UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

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

A SUMMARY REPORT

By

Arthur Grantz, D. A. Dinter, E. R. Hill, S. D. May,
R. H. McMullin, R. L. Phillips and Erk Reimnitz

Open-File Report 82-482

Menlo Park, California

1982

Table of Contents

Illustrations

Introduction

Proposed oil and gas lease sale 87 in the Beaufort and northeast Chukchi Seas (Fig. 1) offers petroleum explorationists the most promising undrilled terrane for medium to giant oil and gas accumulations in the United States. The same area is also by far the most environmentally difficult region for petroleum exploration and development in the nation. Despite the difficulties, however, the National Petroleum Council (1981, p. 5) estimates that "Proven technology and sufficient information and technical expertise for advanced design work is available for the industry to proceed confidently with operations in water as deep as 650 feet in the southern Bering Sea and to about 200 feet in the more severely ice-covered areas of the northern Bering, Chukchi, and Beaufort Seas." The area of the lease sale in which water is 200 feet deep or less comprises about 60×10^3 sq km, or about 30 percent of the sale area.

The area of the proposed lease sale (Fig. 1) extends laterally more than 800 km from the continental shelf boundary between Canada and the United States in the east to 162°00'W. long in the west. Its north-south extent, from the three geographical mile limit off the northern Alaska coast (but 71°00'N. lat in the Chukchi Sea) to 73°00'N. lat ranges from about 175 km at Point Barrow to about 370 km near Demarcation Bay. Sale 87 offers for lease slightly more than 2×10^5 sq km of the Beaufort and Chukchi Seas and adjacent Arctic Ocean.

Sale 87 lies adjacent to the North Slope of Alaska which, despite its remoteness, is extensively developed for petroleum (Fig. 1). The region is served by the Trans-Alaska Pipeline System (TAPS), a common carrier, which will provide an outlet for oil brought to its northern terminus near Prudhoe Bay. If the proposed Alaska Natural Gas Transportation System, a pipeline with a terminus near Prudhoe Bay, is also built it would presumably provide the means for carrying sale 87 natural gas to market. These pipelines favorably affect the economics of developing oil and gas deposits that may be found in the sale area because the feasibility of economically transporting large volumes of oil or gas by tanker year-round from the Alaskan Beaufort Sea to markets in the conterminous United States has yet to be demonstrated.

The present report[1] presents an overview of the geologic framework, petroleum potential, environmental conditions, and geologic hazards of the proposed sale area. It is based mainly on U.S. Geological Survey data, but includes interpretations based on published data from other sources. Its purpose is to assist the Bureau of Land Management in the selection of areas most attractive for leasing, and to identify the geologic and environmental constraints and hazards that might adversely affect development or damage exploration and production structures. Many of these geologic and environmental conditions are encountered, and routinely surmounted or avoided, on other United States continental margins. Other conditions, however, such as the drifting polar ice pack and tabular icebergs, winter darkness and intense cold, and remoteness are absent or less extreme elsewhere than in the area of proposed lease sale 87. These conditions will generally make the control of oil spills and blowouts in the lease sale area more difficult than in more southerly sale areas, and might force long delays in the positioning of equipment to drill relief wells or repair subseabed pipelines. Note in Figure 2 that, while in some years the polar ice pack retreats from the lease sale area for a short period in late summer, in other years almost all of the area remains beneath the ice pack all year and is beyond the reach of ordinary vessels.

The present report is a revision and expansion of U.S. Geological Survey Open-File Report 80-94 (Grantz and others, 1980), which summarizes the geologic framework, petroleum potential and geologic environmental conditions for proposed oil and gas lease sale 71 on the Alaskan Beaufort shelf from Canada to Point Barrow and from the three geographical-mile limit to the 200 m isobath. Many of the conclusions reached in Open-File Report 80-94 are repeated here, but additional studies in the Beaufort Sea and some new data in the northern Chukchi Sea have resulted in a number of new or revised interpretations in the present report. Our principal data base consists of the multichannel seismic-reflection

---

[1] Grantz and May prepared the Introduction and the sections on Bathymetry and Physiography, Geologic Framework, Petroleum Potential, Gas Hydrate and Overpressured Shale; McMullin the section on Resource Appraisal Estimates; Grantz and Dinter the sections on Landslides and Young Faults; Dinter the section on Shallow Gas; Dinter, Phillips and Reimnitz the sections on Permafrost and Unconsolidated Deposits; Reimnitz and Phillips the sections on Polar Ice Pack, Ice Gouging, Oceanographic Regime and Currents, Storm Surge Effects, Coastal Erosion, River Overflow and Strudel Scour, and Suspended Sediment; and Hill the section on Seismicity.

profiles and accompanying high-resolution profiles shown in Figure 1 and some additional single channel seismic-reflection profiles, sonobuoy refraction measurements, side scan sonograms, sea bed samples and bathymetric data.

Bathymetry and physiography

Proposed lease sale 87 offers for bid the entire Outer Continental Shelf (OCS) in the Alaskan Beaufort Sea and almost all of the OCS in the Chukchi Sea north of 71°00'N. lat and east of 162°00'W. long (Fig. 1). Areas shallower than 200 feet, where the National Petroleum Council (1981, p. 5) considers that the petroleum industry can confidently proceed with operations, underlie most of the Alaskan OCS (i.e., the continental shelf out to the 200 m isobath) east of the Barrow sea valley and canyon, and almost 60 percent of the OCS within the lease sale boundaries west of the sea valley and canyon (Fig. 16). The lease sale area also includes all of the continental slope and rise off the Beaufort Sea coast of Alaska, part of the slope and rise off the Chukchi Sea coast, part of the Mackenzie cone of the Canada continental rise, and part of the abyssal plain of the Canada Basin beneath the Arctic Ocean (Fig. 16). Water depths in the sale area range from less than 10 m on the shelf along the Alaskan Beaufort coast to more than 3,800 m on the abyssal plain near the northern boundary of the sale area at 73°00'N. lat. The bathymetry of most of the lease sale area (from the Canadian border west to 158°00'W. long) is given at scale 1:500,000 by Greenberg and others (1981). The area west of 158°00'W. long is given at scale 1:1,000,000 in Naval Oceanographic Chart N.O.16002, published by the Defense Mapping Agency Hydrographic Center, Washington, D.C. 20390. Both of these maps use the polar stereographic projection, which is a conformal projection in which meridians converge toward the north pole. Nautical charts based on the nonconformal modified Mercator projection, and including more detailed charts of the nearshore areas, are available from the National Ocean Survey, U.S. Department of Commerce, Washington, D.C. The maps in the present report are based on the conformal polar stereographic projection because conformal projections approximate true distances and areas whereas nonconformal projections grossly distort them.

Geologic framework

Proposed lease sale 87, which consists of two sectors of contrasting continental shelf geologic structure, has petroleum potential in two distinctive, overlapping , sedimentary sequences (Figs. 3 and 4). The western (Barrow) sector extends from the western part of the sale area to a bend in a tectonic hinge line near 145° W long. The eastern (Barter Island) sector extends from near 145° W long to the Canadian border. The hinge line is a flexure produced when the crust to the north subsided rapidly following the mid-Neocomian (early Early Cretaceous) culmination of the rifting process begun in Early Jurassic time, that produced the continental margin north of Alaska. For convenience in describing its petroleum potential, the sale area has been divided into six petroleum provinces and five subprovinces. These are enumerated in Table 1 and their areal extent and relation to major geologic and physiographic features of the region are shown in Figure 16. Figures 3, 4 and 7 show the general geology and the stratigraphy, lithology, and depositional and structural history of northern Alaska and of the Beaufort and northeast Chukcvhi shelves. Figure 5 gives the approximate relation between seismic-reflection times to geologic horizons, given in Figure 4 and other illustrations, and actual depth. The thickness of sedimentary rocks above basement for oil and gas deposits is given in Figure 6, and typical cross-sections and seismic profiles are presented in Figures 7 to 15. Data for this section and that on Petroleum Potential for the offshore are mainly from Grantz and May, in press; Grantz and others, 1979 and 1981; and Eittreim and Grantz, 1979. Data for the onshore are from Alaska Geological Society, 1971, 1972, 1977, and 1981; Brosgé and Tailleur, 1971; Jones and Speers, 1976; Grantz and Mull, 1978; and especially Tailleur and others, 1978; Miller and others, 1979; and Guldenzopf and others, 1980.

Sedimentary sequences

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 (Figs. 3 and 7). The Cambrian to Devonian Franklinian sequence, consisting of mildly to strongly metamorphosed sedimentary and some volcanic rocks, is inferred to constitute economic basement for the Beaufort Shelf. Following mild 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 thjan 200 million years. During this time a lithologically diverse suite of clastic and carbonate sedimentary rocks, the Ellesmerian sequence, was deposited on the platform. This sequence contains both marine and nonmarine beds including stratigraphically condensed 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.

North of Icy Cape, in the western part of the study area, the Arctic platform appears to be downfaulted and downwarped into a deep, northerly trending trough that contains as much as 8 km of sedimentary rocks interpreted to belong to the Ellesmerian sequence. A fault boundary was observed between the Hanna trough and the Barrow arch on one multichannel seismic line near 71°20' N. lat. The strike of this fault, and the extension of the fault and the Hanna trough north from about 71°40' N. lat, is based only on qualitative interpretation of reconnaissance gravity data, and on some shallow penetration sparker seismic-reflection profiles. If correctly interpreted, the fault forms the western boundary of the Barrow arch as expressed on the Arctic platform (the top of Franklinian basement) and the east boundary of much of the prism of interpreted Ellesmerian strata in the Hanna trough. However, structural contours at the base of interpreted Albian beds, at the local base of the mainly Cretaceous and Tertiary Brookian sequence (see Fig. 3), overstep the fault without offset and show that the Barrow arch both postdates the fault and extends west of it.

In Early Cretaceous time the northern part of the Arctic platform, the source terrane for the Ellesmerian shelf sediments, was separated from northern Alaska by the rifting event 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 the area of the present Brooks Range. An asymmetric foreland basin, the Colville foredeep, formed on the southward tilted platform and received large volumes of sediment from the nascent Brooks Range to the south. Because of their provenance, these deposits have been named the Brookian sequence by Lerand (1973). The section in the Colville foredeep consists of Middle Jurassic to Cretaceous and, on the eastern North Slope, of Tertiary clastic sedimentary rocks. In the southern part of the assymetric Colville geosyncline, where it consists mainly of Late Jurassic and Early Cretaceous flysch and mid- and Late Cretaceous molasse, the section is more than 9,000 m thick. The Brookian sequence thins northward to between 500 m and 2,000 m, and its basal beds are Albian, where it onlaps the Barrow Arch beneath the northern North Slope, northern Chukchi Sea, and Beaufort Shelf.

Barrow sector

The Barrow Arch, a broad basement high which trends parallel to the coast, is the dominant structure of the Barrow Sector of the Beaufort shelf. The south flank of the arch is defined by the south-sloping Arctic platform. The north flank of the arch, which mainly underlies the Beaufort Shelf, is defined by the Arctic platform where it dips north as a result of uplift and erosion adjacent to the Early Cretaceous rift, and rapid subsidence caused by postrift crustal cooling and sediment loading. Synrift and early postrift faulting, erosion and tilting on the arch created the rich oil-bearing structure at Prudhoe Bay.

The position of the tectonic hinge line off northern Alaska is the major determinant of the distribution of geologic provinces beneath the continental shelf and slope in the Barrow sector of lease sale 87. The location of these provinces--the Arctic platform, Dinkum graben, and Nuwuk basin--is shown in Figure 16. Some of the geologic features of the Barrow sector are encountered in test wells on the North Slope of Alaska. Others, however, are absent from the North Slope and are known only from seismic-reflection and sonobuoy refraction data.

Arctic platform: The Arctic platform in the sale area extends offshore from northern Alaska with typically gentle dips to the tectonic hinge line beneath the shelf (Figs. 4, 8-9, 11-13), where it is bent down to the north and is in places faulted. The crest of the broad Barrow arch (Figs. 4 and 8), which formed during Early Cretaceous rifting, underlies the sale area west of Point Barrow and between Dease Inlet and the Colville River delta. The northern edge of the Ellesmerian sequence of stable shelf clastic and carbonate rocks, which contains the giant oil and gas deposits near Prudhoe Bay and small gas deposits near Barrow, also extends offshore from the North Slope. A rough estimate of the position of this edge offshore, based mainly on projection of onshore trends, is shown in Figures 4 and 16. Seaward of the wedge edge of the Ellesmerian beds, the Arctic platform and the Franklinian sequence (economic basement) into which the platform was cut are directly overlain by upper Lower Cretaceous to Tertiary rocks of the Brookian sequence. The Ellesmerian strata range upward in thickness from the wedge edge to 1,000 m or more near the shoreward boundary of the sale area (Alaska Geological Society, 1977). The overlying Brookian rocks range in thickness from 0.3 km or less in the crestal region of Barrow arch northwest of Point Barrow to as much as 6 km on the outer continental shelf east of Prudhoe Bay.

Structurally, the Arctic platform province in the sale area is dominated by the broad Barrow arch (Figs. 4 and 8), and dips are generally low (Figs. 9-11). Belts of normal faults, however, offset the platform and the underlying Franklinian basement at and near the tectonic hinge line (Figs. 10, 11 and 13), at the margins of Dinkum graben (Figs. 12 and 13), and on the north side of the faulted anticline that contains the Prudhoe Bay oil field (Jamison and others, 1980). The faults north of the Prudhoe Bay field extend beneath the nearshore area of the adjacent Beaufort shelf, and probably extend into the area of sale 87. The seismic profiles (Fig. 1), however, lie too far offshore to demonstrate this. In addition to the normal faults which cut basement and offset the Arctic platform, an extensive system of large suprabasement growth faults offsets the Brookian (Cretaceous and Tertiary) sedimentary rocks over and seaward of the hinge line. Some of these faults extend updip into the Brookian prism over the outer (seaward) part of the Arctic platform province (Figs. 4, 11-13, and 16).

The normal faults associated with the tectonic hinge line (Figs. 10-11 and 13) displace basement, the Arctic platform, and the lowest part of the overlying Cretaceous section, but they do not extend very far upwards into the overlying Albian beds. A large normal fault with many splays that begins about 10 km northeast of Point Barrow and trends east-southeast along the coast to within 35 km of Harrison Bay (Miller and others, 1979) may also be related to the hinge line. This fault, as do the other hinge line faults, also appears to cut basement and the lower part of the Cretaceous section, but not beds as high as the upper part of the Nanushuk Group at the top of the Lower Cretaceous.

Jamison and others (1980) indicate that the system of basement-cutting, northwest and west-striking down-to-the-north normal faults on the north side of the Prudhoe Bay faults are cut by the pre-Pebble shale (mid-Neocomian) unconformity. Small normal faults, with similar stratigraphic relations, also occur nearby on the south side of the Dinkum graben (Fig. 12). The similarities between the Prudhoe Bay faults and these Dinkum graben faults suggest that they may belong to the same structural set, and that a number of similar faults may underlie the region between the north side of the Prudhoe Bay structure and the graben.

Dinkum graben: The eastern part of the Arctic platform province is disrupted by the deep, strongly assymetric east-southeast-trending Dinkum graben, or half graben (Figs. 4, 12 and 13). Franklinian basement beneath the deepest parts of the graben is more than 6 s (10.5 km) below sea level. The oldest seismic-stratigraphic unit within the graben consists of fairly strong, well developed reflectors postulated to be Jurassic or older Ellesmerian sandstone and/or carbonate (unit JpJe in Figs. 12 and 13). They are overlain by a thick section of weaker reflectors that may be the Jurassic and early Neocomian (Early Cretaceous) Kingak Shale (unit KJk, figs. 12 and 13). These units are tilted to the north and down-dropped against a large fault, apparently pre-Pebble shale in age, that is the main graben-forming structure. Early post-Pebble shale unit displacement has augmented the structural relief on the north side of the graben (Fig. 12). This fault movement, in combination with residual structural relief and perhaps renewed displacement on the older (pre-Pebble shale) fault, produced a late-stage basin in the graben. A thick post-Pebble shale Cretaceous and Paleogene fill was deposited in this basin. A shallow syncline in this fill near the north-graben fault system suggests renewed displacement of the fault system, and perhaps some differential compaction, in Paleogene time. The graben appears to die out, and its sedimentary fill to thin, where it strikes southwest out of our area of seismic coverage. The east end is structurally well-developed where we lose it, near Camden Bay, beneath the thick sedimentary section of the Kaktovik basin.

Nuwuk basin: From the Prudhoe Bay area west, the outer continental shelf and slope is underlain by a deep sedimentary basin that contains more than 12 km of post-mid-Neocomian Cretaceous and Tertiary (Brookian) clastic sediment. The sediment was prograded across the subsided Arctic platform and underlying basement seaward of the tectonic hinge line (Figs. 4, 8, 10 and 11), and it constitutes a progradational continental terrace sedimentary prism rather than a true sedimentary basin. It is probable that somewhere near the shelf break, the fill steps from the continental basement of the Arctic platform onto transitional or oceanic crust of the Arctic basin.

The Nuwuk basin fill contains both foreset and topset beds, and numerous large erosional channels and channel fills. Structurally it is dominated by large multi-strand growth fault systems that preliminary studies suggest were active since Late Cretaceous or early Tertiary time. The youngest faults of this system displace Holocene sediment, and in places the seabed. The faults appear to be restricted to the Brookian sequence and curve into, but do not displace, the upper surface of pre-Brookian bedrock. The growth faults bound two rootless anticlines (rotational megaslumps) of regional extent that were produced by movement on the growth faults. The widely spaced profiles (Fig. 1) suggest that the rootless anticlines are continuous or semicontinuous features that are as much as 200 km long, and that they have variable structural relief that commonly exceeds 1/2 km.

Barter Island sector

The deep Kaktovik basin (Figs. 4 and 16), which contains large detachment folds and diapiric shale ridges, characterizes the Barter Island sector. It may be tectonically significant that the field of diapiric anticlines of the continental slope and rise of the eastern Alaskan Beaufort Sea (Figs. 4, 6, 16) is limited to this sector.

Kaktovik basin: Between Prudhoe Bay and the Canning River (Fig. 4) the tectonic hinge line swings southeast from a position near the shelf break toward the coast of eastern Camden Bay. From about the same place, the structural shelf break swings northeast and the continental terrace for some distance to the east remains somewhat wider than it is to the west. The widened continental terrace sedimentary prism east of the hinge line is the Kaktovik basin (Figs. 14-16). It is likely that much of the prism rests on transitional and oceanic crust. The thick pre-Pebble shale unit sedimentary prism of the Dinkum graben trends beneath the basin fill and has not as yet been distinguished from it on our seismic records. The Pebble shale and younger (Brookian) graben fill and the Brookian sedimentary prism of the Arctic platform province are stratigraphically continuous with the sedimentary fill in the Kaktovik basin. The total thickness of suprabasement sedimentary rocks beneath the Kaktovik basin exceeds 12.5 km, and local subbasins (RSB and DSR in Fig. 4) are filled with Tertiary strata as much as 7.2 km thick. The seismic profiles record Franklinian basement in only a small part of the Kaktovik basin and therefore the horizon that is contoured in the area of the basin in Figure 4 is mid-Paleogene (middle Eocene?) for reasons discussed by Grantz and May (in press). Onshore outcrops in Alaska and subsurface data on the Canadian Beaufort shelf (Hea and others, 1980) suggest that if Jurassic to mid-Upper Cretaceous beds underlie the Kaktovik basin, they will be marine sedimentary rocks. Uppermost Cretaceous beds and Paleocene beds are likely to be nonmarine nearshore, and paralic and probably marine offshore. Higher Tertiary beds are probably both marine and nonmarine.

Contrasting structural styles distinguish the eastern and western parts of the Kaktovik basin. West of the general vicinity of Barter Island the basin appears to deepen uniformly northward and eastward, but the upper part of the section is broken by the large northeast-striking Camden detachment anticline (CA on fig. 4) and a few small parallel folds. The Camden anticline appears (Fig 14) to be detached at about 4 s subsea, probably near the base of the Tertiary. The involvement of beds as young as Holocene in the fold and the distribution of shallow earthquakes in the Camden Bay area (Fig. 24) suggests that the folds are active (Grantz and others, 1982). In places a number of large, northward dipping growth faults, at least in part related to the hinge line, offset the basin sediments and, in places, the Camden anticline (Fig. 14). A large fold, inferred to be a rootless rotational-slump anticline related to growth faulting in the Brookian strata north of the hinge line, occurs beneath the western part of the Kaktovik basin seaward of the detachment folds (Fig. 4). The fold is broad, apparently deep, and is obscured on the east by a thick section of undeformed Neogene(?) beds in the upper part of the Kaktovik basin fill.

East of the vicinity of Barter Island the structure of Kaktovik basin is dominated by large diapiric shale ridges, or anticlines (Figs. 4 and 15), and Tertiary sedimentary subbasins (BSB and DSB on Fig. 4) that formed contemporaneously with the diapirs. Multiple unconformities observed over one of the diapiric structures (Fig. 15) record at least three episodes of diapiric movement. At the oldest of these unconformities the core sediments of the fold were raised above wave base, and perhaps above sea level. In places, delta-like topset-foreset-bottomset sedimentary packets were built out from structurally high areas in the subunconformity section. Regional geologic relations (Grantz and May, in press) suggest that the cores of the diapiric structures contain Jurassic, Cretaceous and early Paleogene clastic sedimentary rocks, and that the overlying, less strongly deformed beds may be mid-Eocene and younger.

Diapiric fold province: Numerous diapiric folds underlie the continental slope and adjacent rise in the Barter Island sector east of 146°W. long (Figs. 4 and 15). These structures are much smaller and have more regular cross-sectional geometries than do the large diapiric anticlines of the eastern Kaktovik basin. They are symmetrical diapiric folds or domes, rather than piercement structures or irregular shale ridges. Although the reflection profiles are too widely spaced to allow us to map these structures, they suggest that the structures are subcircular or moderately elongate and that individual folds are not of regional extent.

The diapiric folds are typically 2 to 10 km wide on seismic crossings, and the largest folds have at least 1.5 s (1.25 km) of structural relief in two-way reflection time. The most northerly structures (100 km north of the shelf break) die out upward, and are overlain by undisturbed beds, about 2 s (2 km) below the seabed. The tops of the folds extend progressively higher in the section landward, and beginning about 50 or 60 km from the shelf break they buckle the seabed and act as dams for clastic sediment and landslide debris moving down the continental slope.

The diapiric anticlines appear to constitute a westward extension of the shale-diapir province of the western Canadian Beaufort shelf. Seismic-reflection interval velocities of about 1.8 to 3.5 km/s in the intruded beds (Eittreim and Grantz, 1979), and lateral tracing of reflectors, suggest that these diapiric structures penetrate Tertiary and Quaternary beds. Lateral tracing of reflectors also indicates that those which are closest to the shelf, and which are strongly developed in the shallow part of the section and disrupt the seabed, originated in lower Tertiary and possibly deeper beds. The broad folds farthest from the shelf, which die out upward at about 2 s two-way reflection time subbottom, and are no more than broad warps at 3.5 s subbottom, are not obviously diapiric. We assign these structures to the diapiric province because they are contiguous with the strong folds and weaken progressively away from them. If they are diapiric, these folds must have originated at a considerable depth below our deepest records, possibly in early postrift Lower Cretaceous sedimentary deposits of the Canada Basin or in prebreakup Jurassic rift-valley sedimentary deposits.

Canada basin

Water depths exceeding 3,500 m, dispersion patterns of Lg-phase seismic waves (Oliver and others, 1955), and seismic refraction measurements (Mair and Lyons, 1981; Grantz and others, 1981) indicate that the Canada basin is underlain by oceanic crust and was therefore formed by seafloor spreading. The inferred thickness of sediment in the southern part of the basin is shown in Figure 6 and the three major physiographic provinces into which it can be subdivided are shown in Figure 16. All three provinces--the Alaska continental rise, the Mackenzie cone, and the Abyssal plain--are the result of rapid sedimentation from the continental landmasses that surround the basin. Their relative areal extent, and the relative thicknesses of the sedimentary prisms which underlie them, are the result of the positions of the major rivers and glaciers which entered the Canada basin since it was formed in Cretaceous time.

