UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

GEOLOGIC FRAMEWORK, HYDROCARBON POTENTIAL, ENVIRONMENTAL CONDITIONS, AND ANTICIPATED TECHNOLOGY FOR EXPLORATION AND DEVELOPMENT OF THE BEAUFORT SHELF NORTH OF ALASKA

A SUMMARY REPORT

U.S. DEPARTMENT OF THE INTERIOR

POSSIBLE OIL AND GAS LEASE SALE

NO. 71

By

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Open-File Report 80-94

This report is preliminary and
has not been edited or reviewed
for conformity with Geological
Survey standards and nomenclature

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Introduction

The continental shelf beneath the Beaufort Sea, the site of possible oil and gas lease sale 71, is probably the most promising untested terrane for giant accumulations of oil and gas under the jurisdiction of the United States, and environmentally the most difficult area to explore and develop. This report[1/] presents an overview of the geologic framework, petroleum potential, environmental conditions, geologic hazards and anticipated technology for development of this shelf. Its purpose is to assist the Bureau of Land Management in the selection of areas most attractive for leasing, to identify the geologic environmental constraints and hazards, and to make projections concerning the technology that will be required for petroleum exploration and development.

The area of the possible lease sale (fig. 1) extends from Point Barrow on the west to the maritime boundary with Canada on the east and from the three geographical mile line on the south to approximately the 200-m isobath on the north. The possible lease sale area is near the National Petroleum Reserve in Alaska (NPRA), the Trans-Alaska Pipeline System (TAPS), and a number of onshore oil and gas fields and seeps (fig. 1). The tract is adjacent to areas of active petroleum exploration and development by industry on state lands between NPRA and the Arctic National Wildlife Range (ANWR), and by the U.S. Geological Survey in NPRA.

The present report is an expansion of U.S. Geological Survey Open-File Report 76-830 (Grantz and others, 1976), which summarizes the geologic framework, petroleum potential, geologic environment and operational considerations for proposed oil and gas lease sale 50 in the central and western Beaufort Sea. The expansion includes the addition of maps which delineate the bathymetry and principal environmental geologic features and hazards of the region. A list of published geologic and geophysical surveys of the Beaufort Shelf is presented as an Appendix.

[1/] Grantz and Dinter prepared the sections on Geologic Framework and Petroleum Potential, and the Environmental Geology subsections from Unconsolidated Sediments and Tectonic Instability to Overpressured Shale; Scott prepared the Resource Appraisal Estimate; Barnes and Reimnitz prepared the Environmental Geology subsections from Shelf Deposits to Suspended Sediment; and Lynch prepared the section on Technology.

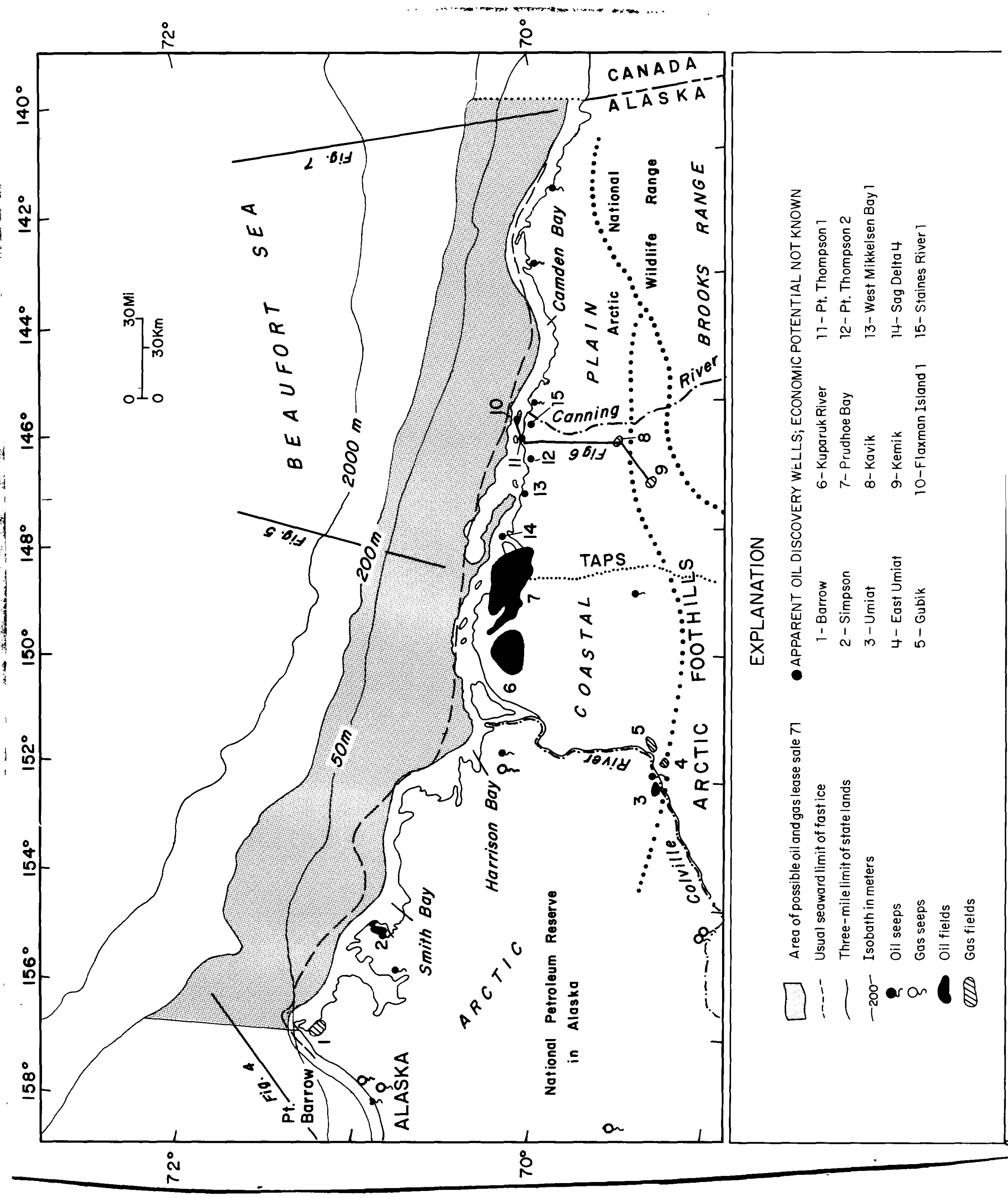

Figure 1. Area of possible Beaufort Sea oil and gas lease sale no. 71, showing the proximity of oil and gas fields and seeps in northern Alaska and the Trans-Alaska Pipeline System (TAPS).

Geologic framework of potentially petroliferous rocks

Possible lease sale no.71, covering the entire Beaufort Shelf north of Alaska, is conveniently divided into two sectors of contrasting geologic structure and generally distinctive, but overlapping, sedimentary sequences. The western (Barrow) sector extends from Point Barrow to approximately 145° W. long.and the eastern (Barter Island) sector from 145° W. long. to the Canadian border. Figures 2 and 3 show the general geology and the stratigraphy, lithology, and depositional and structural history of northern Alaska and the Beaufort Shelf. Typical cross-sections are presented in figures 4 to 7. Data for this section and that on Petroleum Potential for the offshore are mainly from Grantz and others, 1979, and Eittreim and Grantz, 1979. Data for the onshore are from Alaska Geological Society, 1971 and 1972; Brosgé and Tailleur, 1971; Jones and Speers, 1976; Grantz and Mull, 1978; and especially Tailleur and others, 1978.

The sedimentary strata of northern Alaska and the Beaufort Shelf are conveniently grouped into three regionally extensive sequences of contrasting lithology, tectonic character and hydrocarbon potential summarized in figure 3. The Cambrian to Devonian Franklinian sequence, consisting of mildly to strongly metamorphosed sedimentary and some volcanic rocks, constitutes economic basement for the Beaufort Shelf. Following metamorphism and regional deformation, an extensive platform was cut across the Franklinian rocks in Late Devonian and Early Mississippian time. This, the Arctic Platform, was a surface of low relief that was remarkably stable from Early Mississippian to Early Cretaceous time, an interval of more than 200 million years. During this time a lithologicallydiverse suite of clastic and carbonate sedimentary rocks, the Ellesmerian sequence, was deposited on the platform. This sequence contains both marine and nonmarine beds including organic-rich shale, texturally mature sandstone and conglomerate, and some dolomitized limestone. Clastic components were derived from a northerly source terrane that then lay beneath and north of the present outer Beaufort Shelf.

In Late Jurassic and Early Cretaceous time the northern part of the Arctic Platform, the source terrane for the Ellesmerian shelf sediments, was separated from northern Alaska by rifting which created the present continental margin of northern Alaska. Concurrently, the Arctic Platform was tilted down to the south and overridden by nappes from newly formed tectonic highlands in

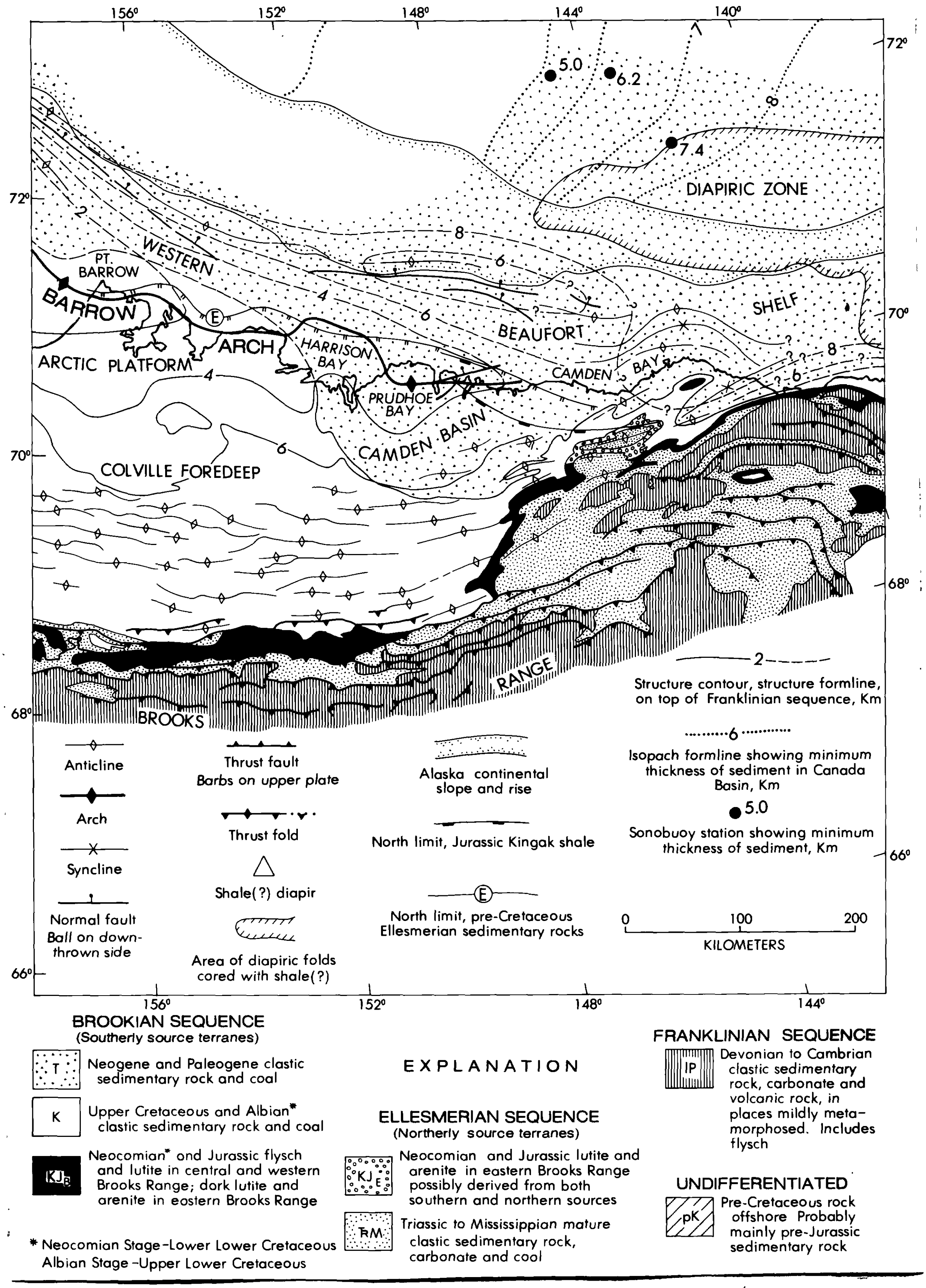

Figure 2. Generalized geologic map of northern Alaska and the Beaufort Shelf.

