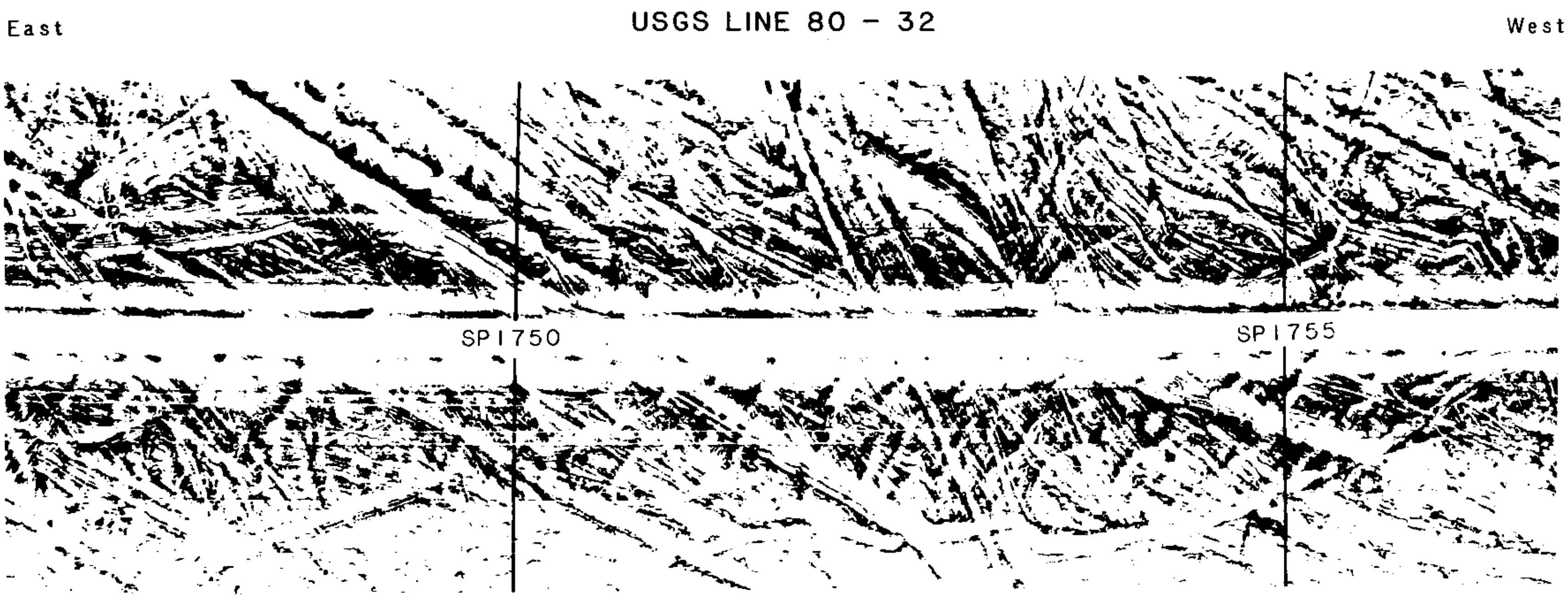


Figure 34B.

Composite map of all major ice ridges observed in the western Beaufort Sea (Smith Bay to Prudhoe Bay) between 1973 and 1977. (Source: Stringer, 1981.)



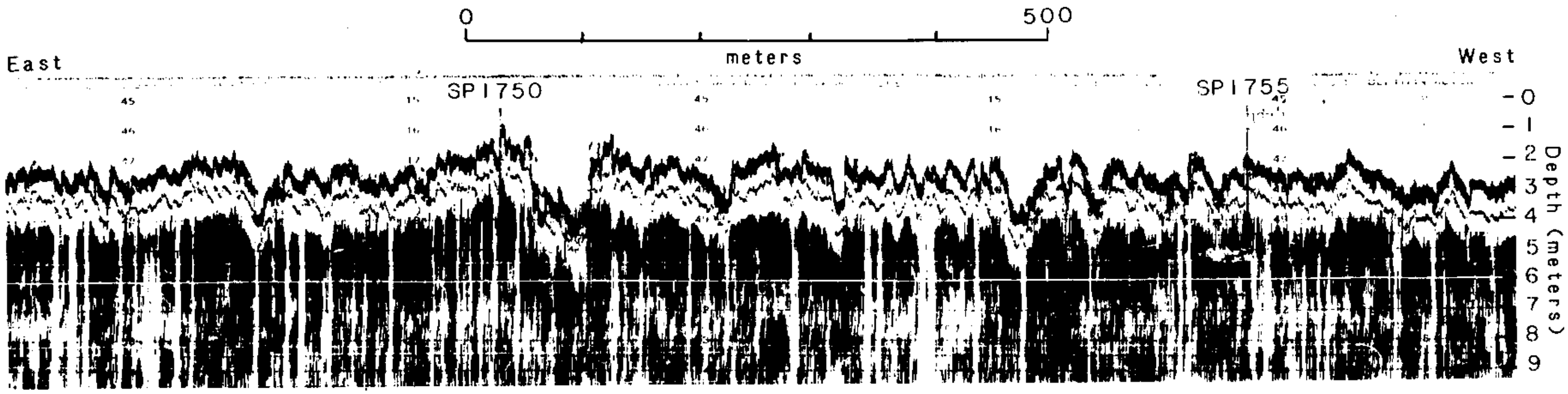


Figure 35A.
Side-scan sonar record of the ice-gouged seafloor offshore of Cape Halkett. For the location of the survey line, see figure 36.

Figure 35B.
Fathometer profile (7- and 200-kHz systems) along the side-scan sonar line shown in figure 35A above. The ice gouge just west of shot point 1750 has 3 meters of relief.

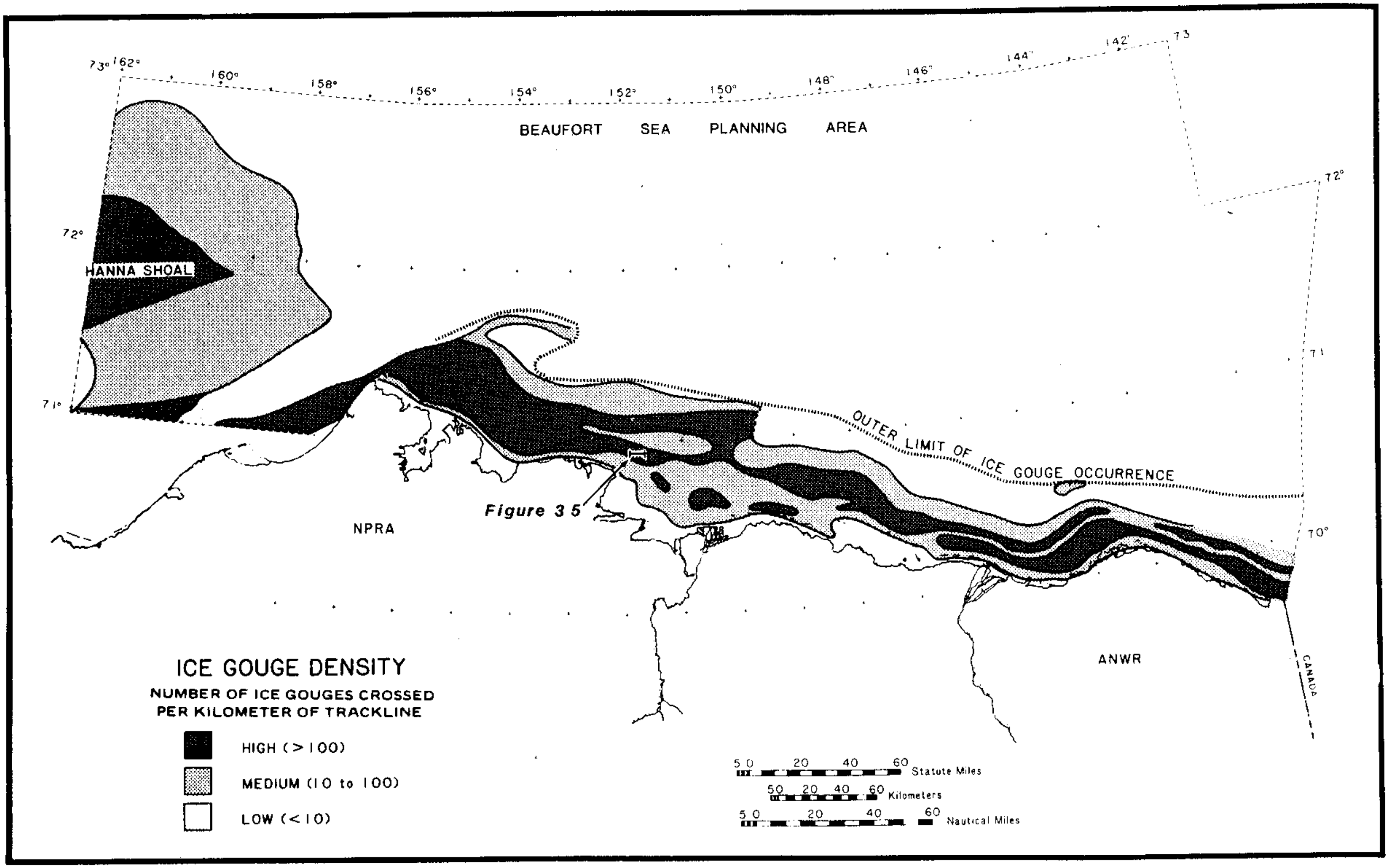


Figure 36.
Generalized distribution of ice gouge density in the Beaufort Sea Planning Area. Data in the Beaufort Sea collected by Barnes (1981). Data in the Chukchi Sea after Grantz and others (1982a).

Offshore of the stamukhi zone, water depth increases, and the number of ice keels large enough to reach the bottom decreases. However, ice gouges have been reported in water as deep as 58 m (Reimnitz and others, 1982). Canadian workers estimate that at this depth, gouging takes place only once every few hundred years (Peter Wadhams, personal commun., cited in Reimnitz and others, 1982). Near the outer shelf edge, strong geostrophic currents probably have acted to erode and fill older ice gouges (Reimnitz and others, 1982).

Ice gouges on the Beaufort shelf are generally oriented east-west, although on the inner shelf where shoals and other bottom features deflect the ice, orientations can vary considerably. The east-west orientation reflects the prevailing wind and surface current directions.

On the Chukchi shelf, ice gouge density and dynamics are not as well understood as on the Beaufort shelf. From the data available, it is apparent that ice-gouged areas are extensive, but more patchy than on the Beaufort shelf. The highest intensity gouging occurs on the northeastern flank of large shoals, such as Hanna Shoal, and in areas of steep bathymetric gradient, such as along the Barrow Sea Valley (Toimil, 1978) (fig. 36). Elsewhere, heavily gouged zones occur adjacent to areas only sparsely gouged (Toimil, 1978). It is consequently difficult to predict the expected intensity of ice gouging at any given spot on the Chukchi shelf. On the Chukchi shelf near Point Barrow, ice gouges generally are oriented parallel to the coast. Elsewhere on the shelf, ice gouge orientations are highly variable. No ice gouges have been observed in water deeper than 58 m. However, gouges in water 43 m deep show evidence of infilling by recently transported sediment, suggesting that these gouges are modern features (Toimil, 1978).

ICE PUSH

On islands and coastal regions throughout the Beaufort and Chukchi Seas, ice push and ice override events transport and erode significant amounts of sediment. Ice push is the process whereby ice blocks, forced onshore by strong winds or currents, push sediment from the coast into ridges farther inland. Ice push is most important on the outer barrier islands (Narwhal and Cross Islands). There, ice push ridges up to 2.5 m high, extending 100 m inshore from the beach, have been identified (Hopkins and Hartz, 1978a). Ice push rubble is found at least 20 m inland over most of the Arctic coast (Kovacs, 1984). Boulders in excess of 1.5 m in diameter are found on some of these rubble piles. There are several historic accounts of ice push events which have damaged man-made structures along the Beaufort coast. In January of 1984, ice pileup overtopped the Kadluk, an 8-m-high caisson-retained drilling island located in Mackenzie Bay on the Canadian Beaufort (Kovacs, 1984).

CURRENTS AND CURRENT SCOUR

Marine currents across the inner shelf of the Beaufort Sea are wind driven and strongly regulated by the presence or absence of ice. These currents cause longshore sediment transport along barrier islands and coastal promontories. However, because of the short open-water season, the annual rate of longshore sediment transport is relatively low. Inner shelf currents generally flow to the west in response to the prevailing northeast wind (fig. 37), although current reversals are common close to shore and during storms. On the open shelf, currents average between 7 and 10 cm/s (0.2 knots) (Matthews, 1981). During storms, east-flowing currents with peak velocities of 95 cm/s (2 knots) have been measured, although typical storm current velocities are an order of magnitude lower (Kozo, 1981). During the winter, under-ice currents are generally weak (less than 2 cm/s), although some have been measured up to 25 cm/s (0.5 knots) in restricted passages around grounded ice blocks (Matthews, 1981). Geostrophic currents with velocities of up to 50 cm/s (1 knot) occur on the outer shelf, flowing parallel to the shelf-slope break. Both easterly and westerly directed currents occur there. The tidal range on the Beaufort shelf is small (15 to 30 cm), and except in confined passages, tidal currents exert only a minor influence on the sedimentary regime (Matthews, 1981). They can be important scouring agents, however, where water flow on the shelf is restricted by bottom-fast ice (Reimnitz and Kempema, 1982b) and by narrow passages between barrier islands and shoals.

On the Chukchi shelf, northeastward-flowing longshore currents erode and transport significant amounts of sediment. Nearshore currents are predominantly wind generated, while farther offshore, northeast-flowing geostrophic currents (the Alaska Coastal Current) and storm-generated currents predominate. Surface velocities of 200 cm/s (approximately 4 knots) and mid-depth velocities of 70 cm/s have been measured in the Alaska Coastal Current north of Wainwright. A southwest-flowing countercurrent of 80 cm/s has been measured near the head of the Barrow Sea Valley northwest of Wainwright (Hufford, 1977, as cited by Grantz and others, 1982a).

WAVES AND COASTAL EROSION

Throughout most of the year the wave heights on the Beaufort shelf are low because of the short fetch resulting from the pervasive ice cover. However, considerable fetch is developed both seaward and shoreward of the barrier islands late in the fall open-water season. During this time, storm waves up to 6 m high have been observed (Hopkins and Hartz, 1978a). These waves can become effective erosive agents both onshore and along the exposed faces of the barrier islands. During storms, wind-induced storm surges force ice and water onshore and can raise sea level as much as 3 m (Hopkins and Hartz, 1978a). Low atmospheric pressures associated with the storms can raise sea level an additional meter (Barnes and Reimnitz, 1974). During the most extreme surges, coastal islands are completely flooded, and major changes in the size and shape of these islands can occur during very short time periods (Reimnitz and Maurer, 1978b).

Despite the short open-water season in the Beaufort Sea, wave action, in combination with the melting of coastal permafrost, causes dramatic rates of coastal erosion (fig. 38). Across the Beaufort coast, average rates of erosion vary from 1.5 to 4.7 m/yr and short term rates of 30 m/yr have been measured (Hopkins and Hartz, 1978a). At Oliktok Point, the coast receded by 11 m during one 2-week period (Hopkins and Hartz, 1978a). The highest rates of erosion occur along coastal promontories where the bluffs are composed of fine-grained sediments and ice lenses (fig. 38). Sand and gravel eroded from bluffs cut in coarse-grained deposits form beaches which partially isolate those bluffs from wave action. Bluffs cut in fine sediment are not protected by beaches and tend to erode more rapidly. Between Point Barrow and Cape Halkett, where predominantly fine-grained sediments crop out in coastal bluffs, the coast is receding at an average rate of 4.7 m/yr. East of Harrison Bay, where coarser grained sediments crop out, the average retreat rates are between 1.5 and 2.5 m/yr.

Erosion rates along the Chukchi coast are an order of magnitude lower than rates along the Beaufort coast (fig. 38) (Hopkins and Hartz, 1978a). This is probably because bluffs along the Chukchi coast contain more coarse-grained sediment and the bases of many of the bluffs are cut in lithified Cretaceous sediments. In addition, while bluffs along the Beaufort coast are typically less than 3 m high and are highly susceptible to erosion and thaw by wave action, bluffs on the Chukchi coast are generally higher (10 to 30 m high between Peard Bay and Barrow), and most of the bluff is not attacked directly by wave action (Hopkins and Hartz, 1978a).

The only prograding shoreline areas along the Beaufort or northeast Chukchi coasts occur off the deltas of major rivers. In those areas, the rate of progradation is slow (averaging 0.4 m/yr on the Colville River) (Reimnitz and others, 1985).

BARRIER ISLAND MIGRATION

The constructional barrier islands on the Beaufort shelf are migrating rapidly westward and landward. Hopkins and Hartz (1978a) determined maximum migration rates of 19 to 30 m/yr westward and 3 to 7 m/yr landward. At these rates, it takes only 30 to 40 years for an island to cross a given point on the seafloor. Generally the islands are becoming narrower and are breaking up into smaller segments as they migrate. Between 1950 and 1978, Reindeer Island split in two. Cross, Argo, and Narwhal Islands have also broken up in the recent past, and channels between the island fragments appear to be deepening (Reimnitz, Kempema, and others, 1979). Other islands

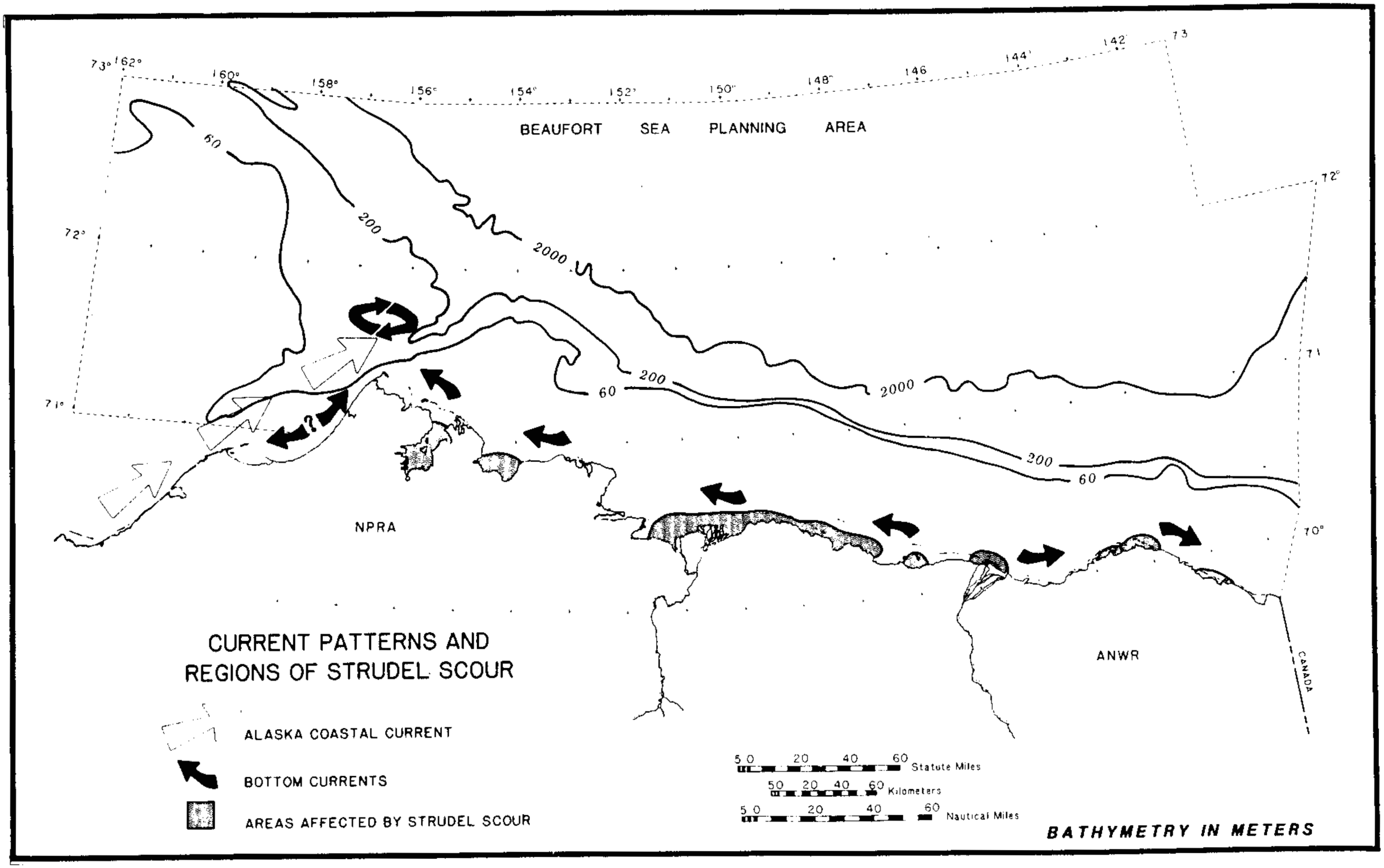


Figure 37.

Current patterns and regions of strudel scour on the Alaskan Beaufort and northeastern Chukchi shelves (adapted from Grantz and others, 1982b).

have gone through marked changes in morphology since studies began in the 1950's. Presumably the sediment derived from these islands is being redeposited as shoals and sand ridges. Dinkum sands, a shallow shoal between Narwhal and Cross Islands, is probably a remnant of a barrier island. In 1950, it was exposed 1 m above mean high water. Because of subsequent erosion, it has not been exposed since 1975 (Reimnitz, Ross, and Barnes, 1979). Ice push, storm surges, and longshore drift occurring during the open-water season contribute to the rapid migration and breakup of the barrier islands. Grain size analysis and cobble lithologies on the constructional islands indicate that most are isolated from their original depositional source (Hopkins and Hartz, 1978a). This implies that removing material from these islands may permanently affect their size and influence on coastal processes.

STRUDEL SCOUR

During spring runoff, the landfast sea ice is inundated by the river flood waters. Extensive areas of the fast ice are covered as far as 30 km from the river mouths to depths of up to 1.5 m. When the flood water reaches holes or leads in the ice, it rushes through with enough force to scour the bottom to depths of several meters by the process of "strudel scour" (Reimnitz and others, 1974). On the Beaufort shelf, strudel scour craters 6 m deep and 20 m across have been mapped by shallow bathymetric surveys and scuba diving observations (fig. 37) (Reimnitz and others, 1974). Sheltered coastal areas and bays off major rivers, such as the Colville, Sagavanirktok, and Canning, are particularly susceptible to strudel scouring. In these areas, deltas can be totally reworked by strudel scouring in several thousand years (Reimnitz and Kempema, 1982a).

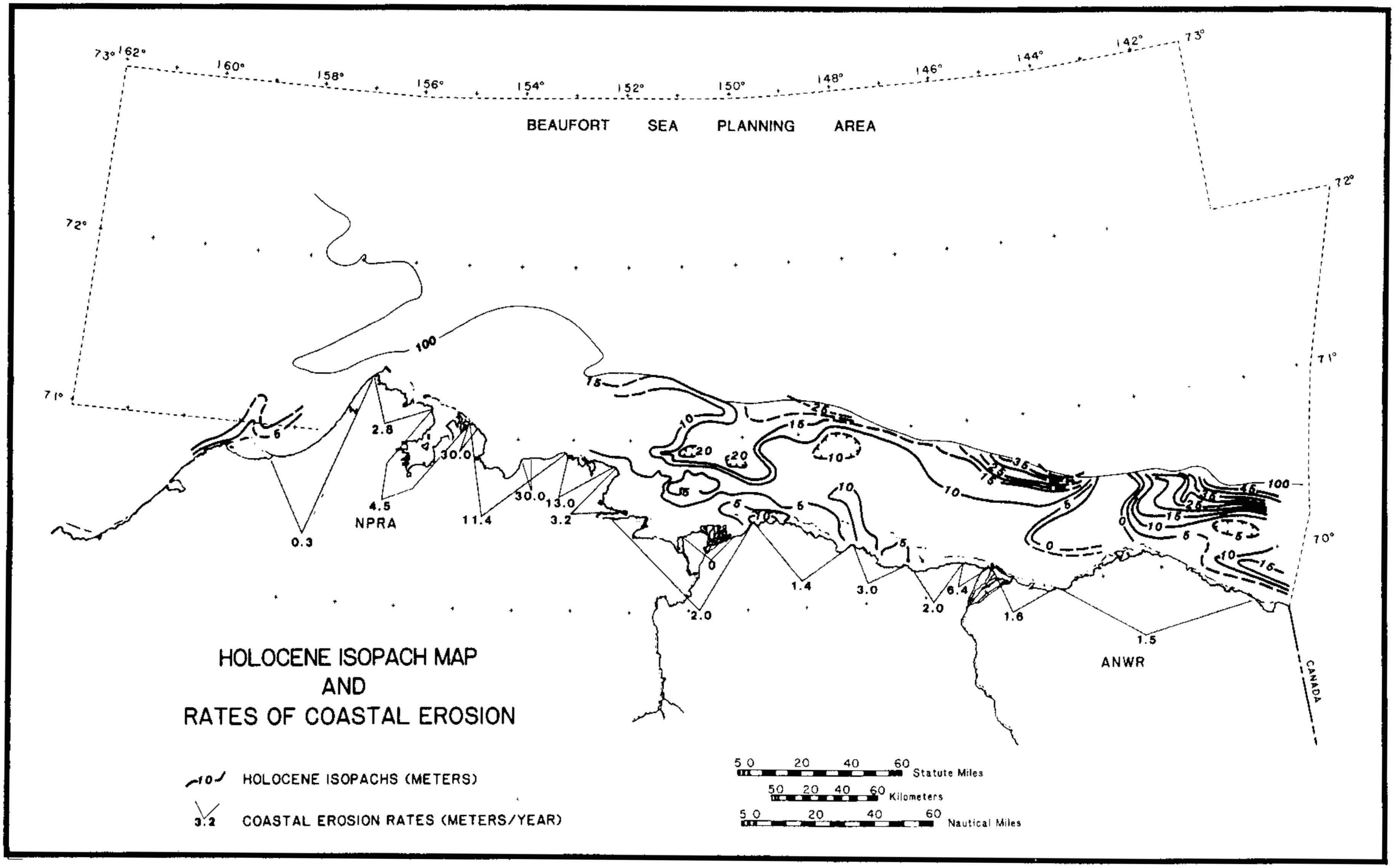


Figure 38.
Isopach map (in meters) of the thickness of the shallow, seismically transparent unit interpreted to be Holocene in age (modified from Dinter, 1982), and rates of coastal erosion in meters/year measured over intervals of 20 to 30 years (data from Hopkins and Hartz, 1978a).

11

Quaternary Geology

The lithology of Quaternary sediments on the Beaufort shelf is known from 20 boreholes collected in the BF-79 sale area by the USGS (Harding-Lawson, 1979), from 8 boreholes collected in the Prudhoe Bay area by the USGS and the U.S. Army Corp of Engineers Cold Regions Research and Engineering Laboratory (CRREL) (Hopkins and Hartz, 1978b), and from surficial geologic samples collected across the Beaufort shelf by the USGS between 1972 and 1983. The distribution of Quaternary sediments is inferred from data collected during numerous high-resolution geophysical cruises which occurred between 1970 and 1980. These data include 5,600 km of uniboom high-resolution seismic data collected in 1977 along reconnaissance lines on the shelf and upper continental slope by the USGS RV SP Lee (Dinter, 1982); a large number of high-resolution seismic lines collected nearshore by the USGS Geologic Division (over 7,000 km of uniboom, bathymetry, and sidescan sonar records were collected on the RV Karluk between 1975 and 1978) (Barnes and others, 1984); and a 1,600-km gridded high-resolution seismic survey conducted in Harrison Bay by the USGS Conservation Division (now U.S. Minerals Management Service) (Craig and Thrasher, 1982). In addition to these, industry contractors have collected over 6,000 km of permitted proprietary high-resolution data regionally on the Beaufort shelf and numerous site-specific gridded surveys over proposed drilling sites.

On the Beaufort shelf, the thickness of Quaternary sediments ranges from near zero over structural highs offshore of Barter Island to at least 100 meters elsewhere (Dinter, 1985). In contrast, on the Chukchi shelf, the Quaternary sequence is generally less than 5 meters thick and thickens to a maximum of only 15 meters nearshore (Grantz and others, 1982a).