Alaska continental rise: The Alaska continental rise, at water depths of about 2,000 m to 3,800 m, is underlain by clastic sedimentary rocks of the Brookian sequence derived from sources to the south, in continental Alaska and probably Eurasia. The strata are inferred to consist dominantly of foreset and bottomset lutites, but there are probably some turbidite sandstones and submarine slump deposits. As deposited, these sediments were in stratigraphic continuity with the beds of the progradational continental terrace sedimentary prisms herein called the Nuwuk and Kaktovik basins. A few of the seismic profiles shown in Figure 1 extend over the rise and show it to be underlain by well-bedded, uniformly basinward-dipping strata. These strata are internally deformed beneath their upslope margin by submarine slumps and the distal ends of listric growth faults that originate on the continental slope and outer shelf seaward of the tectonic hinge line. The age of the sedimentary prism is inferred to range from late Neocomian (mid-Early Cretaceous) to Quaternary. The distribution of Brookian rocks and facies in northern Alaska suggests that the sedimentary prism may consist mainly of Albian strata near Point Barrow and mainly Tertiary strata in the Barter Island sector. It is possible that Jurassic and early Early Cretaceous beds of the rift valley stage of rifting on the Alaskan continental margin (Grantz and May, in press) may in places underlie the Neocomian beds. The thickness of the sedimentary prism beneath the Alaska continental rise is estimated to range from 6 km to more than 10 km (Fig. 6).

Mackenzie cone: The Mackenzie cone is the portion of the Canada continental rise lying off the mouth of the Mackenzie River. Water depths on the cone in the sale area (Fig. 16) range from about 1,800 m to 3,700 m. The cone, which occupies about three-fifths of the southern Canada basin north of the Alaska continental rise, owes its areal extent and the thickness of its underlying sedimentary prism (Fig. 6) to its proximity to the delta of the large Mackenzie River system and to the heavily glaciated Arctic Islands and Canadian shield. These sources supplied voluminous sediment to the cone and, at least in Tertiary time, the cone grew much more rapidly than the Alaska continental rise sedimentary prism, which it overwhelmed. The oldest sediments in the cone are inferred to be upper Lower Cretaceous, and the youngest Quaternary. Seismic reflection profiles show the sediments to consist, beyond the limits of the field of diapiric folds, of flat, basinward-dipping strata that produce some well-defined, but mainly weak, seismic reflections. The sequence is interpreted to consist dominantly of lutite with some turbidite beds, and to range in thickness from less than 6 km to more than 10 km (Fig. 6).

Abyssal plain: The Abyssal plain of the Canada Basin (Fig. 16) occupies about two-fifths of the southern Canada basin north of the Alaska continental rise. Water depths over the plain range from about 3,700 to about 4,000 m. We have no seismic reflection data over the Abyssal plain in the sale area, and can only speculate on the character of the underlying sedimentary prism.

Presumably, it is mainly a basinward extension of the Mackenzie cone sequence and consists of lutites with some fine grained turbidites. In addition, there may have been a contribution from the smaller Alaska continental rise. Extrapolation of seismic refraction data indicates that the sedimentary section beneath the portion of the Abyssal plain that underlies sale 87 is a little less than 6 km thick.

Petroleum potential

It is probable that commercial deposits of oil and gas will be found in the area of lease sale 87. Large economic and potentially economic oil and gas pools of several ages have been developed or discovered along the Beaufort Sea coast in the Prudhoe Bay area (Jamison and others, 1980), and between the Sagavanirktok and Canning Rivers (Fig. 1). Some of these are known, and others can be surmised, to extend offshore. It is remarkable that every major stratigraphic unit of formation or group rank beneath the Arctic coastal plain of northern Alaska has been found to contain commercial or potentially commercial pools, or strong shows, of oil and gas (Fig. 17). All of these major stratigraphic units can be interpreted to extend offshore beneath the Beaufort shelf.

The foregoing facts indicate that oil and gas have been generated beneath the Beaufort shelf. The chances for potentially commercial discoveries are considered good because, in addition to favorable sedimentary rocks, the area contains many structures and stratigraphic configurations that have been found to trap economic petroleum deposits in other regions. The chief concern appears to be whether sufficiently large deposits can be found to support the anticipated substantial cost of offshore exploration and develpment in the Beaufort and Chukchi Seas and adjacent Arctic Ocean, and to support the development of new technologies to make these operations possible.

As noted in the Introduction, industry believes (National Petroleum Council, 1981) that petroleum exploration and development can now be contemplated with confidence out to water depths of about 200 feet (60 m) in the area of lease sale 87. Presumably, the industry will explore this large area before it considers the somewhat deeper waters of the shelf beyond the 200-foot isobath and the much deeper waters of the continental slope and Canada Basin (Fig. 16). Experience gained during development of the area within the 200-foot isobath, and any exploration and development structures built in that area, will greatly facilitate future operations in deeper waters. Accordingly, we anticipate that leasing activity in sale 87 will be concentrated within the 200-foot (60 m) isobath, and our discussion of the petroleum potential will concentrate on this area. Future sales, however, may find interest in areas of deeper water.

Table 1

<u>Petroleum provinces of proposed oil and gas lease sale 87</u>

(see Figure 16 for location of provinces)

1. Arctic platform
2. Dinkum graben west of Kaktovik basin
3. Nuwuk basin
4. Kaktovik basin
   - A. West Kaktovik basin (area west of diapiric shale ridges)
   - B. East of Kaktovik basin (area of diapiric shale ridges and related Tertiary subbasins)
5. Diapiric fold province (minimum extent shown in Figure 16)
6. Canada basin
   - A. Alaska continental rise seaward of 2400 m isobath
   - B. Mackenzie cone of Canada continental rise exclusive of diapiric fold province
   - C. Abyssal plain

Thermal maturity of post-rift sediments

To determine the potential of a sedimentary package to have generated petroleum hydrocarbons, two factors must be considered; first,was there organic material of suitable type within the sediments to be converted to petroleum hydrocarbons, and second has the thermal history of the sediments been conducive to the chemical transformation of organic material into petroleum hydrocarbons. The widespread occurrence of oil and gas pools and shows in the Cretaceous and Tertiary sedimentary rocks of coastal northern Alaska (Fig. 17) suggests that adequate amounts of suitable organic matter were probably also present in these rocks beneath the Beaufort and northeast Chukchi Seas. In this section the second of these factors, the temperature history or thermal maturity of these sedimentary rocks, will be considered. A method to determine the thermal history in the region of a passive continental margin has been developed by Royden and others (1980). This method is based on a relationship between the amount of subsidence an area of a passive margin undergoes following breakup of the continent, and the heat flow through time in that area. Therefore, if the depth to the breakup unconformity can be measured in an area, the thermal history of that area can be reconstructed.

Using this method, the depth range at which petroleum hydrocarbons may have been generated in the post-breakup (post-Neocomian) sedimentary rocks of the Beaufort and northeast Chuckhi Seas is shown in Figure 18. The area has been analyzed as three separate regions based on the thickness of the sedimentary section and the heat flow curves.

Arctic platform

Most of this province (area 1 in Fig. 16) is prospective for petroleum. Thermal history calculations indicate that the Cretaceous rocks are within the oil window (Fig. 18), and the Ellesmerian rocks are known to be productive onshore. The areas of greatest potential lie along the broad crest of the Barrow arch off Prudhoe and Harrison Bays, where significant sections of Ellesmerian rocks can be extrapolated offshore. Lesser prospects of this type are projected for the crestal region of the arch near Smith Bay and west of Point Barrow because onshore and some offshore data (Figs. 4 and 7) suggest that the lower part of the Ellesmerian section is much attenuated, or missing, in those areas. The possibility that the pre-Pebble shale faults on the north side of the Prudhoe Bay structure extend to the south side of the Dinkum graben further enhances the prospects of the area between Prudhoe Bay and the graben.

Additional prospects in the Arctic platform province are fault-block plays in Cretaceous rocks, and possibly in places Ellesmerian rocks, on the north side of the hinge-line-related faults that lie about 10 km to 15 km off the coast between Point Barrow and Harrison Bay. Hinge line-associated growth faults and rollovers in Brookian rocks in the northern part of the province may also have some potential, but perhaps not for large accumulations. Interdigitated topset and foreset seismic-stratigraphic units of inferred Cretaceous and Paleogene age in appropriate structural configurations may offer prospects in parts of the Arctic platform province, but it is difficult to infer from our data how large such stratigraphically controlled accumulations might be.

Dinkum graben

From Figure 18 we estimate that the lowest Tertiary and Cretaceous strata in the thick sedimentary section of Dinkum graben (area 2 in Figure 16) are now within the oil window. The underlying Jurassic(?) or pre-Jurassic(?) Ellesmerian beds within the deep central parts of the graben range from just below the oil window into the overmature zone, and would be of interest mainly as a source of oil or gas that migrated out of these beds during Cretaceous or Paleogene time. Good prospects may exist where the Cretaceous and lower Tertiary beds of the graben fill are upturned against pre-graben rocks at buttress unconformities or fault contacts, provided these beds are no deeper than about 5 km. However, our data do not allow a reasonable speculation on the size of any such accumulations.

Nuwuk basin

The section between roughly 3 km and 6 km subseabed in the thick (more than 12 km) Brookian sedimentary prism in the Nuwuk basin (area 3 in Figure 16) is in the oil window. Thus, the many early-formed growth faults and associated large rootless anticlines (rotational megaslumps) and smaller rollover anticlines were potentially available to trap migrating hydrocarbons. The presence of topset, as well as foreset and bottomset seismic-stratigraphic units in the Cretaceous and lower Tertiary beds of the basin holds out the possibility that reservoir sands may be present in these structures. The seismic lines are too widely spaced to demonstrate closure on the possible structures and stratigraphic traps recognized on seismic profiles, but suggest that large closed structures could be present in most parts of the Nuwuk basin.

Kaktovik basin

Heat flow considerations (Fig. 18) suggest that the section between roughly 3 km and 6 km below the seabed in the Kaktovik basin is in the oil window. The window includes the upper (but not the highest) parts of the diapiric anticlines and the deeper parts of the Tertiary subbasins in the eastern part of the province (area 4B in Figure 16). The subbasins formed contemporaneously with diapirism and the buttress unconformities at their upturned and locally faulted margins may offer good prospects for large accumulations of oil or gas. In addition, up-dip migration of hydrocarbon fluids might have created local accumulations in the tops of the diapiric anticlines.

The discovery of lower Tertiary and Cretaceous oil deposits at or near the coast between the Sagavanirktok and Canning Rivers, and the presence offshore of a large anticline of inferred growth-fault-related origin, indicates that the western Kaktovik basin (area 4A in Figure 16) also has good prospects. The large Camden anticline and related smaller structures of this part of the province (Figs. 4 and 14) may not be as attractive, however, as the substantial length, width, and structural relief of the anticline might suggest. The anticline is apparently still growing, and it is probably an entirely Neogene and perhaps even a Quaternary structure. If the fold is indeed this young, it may substantially postdate the migration of oil from the lower Tertiary and older beds of the basin, and there may not have been sufficient time to accumulate large quantities of hydrocarbons generated in the Tertiary strata. Because of its youthfulness, the Camden anticline may be more prospective for gas than for oil.

Diapiric fold province

Most of the numerous anticlinal structures of the diapiric fold province (area 5 in Figure 16) lie beneath 1500 m to 3000 m of water in areas of the Arctic basin that are seldom ice-free (Fig. 2). They offer, for possible future exploration, many structural traps within the oil window, and up-dip migration may have carried hydrocarbon fluids into higher structural positions on the folds. A large unknown in the diapiric fold province is whether suitable hydrocarbon source beds and reservoir rocks are present.

Canada basin

Water depths exceeding 2400 m, perennial ice cover (Fig. 2), and uncertainties concerning the presence of source and reservoir rocks appear to assure that petroleum exploration in the areas of the lease sale within the Canada basin (areas 6A, 6B, and 6C in Figure 16) will not be undertaken in this century. However, the sedimentary rocks of the basin, which are interpreted to be of Brookian age, are potentially prospective because they are 5 km to more than 10 km thick and a substantial part of the section is estimated to be in the oil window (Fig. 18). The adequacy of hydrocarbon source beds and of reservoir rocks is not known, but suitable source beds and porous turbidite sands could be present. Seismic-reflection profiles across part of the Alaskan continental rise subprovince (area 6A in Fig. 16) demonstrate the presence of low-angle faults and buckled beds and fault planes at the toes of growth faults and deep slumps. These low-angle faults originated in Nuwuk basin and beneath the continental slope. Such complex structures might have formed suitable traps for the accumulation of hydrocarbons, but the seismic lines are too widely spaced to demonstrate structural closures.

Gas hydrate

Where water depths in the area of lease sale 87 exceed about 400 m, the top 300 m to 700 m of subsea floor sediment is in the temperature-pressure range for the formation and stability of natural gas hydrate (Fig. 19). Evidence for the occurrence of gas hydrate was found on about 75 percent of our seismic-reflection coverage in the sale area between the 400-m isobath and the north end of our seismic lines or the 2800 isobath. The zone of gas hydrate may also extend beyond the 2800 isobath, but the evidence is difficult to recognize in the nearly flat sedimentary strata that underlie the Canada Basin at those depths.

It is not known from our seismic data what portion of the potential zone of occurrence has actually been cemented with gas hydrate. Hydrate formation requires either the in situ generation of gas in the appropriate temperature-pressure zone, or the introduction of gas by migration from outside the zone. The completeness of hydrate cementation within the hydrate pressure-temperature zone depends heavily on the availability of gas or of suitable organic matter for the generation of gas, the permeability of the sediment, and the existence of appropriate pathways for gas migration. It is assumed that the hydrate contains mostly methane because this is the most abundant gas in naturally-occurring gas hydrates, but this has yet to be demonstrated. Until the hydrate zone is sampled, its resource potential can only be conjectured, but theoretical calculations suggest that the potential resource could be very large. To date, however, attempts onshore in the Soviet Union and Canada to decompose subpermafrost hydrate in situ have apparently not led to a method for producing hydrate-bound methane gas commercially. Subsurface gas hydrate is of greater current interest as a potential geohazard than as a resource. Under the environmental conditions of the Arctic Ocean, development of the gas hydrate resource will probably be undertaken first, if at all, in conjunction with the development of deeper, conventional deposits of oil and gas in the region of hydrate occurrence.

A more likely resource in the region of gas hydrate is the free gas that, in many places, can be interpreted to immediately underlie the base of the hydrate zone. Many of the strongest concentrations occur under pseudo-anticlines formed where the base of the gas hydrate, which tends to parallel the seabed, underlies bathymetric highs (Fig. 20). Large volumes of low to moderate pressure gas could be present in such structures and other subhydrate accumulations. However, sampling to determine the properties of the potential reservoirs, the composition of the gas, the thickness of the gas zone, and the gas content of the associated connate water, as well as additional seismic reflection profiles, will be required to estimate the resource that may be present.

Relative prospectiveness of the provinces

Prospects for the occurrence of large petroleum deposits, without regard to economic realities, appear to be highest in the Arctic platform province east from Smith Bay, and in the Kaktovik and Nuwuk basins. Dinkum graben, the Arctic platform near the hinge line (including the area with hinge-line-related faults between Point Barrow amd Harrison Bay), the Arctic platform south of the wedgeout of Ellesmerian strata west of Point Barrow, and probably the diapiric fold province are also prospective. These are, however, probably somewhat less favorable for large deposits than the foregoing areas. The structurally shallow area of the Arctic platform in the broad crestal region of the Barrow arch northwest of the Ellesmerian wedgeout in the Chukchi Sea has poor prospects. There are insufficient data and a lack of suitable analogs from which to rank the subprovinces of the Canada basin or the gas hydrate zone. The best prospects in the Canada basin, exclusive of the diapiric folds, may lie in the structurally disturbed and stratigraphically complex zone that lies at the foot of the listric growth faults within the upslope (landward) part of the Alaska continental rise sedimentary prism.

Resource appraisal estimates

Estimates of the economically recoverable oil and gas in the planning area for the proposed sale no. 87 have been developed from recent, unpublished Geological Survey estimates for the Beaufort Shelf Province. The province estimates, shown in Table 2, were obtained by subjective probability techniques that incorporate geologic judgment and analysis of the petroleum characteristics of the basin. The analytical procedures include:

1. A review and interpretation of available geological and geophysical data.
2. Application of arbitrary hydrocarbon yields derived from various United States hydrocarbon-producing basins.
3. Comparison with other petroleum provinces.

The assessments in Table 2 are probability estimates of "more than" quantities associated with given probabilities of occurrence. Usually in such assessments conditional and unconditional estimates are given. However, since the marginal probability for the Beaufort shelf was estimated to be 1.0, the conditional and unconditional values are the same and only the conditional values are shown on Table 2.

The estimates shown in Table 2 are assessments of undiscovered recoverable oil and gas for the total Beaufort shelf if technology permits their exploitation beneath the Arctic pack ice. They must be reduced to obtain an estimate of economically recoverable oil and gas because they include resources on State lands and resources that are currently not economically recoverable because of the Arctic pack ice. Based on information published by the National Petroleum Council (1981), resources are not considered recoverable with present technology in areas of Arctic pack ice where water depths are greater than 200 feet. Economically recoverable resources in the portion of the Beaufort shelf province between the State three-mile limit and the 200-foot water depth contour are estimated to be 50 percent of the total shelf resources shown in Table 2.

Table 2

Estimates of Total Undiscovered Oil and Gas, Beaufort Shelf[1]

	95th Fractile[2]	5th Fractile[2]	Mean	Marginal Probability
Oil (Billions of barrels)				
Conditional	2.12	18.68	7.79	1
Assoc./Dissolved Gas (TCF)[3]				
Conditional	3.39	29.89	12.46	1
Non-Assoc. Gas (TCF)[3]				
Conditional	7.17	65.25	26.84	1
Aggregated Gas (TCF)[3]				
Conditional	15.26	82.87	39.30	1

[1]These quantities can be considered recoverable <u>only</u> if technology permits their exploitation beneath the Arctic pack ice--a condition not yet met.

[2]The probability of <u>more than</u> the amount at the 95th fractile is 95 percent. The 5th fractile is defined similarly.

[3]TCF, trillion cubic feet.

Environmental geology

General description

Sea ice, Holocene tectonism, active slumping and sliding, shallow free gas concentrations, unconsolidated sediment, natural gas hydrates, subsea permafrost, and other factors will complicate petroleum development in the Beaufort and northeastern Chukchi Seas. The continental shelves here are mostly ice-free and accessible to drill ships for up to two months during occasional favorable years; however, other troublesome subsea conditions will hamper drilling even when the sea ice does not.

Natural gas hydrate with a zone of free gas at its base 300 to 700 m beneath the seafloor is widespread where water is deeper than 300 m. Shale diapirs, presumably overpressured, disrupt the continental slope east of 147°W. long. Shallow, low-angle bedding-plane slides as wide as 38 km underlie most of the outer shelf. The slides are sufficiently young to preserve open crevasses as deep as 17 m (exceptionally 37 m). East of 146°W. long production facilities may be subject to earthquakes as large as magnitude 6 and in places to active faulting, uplift, and subsidence. Subsea permafrost, probably containing gas pockets, extends from near the sea-bottom to depths of several hundred meters in sediments near the coast and may present thawing and compaction hazards to drillholes on the inner shelf. Shallow free gas is concentrated in isolated patches on the inner shelf and in a long and continuous but narrow zone near the shelf break.

The westward-drifting polar ice pack, which lies seaward of a zone of shorefast and bottom-fast ice inside the 10- 20-m isobath, will be a major obstacle to exploration and production activities. In addition, the seabed between the coastline and at least the 60-m isobath is gouged by keels of drifting ice ridges and tabular icebergs. Subbottom completions in this zone, and pipelines crossing it, will have to be buried below the gouges, which locally exceed 5 m in depth. River flooding of shorefast ice, strudel scouring, high storm tides, rapid currents in tidal passes, rapid coastal retreat, and ice buildup on beaches and barrier islands present additional engineering hazards in the nearshore area.

Unconsolidated deposits

The shelf of the Beaufort Sea is essentially a seaward extension of the low, flat coàstal 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 more than 45 m of marine mud and sand. The textural character of the surficial sediments is shown on figure 21. Local accumulations of gravel and boulders, mainly along the shelf break, apparently represent relict ice-rafted materials. 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 deformed by 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. 27). Extreme retreats of 30 to 50 m have been recorded at coastal promontories during single major storms.

The Holocene sediment cover over the shallow offshore parts of the eastern Chukchi Sea apparently is thin, less than 5 m in most places, but locally can be as much as 12 m thick (Moore, 1964). In nearshore regions Holocene sediment on the northeast Chukchi Shelf forms a thin veneer over Cretaceous bedrock. The maximum Holocene sediment thickness, 16 m, occurs directly off Point Franklin. The surficial deposits consist of mixtures of mud, sand, and gravel. Fields of actively northeast-migrating sandwaves occur north of Peard Bay, starting at depths of 18 to 20 m, and extend seaward to unknown depths along the east flank of the Barrow Sea Valley. Surficial gravel patches also occur near the sandwave fields. Kelp beds, associated with surficial gravel patches and possible bedrock outcrops on the sea floor, occur northeast of Peard Bay at depths less than 15 m (Fig. 21) and may continue as scattered fields north toward Point Barrow.

The most poorly consolidated sediments on the Beaufort Shelf are the Holocene marine muds and silts whose thickness is contoured on figure 22. On the outer shelf they have been interpreted and measured on high-resolution (Uniboom) seismic profiles on the basis of acoustic properties and geometric considerations. On the inner shelf, drilling, sampling, and diving information corroborates and therefore allows for considerable certainty in interpreting the acoustic data. The Holocene deposits 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 thin or 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 probably have low shear strength, as indicated by the development of very low-angle bedding plane slides, and deposits with significant sand and silt contents 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 plan slide terrane of the outer shelf (Fig. 23), where failure might be triggered by earthquakes or by the release of large slump masses in the adjacent slide terrane, is also hazardous. 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.

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 late Quaternary 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. 24). Structures emplaced on the thick Holocene sediments flanking this uplifted, seismically active area will be subject to especially strong shaking during earthquakes.

Landslides

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 2eveloped in unconsolidated or poorly consolidated Holocene and Pleistocene sediments (Fig. 23). 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 sags at the heads of extensional zones, coherent bedding-plane slide zones in which large tabular blocks that have 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 commonly 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 early Holocene age. These deposits are typically 30 to 50 m thick near the head of the slide terrane (Fig. 22).

In view of the evidence for repeated and continuing 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.

Young faults

High-angle normal and possibly reverse faults, some of which affect Holocene deposits and the seabed, and monoclines overlying such faults are abundant off Camden Bay (Fig. 24). The youthfulness and local abundance of these features and their areal coincidence with a zone of Holocene uplift and modern earthquakes strongly suggest that at least some of them are active. These faults lie within the western end of a terrane of large-amplitude, late Cenozoic detachment folds that characterize the western part of the Barter Island sector of the Beaufort shelf, and appear to represent part of the active front of the tectonic system that produced these folds.

In addition to these tectonic, apparently seismogenic faults, two types of north-dipping, down-to-the-basin gravity faults underlie the western Beaufort shelf (Fig. 24). These faults are listric surfaces along which the sedimentary prism of the shelf has failed and moved toward the "free face" of the continental slope. 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 late Pleistocene.

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.

Seismicity

Most of the area of lease sale 87 has historically been aseismic with the exception of an anomalous earthquake located by the worldwide network about 200 km north of the Colville River delta and a zone of concentrated seismic activity in the vicinity of Barter Island in the southeast quadrant of the lease sale area. The epicenters of representative earthquakes with magnitudes of 3.0 or greater in the sale area, as recorded by the worldwide seismograph network through 1980 (Meyers, 1976a, and U.S. Geological Survey, unpublished), and by the Canadian and by a local seismographic network in northeast Alaska from 1968 to 1977 (Biswas and Gedney, 1978) are shown in Figure 24. Biswas and Gedney conclude that the active seismic zone in the vicinity of Barter Island is a northeastern extension of the central Alaska seismic zone. Seismic-reflection data on the eastern Alaskan Beaufort shelf suggest further that the earthquakes are associated with Quaternary movement on the Camden and Marsh detachment anticlines and related structures in northeastern Alaska and adjacent offshore.