AGE		SEQUENCE	STRATIGRAPHY (South – North)	THICKNESS (m)	GENERALIZED LITHOLOGY	DEPOSITIONAL CHARACTERISTICS	STRUCTURAL HISTORY
CENOZOIC	QUATERNARY	BROOKIAN	GUBIK FORMATION	10-200	Marine sand, gravel, silt, clay.	Sediments derived from Brooks Range, Arctic Foothills, wave erosion of sea cliffs, and melting icebergs.	On eastern North Slope, gently warped in broad Holocene folds.
CENOZOIC	TERTIARY: NEOGENE; PALEOGENE	BROOKIAN	SAGAVANIRKTOK FM. (Eastern North Slope only)	0-2500 W - E	Poorly consolidated nonmarine and marine shale, sandstone, and conglomerate, with some carbonaceous shale, lignite, and bentonite.	Sediments mostly prograded northward from the nascent Brooks Range into the southward-deepening Colville Foredeep, an east-west elongate trough created when the Arctic Platform tilted southward, probably as a result of Brooks Range thrust sheets being loaded onto its southern edge. When the Colville Foredeep was filled, Cretaceous and Tertiary sediments overtopped the Barrow Arch and were prograded northward onto the Western Beaufort Shelf, where they are observed to thicken northward.	Offset by down-to-the-Canada Basin normal faulting related to subsidence of the continental margin subsequent to Early Jurassic rifting. Broken by northward-directed thrusts and involved in genetically related long, broad, roughly east-west folds which become tighter southward and are sometimes overturned to the north. This deformation is related to the late Mesozoic and Tertiary Brooks Range Orogeny.
MESOZOIC	CRETACEOUS: UPPER	BROOKIAN	COLVILLE GROUP (Central and eastern North Slope only)	0-3600 W - E	Predominantly nonmarine with coal in west. Mainly shallow marine clastics in east.		
MESOZOIC	CRETACEOUS: LOWER	BROOKIAN	NANUSHUK GROUP (W. North Slope)	0-3300+; 200-1200+	Marine and nonmarine shale, siltstone, sandstone, coal, conglomerate, bentonite. / Marine graywacke, siltstone, and shale.		
MESOZOIC	CRETACEOUS: LOWER	BROOKIAN	FORTRESS MT. FM. / TOROK SHALE (W. North Slope); BATHTUB GYKE. (E. No. Slope)	400->3000; 1000-3000; 200-1200+	Marine shale, sandstone and conglomerate. / Marine shale and siltstone, turbidites. / Marine graywacke, siltstone, and shale.		
MESOZOIC	CRETACEOUS: LOWER	ELLESMERIAN	"PEBBLE SHALE" and KONGAKUT FM. KEMIK SANDSTONE	100-700	Shelf and basinal marine shale and siltstone with rounded quartz grains and chert pebbles. Coquinoid to south; quartzose sandstone at base in east.	The Ellesmerian sequence on the Alaskan North Slope (except for the Kingak Shale and the Kongakut Formation, which were also derived in part from the south and east) was derived from a northern source terrane called Barrovia by Tailleur,1973. Ellesmerian equivalents in the Arctic Islands to the northeast have mostly southern and eastern sources. The constituent formations thin and coarsen northward and onlap the uplifted northern Arctic Platform in the crestal region of Barrow Arch, which lies approximately beneath the present coastline of northern Alaska. Only the thin "Pebble Shale" unit and locally the Kuparuk River Sands (at the top of the Kingak Shale) appear to extend north of Barrow Arch.	Sediments underwent local,erosional truncation 1) at the beginning of Permian time, 2) during Middle Triassic time, and 3) during Late Jurassic to Lower Cretaceous time. The sequence was tilted to the south in the initial (Jurassic and Early Cretaceous) phases of the Brooks Range Orogeny. During the Late Mesozoic and Tertiary phases of the orogeny, southern (mostly deeper-water) facies were thrust northward over shallower-water facies in the southern North Slope. The deformation died out to the north, reaching the coast only in northeasternmost Alaska.
MESOZOIC	JURASSIC	ELLESMERIAN	KINGAK SHALE (locally includes KUPARUK RIVER SANDS at the top)	0-1200+	Marine shale, siltstone, and chert, locally with glauconitic sandstone (in the west). Shallower-water facies are apparently the northerly ones.		
MESOZOIC	TRIASSIC	ELLESMERIAN	SHUBLIK FORMATION	0-225	To north; marine shale, carbonate, and sandstone (locally glauconitic). Includes Sag River Sandstone. To south; shale, chert, limestone, oil shale.		
PALEOZOIC	PERMIAN	ELLESMERIAN	SADLEROCHIT GROUP (and SIKSIKPUK FM. on Western North Slope)	0-700+	Eastern north slope; marine and nonmarine sandstone, shale and conglomerate grade downward into marine sandstone, siltstone and shale. Western north slope; Sandstone, conglomerate, and shale to north; argillite, chert, and shale to south.		
PALEOZOIC	PENNSYLVANIAN	ELLESMERIAN	LISBURNE GROUP	0-2000+	Fossiliferous marine limestone and dolomite, with some chert, sandstone, siltstone, and shale.		
PALEOZOIC	MISSISSIPPIAN	ELLESMERIAN	ENDICOTT GROUP	0-1000+	Marine sandstone, mudstone, shale, conglomerate, interbedded limestone, coal, and conglomerate.		
PALEOZOIC	PRE-MISSISSIPPIAN	FRANKLINIAN	(Pre-Mississippian rocks) IVIAGIK GROUP of Martin, 1970 (Lisburne Peninsula only)	Thousands of meters	Eastern north slope; argillite, graywacke, limestone, dolomite, chert, quartzose sandstone, shale, and metamorphic equivalents. Western north slope; argillite and graywacke.	Deposited during Middle Cambrian to Late Devonian time in the Franklinian geosyncline, which trended generally parallel to the Arctic margin of North America. North and northwestern facies mostly eugeoclinal. South and southeastern facies mostly miogeoclinal. Probably extends north beneath the Beaufort and Chukchi shelves to the continental slope and upper rise.	Folded, faulted, metamorphosed, and uplifted during the Late Devonian Ellesmerian (Antler) Orogeny. Truncated by regional erosion during Late Devonian time to form the Arctic Platform. Offset by Jurassic and younger down-to-the-Canada Basin normal faults north of Barrow Arch. Thrust-faulted and folded during the Brooks Range Orogeny.

Figure 3. Stratigraphy and depositional framework of northern Alaska and the Beaufort Shelf.

the area of the present Brooks Range. An asymmetric foreland basin, the Colville geosyncline, formed on the southward tilted platform north of the nascent mountain range.

The Colville geosyncline shoals northward toward the structural apex of the southward tilted Arctic Platform, the Barrow Arch, a basement high which trends parallel to the coast in the Barrow sector of the Beaufort Shelf. The south flank of the arch is the Arctic Platform underlying the Colville geosyncline; the north flank is the greatly modified scarp created by the rifting episode which created the continental margin to the north. Modification was by deep erosion and subsidence. Post-rift tilting, folding and faulting have created economically important geologic structures over the arch.

The Colville geosyncline was filled rapidly with Late Jurassic, Cretaceous and, on the eastern North Slope, Tertiary clastic sediments of the Brookian sequence derived from the proto-Brooks Range highlands to the south. They exceed 6,000 m in thickness in the southern part of the asymmetric Colville geosyncline, where they consist mainly of Late Jurassic and Early Cretaceous flysch and mid- and Late Cretaceous molasse, and thin northward to between 500 m and 2,000 m where they overlap the Barrow Arch. Because the progradation of the Brookian Colville sediments northward onto the Barrow Arch was gradual, and because the waning northern highlands were still shedding Ellesmerian sediments southward during the Brookian progradation, the boundary between the Ellesmerian and Brookian sequences is time transgressive. It lies within the Middle or Upper Jurassic in the Brooks Range, and rises into the Lower Cretaceous over the Barrow Arch and on the Beaufort Shelf.

Barrow sector: The geologic structure of the Barrow sector is dominated by the broad crest of the Barrow Arch near the coast and by the gently dipping north flank of the arch between the crest and the outer shelf. The gently north-dipping beds of the inner and central shelf are disrupted only by down-to-the-north normal faults of small displacement and by a broad fold on the outer shelf northeast of Point Barrow. The outermost shelf, in contrast, is the site of large rotational fault blocks bounded by normal faults, some of them growth faults, with large displacement. The terrane of faulted and rotated blocks is 10 to 25 km wide and more than 300 km long in the Barrow sector (figs. 2,4 and 5). Offshore of Prudhoe Bay the outer shelf is underlain by a broad erosional remnant (fig. 5). Both the large rotated fault blocks and the erosional remnant are in part onlapped, but mainly buried, by Brookian strata.

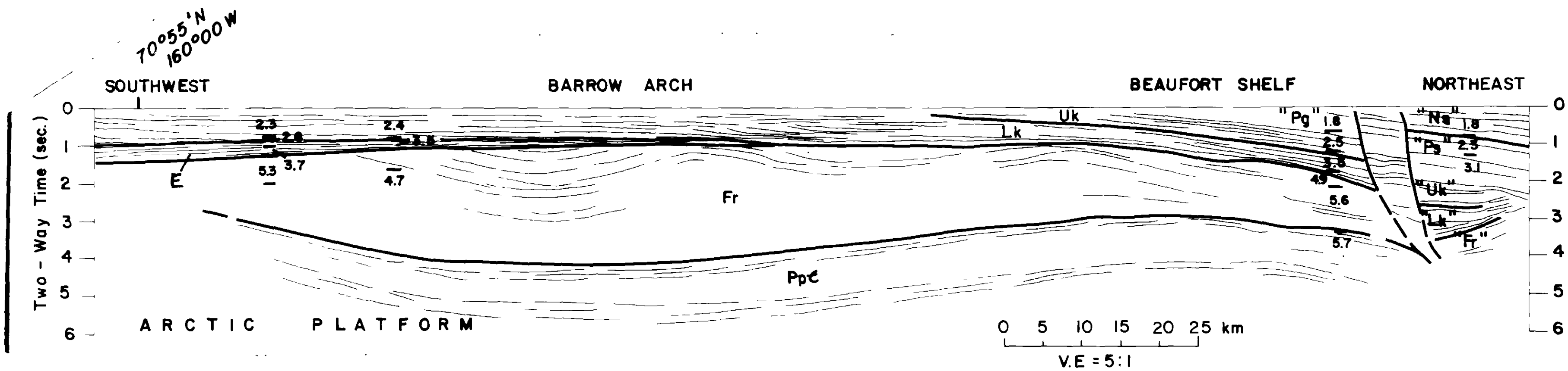

Figure 4. Cross-section based on seismic reflection profile near Point Barrow. See Figure 1 for location.

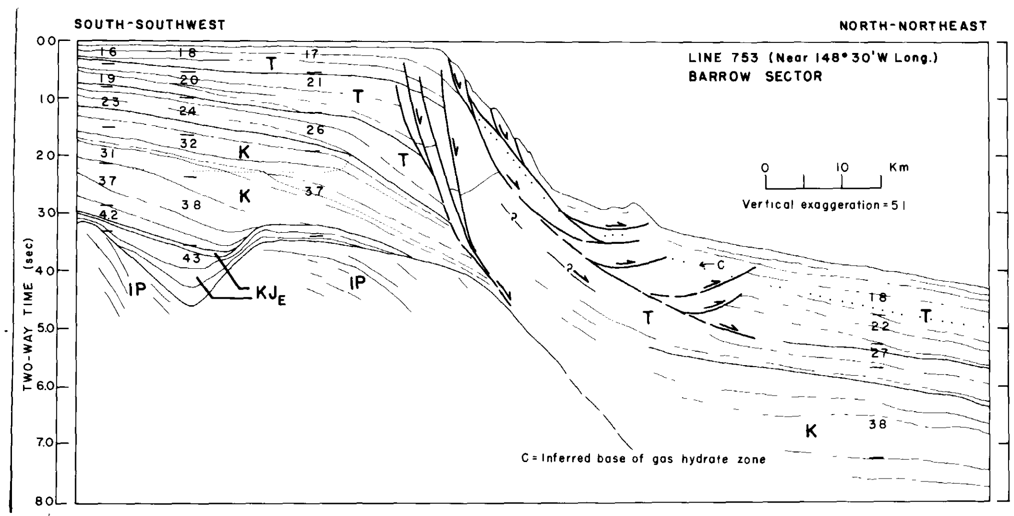

Figure 5. Cross-section based on seismic reflection profile near Prudhoe Bay. See Figure 1 for location.