SURFICIAL SEDIMENTS

The distribution of modern sediments on the Beaufort and northern Chukchi shelves reflects the original distribution of sediments on the subaerial Pleistocene coastal plain, the depositional environment during the early Holocene period of continental ice sheet breakup and sea-level rise, and the environmental and oceanographic conditions on the modern Beaufort shelf. In the present sedimentary regime, the intensity of ice gouging, the wave and current activity, and the composition of sediment delivered from rivers and from coastal bluffs are the most important factors affecting sediment composition and texture.

Surface sediment textures reported by Barnes and Reimnitz (1974) and Rodeick (1979) are shown in figure 39. In general, surface sediments east of Oliktok Point contain a greater coarse-grained fraction than those to the west. Most of this sediment is derived from coastal bluffs and reflects the character of sediments on the adjacent coastal plain. In the western Arctic slope, the coastal plain is broad (the Brooks Range sediment source is over 150 km south of the present coast), and rivers crossing the coastal plain are characteristically slow and meandering. The coastal plain sediments are predominantly fine-grained fluvial and thaw lake deposits. East of Oliktok Point, the coastal plain is narrower and higher in average gradient. There, coastal plain sediments are composed of coarse sediment derived from coalescing alluvial fans and braided river systems.

Barnes and Reimnitz (1974) divided the shelf into three zones based on surficial sediment textures and the sedimentary environment: the inner shelf, from the coast to the 20-m isobath; the central shelf, from the 20-m isobath to the shelf break (the 60-m isobath); and the shelf break, between the 60-m and 200-m isobaths. The inner shelf is characterized by moderately- to well-sorted silts and fine sand, which are actively transported by waves and currents during the open-water season. This area lies in the fast ice zone and is relatively unaffected by ice gouging. Hydraulic bed forms dominate over ice gouge features. The sediments here are derived primarily from coastal erosion and river effluents. The central-shelf sediments are predominantly gravelly muds. These sediments are highly disrupted by ice gouging and few sedimentary structures are preserved. The coarse clasts in the muds are angular and frequently striated, suggesting that they were emplaced as ice-rafted debris. The shelf break facies is characterized by a 5- to 20-cm-thick unit of muddy gravel overlying a clayey silt unit. The surface unit generally becomes coarser grained to the east. It contains abundant fauna and is bioturbated. In the lower unit, coarse sediment and bioturbation are uncommon. Ice gouging is less pronounced here than on the midshelf because water depths exceed the depth attained by all but the largest ice keels.

Superimposed on these general sediment zones are numerous areas of coarse-grained surface sediments on the Beaufort shelf (fig. 40). These are generally thin and discontinuous. However, large bodies of coarse sediment are located on the shelf as constructional islands (discussed above) and submerged shoals. The most prominent of the shoals is the Reindeer-Cross Islands ridge, which extends several kilometers northwest of Reindeer Island (located in the Midway Islands, plate 11) (Rodeick, 1979). Another prominent shoal, between Spy

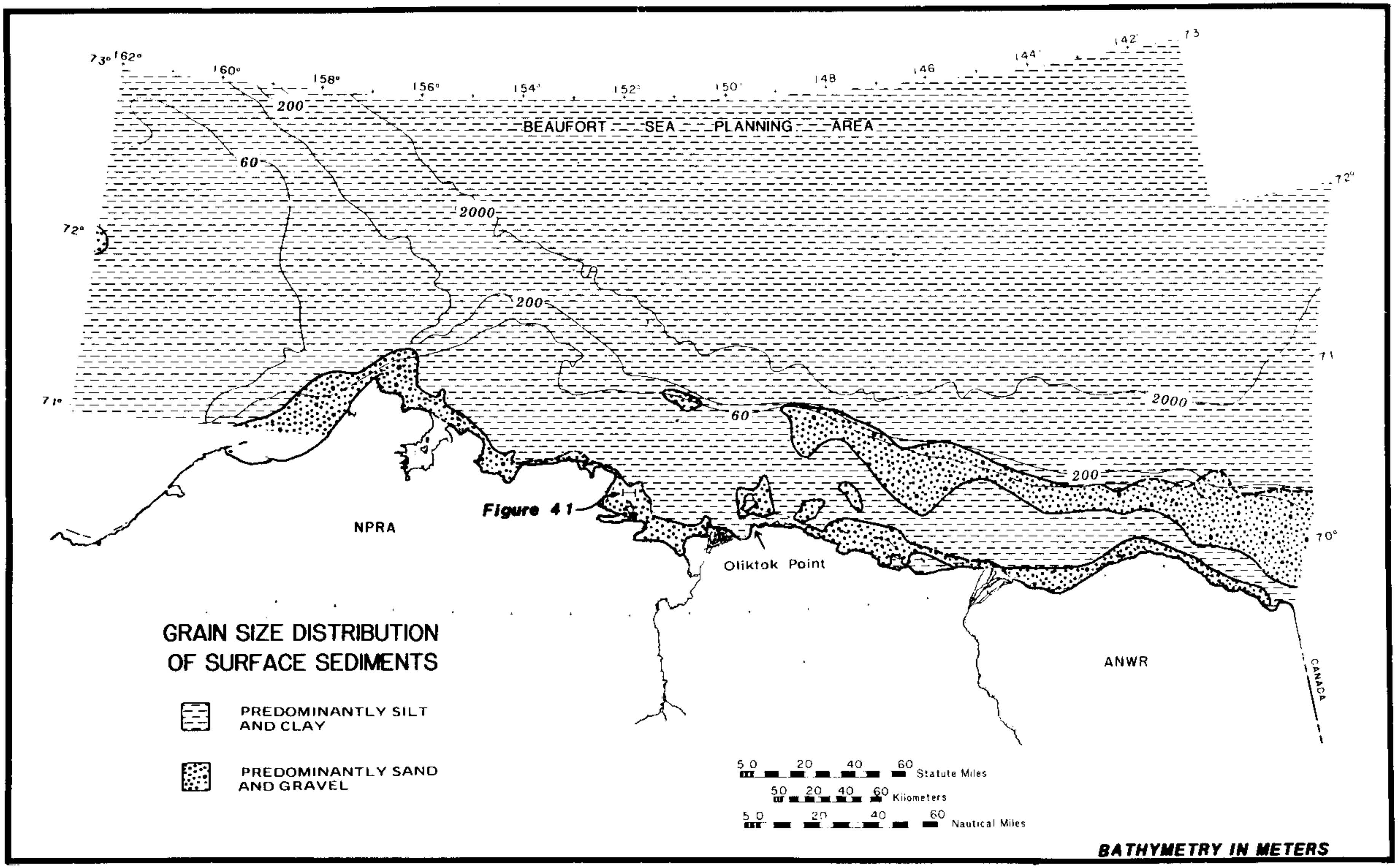


Figure 39.

Generalized distribution of coarse-grained (sand and gravel) and fine-grained (silt and clay) surface sediments in the Beaufort Sea Planning Area. Coarse-grained sediments on the outer shelf may occur as thin, discontinuous glaciomarine lag deposits overlying finer grained sediments. Data from Briggs (1983) and Grantz and others (1982b).

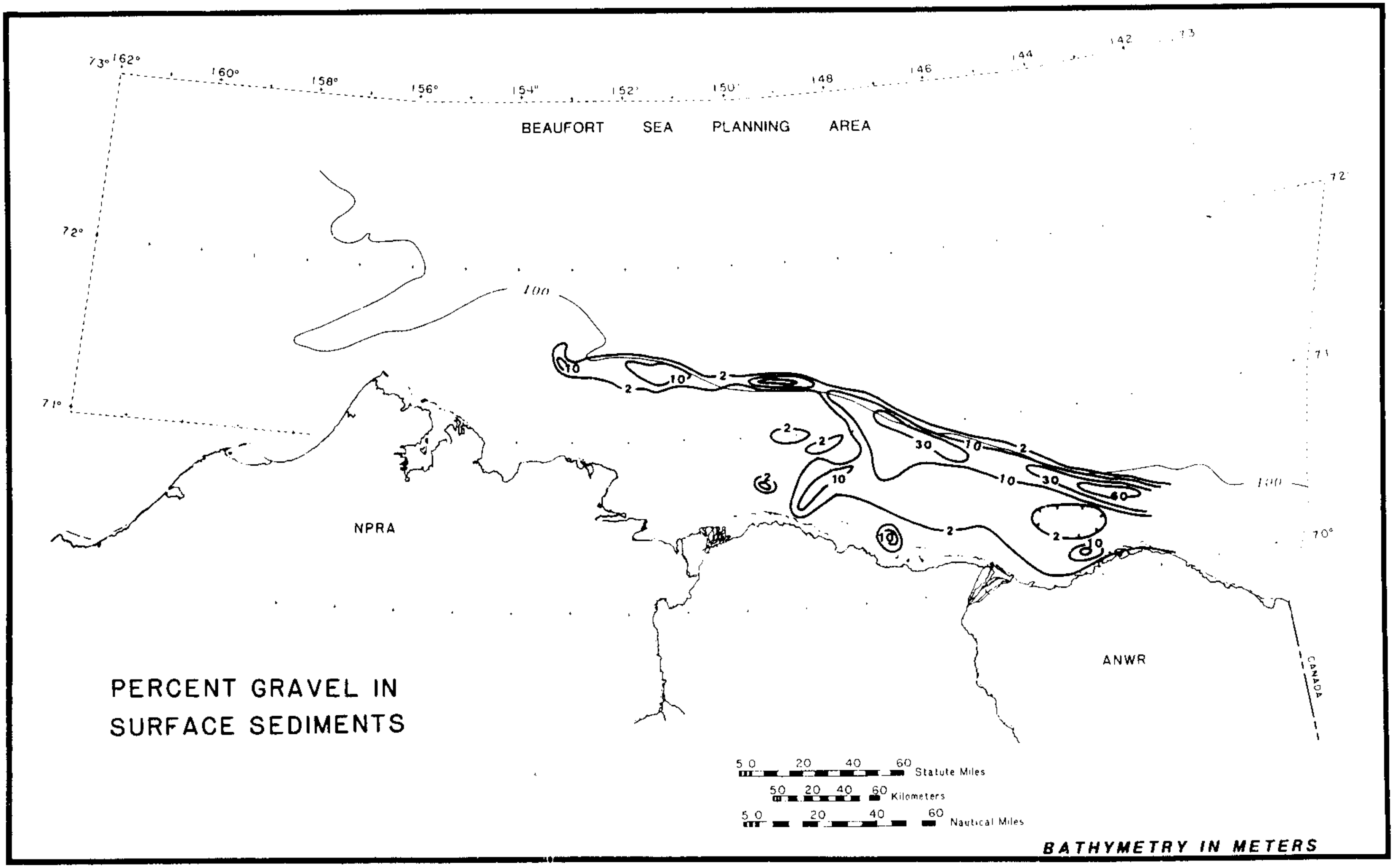


Figure 40.

Generalized distribution of surficial gravel (particle size greater than 2 mm) in the Beaufort Sea Planning Area (adapted from Briggs, 1983).

and Thetis Islands (offshore of Oliktok Pt., plate 11), is estimated to contain 10,000 m^3 of clean gravel (Hopkins, 1981). In Harrison Bay, two low sandy shoals of coalescing sand waves occur. These each may contain 100,000 m^3 of sand (Briggs, 1983). High-resolution seismic profiles indicate that at least some of these shoals and sand waves are migrating over ice-gouged sediments (fig. 41).

In outer Harrison Bay, a series of shoals lies in 15 to 20 m of water. Located at the shoreward edge of the stamukhi zone, they are evidently related to physical processes within this zone (Reimnitz and Maurer, 1978a). These shoals include Weller Bank, in outer Harrison Bay, and Stamukhi Shoal, north of the Jones Islands. The surface of these features is covered by coarse sand and gravel. However, sandy mud found in ripple troughs on Weller Bank (Barnes and Reiss, 1981) indicates that finer material may underlie the surface of these features.

Gravel and boulder lag deposits are present at the surface of many of the barrier islands and in patches in Stefansson Sound. The largest of these, known as the "Boulder Patch," contains boulders up to 2 m in diameter and supports an abundant fauna (Reimnitz and Ross, 1979). The Boulder Patch is probably a remnant Pleistocene island or coastal plain fragment, similar to Flaxman Island or Brownlow Point, from which the fines have been winnowed (Reimnitz and Ross, 1979).

Fine-grained sediments on the Beaufort shelf include illite clay and minor amounts of smectite, kaolinite, and chlorite. The distribution of these clays reflects their detrital source and not in situ diagenetic alterations (Naidu and Mowatt, 1983). Relatively high concentrations (20 to >30 percent) of expandable clays (smectite) occur at the mouth of the Colville River and in isolated areas on the outer shelf (fig. 42). The expandable clays at the mouth of the Colville River reflect the high concentration of smectite in sediments transported by the river. Seaward of the Colville Delta, a linear decrease in the concentration of smectite relative to illite has been reported (Naidu and Mowatt, 1983). On the outer shelf, there is no obvious modern source for the smectite. These clays may be relict, derived from Pleistocene or older sediments. If so, this implies that there has been little or no modern sedimentation on these parts of the shelf.

On the northeastern Chukchi shelf, surface sediments are primarily muds, although in nearshore areas and on Hanna Shoal, sandy sediments predominate (fig. 39). Nearshore, an extensive gravel bed occurs between Wainwright and Barrow, and sandy sediments form migrating sand wave fields and sand ridges up to 0.5 m high. The nearshore sediments are probably derived from coastal beach cliffs, many of which contain high percentages of coarse material (Lewbel, 1984). Toimil and Grantz (1976) suggest that the coarse sediments on Hanna Shoal are possibly ice-rafted, glaciomarine erratics (dropstones) that have been winnowed and concentrated by the combined action of currents and ice gouging.

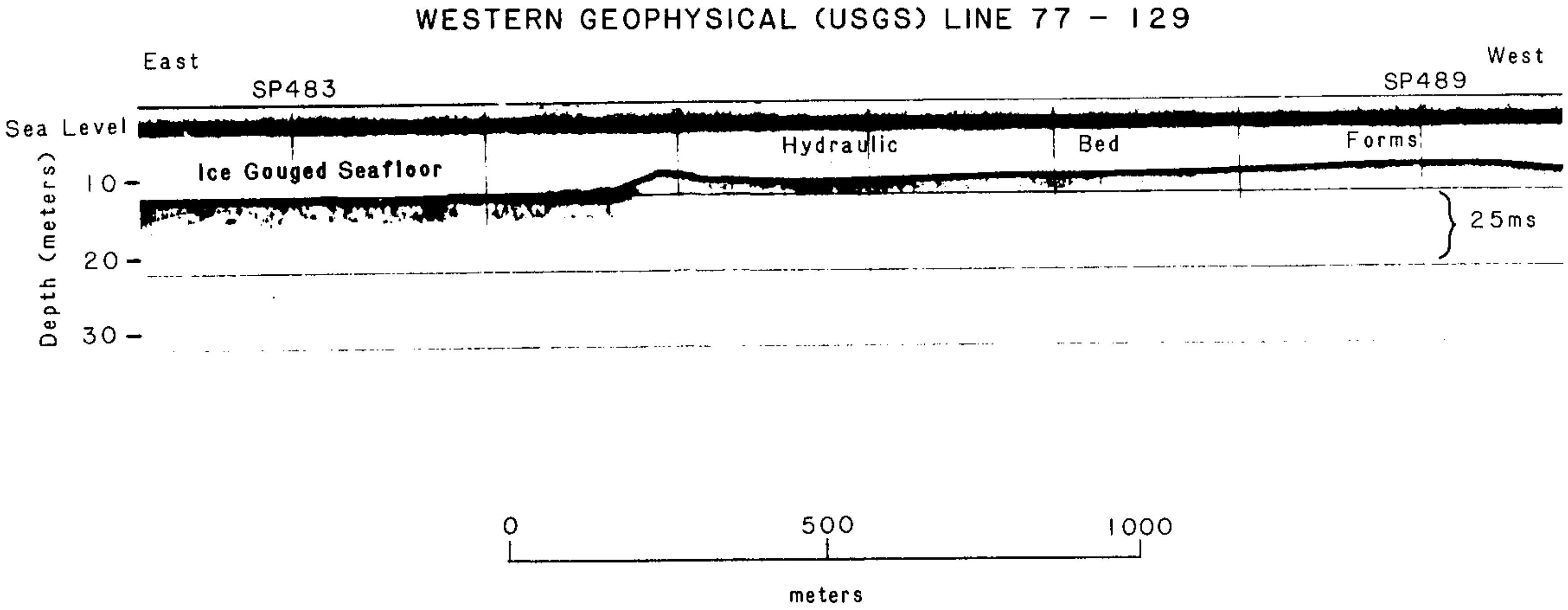


Figure 41.
Fathometer profile from Harrison Bay showing a hydraulic bed form migrating over ice-gouged seafloor sediment (after Craig and Thrasher, 1982). For the location of this profile, see figure 39.

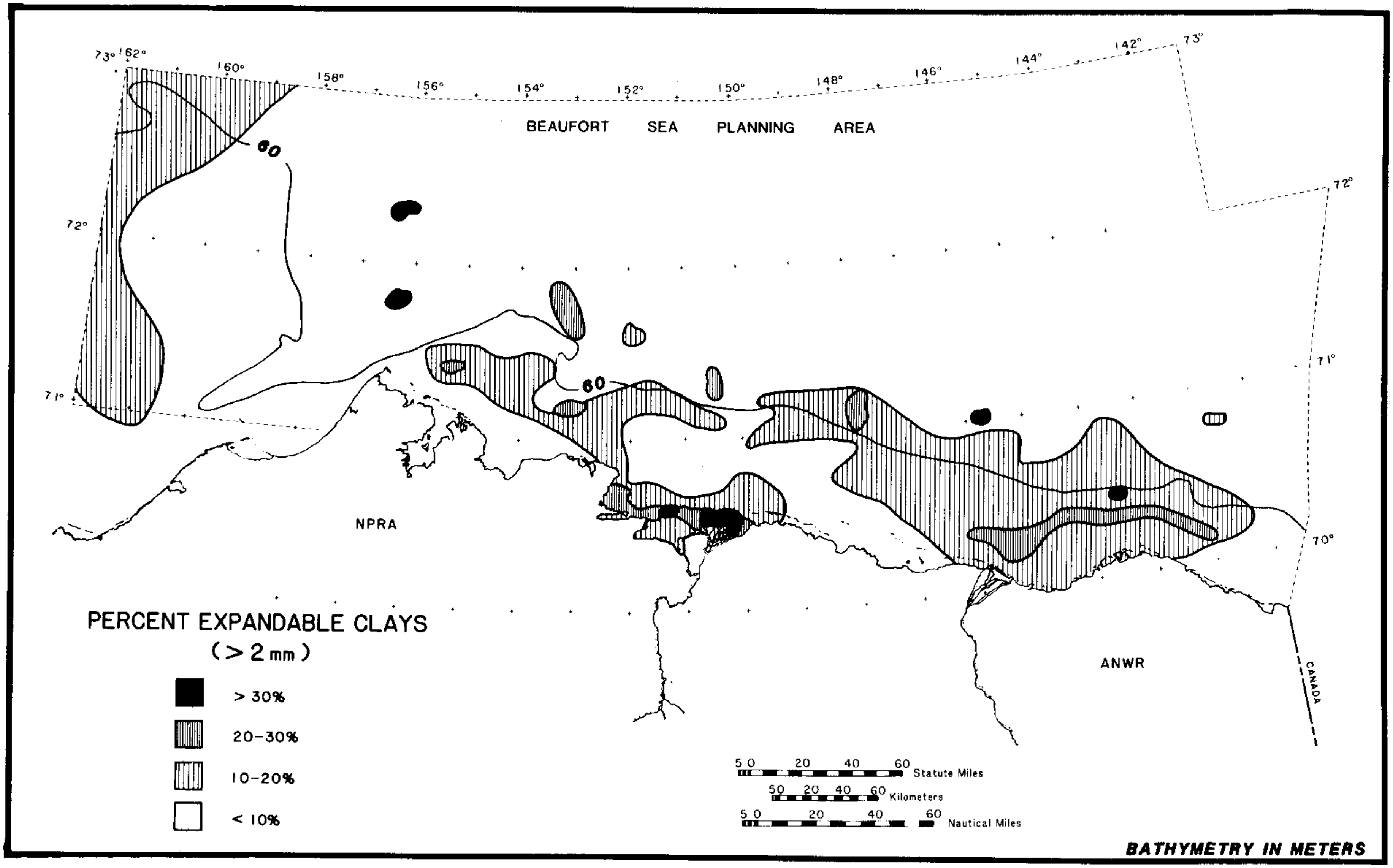


Figure 42.
Distribution of expandable clays in the Beaufort Sea Planning Area (adapted from Naidu and Mowatt, 1983).

Overconsolidated surface sediment (sediment that is consolidated beyond that expected from present overburden pressure) is widespread on the Beaufort shelf (Chamberlain, 1978; Reimnitz and others, 1982). Overconsolidation occurs in various sedimentary facies, although it is most prominent in fine-grained sediments. Two principal mechanisms have been proposed which could overconsolidate submarine surface sediments: (1) freeze-thaw action (Chamberlain, 1978) and (2) compaction by ice gouging (Reimnitz and others, 1980). The former necessitates freezing of the sediment after deposition. It has not been demonstrated, however, that bottom water temperatures on the shelf are low enough to freeze sediments in greater than 1 to 2 meters of water (Hunter and Hobson, 1974). Evidence for overconsolidation by ice gouging is equivocal (Reimnitz and others, 1982). Intuitively, ice gouging would remold rather than consolidate surface sediments. Some other mechanism may be responsible for this phenomenon.

HOLOCENE SEQUENCE

On high-resolution seismic profiles, the Holocene sequence is characterized as a thin transparent layer which overlies a generally strong hummocky reflector. The transparent nature of the surficial layer indicates that coherent beds, which would produce reflectors, are generally absent in this layer. Reimnitz and others (1982) concluded that ice gouging on the shelf has destroyed most of the primary stratification in the Holocene sequence. The underlying hummocky horizon has been interpreted to represent a lithologic change at the top of the Pleistocene sequence or other changes in the physical properties of the shallow sediments, such as the surface of ice bonding (Craig and Thrasher, 1982).

On the inner shelf, between Harrison Bay and Flaxman Island, the acoustically transparent layer is generally less than 10 m thick (fig. 38) (assuming a two-way velocity of 1.6 km/s). USGS boreholes (Harding-Lawson, 1979) confirm this estimate of the Holocene thickness on this part of the inner shelf. Dinter (1982) reports that the Holocene sequence is either very thin (below the resolution limits of the uniboom system) or absent close to shore.

In Harrison Bay, the transparent layer thickens from less than 2 m off the Colville Delta to greater than 20 m offshore (Craig and Thrasher, 1982). In outer Harrison Bay, it thickens abruptly along a feature suggested by Craig and Thrasher (1982) to represent a Pleistocene paleo-shoreline. It is possible that the deeper sediment within the transparent layer north of this boundary is Pleistocene in age. If this is the case, then this change in the thickness of the transparent layer may be due to a change in the depth to the surface of ice-bonding and not to a significant lithologic break between Holocene marine and Pleistocene nonmarine sediments.

The thickness of Holocene sediments on the outer shelf of the Beaufort Sea is unknown due to a lack of geologic data there. Uniboom lines, interpreted by Dinter (1982), indicate that the transparent layer (Holocene sequence?) is wedge shaped, thickening to over 45 m at the shelf edge off Camden Bay (fig. 38). Reimnitz and others (1982) collected grab samples from the outer shelf in the same area and reported the occurrence of relict surficial gravels. They suggest that much of what Dinter (1982) identified as Holocene in age is actually Pleistocene. Because the outer shelf and upper slope are characterized by massive slump blocks and gravity faults, data on the age of the sediment involved in these slumps are important in determining whether or not they are presently active. Most workers agree that the Holocene sequence is thin or absent over the anticlines north of Barter Island where historic seismicity and shallow faults indicate the occurrence of recent tectonic activity (fig. 38).

On the Chukchi shelf, unconsolidated sediments are thin (averaging 2 to 5 m thick). The thickest accumulations fill channels cut in pre-Pleistocene units (Grantz and others, 1982a). These sediments may include both Pleistocene and Holocene material.

PLEISTOCENE SEQUENCE

The Pleistocene stratigraphy of the Beaufort shelf is extrapolated from onshore geologic mapping and shallow borings offshore. Publicly available geologic data offshore are sparse outside of the BF-79 sale area (Harding-Lawson, 1979; Hopkins and Hartz, 1978b). There is one publicly available borehole collected west of Cape Halkett (Harrison and Osterkamp, 1981). The Pleistocene stratigraphy on the rest of the Beaufort Sea Planning Area has been inferred from high-resolution seismic surveys only (Barnes and Reimnitz, various reports; Dinter, 1982, 1985; Craig and Thrasher, 1982). Data quality varies with the different systems deployed, but is generally better in deeper water. Unfortunately, because of heavy ice cover and rapid ice incursions during the short open-water season, most of these high-resolution data have been collected on the inner shelf only.

The Pleistocene sequence can be characterized as cycles of marine and nonmarine deposition related to alternating glacial and interglacial episodes. Onshore, Pleistocene rocks are grouped into the Gubik Formation (Black, 1964), which sits unconformably on Cretaceous or Tertiary sediments of the Brookian sequence. It consists of sticky marine muds, poorly sorted marine sands and cobbles, clean quartz beach sands and gravels, nonmarine thaw lake muds, eolian silts and fine sands, and fluvial gravels. Ice locally constitutes more than half of the volume of the Gubik sediments, and organic matter is abundant.

In the offshore boreholes in Stefansson Sound, the Pleistocene sequence is composed of stiff silty clay overlying coarse sand and gravel. The thickness of the silty clay and the depth to the coarse-grained unit vary from borehole to borehole. In several of the boreholes, the top of the Pleistocene sequence occurs at or near the seafloor. Pollen collected from this unit give dates of up to 50,000 years B.P. (Miller and Bruggers, 1980), indicating that little or no Holocene sediment has accumulated there. Elsewhere in Stefansson Sound, the Pleistocene sequence underlies up to 13 m of Holocene sediment (generally soft silt and clay). The depth to the surface of the coarse-grained Pleistocene unit generally increases offshore and to the east in Stefansson Sound.

Dinter (1985) has identified several Quaternary transgressive and regressive cycles on the Beaufort outer shelf from uniboom and 3.5-kHz seismic records. These cycles consist of transparent to well-laminated units, interpreted to be marine transgressive deposits, unconformably overlain by thin, hummocky-surfaced units, interpreted to be nonmarine regressive deposits (fig. 43). On the eastern Beaufort shelf, these units form two northward-thickening sedimentary wedges separated by the structural high offshore of Barter Island (fig. 38). The age relationship between these transgressive and regressive cycles and the cycles recorded in the Gubik Formation on the adjacent coastal plain is uncertain. However, based on the depths below present sea level to each unit, Dinter (1985) has tentatively correlated these units with published sea-level curves. His conclusions suggest that a relatively complete Pleistocene section may be preserved on parts of the Beaufort shelf. The youngest presumed nonmarine Pleistocene sequence terminates on the outer shelf as a ridge 8 to 18 m high (fig. 43). This ridge may represent the northernmost extent of the latest Wisconsin marine regression on the Beaufort shelf (Dinter, 1982).

Within the Pleistocene section, seismic data suggest that buried paleovalleys exist on the Beaufort and Chukchi shelves (Dinter, 1985; Grantz and others, 1982b). These paleochannels occur offshore of the Sagavanirktok River (Hartz and Hopkins, 1980), the Canning River (Hopkins and Hartz, 1978a; Dinter, 1982), and possibly the Colville River (Hopkins, 1981). Some of the Pleistocene gravel cored in Stefansson Sound between Prudhoe Bay and Reindeer Island may occur in the Sagavanirktok River paleovalley. On the Chukchi shelf, where the Quaternary section is generally thin, paleovalleys are cut in Tertiary and older bedrock. The thickest accumulation of Quaternary sediment occurs in those valleys.

Consolidated bedrock is probably exposed at or near the seafloor on the Beaufort shelf north of Barter Island where Dinter (1982) has outlined an area of zero Holocene thickness. In this area, CDP and uniboom seismic records show shallow dipping reflectors of probable Tertiary age approaching the seafloor (Reimnitz and others, 1982) (plate 6, fig. 44). On the northeast Chukchi shelf, bedrock may crop out in the vicinity of Hanna Shoal, along the walls of the Barrow submarine canyon, and in local sites across the inner shelf between Wainwright and Barrow (Grantz and others, 1982a).