The magnitudes of measured earthquakes near Barter Island range from less than 1.0 to a maximum of 5.3. Consequently, structures designed for use in oil and gas exploration and development in the southeastern portion of the lease sale area should be able "to withstand ground vibrations corresponding to those from a shallow earthquake (less than 20 km) of at least magnitude 6.0" (Biswas and Gedney, 1978). Studies by Thenhaus and others (1982) on seismic horizontal ground motion in Alaska and adjacent offshore areas indicate that there is a 90 percent probability that ground accelerations with maximum values of 4.0-5.0 percent of gravity will not be exceeded, and a 10 percent probability that they will be exceeded, in 50 years in the southern half of the lease sale area. An isoseismal map, modified from Meyers (1976b), showing projected maximum intensities of major earthquakes occurring in and near Alaska between 1786 and 1974 is shown in Figure 25. According to the projections on this map, the southeastern portion of the lease sale area has been exposed to earthquakes of low to moderate intensity (III to VII on the twelve-step Modified Mercalli Scale).

Shallow gas

Shallow free gas has accumulated in several geologic environments beneath the shelf and slope of the western Beaufort and northeastern Chukchi Seas. In some cases this gas may indicate the presence of natural gas deposits in underlying sedimentary strata (thermogenic origin). In other cases the gas may originate in surficial sediment as a product of bacterial metabolism of organic constituents (biogenic origin). Wherever it occurs, shallow free gas must be considered a potential engineering hazard to petroleum exploration or development structures founded on the seabed. Such gas can inhibit the normal consolidation of accumulating sediment, leading to abnormally low shear strengths. In addition, gas concentrated in overpressured pockets might cause blowouts during drilling.

High concentrations of shallow gas have been mapped in scattered, isolated areas of the inner shelf and in a rather continuous band at or near the head of the landslide terrane near the shelf break from high-resolution (Uniboom) seismic reflection profiles (Fig. 19). Varying gas concentrations are distinguishable on these records as acoustically "turbid" intervals, in which normally strong reflectors are hazy or completely wiped out. Delineation of the zones mapped in Figure 19 depends on the assumption that the degree to which a reflection record is degraded or "turbid" is a function of how much free gas is present in the bubble phase. Ambiguity arises where records have been degraded due to strong ship motion during storms. In a few areas high gas concentrations are marked not by turbid intervals, but by prominent reflectors that commonly exhibit reversed polarity (Boucher and others, 1981). Such reflectors occur where gas has accumulated beneath a relatively impermeable stratum, thus enhancing the acoustic impedence contrast at the base of the stratum.

On the middle and inner shelf high concentrations of shallow gas are most commonly associated with buried Pleistocene delta and channel systems, and with active faults overlying natural gas sources. Additional pockets probably occur within and beneath permafrost very near shore, but data to study this type of occurrence are sparse.. Beneath the outer shelf and continental slope, shallow gas is concentrated in two, probably related, environments. It is thought to underlie a large body of gas hydrate (see section on Gas Hydrates below), and also occurs almost ubiquitously at the head of the landslide terrane on the outermost shelf and upper slope. As this terrane lies just inshore and updip from the gas hydrate sheet, it seems likely that the gas here has migrated from beneath the hydrates.

Gas hydrate

Gas hydrates (solids composed of light gases caged in the interstices of an expanded ice crystal lattice) are stable and have widespread occurrence under the low temperature and relatively high pressure conditions prevailing within the uppermost 300 to more than 700 m of sediment beneath the continental slope and outermost shelf of the Beaufort Sea where water depths exceed about 300 m. The hydrate, the gas component of which consists mostly of methane in submarine strata, tends to cement the sediment, somewhat increasing its seismic velocity and creating a zone of reduced permeability that traps free gas at its base. Gas hydrate is widespread in the area of sale 87 (Fig. 19), but they do not occur in water as shallow as the 200-foot isobath suggested as an operating limit by the National Petroleum Council (1981). Seismic reflection data indicate that large amounts of free gas accumulated beneath the impermeable gas hydrate (Fig. 20). The presence of this free gas and the danger that the hydrate may decompose and release large quantities of methane and perhaps other hydrocarbon gases during drilling pose a substantial potential hazard to exploratory drilling in this extensive area of sale 87. However, the petroleum industry, particularly in the Canadian Arctic, has acquired considerable experience in coping with gas hydrate in bore holes. The resource potential of the gas hydrate and underlying free gas are considered in the section on Petroleum Potential, above.

Overpressured shale

Numerous diapiric folds disrupt the sediments and, in places, the seafloor beneath the continental slope and rise east of 146°W. long (Fig. 4). These folds are interpreted to be cored by shale because they appear to be a westward extension of the shale-diapir province of the western Canadian Beaufort shelf. Shale diapirism, the result of lower density in the shale section than in the overlying strata due to incomplete dewatering of the shale, is an indication of overpressuring within the shale. This condition may pose a drilling hazard throughout the diapiric fold province.

Permafrost

Prior to about 10,000 years ago, during the last glacial sea-level lowstand, the present Beaufort and Chukchi shelves were exposed subaerially to frigid temperatures, and ice-bonded permafrost probably formed 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 certain terranes 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 some 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 sea floor. 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 on the coastal and outer shelf is unknown, the base of Holocene marine sediments on the Beaufort shelf, contoured in figure 22, 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 sea level. 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.

Permafrost might occur locally in the Chukchi Sea. Ice-bonded permafrost is known to occur in Elson Lagoon, which connects with the Beaufort Sea just east of Point Barrow, but none was found in the Chukchi Sea 705 m from shore near Barrow (Osterkamp and Harrison, 1980). Nearshore permafrost is most likely to occur in areas where coastal erosion is rapid. Because the rates of coastal erosion are typically lower in the Chukchi Sea than in the Beaufort Sea, permafrost may not be as common in the Chukchi Sea (Harper, 1978). The most complete evaluation of the possible occurrence of subsea permafrost in the Chukchi Sea was by Osterkamp and Harrison (1980), who stressed the unpredictability of its occurrence at any specific locality.

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 1 m thick, and it thickens to a maximum of about 2 m in May. In late May and early June, 24-hour insolation aids rapid onland thawing, 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 accompanying 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 retreats 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. 27) into three broad categories (Reimnitz and others, 1977): 1) Seasonal floating fast ice and bottom-fast ice of the inner shelf, 2) a brecciated shear (stamukhi) zone containing grounded ice ridges that mark 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 ice keel that has been measured in the Arctic basin had a draft of 47 m. The general drift of the pack on the Beaufort shelf is westward under the influence of the clockwise-rotating Pacific Gyre. Patterns of pack-ice movement in the Chukchi Sea during the spring and summer have been reported by Colony (1979), Pritchard (1978), and Shapiro and Barry (1978). These and other workers agree in finding movement largely to the west and north, except for some southward movement during the spring. Considerable, but episodic southward movement toward and through Bering Strait occurs during the winter and early spring (Ahlnas and Wendler, 1979; Shapiro and Burns, 1975).

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 and 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 exert tremendous stresses on the sea bottom and on any structures present in a band of varying width between the 10- and 50-m isobaths. In some places the extent of shorefast ice may be deflected seaward by future 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 which are found from near shore out to water about 60 m deep (Fig. 28). The physical disruption of seafloor sediments by moving ice keels is a serious threat to seafloor installations. Most studies of the phenomenon have been conducted in the Beaufort Sea (Barnes and Reimnitz, 1974; Reimnitz and

Barnes, 1974; Reimnitz and others, 1978; Rearic and others, 1981). Here 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. High gouge densities 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 (Barnes and Reimnitz, 1979). Rates of gouging inshore of the protective stamukhi zone have been measured at 1 to 2 percent of the sea floor per year (Reimnitz and others, 1977; Barnes and others 1978). The product of maximum ice gouge incision depth (D^{max}), maximum width of ice gouges (W^{max}), and gouge density per kilometer interval (Z), here called ice gouge intensity (I), is considered the best single measure of the severity of the process, and has been contoured in Figure 28.

Information on orientation, densities, depth of gouging and rates of gouging is as yet very limited for the Chukchi Sea nearshore region. Limited data show shore-parallel ice gouges from depths of 2 m to approximately 9 m near Barrow; seaward of the 9 m isobath ice gouge orientation is variable. As in the Beaufort Sea, the density of ice gouging indicates a seaward increase in gouging within the stamukhi zone at depths of 10 to 20 m. Rex (1955) reports the greatest density of gouging between 6 to 24 m west of Barrow. The incision depth of ice gouging varies from less than 1 m in shallow regions southwest of Barrow to a maximum of 3.8 m west of Barrow (Rex, 1955), to 4.5 m at 38 m depth in the Chukchi Sea (Barnes and Hopkins, 1978). The rates of ice gouging are unknown for this coastal region but could be expected to range from 1 to 2 percent of the sea floor gouged annually, as reported for the nearshore Beaufort shelf (Barnes and others, 1980).

Oceanographic regime and currents

Beaufort Sea - The overall movement of water on the shelf off northern Alaska is toward the west. This net transport is shown by surface and bottom drifters released at various times (Barnes and Toimil, 1979; Barnes and others, 1977; Matthews, 1981a), although at least in the eastern sector surface drift to the east may at times dominate (Fig. 26). On the inner shelf, the oceanographic regime is strongly influenced by winds and the presence or absence of ice. In most parts of the inner shelf, sub-ice current velocities are less than 2 cm sec^{-1} (Matthews, 1981b). However, where the tidal prism is constricted by ice growth and in inlet channels, velocities up to 25 cm sec^{-1} have been recorded. Along the outer shelf edge, slope-parallel current pulses with velocities up to 50 cm sec^{-1} and with both easterly and westerly directions have been measured.

Chukchi Sea - tidal currents, wave-generated and wind-generated currents, and the offshore, shore-parallel Alaska Coastal Current modify the sea floor along the eastern Chukchi Sea by erosion and transportation of sediment as migrating bedforms. The nearshore currents are generated mostly by winds, and the offshore region is dominated by northeast-directed storm currents and by the northeast-flowing Alaska Coastal Current (Fig. 26).

The tides are small in the Chukchi Sea, and the tidal range along the eastern coast is generally less than 30 cm. The tides are of the semidiurnal type (Creager, 1963; Wiseman and others, 1973). The tidal wave moves from north to south in the Chukchi Sea (Coachman and Aagaard, 1974). Tide-generated currents can be expected to be of limited velocity along the open coast. Within lagoons and embayments, however, tide-generated currents are reported up to 204 cm sec^{-1} within the tidal passes east of Barrow (Rex, 1955). Similar velocities can be expected within the tidal passes along the Chukchi Sea.

Storms during the summer months usually result in winds from the southwest which move across the Chukchi Sea. The maximum fetch then develops across the open water (Wiseman and Rouse, 1980). The resulting storm waves and storm-generated currents may erode and scour the sea floor as well as result in intense sediment transport on the shelf and on the shoals.

Wind-generated currents are extremely variable both in velocity and in direction of movement within the nearshore region (Wiseman and Rouse, 1980). The predominant summer winds are from the northeast, generating nearshore current velocities of 4 to 20 cm sec^{-1} (Hufford, 1977). The wind-generated currents generally follow the bottom contours (Wiseman and others, 1974). Daily variations in current direction are reported for the nearshore region (Wiseman and Rouse, 1980).

The Alaska Coastal Current represents a northeast flowing "warm" water mass derived from the Bering Sea (Paquette and Bourke, 1972; Coachman and others, 1976). The current varies in width and can be as narrow as 20 to 37 km (Aagaard and Coachman, 1964; Hufford, 1977). At the few times and places where they have been measured, the velocities of the coastal current vary from 50 cm sec^{-1} near Cape Lisburne (Sharma, 1979) to 51 to 87 cm sec^{-1} south of Icy Cape (Ingham and Rutland, 1972), to 55 cm sec^{-1} north of Wainright (Hufford, 1977). To the northwest of Wainright near the Barrow Submarine Canyon head west of the Alaska Coastal Current, a returning southwest-directed current is reported with surface velocities of 80 cm sec^{-1} (Hufford, 1977). The southwest-flowing current is poorly defined in space and time. Large clockwise rotating spiral currents are reported west of Barrow (Solomon and Ahlnas, 1980) and may represent interaction between the Alaska Coastal Current and the westward-flowing current of the Beaufort Gyre.

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 storm surges up to over 3 m higher than mean sea level. 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 surges deeply erode coastal bluffs and island shorelines, deepen the channels between barrier islands, and can be expected to scour the foundations of drilling platforms and the flanks of 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.

Storm surges pose an erosional hazard as well as a flood hazard to coastal areas of the Chukchi Sea as well as the Beaufort Sea. Several storm surges have caused severe coastal erosion at Barrow during the last several decades (Hume and Schalk, 1967). Observations of spindrift lines and other features along the Chukchi Sea coast south of Barrow (Hopkins and Hartz, 1978; Hopkins and others, 1979) suggest that storm surges are not restricted to the vicinity of Barrow but rather occur along the entire

Chukchi Sea coast. Storm surges reach as high as 3 to 3.5 m above sea level at Barrow and elsewhere along the Chukchi Sea coast (Aagaard, 1978; Hopkins and Hartz, 1978). Storm surges of this height cause extensive overwash across the barriers.

Coastal 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.

The cliff sections of coastline along the Chukchi Sea were formed by erosion, but rates of cliff retreat are not necessarily high enough at the present time to pose a serious hazard (Fig. 27). The barriers and spits, in contrast, are depositional features, but they are not necessarily stable or undergoing further growth at the present time. Some of the barriers are known to be migrating landward by erosion on their seaward sides, overwash across their crests, and deposition on their lagoonal sides.

River overflow and strudel scour

The yearly spring flooding of vast expanses of fast ice on the inner shelf in the Arctic, and the often violent draining of these floodwaters through the ice, result in the formation of large scour craters, called strudel scours (Reimnitz and Bruder, 1972; Reimnitz and others, 1974). Strudel scours commonly are 15 to 25 m in diameter, over 4 m deep, and are considered by industry to be the most severe threat to pipelines in shallow water regions. Regions so affected are shown in Figure 26. The sudden impulse of river water interacting with a sub-ice oil spill would result in rapid spreading of the spill.

Suspended sediment

Water clarities are generally highest below the winter ice cover, and are considerably higher in Chukchi coastal waters than in the Beaufort Sea. Water clarity could be reduced by construction activities, which may serve to resuspend particulate matter. This would have a directly adverse effect on the productivity of benthic communities on the sea floor and sub-ice surfaces.

Recent observations show that strong winds occurring during initiation of freeze-up on the shelf produce large volumes of slush ice (frazil) on the sea surface together with a heavy load of resuspended sediment caused by storm wves. Congelation of this sediment-laden slush into solid ice during the winter results in a very turbid ice canopy that is opaque to sunlight. The water column below this dirty ice also remains turbid through most of the winter. During the following summer the dark ice absorbs more solar radiation than the normally clean fast ice, and therefore breaks up sooner. The consequences of the formation of slush ice in the fall and its effect on ice strength, biological activity, sediment transport, and spilled oil, are still poorly understood.

References cited

Aagaard, Knut, ed., 1978, Physical oceanography and meteorology, in Environmental assessment of the Alaskan continental shelf; interim synthesis: Beaufort/Chukchi: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Boulder, Colorado, Annual Report, p. 56-100.

Aagaard, K., and Coachman, L. K., 1964, Notes on the physical oceanography of the Chukchi Sea, in U.S. Coast Guard Oceanographic Report no. 1: Washington, D.C., U.S. Government Printing Office, p. 13-16.

Ahlnas, K., and Wendler, G., 1980, Sea-ice observations by satellite in the Bering-Chukchi-, and Beaufort Sea, in Proceedings of International Conference on Port and Ocean Engineering Under Arctic Conditions, 5th, Trondheim, Norway, Aug. 13-17, 1979: Trondheim, University of Trondheim and Norwegian Institute of Technology, v. 1, p. 313-329.

Alaska Geological Society, 1971, West to east stratigraphic correlation section, Point Barrow to Ignek Valley, Arctic North Slope, Alaska: Anchorage, Alaska Geological Society.

_____1972, Northwest to southeast stratigraphic correlation section, Prudhoe Bay to Ignek Valley, Arctic North Slope, Alaska: Anchorage, Alaska Geological Society,

_____1977, North to south stratigraphic correlation section, Beaufort Sea-Prudhoe Bay-Nora No. 1, Arctic Slope, Alaska: Anchorage, Alaska Geological Society.

_____1981, West to east stratigraphic correlation section, N.P.R.A.-Prudhoe Bay, Arctic Slope, Alaska: Anchorage, Alaska Geological Society.

American Association of Petroleum Geologists and United States Geological Survey, 1976, Geothermal gradient map of North America: 2 sheets, scale 1:5,000,000.

Barnes, P. W., and Hopkins, D. M., eds., 1978, Geological sciences, in Environmental assessment of the Alaskan Continental Shelf. Interim synthesis: Beaufort/Chukchi: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Boulder, Colorado, Annual Report, p. 101-133.

Barnes, P. W., McDowell, D. M., 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 northern coast of Alaska, in Reed, J. C., and Sater, J. E., eds., The coast and shelf of the Beaufort Sea. Proceedings of the Arctic Institute of North America Symposium on Beaufort Sea coast and shelf research: Arlington, Virginia, Arctic Institute of North America, p. 439-476.

_____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., Reimnitz, Erk, Drake, D. E., and Toimil, L. J., 1977, Miscellaneous hydrologic and geologic observations on the inner Beaufort Sea shelf, Alaska: U.S. Geological Survey Open-File Report 77-477, 95 p.

Barnes, P. W., and Toimil, L. J., 1979, Maps showing inner shelf circulation patterns, Beaufort Sea, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1125.

Biswas, N. N., and Gedney, L., 1978, Seismotectonic studies of northeast and western Alaska: University of Alaska Geophysical Institute, 45 p.

Boucher, Gary, Reimnitz, Erk, and Kempema, Edward, 1981, Seismic evidence for an extensive gas-bearing layer at shallow depth, offshore from Prudhoe Bay, Alaska: Cold Regions Science and Technology, v. 4, p. 63-71.

Brosgè, 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: American Association of Petroleum Geologists Memoir 15, p. 68-99.

Brower, William A., Jr., Searby, H. W., Dias, H. F., Prechtel, A. S., and Wise, J. L., 1977, Climatic atlas of the outer continental shelf waters and coastal regions of Alaska; Vol. III, Chukchi-Beaufort Sea: Arctic Environmental Information and Data Center, Pub. #B-77, 409 p.

Coachman, L. K., and Aagaard, Knut, 1974, Physical oceanography of Arctic and subarctic seas, in Herman, Yvonne, ed., Marine geology and oceanography of Arctic seas: New York, Springer-Verlag, p. 1-72.

Coachman, L. K., Aagaard, Knut, and Tripp, R. B., 1976, Bering Strait; the regional physical oceanography: Seattle, Washington, University of Washington Press, 172 p.

Colony, Roger, 1979, Dynamics of nearshore ice: Physical science studies: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Boulder, Colorado, Final Reports, v. 2, p. 156-180.

Creager, J. S., 1963, Sedimentation in a high energy, embayed, continental shelf environment: Journal of Sedimentary Petrology, v. 33, p. 815-830.

Eittreim, Stephen, and Grantz, Arthur, 1979, CDP seismic sections of the western Beaufort continental margin: Tectonophysics, v. 59, p. 251-262.

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, Arthur, Dinter, D. A., and Biswas, N. N., 1982, 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, scale 1:500,000 (in press).

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, Eittreim, Stephen, and Whitney, O. T., 1981, Geology and physiography of the continental margin north of Alaska and implications for origin of the Canada Basin, in Nairn, A. E. M., Churkin, Michael, Jr., and Stehli, F. G., eds., The ocean basins and margins: New York, Plenum Publishing Corporation, v. 5, p. 439-492.

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., 4 figs.

Grantz, Arthur, and May, S. D., 198_. Rifting history and structural development of the continental margin north of Alaska, in Watkins, J. S., and Drake, E., eds., Continental margin processes: American Association of Petroleum Geologists Memoir (in press).

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-1181-A, 1 sheet, scale 1:500,000 and 5 pages of text.

Guldenzopf, E. C., and others, 1980, National Petroleum Reserve, Alaska, Summary geological report fiscal year 1980: Tetra Tech., Inc., prepared for Husky Oil NPRA Operations, Inc., under contract to U.S. Geological Survey, 168 p.

Harper, J. R., 1978, Coastal erosion rates along the Chukchi Sea coast near Barrow, Alaska: Arctic, v. 31, no. 4, p. 428-433.

Hea, J. P., and others, 1980, Post-Ellesmerian basins of Arctic Canada; their depocentres, rates of sedimentation, and petroleum potential, in Miall, A. D., ed., Facts and principles of world petroleum occurrence: Canadian Society of Petroleum Geologists Memoir 6, p. 447-488.

Hopkins, D. M., and Hartz, R. W., 1978, Shoreline history of Chukchi and Beaufort Seas as an aid to predicting offshore permafrost conditions in Environmental assessment of the Alaskan continental shelf: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Boulder, Colorado, Annual Reports, v. 12, p. 503-574.

Hopkins, D. M., Hartz, R. W., and Robinson, S. W., 1979, Record of a prehistoric storm surge in the Wainwright Inlet-Kuk River area: U.S. Geological Survey Circular 804-B, p. 29-31.

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

Hume, J. D., and Schalk, M., 1967, Shoreline processes near Barrow, Alaska; a comparison of the normal and the catastrophic: Arctic, v. 20, no. 2, p. 86-103.

Ingham, M. C., and Rutland, B. A., 1972, Physical oceanography of the eastern Chukchi Sea off Cape Lisburne-Icy Cape: U.S. Coast Guard Oceanographic Report Series no. 50, p. 1-86.

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: American Association of Petroleum Geologists Memoir 30,

p. 289-314.

Jones, H. P., and Speers, R. G., 1976, Permo-Triassic reservoirs of Prudhoe Bay field, North Slope, Alaska: American Association of Petroleum Geologists Memoir 24, p. 23-50.

Lachenbruch, A. H., and Marshall, B. V., 1966, Heat flow through the Arctic Ocean floor--the Canada Basin-Alpha Rise boundary: Journal of Geophysical Research, v. 71, p. 1223-1248.

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

Mair, J. A., and Lyons, J. A., 1981, Crustal structure and velocity anistrophy beneath the Beaufort Sea: Canadian Journal of Earth Sciences, v. 18, p. 724-741.

Martin, A. J., 1970, Structure and tectonic history of the Western Brooks Range, De Long Mountains and Lisburne Hills, northern Alaska: Geological Society of America Bulletin, v. 81, p. 3605-3622.

Matthews, J. B., 1981a, 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.

-----1981b, Observations of under-ice circulation in a shallow lagoon in the Alaska Beaufort Sea: Ocean Management, v. 6, p. 223-234.

Meyers, H., 1976a, A historical summary of earthquake epicenters in and near Alaska: NOAA Technical Memo EDS NGSDG-1, 57 p.

Meyers, H., and others, 1976b, An analysis of earthquake intensities and recurrence rates in and near Alaska: NOAA Technical Memo EDS NGSDC-3, 101 p.

Miller, C. C., and others, 1979, National Petroleum Reserve, Alaska, Summary geophysical report fiscal year 1979: Tetra Tech., Inc., prepared for Husky Oil NPR Operations, Inc., under contract to U.S. Geological Survey, 47 p.

Moore, D. G., 1964, Acoustic reflection reconnaissance of continental shelves; the Bering and Chukchi Seas, in Miller, R. I., ed., Papers in Marine Geology, Shepard Commemorative Volume: New York, MacMillan, p. 319-362.

National Petroleum Council, 1981, U.S. Arctic oil and gas: Washington, D.C., National Petroleum Council, 286 p.

Oliver, Jack, Ewing, Maurice, and Press, Frank, 1955, Crustal structure of the Arctic regions from the Lg phase: Geological Society of America Bulletin, v. 66, p. 1063-1074.

Osterkamp, T. E., and Harrison, W. D., 1977, Sub-sea permafrost regime at Prudhoe Bay, Alaska, U.S.A.: Journal of Glaciology, v. 19, no. 81, p. 627-637.

Paquette, R. G., and Bourke, R. H., 1974, Observations on the coastal current of Arctic Alaska: Journal of Marine Research, v. 32, no. 2, p. 197-207.

Pritchard, R. S., 1978, Dynamics of nearshore ice in Environmental assessment of the Alaska continental shelf: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Boulder, Colorado, Annual Report, v. 11, p. 39-49.