Ellesmerian strata, due to original depositional patterns and to Early Cretaceous and older erosion, occur only in the southern part of the Barrow sector (fig. 2), where their thickness ranges from 0 to perhaps several hundred meters. These beds, and the Franklinian rocks that lie beneath and north of them, are overlain unconformably by Brookian clastic rocks of Albian (late Early Cretaceous) to Tertiary age. Brookian strata constitute most of the sedimentary volume of the Beaufort Shelf.

The Cretaceous beds of the Brookian sequence are both marine and nonmarine beneath the Arctic coastal plain of northern Alaska, but appear on seismic sections to become dominantly or entirely marine on the outer shelf. The Tertiary beds are nonmarine onshore, but appear to also contain marine facies offshore. The entire sequence is 500 to 2,000 m thick over Barrow Arch, but thickens northward to more than 6,000 m on the outer shelf.

<u>Barter Island sector</u>: Structurally, the Barter Island sector is dominated by two anticlines and an intervening syncline developed in late Cenozoic sedimentary rocks. The anticlines have amplitudes exceeding 1 km, widths exceeding 10 km, and are more than 150 km long (figs. 2 and 7). A deep synclinal basin on the south side of the folded terrane appears to trend southwest beneath the Arctic coastal plain near the Canadian border. The folded terrane of the Barter Island sector is transitional to the monoclinal terrane of the Barrow sector through a zone of numerous down-to-the-basin normal faults north of the western part of Camden Bay.

Brookian strata resting on Franklinian rocks, and perhaps locally on oceanic crust, underlie the Barter Island sector. Regional trends indicate that Ellesmerian strata are probably absent (Grantz and Mull, 1978). In the western part of the Barter Island sector the Brookian sequence consists of a thick section of Tertiary strata underlain by a thin section of Cretaceous beds (fig. 6) and by Franklinian rocks. In the eastern part of the sector (fig. 7), the Tertiary rocks are inferred, from regional trends and from seismic reflection profiles, to rest on a thick section of Jurassic and Cretaceous clastic sedimentary rocks of southern (Brookian) origin. The Jurassic and Cretaceous beds are predominantly marine onshore, and probably become mainly or entirely marine offshore. The Tertiary sequence is mainly nonmarine beneath the Arctic coastal plain, but contains beds of shallow marine origin in at least its upper part. The sequence presumably becomes increasingly marine seaward. The Tertiary rocks are locally as much as 4,000 m thick at the coast and may thicken in places to 6,000 m or more offshore.

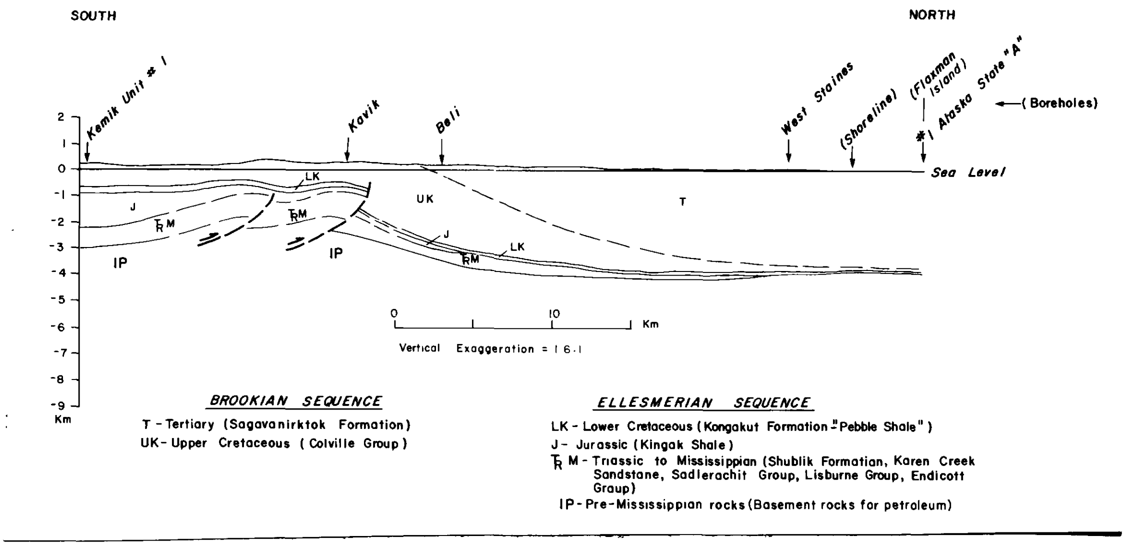

Figure 6. Cross-section based on test wells near the Canning River. See Figure 1 for location.

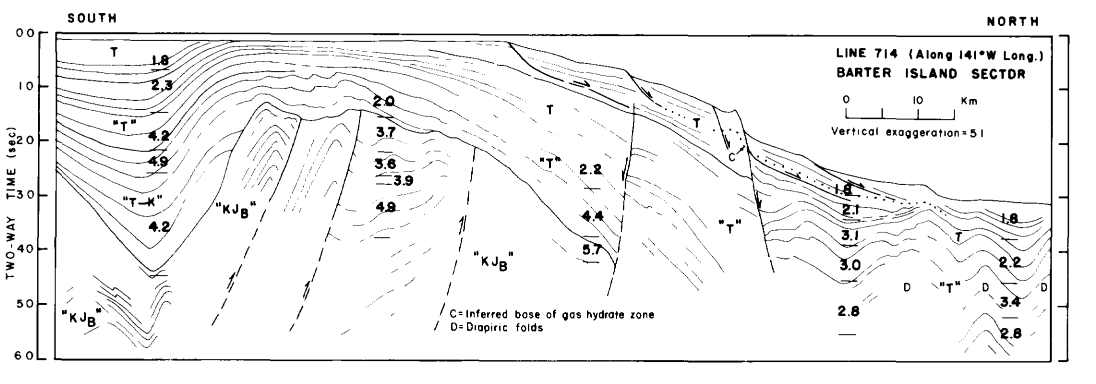

Figure 7. Cross-section based on seismic reflection profile near Demarcation Bay. See Figure 1 for location.

Petroleum potential

The area of possible lease sale no. 71 is almost ubiquitously prospective for petroleum. Unmetamorphosed sedimentary rocks of adequate thickness to contain commercial deposits underlie the entire area, and oil or gas occur at many stratigraphic levels beneath the adjacent coastal plain of northern Alaska. Ten of the thirteen major stratigraphic units of the Ellesmerian and Brookian sequences beneath the coastal plain contain commercial pools or strong shows of oil or gas (fig. 8). A giant and a supergiant oil field, a small producing gas field, six undeveloped oil discoveries of unknown or unannounced economic potential, and several oil and gas seeps are known to lie within 10 km of the coast. Exploration on the Canadian portion of the Beaufort Shelf has reportedly led to the discovery of large deposits of oil and gas in rocks that trend toward the Barter Island sector of the Beaufort Shelf. The prolifically petroliferous Ellesmerian beds, which contain supergiant pools of oil and gas at Prudhoe Bay, extend beneath the southern part of the Barrow sector to a structurally favorable position above the crestal region of the Barrow Arch. The Brookian beds, in which there are many shows of oil and gas along the coast, contain promising accumulations of oil and gas at Flaxman Island and Point Thompson. These rocks also extend northward beneath the Beaufort Shelf.

The petroliferous rocks which trend beneath the Beaufort Shelf from northern Alaska contain a number of structures potentially favorable for trapping economic accumulations of oil and gas. Seismic reflection profiles show part of the crestal region of the Barrow Arch, two large, compound anticlinal arches of regional extent, a few broad folds, interfingering lithofacies, and gently seaward-dipping sedimentary rocks broken by numerous down-to-the-basin normal and growth faults of small to moderate displacement. The presence of a thick section of oil- and gas-bearing rocks with many potential trapping structures, some of them very large, suggests that the Beaufort Shelf could contain large accumulations of oil and gas.

Resource appraisal estimate

The area evaluated for hydrocarbon resources extends from Point Barrow (approximately 156°30'W) eastward to the maritime boundary between the United States and Canada and seaward from the shoreline to the 200-m isobath. This area is the shelf portion of the Beaufort Sea Province, and includes both federal and state acreage.

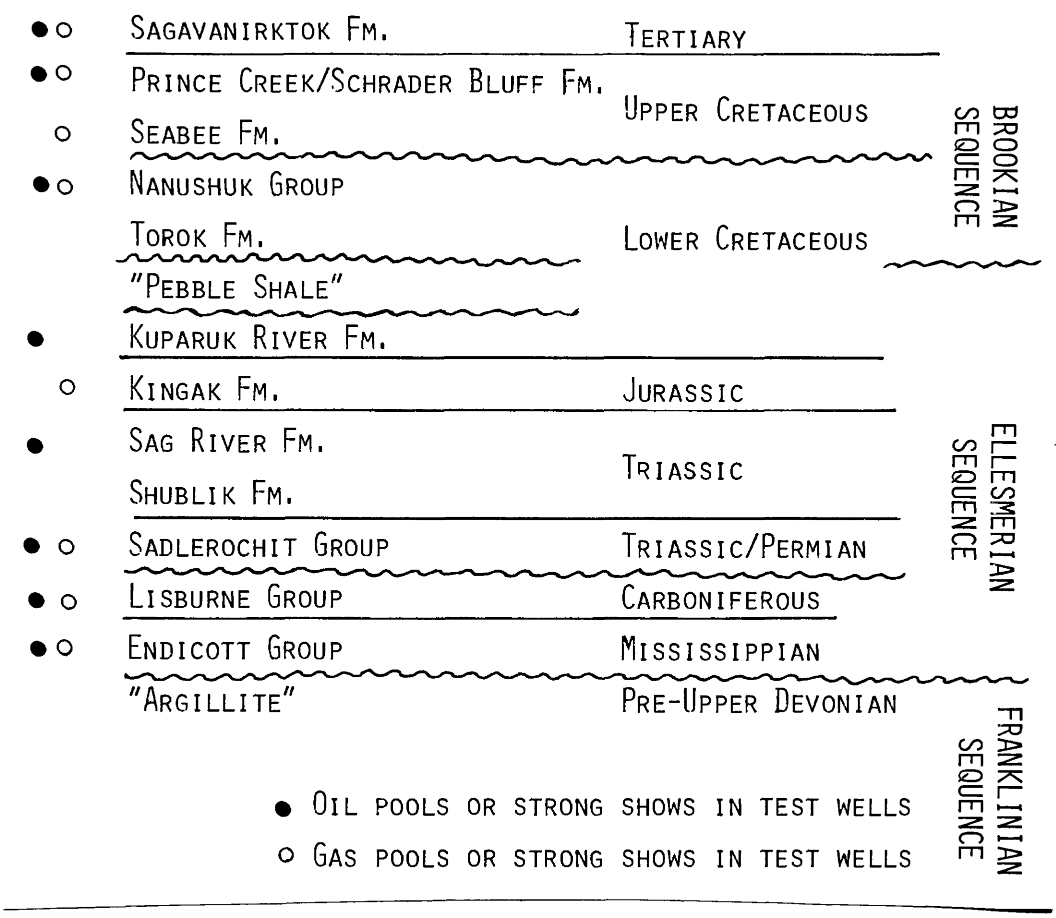

Figure 8. Generalized stratigraphic column beneath the Arctic coastal plain of northern Alaska, showing position of oil and gas pools and of strong shows of oil and gas encountered in test wells. (Data from Alaska Geological Society, 1971, and 1972; Brosgé and Tailleur, 1971; Jones and Speers, 1976; and industry announcements).

Estimates for the Beaufort Sea Shelf are given in two ways. First, the conditional estimates represent those quantities of oil and gas estimated to be present, given that commercial quantities do exist. Second, the unconditional estimates represent those quantities estimated to be present, but incorporating the risk of no commercial accumulations. These latter figures represent statistical expectations of undiscovered recoverable resources.