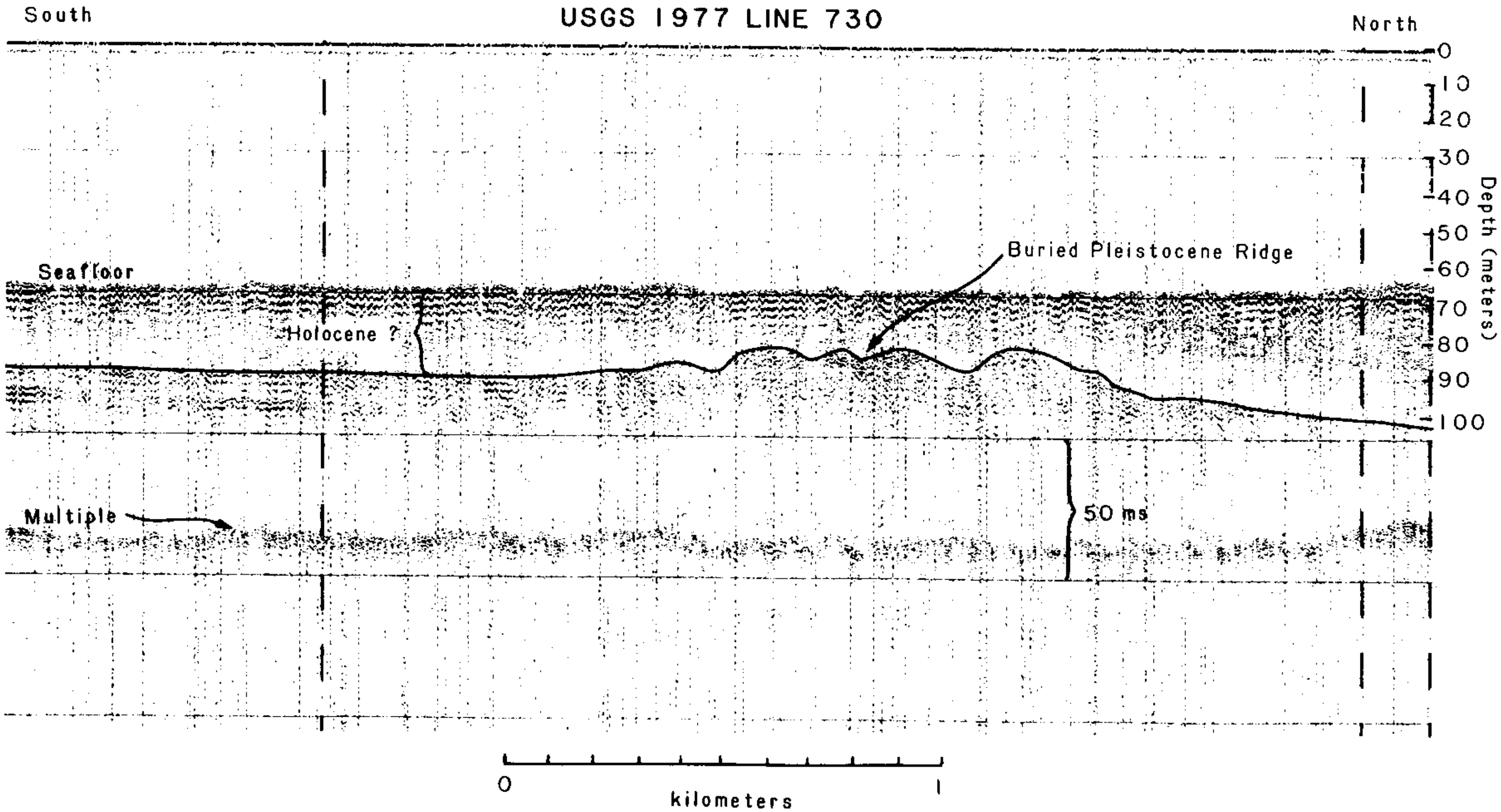


Figure 43.

Uniboom profile showing a Pleistocene subbottom ridge probably formed at the northern edge of the late Wisconsin regression. For the location of this profile, see figure 50.

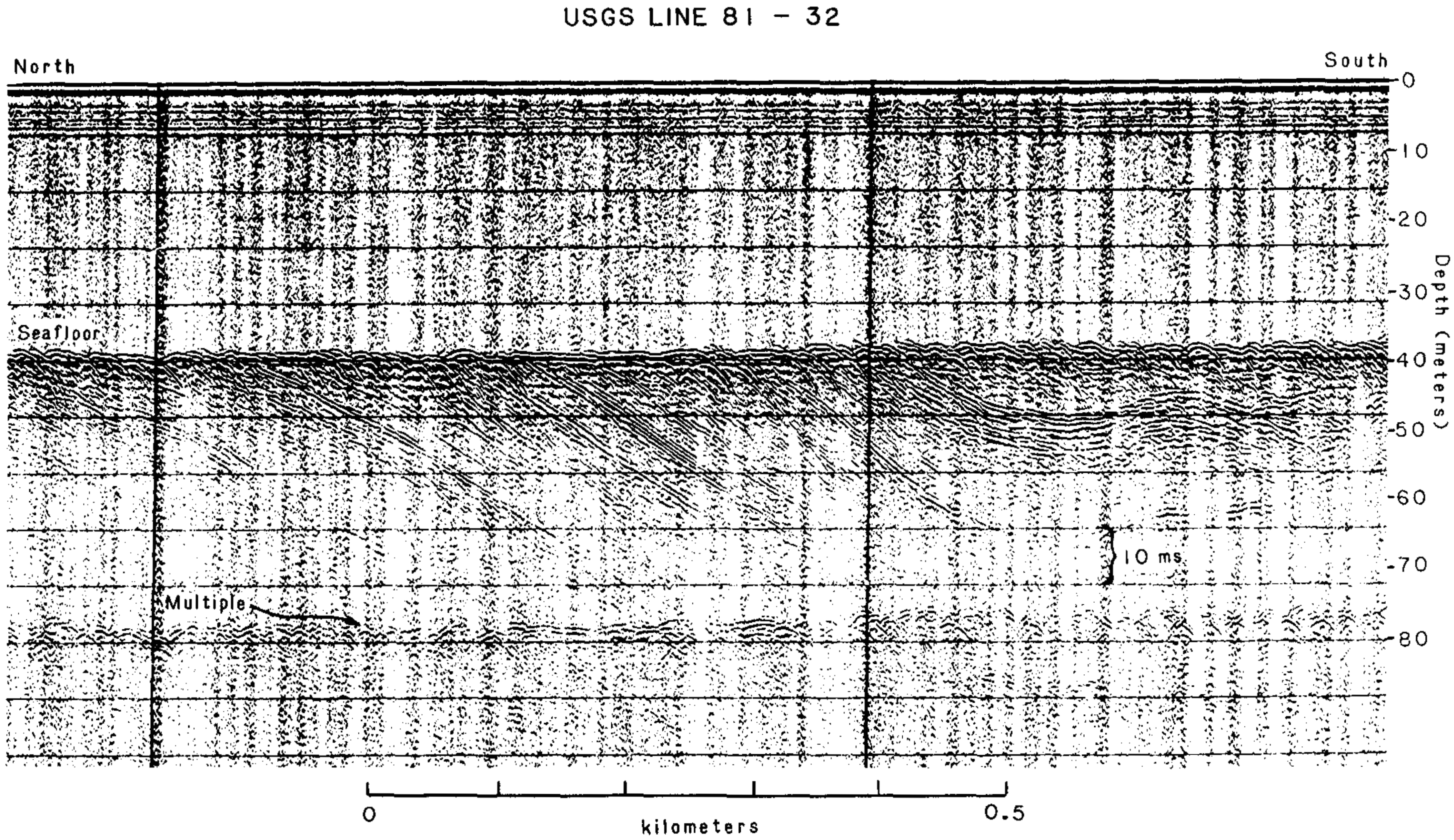


Figure 44.

USGS uniboom line from the Barter Island area (for location, see figure 50) showing shallow dipping bedrock of probable Tertiary age intersecting or nearly intersecting the seafloor. The rough seafloor surface may be caused by ice gouging or differential weathering of the bedrock units.

12

Subsurface Geologic Features

PERMAFROST

The Beaufort shelf was subaerially exposed to the Arctic climate during several Pleistocene lowstands of sea level (Wang and others, 1982). During this time, well-bonded permafrost formed to depths of several hundred meters beneath the exposed shelf (Hunter and Hobson, 1974). During subsequent highstands of sea level, the permafrost has in part melted by saline advection from the seawater into the underlying sediment and by geothermal heating. Numerous refraction, borehole, and conductivity surveys indicate that permafrost is widespread beneath the Beaufort inner shelf (fig. 45). Seismic refraction surveys were performed in Harrison Bay by Rogers and Morack (1981) and Neave and Sellmann (1983), in Simpson Lagoon by Neave and Sellmann (1983), on the barrier islands by Rogers and Morack (1981), and on the Canadian Beaufort shelf by Morack and others (1983). Further data have been obtained from boreholes (Harding-Lawson, 1979) and thermal probes in the BF-79 sale area (Rogers and Morack, 1981; Hopkins and Hartz, 1978b) and offshore of Cape Simpson (Harrison and Osterkamp, 1981). On the Canadian Beaufort, permafrost has been cored as far offshore as 32 km north of Cape Bathurst (Hunter and Hobson, 1974). Seismic refraction work by Sellmann and others (1981) indicates that on the Alaskan Beaufort shelf, a high-velocity layer interpreted to represent permafrost is present at least 15 km north of Reindeer Island and at least 25 km offshore of Harrison Bay (fig. 45).

The depth to the surface of subsea permafrost is highly variable (fig. 46), reflecting varying degrees of ice-bonding prior to the Holocene marine transgression as well as the degree of subsequent thawing due to the advection of saline groundwater. In Stefansson Sound, USGS boreholes (Harding-Lawson, 1979) commonly encountered ice (presumed to be permafrost) at depths shallower than 15 m. In these holes, the depth to the surface of bonded permafrost varies greatly from less than 9 m to greater than 30 m over a distance of less than 12 km (Harding-Lawson, 1979). Some of the boreholes encountered a transition zone of partially bonded sediments between the unfrozen surface sediments and deeper, well-bonded sediments (Harrison and Osterkamp, 1981). This transition zone makes it difficult to accurately interpret the depth to the permafrost surface from both borehole logs and seismic refraction data. Frozen

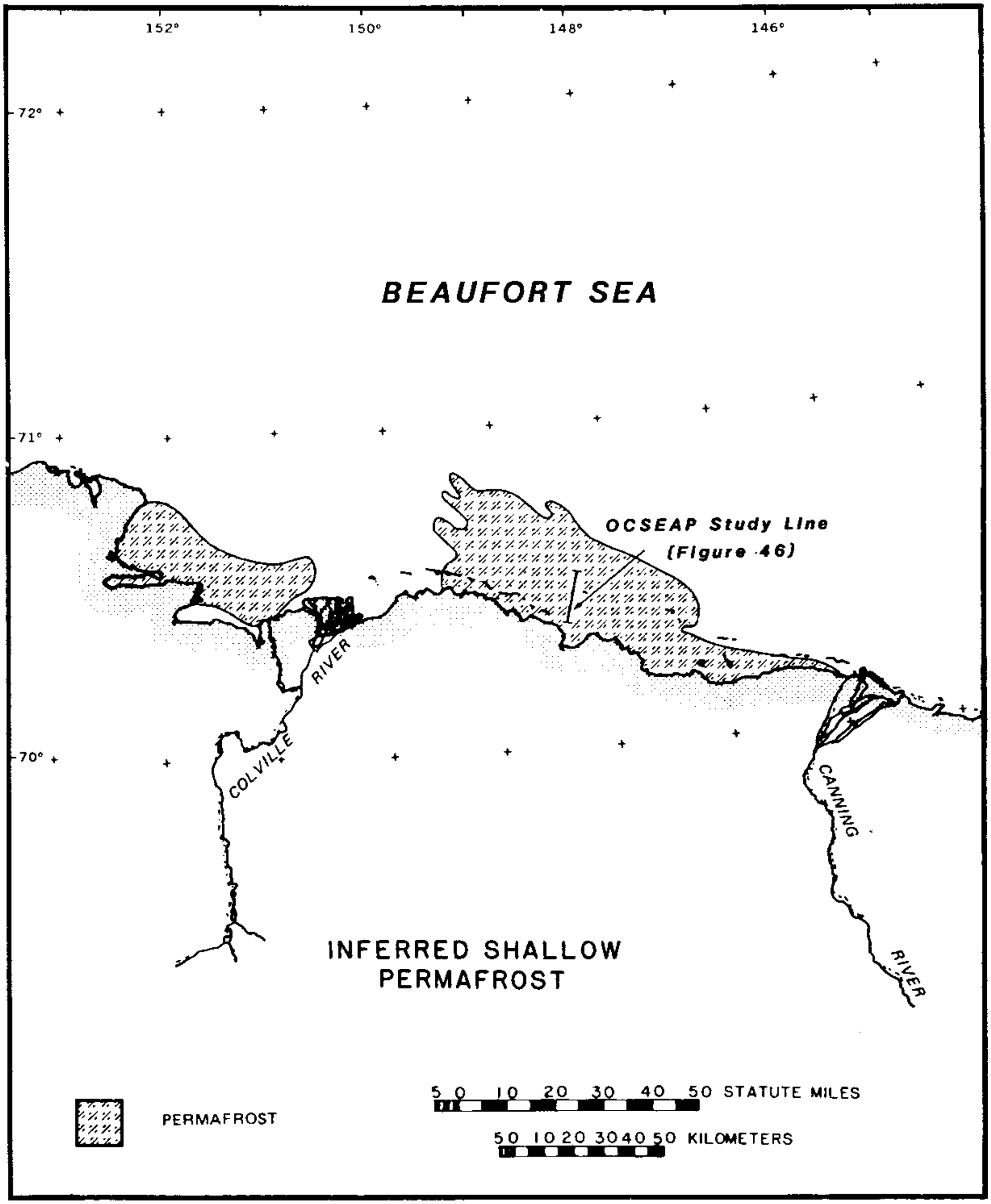


Figure 45.
Known distributions of high-velocity material inferred to be ice-bonded sediments from Harrison Bay to the Canning River. Data east of the Colville River are from Neave and Sellmann (1983). Data west of the Colville River are from Sellmann and others (1981).

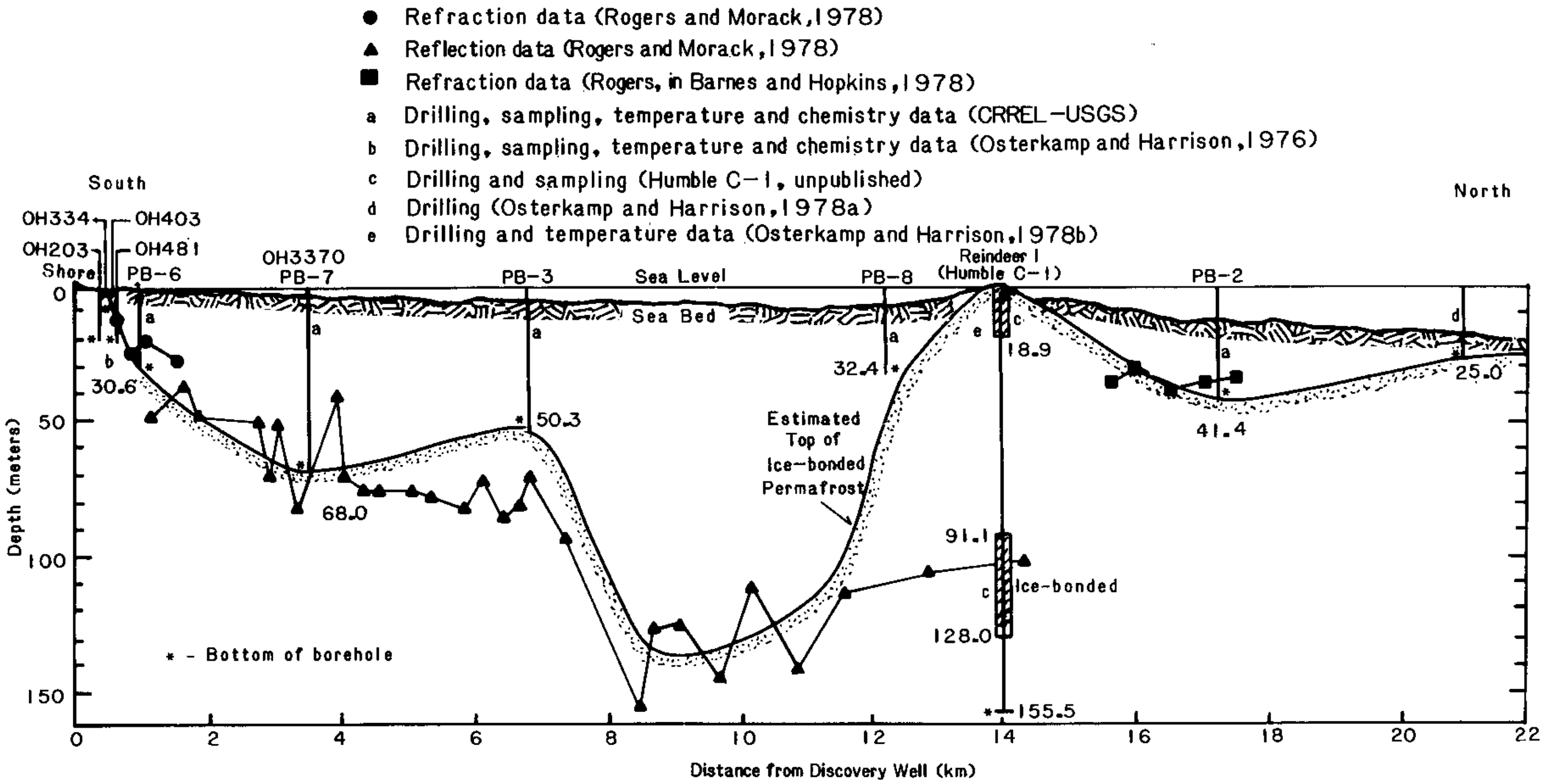


Figure 46.

Summary of the depth to ice-bonded permafrost along an OCSEAP study line near Prudhoe Bay, as reported by Sellmann and Chamberlain (1979). For the location of the study line, see figure 45. The two layers of permafrost detected in the Humble C-1 well may alternatively be interpreted as a deep relict permafrost layer (below 91 m) formed during a Pleistocene lowstand of sea level and a surficial permafrost layer (above 19 m) formed under modern Arctic conditions since Reindeer Island migrated to its present site.

sediment encountered in boreholes and interpreted to be well-bonded permafrost, may in fact be lenses of ice-bonded material in the transition zone. Similarly, high-velocity refractors may represent physical changes in the permafrost layer and may lie below the permafrost surface in the transition zone. As a result, in the BF-79 sale area, there are differing interpretations of the depth to ice-bonded material between the USGS boreholes (Harding-Lawson, 1979) and the seismic refraction data of Rogers and Morack (1981).

Hopkins and Hartz (1978a) estimate that it takes only 40 to 50 years for well-bonded permafrost to form in a subaerial arctic environment. Permafrost is therefore expected to occur in the core of some barrier islands which migrate across the seafloor. On Reindeer Island, the Humble Oil C-1 well encountered two layers of permafrost at depths of 0 to 18.9 m and 91 to 128 m (Sellmann and Chamberlain, 1979) (fig. 46). The deeper layer is probably relict Pleistocene permafrost, while the shallow layer may have formed under modern arctic conditions since the island migrated to its present site.

The thickness of permafrost on the Beaufort shelf cannot be determined from seismic refraction data or shallow boreholes. However, the thickness of the permafrost layer beneath the coastal plain has been measured from numerous onshore wells in Arctic Alaska and Canada. Onshore wells near Harrison Bay indicate that the permafrost layer thins to the west. East of Oliktok Point it is 500 m thick, whereas west of the Colville River it is 300 to 400 m thick (Osterkamp and Payne, 1981). The depth to the surface and overall thickness of permafrost on the eastern Beaufort (off ANWR) and northern Chukchi shelves is not known. It has been suggested that in areas of relatively slow coastal retreat, such as the Chukchi coast, permafrost would be degraded and found deeper than on a rapidly retreating coast such as the Beaufort coast (Grantz and others, 1982a).

NATURAL-GAS HYDRATES

Natural-gas hydrates (solids composed of light gases caged in the interstices of an expanded ice crystal lattice) commonly occur in deepwater areas of continental margins under low-temperature, high-pressure conditions (Macleod, 1982). On Arctic shelf areas, gas hydrates may form at shallow depths associated with permafrost (Kvenvolden and McMenamin, 1980). In the Alaskan Arctic, gas hydrates are known to occur at shallow depths onshore at Prudhoe Bay (Kvenvolden and McMenamin, 1980), and hydrates may occur under similar conditions beneath the Beaufort inner shelf in areas underlain by permafrost (Sellmann and others, 1981). Beneath the Beaufort continental slope, a gas hydrate horizon is identified where water depths exceed 300 m (fig. 47) (Grantz and others, 1982b).

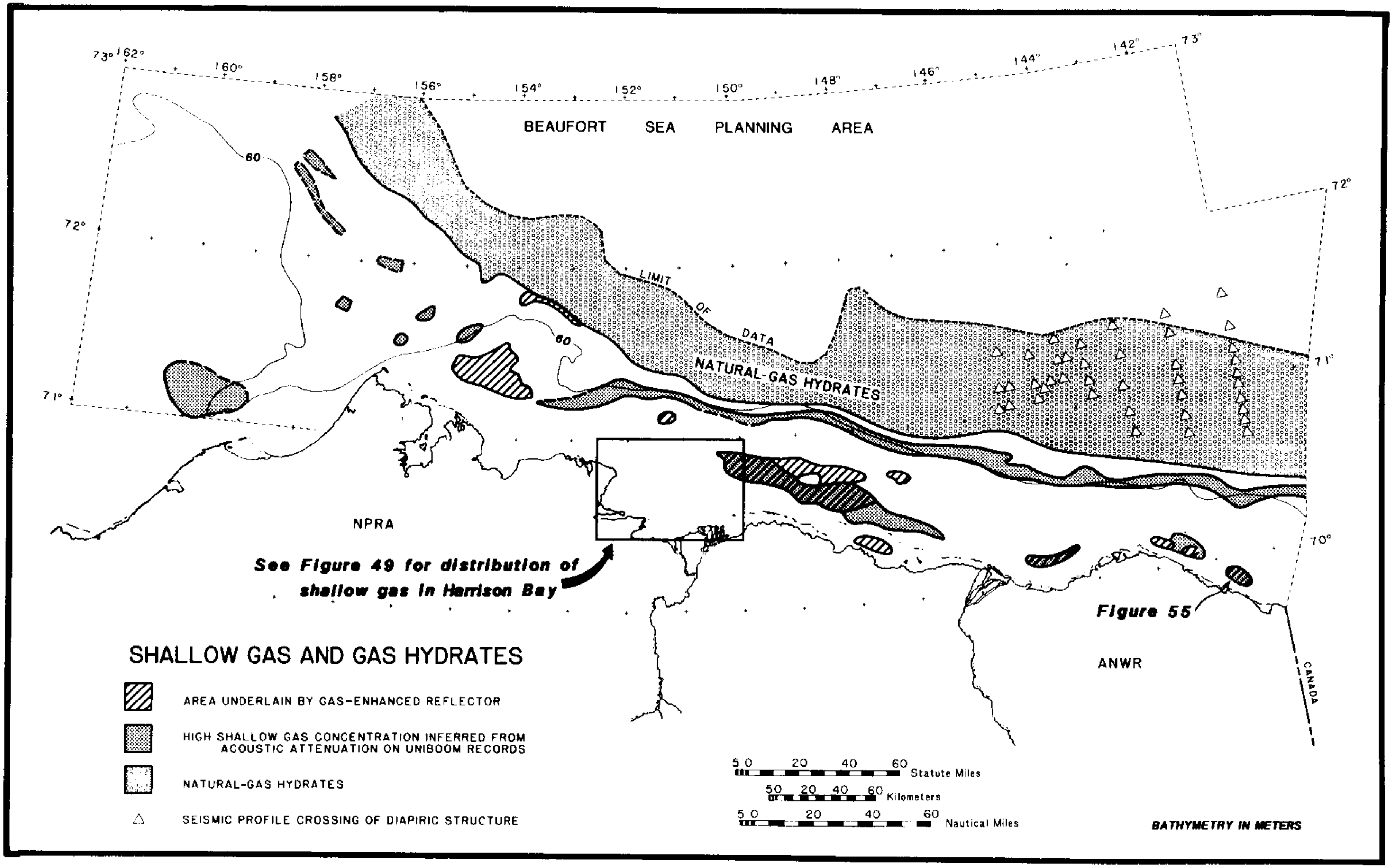


Figure 47.

Map showing the distribution of shallow gas concentrations, the minimum area inferred to be underlain by natural-gas hydrates, and the distribution of diapiric structures in the Beaufort Sea Planning Area (modified from Grantz and others, 1982b).

FAULTING AND SEISMICITY

Several types of shallow faults are identified on the Beaufort shelf: high-angle, basement-involved normal faults (mapped principally along the Barrow Arch in Harrison Bay), listric growth faults (mapped seaward of the Hinge Line), and down-to-the-north gravity faults (mapped along the shelf-slope break) (fig. 48) (Grantz and others, 1982b). Locally two or more types may occur in close proximity.

High-angle faults occur along the Barrow Arch and are genetically related to basement tectonics of the Arctic Platform. In Harrison Bay, they offset Tertiary and older units (fig. 49) (Craig and Thrasher, 1982). There is little evidence of Quaternary movement and no recent seismicity associated with these faults. They may act as conduits for gas migration, however, for "bright spot" anomalies are commonly identified adjacent to the fault traces (Craig and Thrasher, 1982).

The shallow faults seaward of the Hinge Line include upper extensions of detached listric growth faults that sole deep in the Brookian section (plates 4 and 6), some of which may have been reactivated in late Cenozoic time. The distribution of these growth faults is only partially known because of a lack of high-resolution seismic coverage on the outer Beaufort shelf, especially in the west. These faults are mapped in greatest detail in the Camden Bay area where the Hinge Line approaches the Beaufort coast (fig. 50) and where USGS high-resolution seismic coverage is relatively dense. Shallow faults have also been mapped beneath the outer shelf west of Cape Halkett and are reported to show 3 to 10 m of Quaternary offset (fig. 48) (Grantz and others, 1983). No seismicity has been recorded in this area in 10 years of monitoring (fig. 51) (Biswas and Gedney, 1979).