Rearic, D. M., Barnes, P. W., and Reimnitz, Erk, 1981, Ice gouge data, Beaufort Sea, Alaska, 1972-1980: U.S. Geological Survey Open-File Report 81-950, 8 microfische cards.

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 the Arctic Institute of North America Symposium on Beaufort Sea Coast and Shelf Research: Arlington, Virginia, Arctic Institute of North America, p. 301-351.

Reimnitz, Erk, Barnes, P. W., Toimil, L. J., and Melchoir, John, 1977, Ice gouge recurrence and rates of sediment reworking, Beaufort Sea, Alaska: Geology, v. 5, p. 405-408.

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, no. 3, p. 861-866.

Reimnitz, Erk, and Maurer, D. K., 1979, Effects of storm surges on the Beaufort Sea coast, northern Alaska: Arctic, v. 32, no. 4, p. 329-344.

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

Rex, R. W., 1955, Microrelief produced by sea ice grounding in the Chukchi Sea near Barrow, Alaska: Arctic, v. 8, p. 177-186.

Royden, Leigh, Sclater, J. G., and von Herzen, R. P., 1980, Continental margin subsidence and heat flow; important parameters in formation of petroleum hydrocarbons: American Association of Petroleum Geologists Bulletin, v. 64, no. 2, p. 173-187.

Sellman, P. V., and Chamberlain, E., 1979, Delineation and engineering characteristics of permafrost beneath the Beaufort Sea: National Oceanic and Atmospheric Administration, Arctic Projects Office, Fairbanks, Alaska, Quarterly Report to U.S. Department of Commerce.

Shapiro, L., and Barry, R. G., 1978, The sea ice environment, in Environmental assessment of the Alaskan Continental Shelf, interim synthesis; Beaufort/Chukchi: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Boulder, Colorado, p. 3-55.

Shapiro, L. H., and Burns, J. J., 1975, Satellite observations of sea ice movement in the Bering Strait region, in Climate of the Arctic: Fairbanks, University of Alaska, p. 379-386.

Sharma, G. D., 1979, The Alaska Shelf; hydrographic, sedimentary, and geochemical environment: New York, Springer-Verlag, 498 p.

Solomon, H., and Ahlnas, K., 1980, Ice spirals off Barrow as seen by satellite: Arctic, v. 33, no. 1, p. 184-188.

Tailleur, I. L., 1973, Probable rift origin of Canada Basin: American Association of Petroleum Geologists Memoir 19, p. 526-535.

Tailleur, I. L., Pessel, G. H., Levorsen, J. A., and Engwicht, S. E., 1978, Maps showing land status and well locations and tables of well data, eastern North Slope petroleum province, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-928-A, 5 sheets.

Thenhaus, P. L., Ziony, J. I., Diment, W. H., Hopper, M. G., Perkins, D. M., Hanson, S. L., and Algermissen, S. T., 1982, Probabilistic estimates of maximum seismic horizontal ground motion on rock in Alaska and the adjacent outer continental shelf, in Coonrad, W. L., ed., The United States Geological Survey in Alaska: Accomplishments during 1980: U.S. Geological Survey Circular 844, p. 5-9.

Wiseman, William J., Jr., and others, 1973, Alaska Arctic coastal processes and morphology: Coastal Studies Institute Technical Report 149, Baton Rouge, Louisiana State University, 171 p.

Wiseman, William J., Jr., and Rouse, L. J., Jr., 1980, A coastal jet in the Chukchi Sea: Arctic, v. 33, no. 1, p. 21-29.

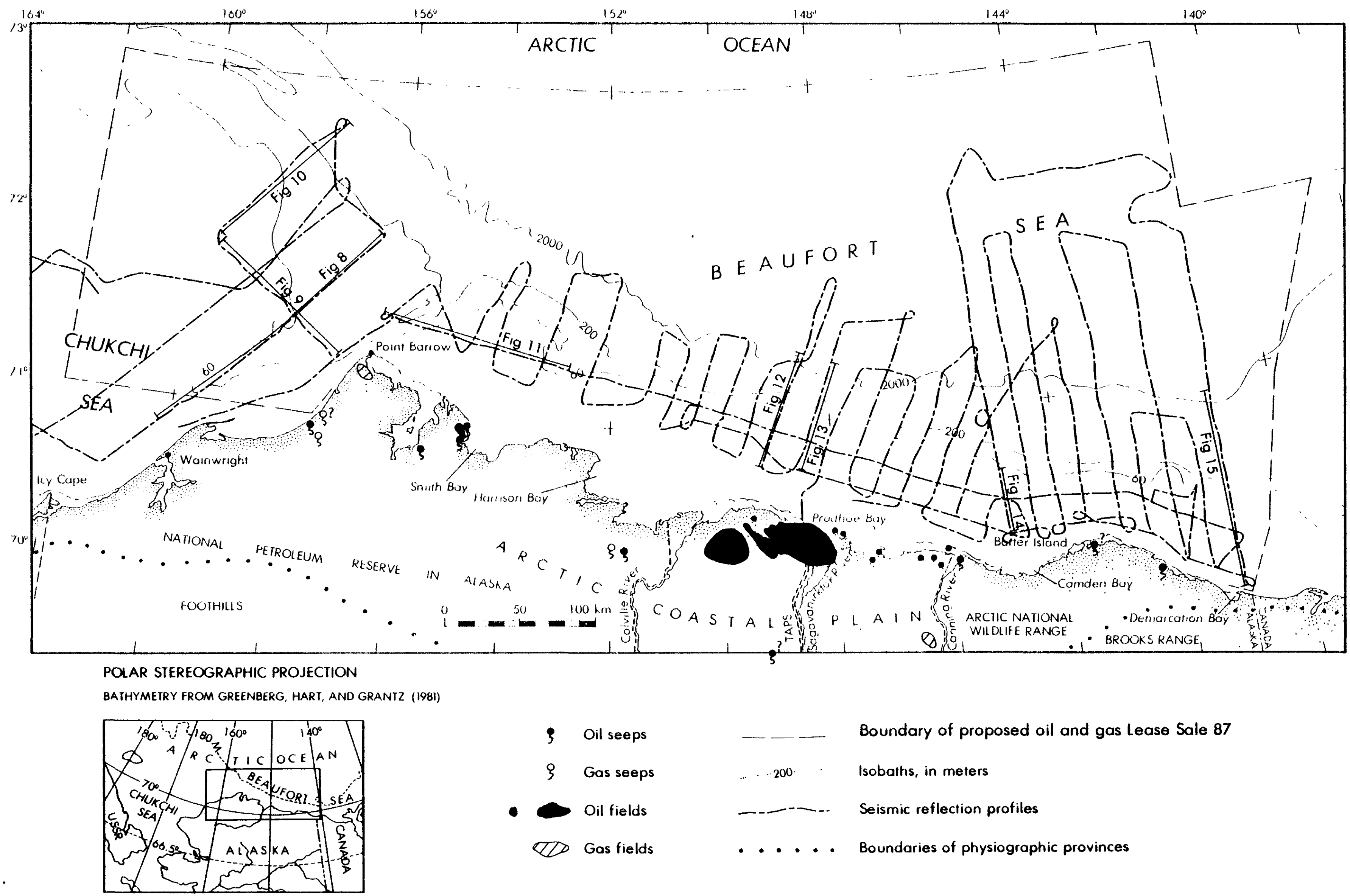


Figure 1. Bathymetric map of the Alaskan Beaufort and northeastern Chukchi Seas showing area of proposed oil and gas lease sale no. 87, oil and gas fields and seeps in northern Alaska, the Trans-Alaska Pipeline System (TAPS), U.S. Geological Survey multichannel seismic-reflection profile data base, and location of geologic cross-sections shown in other figures.

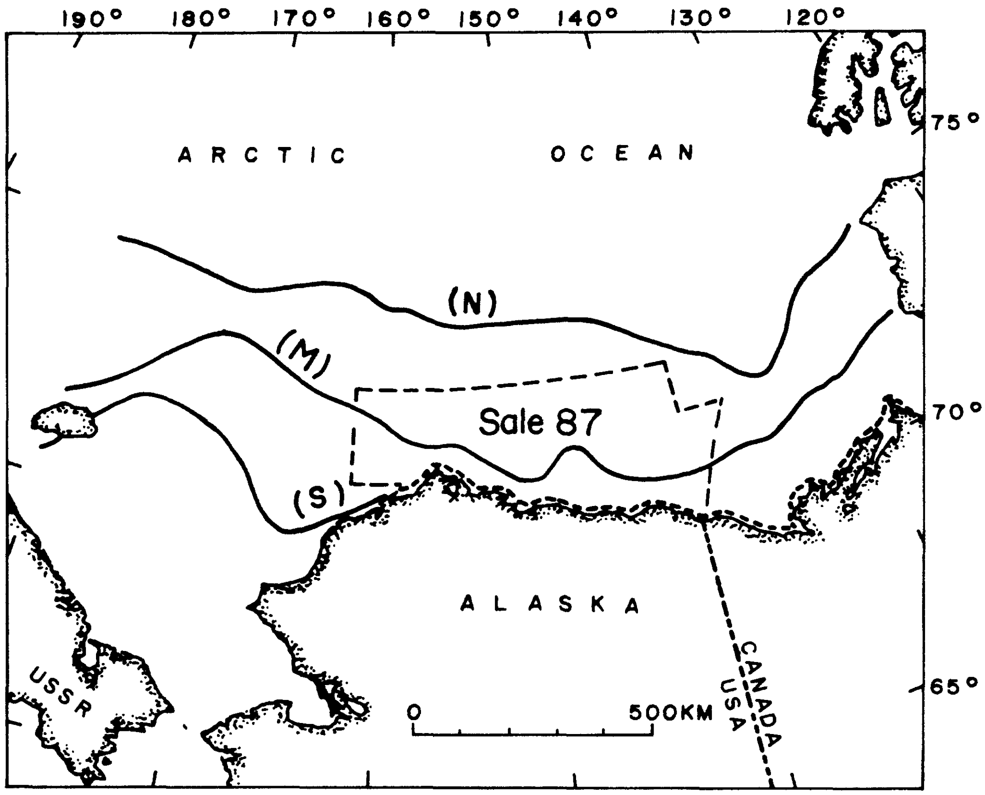
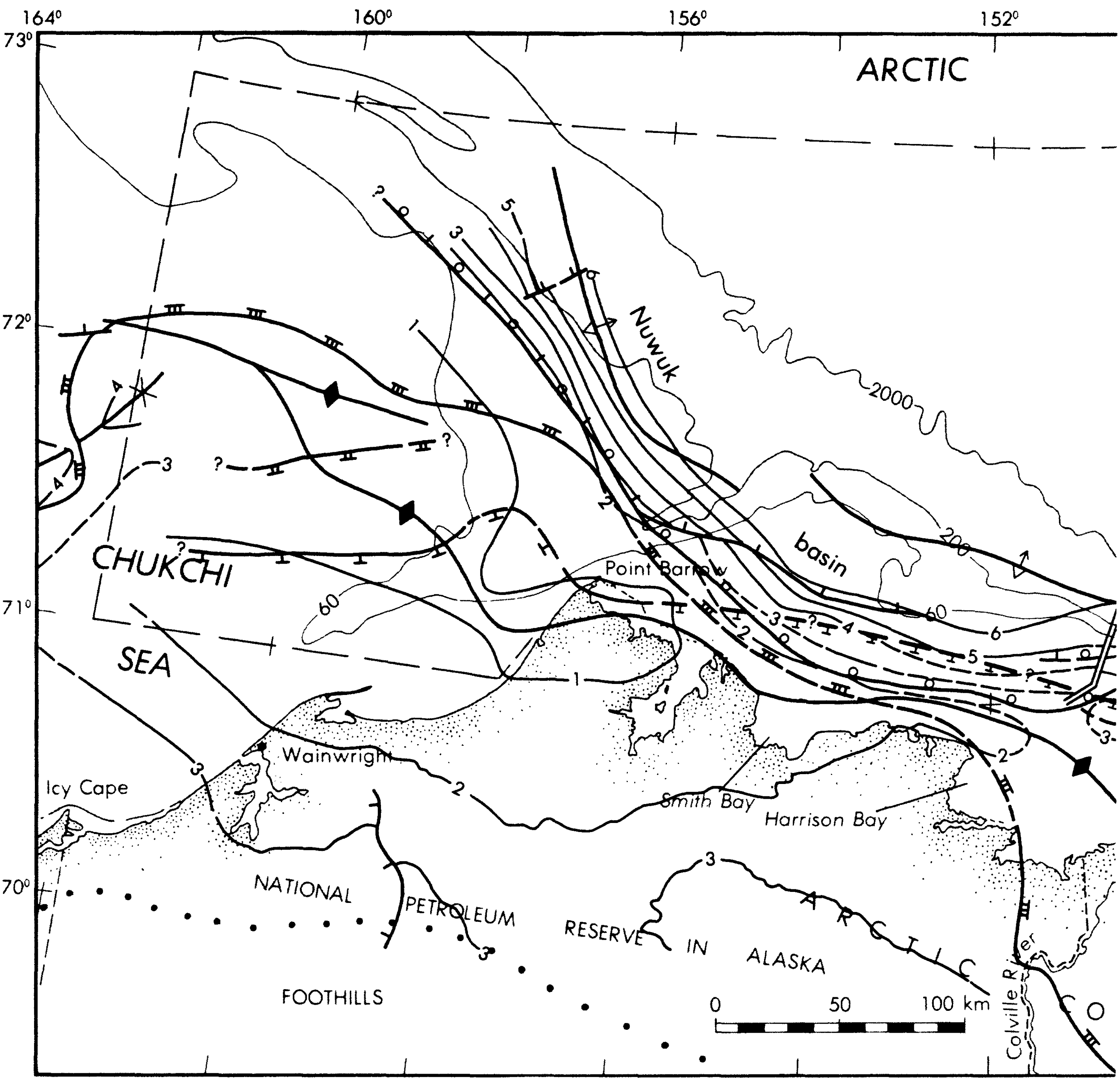


Figure 2. Most northerly (N), most southerly (S), and median (M) position of the southern edge of the Arctic ice pack north of Alaska during the usual period of maximum retreat, September 16 to 30, based on data from 1954 through 1970 (after Brower and others, 1977).

AGE			SEQUENCE	STRATIGRAPHY (South – North)	THICKNESS (m)	GENERALIZED LITHOLOGY	DEPOSITIONAL CHARACTERISTICS
CENOZOIC	QUATERNARY		BROOKIAN	GUBIK FORMATION	10-200	Marine sand, gravel, silt, and clay.	Sediment derived from the Brooks Range, the Arctic foothills, wave erosion of sea cliffs, and melting icebergs.
CENOZOIC	TERTIARY	NEOGENE / PALEOGENE	BROOKIAN	SAGAVANIRKTOK FM. (eastern North Slope only)	0-2,500 W - E	Poorly consolidated nonmarine and marine shale, sandstone, and conglomerate, with some carbonaceous shale, lignite, and bentonite.	Sediment mostly prograded northward from the 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 loading of Brooks Range thrust sheets and clastic sediment on the south part of the platform. When the Colville foredeep was filled, Cretaceous and Tertiary sediments overtopped the Barrow arch and prograded northward onto the western Beaufort shelf, where they thicken northward.
MESOZOIC	CRETACEOUS	UPPER	BROOKIAN	COLVILLE GROUP (central and eastern North Slope only)	0-3,600 W - E	Predominantly nonmarine, with coal in the west, mainly shallow-marine clastic rocks in the east.	
MESOZOIC	CRETACEOUS	LOWER	BROOKIAN	NANUSHUK GROUP (W. North Slope)	0-3,300+ / 200-1,200+	Marine and nonmarine shale, siltstone, sandstone, coal, conglomerate, and bentonite.	
MESOZOIC	CRETACEOUS	LOWER	BROOKIAN	FORTRESS MT. FM. (W. North Slope); TOROK FORMATION	400-3,000; 1000-3,000	Marine shale, sandstone, and conglomerate. Marine shale and siltstone, turbidites.	
MESOZOIC	CRETACEOUS	LOWER	ELLESMERIAN	PEBBLE SHALE UNIT, KONGAKUT FM., and KEMIK SANDSTONE	0-700	Shelf and basinal marine shale and siltstone containing rounded quartz grains and chert pebbles. Coquinoid to south; quartzose sandstone at base in east.	The Ellesmerian sequence on the Alaskan North Slope was derived from a northerly source terrane called Barrovia by Tailleur (1973). The constituent formations generally thin and coarsen northward, and onlap the uplifted northern Arctic platform in the crestal region of the Barrow Arch.
MESOZOIC	JURASSIC		ELLESMERIAN	KINGAK SHALE (locally includes KUPARUK RIVER SANDS at the top)	0-1,200+	Marine shale, siltstone, and chert, locally containing glauconitic sandstone (in the west). Shallower water facies are apparently the northerly ones.	
MESOZOIC	TRIASSIC		ELLESMERIAN	SHUBLIK FORMATION	0-225	To the north, marine shale, carbonate, and sandstone. As shown, includes the Sag River Sandstone. To the south, shale, chert, limestone, and 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; marine sandstone, siltstone, and shale. Western North Slope: sandstone, conglomerate, and shale to the north; argillite, chert, and shale to the south.	
PALEOZOIC	PENNSYLVANIAN		ELLESMERIAN	LISBURNE GROUP	0-2,000+	Fossiliferous marine limestone and dolomite, with some chert, sandstone, siltstone, and shale.	
PALEOZOIC	MISSISSIPPIAN		ELLESMERIAN	ENDICOTT GROUP	0-1,000+	Marine sandstone, mudstone, shale, conglomerate, interbedded limestone, coal, and conglomerate.	
PALEOZOIC	PRE-MISSISSIPPIAN		FRANKLINIAN	Marine sedimentary rocks (includes IVIAGIK GROUP of Martin (1970) on Lisburne Peninsula)	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 are mostly eugeoclinal, south and southeastern facies mostly miogeoclinal. Probably extends northward beneath the Beaufort and Chukchi shelves.

Figure 3. Generalized stratigraphy of northern Alaska and adjacent Beaufort shelf.



—2— Structural contour, two-way seismic reflection time, in seconds

Barrow arch

Rootless rotational-slump anticline

Anticline

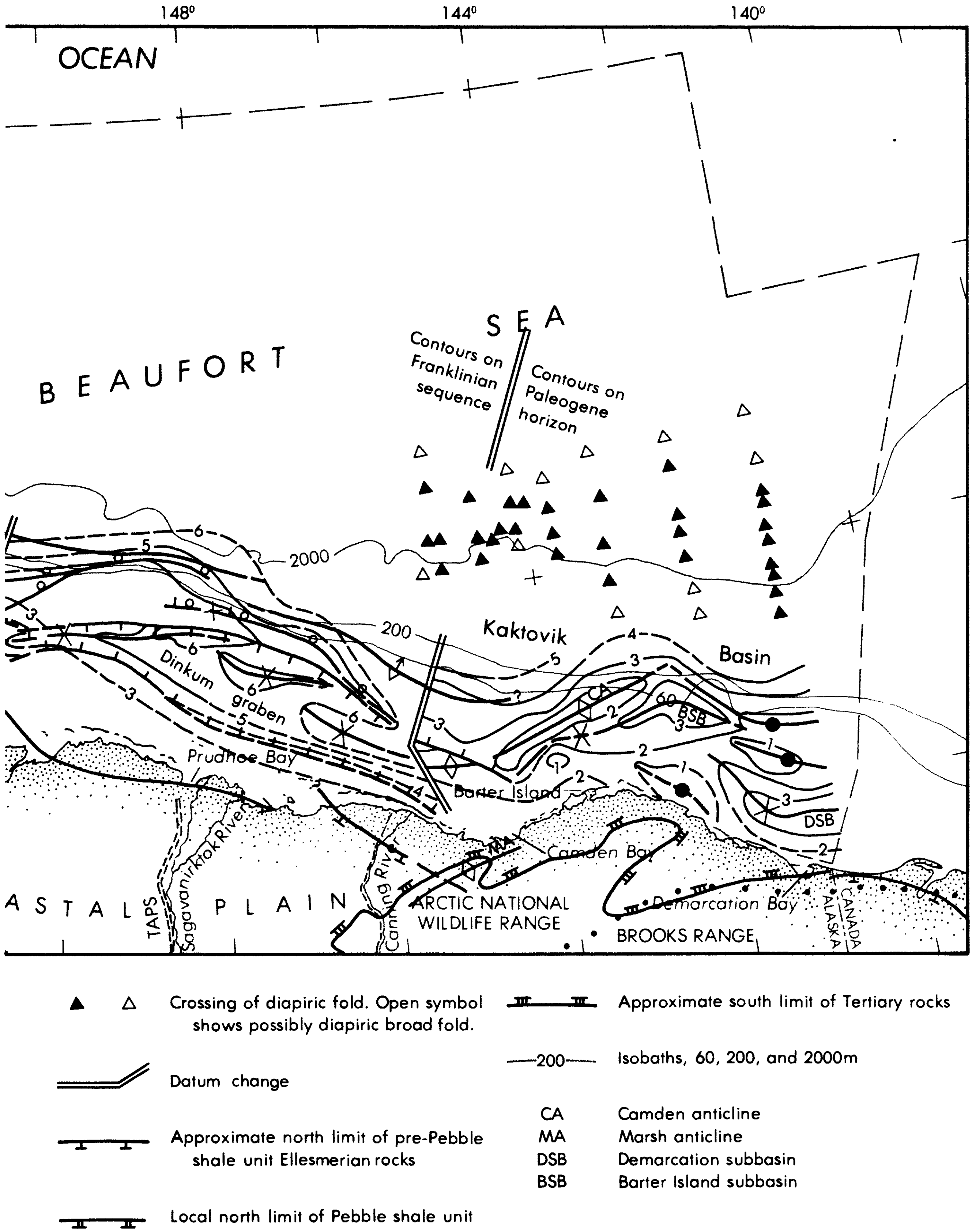
Diapiric shale ridge

Syncline

Hinge line. Dots on downwarped side, hachures on downthrown side where faulted

Normal fault. Hachures on downthrown side

Figure 4. Structural geologic map of areas of proposed oil and gas lease sale 87 covered by U.S. Geological Survey seismic-reflection data (see Fig. 1). All



lines dashed where inferred or projected. Onshore data west of Colville River from Miller and others (1979).