The odds of finding commercial quantities of oil and gas are uncertain in frontier areas, and a marginal probability is assigned to express this risk. The marginal probability assigned in this case is .81, or an 81 percent chance of finding a commercial accumulation. This high figure is based upon the close proximity of onshore production to this offshore area.

Following are both the conditional and unconditional oil and gas resource estimates for the Beaufort Sea Shelf:

	95% Probability	5% Probability	Statistical Mean	Marginal Probability
Conditional				
Oil (B. bbls)	2.2	10.4	5.4	
Gas (Tcf)				
Assoc/Dissolved	3.1	14.6	7.5	
Non-Assoc.	5.4	24.8	12.8	
Unconditional				
Oil (B. bbls)	0.0	10.4	4.3	.81
Gas (Tcf)				
Assoc/Dissolved	0.0	13.8	6.1	.81
Non-Assoc.	0.0	25.5	10.4	.81

The above estimates represent assessments of undiscovered recoverable oil and gas. Much of the acreage within the assessed area is believed to be amenable to drilling and producing operations under present or foreseeable conditions of economy and technology. These are qualifying conditions for recoverable resources.

The resource values and distributions shown in this report result from the statistical processing of original subjective probability estimates. These procedures incorporate computer curve fitting techniques and computer random sampling (Monte Carlo) techniques. Both produce natural small variations in output values between successive runs, or in what might be theoretically

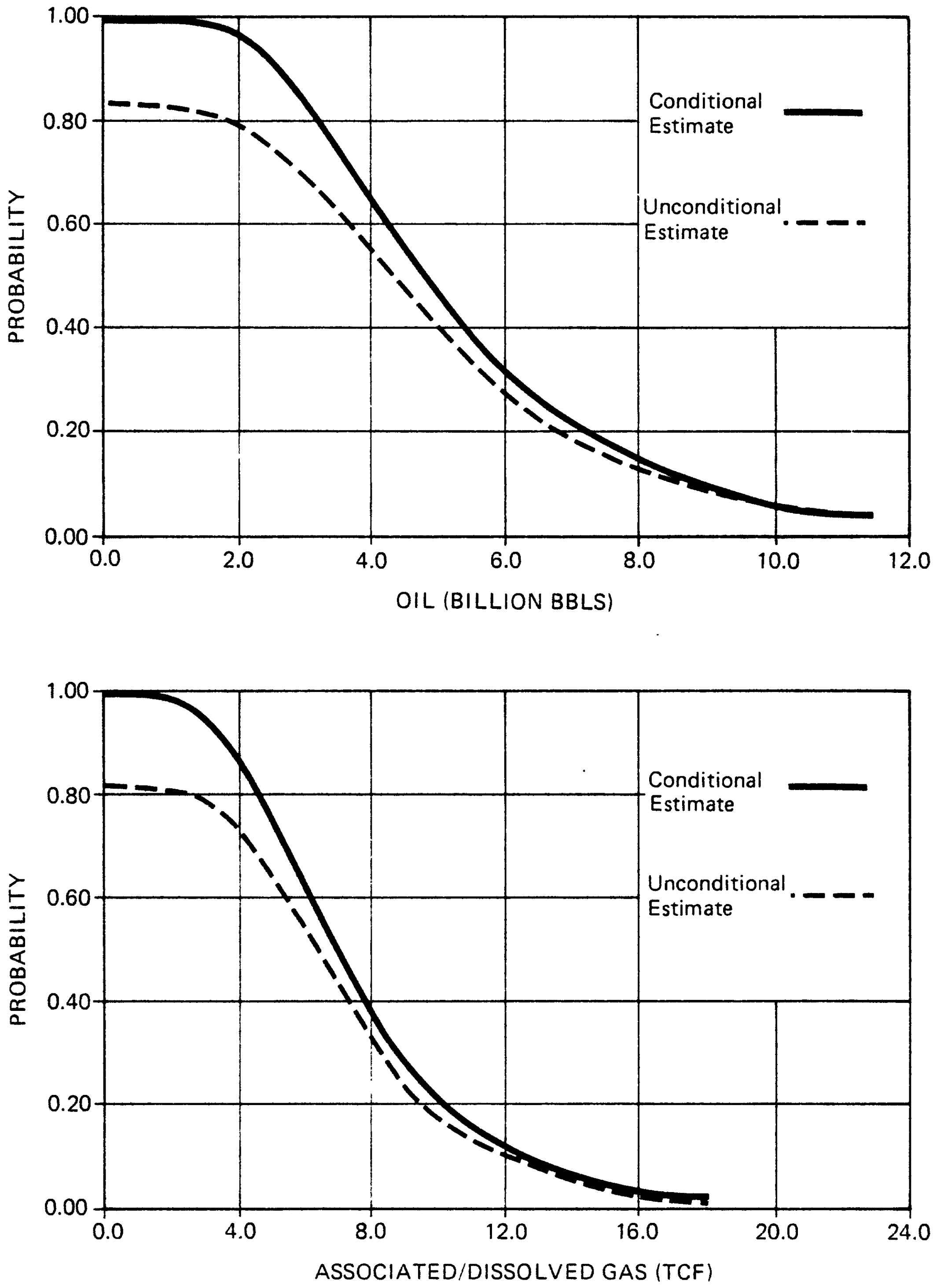

Figure 9. Probability distribution of undiscovered recoverable resources of oil and associated/dissolved gas for Beaufort Sea OCS Sale no. 71 (0.200 m).

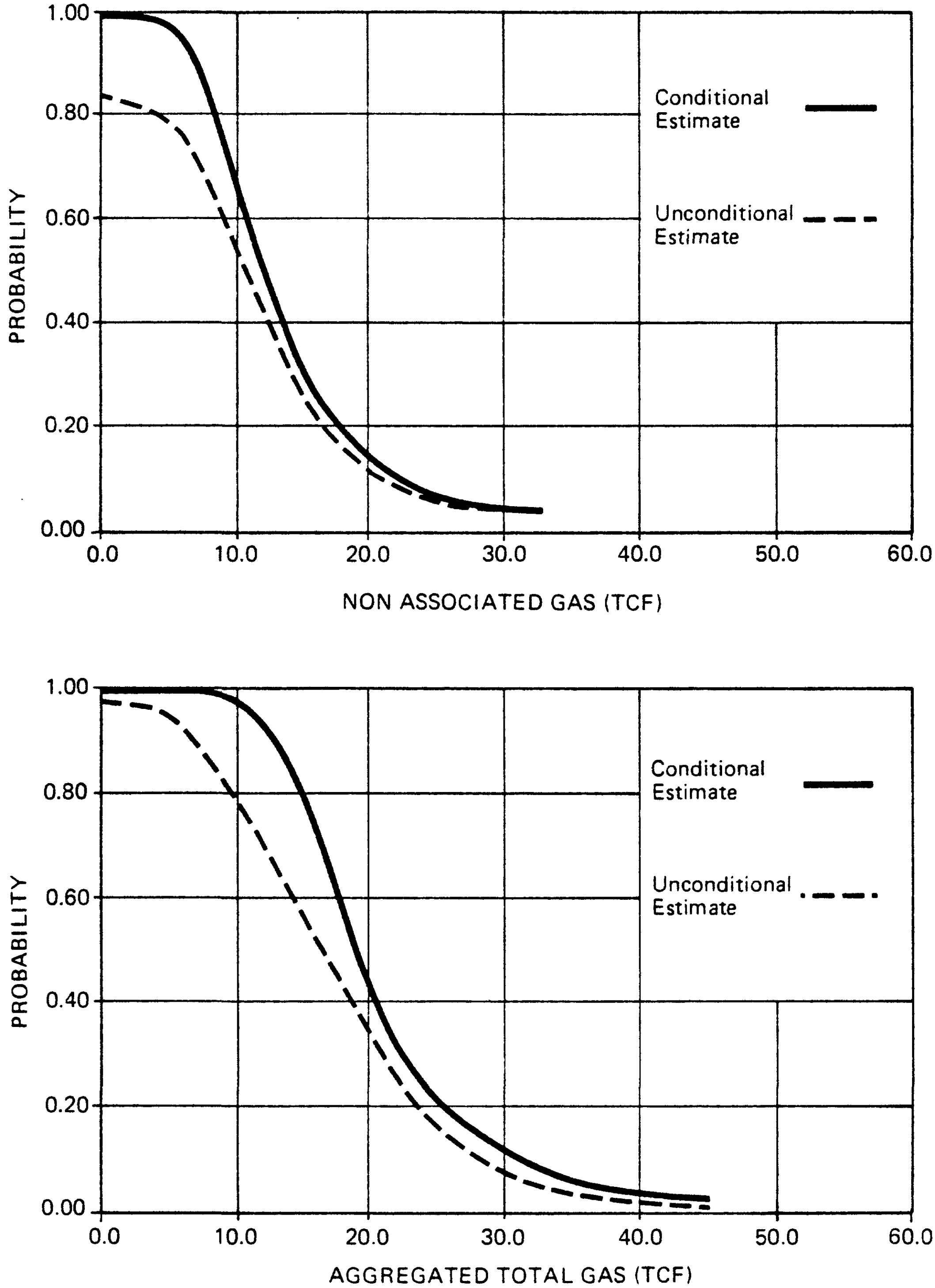

Figure 10. Probability distribution of undiscovered recoverable resources of non-associated and aggregated total gas for Beaufort Sea OCS Sale no. 71 (0-200 m).

calculated. As a consequence, values are shown which may occasionally appear inconsistent relative to other output, but are valid and well within limits of accuracy of the assessment.

The estimates of undiscovered oil and gas were computerized and processed as probability distributions, utilizing log-normal curves, as shown in figures 9 and 10.

Environmental geology

Sea ice and other factors related to the Arctic climate are so influential in shaping the geologic environment of the Beaufort Shelf that information gained by studying recent geologic processes in temperate latitudes is only partly applicable. The shelf is also unusual in that, although it overlies a passive continental margin, it is being deformed by modern normal and thrust faults, some of which generate shallow earthquakes.

General description: The bathymetry of the western Beaufort Sea is presented in figure 11. The coastline is characterized by low tundra bluffs and a complex of river estuaries, bays, barrier island chains and coastal lagoons. The continental shelf ranges in width between 45 and 90 km and slopes gently to the north. Most areas of the inner and central shelf are essentially flat except for extensive micro-relief caused by the plowing and churning action of drifting ice in contact with the seafloor. Landward of the 20 m isobath subtle linear topographic highs parallel the coast. Nearshore, a prominent bench inside the 2 m isobath is apparently related to the seasonal growth of sea ice. Off Camden Bay the flat seabed is disrupted by scarps as high as 6 m that mark Holocene faults. Seaward of the 50 to 65 m isobath the seabed is broken by scarps, sags and rotated slump blocks with local relief as great as 22 m. This rough seabed is within the headwall extension zone of an extensive bedding plane slide terrane that underlies the outer shelf.

Unconsolidated sediments and tectonic instability: The most poorly consolidated sediments on the Beaufort Shelf are the Holocene marine muds and silts whose thickness is contoured on figure 12. They have been identified and measured on high-resolution (Uniboom) seismic profiles on the basis of acoustic properties and geometric considerations. Inshore drilling information locally corroborates the acoustic data. The Holocene deposits apparently form a wedge which thickens offshore to a maximum of about 40 to 50 m near the shelf-break, where the wedge overlaps the shoreward boundary of the chaotic slump terrane. The wedge is apparently thinner on the western half of the shelf than in the east, but records in the west are much less definitive. Holocene deposits are notably absent along the coast. Little sediment appears to be accumulating in deltas and offshore from rivers.

The Holocene sediments on the middle and outer shelf and probably a substantial thickness of the underlying Pleistocene sediments have low shear strength, as indicated by the development of very low-angle bedding-plane slides, and they may be susceptible to liquefaction as well. The instability of these deposits poses the greatest potential hazard to pipelines, platforms and artificial islands on the outer shelf, where the deposits are thickest and have the steepest gradient, and near the active seismic zone near Camden Bay. A band of unknown width shoreward of the bedding plane slide terrane of the outer shelf (fig. 13), where failure might be triggered by earthquakes or by the release of large slump masses in the adjacent slide terrane, is also hazardous.