In the Camden Bay area, near-surface faults have several tens of meters of Quaternary offset (fig. 52) (Grantz and others, 1983), and, in contrast to the rest of the Beaufort shelf, Camden Bay is seismically active (fig. 51). This tectonic area is located at the northern end of a north-northeast-trending band of seismicity that extends north from east central Alaska (Biswas and Gedney, 1979). The largest earthquake recorded in northeast Alaska was a magnitude 5.3 quake located 30 km (18 mi) north of Barter Island (Biswas and Gedney, 1979). Since monitoring began in 1978, a large number of earthquakes, ranging in magnitude from 1 to 4, have been recorded in this area. These events cluster along the axis of the Camden anticline (fig. 50). Tertiary and Quaternary units dip away from and are truncated at the top of this fold, indicating that it has been growing in recent geologic time. In contrast to the northeast-southwest trend of the Camden anticline and of the roughly parallel zone of earthquake epicenters, the faults in Camden Bay trend northwest-southeast, parallel to the Hinge Line

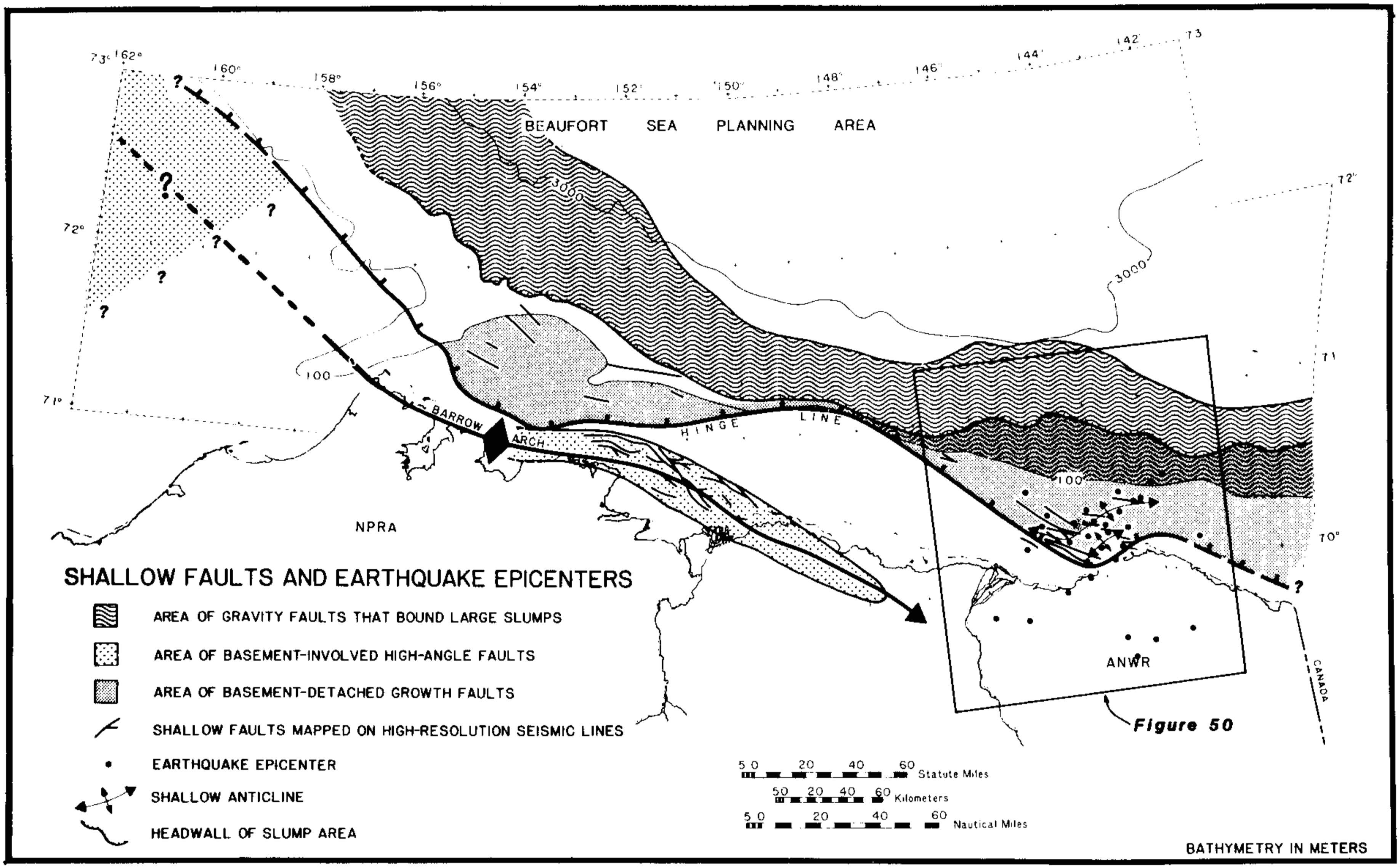


Figure 48.

Map showing areas where shallow faults are mapped or expected in the Beaufort Sea Planning Area, and the distribution of earthquake epicenters. The Hinge Line and Barrow Arch are plotted to show the relationship between shallow faults and major structural trends. Fault data are from Grantz and others (1982b) and Craig and Thrasher (1982).

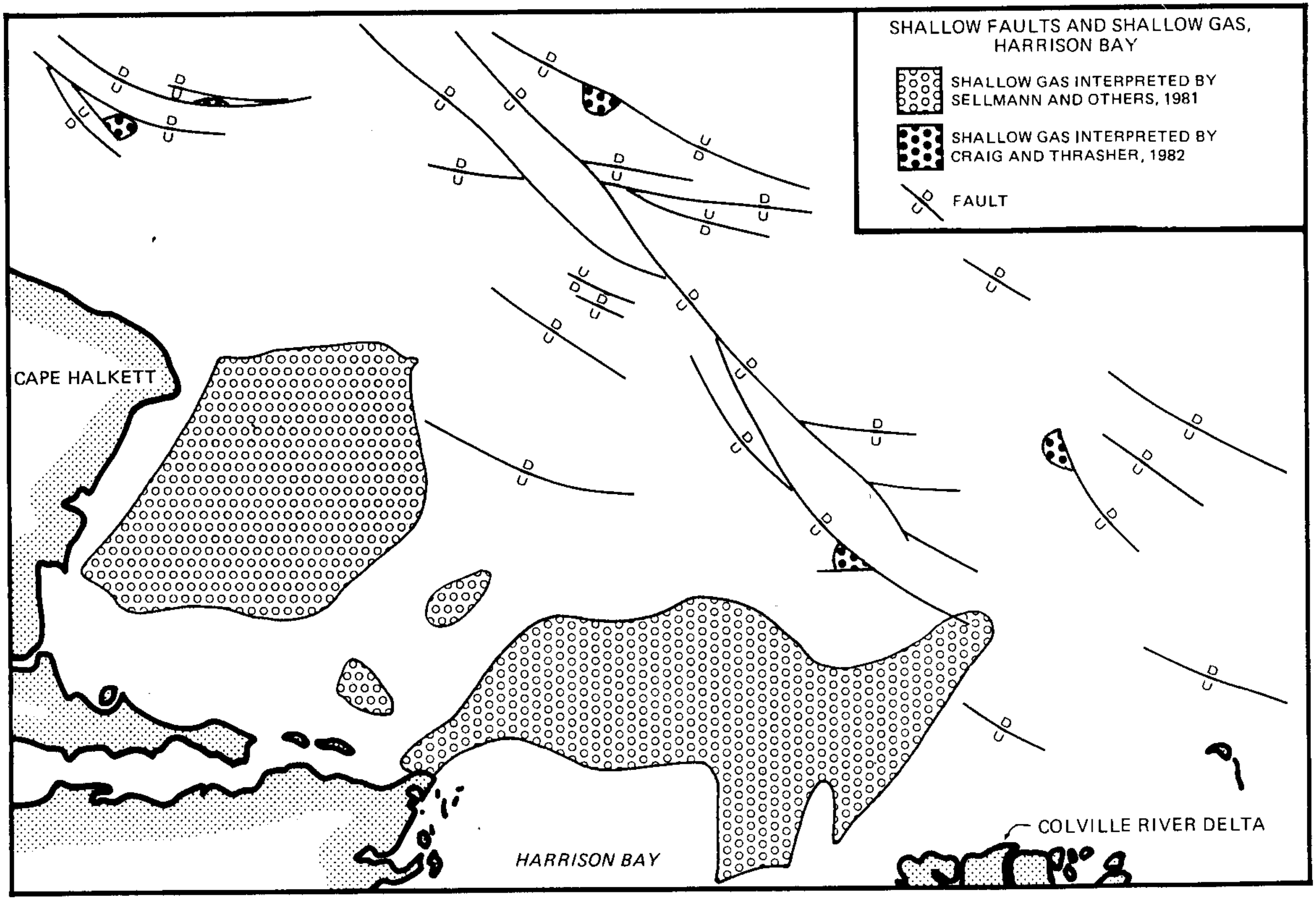


Figure 49.

Distribution of inferred shallow gas and shallow faults in Harrison Bay. Gas associated with faults in central and outer Harrison Bay was mapped by Craig and Thrasher (1982) on the basis of acoustic anomalies with bright spots, reflector pulldown, and high-frequency signal attenuation. Large areas inferred to contain gas in inner Harrison Bay were mapped by Sellmann and others (1981) on the basis of high-frequency signal attenuation only.

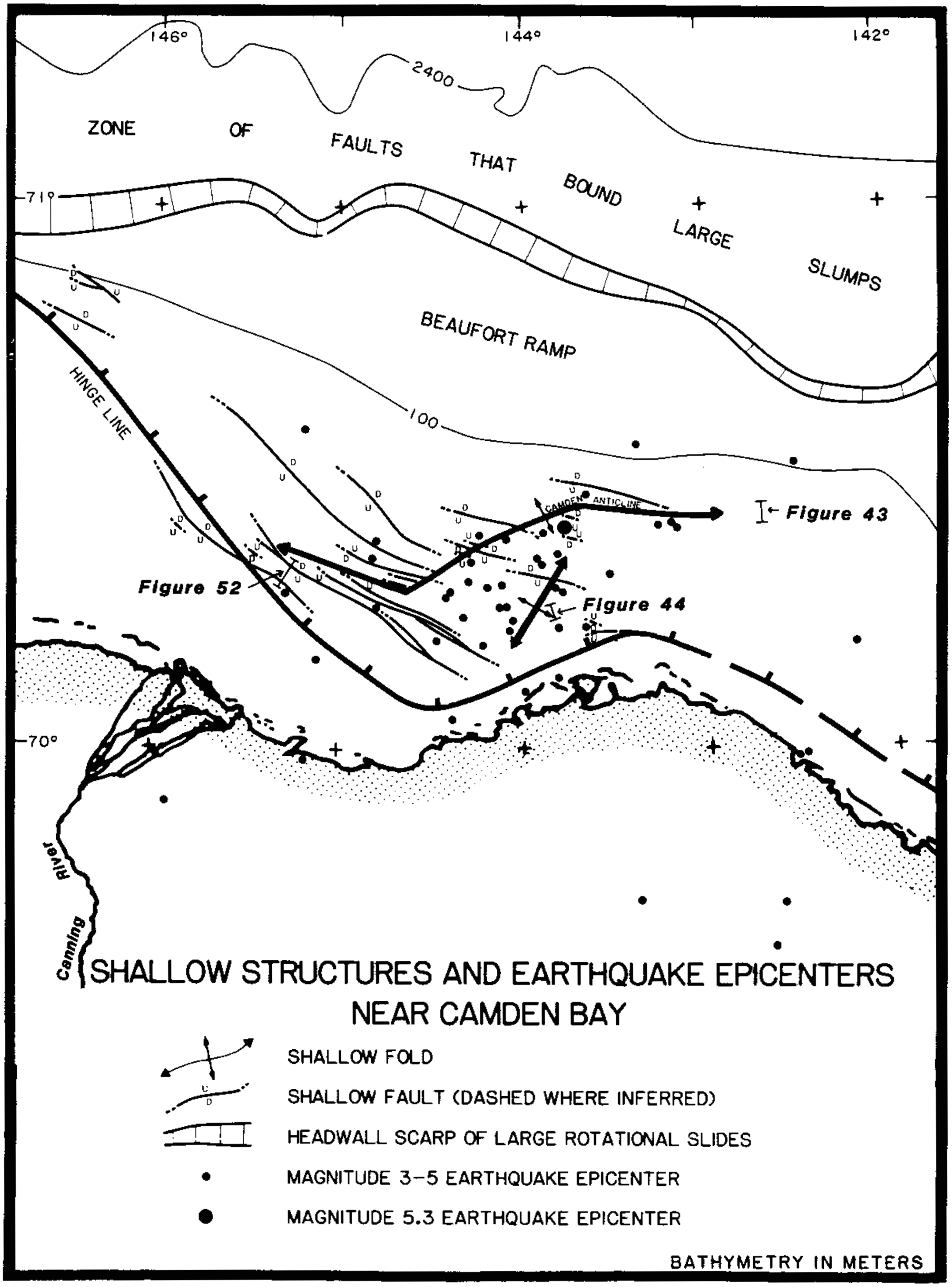


Figure 50.

Distribution of shallow faults, fold axes, and earthquake epicenters in the Camden Bay area. Note the northeast trend of the folds and earthquake epicenters, in contrast to the northwest trend of the faults. For the location of the map, see figure 48.

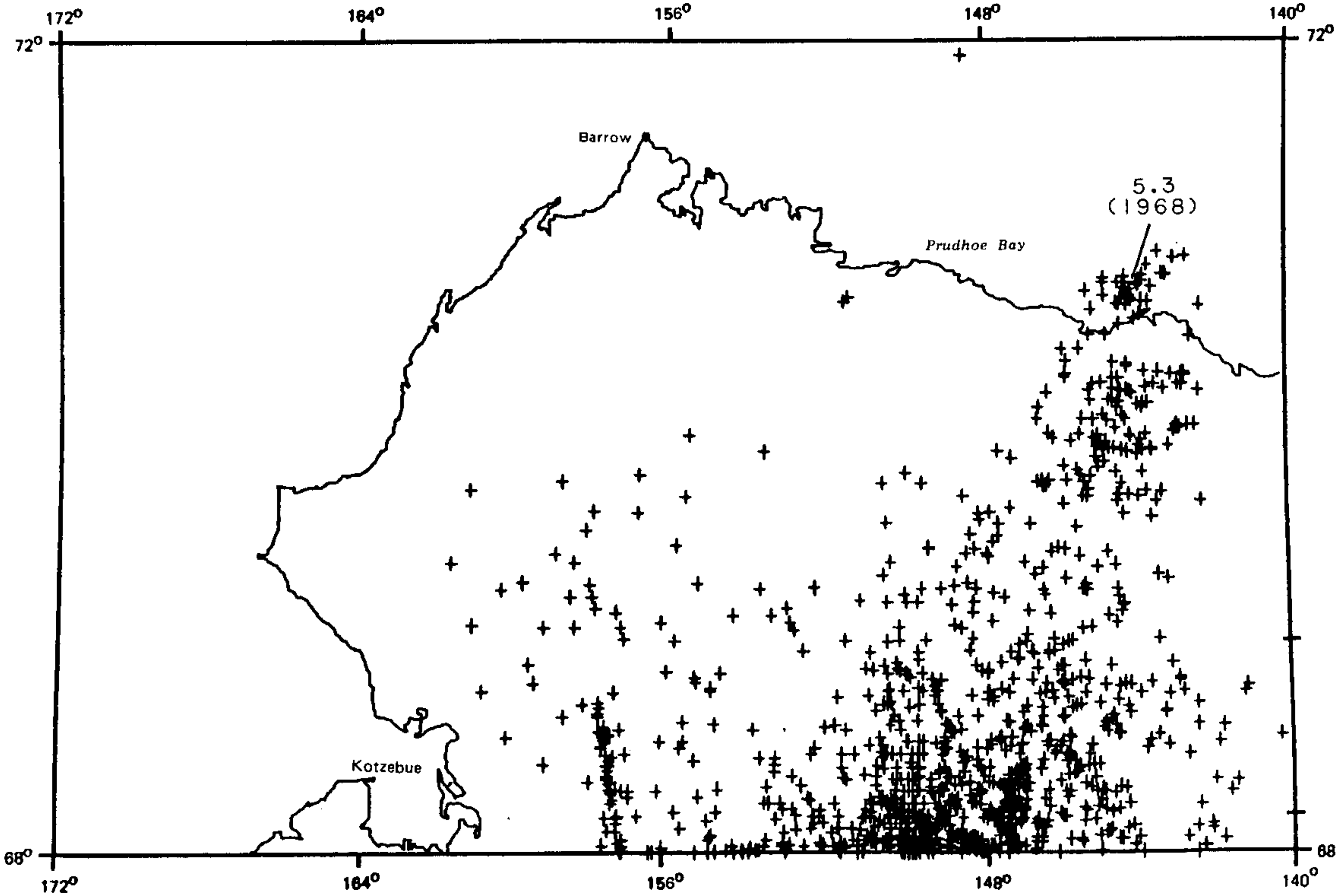


Figure 51.
Earthquake epicenters recorded between 1968 and 1978 in northern Alaska by local seismograph networks (Biswas and Gedney, 1979). The 5.3-magnitude earthquake offshore of Barter Island is the strongest earthquake recorded in northeastern Alaska. Note the absence of seismicity in the western Beaufort Sea and adjacent coastal plain.

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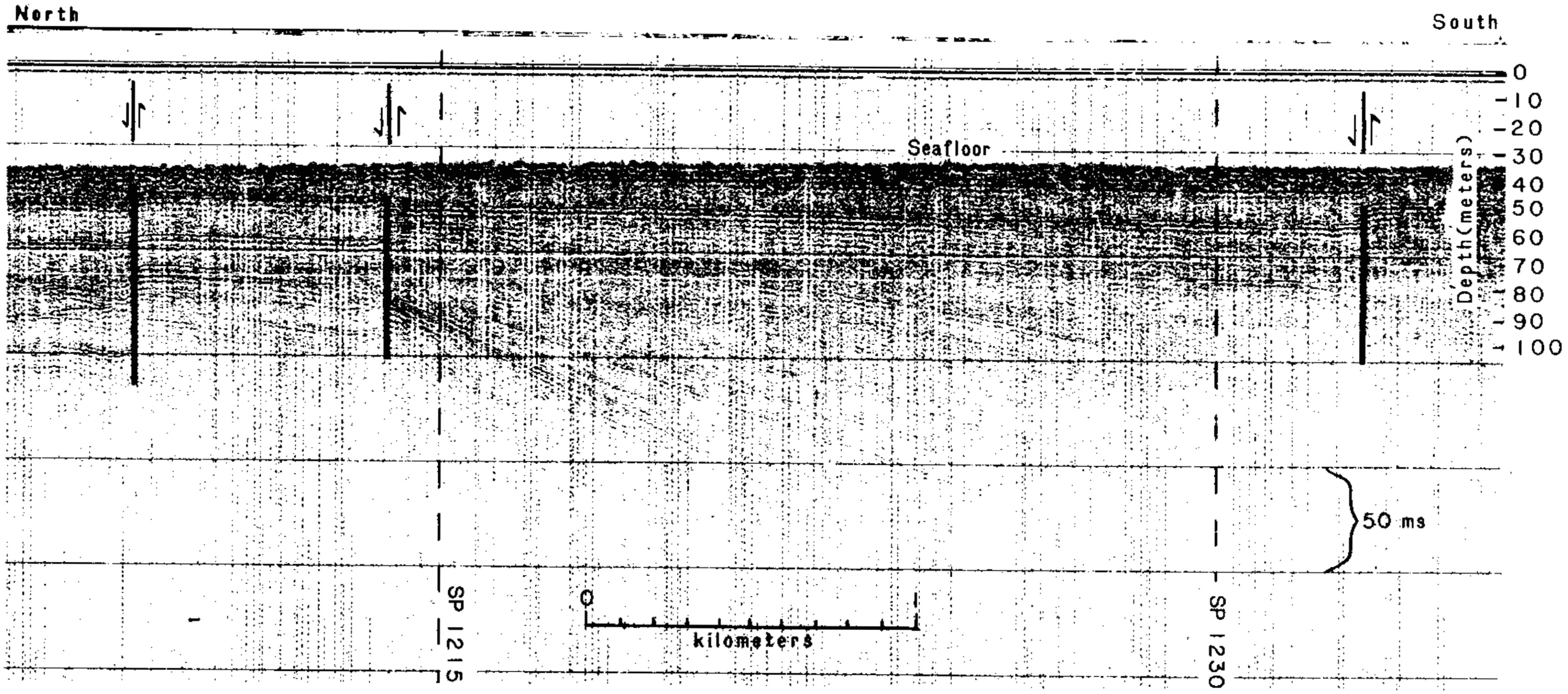

Figure 52.

Uniboom profile from Camden Bay (for location, see figure 50) showing shallow faults offsetting Quaternary and older sediments. A subtle seafloor sag (down to the north) just north of shot point 1215 indicates that these faults are presently active.

(fig. 50). As they approach and intersect the axis of the fold, they offset progressively younger units. This relationship suggests that these faults are older Hinge Line-related structures that were reactivated in late Tertiary and Quaternary time by the uplift of the Camden anticline. Grantz and Dinter (1980) mapped fault scarps along two fault segments in Camden Bay, where they observed 6 m of seafloor displacement. The evidence of seafloor scarps in this area is equivocal, however, because scarp heights are of the same magnitude as ice gouge relief. In addition, the ice-gouging process should quickly smooth scarps formed on the seafloor. Therefore, active near-surface faults may be much more numerous in Camden Bay than indicated by the number of seafloor scarps previously reported.

Faults on the outer Beaufort shelf and upper slope are gravity faults related to large rotational slump blocks (Grantz and Dinter, 1980). On the eastern Alaskan Beaufort shelf, these slumps bound the seaward edge of the Beaufort Ramp (figs. 53B, 54B). Shoreward of the Ramp, faults have surface offsets that usually range from 15 to 20 m and, at one site, possibly as high as 70 m (Grantz and others, 1982b). The Beaufort Ramp itself may be a gigantic slump block which is bounded by these gravity faults. The age of the shelf edge faults is uncertain. If Grantz and others (1982b) are correct in assuming that sediments on the outer shelf are Holocene in age, then these faults have been active in Recent geologic time. If the surface sediments on the outer shelf are relict Pleistocene deposits, as suggested by Reimnitz and others (1982), then these large gravity faults may have been quiescent throughout Holocene time (12,000 years B.P. to present). These faults pose an extreme hazard to bottom-founded structures on the outer Beaufort shelf and slope because they could result in large downslope displacements. Even though there has been no historic seismicity associated with this type of fault on the Beaufort shelf, they may be moving by slow, aseismic creep. Large-scale gravity slumping of blocks on the outer shelf could be triggered by shallow-focus earthquakes centered in Camden Bay or in the Brooks Range.

SEDIMENT SLIDES

A chaotic sediment slide terrane occurs along the length of the Beaufort outer shelf and upper slope seaward of the 50- to 60-m isobath (figs. 53, 54). Grantz and others (1982b) have mapped several distinct landslide types, including large bedding-plane slides (figs. 53B, 54B) and block glides (figs. 53A, 54A). The bedding-plane slides are most extensive on the Beaufort Ramp between 148° west longitude and the Mackenzie Sea Valley (figs. 53B, 54B) (Grantz and Eittreim, 1979). These slides are 10 to 43 km long and 70 to 230 m thick. Pull-apart grabens and scarps are common on the landward margin of the slide terrane. Horizontal displacements

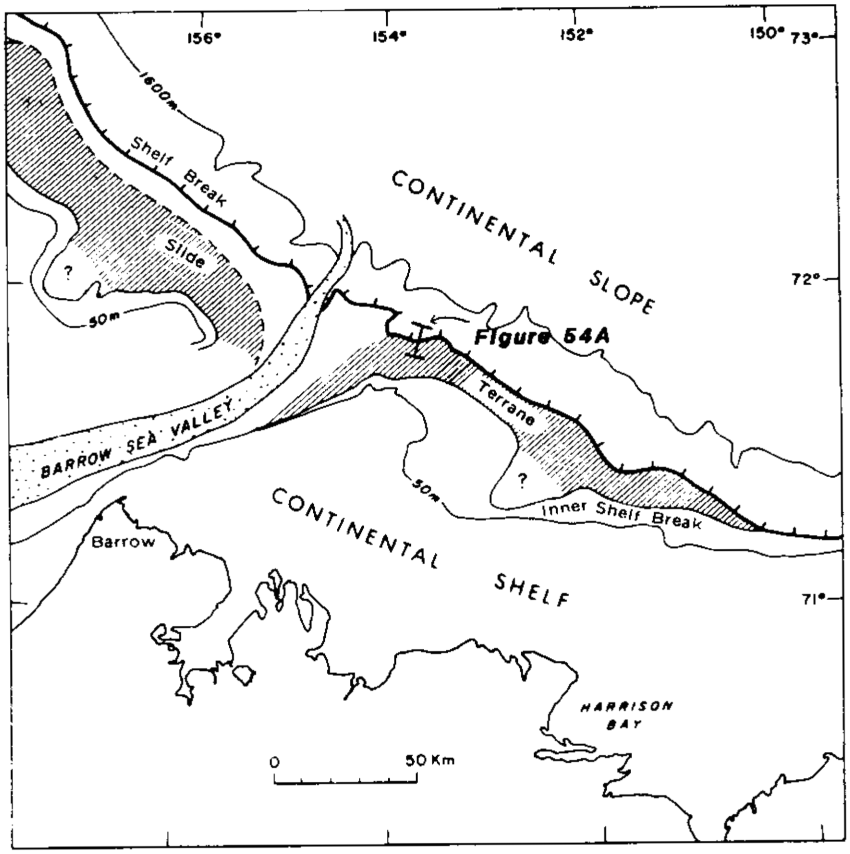

Figure 53A.

Block glide terrane on the outer Beaufort shelf in the western part of the Beaufort Sea Planning Area (Grantz and Eittreim, 1979).

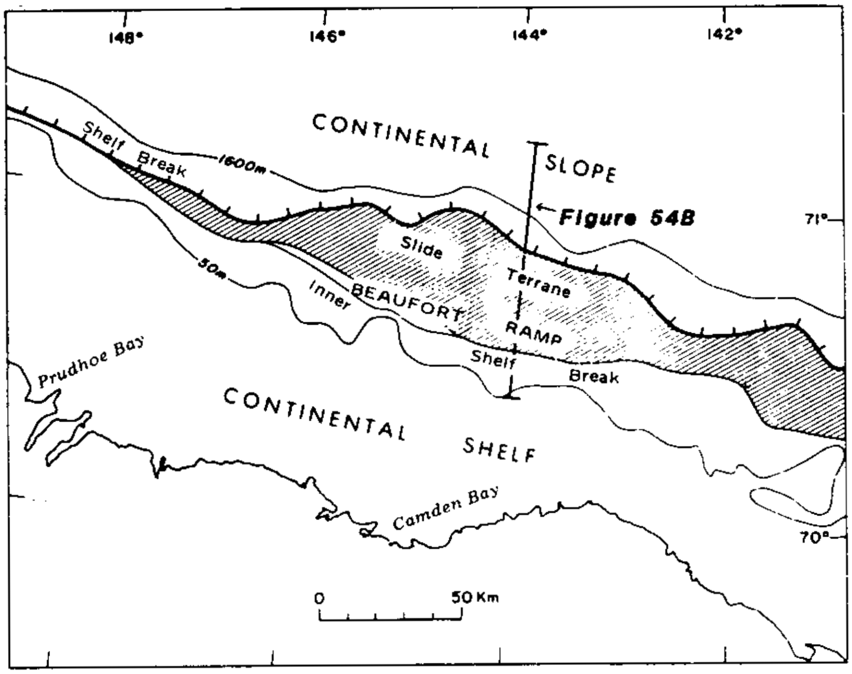

Figure 53B.

Zone of bedding-plane slides on the Beaufort shelf east of 147° west longitude (Grantz and Eittreim, 1979).

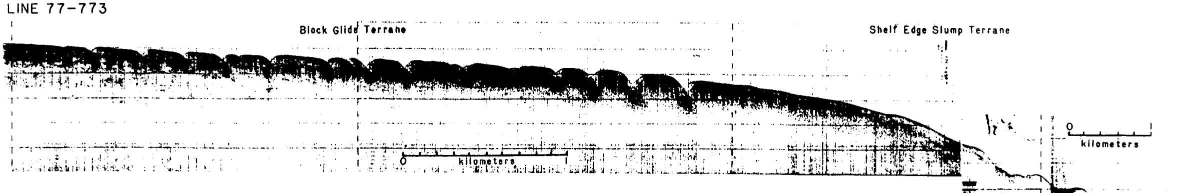

Figure 54A.
Uniboom profile across the western Beaufort block glide terrane. For location of the profile, see figure 53A.

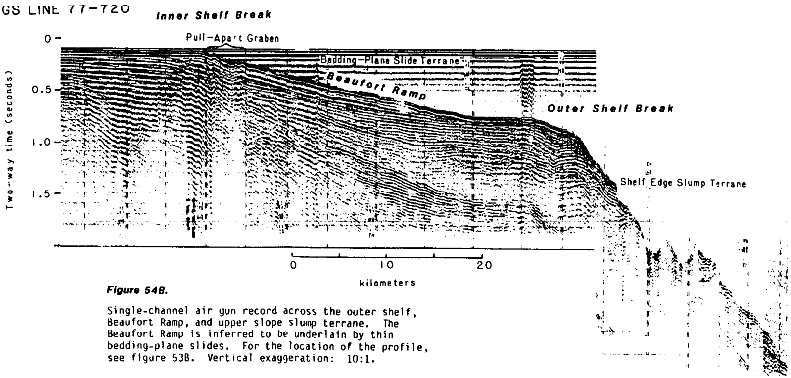

Figure 54B.

Single-channel air gun record across the outer shelf, Beaufort Ramp, and upper slope slump terrane. The Beaufort Ramp is inferred to be underlain by thin bedding-plane slides. For the location of the profile, see figure 53B. Vertical exaggeration: 10:1.

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of 200 to 2,300 m are estimated to have occurred along slip planes which dip only 0.5° to 1.5° (Grantz and Eittreim, 1979). The thinner slides are probably Holocene in age, although the sediments involved in sliding have not been directly dated.

Block glides are prominent between 155° and 158° west longitude along the outermost shelf in water depths greater than 70 m (figs. 53A, 54A) (Grantz and Eittreim, 1979). Multiple open cracks 8 to 17 m deep, spaced 100 to 500 m apart, occur throughout this slump terrane. Seismic reflection data indicate that these blocks slide along failure surfaces which are subparallel to the underlying bedding. The geomorphic character of the blocks indicates they may be presently active.