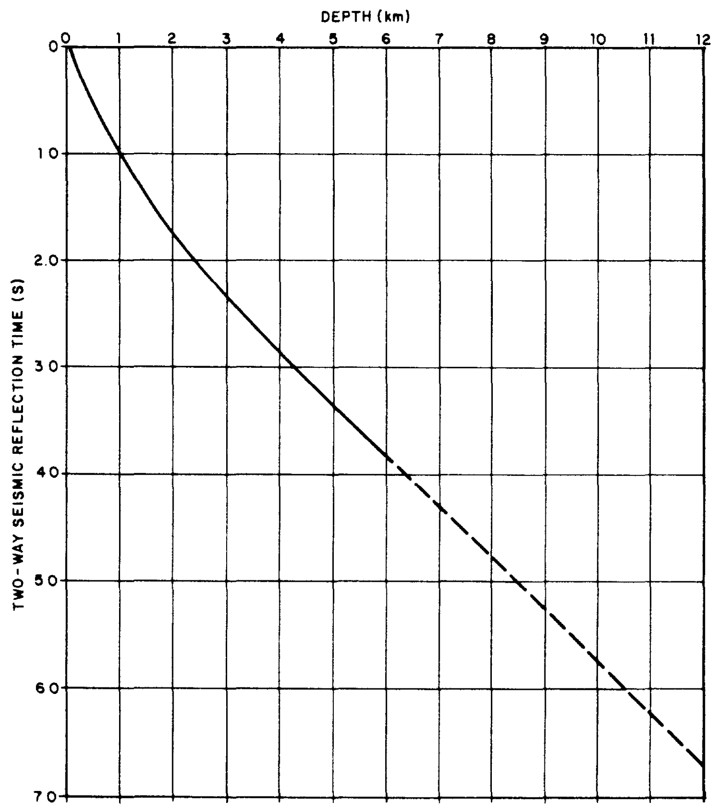
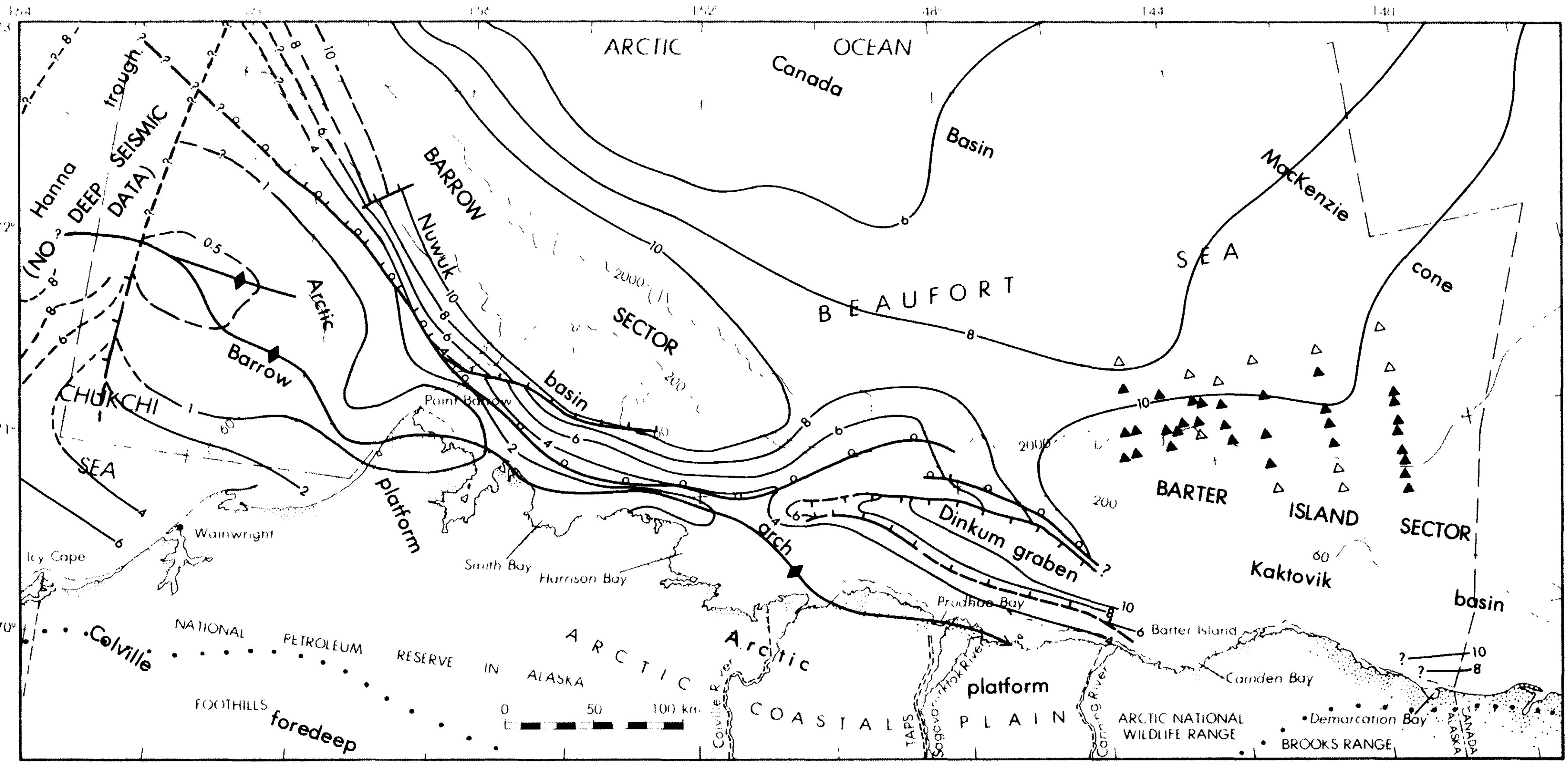


Figure 5. Generalized average seismic-reflection time as a function of depth for Beaufort shelf, derived from seismic-stacking-velocity measurements.



—4— Isopach (km) of sedimentary rocks (post-Franklinian section) prospective for petroleum

Normal fault. Hachures on downthrown side, dashed where inferred

Hinge line. Dots on downwarped side, hachures on downthrown side where faulted, dashed where projected

▲ △ Crossing of diapiric fold. Open symbol shows possibly diapiric broad fold

Figure 6.--Interpretive map showing thickness of sedimentary rocks prospective for petroleum in and near proposed lease sale 87.

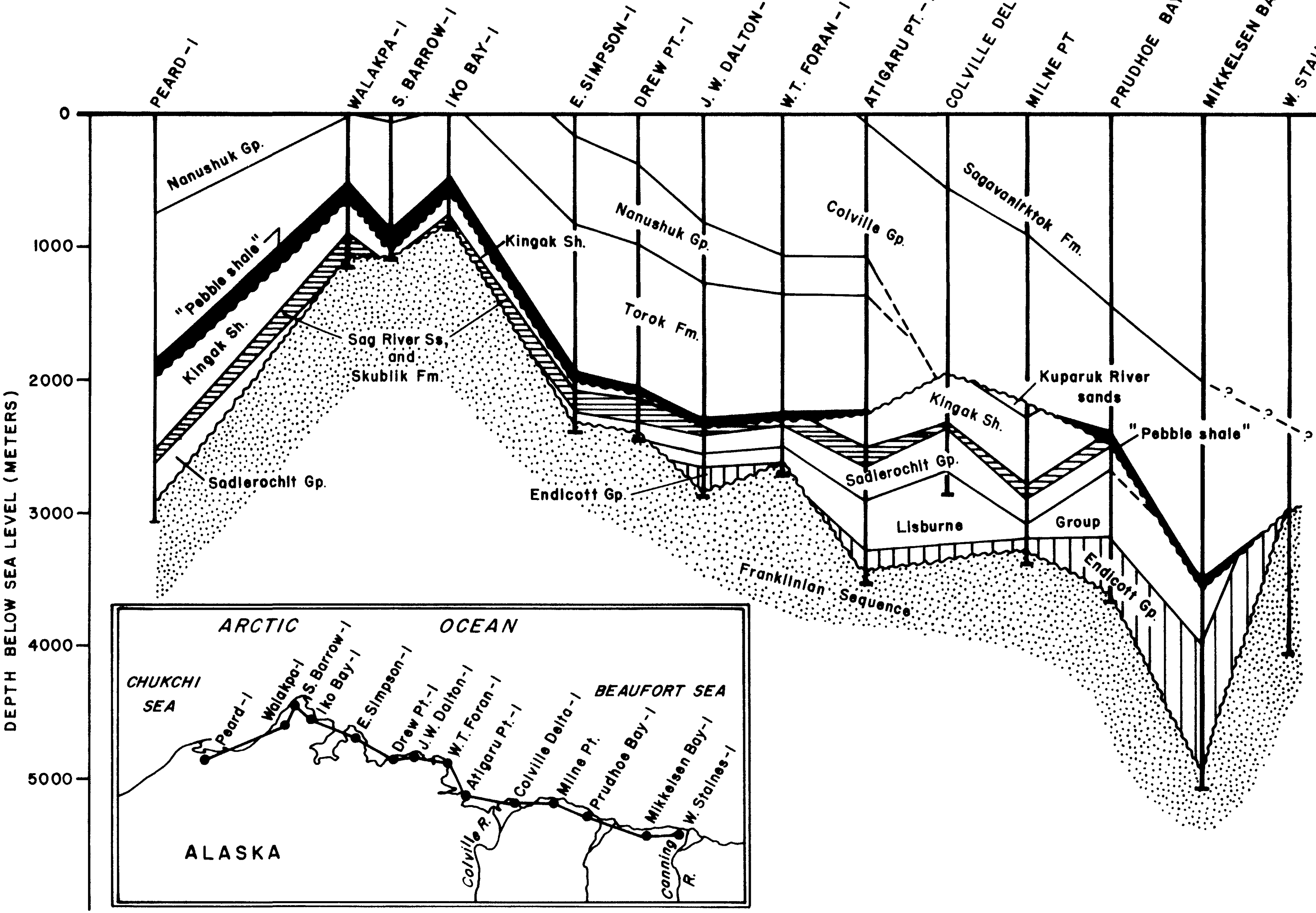


Figure 7. Correlated well section in northern Alaska adjacent to proposed oil and gas lease sale 87.

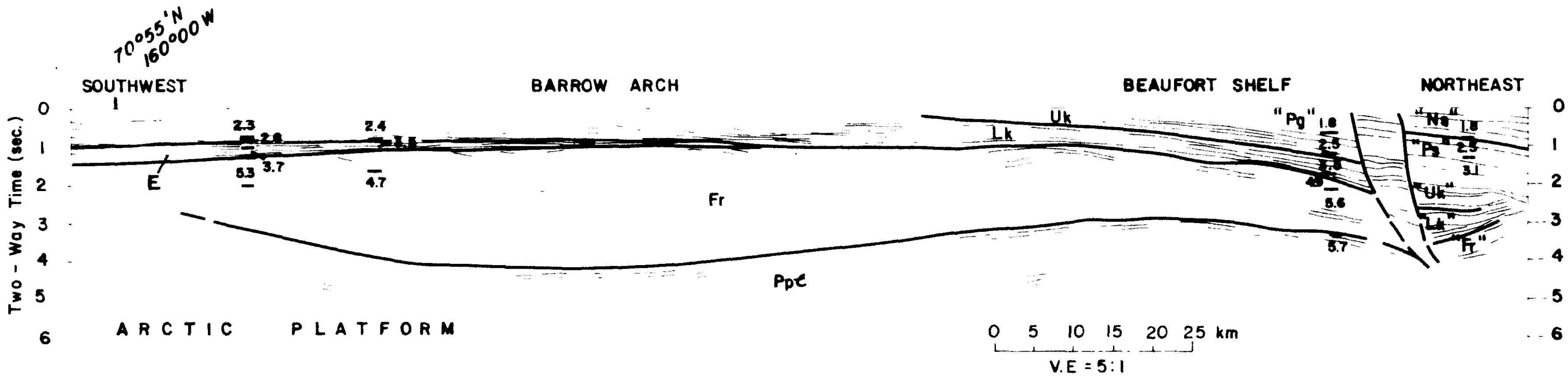


Figure 8. Northeast-southwest regional geologic section, based on seismic-reflection profiles across Barrow arch in the northeastern Chukchi Sea. Pp€, lower Paleozoic or Precambrian bedded rocks; Fr, Franklinian sequence; E, Ellesmerian sequence; Lk, Uk, "Pg" and "Ng" are Lower Cretaceous, Upper Cretaceous, Paleogene(?) and Neogene(?) sedimentary rocks. Numbers are sonobuoy velocities in Km/s. See Figure 1 for location.

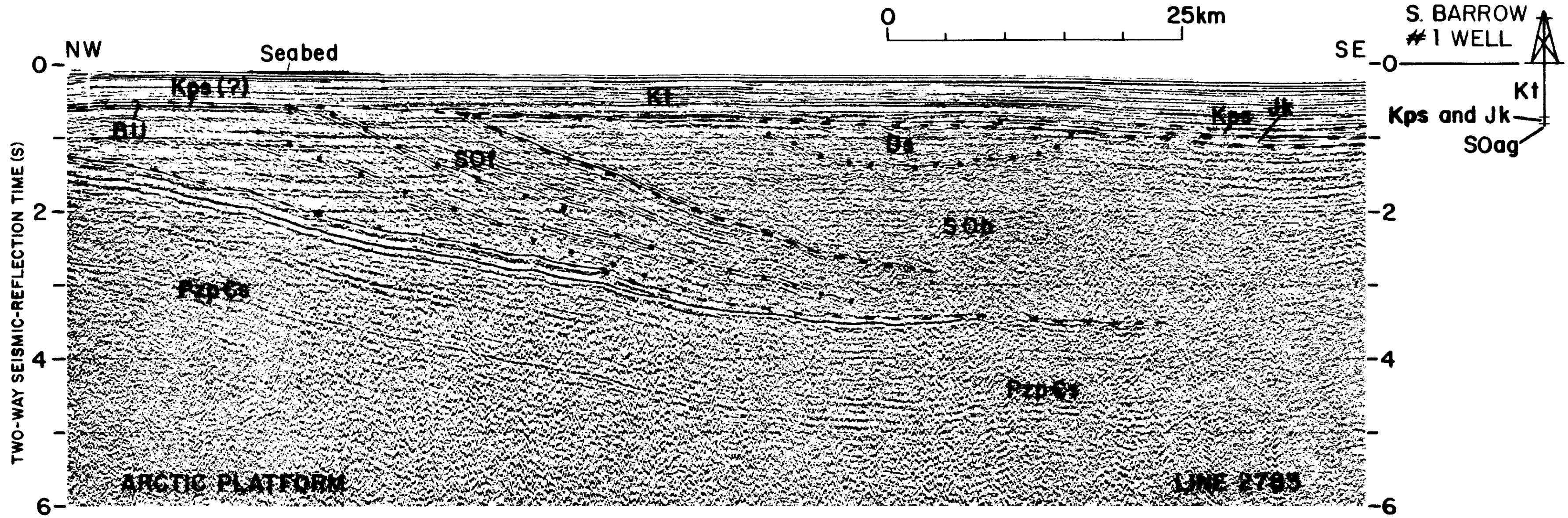


Figure 9. CDP seismic-reflection profile 2783 showing pre-Jurassic clastic wedge (SOf) beneath Arctic platform west of Point Barrow. BU, breakup unconformity. Inferred acoustic units: Kt, Torok Formation (Albian foreset beds), traversed oblique to paleoslope; Kps, Pebble shale unit (Hauterivian to Barremian bottom-set beds); Jk, shale, siltstone, and sandstone of lower (Jurassic) part of Kingak Shale of Jurassic to early Neocomian age; SOf, inferred submarine-fan deposits, and SOb, marine basinal deposits correlated with Ordovician and Silurian marine argillite and graywacke (SOag) of subsurface northern Alaska; Ds, Devonian(?) bedded, presumable sedimentary rocks; PzpЄs, upper Precambrian(?) and lower Paleozoic bedded, presumable sedimentary rocks. See Figure 1 for location of profile.

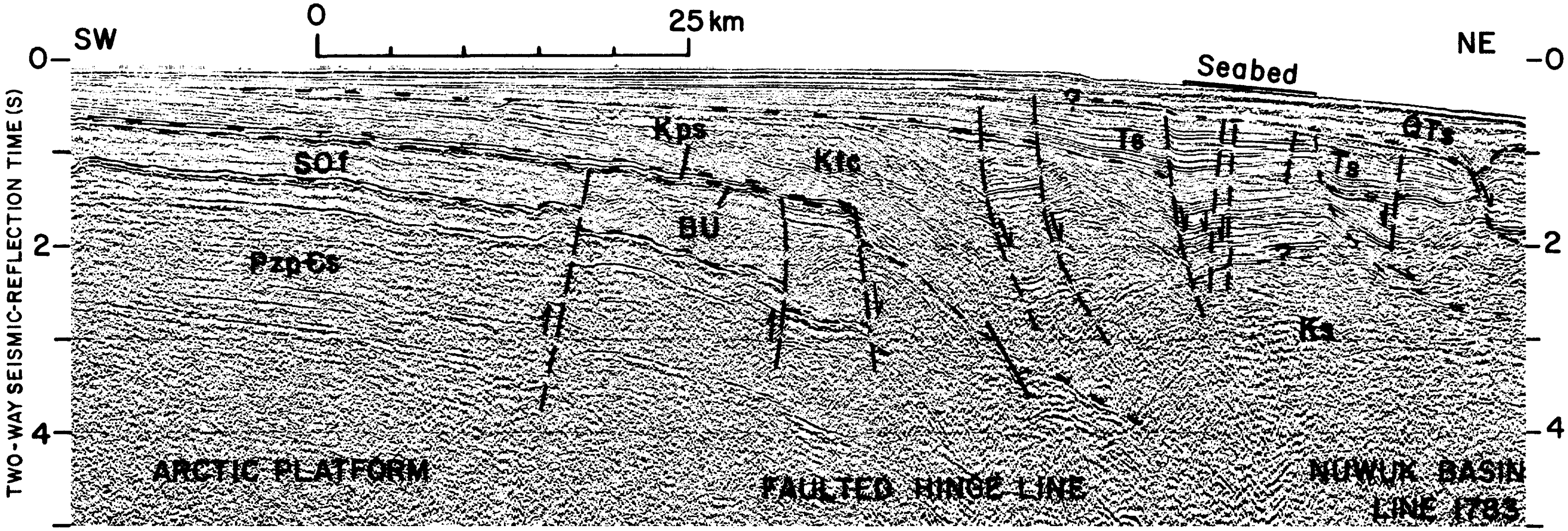


Figure 10. CDP seismic-reflection profile 1783, a dip line across rifted continental margin northwest of Point Barrow. Note rifted edge of Arctic platform, breakup unconformity (BU), faulted subsidence hinge line, deep Nuwuk basin seaward of hinge line, and growth faults beneath outer shelf. Inferred acoustic units: QTs, Quaternary and upper Tertiary(?) clastic sedimentary rocks; Ts, Tertiary and possibly Upper Cretaceous clastic sedimentary rocks; Ktc, Torok Formation (Albian foreset beds), and Colville Group (Upper Cretaceous) and possibly Tertiary clastic sedimentary rocks; Kps, probably the Pebble shale unit (Hauterivian to Barremian bottom-set beds), possibly includes bottom-set beds of basal part of Torok Formation (Albian); Ks, Lower and Upper Cretaceous clastic sedimentary rocks of Nuwuk basin; SOf, inferred submarine-fan deposits tentatively correlated with Ordovician and Silurian marine argillite and graywacke of subsurface northern Alaska; PzpЄs, upper Precambrian(?) and lower Paleozoic bedded, presumable sedimentary rocks. See Figure 1 for location of profile.

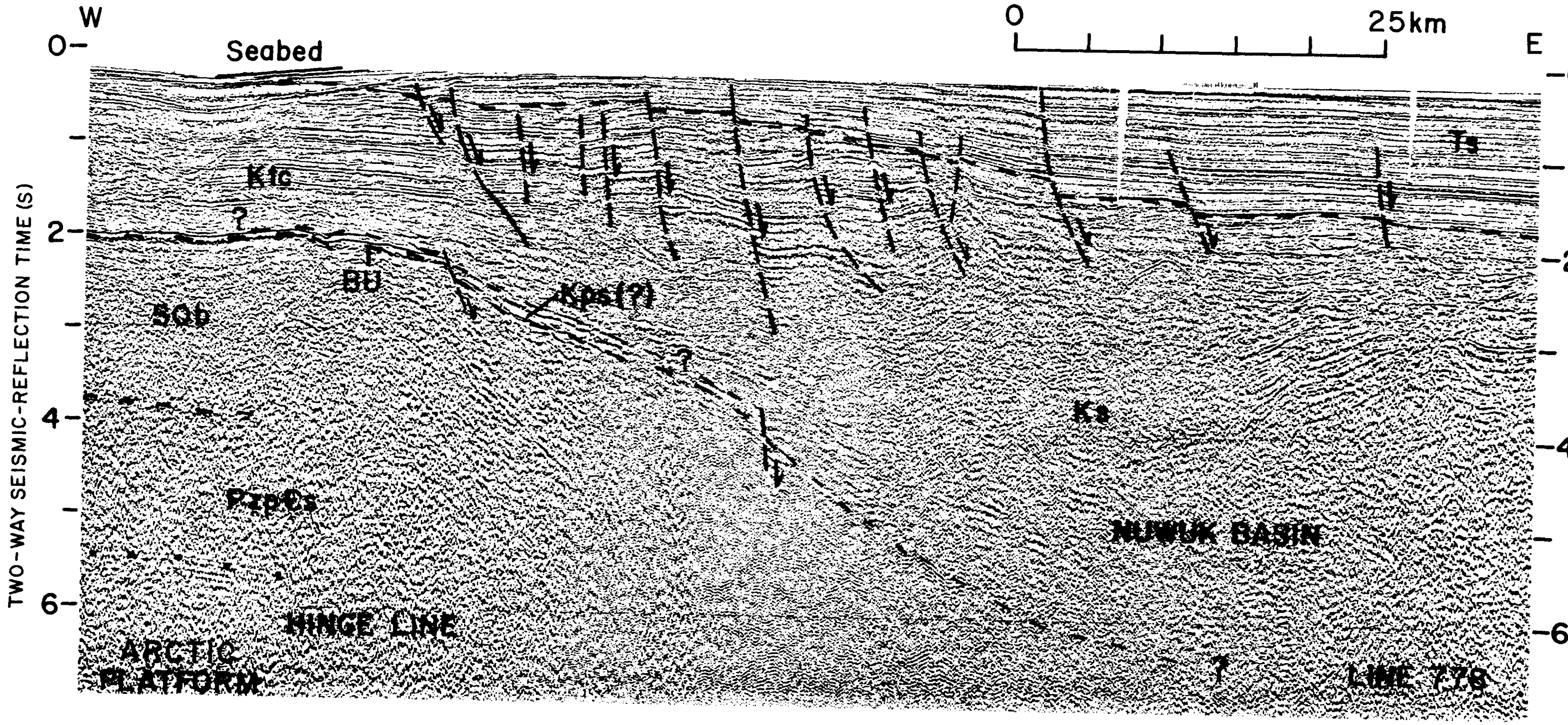


Figure 11. Oblique crossing of rifted continental margin along CDP seismic-reflection profile 778 northeast of Point Barrow, showing Arctic platform, breakup unconformity (BU), subsidence hinge line, and Nuwuk basin. Inferred acoustic units: Ts, Tertiary and possibly Upper Cretaceous clastic sedimentary rocks; Ktc, Torok Formation (Albian) and Colville Group (Upper Cretaceous) marine and possibly some paralic sedimentary rocks; Kps(?), probably Pebble shale unit (Hauterivian to Barremian bottom-set beds); Ks, Lower and Upper Cretaceous clastic sedimentary rocks of Nuwuk basin; SOb, inferred basinal deposits, tentatively correlated with Ordovician and Silurian marine argillite and graywacke of subsurface northern Alaska; PzpЄs, Upper Precambrian(?) and lower Paleozoic bedded, presumable sedimentary rocks. Note concentration of growth faults over steep slope north of subsidence hinge line, and extensive slumping and channeling in Cretaceous beds of Nuwuk basin. See Figure 1 for location of profile.