Abrupt changes in thickness of the Holocene sediment on the shelf north of Camden Bay are interpreted to be the result of 10 to 25 m of Holocene uplift in a northeast-trending zone about 30 km wide and at least 60 km long. Many historical earthquakes have epicenters in this zone (fig. 14) and the seabed there is offset by scarps as high as 6 m. Structures emplaced on the thick Holocene sediments flanking this uplifted, seismic area will be subject to especially strong shaking during earthquakes. Tectonically triggered sediment instability apparently presents no threat to petroleum development on the inner shelf landward of the 20-m isobath, where slopes are gentle and Holocene deposits thin.

Earthquakes: The seismicity of northeastern Alaska and the adjacent Beaufort Shelf, based on regional and local network data from 1968-1977, has been summarized by Biswas and Gedney (1978). The larger earthquakes of Alaska, including the Beaufort Shelf, as determined from the worldwide network, are reported by Meyers (1976). All epicenters on and near the Beaufort Shelf reported in these sources are plotted on figure 14. It is apparent that the only area of the Beaufort Shelf with recordable seismic activity since 1935 is the area of young faulting and Holocene uplift off Camden Bay. According to Biswas and Gedney, these earthquakes are all from shallow crustal sources. The largest of them, that of January 22, 1968, had a magnitude of 5.3. This earthquake and its aftershocks dominate the seismic record on the shelf. Biswas and Gedney (1978, p. 1) state that one of the design criteria for structures built for the exploration and development of hydrocarbons in the Barter Island area of the Beaufort Shelf should be the ability "...to withstand ground vibrations corresponding to those from a shallow earthquake (less than 20 km) of at least magnitude 6.0."

The Beaufort Shelf east of the seismic zone off Camden Bay may also be seismically active because late Cenozoic folds and local Holocene warping, which are spatially associated with this seismic zone, extend eastward to the Canadian border. However, only two earthquakes have been reported from the Alaskan shelf east of the seismic zone off Camden Bay, and the Holocene warping that is found to the east is of lesser amplitude and areal extent than it is off Camden Bay. If the area to the east is seismic, it is apparently only weakly so.

Young tectonic faults: Normal and reverse faults, many of which offset Holocene deposits and the seabed, and monoclines overlying such faults are abundant off Camden Bay (fig. 14). The youthfulness and local abundance of these features and their coincidence with the area of Holocene uplift and shallow earthquakes, strongly suggest that at least some of them are active. The zone of abundant young faults off Camden Bay coincides with the west end of the terrane of large late Cenozoic folds that characterize the Barter Island sector of the Beaufort Shelf and appears to represent a locally active front of the tectonic system that produced the folds. The maximum observed offset of the seabed on these faults and monoclines is 6 m.

There are insufficient data from which to calculate a definitive recurrence interval for displacement events on the faults off Camden Bay. A rough estimate can be made, however, if the area is capable of generating shallow, magnitude 6 earthquakes, as suggested by Biswas and Gedney (1978), and if we assume the common case that fault displacement events here are episodic and produce earthquakes. Surface fault offsets accompanying historic worldwide shallow earthquakes of magnitude 5 to 6, according to a compilation by Slemmons (1977), have ranged from 0.015 to 0.61 m. A curve relating the Holocene rise in sea level off northern and western Alaska (Hopkins, 1979) to time suggests that inundation of the sea floor offset by the faults, allowing for 10 to 25 m of observed Holocene tectonic uplift, occurred about 13,000 to 16,000 years ago. As the fault-related seabed morphology does not appear to have been modified by the passage of a strand-line, the offset seabed is probably younger than 13,000-16,000 years. From these observations and assumptions we calculate that the faults which produced the 6-m seabed offsets, which we assume from the seismicity of the area to be still active, have a maximum recurrence interval for displacement events and related earthquakes of between 30 and 1,600 years. The longer intervals would pertain if typical earthquakes are closer to magnitude 6, and the expected offsets would be in the upper part of the range of offsets compiled by Slemmons. In view of the short instrumental seismic record, the magnitude 5.3 earthquake of 1968 should not be considered typical for Holocene earthquakes in this area. We suggest that a recurrence interval of a few hundred years may be the most realistic estimate that can be made at present for earthquake-generating displacement events on the largest seabed-offsetting faults off Camden Bay.

Young gravity faults: Two types of down-to-the-basin, north-dipping gravity faults along which the sedimentary prism of the shelf failed and moved toward the "free face" of the continental slope, underlie the western Beaufort Shelf (fig. 14). These faults include all those shown outside of the northeast-trending zone of seismicity and Holocene uplift off Camden Bay. The first type of gravity fault, which is restricted to the outermost shelf and upper slope, has total displacements as great as 1,055 m and bounds shallow structural blocks that are akin to large rotational slumps. Most of the offsets along these faults may have occurred in one or a few large displacement events. Additional features of this type are likely to disrupt the adjacent outermost shelf in the future.

The second set of gravity faults, which occurs beneath the middle and outer shelf, is characterized by much smaller offsets of Quaternary deposits and the seabed than the first set and includes many growth faults with a long history of activity. The outer shelf faults of this set displace Holocene deposits and the seabed as much as 15 to 20 m, and in one area possibly as much as 70 m. Those on the mid-shelf displace sediments no younger than Pleistocene or early Holocene.

The gravity faults are active in the sense that they formed in the present tectonic environment and displace Pleistocene or Holocene sediments. However, they have not generated earthquakes of sufficient magnitude to be detected by the regional and local seismograph networks in place since 1968. The lack of seismicity may be due to the fact that low stress drops are characteristic of movement along gravity faults. In the absence of earthquakes or detailed physical stratigraphy, the recurrence interval of displacement events along the gravity faults is impossible to calculate. We estimate, however, that the faults beneath the outer shelf, which show large Holocene offsets, may have recurrence intervals in the range of a few hundred to several thousand years. Those on the mid-shelf, which show only Pleistocene or early Holocene offsets, may be quiescent or have very long recurrence intervals.

Slumping and sliding: Most of the Beaufort outer shelf and upper slope seaward of the 50 to 65 m isobaths is disrupted by active bedding-plane slides and massive slumps developed in unconsolidated or poorly consolidated Holocene and Pleistocene sediments (fig. 13). High resolution seismic records (principally Uniboom) collected across the entire western shelf and slope at 15 to 50 km intervals have allowed the delineation of several distinct instability terranes. These terranes include sag zones at the heads of extensional terranes, coherent bedding-plane slide zones in which large tabular blocks that moved seaward are separated by deep, open crevasses, rotational slump terranes in which large slump masses broke along listric surfaces and slid downslope at high angles, and hummocky rubble piles at the base of the slide terrane where slump masses accumulated.

The bedding-plane masses are tabular sheets up to 38 km long and typically 20 to 230 m thick that move seaward along slip planes which, since they dip only 0.5° to 1.5°, must include materials of very low shear strength. Locally, up to three generations of slide masses are superimposed, and reactivation of sliding along the older slip planes is apparently common. The sediments involved in sliding have not been dated paleontologically; however, the thinner slides and the uppermost parts of the thicker ones formed in a unit of unconsolidated deposits that is inferred from acoustic stratigraphy to be of Holocene age. These deposits are typically 30 to 50 m thick near the head of the slide terrane (fig. 13).

In view of the evidence for repeated failure of broad, thick masses of unconsolidated and poorly consolidated sediment at as many as three levels in the sediment column, much of the lease area seaward of the 50 to 65 m isobaths is hazardous or potentially hazardous to petroleum development structures.

Permafrost: Prior to about 10,000 years ago, during the last glacial sea-level lowstand, the present Beaufort Shelf was exposed subaerially to frigid temperatures and ice-bonded permafrost probably aggraded downward in the sediments to depths exceeding 300 m. Reflooding of the shelf exposed these sediments to saline water at temperatures above the freezing point and much of the permafrost terrane has probably warmed and remelted.

Studies are underway to seismically assess the depth to and thickness of relict permafrost over the entire Beaufort Shelf; however, only the terranes inshore of the barrier islands on the inner shelf have been characterized thus far. Sellman and Chamberlain (1979) report that, in this area, there are three obvious groups of seismic velocities which are apparently related to the degree of ice-bonding in the sediments. Fully ice-bonded permafrost with ice-saturated pores and velocities greater than 4.0 km/sec. crops out onshore and on the barrier islands and in adjacent wide zones landward of the 2-m isobath that are overlain by bottom-fast ice in winter. Between the shore and the barrier islands fully ice-bonded permafrost lies at highly variable depths as great as several hundred meters beneath the seafloor. The ice-bonded permafrost is overlain in this area mostly by materials with velocities centered around 2.7 km/sec. which are taken to represent partially ice-bonded sediments containing varying proportions of unfrozen pore water. Materials with velocities less than 2.2 km/sec. are sparse and assumed to be unbonded.

Although the distribution of relict permafrost seaward of the barrier islands is unknown, the base of Holocene marine sediments on the Beaufort Shelf, contoured in figure 12, provides a probable minimum depth to its upper surface there. This is so because it is unlikely that permafrost aggraded upward into the Holocene saline marine muds deposited on the shelf after the rise in sealevel. By analogy with the conditions described nearshore, any permafrost in the uppermost sediments beneath the Holocene sediment "wedge" was probably melted or partially melted down to unknown depths. Depending on such parameters as pore water, salinity, original thickness and temperature of the subaerial permafrost, and the insulating effect of the Holocene muds, fully ice-bonded permafrost may or may not be encountered at depth offshore. Where it exists, care must be taken to avoid melting beneath pipelines and drilling platforms and within frozen intervals encountered in drilling.

<u>Shallow gas</u>: Shallow gas may accumulate in three distinct geologic environments beneath the shelf and slope of the western Beaufort Sea. It forms isolated pockets within and beneath permafrost, is inferred to underlie sheets of solid gas hydrate beneath the slope and deepest parts of the outer shelf, and may be present in scattered, isolated concentrations seeping through or generated within loosely consolidated Quaternary sediment (fig. 15). These conclusions are based on the interpretation of high and low frequency seismic reflection profiles which delineate the gas hydrates fairly well, but yield little direct information pertaining to permafrost distribution.

The existence and extent of shallow, free gas is only nominally established, due in part to the rather erratic distribution of such gas and in part to intermittent degradation of our high-resolution data during storms.

Gas hydrates (solids composed of light gases caged in the interstices of an expanded ice lattice) are stable under the low temperature and relatively high pressure conditions prevailing within the uppermost 300 to 700 m of sediment beneath the continental slope of the Beaufort Sea. Although the hydrates probably do not extend into the lease area, the rather common, linear irregularities along the base of the hydrate zone may form conduits along which free gas that accumulated beneath the hydrates could migrate upslope to form pockets in sediment beneath the upper slope and outer shelf.

"Turbid" zones on high resolution (Uniboom) seismic profiles in which strong, continuous reflectors are "wiped out" for short distances, have been ascribed to the presence of shallow gas, probably predominantly biogenic methane,in Quaternary sediments. The "turbid" intervals are apparently restricted mostly to the inner shelf and are most abundant in a zone about 50 km north and northwest of Prudhoe Bay (fig. 15).

Overpressured shale : Numerous diapirs disrupt the sediments and, in places, the seafloor beneath the continental slope and rise east of 146° W. long. (fig. 15). The source of these diapirs is interpreted from multichannel seismic data to be a layer of low seismic interval velocities ($\sim$2.7 km/sec.) underlying beds with somewhat higher interval velocities about 3 km beneath the seabed. These source beds are interpreted to be overpressured shales that extend shoreward beneath the upper slope and outer shelf, where they may pose hazards to drilling in the lease area.

Shelf deposits: The shelf of the Beaufort Sea is essentially a seaward extension of the low, flat coastal plain of northern Alaska, and like the coastal plain is probably underlain by shallow-water marine and terrestrial sediments of the Gubik Formation. These sediments crop out in ice gouges, in current-scour depressions and where Holocene sediments are absent. Surficial Holocene deposits generally consist of 5 to possibly more than 45 m of fine-grained marine mud and sand. The textural character of the surficial sediments is shown on figure 16. Local accumulations of gravel and boulders, mainly along the shelf break, apparently represent relict ice-rafted materials. Modern ice-rafting does not appear to be a significant modern process of sediment transport for coarse-grained materials in this area, but may be important in transporting silts and clays.

The thin veneer of Holocene sediments and the low regional slopes of the shelf indicate that shoreward of the 50 to 60 m isobath the materials are not subject to large-scale slumping. The surficial sediments are, however, frequently disrupted and reworked by keels of deep-draft sea ice. The coastal bluffs are slumping and mass wasting, due primarily to the erosion of ground ice and frozen soil by surface water during the summer months. As a result, the coastal bluffs retreat at average rates of 1 to 3 m per year along the entire coast (fig. 17). Extreme rates of 30 to 50 m have been recorded at coastal promontories during major storms.