Massive slumps occur on the Beaufort continental slope (fig. 54). As discussed previously, these features are bounded by gravity faults with total displacements estimated to be as great as 1,000 m (Grantz and others, 1982b).

OVERPRESSURED SEDIMENTS

In the planning area, abnormally high pore pressures probably will be found in areas where Cenozoic strata are uncommonly thick, such as in the Kaktovik, Camden, and Nuwuk Basins. Onshore in the Camden Basin, abnormal pressures are observed in both Tertiary and Cretaceous formations where burial depths of Tertiary strata exceed 3,000 m. Abnormal pore pressures have not been encountered in onshore wells elsewhere on the Arctic Platform. In the Point Thomson area, pore pressure gradients as high as 0.8 pounds per square inch per foot (psi/ft) have been measured in sediments at burial depths of 4,000 m (a pore pressure gradient of 0.433 psi/ft is considered normal). Excess pore pressures are also widespread in Cenozoic strata of the Mackenzie Delta area in the Canadian Beaufort. Here, pore-pressure gradients as high as 0.76 psi/ft have been observed at depths as shallow as 1,900 m (Hawkings and others, 1976).

In the Kaktovik Basin, the recently exhumed sedimentary rocks which now lie near the axis of the Camden anticline, may preserve high pore pressures developed during a prior period of deep burial. The degree to which these sediments are overpressured would depend upon the amount these sediments have been uplifted since folding began. Along the continental slope east of 146° west longitude, a series of shale diapirs disrupt Tertiary sediments (fig. 47). These features have been attributed to liquefaction of the shale in response to an overpressured condition resulting from incomplete dewatering.

SHALLOW GAS

Shallow gas is likely to be found on the Beaufort shelf as isolated pockets beneath permafrost, in association with faults that cut Brookian strata, and as isolated concentrations in

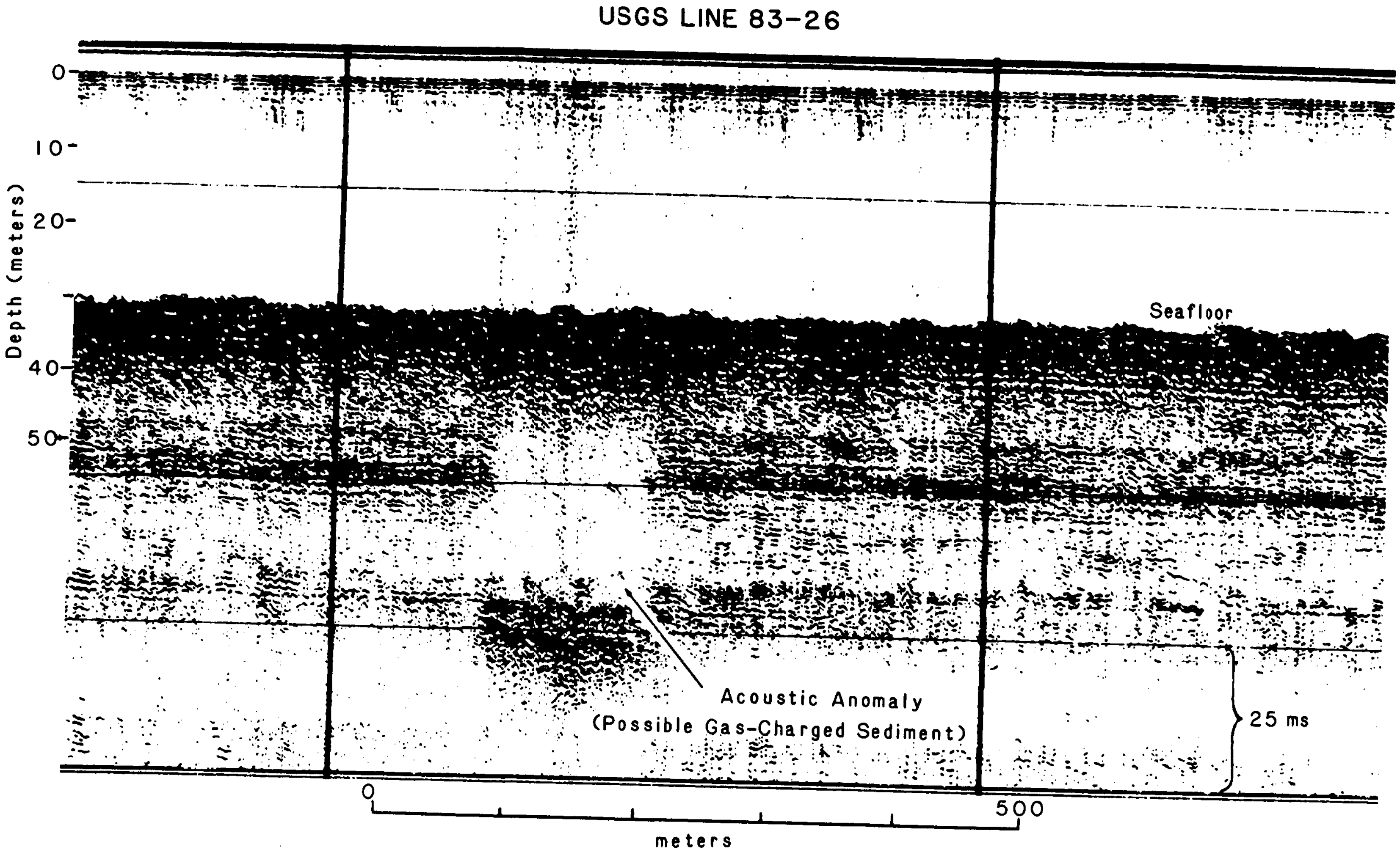

Figure 55.

USGS uniboom profile from northwest of Demarcation Bay showing a wipe-out zone inferred to be caused by gas-charged sediments. The location of the profile is shown in figure 47.

Pleistocene coastal plain sediments (Grantz and others, 1982b). The presence of shallow gas beneath the shelf has been inferred from seismic data collected in Stefansson Sound (Boucher and others, 1980), in Harrison Bay (Craig and Thrasher, 1982; Sellmann and others, 1981), and on extensive areas of the outer shelf and upper slope (Grantz and others, 1982b) (fig. 47). Free-flowing gas was encountered directly in one USGS borehole in Stefansson Sound (Harding-Lawson, 1979). High-resolution seismic reflection surveys over the drill site show a strong reflector at depths of 19 to 35 m below mudline which Boucher and others (1980) have related to the trapped gas zone.

Elsewhere beneath the inner shelf, the presence of gas is indicated by "acoustically turbid" zones (figs. 47, 55) and high-frequency signal attenuation on high-resolution seismic records. Figure 49 is a map of Harrison Bay showing the area where high-frequency signal attenuation occurs (Sellmann and others, 1981). Craig and Thrasher (1982) suggest that some of this signal disruption may be caused by shallow permafrost or difficult recording conditions in hard-bottom, shallow-water areas. Elsewhere in Harrison Bay, Craig and Thrasher (1982) mapped shallow gas adjacent to near-surface faults on the basis of acoustic anomalies with bright spots (amplitude increase), reflector pulldown, and high-frequency signal attenuation (fig. 49).

On the outer shelf, a continuous band of "acoustically turbid" sediment, which Grantz and others (1982b) interpret to be shallow gas, extends from the Canadian border west to at least 158° west longitude (fig. 47). There is also a large area inferred to have a high concentration of shallow gas in the southwestern corner of the planning area north of Wainwright (Grantz and others, 1982a).

13

Summary of the Effects of Environmental Factors on Offshore Petroleum Activities

The Arctic physical environment, surficial and deep geologic processes, and Quaternary stratigraphy are all important factors which affect the economics and viability of offshore petroleum exploration and development in the Beaufort Sea Planning Area. The Arctic continental shelf is unique in both the number and severity of geologic and environmental factors which affect petroleum development. In addition to the hazards and constraints typically encountered in temperate marine environments, petroleum development on the Arctic shelf must contend with cold-temperature-related factors such as ice-pack movement, permafrost, ice gouging, equipment icing, and the generally hostile climate.

The short summer open-water season is the period of greatest industry activity on the Beaufort shelf. During this time, exploratory wells are drilled from floating drilling platforms; geophysical data are collected from seismic vessels; winter season drilling structures are moved to new exploration sites; and the annual sealift, transporting supplies to the Prudhoe Bay area production facilities, arrives. This is also the period when storms are prevalent, sea ice is highly mobile, and visibility is often limited by fog. Unexpected wind shifts can result in the rapid advance of the sea ice, trapping and possibly damaging vessels working offshore. Most of the coastal erosion and barrier island migration occurs during this time. In some years, ice conditions are such that little or no offshore work can be done seaward of the barrier islands.

After freezeup, and throughout the long Arctic winter, exploratory drilling can take place only from bottom-founded drilling platforms, such as gravel or ice islands and caisson-type structures. In the fast-ice zone, ice roads are usually constructed to artificial islands. Small ice movements can result in dangerous open leads and ice pileup conditions. Seaward of the fast-ice zone, the pack ice is constantly in motion, frequently moving tens of kilometers per day. Ice ridges tens of meters high form, and open-water leads in the ice occur throughout the winter months. These large ice movements result in ice gouging, ice pileup, and ice override events which can damage offshore or island-based facilities. In addition, the extreme cold and months of total darkness increase the logistical difficulties and therefore the cost of drilling during this period.

Coastal facilities such as ports, pipeline facilities, and work camps developed in support of OCS activities will have to be sited and designed to withstand active coastal processes such as strudel scour, bluff erosion, ice push, and island migration. Port facilities and pipelines which cross the coastal zone must be sited in areas where these coastal processes are at a minimum or can be controlled. Strudel scouring off the mouths of Arctic rivers can severely damage pipelines and other seafloor installations. Facilities built on barrier islands must be designed and sited to withstand occasional ice-override and storm-surge events as well as the long-term island migration process. Ice and wave forces which act on the barrier islands will also act on artificial islands and other structures installed on the Beaufort shelf. These structures must be built to withstand such forces. This is particularly important for production facilities which will remain on a site for several decades.

The distribution and depth of ice gouges will be important considerations in the siting and design of subsea pipelines. Pipelines must be buried below the depth of the maximum expected ice gouge in an area or must be reinforced to withstand or deflect ice forces. Burying a pipeline may be difficult or prohibitively expensive in areas underlain by shallow permafrost, highly overconsolidated sediment, or shallow bedrock. The density and incision depth of ice gouges suggest the intensity of ice ridging at a given site. Therefore, detailed ice gouge surveys are also important for the planning and safe design of offshore development facilities.

Surficial sediment type and Quaternary geologic features have an important effect on the design and cost of offshore facilities. A cheap and easily accessible source of gravel is critical for the construction of gravel islands, causeways, or pads for caisson and other types of drilling platforms. In nearshore areas, gravel has been trucked over the fast ice from onshore sources. However, as development proceeds toward deeper water and more remote locations, alternative offshore sources of gravel will have to be utilized for economic reasons. These sources may include marine shoals, coarse deposits on barrier islands, buried Pleistocene channels, and seabed areas covered by coarse lag gravels. The viability of offshore gravel mining depends upon potential environmental impacts on marine biologic habitats, the distribution of subsea permafrost, and the physical properties of sediment overlying the gravel deposits. Gravel extraction would be inhibited if the gravel is overlain by a significant thickness of overconsolidated, fine-grained sediments. New designs for drilling platforms and methods for foundation fortification will probably be developed as a more cost-effective alternative to gravel islands, particularly in water depths greater than 15 m. This may significantly decrease the total amount of gravel needed for petroleum activities in the planning area. Recently developed mobile gravity platforms, such as Global Marine's CIDS (Concrete Island Drilling System) employed by Exxon to drill the Antares and other prospects, require little foundation preparation or gravel at some drilling locations.

The distribution of permafrost on the Beaufort and Chukchi shelves must be considered in the design of offshore structures and pipeline corridors. During the drilling of wells or during subsequent petroleum production, there is the potential for melting the permafrost surrounding the borehole. This could cause subsidence and rupture of well casings and consequent loss of well control. This hazard can be minimized by proper insulation of the casing through which the warm petroleum or drilling fluids are pumped. Likewise, pipelines transporting warm petroleum from production platforms to onshore processing facilities must be insulated or otherwise designed to prevent melting of the surrounding permafrost (Walker and others, 1983). Proper insulation of the well casing and other techniques, such as the use of cold drilling mud, which minimize the thermal degradation of permafrost, have been previously used with complete success in onshore drilling activities in Arctic Canada and Alaska. Because permafrost can act as a seal for gas accumulations at shallow subsurface depths, proper well-control techniques must be used when drilling through the permafrost zone. As discussed above, shallow permafrost could inhibit the mining of gravel needed for offshore islands or for foundations of caisson-type drilling platforms. On the other hand, its presence might enhance the strength of soft surficial sediments, thereby providing a strong footing for large structures in offshore areas that would otherwise have unsuitable foundation conditions.

Subsurface features such as shallow gas, gas hydrates, faults, areas of slump blocks, and overpressured sediments must be delineated on a site-specific basis before offshore petroleum structures are emplaced. Shallow gas is potentially both a drilling hazard and a foundation hazard in many parts of the planning area. In addition to generating the danger of blowouts during drilling, it can inhibit normal consolidation of sediments, leading to low shear strengths and poor foundation conditions. In nearshore areas where subsea permafrost is expected, shallow gas may be trapped within and beneath the permafrost zone. It also may be trapped along shallow faults. The occurrence of shallow gas may be indicated by high-resolution seismic data, and, where present, shallow gas can be controlled by careful drilling operations. In Harrison Bay, in Camden Bay, and along the shelf edge, acoustic anomalies, which may indicate gas-saturated sediments, are particularly apparent. Gas hydrates beneath the Beaufort continental slope are not likely to be a significant problem in the foreseeable future since they occur at water depths in excess of 300 m, well beyond the operating limit for petroleum development (now considered to be 60 m) (National Petroleum Council, 1981). Excessively high formation pressures, such as those measured in the Camden Basin area and the Canadian Beaufort, are a potential hazard to drilling operations. High-pressure zones, however, are frequently encountered elsewhere and can be successfully controlled through safe drilling practices.

Seismicity in Camden Bay poses a potential hazard to the foundations of production facilities on the eastern Beaufort shelf.

Because of the lack of a long-term data base, the size of the maximum earthquake to be anticipated in engineering design is uncertain. Modern earthquakes with magnitudes of 5.3 on the Richter scale have been measured in this area (Biswas and Gedney, 1979). Seafloor installations constructed on the eastern Beaufort shelf should be designed to withstand moderate to strong, shallow-focus earthquakes with significant surface offsets along faults. Movement of slump blocks on the outer Beaufort shelf and continental slope could result in major damage to exploration or development structures. The age and activity of the large, easily recognized slump features on the outer shelf is unknown, but should be determined before siting exploration or production platforms in this area.

In 15 years of extensive studies, much has been learned about the physical environment in the Beaufort Sea Planning Area. However, it is still largely a frontier region, and the origin and distribution of many of the physical processes and features that may affect offshore petroleum development are only partially understood. Most of our knowledge is based on data collected on the inner shelf, particularly in Stefansson Sound (BF-79 lease sale area) and Harrison Bay (OCS Lease Sale 71 area). Because of severe ice conditions and the remoteness of the central and outer shelf, very little work has been done in areas included in OCS Sale 87 or proposed for inclusion in OCS Sale 97. From data collected in Stefansson Sound, it is evident that the type and extent of shallow geologic features vary greatly over very short distances. It is, therefore, difficult to predict the occurrence and distribution of features such as shallow gas concentrations, subsea permafrost, surficial sediment type, and near-surface faults on a site-specific basis from regional reconnaissance surveys. Detailed high-resolution seismic surveys and shallow coring are now routinely conducted at proposed drilling locations to fill this site-specific data gap. Integration of these data with regional surveys will expand our data base and greatly improve our understanding of the Arctic offshore environment.

Conclusion

This report summarizes our observations and preliminary conclusions concerning the environmental and petroleum geology of the Beaufort Sea Planning Area. It is the latest in a series of regional reports on the geology of the Alaskan OCS published by the Minerals Management Service. This geologic report was prepared as part of the support documentation related to Federal OCS Lease Sale 97.

Sale 97 will be the second area-wide lease sale in the Beaufort Sea and the fourth Federal OCS sale in this planning area. Because of high industry interest in the previous lease sales, approximately 376 tracts are now under lease. The most prospective tracts are located in relatively shallow water, near onshore well control, and over large structures. Two possible commercial discoveries have been reported in the BF-79 sale area (Endicott Field and Seal Island). Unleased tracts which will be offered in Sale 97 generally lie in deeper and more remote areas of the Beaufort and northeastern Chukchi shelves. These tracts will be more expensive and logistically difficult to explore. At present, well control is absent and seismic data coverage is sparse in these remote areas.

Only tracts on the continental shelf are thought to have any potential for commercial hydrocarbon development in the foreseeable future based on geological and logistical considerations. Of the untested tracts on the continental shelf, structural traps involving Brookian strata in the Kaktovik Basin are the most prospective. On the central Beaufort shelf, structural traps in Brookian strata in the Nuwuk Basin and fault traps in Rift sequence deposits in infrarift grabens form less prospective plays. Structural traps involving lower Ellesmerian rocks form the most conspicuous exploration objective in the Northeast Chukchi Basin. Shallow, areally large stratigraphic traps in the upper Ellesmerian and Rift sequences in the Chukchi sector form less attractive exploration plays. A variety of subtle stratigraphic traps may occur in all of the offshore provinces, but they are difficult to identify in regional seismic data.

The Arctic ice pack remains the most formidable environmental obstacle to petroleum activities in the planning area. At the present time, year-round drilling in the Beaufort Sea is conducted from gravel islands or bottom-founded mobile platforms in relatively shallow water (approximately 50 feet or less). Prospects in deeper areas of the continental shelf may be tested by floating platforms or drillships only during the short open-water season, usually in August and September. Geologic phenomena, some unique to the Arctic, represent engineering constraints which will add to the cost of production facilities near the coastline. These include over-ice flooding and strudel scour off river mouths, subsea permafrost, rapid coastal erosion, ice override events, and ice gouging of the seafloor. Shallow subsurface geologic conditions, including natural gas accumulations, near-surface faults, large-scale gravity slides, and abnormally high formation pressures, may be significant hazards to drilling operations on the continental shelf.

Given the great diversity of hydrocarbon plays both leased and available for future OCS lease sales, it is not unreasonable to expect significant discoveries of oil and gas in this large unexplored region. The greatest challenge will be to delineate fields large enough to warrant their commercial development. Once in place, future infrastructure on the continental shelf may encourage the exploration and development of smaller, but perhaps more numerous, accumulations in the Beaufort Sea Planning Area.

REFERENCES

Aagaard, Knut, 1981, Current measurements in possible dispersal regions of the Beaufort Sea, Final narrative report, in Environmental assessment of the Alaskan continental shelf, final reports of principal investigators, v. 3, Physical science studies: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Research Unit 91, p. 1-74.

AAPG, 1976, Geothermal gradient of north and south central Alaska [Cook Inlet and North Slope], portfolio map area no. 26, Geothermal Survey of North America: Tulsa, Oklahoma, AAPG, 1 map, scale 1:1,000,000.

Alaska Oil and Gas Conservation Commission, 1984, 1984 Statistical report: Anchorage, Alaska Oil and Gas Conservation Commission, 187 p.

Armstrong, A. K., and Bird, K. J., 1976, Facies and environments of deposition of Carboniferous rocks, Arctic Alaska, in Miller, T. P., ed., Recent and ancient sedimentary environments in Alaska: Alaska Geological Society Symposium, Anchorage, Alaska, April 2-4, 1975, Proceedings, p. A1-A16.

Bane, S. C., and Chanpong, R. R., 1980, Geology and development of the Teak oil field, Trinidad, West Indies, in Halbouty, M. T., ed., Giant oil and gas fields of the decade 1968-1978: AAPG Memoir 30, p. 387-398.

Barnes, D. A., 1985, Sag River Formation, Prudhoe Bay, Alaska: Depositional environment and diagenesis [abs.]: AAPG Bulletin, v. 69, no. 4, p. 656.

Barnes, P. W., McDowell, David, and Reimnitz, Erk, 1978, Ice gouging characteristics, their changing patterns from 1975-1977, Beaufort Sea, Alaska: U.S. Geological Survey Open-File Report 78-730, 42 p.

Barnes, P. W., and Reimnitz, Erk, 1974, Sedimentary processes on Arctic shelves off the northern coast of Alaska, in Reed, J. C., and Sater, J. E., eds., The coast and shelf of the Beaufort Sea, proceedings of a symposium on Beaufort Sea coast and shelf research: Arlington, Virginia, Arctic Institute of North America, p. 439-476.

Barnes, P. W., and Reimnitz, Erk, 1979, Ice gouge obliteration and sediment redistribution event, 1977-1978, Beaufort Sea, Alaska: U.S. Geological Survey Open-File Report 79-848, 22 p.

Barnes, P. W., and Reiss, T., 1981, Geological comparison of two arctic shoals, in Environmental assessment of the Alaskan continental shelf, annual reports of principal investigators for the year ending March 1981: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Attachment C, p. C1-C23.

Barnes, P. W., ed., 1981, Physical characteristics of the Sale 71 area, chap. 3 in Norton, D. W., and Sackinger, W. M., eds., Beaufort Sea, Sale 71, synthesis report, proceedings of a synthesis meeting, Chena Hot Springs, Alaska, April 21-23, 1981: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, p. 79-113.

Barnes, P. W., and Hopkins, D. M., eds., 1978, Geological sciences, chap. 3 in Environmental assessment of the Alaskan continental shelf, interim synthesis report, Beaufort/Chukchi: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, p. 101-133.

Barnes, P. W., Schell, D. M., and Reimnitz, Erk, eds., 1984, The Alaskan Beaufort Sea, ecosystems and environments: Orlando, Florida, Academic Press, 466 p.

Barry, R. G., 1979, Study of climatic effects on fast ice extent and its seasonal decay along the Beaufort-Chukchi coasts, in Environmental assessment of the Alaskan continental shelf, final reports of principal investigators, v. 2, Physical science studies: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Research Unit 244, p. 273-375.

Barss, D. L., Copland, A. B., and Ritchie, W. D., 1970, Geology of Middle Devonian reefs, Rainbow area, Alberta, Canada, in Halbouty, M. T., ed., Geology of giant petroleum fields, a symposium of papers...including those presented at the 53rd annual meeting of the Association, Oklahoma City, Oklahoma, April 23-25, 1968: AAPG Memoir 14, p. 19-49.

Bartsch-Winkler, Susan, 1979, Textural and mineralogical study of some surface and subsurface sandstones from the Nanushuk Group, western North Slope, Alaska, in Ahlbrandt, T. S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 61-76.

Behrman, P. G., Woidneck, R. K., Soule, C. H., and Wu, J. L., 1985, Reservoir description of Endicott field, Prudhoe Bay, Alaska [abs.]: AAPG Bulletin, v. 69, no. 4, p. 656.

Bell, J. S., 1973, Late Paleozoic orogeny in the northern Yukon, in Aitken, J. D., and Glass, D. J., eds., Canadian Arctic geology: Symposium on the geology of the Canadian Arctic, Saskatoon, Canada, 1973, Proceedings: Geological Association of Canada and Canadian Society of Petroleum Geologists, p. 23-38.

Bird, K. J., 1981, Petroleum exploration of the North Slope in Alaska, U.S.A.: U.S. Geological Survey Open-File Report 81-227, 43 p.

Bird, K. J., 1982, Rock-unit reports of 228 wells drilled on the North Slope, Alaska: U.S. Geological Survey Open-File Report 82-278, 106 p.

Bird, K. J., and Jordan, C. F., Jr., 1977a, Lisburne Group (Mississippian and Pennsylvanian), potential major hydrocarbon objective of Arctic Slope, Alaska: AAPG Bulletin, v. 61, no. 9, p. 1493-1512.

Bird, K. J., and Jordan, C. F., Jr., 1977b, Petroleum potential of the Lisburne group, eastern Arctic slope, Alaska: Oil and Gas Journal, April 18, 1977, p. 90-94.

Biswas, N. N., and Gedney, L., 1978, Seismotectonic studies of northeast and western Alaska, in Environmental assessment of the Alaskan continental shelf, annual reports of principal investigators for the year ending March 1978, v. 12, Hazards: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Research Unit 483, p. 575-619.

Biswas, N. N., and Gedney, L., 1979, Seismotectonic studies of northern and western Alaska, in Environmental assessment of the Alaskan continental shelf, annual reports of principal investigators for the year ending March 1979, v. 10: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Research Unit 483, p. 155-208.

Black, R. F., 1964, Gubic Formation of Quaternary age in northern Alaska, chap. C in Exploration of Naval Petroleum Reserve No. 4 and adjacent areas, northern Alaska, 1944-53, pt. 2, Regional geology: U.S. Geological Survey Professional Paper 302, p. 59-91.

Blanchard, D. C., and Tailleur, I. L., 1982a, Preliminary geothermal isograd map, NPRA, in Coonrad, W. L., ed., The United States Geological Survey in Alaska, accomplishments during 1980: U.S. Geological Survey Circular 844, p. 46-48.

Blanchard, D. C., and Tailleur, I. L., 1982b, Temperatures and interval geothermal-gradient determinations from wells in National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 82-391, 79 p.

Boucher, Gary, Reimnitz, Erk, and Kempema, Ed, 1980, Seismic evidence for an extensive gas-bearing layer at shallow depth offshore from Prudhoe Bay, Alaska: U.S. Geological Survey Open-File Report 80-809, 19 p.

Briggs, S. R., 1983, Geology report for proposed Beaufort Sea OCS sand and gravel lease sale: U.S. Geological Survey Open-File Report 83-606, 65 p.

Brosgé, W. P., and Dutro, J. T., Jr., 1973, Paleozoic rocks of northern and central Alaska, in Pitcher, M. G., ed., Arctic geology: International Symposium on Arctic Geology, 2nd, San Francisco, California, February 1-4, 1971, Proceedings: AAPG Memoir 19, p. 361-375.

Brosgé, W. P., Dutro, J. T., Jr., and Gutman, S. I., 1983, Paleogeologic map of northern Alaska and northern Yukon at the end of the Devonian time: Unpublished map presented at New developments in the Paleozoic geology of Alaska and the Yukon, Alaska Geological Society Symposium, Anchorage, Alaska, April 22, 1983.

Brosgé, W. P., and Tailleur, I. L., 1971, Northern Alaska petroleum province, in Cram, I. H., ed., Future petroleum provinces of the United States--their geology and potential: AAPG Memoir 15, p. 68-99.

Brower, W. A., Searby, H. W., and Wise, J. L., 1977, Climatic atlas of the Outer Continental Shelf waters and coastal regions of Alaska, v. 3, Beaufort/Chukchi: Boulder, Colorado, U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Research Unit 347, 409 p.

Brown, L. F., Jr., and Fisher, W. L., 1977, Seismic-stratigraphic interpretation of depositional systems--examples from Brazilian rift and pull-apart basins, in Payton, C. E., ed., Seismic stratigraphy--applications to hydrocarbon exploration: AAPG Memoir 26, p. 213-248.

Carman, G. J., and Hardwick, Peter, 1983, Geology and regional setting of Kuparuk oil field, Alaska: AAPG Bulletin, v. 67, no. 6, p. 1014-1031.

Carter, Claire, and Laufeld, Sven, 1975, Ordovician and Silurian fossils in well cores from North Slope of Alaska: AAPG Bulletin, v. 59, no. 3, p. 457-464.

Carter, R. D., Mull, C. G., Bird, K. J., and Powers, R. B., 1977, The petroleum geology and hydrocarbon potential of Naval Petroleum Reserve No. 4, North Slope, Alaska: U.S. Geological Survey Open-File Report 77-475.

Chamberlain, Edwin, 1978, Overconsolidated sediments in the Beaufort Sea: The Northern Engineer, v. 10, no. 3, p. 24-29.

Churkin, Michael, Jr., 1973, Paleozoic and Precambrian rocks of Alaska and their role in its structural evolution: U.S. Geological Survey Professional Paper 740, 64 p.

Collins, F. R., 1961, Core tests and test wells, Barrow area, Alaska, in Exploration of Naval Petroleum Reserve No. 4 and adjacent areas, northern Alaska, 1944-53, pt. 5, Subsurface geology and engineering data: U.S. Geological Survey Professional Paper 305-K, p. 569-644, 5 plates.