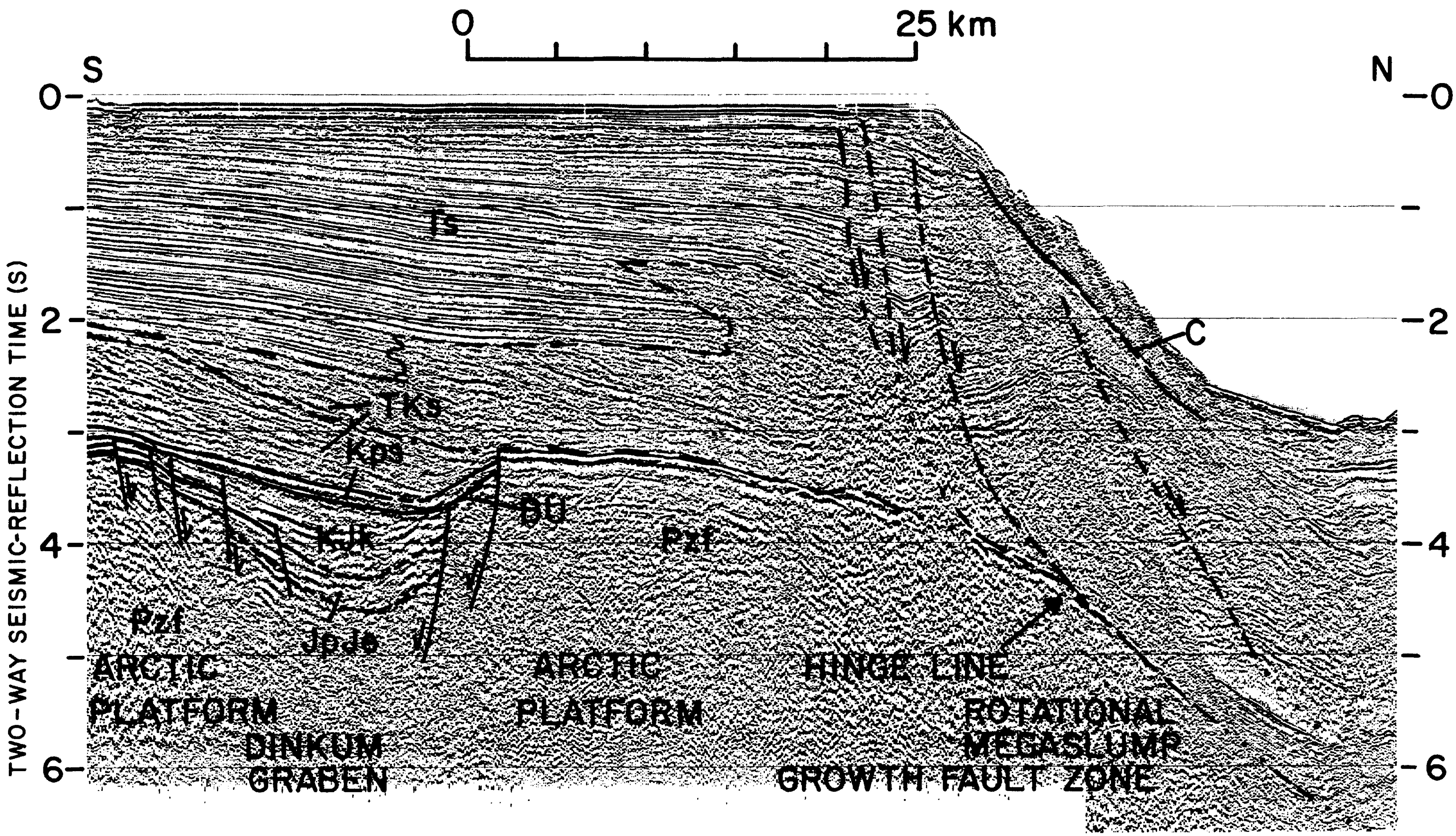


Figure 12. CDP seismic-reflection profile 753, a dip line across continental margin northwest of Prudhoe Bay, showing rifted Arctic platform, Dinkum graben, subsidence hinge line, breakup unconformity (BU), and growth faults and associated rotational megaslump near shelf break. Interpreted acoustic units: Ts, topset beds in Tertiary regressive sequence in upper part of postbreakup progradational sedimentary prism; TKs, Cretaceous and lower Tertiary foreset and some bottom-set beds in mainly transgressive lower part of postbreakup progradational sedimentary prism. Dot-dashed line within TKs unit is a rough estimate for base of Tertiary, projected from onshore; Kps, Pebble shale unit and possibly condensed bottom-set beds at base of Torok Formation; KJk, weakly reflective beds (Kingak Shale(?)) in Dinkum graben; JpJe, moderately reflective beds (sandstone(?) and possibly carbonate(?)) of Ellesmerian sequence in Dinkum graben (Jurassic or older); Pzf, Franklinian sequence (Cambrian to Devonian); C, basal reflector of zone of gas hydrate. See Figure 1 for location of profile.

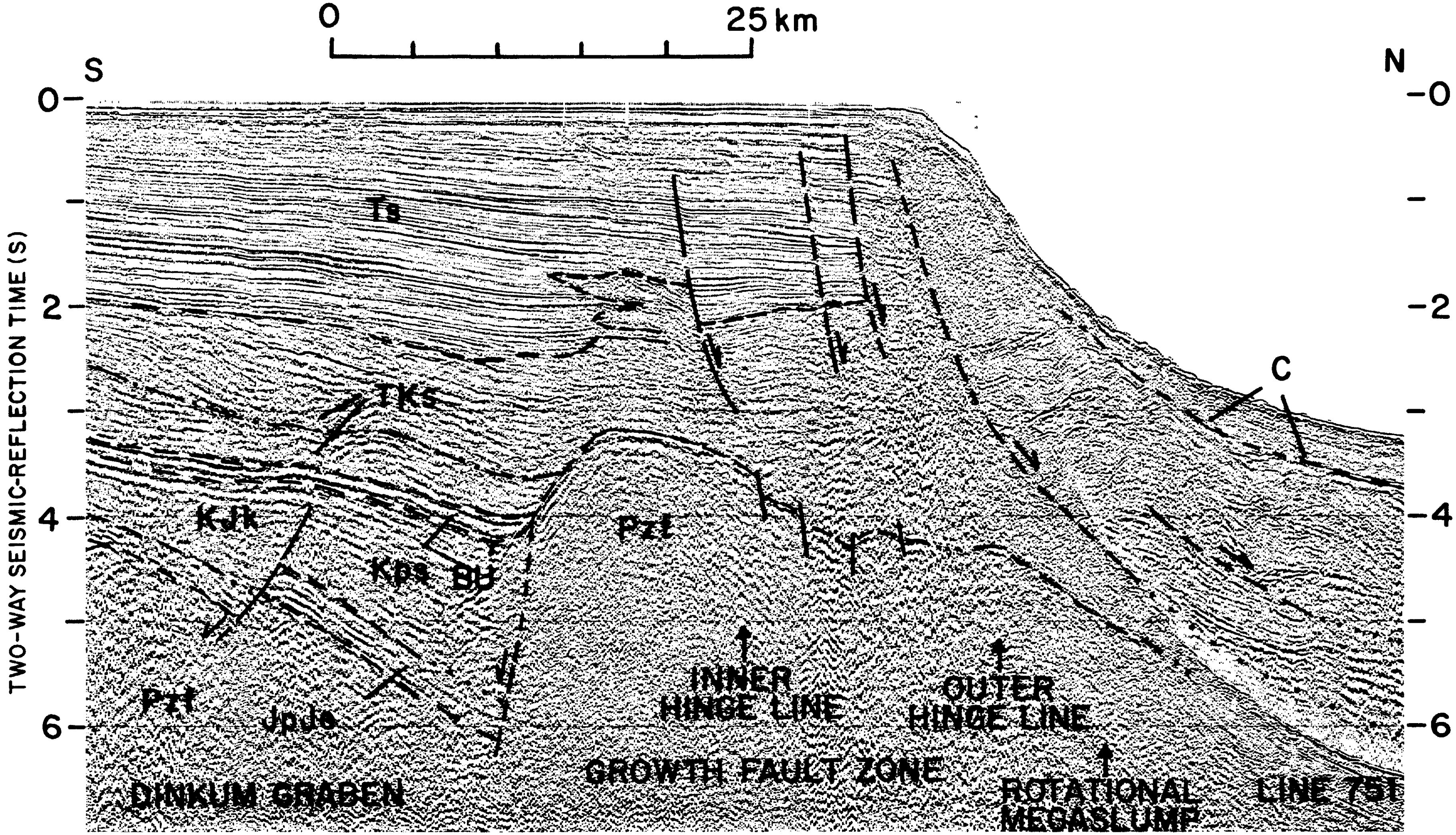


Figure 13. CDP seismic-reflection profile 751, a dip line across continental margin north of Prudhoe Bay, showing Dinkum graben, compound subsidence hinge line, breakup unconformity (BU), and zone of growth faults and associated rotational megaslump overlying hinge zone. Interpreted acoustic units same as in Figure 12. See Figure 1 for location of profile.

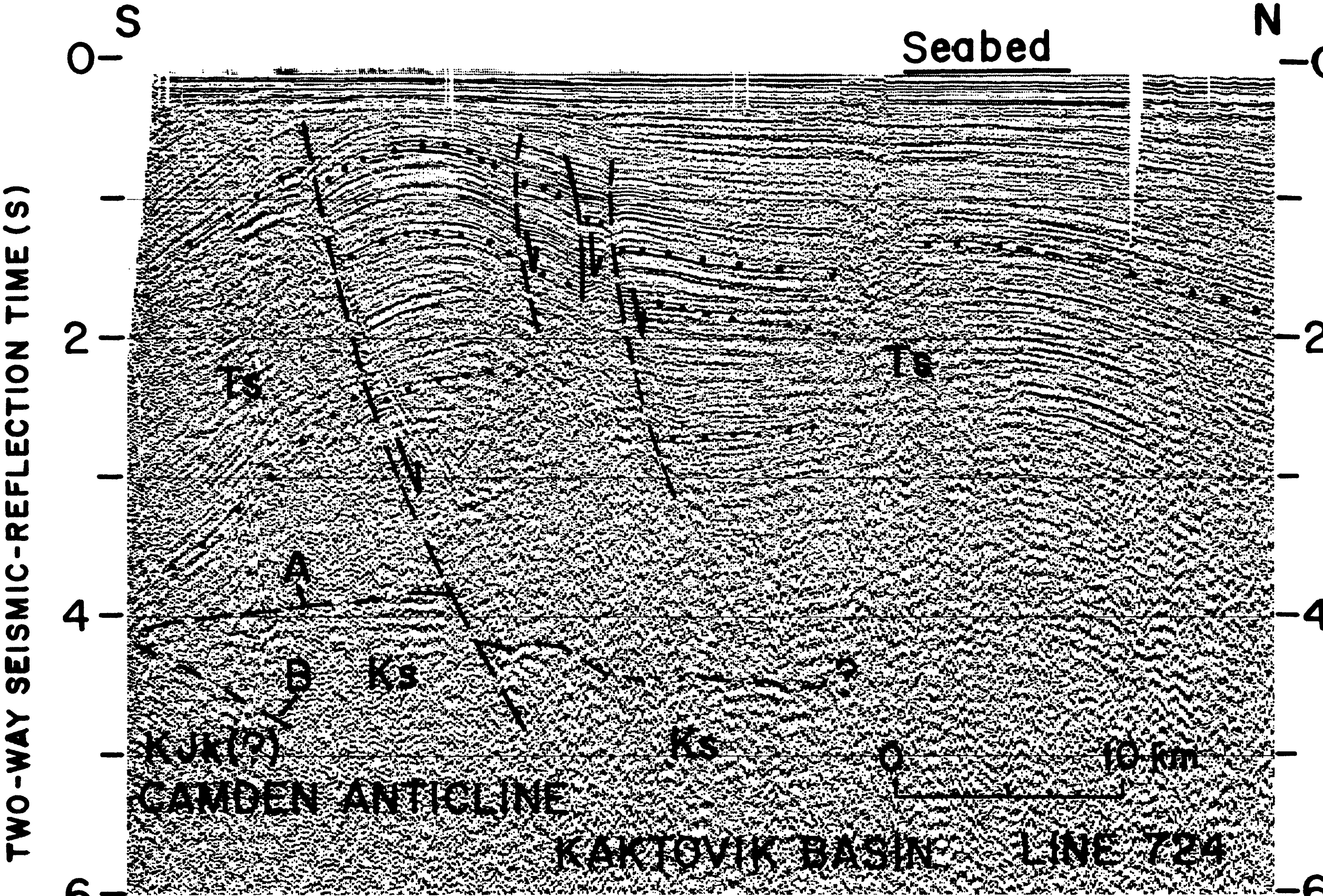


Figure 14. CDP seismic-reflection profile 724 across Camden anticline, a large east-northeast-striking detachment fold off Camden Bay. Fold is inferred, from discordance between horizon A and higher beds, to be detached near 4 s isochron. Horizon A is estimated by rough projection from onshore to be near base of Tertiary sedimentary rock unit Ts. Horizon B may be at top of a thin sequence of Lower Cretaceous bottomset shale beds that possibly overlies the Jurassic and Lower Cretaceous Kingak Shale (KJk). Unit Ks may be Cretaceous marine sedimentary rocks. See Figure 1 for location of profile.

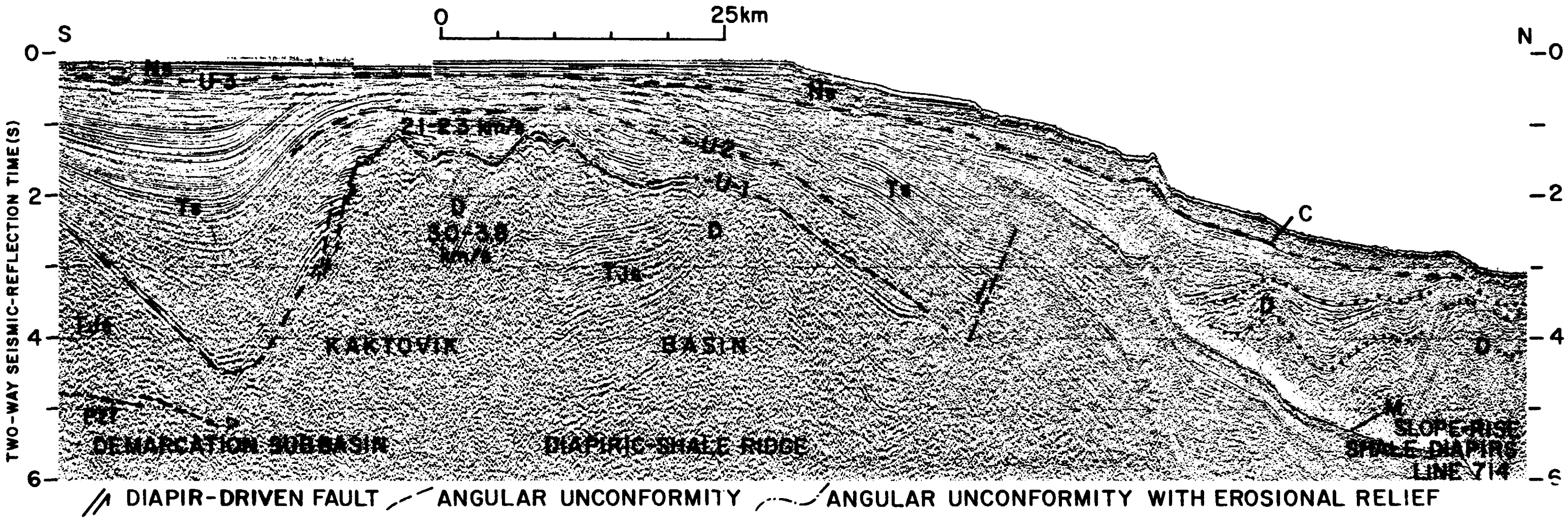
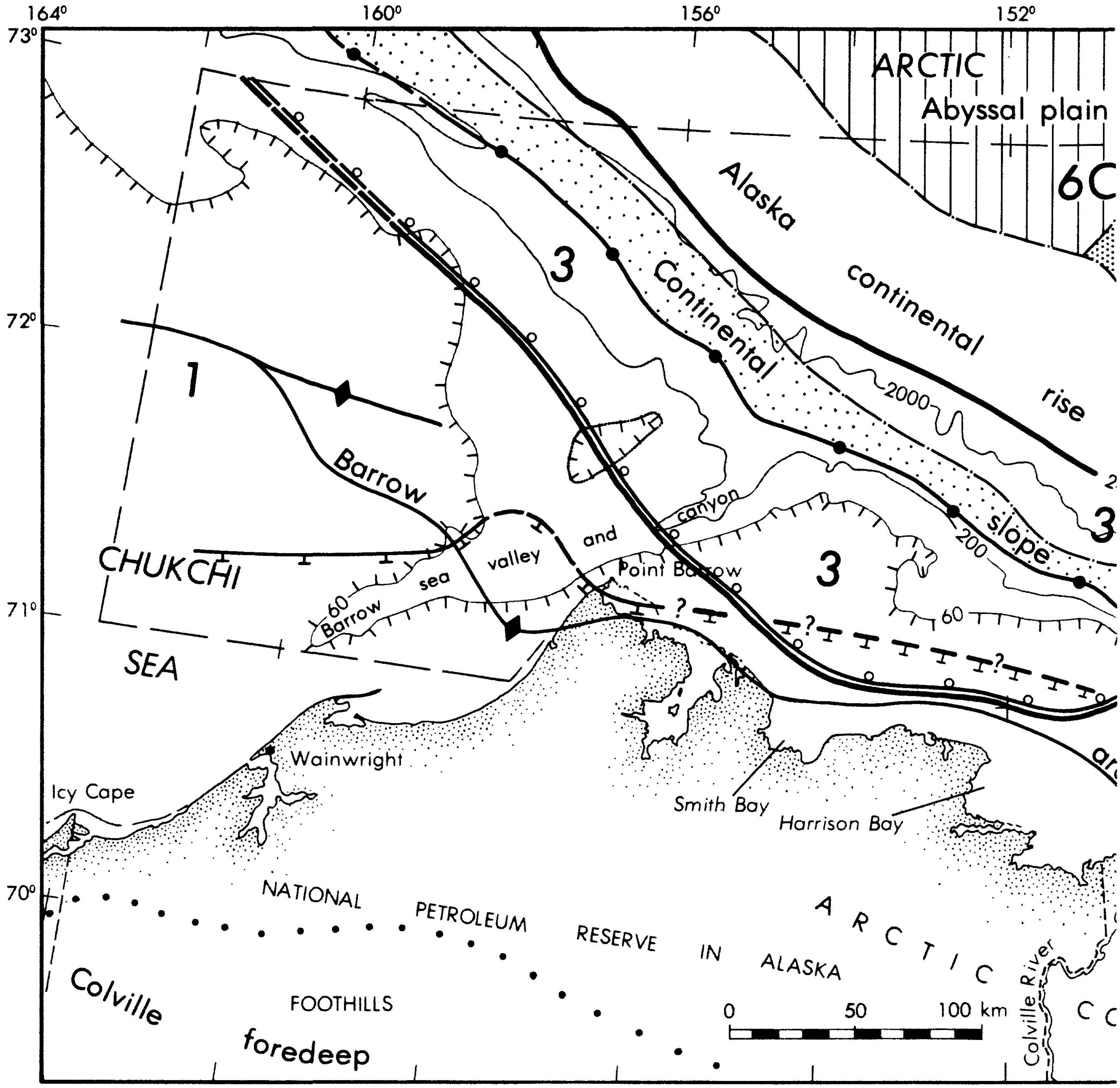
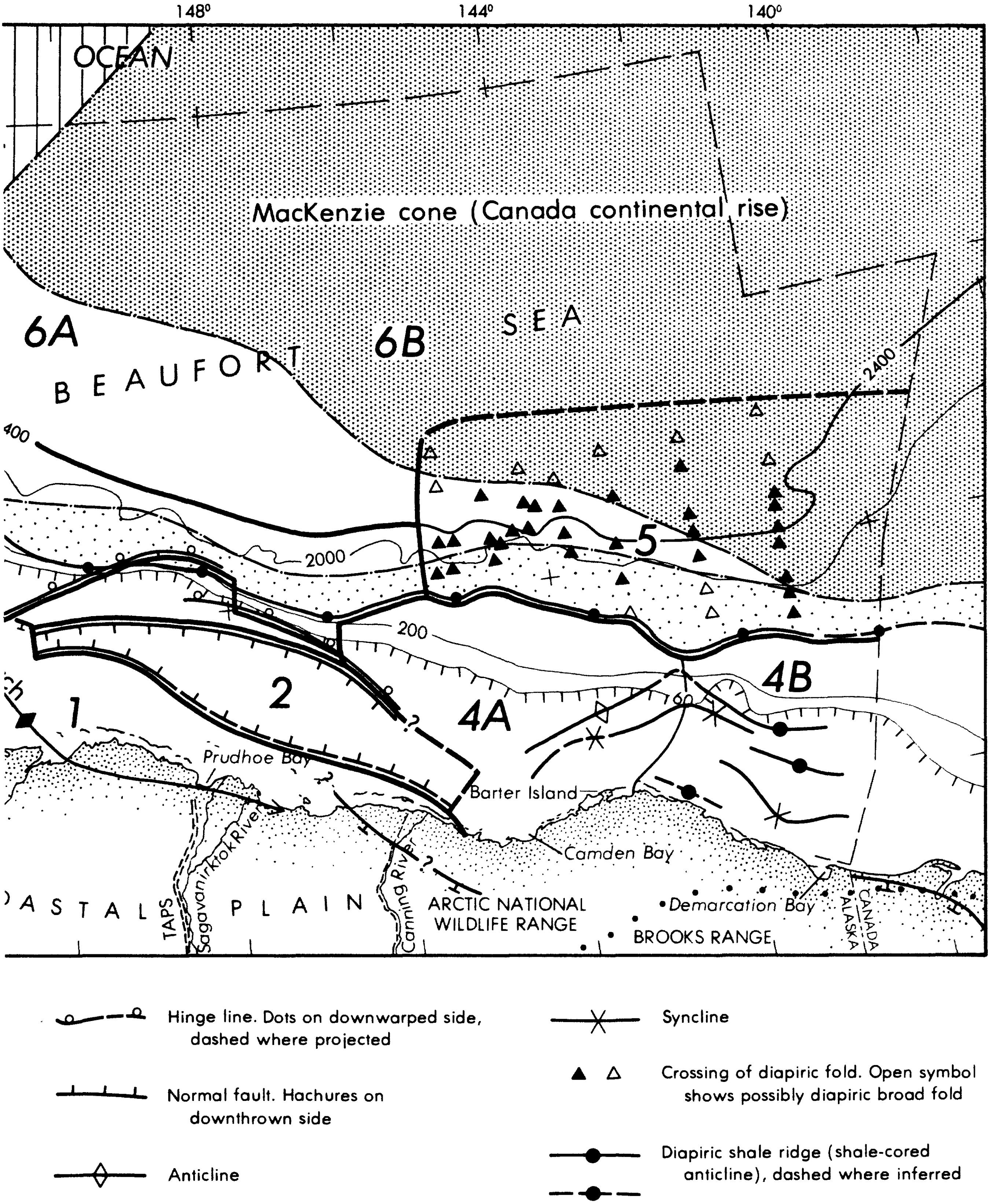


Figure 15. CDP seismic-reflection profile 714 across Kaktovik basin north of Alaska-Yukon Territory boundary, showing Demarcation subbasin, diapiric shale ridge that dominates shelf structure in this area, and a few shale-cored diapiric folds of continental slope and rise. Inferred acoustic units: Ns, Neogene nonmarine and marine sedimentary rocks; Ts, middle Tertiary (Oligocene(?) and Eocene) marine and nonmarine(?) sedimentary rocks; TJs, Jurassic and Cretaceous marine and possibly lower Paleogene marine or nonmarine sedimentary rocks; Pzf, Franklinian sequence(?); D, diapiric structure; C, base of gas hydrate; M, seabed multiple; km/s, sonobuoy seismic velocity (in kilometers per second). Note that three angular unconformities (dashed lines U-1, U-2, and U-3) cross top of diapiric ridge. Lowest of these unconformities (U-1) shows rough erosional relief and, on south flank of diapiric ridge, is interpreted to be disrupted by normal faults related to diapirism. Unconformities and axial thickening of reflector packets in Demarcation subbasin demonstrate that diapirism and sedimentation were penecontemporaneous. See Figure 1 for location of profile.



2	Petroleum province. See Table 1 for province names	— 60 —	Isobath, in meters
	Boundaries of Physiographic provinces seaward of shelf break. Selected provinces highlighted by patterns		200 ft isobath. Current limit of petroleum operations (National Petroleum Council, 1981)
	Structural shelf break		Approximate north limit of pre-Pebble shale unit Ellesmerian rocks

Figure 16. Petroleum provinces of proposed oil and gas lease sale 87. (See Table 1 for names of provinces). The National Petroleum Council (December, 1981) estimates that proven technology and sufficient information and technical expertise



exist to allow petroleum operations out to about the 200-foot isobath on the Beaufort and northeast Chukchi shelves.