Polar ice pack: The seasonal freeze-thaw cycle along the coast starts with the formation of river and sea ice during late September. By the end of December the sea ice is commonly a meter thick, and it thickens to a maximum of about 2 m in May. In late May and early June, 24-hour insolation aids rapid thawing in drainage basins and river flow is initiated, which floods the as yet unmelted sea ice off river mouths. Much of the lagoonal and open-shelf fast ice inside the 10-m contour melts with little movement by the middle of July. The ice-melt zone off river mouths can reach a width of 10 to 15 km in response to the influx of warm river water. The remaining sea ice continues to melt and retreat offshore through the completion of the cycle in late July, August and early September.

The winter ice canopy overlying the shelf can be divided (fig. 18) into three broad categories: 1) seasonal floating and bottom-fast ice of the inner shelf, 2) a brecciated shear (stamukhi) zone containing grounded ice ridges that marks the zone of interaction between the stationary fast ice and the moving polar pack, and 3) the polar pack of new and multi-year floes on the average 2 to 4 m thick, pressure ridges, and ice-island fragments that are in almost constant motion. The deepest pressure-ridge keel that has been measured had a draft of 47 m. The general drift of the pack on the Beaufort Shelf is westerly under the influence of the clockwise-rotating Pacific Gyre.

The fast-ice zone is composed mostly of seasonal first-year ice, which, depending on the coastal configuration and shelf morphology, extends out to the 10 to 20 m isobath. By the end of winter, ice inside the 2 m isobath rests on the bottom over extensive areas. In early winter the location of the boundary between undeformed fast ice and the westward-drifting polar pack is controlled predominantly by the location of major coastal promontories and submerged shoals.

Pronounced linear pressure and shear ridges form along this boundary and are stabilized by grounding. Slippage along this boundary occurs intermittently during the winter forming new grounded ridges in a widening zone (the stamukhi zone). A causal relationship appears to exist between major ridge systems of the stamukhi zone and the location of offshore shoals downdrift of major coastal promontories. These shoals, which absorb a considerable amount of kinetic energy during the arctic winter, appear to have migrated shoreward up to 400 m over the last 25 years.

Grounded pressure-ridge keels in the stamukhi zone will exert tremendous stresses on the seabottom and on any structures present in a band of varying width between the 10 and 40 m isobaths. In some places the extent of shorefast ice may be deflected seaward by artificial structures.

Ice gouging: Ice moving in response to wind, current, and pack ice pressures often plows through and disrupts the shelf sediments, forming seabed gouges from nearshore out to water depths of at least 60 m (fig. 18). Gouges are generally oriented parallel to shore and commonly range from 0.5 to 1 m deep. However, gouges cut to a depth of 5.5 m have been measured on the outer shelf. When first formed, the gouges may be considerably deeper. Regions of high gouge density are common within the stamukhi zone and along the steep seaward flanks of topographic highs. Inshore of the stamukhi zone, seasonal gouges may be abundant but can be smoothed over during a single summer by wave and current activity. Rates of gouging inshore of the protective stamukhi zone have been measured at 1 to 2 percent of the seafloor per year.

Oceanographic regime: The overall movement of water on the shelf off northern Alaska is toward the west. On the inner shelf, the oceanographic regime is strongly influenced by winds and the presence or absence of ice. In most places, inner shelf sub-ice current velocities are less than 2 cm/sec. However, where the tidal prism is constricted by ice growth and in inlet channels velocities up to 25 cm/sec. have been recorded. Offshore, slope-parallel current pulses with velocities up to 50 cm/sec. and with both easterly and westerly directions have been observed near the shelf break.

Storm surge effects: Although the lunar tide range along the Beaufort coast in Alaska is less than 0.5 m, low barometric pressures and very strong westerly winds prevailing during exceptional storms can cause flood tides up to 3 m higher than mean sealevel (figs. 17 and 18). Depending on local topography barrier islands, artificial islands, standard offshore drilling platforms, and coastal facilities up to 1 km inland may be flooded during such storms, which occur primarily during the fall. In addition, the extremely strong currents moving across the inner shelf during the waxing and waning of these floods will deeply erode coastal bluffs, deepen the channels between barrier islands, and scour the foundations of drilling platforms and the flanks of natural and artificial islands. Major onshore ice movements may be associated with the storm-related sealevel changes and may also be damaging to nearshore structures.

Persistent northeast winds and large open-water areas can develop in the Beaufort Sea in late summer and early fall. Although sea level is lowered with these winds, they create large seas and swells which result in coastal erosion and retreat of as much as 50 m in one season.

Erosion: Coastal thermokarst erosion and barrier island migration will be a significant factor during the lifetime of structures built in these areas. Construction of causeways and mining of barrier islands for sand and gravel will require a thorough prior understanding of nearshore sedimentary processes and the origin of the sand and gravel in the islands.

River flooding: The initial snow melt and river flooding of the sea ice, followed by flood-water drainage has the potential to transport and widely distribute within a few days any pollutants and debris accumulated in the drainage basin during the winter. Scour activity at drainage holes in shorefast and bottomfast ice could be significant. A sudden impulse of river water interacting with an offshore (sub-ice) oil spill would probably enlarge the area affected by a spill.

Suspended sediment: Water clarities, in the past thought to be highest in winter, could be altered by construction activities, which may serve to resuspend particulate matter. This would have a direct adverse effect on the productivity of benthic communities on the seafloor and sub-ice surfaces.

Recent evidence shows that an intermittently occurring fall phenomenon, possibly involving the formation of underwater ice or anchor ice, is followed by long periods of highly turbid water and a sediment-laden seasonal ice cover. Supercooling of the water column in early fall may trigger such events. The consequences of the phenomenon on ice strength, sediment transport, melting rates during the following season, and biologic productivity are poorly understood. It is possible that man's activities, including the discharge of large volumes of brine during ice island and ice road construction, and the discharge of drilling muds could result in the formation of slushy underwater ice capable of affecting the transport of pollutants.

Technology

Estimated development timetable: Estimation of development times in remote Arctic regions is difficult. Extremely low temperatures and darkness for much of the year, environmental hazards and difficult access create problems that may cause extensive delays with attendant cost increases. Exploratory drilling would probably commence within three years after the lease sale. It may take at least one year and perhaps two to construct an exploratory drilling platform, possibly a grounded ice island, gravel island, or sunken barge. Drillships may be used in deeper waters in a shorter time frame. Assuming exploratory success, production platform installation would begin during the sixth or seventh year after leases are issued and be completed by the fifteenth year. Subsea completions may be included in this development phase.

Peak oil production, as limited by marketing facilities, would occur about the tenth year after the lease sale. Individual fields would have approximately a 25-year life and all platforms will have been removed by the fortieth year after production begins. Based on Arctic experience to date, it is estimated that only giant-class fields of about 500,000,000 bbl. minimum size can be developed economically; however, the rapidly escalating price of oil and the existence of nearby processing and transportation facilities may allow development of smaller fields to be economically viable. Assuming 5 MM bbl. recovery per well, 40 wells per production platform would give the following figures for the number of wells and daily production of oil and gas for the conditional or unrisked minimum, maximum, and most likely cases:

	95% Probability	5% Probability	Statistical Mean
Oil fields (avg. 0.5 BBbl.)	5	21	11
Wells (including service)	495	2,340	1,215
Peak production, MBD	258	1,219	633
Peak gas, MMCFD (assuming gas-oil ratio of 1400 MCF gas per bbl. of oil)	361	1,706	886

The nonassociated gas fields would have the following conditional, or unrisked, resources and parameters at an average of about 2.5 TCF/field and a 20-year constant production life:

	95% Probability	5% Probability	Statistical Mean
Gas, TCF	5.4	24.8	12.8
Gas fields	2	10	5
Gas, MMCFD	739	3,395	1,752
Gas wells	25	115	60

In the event that gas not associated with oil is found in close proximity to oil-associated gas (i.e., gas cap and dissolved gas), it may be feasible to use the same pipelines to transport them to shipping facilities by installing larger diameter or parallel smaller pipes. During the first years of production of an oil field associated or nearby non-associated gas is often reinjected into the reservoir to enhance recovery of oil. Depending on market conditions and engineering considerations, peak demand on the pipeline system may be attenuated so as to allow a smaller, more economical system to transport both associated and non-associated gas to market.

Estimated facilities: Exploration bases would probably be at Prudhoe Bay and Barrow, which are about 340 km apart (fig. 1). Prudhoe Bay is well equipped to serve as an exploration base, but Barrow would require the extensive construction of facilities to support large-scale operations. Institutional factors at Barrow may be unfavorable.

Technology for drilling and production in offshore Arctic environments is being rapidly developed in northern Canada and the Prudhoe Bay area. By the time of this sale (1983), further experience will have been accrued from development following the Beaufort Sea oil and gas lease sale of December 1979.

At present, gravel islands, ice islands, and sunken barges are employed as drilling platforms where water depths are less than 20 m. Man-made gravel islands, which usually require two summers to complete, are the safest and most economical platforms in most locations with these water depths. Grounded ice islands are being tested for multi-year use and have been employed in very shallow water depths for one-season exploratory drilling to moderate depths. In deeper water, ice-strengthened drill ships are used. Drill ships that can be quickly disconnected from the well are favored where moving ice is a potential problem. Ballasted barges, which have served successfully as drilling platforms in up to 2.3 m of water, have the advantage of being movable and reusable, but are limited to water about 1.5 to 5 m deep.

Steel monopods and monocones are being considered for use as production platforms in waters deeper than 20 m, but their ability to withstand moving polar pack ice has not yet been tested. A monopod has been used successfully in Cook Inlet, but the ice forces there are considerably less than those expected in the Beaufort Sea. A cone design for which model testing has been conducted causes the moving ice to ride up and fail by tension bending rather than by crushing. This particular structure, which consists of a cone surrounding a monopod, is under consideration for year-round operation in water depths up to 75 m in the Beaufort Sea.

The probable route to market for any oil found in the Beaufort Sea will be the Trans-Alaska Pipeline from Prudhoe Bay to Valdez and then by tanker to the West Coast. In the event of major gas discoveries, a planned gas pipeline from Prudhoe Bay across Alaska and Canada to the United States midwest may be available to transport Beaufort Sea gas.

Pipelines from offshore fields to onshore pipeline terminals could follow mainly subsea routes or combined subsea and shoreline routes, either of which will be ecologically sensitive. Subsea pipelines would have to be buried below the local depth of gouging by sea-ice pressure-ridge keels.

Dome Oil Company of Canada has proposed a system that would load ice-breaking oil or LNG tankers from artificial islands in the Canadian sector of the Beaufort Sea. They believe that this would be economically superior to a combination of subsea pipelines to shore in the Mackenzie Delta region and overland pipelines from there south. More will be known of this scheme by the time of the 1983 Beaufort Sea sale, but its relevance to development on the Alaskan Beaufort Shelf is uncertain because ice conditions are very different in the Canadian and Alaskan sectors. Another scenario would take western Beaufort Sea petroleum ashore near Barrow, where it would enter an additional pipeline running overland to a tanker terminal at Nome. The future of this plan depends on whether owners of large discoveries in the Chukchi Sea, Kotzebue Sound, Norton Sound, or the NPRA would share the construction costs.

If there are enough discoveries to justify the cost, a pipeline could also be built from coastal terminals in eastern northern Alaska to the Mackenzie Delta in Canada, and thence to a tanker terminal at Skagway. The Arctic National Wildlife Range may be a barrier to this route.

<u>Manpower</u>: Approximately 80 percent of the exploration manpower would come from outside Alaska. For production and construction, approximately 80 percent of the workers would come from personnel already in Alaska.

Drilling equipment availability: No shortage of drilling equipment is anticipated.

Weather: Weather is cold, windy, and dry. The mean temperatures at Barrow are below freezing in all months except June, July, and August. Six months have mean temperatures below 0°F. The lowest temperature recorded at Barrow has been -56°F and the highest +78°F. Prevailing winds are from the west with brief storms, sometimes intense, moving quickly in an easterly direction. The mean annual wind speed has been 10.6 knots. About 185 days a year have fog, with more foggy days in summer than in winter. Mean annual cloud cover is seven-tenths. From May through September, fog is common and sometimes interferes with flight operations. The mean annual precipitation has been 4.89 inches spread over 278 days. Mean annual snowfall is 29.3 inches, falling on 193 days.