Cony, Ann, 1983, Beaufort Sea oil prospect looks like bust: Anchorage, Alaska, Anchorage Daily News, v. XXXVIII, no. 340, December 6, 1983, p. A1, A2.

Cook, D. G., and Aitken, J. D., 1973, Tectonics of northern Franklin Mountains and Colville Hills, District of Mackenzie, Canada, in Pitcher, M. G., ed., Arctic geology: International Symposium on Arctic Geology, 2nd, San Francisco, California, February 1-4, 1971, Proceedings: AAPG Memoir 19, p. 13-22.

Craig, J. D., and Thrasher, G. P., 1982, Environmental geology of Harrison Bay, northern Alaska: U.S. Geological Survey Open-File Report 82-35, 25 p., 6 plates.

Demaison, G. J., and Moore, G. T., 1980, Anoxic environments and oil source bed genesis: AAPG Bulletin, v. 64, no. 8, p. 1179-1209.

Detterman, R. L., 1974, Fence diagram showing lithologic facies of the Sadlerochit Formation (Permian and Lower Triassic), northeastern Alaska: U.S. Geological Survey Miscellaneous Field Studies, Map MF-584.

Detterman, R. L., 1981, The Sadlerochit Group--Paleozoic-Mesozoic boundary in Arctic Alaska [abs.], in International Symposium on Arctic Geology, 3rd, Calgary, Alberta, Canada, 1981 [Program and abstracts]: Canadian Society of Petroleum Geologists, p. 39.

Detterman, R. L., 1984, Measured sections of upper Paleozoic to early Tertiary rocks, Demarcation Point quadrangle, Alaska: U.S. Geological Survey Open-File Report 84-370, 1 sheet.

Detterman, R. L., Reiser, H. N., Brosgé, W. P., and Dutro, J. T., Jr., 1975, Post-Carboniferous stratigraphy, northwestern Alaska: U.S. Geological Survey Professional Paper 886, 46 p.

Dinter, D. A., 1982, Holocene marine sediments on the middle and outer continental shelf of the Beaufort Sea north of Alaska: U.S. Geological Survey Miscellaneous Investigations Series, Map I-1182-B, scale 1:500,000, 2 sheets.

Dinter, D. A., 1985, Quaternary sedimentation of the Alaskan Beaufort shelf--influence of regional tectonics, fluctuating sea levels, and glacial sediment sources: Tectonophysics, v. 114, p. 133-161.

Dome Petroleum, Ltd., 1979, Well history report, Dome Pacific et al. PEX Natsek E-56: Report submitted to Canada, Department of Indian and Northern Affairs, Northern Natural Resources and Environment Branch, 2 v. [available from Riley's Datashare International, Ltd., Calgary, Alberta, Canada].

Dow, W. G., 1977, Petroleum source beds on continental slopes and rises, in Geology of continental margins: AAPG Continuing Education Course, Note Series 5, p. D1-D37.

Dutro, J. T., Jr., 1970, Pre-Carboniferous carbonate rocks, northeastern Alaska, in Adkinson, W. L., and Brosgé, W. P., eds., Proceedings of the geological seminar on the North Slope of Alaska: Los Angeles, Pacific Section, AAPG, p. M1-M8.

Dutro, J. T., Jr., 1981, Geology of Alaska bordering the Arctic Ocean, chap. 2 in Nairn, A. E. M., Churkin, Michael, Jr., and Stehli, F. G., eds., The ocean basins and margins, v. 5, The Arctic Ocean: New York, Plenum Press, p. 21-36.

Dutro, J. T., Jr., Brosgé, W. P., and Reiser, H. N., 1972, Significance of recently discovered Cambrian fossils and reinterpretation of Neruokpuk Formation, northeastern Alaska: AAPG Bulletin, v. 56, no. 4, p. 808-815.

Eckelmann, W. R., Fisher, W. L., and DeWitt, R. J., 1976, Prediction of fluvial-deltaic reservoir geometry, Prudhoe Bay field, Alaska, in Miller, T. P., ed., Recent and ancient sedimentary environments in Alaska: Alaska Geological Society Symposium, Anchorage, Alaska, April 2-4, 1975, Proceedings, p. B1-B8.

Edrich, S. P., 1985, Geological setting of North Slope oil fields, Alaska [abs.]: AAPG Bulletin, v. 69, no. 4, p. 663-664.

Eggert, J. T., 1985, Petrology, diagenesis, and reservoir quality of Lower Cretaceous Kuparuk River Formation Sandstone, Kuparuk River field, North Slope, Alaska [abs.]: AAPG Bulletin, v. 69, no. 4, p. 664.

Ehm, Arlen, 1983, Oil and gas basins map of Alaska: Alaska Department of Natural Resources, Division of Geological and Geophysical Surveys, Special Report 32, scale 1:2,500,000, 1 sheet.

Falvey, D. A., 1974, The development of continental margins in plate tectonic theory: APEA [Australian Petroleum Exploration Association] Journal, v. 14, pt. 1, p. 95-106.

Fox, J. E., 1979, A summary of reservoir characteristics of the Nanushuk Group, Umiat Test Well 11, National Petroleum Reserve in Alaska, in Ahlbrandt, T. S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 42-53.

Grantz, Arthur, Barnes, P. W., Dinter, D. A., Lynch, M. B., Reimnitz, Erk, and Scott, E. W., 1980, Geologic framework, hydrocarbon potential, environmental conditions, and anticipated technology for exploration and development of the Beaufort Shelf north of Alaska: U.S. Geological Survey Open-File Report 80-94, 40 p.

Grantz, A., and Dinter, D. A., 1980, Constraints of geologic processes on Western Beaufort Sea oil developments: Oil and Gas Journal, v. 78, no. 18, p. 304-319.

Grantz, Arthur, Dinter, D. A., and Biswas, N. N., 1983, Map, cross sections, and chart showing late Quaternary faults, folds, and earthquake epicenters on the Alaskan Beaufort shelf: U.S. Geological Survey Miscellaneous Investigations Series, Map I-1182-C.

Grantz, Arthur, Dinter, D. A., Hill, E. R., Hunter, R. E., May, S. D., McMullin, R. H., and Phillips, R. L., 1982a, Geologic framework, hydrocarbon potential, and environmental conditions for exploration and development of proposed oil and gas lease Sale 85 in the central and northern Chukchi Sea, a summary report: U.S. Geological Survey Open-File Report 82-1053, 54 p.

Grantz, Arthur, Dinter, D. A., Hill, E. R., May, S. D., McMullin, R. H., Phillips, R. L., and Reimnitz, Erk, 1982b, Geologic framework, hydrocarbon potential, and environmental conditions for exploration and development of proposed oil and gas lease Sale 87 in the Beaufort and Northeast Chukchi Seas: U.S. Geological Survey Open-File Report 82-482, 71 p.

Grantz, Arthur, and Eittreim, Stephen, 1979, Geology and physiography of the continental margin north of Alaska and implications for the origin of the Canada Basin: U.S. Geological Survey Open-File Report 79-288, 78 p.

Grantz, Arthur, Eittreim, Stephen, and Dinter, D. A., 1979, Geology and tectonic development of the continental margin north of Alaska: Tectonophysics, v. 59, p. 263-291.

Grantz, Arthur, and May, S. D., 1982, Rifting history and structural development of the continental margin north of Alaska, in Watkins, J. S., and Drake, C. L., eds., Studies in continental margin geology: AAPG Memoir 34, p. 77-100.

Grantz, Arthur, and May, S. D., 1984, Summary geologic report for Barrow Arch Outer Continental Shelf (OCS) Planning Area, Chukchi Sea, Alaska: U.S. Geological Survey Open-File Report 84-395, 44 p.

Grantz, Arthur, and Mull, C. G., 1978, Preliminary analysis of the petroleum potential of the Arctic National Wildlife Range, Alaska: U.S. Geological Survey Open-File Report 78-489, 20 p.

Greenberg, Jonathan, Hart, P. E., and Grantz, Arthur, 1981, Bathymetric map of the continental shelf, slope, and rise of the Beaufort Sea north of Alaska: U.S. Geological Survey Miscellaneous Investigations Series, Map I-1182-A, scale 1:500,000.

Gruy, H. J., and Associates, Inc., 1978, Reservoir engineering and geologic study of the East Barrow field, National Petroleum Reserve in Alaska: Report submitted to Husky Oil NPR Operations, Inc., under contract to U.S. Geological Survey, Office of the National Petroleum Reserve in Alaska, 62 p.

Gruy, H. J., and Associates, Inc., 1979, Reservoir engineering and geologic study of the South Barrow gas field, National Petroleum Reserve in Alaska: Report submitted to Husky Oil NPR Operations, Inc., under contract to U.S. Geological Survey, Office of the National Petroleum Reserve in Alaska, Update for 1976 report, 37 p.

Haga, Hideyo, and Mickey, M. B., 1982, South Barrow area Neocomian biostratigraphy, v. 2: San Diego, California, Biostratigraphics Consulting Micropaleontology, USGS Contract No. 14-08-0001-20533, Job No. 05800101, 36 p.

Harding-Lawson, 1979, U.S. Geological Survey geotechnical investigation, Beaufort Sea, 1979: Report to U.S. Geological Survey Conservation Division, Anchorage, Alaska.

Harrison, W. D., and Osterkamp, T. E., 1981, Subsea permafrost--probing, thermal regime, and data analysis, <u>in</u> Environmental assessment of the Alaskan continental shelf, annual reports of principal investigators for the year ending March 1981, v. 7, Hazards: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Research Units 253, 244, and 256, p. 293-349.

Hartz, R. W., and Hopkins, D. M., 1980, Offshore permafrost studies and shoreline history as an aid to predicting offshore permafrost conditions, <u>in</u> Environmental assessment of the Alaskan continental shelf, annual reports of principal investigators for the year ending March 1980, v. 4: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, p. 167-177.

Harwood, R. J., 1983, Exxon Point Thompson No. 3--source rock analysis: Tulsa, Oklahoma, Amoco Production Company, Research Center, 11 p. [available from Alaska Oil and Gas Conservation Commission, Anchorage].

Hawkings, T. J., Hatlelid, W. G., Bowerman, J. N., and Coffman, R. C., 1976, Taglu gas field, Beaufort Basin, Northwest Territories, in Braunstein, Jules, ed., North American oil and gas fields: AAPG Memoir 24, p. 51-71.

Hemphill, C. R., Smith, R. I., and Szabo, F., 1970, Geology of Beaverhill Lake reefs, Swan Hills area, Alberta, in Halbouty, M. T., ed., Geology of giant petroleum fields, a symposium of papers...including those presented at the 53rd annual meeting of the Association, Oklahoma City, Oklahoma, April 23-25, 1968: AAPG Memoir 14, p. 50-90.

Heritier, F. E., Lossel, P., and Wathne, E., 1980, Frigg field--large submarine-fan trap in lower Eocene rocks of the Viking graben, North Sea, in Halbouty, M. T., ed., Giant oil and gas fields of the decade 1968-1978: AAPG Memoir 30, p. 59-79.

Hill, E. R., Grantz, Arthur, May, S. D., and Smith, Marilyn, 1984, Bathymetric map of the Chukchi Sea: U.S. Geological Survey Map I-1182 D.

Hill, P. J., and Wood, G. V., 1980, Geology of the Forties field, U.K. continental shelf, North Sea, in Halbouty, M. T., ed., Giant oil and gas fields of the decade 1968-1978: AAPG Memoir 30, p. 81-93.

Hopkins, D. M., and Hartz, R. W., 1978a, Coastal morphology, coastal erosion, and barrier islands of the Beaufort Sea, Alaska: U.S. Geological Survey Open-File Report 78-1063, 54 p.

Hopkins, D. M., and Hartz, R. W., 1978b, Offshore permafrost studies, Beaufort Sea, in Environmental assessment of the Alaskan continental shelf, annual reports of principal investigators for the year ending March 1978, v. 11, Hazards: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Research Unit 204, p. 75-147.

Hopkins, D. M., ed., 1981, Gravel sources and management options, chap. 7 in Norton, D. W., and Sackinger, W. M., eds., Beaufort Sea, Sale 71, synthesis report, proceedings of a synthesis meeting, Chena Hot Springs, Alaska, April 21-23, 1981: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, p. 169-178.

Hufford, G. L., 1977, Northeast Chukchi Sea coastal currents: Geophysical Research Letters, v. 4, no. 10, p. 457-460.

Hunt, J. M., 1979, Petroleum geochemistry and geology: San Francisco, W. H. Freeman, 617 p.

Hunter, J. A., and Hobson, G. D., 1974, Seismic refraction method of detecting subsea bottom permafrost, in Reed, J. C., and Sater, J. E., eds., The coast and shelf of the Beaufort Sea, proceedings of a symposium on Beaufort Sea coast and shelf research: Arlington, Virginia, Arctic Institute of North America, p. 401-416.

Husky Oil NPR Operations, Inc., 1982, Geological report, Peard test well No. 1, National Petroleum Reserve in Alaska: Anchorage, Alaska, Husky Oil NPR Operations, Inc.; prepared for the U.S. Geological Survey, Office of the National Petroleum Reserve in Alaska.

Husky Oil NPR Operations, Inc., 1983a, Geological report, Walakpa test well No. 1, National Petroleum Reserve in Alaska: Anchorage, Alaska, Husky Oil NPR Operations, Inc; prepared for the U.S. Geological Survey, Office of the National Petroleum Reserve in Alaska.

Husky Oil NPR Operations, Inc., 1983b, History of drilling operations, J. W. Dalton test well No. 1, National Petroleum Reserve in Alaska: Anchorage, Alaska, Husky Oil NPR Operations, Inc.; prepared for the U.S. Geological Survey, Office of the National Petroleum Reserve in Alaska, 83 p.

Husky Oil NPR Operations, Inc., 1983c, History of the second exploration 1975 to 1982: Anchorage, Alaska, Husky Oil NPR Operations, Inc.; prepared for the U.S. Geological Survey, Office of the National Petroleum Reserve in Alaska, 89 p.

Jackson, J. B., Golden, B. F., Stadnychenko, Anne, and Kolasinski, Sharon, 1981, Arctic summary report: U.S. Geological Survey Open-File Report 81-621, Outer Continental Shelf Oil and Gas Information Program, 137 p.

Jackson, J. B., and Kurz, F. N., 1983, Arctic summary report, January 1983, Outer Continental Shelf oil and gas activities in the Arctic and their onshore impacts: U.S. Minerals Management Service, Outer Continental Shelf Oil and Gas Information Program, Contract No. 14-08-0001-19719, 81 p.

Jamison, H. C., Brockett, L. D., and McIntosh, R. A., 1980, Prudhoe Bay--a 10-year perspective, in Halbouty, M. T., ed., Giant oil and gas fields of the decade 1968-1978: AAPG Memoir 30, p. 289-314.

Jones, H. P., and Speers, R. G., 1976, Permo-Triassic reservoirs of Prudhoe Bay field, North Slope, Alaska, in Braunstein, Jules, ed., North American oil and gas fields: AAPG Memoir 24, p. 23-50.

Jones, P. B., 1982, Mesozoic rifting in the western Arctic Ocean basin and its relationship to Pacific seafloor spreading, in Embry, A. F., and Balkwill, H. R., eds., Arctic geology and geophysics: International Symposium on Arctic Geology, 3rd, Calgary, Alberta, Canada, June 28-July 1, 1981, Proceedings: Canadian Society of Petroleum Geologists Memoir 8, p. 83-100.

Kane, F. H., and Jackson, K. S., 1980, Controls on occurrence of oil and gas in the Beaufort-Mackenzie Basin, in Miall, A. D., ed., Facts and principles of world petroleum occurrence: Canadian Society of Petroleum Geologists Memoir 6, p. 490-501.

Keigwin, L. D., Jr., 1980, Palaeoceanographic change in the Pacific at the Eocene-Oligocene boundary: Nature, v. 287, p. 722-725.

Keigwin, L. D., Jr., and Keller, Gerta, 1984, Middle Oligocene cooling from equatorial Pacific DSDP site 77B: Geology, v. 12, no. 1, p. 16-19.

Kingston, D. R., Dishroon, C. P., and Williams, P. A., 1983, Hydrocarbon plays and global basin classification: AAPG Bulletin, v. 67, no. 12, p. 2194-2198.

Kososki, B. A., Reiser, H. N., Cavit, C. D., and Detterman, R. L., 1978, A gravity study of the northern part of the Arctic National Wildlife Range, Alaska: U.S. Geological Survey Bulletin 1440, 21 p., 3 maps.

Kovacs, Austin, 1984, Shore ice ride-up and pile-up features, part 2, Alaska's Beaufort Sea coast, 1983 and 1984: Hanover, New Hampshire, U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, CRREL Report 84-26, 29 p.

Kozo, T. L., 1981, Winds, subchap. 2.1 in Norton, D. W., and Sackinger, W. M., eds., Beaufort Sea, Sale 71, synthesis report, proceedings of a synthesis meeting, Chena Hot Springs, Alaska, April 21-23, 1981: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, p. 59-69.

Kvenvolden, K. A., and McMenamin, M. A., 1980, Hydrates of natural gas, a review of their geologic occurrence: U.S. Geological Survey Circular 825, 11 p.

Lantz, R. J., 1981, Barrow gas fields--North Slope, Alaska: Oil and Gas Journal, March 30, 1981, p. 197-200.

Lathram, E. H., 1973, Tectonic framework of northern and central Alaska, in Pitcher, M. G., ed., Arctic geology: International Symposium on Arctic Geology, 2nd, San Francisco, California, February 1-4, 1971, Proceedings: AAPG Memoir 19, p. 351-360.

Lerand, Monti, 1973, Beaufort Sea, in McCrossam, R. G., ed., The Future petroleum provinces of Canada--their geology and potential: Canadian Society of Petroleum Geologists Memoir 1, p. 315-386.

Lerche, I., Yarzab, R. F., and Kendall, C. G. St. C., 1984, Determination of paleoheat flux from vitrinite reflectance data: AAPG Bulletin, v. 68, no. 11, p. 1704-1717.

Lewbel, G. S., 1984, Environmental hazards to petroleum industry development, chap. 3 in Truett, J. C., ed., The Barrow Arch environment and possible consequences of planned offshore oil and gas development, proceedings of a synthesis meeting, Girdwood, Alaska, 30 October - 1 November 1983: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, p. 31-46.

Lyle, W. M., Palmer, I. F., Jr., Bolm, J. G., and Maxey, L. R., 1980, Post-Early Triassic formations of northeastern Alaska and their petroleum reservoir and source-rock potential: Anchorage, Alaska Department of Natural Resources, Division of Geological and Geophysical Surveys, Geologic Report 76, 100 p.

Lynch, Christopher, Slitor, D. L., and Rudolph, R. W., 1985, Arctic summary report, January 1985, Outer Continental Shelf oil and gas activities in the Arctic and their onshore impacts: U.S. Minerals Management Service, Outer Continental Shelf Oil and Gas Information Program, Contract No. 14-12-0001-30042, 84 p.

Macleod, M. K., 1982, Gas hydrates in ocean bottom sediments: AAPG Bulletin, v. 66, no. 12, p. 2649-2662.

Magoon, L. B., and Bird, K. J., 1986, Organic carbon content, hydrocarbon content, visual kerogen, and vitrinite reflectance data within NPRA (National Petroleum Reserve in Alaska)--contour maps to evaluate petroleum source rock richness, type, and thermal maturity, in Gryc, G., ed., Geology of the National Petroleum Reserve in Alaska: U.S. Geological Survey Professional Paper, in press.

Magoon, L. B., and Claypool, G. E., 1981, Two oil types on North Slope of Alaska--implications for exploration: AAPG Bulletin, v. 65, p. 644-652.

Magoon, L. B., and Claypool, G. E., 1984, The Kingak shale of northern Alaska--regional variations in organic geochemical properties and petroleum source rock quality: Organic Geochemistry, v. 5, no. 4, p. 1-10.

Mast, R. F., McMullin, R. H., Bird, K. J., and Brosgé, W. P., 1980, Resource appraisal of undiscovered oil and gas resources in the William O. Douglas Arctic Wildlife Range: U.S. Geological Survey Open-File Report 80-916, 62 p.

Matthews, J. B., 1981, Observations of surface and bottom currents in the Beaufort Sea near Prudhoe Bay, Alaska: Journal of Geophysical Research, v. 86, no. C7, p. 6653-6660.

McCloy, Marjorie, 1983, Independent research yields North Slope study: AAPG Explorer, July issue, p. 14-15.

McGowen, J. H., and Bloch, S., 1985, Depositional facies, diagenesis, and reservoir quality of Ivishak sandstone (Sadlerochit Group), Prudhoe Bay field [abs.]: AAPG Bulletin, v. 69, no. 2, p. 286.

McKenzie, R. M., 1981, The Hibernia--a classic structure: Oil and Gas Journal, v. 79, no. 38, p. 240-246.

Meyer, B. L., and Nederlof, M. H., 1984, Identification of source rocks on wireline logs by density/resistivity and sonic transit time/ resistivity crossplots: AAPG Bulletin, v. 68, no. 2, p. 121-129.

Meyerhoff, A. A., 1982, Hydrocarbon resources in Arctic and subarctic regions, in Embry, A. F., and Balkwill, H. R., eds., Arctic geology and geophysics: International Symposium on Arctic Geology, 3rd, Calgary, Alberta, Canada, June 28-July 1, 1981, Proceedings: Canadian Society of Petroleum Geologists Memoir 8, p. 451-552.

Miller, D. L., and Bruggers, D. E., 1980, Soil and permafrost conditions in the Alaskan Beaufort Sea: Offshore Technology Conference, 12th, Houston, Texas, 1980, Proceedings, v. 4, OTC Paper 3887, p. 325-332.

Mills, H. G., 1970, Geology of Tom O'Connor field, Refugio County, Texas, in Halbouty, M. T., ed., Geology of giant petroleum fields, a symposium of papers...including those presented at the 53rd annual meeting of the Association, Oklahoma City, Oklahoma, April 23-25, 1968: AAPG Memoir 14, p. 292-300.

Molenaar, C. M., 1983, Depositional relations of Cretaceous and lower Tertiary rocks, northeastern Alaska: AAPG Bulletin, v. 67, no. 7, p. 1066-1080.

Morack, J. L., MacAulay, H. A., and Hunter, J. A., 1983, Geophysical measurements of subbottom permafrost in the Canadian Beaufort Sea, in International Conference on Permafrost, 4th, Fairbanks, Alaska, 1983, Proceedings: Washington, D. C., National Academy Press, p. 866-871.

Morgridge, D. L., and Smith, W. B., Jr., 1972, Geology and discovery of Prudhoe Bay field, eastern Arctic Slope, Alaska, in King, R. E., ed., Stratigraphic oil and gas fields--Classification, exploration methods, and case histories: AAPG Memoir 16, Society of Exploration Geophysicists Special Publication no. 10, p. 489-501.

Naidu, A. S., and Mowatt, T. C., 1983, Sources and dispersal patterns of clay minerals in surface sediments from the continental-shelf areas off Alaska: Geological Society of America Bulletin, v. 94, no. 7, p. 841-845.

National Petroleum Council, 1981, U.S. Arctic oil and gas: Prepared for U.S. Department of Energy by National Petroleum Council, Washington, D. C., 286 p.

Neave, K. G., and Sellmann, P. V., 1983, Seismic velocities and subsea permafrost in the Beaufort Sea, Alaska, in International Conference on Permafrost, 4th, Fairbanks, Alaska, 1983, Proceedings: Washington, D. C., National Academy Press, p. 894-898.

Nilsen, T. H., and Moore, T. E., 1982a, Fluvial-facies model for the Upper Devonian and Lower Mississippian(?) Kanayut Conglomerate, Brooks Range, Alaska, in Embry, A. F., and Balkwill, H. R., eds., Arctic geology and geophysics: International Symposium on Arctic Geology, 3rd, Calgary, Alberta, Canada, June 28-July 1, 1981, Proceedings: Canadian Society of Petroleum Geologists Memoir 8, p. 1-12.

Nilsen, T. H., and Moore, T. E., 1982b, Sedimentology and stratigraphy of the Kanayut Conglomerate, central and western Brooks Range, Alaska--report of 1981 field season: U.S. Geological Survey Open-File Report 82-674, 64 p.

Norris, D. K., 1973, Tectonic styles of northern Yukon Territory and northwestern District of Mackenzie, Canada, in Pitcher, M. G., ed., Arctic geology: International Symposium on Arctic Geology, 2nd, San Francisco, California, February 1-4, 1971, Proceedings: AAPG Memoir 19, p. 23-40.

Norris, D. K., and Yorath, C. J., 1981, The North American plate from the Arctic Archipelago to the Romanzof Mountains, chap. 3 in Nairn, A. E. M., Churkin, Michael, Jr., and Stehli, F. G., eds., The ocean basins and margins, v. 5, The Arctic Ocean: New York, Plenum Press, p. 37-103.

Oil and Gas Journal, 1984, Gulf group gauges Beaufort Sea strike: Oil and Gas Journal, v. 82, no. 32, p. 32-33.

Oil and Gas Journal, 1985a, Two more strikes tested off Canada in Beaufort Sea: Oil and Gas Journal, v. 83, no. 13, p. 58.

Oil and Gas Journal, 1985b, Firms prepare for production off east coast of Canada: Oil and Gas Journal, v. 83, no. 14, p. 35-41.

Oil and Gas Journal, 1985c, Milne Point Unit--small but welcome: Oil and Gas Journal, v. 83, no. 25, p. 55-58.

Oil and Gas Journal, 1985d, Sohio, Gulf, move toward Beaufort development: Oil and Gas Journal, v. 83, no. 25, p. 51.

Oil and Gas Journal, 1985e, PIP phaseout pushes Canadian frontier outlay: Oil and Gas Journal, v. 83, no. 31, p. 60-73.

Osterkamp, T. E., and Harrison, W. D., 1976, Subsea permafrost at Prudhoe Bay, Alaska, drilling report and data analysis: University of Alaska, Geophysical Institute Report UAG-R-245.

Osterkamp, T. E., and Harrison, W. D., 1978a, Subsea permafrost--probing, thermal regime and data analysis, in Environmental assessment of the Alaskan continental shelf, quarterly reports of principal investigators for April-June 1978: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Research Unit 253, p. 369-370.

Osterkamp, T. E., and Harrison, W. D., 1978b, Subsea permafrost--probing, thermal regime and data analysis, in Environmental assessment of the Alaskan continental shelf, quarterly reports of principal investigators for October-December 1978, v. 2: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Research Unit 253, p. 319-399.

Osterkamp, T. E., and Payne, M. W., 1981, Estimates of permafrost thickness from well logs in northern Alaska: Cold Regions Science and Technology, v. 5, p. 13-27.

Palmer, I. F., Jr., Bolm, J. G., Maxey, L. R., and Lyle, W. M., 1979, Petroleum source rock and reservoir quality data from outcrop samples, onshore North Slope of Alaska east of Prudhoe Bay: U.S. Geological Survey Open-File Report 79-1634, p. 52, 14 plates.

Petroleum Information, Inc., 1984, Seal Island drilling to probe Texas Eastern lease next: Petroleum Information Alaska Report for week of June 27, 1984, v. 30, no. 26, p. 1.

Poulton, T. P., 1982, Paleogeographic and tectonic implications of the Lower and Middle Jurassic facies patterns in northern Yukon Territory and adjacent Northwest Territories, in Embry, A. F., and Balkwill, H. R., eds., Arctic geology and geophysics: International Symposium on Arctic Geology, 3rd, Calgary, Alberta, Canada, June 28-July 1, 1981, Proceedings: Canadian Society of Petroleum Geologists Memoir 8, p. 13-27.

Pritchard, R. S., 1978, Dynamics of near shore ice, in Environmental assessment of the Alaskan continental shelf, annual reports of principal investigators for the year ending March 1978, v. 11, Hazards: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Research Unit 98, p. 39-49.

Reeder, M. L., and Scotchman, I. C., 1985, Hydrocarbon generation--central and northern North Sea: Oil and Gas Journal, v. 83, no. 12, p. 137-144.

Reimer, R. W., Schedvin, J. C., and Pritchard, R. S., 1981, Chukchi Sea ice motion: Kent, Washington, Flow Research Company, Publication no. 3846, 9 p. [available as OCSEAP Research Unit 567 from the Library/Public Information Room, U.S. Minerals Management Service, Alaska OCS Region, Anchorage, Alaska].