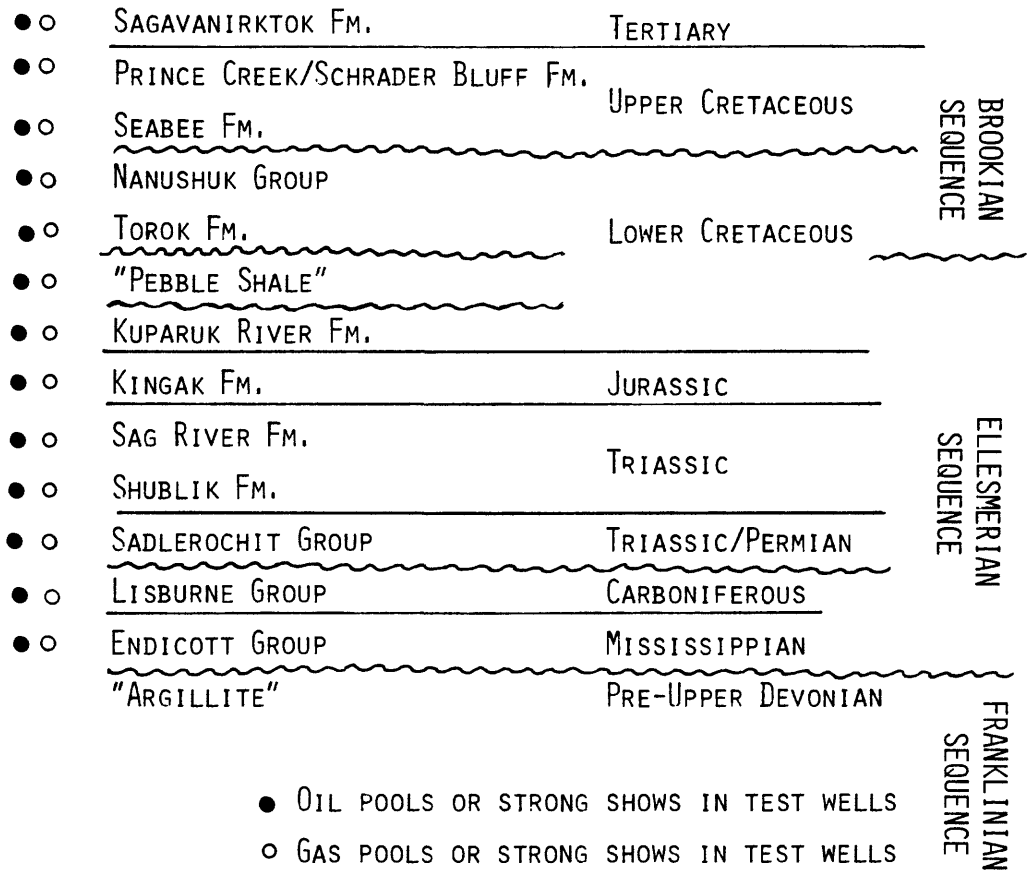


Figure 17. Generalized stratigraphic column beneath the Arctic coastal plain of northern Alaska, showing position of oil and gas pools and of strong shows of oil and gas encountered in test wells. (Data from Alaska Geological Society, 1971, and 1972; Brosgé and Tailleur, 1971; Jones and Speers, 1976; Jamison and others, 1980; and industry announcements.

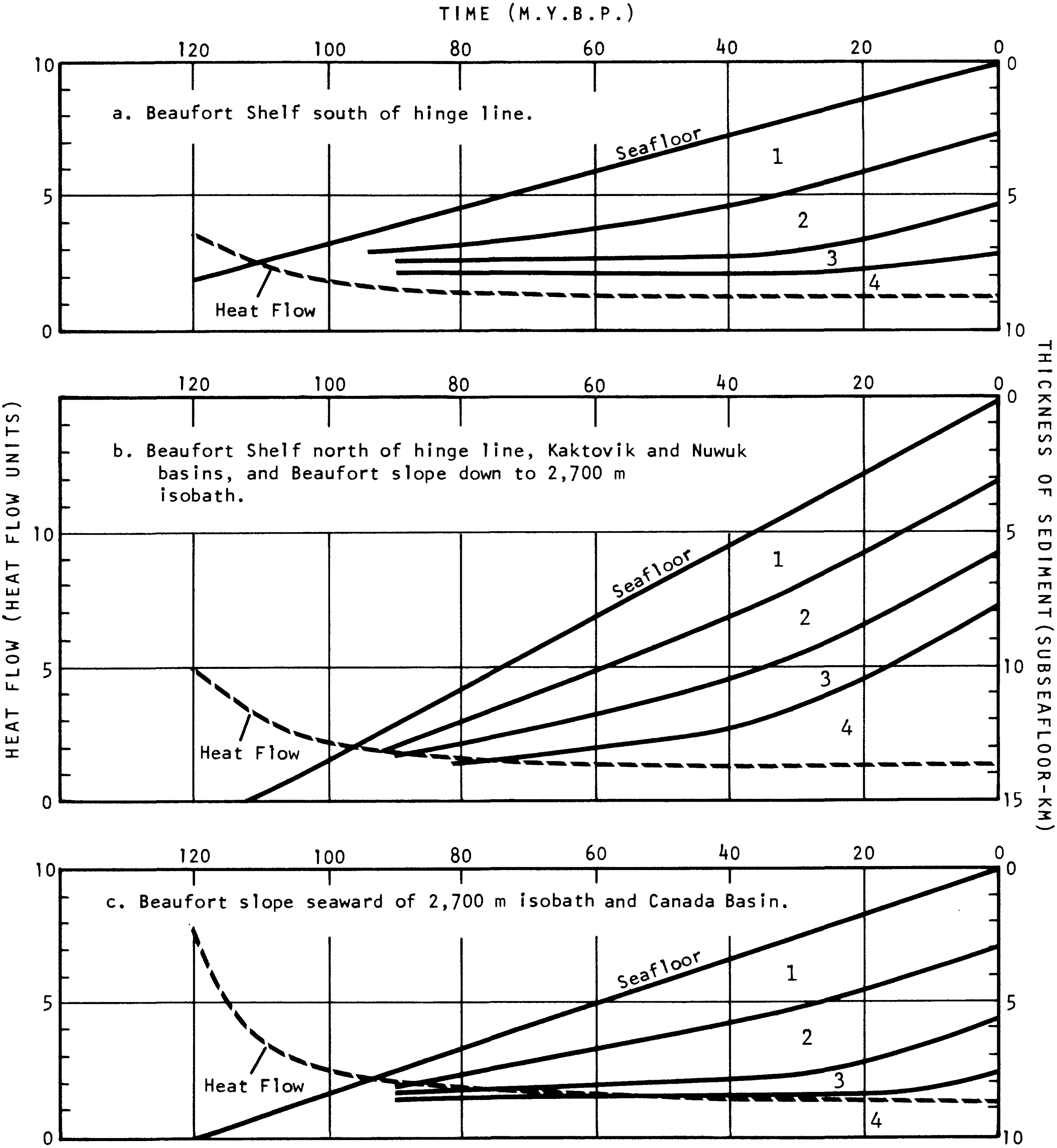


Figure 18.--Thermal maturity of post-rift sediments in the area of sale 87 as a function of time and present depth of burial. Numbered zones represent: 1) Immature zone - generation of biogenic gas only, 2) Oil zone - generation of oil and associated gas, 3) Thermal gas zone - generation of thermal gas and breakdown of liquid hydrocarbons into gas, and 4) Overly mature zone - temperatures above that at which hydrocarbons are stable. Heat flow curves, used to determine the temperature history of the sediments, calculated from heat flow measurements in the Canada Basin by Lachenbruch and Marshall (1966) and from the Geothermal Gradient Map of North America (American Association of Petroleum Geologists and U.S. Geological Survey, 1976). Heat flow curves extrapolated back in time using the method of Royden and others (1980).

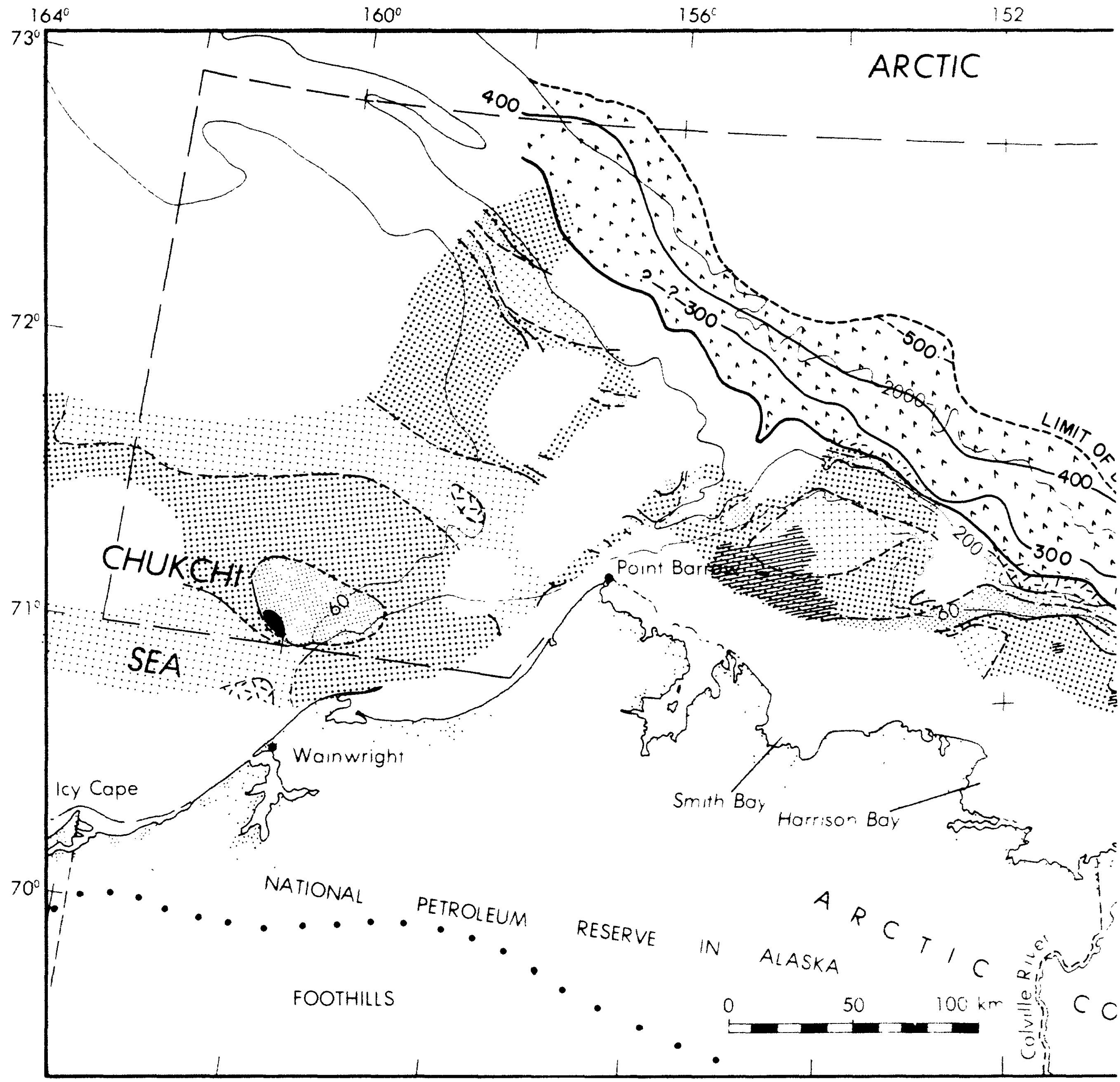
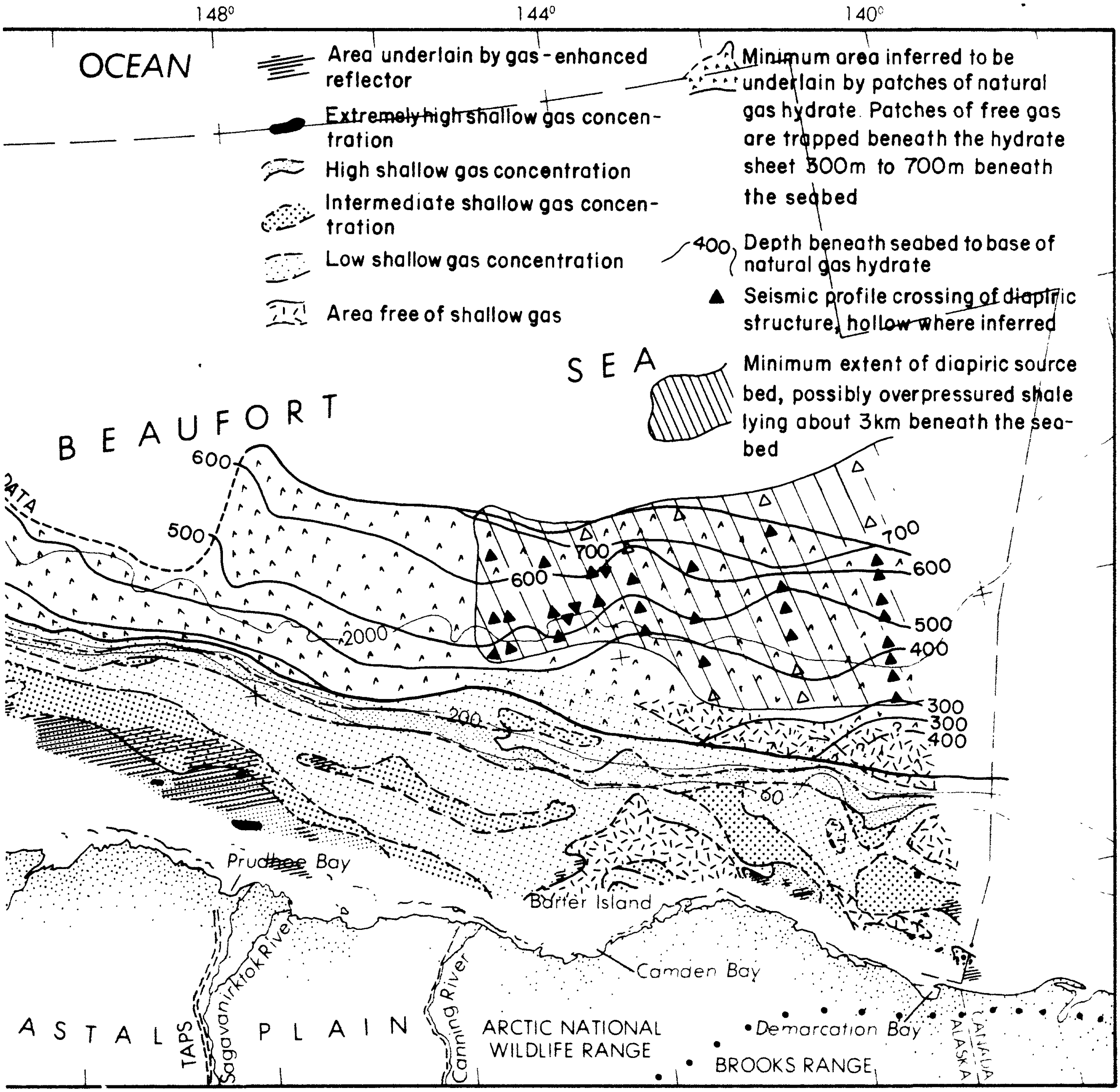


Figure 19. Diapirs, shallow free gas concentrations, depths to base of natural gas hydrate,



and area possibly underlain by overpressured shale offshore of northern Alaska.

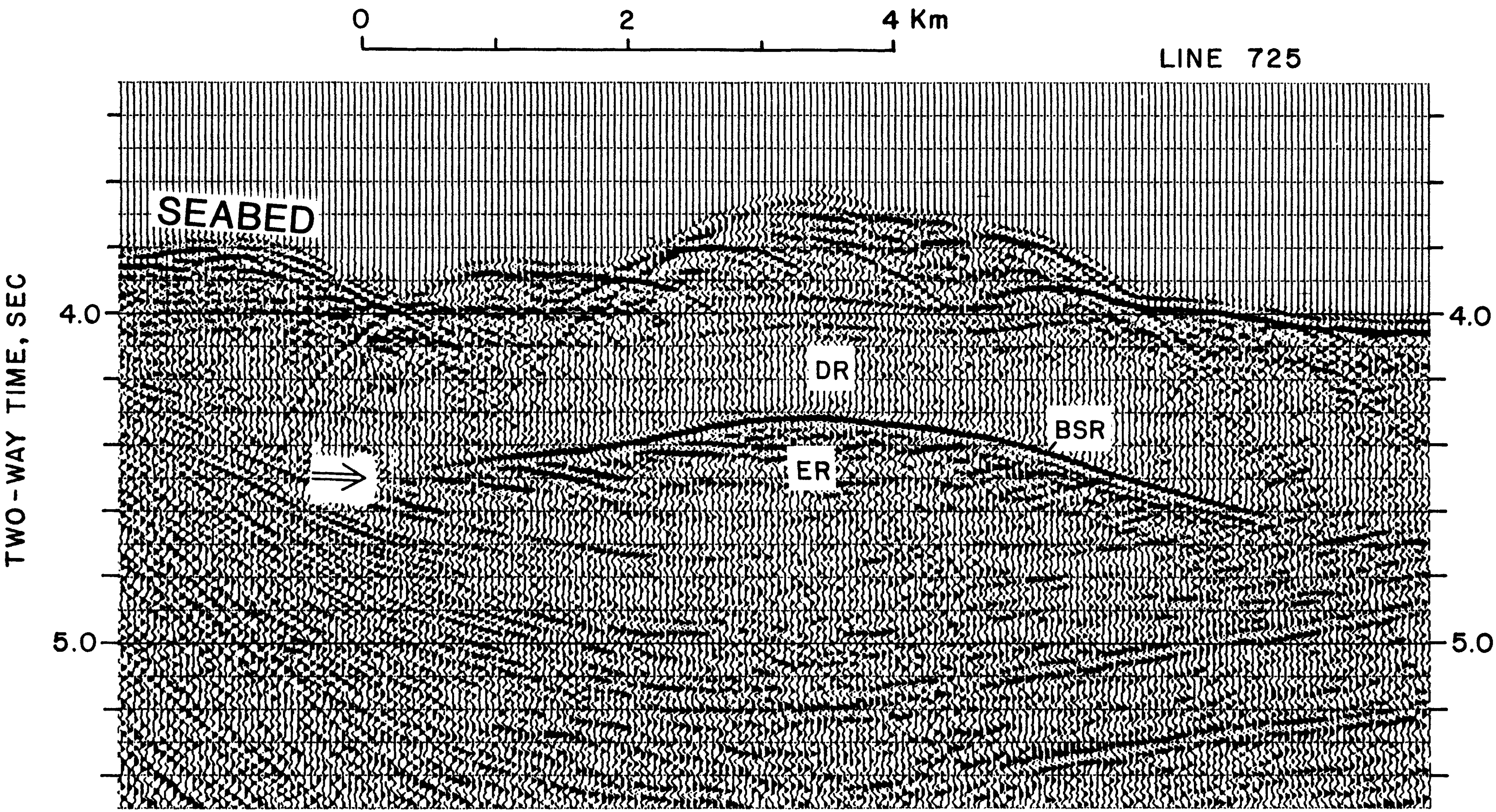


Figure 20. CDP seismic-reflection profile 725, on the continental slope at 2670 to 2935 m water depth off Camden Bay, showing zone of diminished reflections (DR) thought to be caused by cementation with gas hydrate, and the underlying zone of enhanced reflections (ER) interpreted to represent gas-charged sediment beneath the gas hydrate. The strong bottom simulating reflector (BSR) is interpreted to represent the interface between the hydrated zone and the underlying hydrate-free gas-charged sediment. Note that the hydrate-related reflections are best developed under a bathymetric high, where they form a pseudoanticline that is superimposed on the synclinal structure of the bedded country rock.

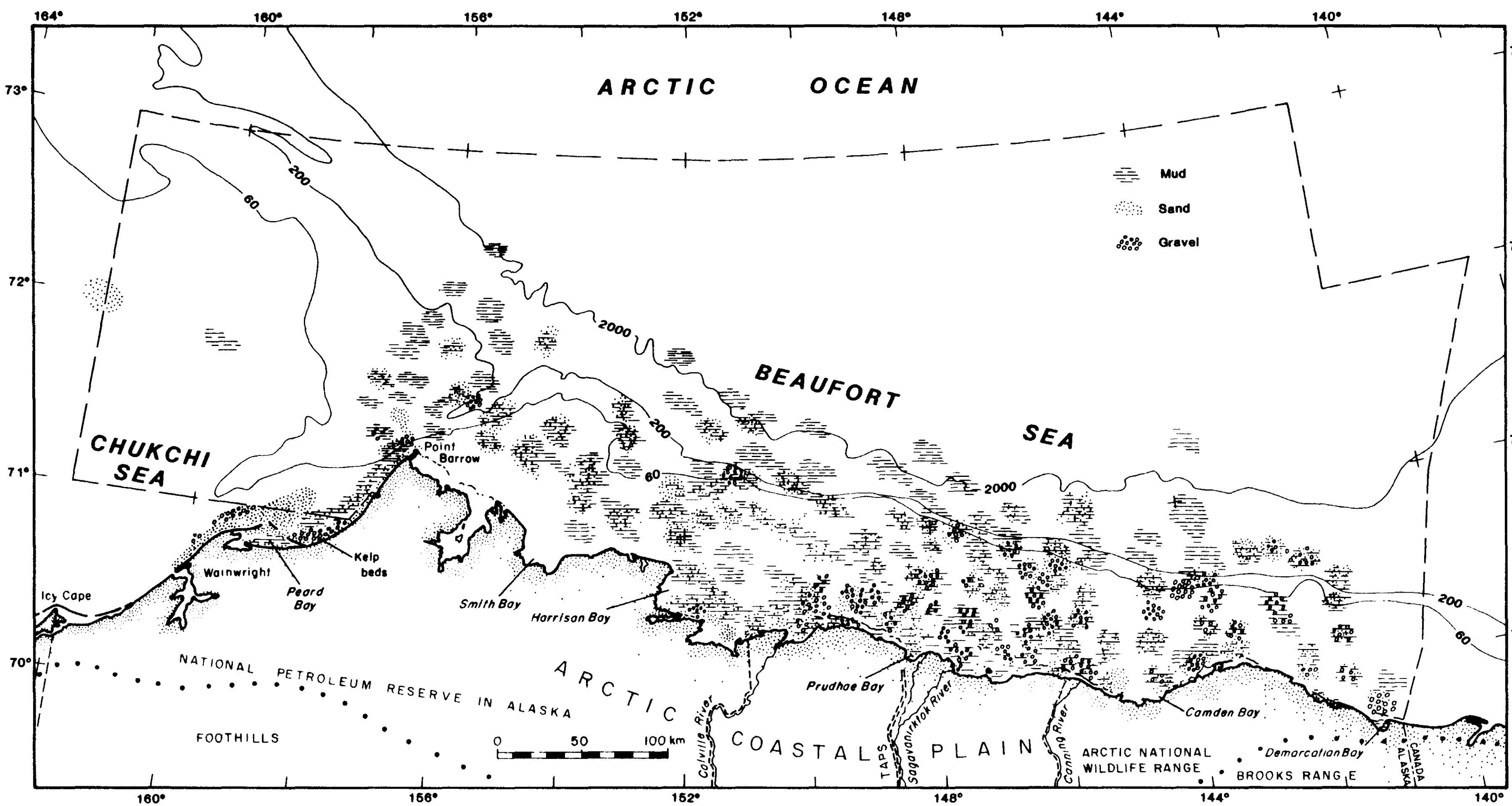


Figure 21. Textural character of surficial sediments on the Alaskan Beaufort and northeast Chukchi shelves.