Access: Getting to the Beaufort Sea is difficult and expensive. There are four major airfields--Barrow, Deadhorse, Prudhoe Bay, and Barter Island--that regularly handle Lockheed C-130 Hercules, Electras, Boeing 727, and Boeing 737, as well as smaller aircraft. Heavy trucks operate the year around on the Pipeline Highway northward from Fairbanks. Ships and barges are usually, but not always, able to traverse the Beaufort Sea nearshore during a couple of months each summer, when the oil companies operating at Prudhoe Bay send barges loaded with heavy equipment from the U.S. West Coast. The availability of this route to shipping commonly depends on open water around Point Barrow. At the nearby town of Barrow the average date of breakup is July 22, but it ranges from June 15 to August 22. The average date of barge traffic past Barrow is August 7. The average date of freezup at Barrow is October 3, with a range from August 31 to December 19.

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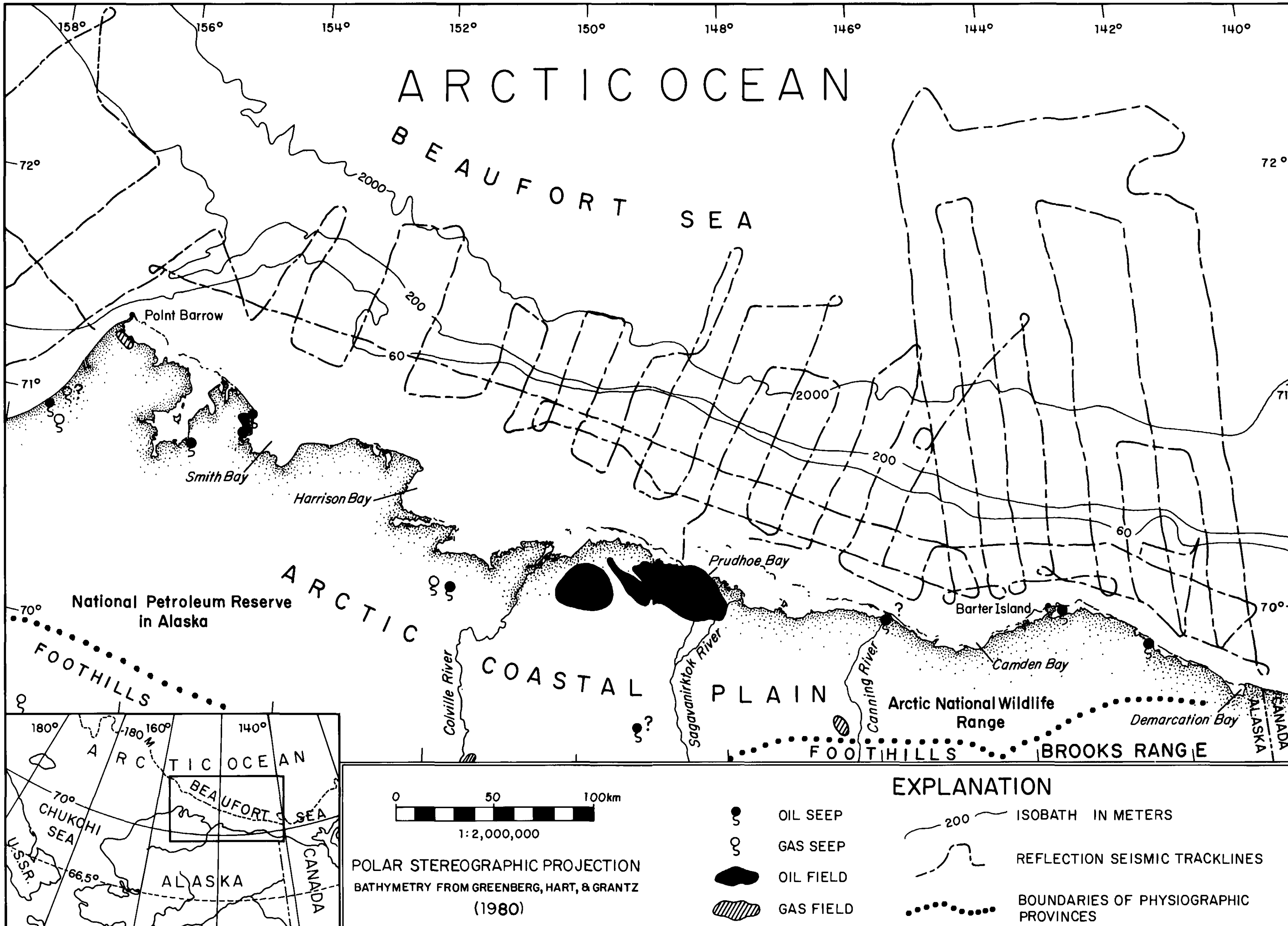


Figure 11. Bathymetric map of the continental shelf, slope, and rise and seismic trackline coverage of the Beaufort Sea north of Alaska.

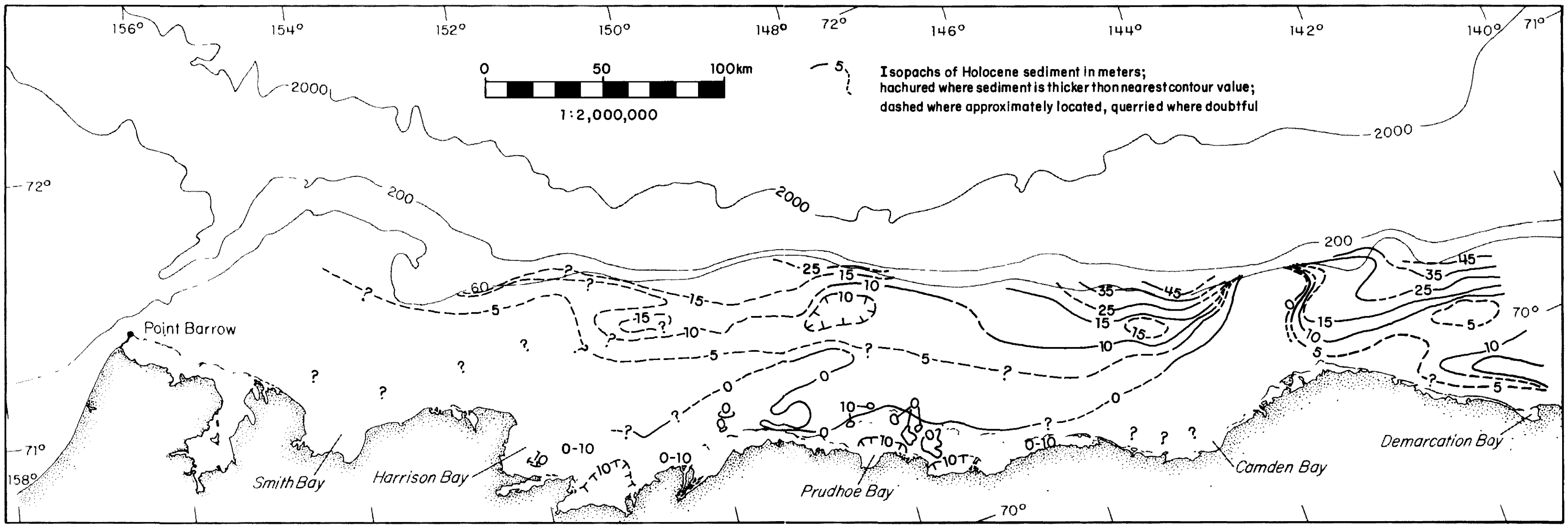


Figure 12. Holocene marine sediment thickness on the Beaufort Shelf north of Alaska.

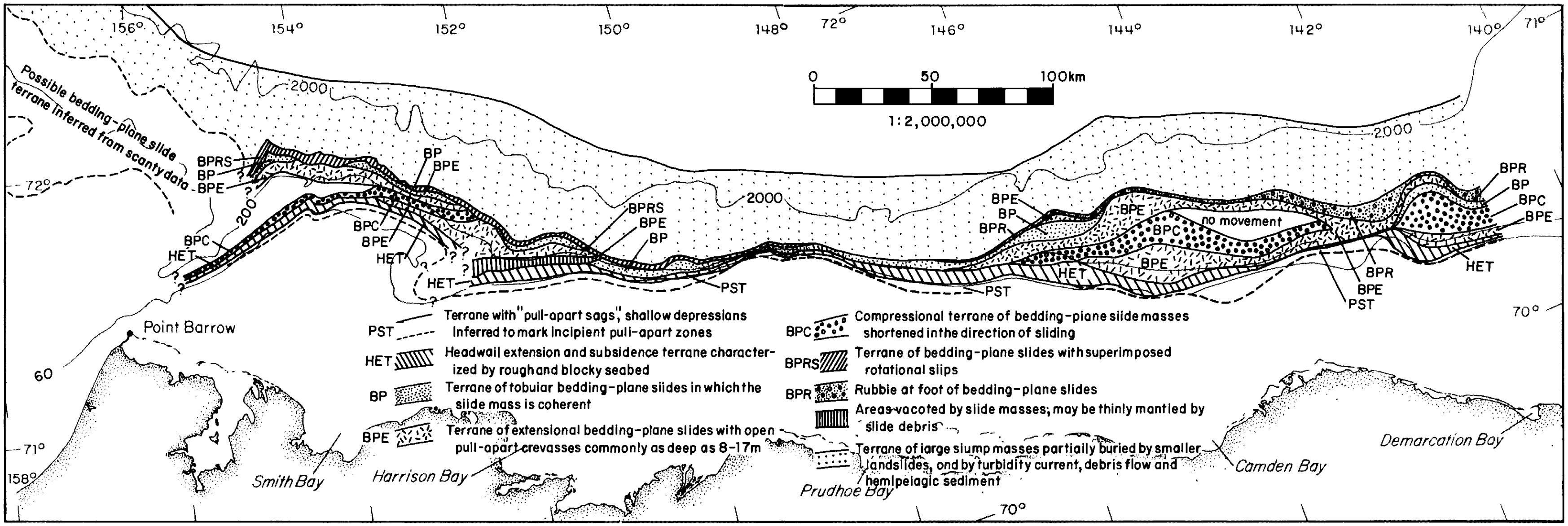


Figure 13. Preliminary map of youthful landslide terranes on the Beaufort Shelf and slope north of Alaska.