Reimnitz, Erk, and Barnes, P. W., 1974, Sea ice as a geologic agent on the Beaufort Sea shelf of Alaska, in Reed, J. C., and Sater, J. E., eds., The coast and shelf of the Beaufort Sea, proceedings of a symposium on Beaufort Sea coast and shelf research: Arlington, Virginia, Arctic Institute of North America, p. 301-351.

Reimnitz, Erk, Barnes, P. W., Rearic, D. M., Minkler, P. W., Kempema, E. W., and Reiss, T. E., 1982, Marine geological investigations in the Beaufort Sea in 1981 and preliminary interpretations for regions from the Canning River to the Canadian Border: U.S. Geological Survey Open-File Report 82-974, 66 p.

Reimnitz, Erk, and Bruder, K. F., 1972, River discharge into an ice-covered ocean and related sediment dispersal, Beaufort Sea, coast of Alaska: Geological Society of America Bulletin, v. 83, p. 861-866.

Reimnitz, Erk, Graves, S. M., and Barnes, P. W., 1985, Beaufort Sea coastal erosion, shoreline evolution, and sediment flux: U.S. Geological Survey Open-File Report 85-380, 58 p., 1 plate.

Reimnitz, Erk, and Kempema, E. W., 1982a, High rates of bedload transport measured from infilling rate of large strudel-scour craters in the Beaufort Sea, Alaska: U.S. Geological Survey Open-File Report 82-588, 18 p.

Reimnitz, Erk, and Kempema, E. W., 1982b, Dynamic ice wallow relief of northern Alaska's nearshore: Journal of Sedimentary Petrology, v. 52, no. 2, p. 451-461.

Reimnitz, Erk, Kempema, E. W., Ross, Robin, and Minkler, P. W., 1980, Overconsolidated surficial deposits on the Beaufort Sea shelf: U.S. Geological Survey Open-File Report 80-2010, 37 p.

Reimnitz, Erk, Kempema, E., Ross, Robin, and Olson, Bob, 1979, Additional observations on geomorphologic changes in the Arctic coastal environment, in Environmental assessment of the Alaskan continental shelf, quarterly reports of principal investigators for April-December 1979, v. 2: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Research Unit 205, p. 171-188.

Reimnitz, Erk, and Maurer, D. K., 1978a, Stamukhi shoals of the Arctic--some observations from the Beaufort Sea: U.S. Geological Survey Open-File Report 78-666, 17 p.

Reimnitz, Erk, and Maurer, D. K., 1978b, Storm surges in the Alaskan Beaufort Sea, in Environmental assessment of the Alaskan continental shelf, annual reports of principal investigators for the year ending March 1978, v. 11, Hazards: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Research Unit 205, p. 166-192.

Reimnitz, Erk, Rodeick, C. A., and Wolf, S. C., 1974, Strudel scour, a unique Arctic marine geologic phenomenon: Journal of Sedimentary Petrology, v. 44, no. 2, p. 409-420.

Reimnitz, Erk, and Ross, Robin, 1979, Lag deposits of boulders in Stefansson Sound, Beaufort Sea, Alaska: U.S. Geological Survey Open-File Report 79-1205, 26 p.

Reimnitz, Erk, Ross, Robin, and Barnes, Peter, 1979, Dinkum sands, in Environmental assessment of the Alaskan continental shelf, quarterly reports of principal investigators for April-December 1979, v. 2: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Research Unit 205, p. 213-220.

Reimnitz, Erk, Toimil, L. J., and Barnes, Peter, 1978, Arctic continental shelf morphology related to sea-ice zonation, Beaufort Sea, Alaska: Marine Geology, v. 28, p. 179-210.

Reiser, H. N., Brosgé, W. P., Dutro, J. T., Jr., and Detterman, R. L., 1980, Geologic map of the Demarcation Point quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations Series, Map I-1133, scale 1:250,000.

Rodeick, C. A., 1979, The origin, distribution, and depositional history of gravel deposits on the Beaufort Sea continental shelf, Alaska: U.S. Geological Survey Open-File Report 79-234, 87 p.

Rogers, J. C., and Morack, J. L., 1978, Geophysical investigation of offshore permafrost, Prudhoe Bay, Alaska, in International Conference on Permafrost, 3rd, Proceedings, v. 1, p. 560-566.

Rogers, J. C., and Morack, J. L., 1981, Beaufort and Chukchi seacoast permafrost studies, in Environmental assessment of the Alaskan continental shelf, annual reports of principal investigators for the year ending March 1981, v. 8, Hazards and data management: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Research Units 610 and 271, p. 293-332.

Ruth, G. W., 1982, Pyrolysis/T. O. C. profiles, eight (8) North Slope Alaska, wells: Consultant study performed by Brown and Ruth Laboratories, Inc., for Mobil Oil Corp., 35 p. [available from Alaska Oil and Gas Conservation Commission, Anchorage.]

Schindler, J. F., 1983, The second exploration, 1975-1982, National Petroleum Reserve in Alaska: Anchorage, Alaska, Husky Oil NPR Operations, Inc.; prepared for the U.S. Geological Survey, Office of the National Petroleum Reserve in Alaska, 89 p.

Schlumberger, Ltd., 1972, Log interpretation charts: Houston, Texas, Schlumberger, Ltd., 92 p.

Seifert, W. K., Moldowan, J. M., and Jones, R. W., 1980, Application of biological marker chemistry to petroleum exploration: World Petroleum Congress, 10th, 1980, Proceedings, v. 2, Exploration supply and demand, p. 425-440.

Sellmann, P. V., and Chamberlain, E. J., 1979, Permafrost beneath the Beaufort Sea near Prudhoe Bay, Alaska: Offshore Technology Conference, 11th, Houston, Texas, 1979, Proceedings, v. 3, OTC paper 3527, p. 1481-1488.

Sellmann, P. V., Neave, K. G., and Chamberlain, E. J., 1981, Delineation and engineering characteristics of permafrost beneath the Beaufort Sea, in Environmental assessment of the Alaskan continental shelf, annual reports of principal investigators for the year ending March 1981, v. 7, Hazards: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Research Unit 105, p. 137-156.

Smith, T. N., 1984, Petroleum development, North Slope of Alaska: Alaska Mines and Geology, v. 33, no. 4, p. 1-4.

Snowdon, L. R., 1980, Resinite--a potential petroleum source in the Upper Cretaceous/Tertiary of the Beaufort-Mackenzie Basin, in Miall, A. D., ed., Facts and principles of world petroleum occurrence: Canadian Society of Petroleum Geologists Memoir 6, p. 509-521.

Snowdon, L. R., and Powell, T. G., 1982, Immature oil and condensate--modification of hydrocarbon generation model for terrestrial organic matter: AAPG Bulletin, v. 66, no. 6, p. 775-788.

Stach, E., Mackowsky, M.-Th., Teichmuller, M., Taylor, G. H., Chandra, D., and Teichmuller, R., 1982, Stach's textbook of coal petrology: Berlin, Gebruder Borntraeger.

Stanley, T. B., Jr., 1970, Vicksburg fault zone, Texas, in Halbouty, M. T., ed., Geology of giant petroleum fields, a symposium of papers...including those presented at the 53rd annual meeting of the Association, Oklahoma City, Oklahoma, April 23-25, 1968: AAPG Memoir 14, p. 301-308.

Stringer, W. J., 1981, Summertime ice concentrations in the Prudhoe Bay/Harrison Bay region: Scientific report supported by the U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Research Unit 267: Fairbanks, Alaska, University of Alaska, Geophysical Institute.

Stringer, W. J., 1982a, Width and persistence of the Chukchi polynya: NOAA-OCS Contract No. 81-RAC00147: Fairbanks, Alaska, University of Alaska, Geophysical Institute, 15 p.

Stringer, W. J., 1982b, Distribution of massive ridges in the eastern Beaufort Sea: prepared for the U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, Contract No. 81, RAC00147: Fairbanks, Alaska, University of Alaska, Geophysical Institute.

Tailleur, I. L., and Brosgé, W. P., 1970, Tectonic history of northern Alaska, in Adkinson, W. L., and Brosgé, W. P., eds., Proceedings of the geological seminar on the North Slope of Alaska: Los Angeles, Pacific Section, AAPG, p. E1-E20.

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

Tetra Tech, Inc., 1982, Petroleum exploration of NPRA, 1974-1981, final report: Houston, Texas, Tetra Tech, Inc., Energy Management Division; prepared for the USGS and for Husky Oil NPR Operations, Inc., Anchorage, Alaska, under USGS-Husky contract No. 14-08-0001-16474, Husky-Tetra Tech subcontract No. GC-81-5: Tetra Tech Report No. 8200, 3 v., 71 geophysical maps in 5 boxes [available from National Geophysical and Solar-Terrestrial Data Center, Boulder, Colorado 80303].

Tissot, B. P., and Welte, D. H., 1978, Petroleum formation and occurrence: New York, Springer-Verlag, 538 p.

Tissot, B. P., and Welte, D. H., 1984, Petroleum formation and occurrence (2nd ed.): New York, Springer-Verlag, 699 p.

Toimil, L. J., 1978, Ice-gouged microrelief on the floor of the eastern Chukchi Sea, Alaska, a reconnaissance survey: U.S. Geological Survey Open-File Report 78-693.

Toimil, L. J., and Grantz, A., 1976, Origin of a bergfield at Hanna Shoal, northeastern Chukchi Sea, and its influence on the sedimentary environment: AIDJEX (Arctic Ice Dynamics Joint Experiment) Bulletin No. 34, p. 1-42.

Trettin, H. P., 1973, Early Paleozoic evolution of northern parts of Canadian Arctic Archipelago, *in* Pitcher, M. G., ed., Arctic geology: International Symposium on Arctic Geology, 2nd, San Francisco, California, February 1-4, 1971, Proceedings: AAPG Memoir 19, p. 57-75.

Union Oil, 1983, Geochemical analysis of well cuttings from the Exxon Pt. Thomson Nos. 1 and 2, and ARCO SE Eileen No. 1 wells, North Slope, Alaska: Union Oil, 4 tables (6 p.) [available from Alaska Oil and Gas Conservation Commission, Anchorage].

U.S. Bureau of Land Management, Alaska OCS Office, 1979, Beaufort Sea final environmental impact statement, proposed Federal/State oil and gas lease sale: Anchorage, Alaska, 3 v.

Vail, P. R., Mitchum, R. M., Jr., and Thompson, S., III, 1977, Seismic stratigraphy and global changes of sea level, part 4, Global cycles of relative changes of sea level, *in* Payton, C. E., ed., Seismic stratigraphy--applications to hydrocarbon exploration: AAPG Memoir 26, p. 83-97.

Walker, D. B. L., Hayley, D. W., and Palmer, A. C., 1983, The influence of subsea permafrost on offshore pipeline design, *in* International Conference on Permafrost, 4th, Fairbanks, Alaska, 1983, Proceedings: Washington D. C., National Academy Press, p. 1338-1343.

Wang, J. L., Vivatrat, Vitoon, and Rusher, J. R., 1982, Geotechnical properties of Alaska OCS silts: Offshore Technology Conference, 14th, Houston, Texas, 1982, Proceedings, v. 4, OTC paper 4412, p. 415-420.

Weeks, W. F., ed., 1978, Environmental hazards to offshore operations, chap. 12 *in* Environmental assessment of the Alaskan continental shelf, interim synthesis report, Beaufort/Chukchi: U.S. National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, p. 335-348.

Werner, M. R., 1985, West Sak and Ugnu Sands: Low-gravity oil zones of the Kuparuk River area, North Slope, Alaska [abs.]: AAPG Bulletin, v. 69, no. 4, p. 682.

Wharton, D. I., 1981, Palynological analyses of core chips from the Mobil Mikkelsen Bay St. No. 1, Humble East Mikkelsen Bay St. No. 1, Mobil West Staines St. No. 1, and Exxon Alaska St. A-1 wells: San Francisco, California, Sohio Petroleum Co., 2 p. [available from Alaska Oil and Gas Conservation Commission, Anchorage].

Willumsen, P. S., and Cote, R. P., 1982, Tertiary sedimentation in the southern Beaufort Sea, Canada, *in* Watkins, J. S., and Drake, C. L., eds., Studies in continental margin geology: AAPG Memoir 34, p. 283-293.

Witmer, R. J., Haga, H., and Mickey, M. B., 1981, Biostratigraphic report of thirty-three wells drilled from 1975 to 1981 in National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 81-1166, 47 p.

Young, Allen, Monaghan, P. H., and Schweisberger, R. T., 1977, Calculation of ages of hydrocarbons in oils--physical chemistry applied to petroleum geochemistry I: AAPG Bulletin, v. 61, no. 4, p. 573-600.

Young, Bruce, Campbell, Graham, and Fraser, Ian, 1981, Structural and stratigraphic overview of the Beaufort shelf: Unpublished paper given at the International Symposium on Arctic Geology, 3rd, Calgary, Alberta, Canada, 1981.

List of Abbreviations for Control Wells on Plates 1-7

Abbreviation	Geologic Unit	Age
Qg	Gubic Formation	Quaternary
Ts	Sagavanirktok Formation	Tertiary
Kc	Colville Group	Late Cretaceous
Kn	Nanushuk Group	Early Cretaceous
Kt	Torok Formation	Early Cretaceous
Kps	Pebble Shale	Early Cretaceous
JRk	Kingak Formation	Jurassic
TR-JRsr	Sag River Formation	Late Triassic to Early Jurassic
TRsh	Shublik Formation	Triassic
TRsr/sh/sd	Sag River to Sadlerochit	Triassic
P-TRs	Sadlerochit Group	Permian to Triassic
PPl	Lisburne Group	Pennsylvanian
Ml	Lisburne Group	Mississippian
B	metamorphic basement (Neruokpuk Formation; Franklinian sequence)	Middle Devonian and older

Additional information on lithostratigraphic column (fig. 3).

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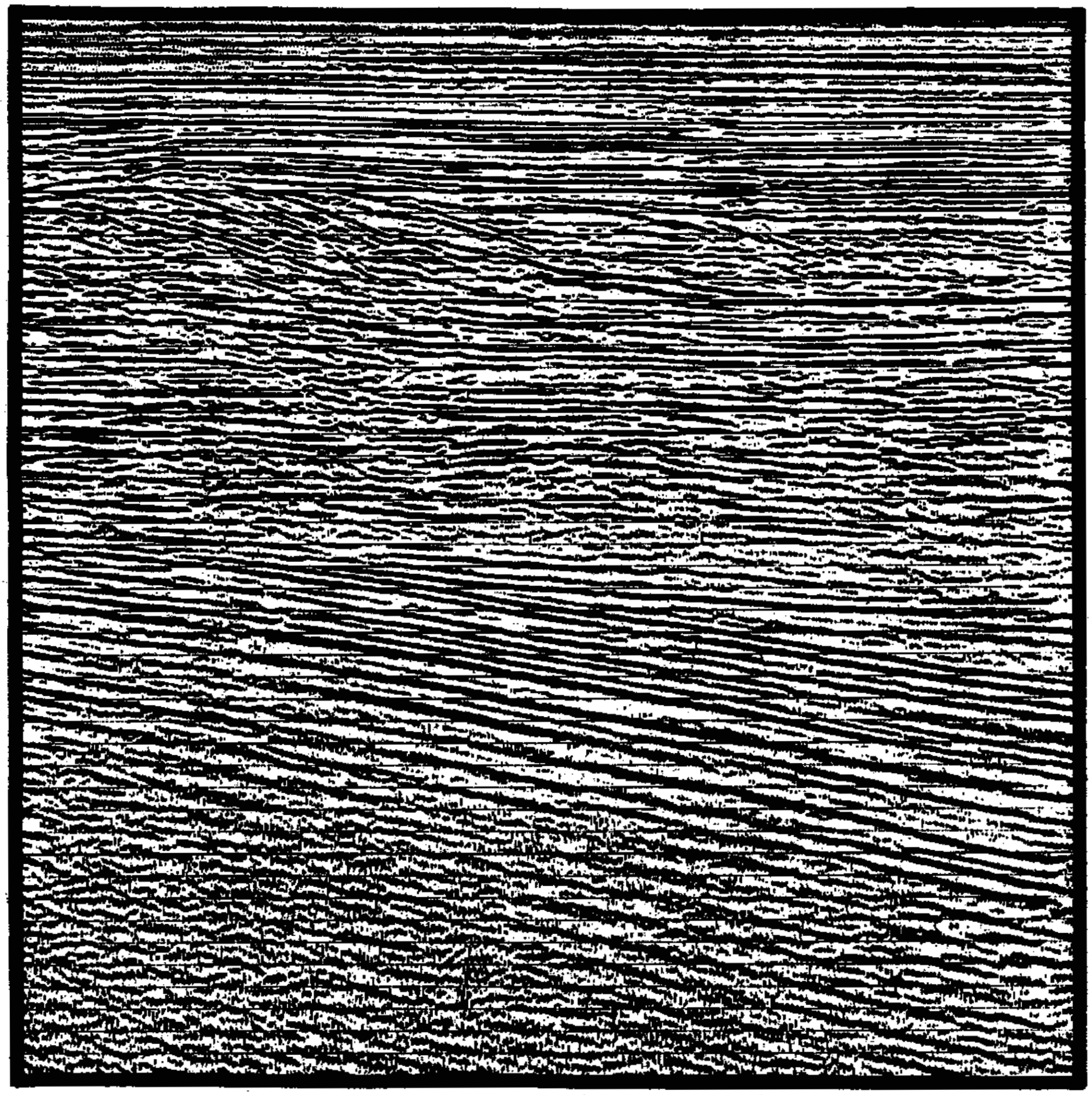
United States Department of the Interior
Minerals Management Service
Alaska Outer Continental Shelf Region



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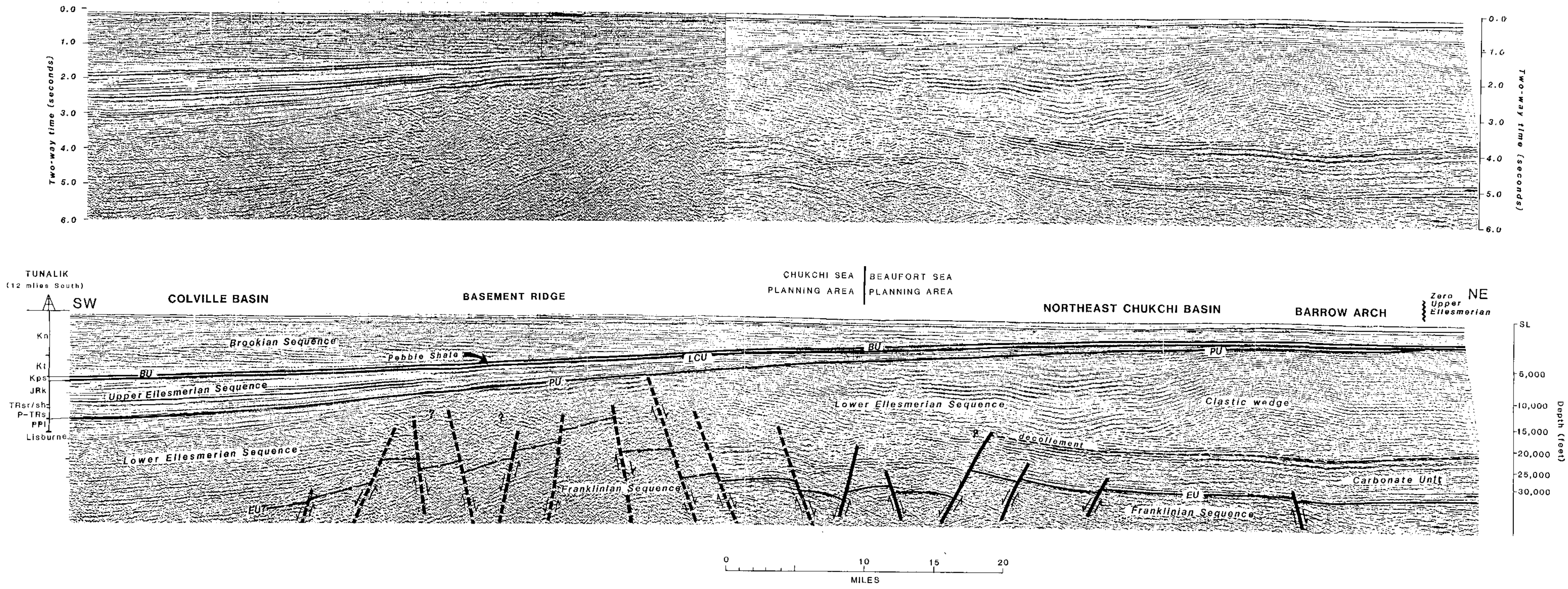
OCS REPORT
MMS 85-0111
PLATE 1 OF 11



Representative seismic profile extending from the Colville Basin to the Northeast Chukchi Basin (courtesy of Western Geophysical Company). Our seismic interpretation is jump-tied to the Husky Tunalik No. 1 well. A regional time-depth conversion scale was derived from typical RMS (stacking) velocities picked from Western Geophysical Company Velans and check-shot data from the well.

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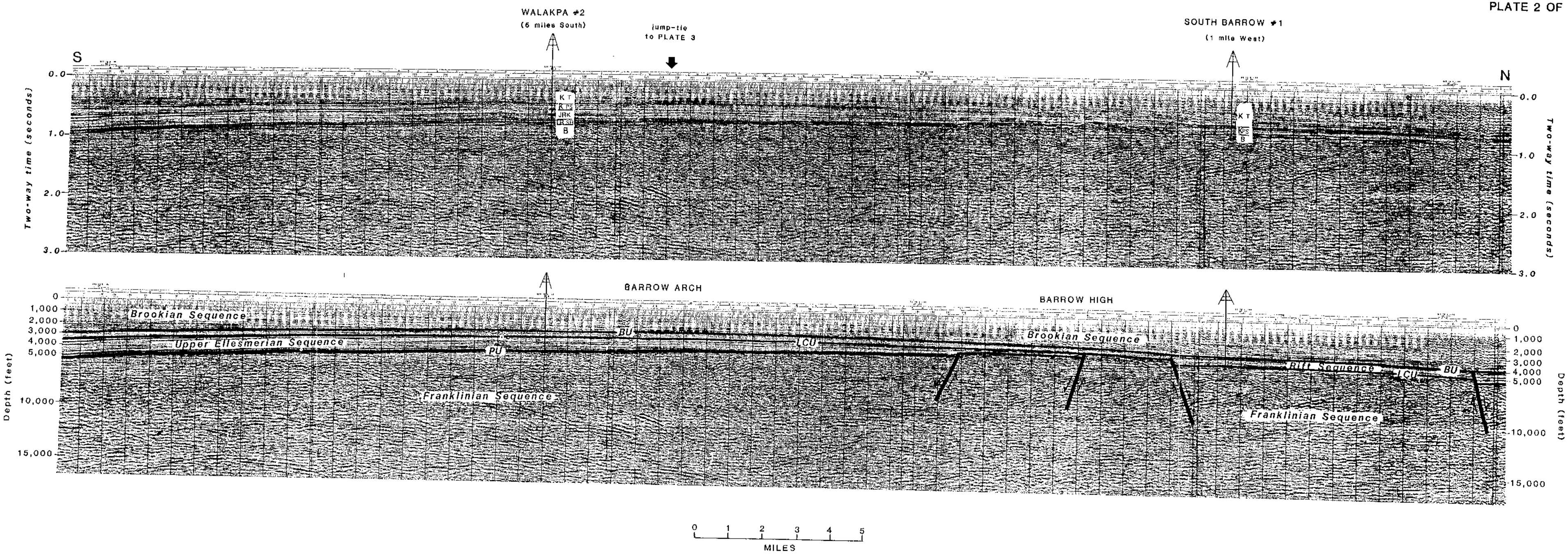
MMS 85-0111
PLATE 2 OF 11



Representative seismic profile (Husky-Geophysical Service, Inc., Line 81-78-1178) on the northern Arctic Platform in the vicinity of Barrow. Seismic ties for this interpretation are supplied by the Husky Walakpa No. 2 and the Navy South Barrow No. 1 wells.

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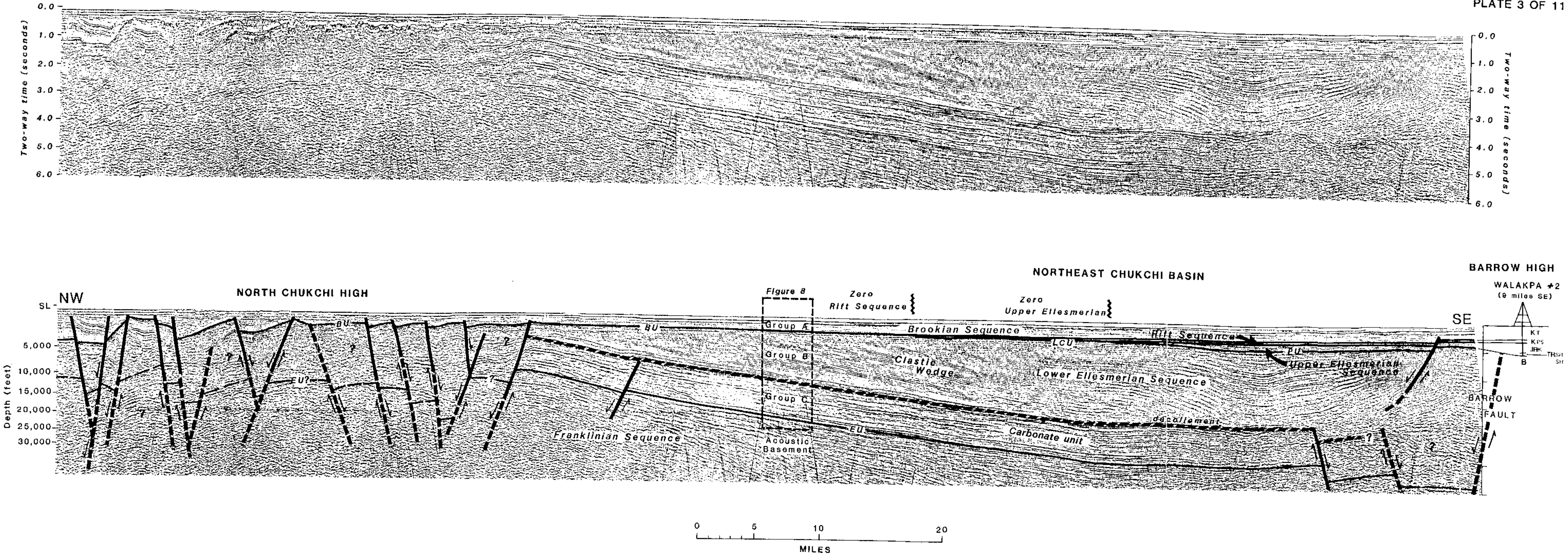
OCS REPORT
MMS 85-0111
PLATE 3 OF 11



Representative seismic profile (courtesy of Western Geophysical Company) across the Northeast Chukchi Basin and parallel to the NW-SE strike of the Barrow Arch. Our seismic interpretation is jump-tied to the Husky Walakpa No. 2 well. The time-depth conversion scale is derived, as in previous plates, from a combination of typical RMS (stacking) velocities and check-shot data from the well.