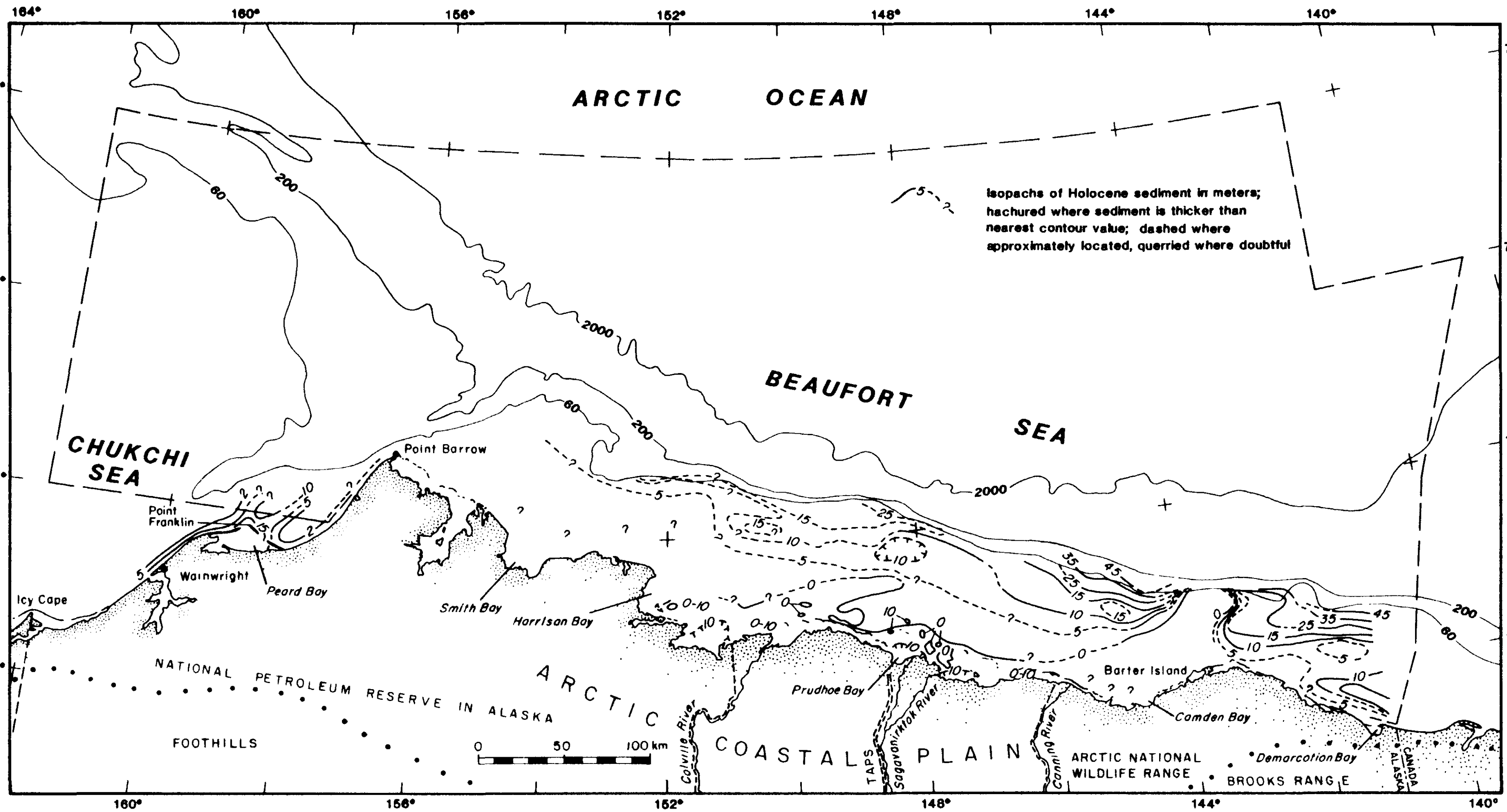


Figure 22. Holocene marine sediment thickness on the Alaskan Beaufort and northeast Chukchi shelves.

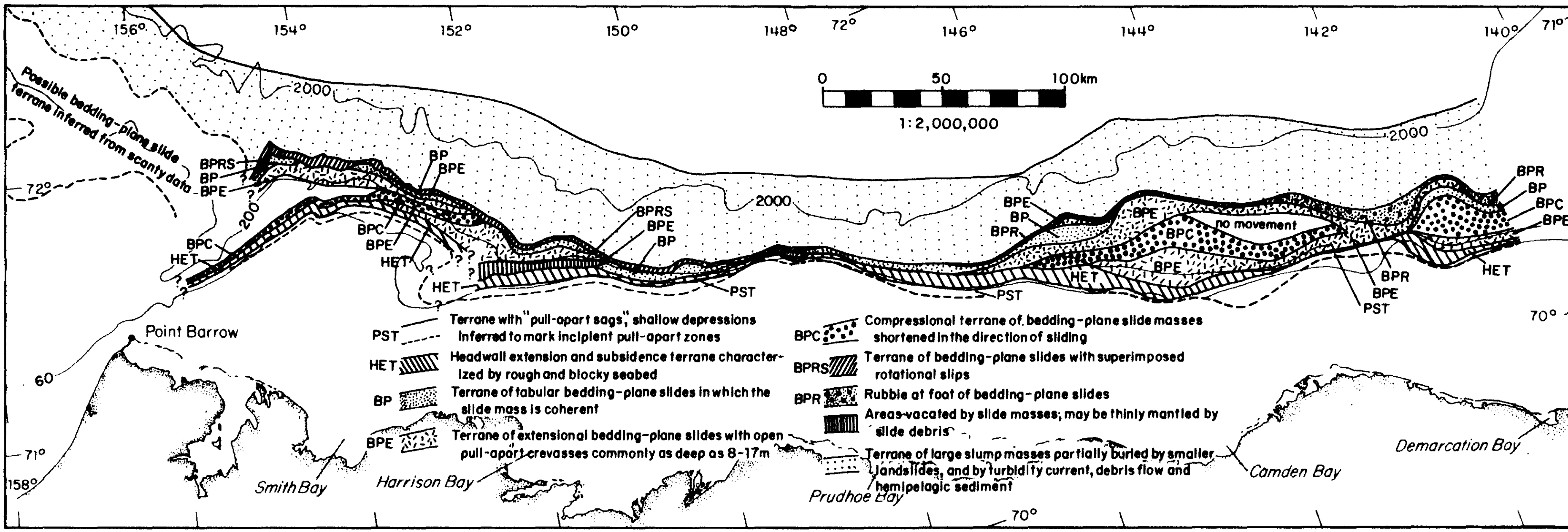


Figure 23. Preliminary map of youthful landslide terranes on the Beaufort shelf and slope north of Alaska.

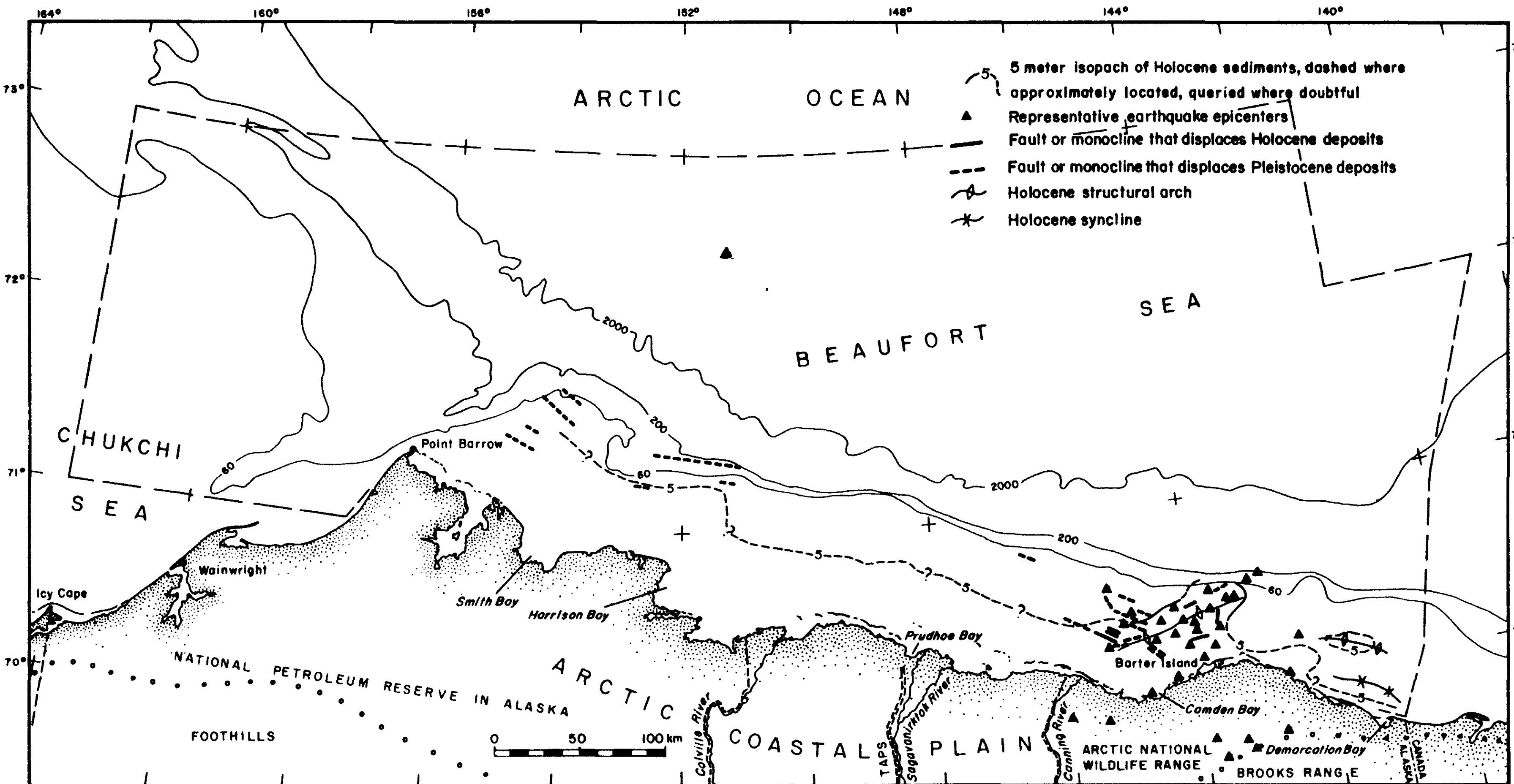


Figure 24. Holocene faults, earthquake epicenters, and structural axes on the continental margin north of Alaska.

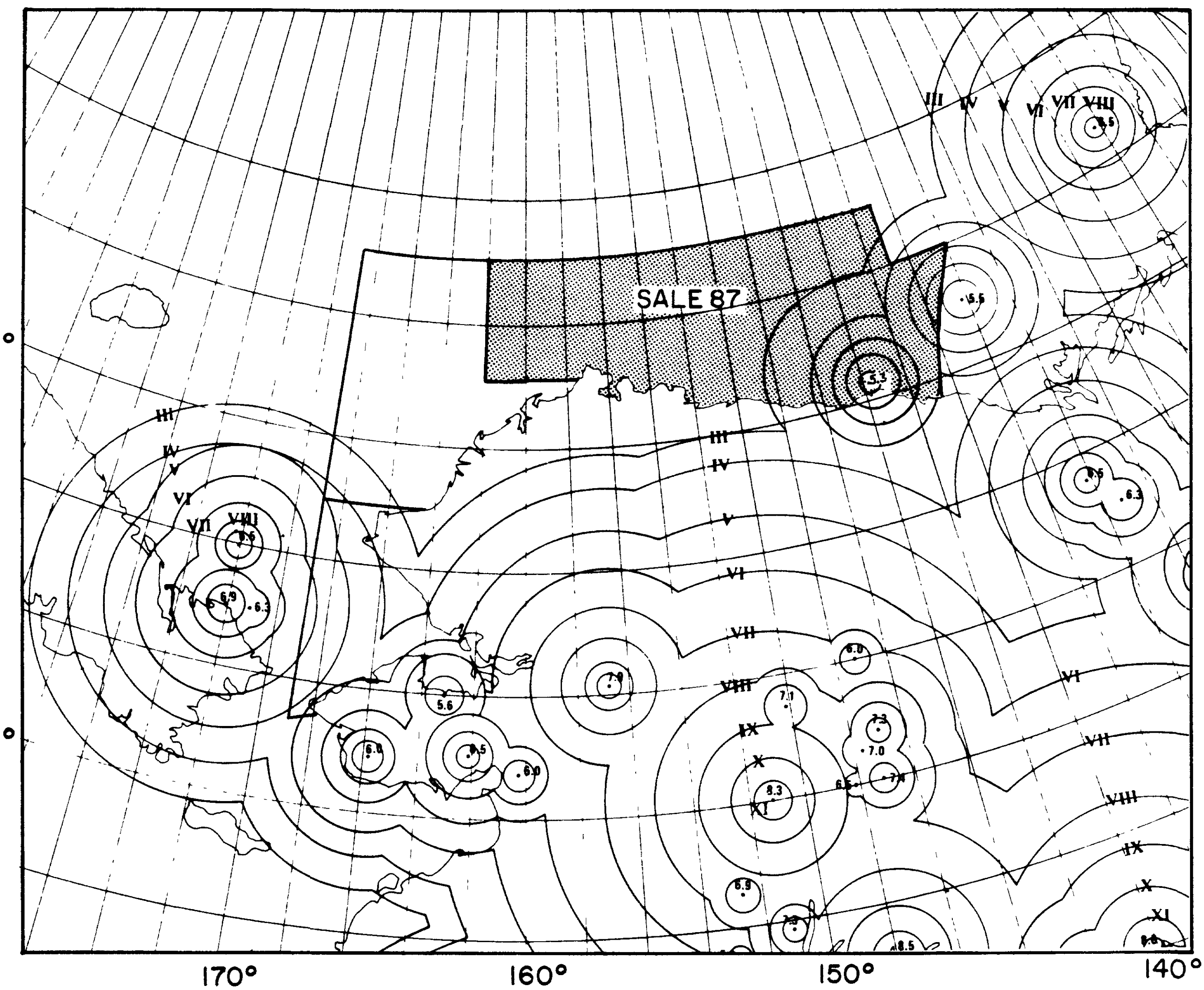


Figure 25. Isoseismal map of northern Alaska showing projected maximum Modified Mercalli intensities of major earthquakes through 1974 (modified from Meyers, 1976b).

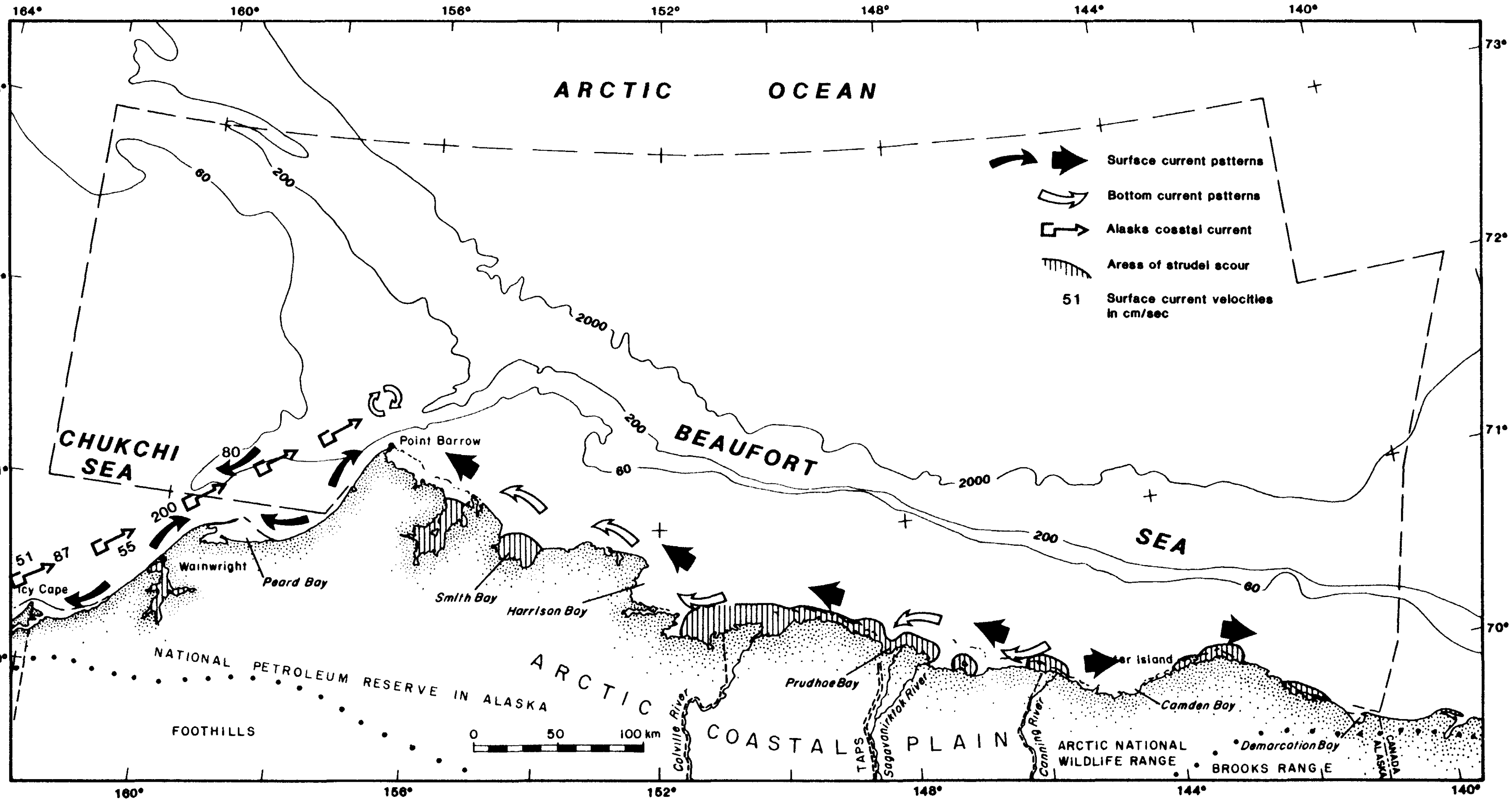


Figure 26. Current patterns and regions of strudel scour on the Alaskan Beaufort and northeast Chukchi shelves.

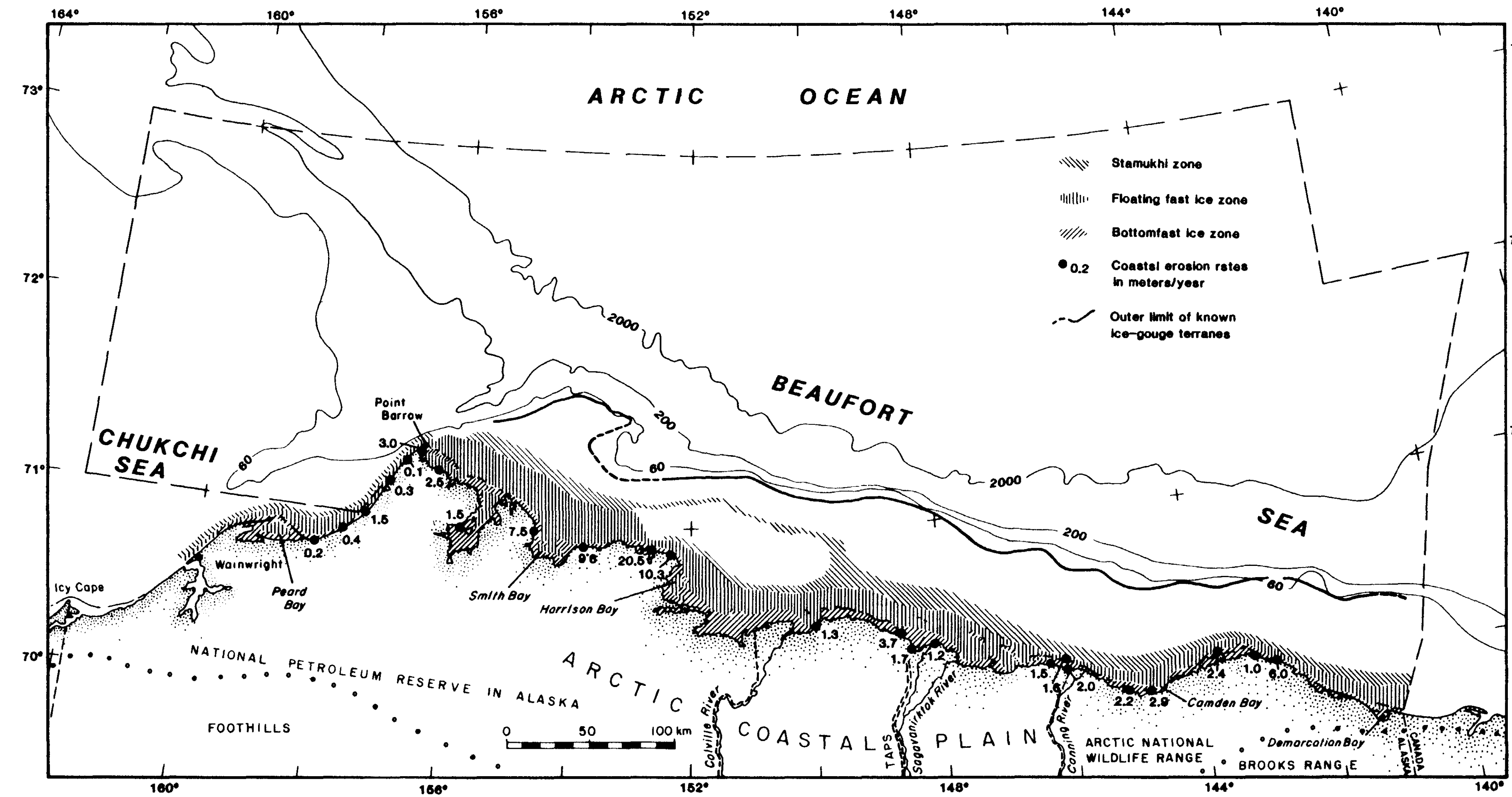


Figure 27. Coastal hazards and ice zonation on the Alaskan Beaufort and northeast Chukchi shelves.

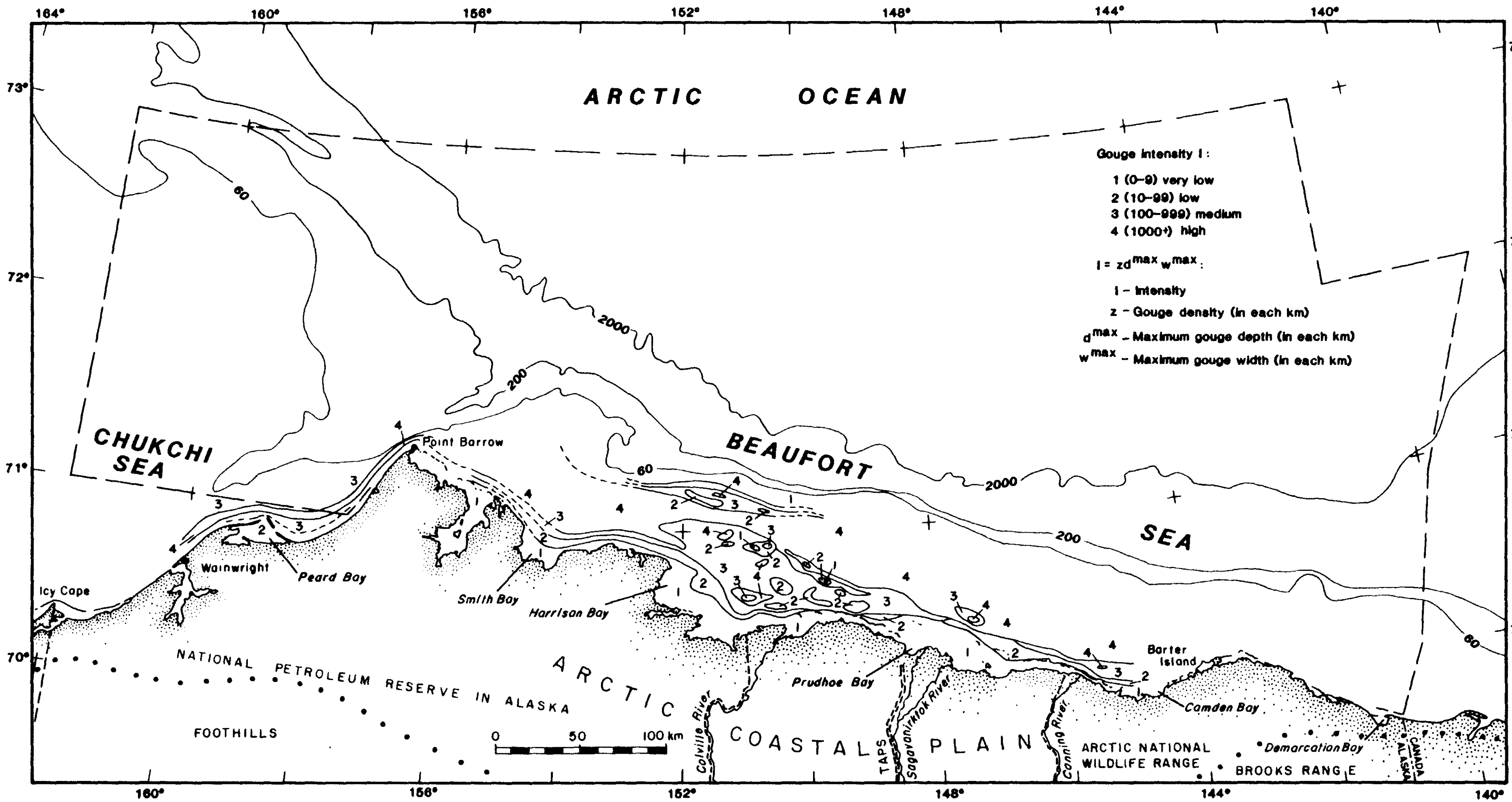


Figure 28. The ice gouge intensity of the Alaskan Beaufort and northeast Chukchi shelves. Ice gouge intensity is a product of maximum gouge incision depth, maximim gouge width, and gouge density per kilometer of ship's track.