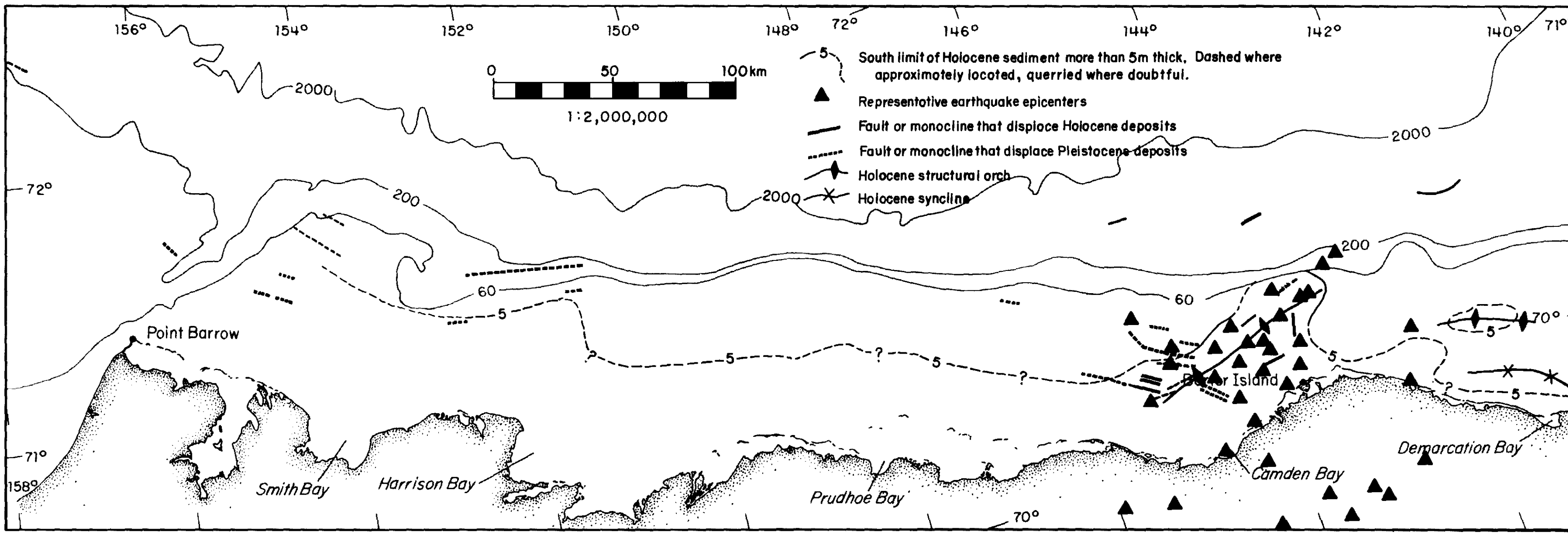
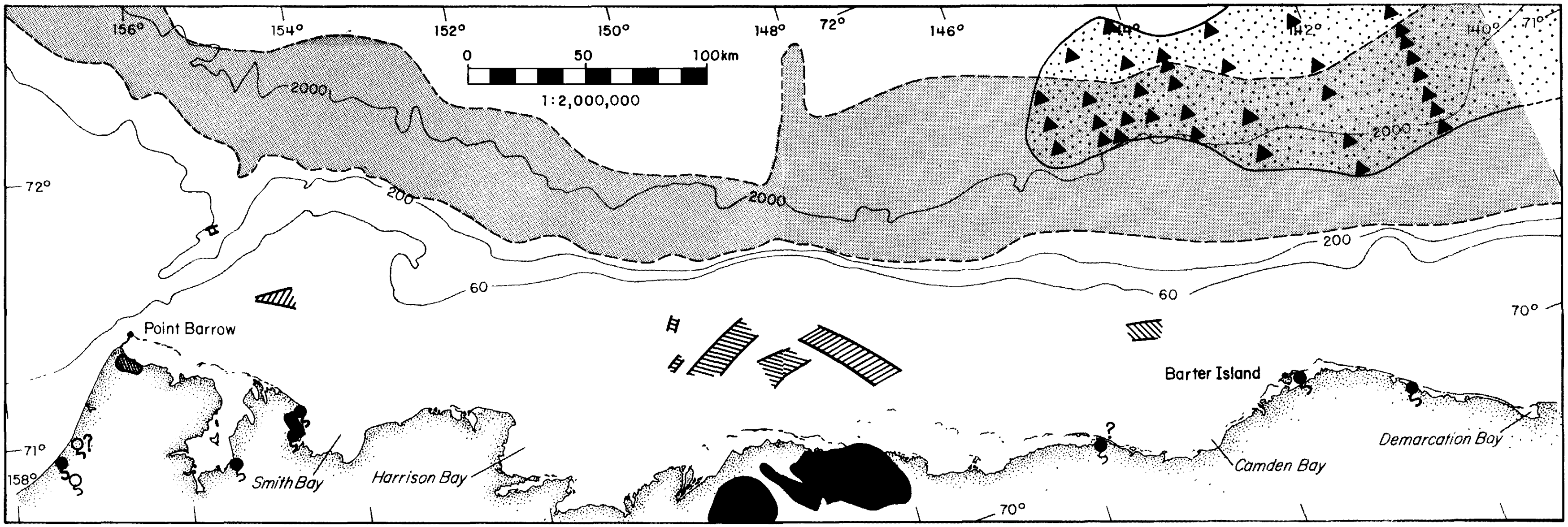


Figure 14. Holocene faulting, uplift and subsidence, and earthquake epicenters on the Beaufort Shelf north of Alaska.



Minimum area inferred to be underlain by patches of natural gas hydrate. Patches of free gas are trapped beneath the hydrate 300m to 700m beneath the sea bed.

Area containing shallow patches of acoustically "turbid" seismic reflectors inferred to be produced by free gas in Quaternary sediments.

▲ Seismic profile crossing of diapiric structure.

Minimum extent of diapiric source bed, inferred to be over-pressured shale lying about 3 km beneath the seabed.

Gas seep

Oil seep

Oil field

Gas field

Figure 15. Oil and gas fields and seeps and areas possibly underlain by shallow free gas, deep overpressured shale, and natural gas hydrate on the Beaufort Shelf and vicinity.

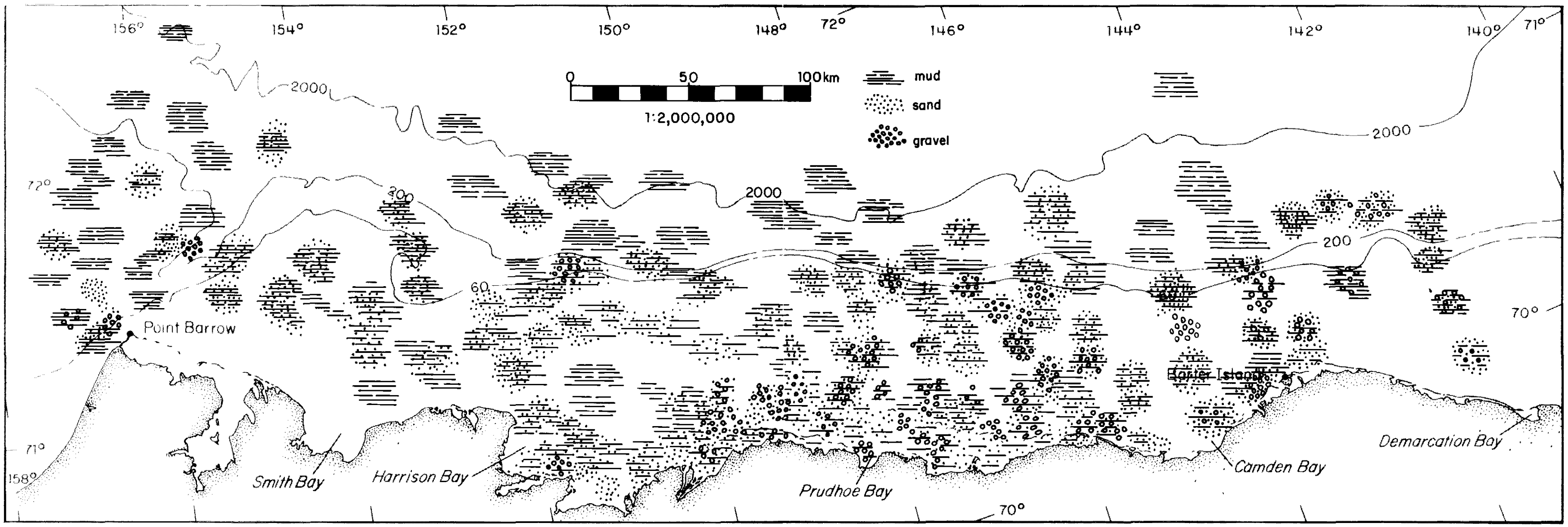


Figure 16. Textural character of surficial sediments on the Beaufort Shelf north of Alaska.

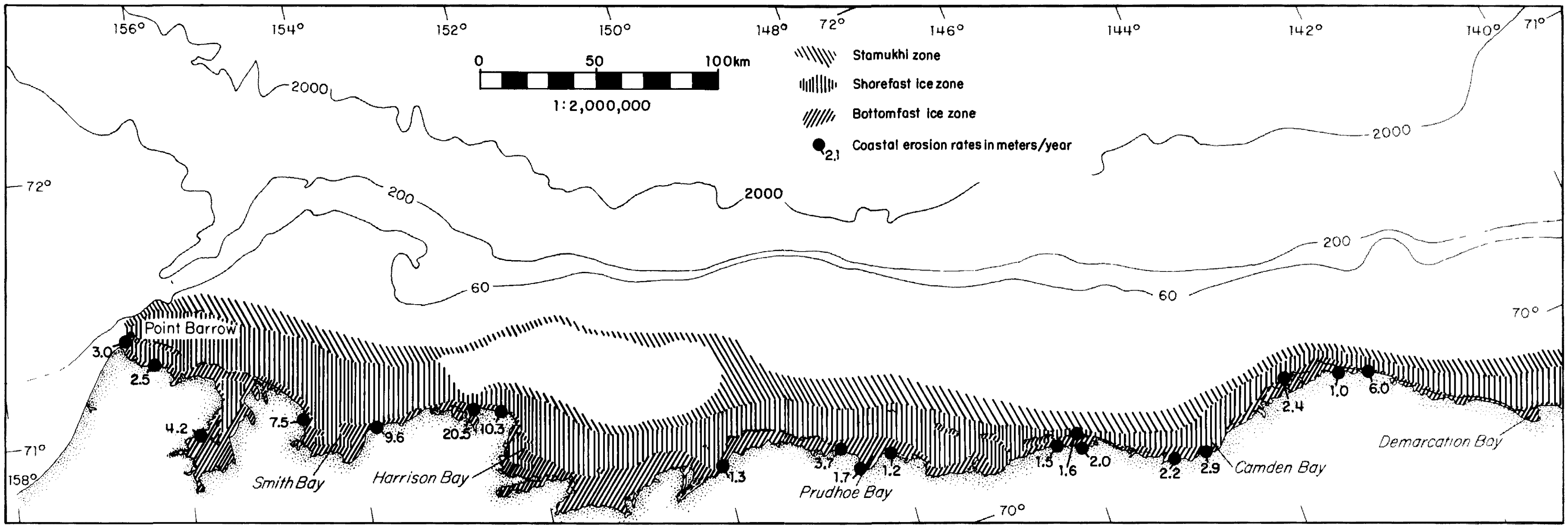


Figure 17. Coastal hazards and ice zonation of the Beaufort Shelf north of Alaska.

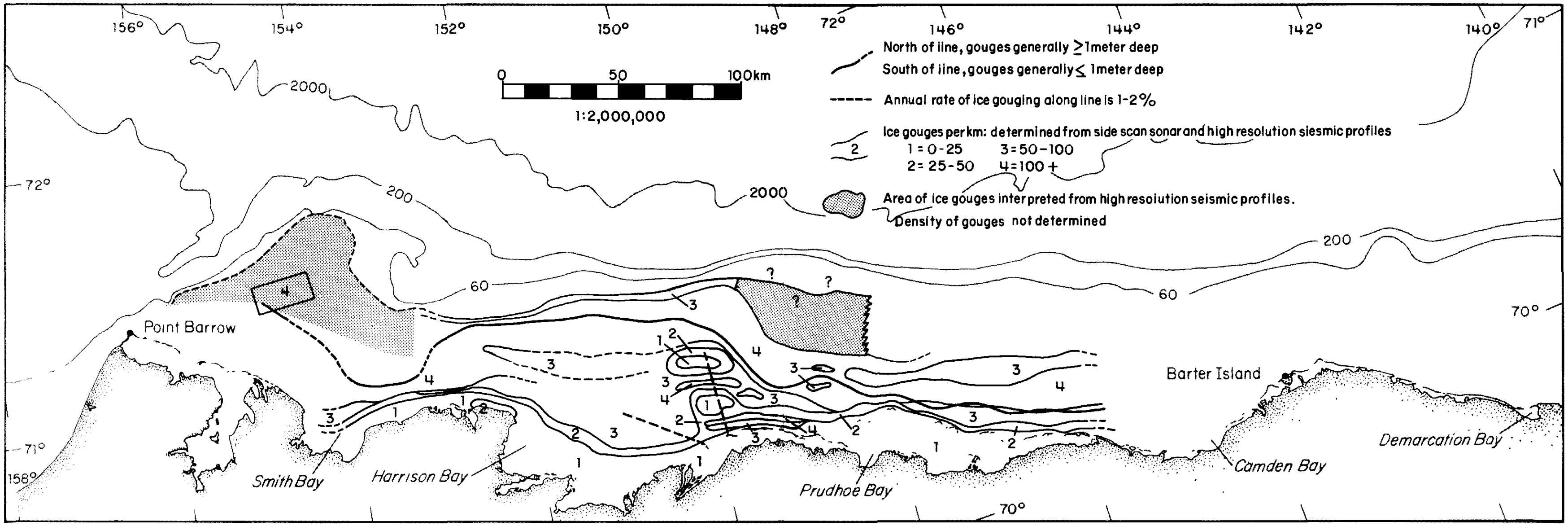


Figure 18. Ice gouge zonation, rates, and density on the Beaufort Shelf north of Alaska.