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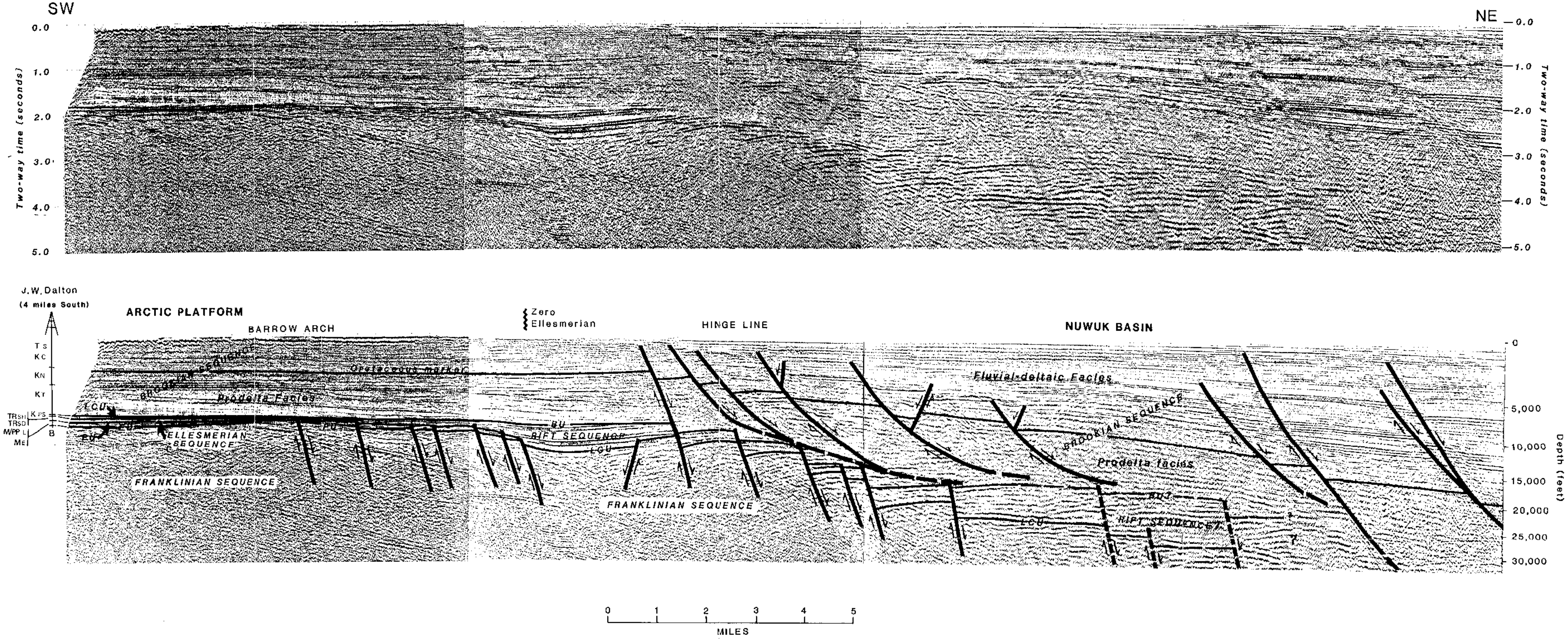
OCS REPORT
MMS 85-0111
PLATE 4 OF 11



Representative seismic profile (courtesy of Western Geophysical Company) illustrating the stratigraphic and structural character of the Arctic Platform and Nuwuk Basin. Our interpretation is controlled by a jump-tie from the Husky J. W. Dalton well in NPRA. The time-depth conversion scale is derived, as in previous plates, from a combination of typical RMS (stacking) velocities and check-shot data from the well.

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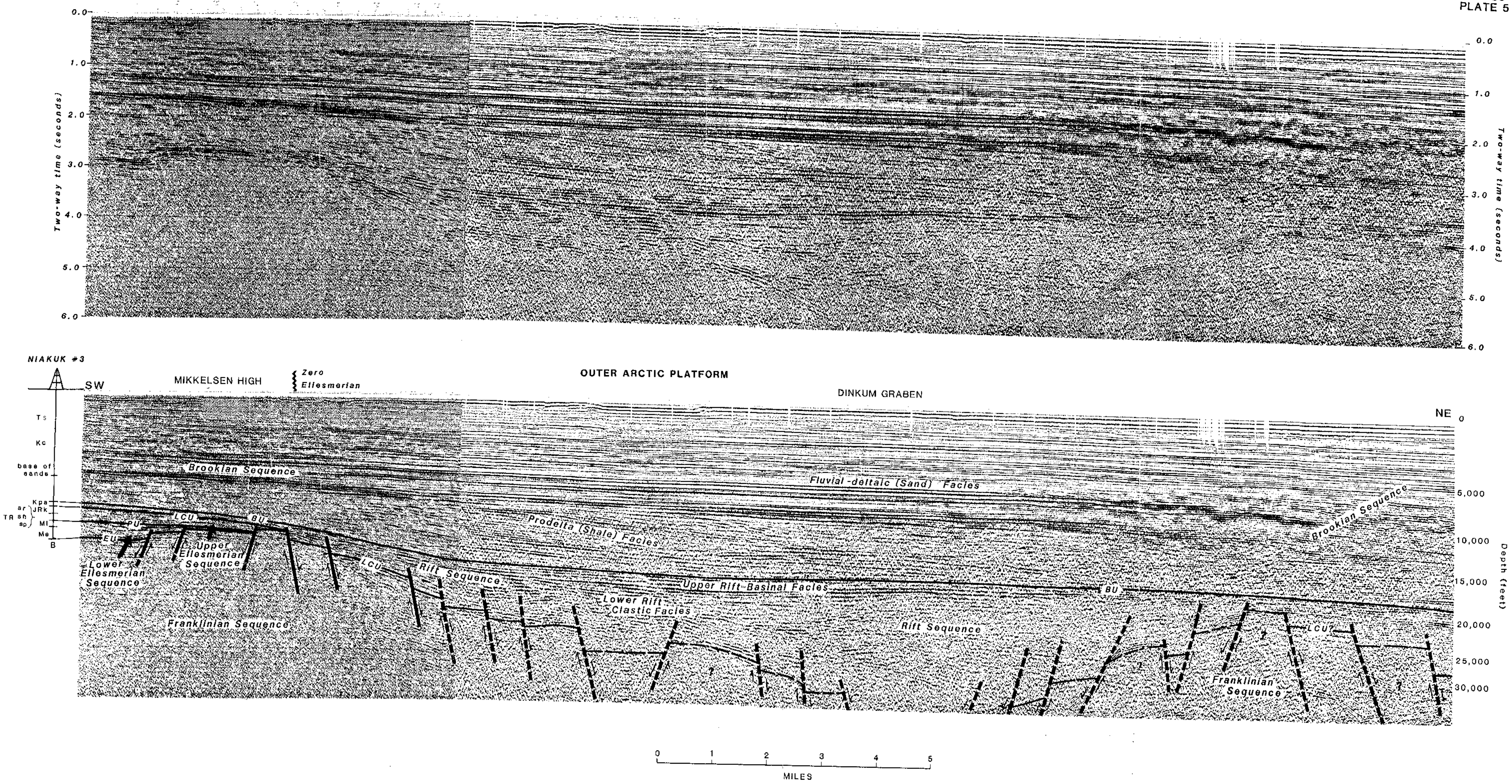
OCS REPORT
MMS 85-0111
PLATE 5 OF 11



Representative seismic profile (courtesy of Western Geophysical Company) showing the thinning of the Ellesmerian sequence over the Mikkelsen high and the stratigraphy of the Early Cretaceous Rift sequence in the Dinkum graben north of this basement ridge. The Sohio Niakuk No. 3 well provides the stratigraphic control for our interpretation.

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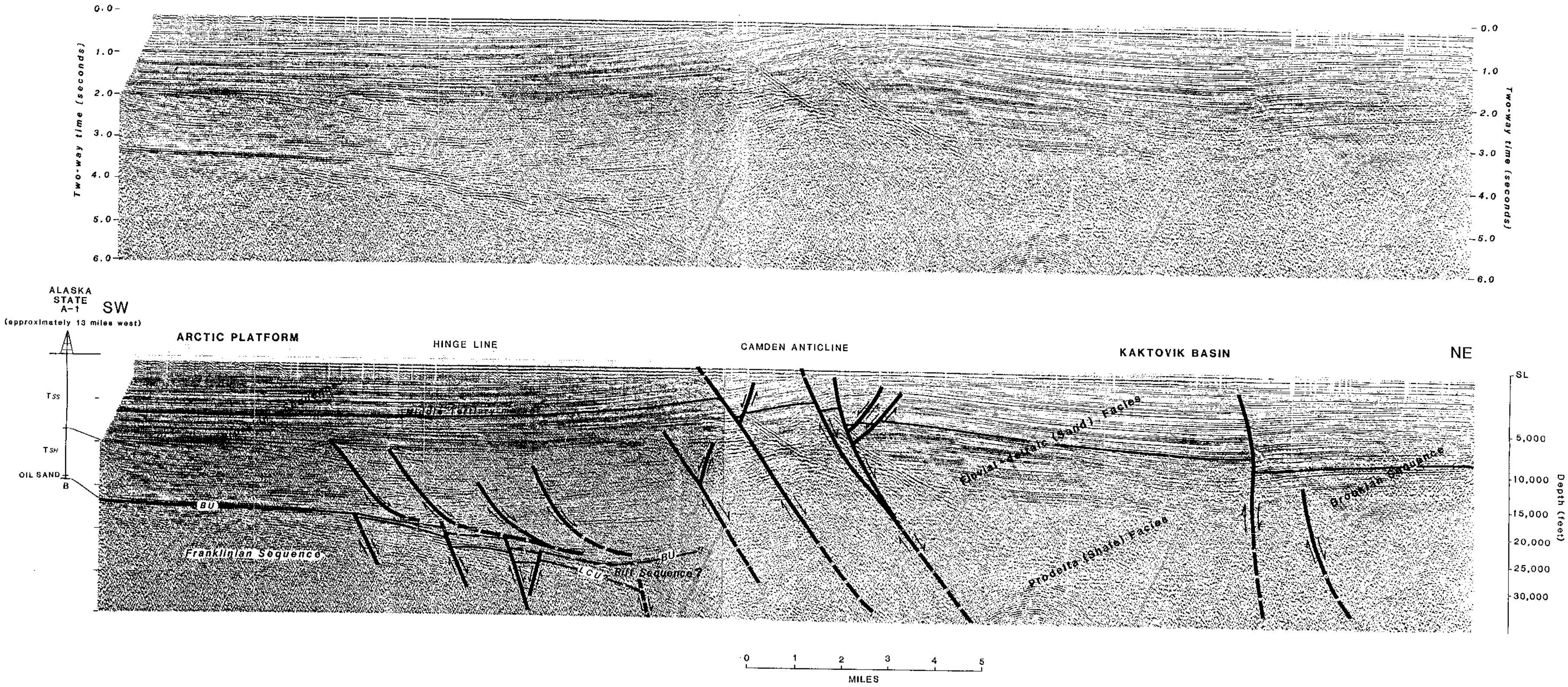
OCS REPORT
MMS 85-0111
PLATE 6 OF 11



Representative seismic profile (courtesy of Western Geophysical Company) illustrating the stratigraphy of the western Kaktovik Basin (Camden sector) and the structural character of the Camden anticline. Although the Camden anticline is similar in profile to rollover anticlines in growth fault zones, the oblique strike of this feature in relation to the Kaktovik Basin margin suggests a tectonic origin. Well control is provided by a jump-tie to the Exxon Alaska State A-1 well.

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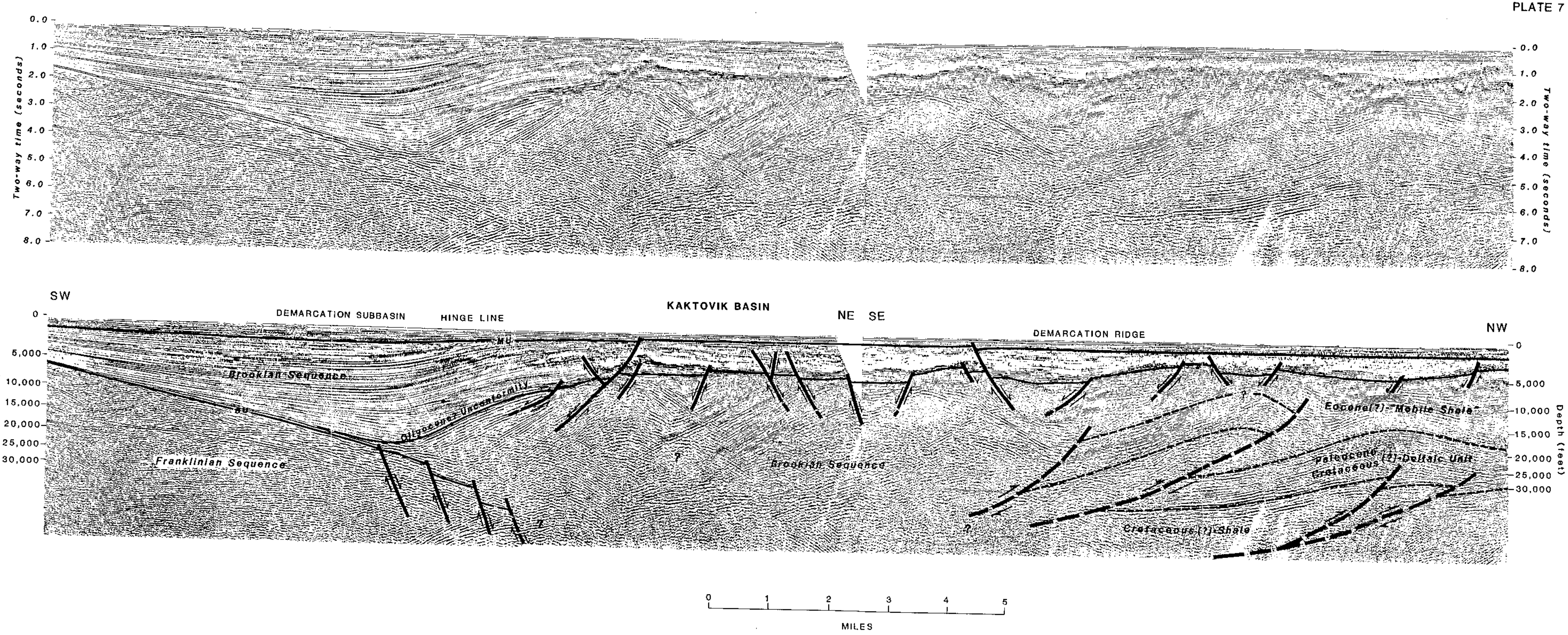
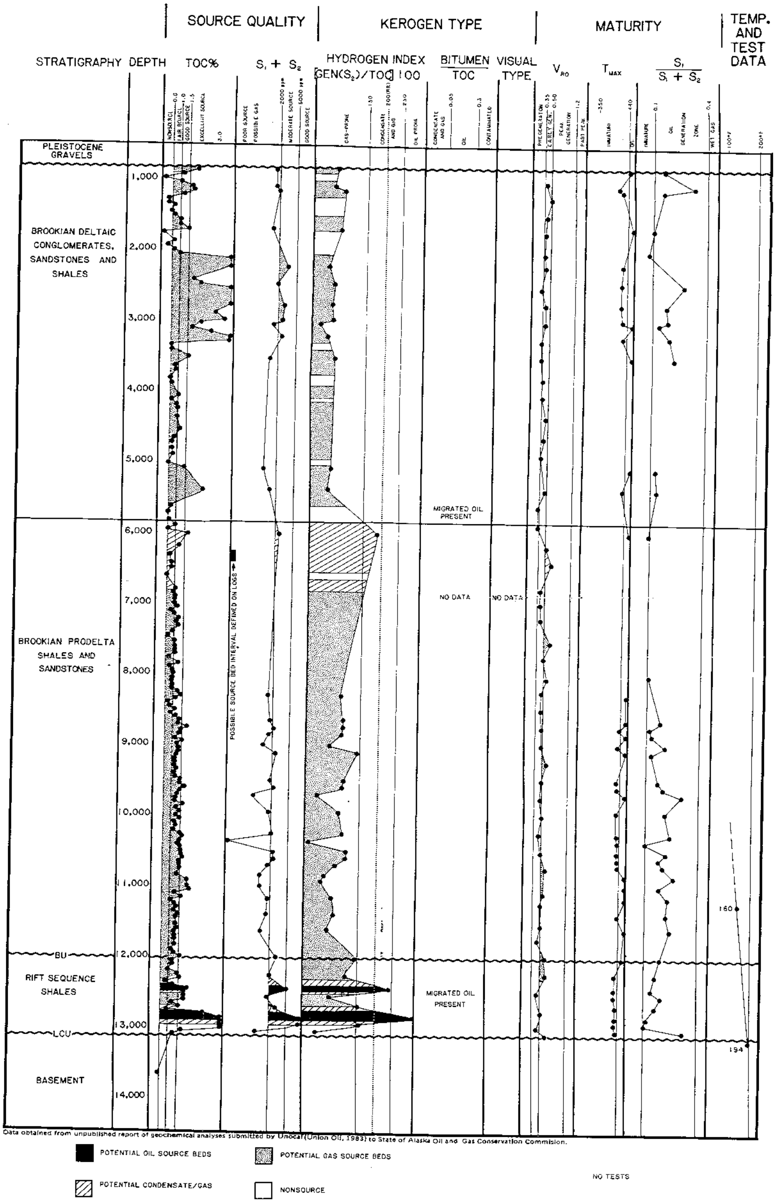
MINERALS MANAGEMENT SERVICE

OCS REPORT
MMS 85-0111
PLATE 7 OF 11



Representative seismic profile (courtesy of Western Geophysical Company) illustrating the complex structure and stratigraphy of the eastern Kaktovik Basin (Demarcation sector). Stratigraphic control for our seismic interpretation is provided by the Dome Natsek E-56 well in Canadian waters. At present there are no publicly available wells between Alaska State A-1 and Natsek E-56, and only one proprietary exploration well in ANWR (Chevron KIC No. 1).



Data obtained from unpublished report of geochemical analyses submitted by Unocal (Union Oil, 1983) to State of Alaska Oil and Gas Conservation Commision.

Source rock geochemical profile for the Mobil West Staines No. 2 well.

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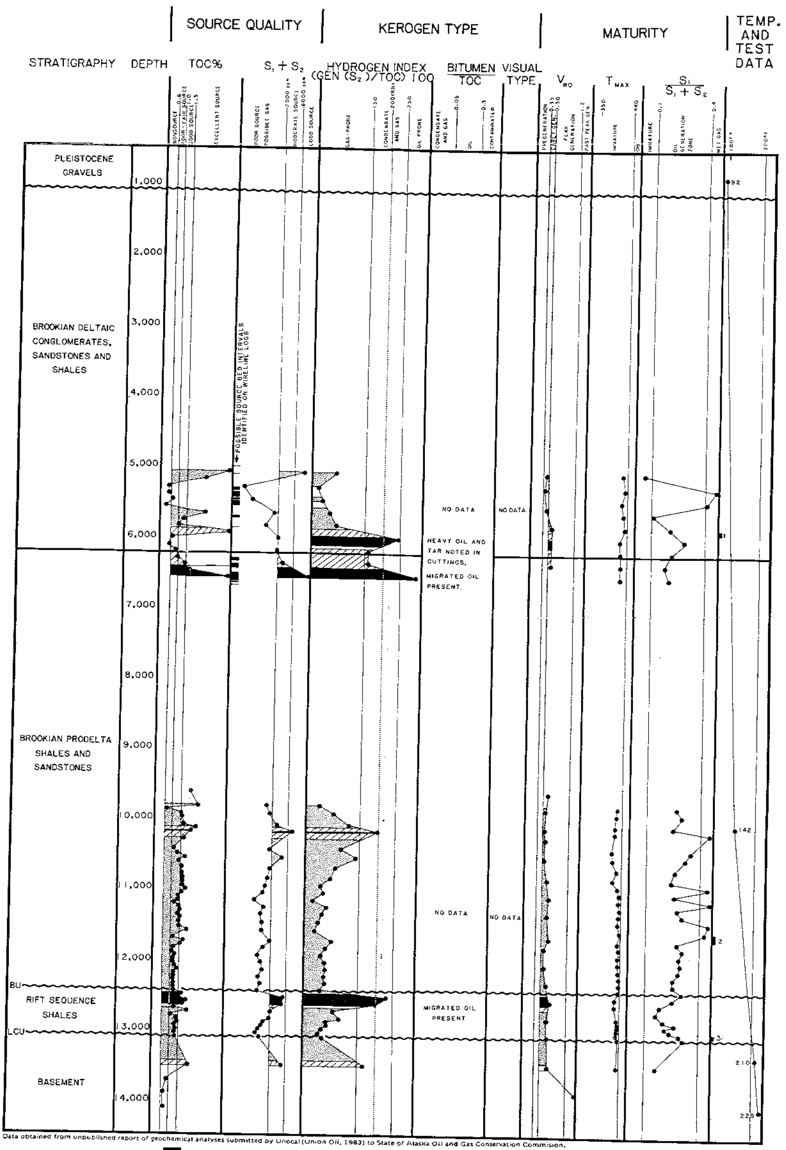
MMS 85-0111
PLATE 9 OF 11



Data obtained from unpublished report of geochemical analyses submitted by Unocal (Union Oil, 1983) to State of Alaska Oil and Gas Conservation Commission.

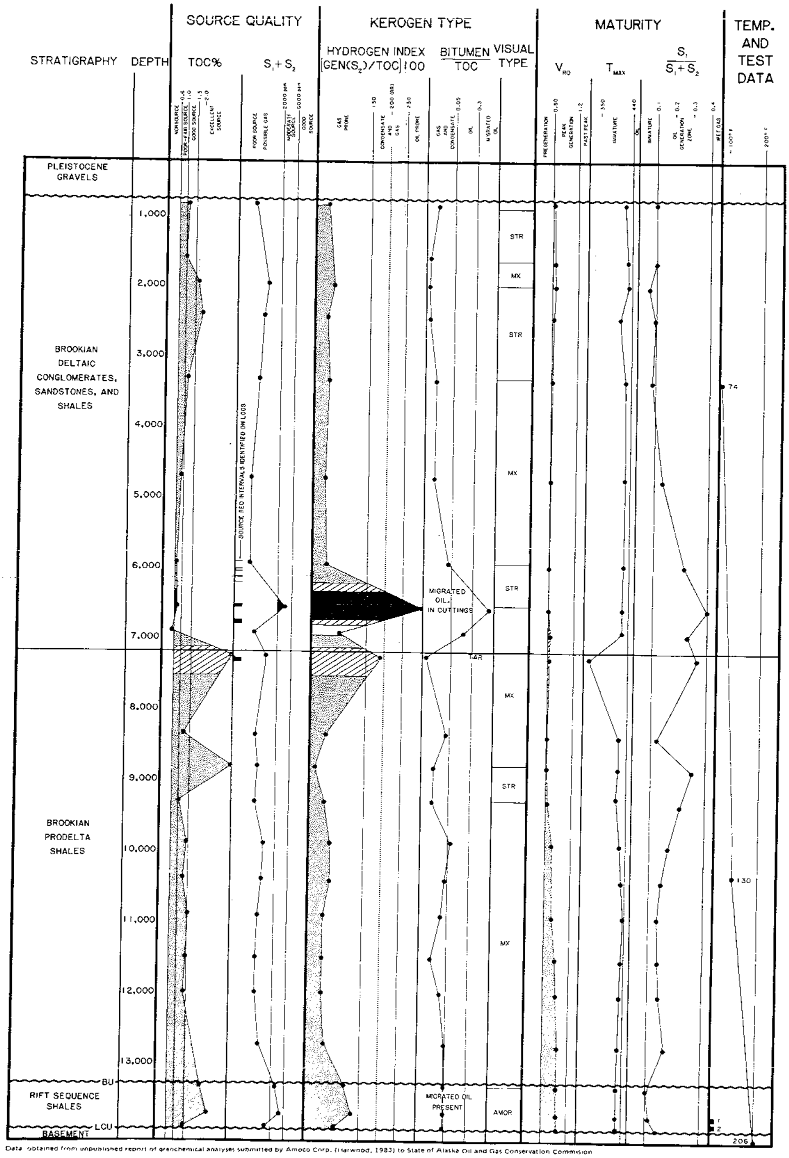
■	POTENTIAL OIL SOURCE BED
▨	POTENTIAL CONDENSATE/GAS SOURCE BED
░	POTENTIAL DRY GAS SOURCE BED
□	NONSOURCE

TEST #1: BROOKIAN SAND
RECOVERED 0.5 BBL DRILLING MUD

TEST #2: BROOKIAN PRODELTA SAND
248 BOPD (21° API) AND 124 MCFD
PRESSURE GRADIENT 0.62 psi/ft

TEST #3: POINT THOMSON SAND (LOWER CRETACEOUS)
RECOVERED 1.5 BBL DRILLING MUD

Source rock geochemical profile for the EXXON Point Thomson No. 2 well.



Data obtained from unpublished report of geochemical analyses submitted by Amoco Corp. (Harwood, 1983) to State of Alaska Oil and Gas Conservation Commision

■ POTENTIAL OIL SOURCE

▨ POTENTIAL CONDENSATE AND GAS SOURCE

⬚ POTENTIAL GAS SOURCE

☐ NONSOURCE

STR: STRUCTURED OR HUMIC KEROGENS
AMOR: AMORPHOUS OR SAPROPELIC KEROGENS
MX: MIXTURE OF AMORPHOUS AND STRUCTURED KEROGENS

TEST #1: POINT THOMSON SAND (LOWER CRETACEOUS)
476 BOPD (38° API) AND 6.4 MMcfd
PRESSURE GRADIENT 0.80 psi/ft

TEST #2: POINT THOMSON SAND (LOWER CRETACEOUS)
REC. 1 BBL MUD

Source rock geochemical profile for the EXXON Point Thomson No. 3 well.

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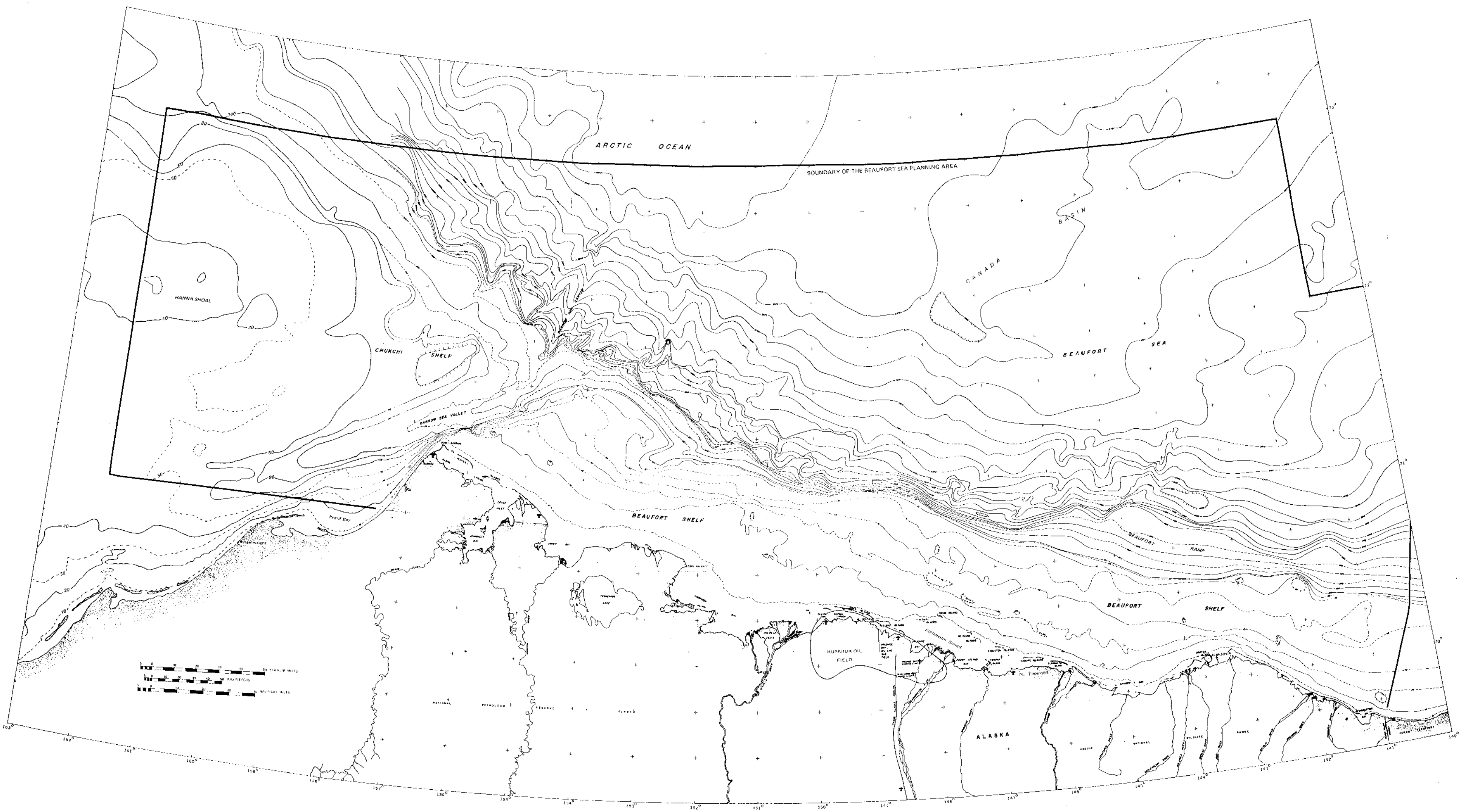
MMS 85-0111
PLATE 11 OF 11



Bathymetric map of the Beaufort Sea Planning Area. Bathymetry in the Beaufort Sea by Greenberg and others (1981). Bathymetry of the Chukchi Sea after Hill and others (1984).