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 85 IN THE CENTRAL AND NORTHERN CHUKCHI SEA

A SUMMARY REPORT

By

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

OPEN-FILE REPORT 82-1053

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature. Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS.

Menlo Park, California
1982

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INTRODUCTION

Proposed oil and gas lease sale 85, in the central and northern Chukchi Sea (Fig. 1), offers for development an extensive frontier terrane that is incompletely explored and entirely untested for petroleum. The area is in most places underlain by a thick section of sedimentary rocks prospective for oil and gas and contains diverse geologic structures and stratigraphic features that may have trapped hydrocarbon fluids. The prospective sedimentary section includes every geologic system from the Devonian(?) or Mississippian to the Tertiary, and includes a number of formations that contain petroleum deposits or strong shows of oil or gas on the North Slope of Alaska. These formations have proved disappointing, however, where tested in a few exploratory wells in the western part of the National Petroleum Reserve in Alaska, which lies adjacent to the east-central part of the proposed sale area.

Petroleum exploration and development in the proposed sale area will be hindered by the Arctic climate, polar ice pack, winter darkness, absence of harbors in Alaska north of the Aleutian Islands, and remoteness from exploration support facilities and supplies. The sale area is entirely covered by the polar ice pack from the months of October or November to June, and part of the area is ice free for a short time in late summer only in favorable ice years (Fig. 2). The bathymetry of the sale area, however, is favorable for exploration. Almost all of the area is less than 60 m (200 ft), and none of it is more than 100 m (330 ft) below sea level (Fig. 3). 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." Thus, essentially all of the area of proposed sale 85 is thought by the National Petroleum Council to be technologically accessible to petroleum exploration and development at the present time.

The proposed lease sale area extends from the three-geographical-mile limit off the coast of northwest Alaska and the west boundary of proposed oil and gas lease sale 87 to the U.S.-Russia convention line of 1867 near 169^{o} W. long (Fig. 1). The south limit lies at the latitude of Point Hope (approximately 68^{o}20' N.) and the north limit at 73^{o}00' N. Its maximum east-west and north-south dimensions are about 400 km and 500 km, respectively, and its area is roughly 115,000 sq km.

Sale 85 lies adjacent to the North Slope of Alaska which, in spite of its remoteness, is extensively explored for petroleum. The National Petroleum Reserve in Alaska (NPRA) occupies the western part of the North Slope (Fig. 1), but the main areas of oil and gas development lie east of the mouth of the Colville River (151° W. long). The principal logistic base for petroleum exploration on the North Slope is in the Prudhoe Bay area, about 350 km east of the area of sale 85.

The Trans-Alaska Pipeline System (TAPS), a common carrier, would provide an outlet for sale 85 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 85 natural gas to market. These pipelines are 400-600 km across the topographically subdued North Slope from the most likely sites for shoreline terminals of pipelines that might bring sale 85 oil and gas onshore. TAPS and the proposed gas pipeline, if it is built, favorably affect the economics of developing oil and gas deposits in the area of sale 85 because the feasibility of economically transporting large volumes of oil or gas by ice-breaking tankers year-round from the Chukchi Sea 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 area of proposed oil and gas lease sale 85. It is based mainly on U.S. Geological Survey data, but includes interpretations based on published data from other sources. Its purpose is to identify for the Minerals Management Service those parts of the proposed sale area that are most prospective for oil and gas, and those geologic and environmental constraints and hazards that might adversely affect development or damage exploration and production structures. Many of

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[1]Grantz and May prepared the Introduction and the sections on Bathymetry and Physiography, Geologic Framework, and Petroleum Potential; McMullin the section on Resource Assessment; and Dinter, Hill, Hunter and Phillips the section on Environmental Constraints to Petroleum Development.

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 sale area. These conditions will generally make the control of oil spills and blowouts in the lease sale area much more difficult, particularly from October to June or July, than in more southerly areas and might force long delays in the positioning of equipment to drill relief wells or repair subseabed pipelines.

Our data base consists of the multichannel seismic-reflection profiles and accompanying high-resolution seismic-reflection 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. The multichannel seismic profiles, which are the main basis for the interpretations presented in the Geologic Framework and Petroleum Potential sections of this report, are not evenly distributed. Ice conditions during data acquisition were such that profile coverage in the north and northwest parts of the sale area is sparse (Fig. 1). Elsewhere, the multichannel profiles are mostly 30 to 90 km apart, with typical line spacing being 40 to 50 km. Because of the wide spacing and irregular distribution of the profiles, and because the profiles are only partially processed, the interpretation of the geologic framework, environmental conditions and petroleum potential presented in this report are only preliminary. Strong artifacts not yet removed from some of the profiles, particularly in the southwestern part of the sale area, further limit the usefulness of the affected profiles for geologic interpretation and resource assessment.

BATHYMETRY AND PHYSIOGRAPHY

The sea bed in the area of sale 85 is remarkably flat (Fig. 3) and more than 80 percent of it lies between the 30 and 60 m isobaths. The head of Barrow sea valley barely enters the sale area north of Wainwright and a couple of broad sea valleys extend a short distance into the sale area near 73°00' N. lat. The deepest parts of these features, however, are only about 75 to 100 m below sea level. Except for the nearshore and the large sand ridges at Blossom Shoals off Icy Cape, the shallowest part of the sale area is at Hanna Shoal, near 72° N. lat, 162° W. long. A small area of the sea bed there is less than 25 m below sea level.

The bathymetry of the sale area is shown at scale 1:1,000,000 on Naval Oceanographic Chart N.O. 16002, published by the Defense Mapping Agency Hydrographic Center, Washington, D.C. 20390. The isobaths in Figure 3, however, were taken from a new bathymetric map of the Chukchi Sea, scale 1:1,000,000, that is now in preparation by the U.S. Geological Survey. 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, 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 at polar latitudes.

GEOLOGIC FRAMEWORK

Proposed lease sale 85 encompasses seven major structural provinces with more or less distinct geologic character and petroleum potential. These provinces are enumerated in Table 1 and their location is shown in Figures 4 and 16. The general stratigraphy and lithology of the region is summarized in Figure 5 and a cross section based on correlated test wells in the adjacent onshore is presented in Figure 6. The offshore geologic data are mostly new, but some material was taken from Eittreim and others (1978, 1979) and Grantz and others (1981). Onshore data are mainly from Alaska Geological Society (1981), Lathram (1965), Miller and others (1979), and Guldenzopf and others (1980).

Depth to seismic horizons, and commonly the thickness of seismic-stratigraphic units in this report is given in seconds of two-way seismic reflection travel time. An approximate conversion of the travel-times to km can be made through the graphs in Figure 7, which represent the average regional velocity structure. The graph for the North Chukchi basin also approximates conditions in Hope basin and the young sedimentary sequence in the Tertiary canyon fill. The graph for the Chukchi shelf has been biased by the Tertiary canyon fill and gives depths that are somewhat shallower than actual where the canyon fill is not present.

TABLE 1

Structural Provinces of

Proposed Oil and Gas Lease Sale 85

(See Figures 4 and 16 for location of provinces)

1. Barrow arch and Arctic platform east of Hanna trough
2. Hanna trough
3. Arctic platform west of Hanna trough
4. Foreland fold belt of Colville foredeep
5. Herald arch overthrust belt
6. Hope basin
7. North Chukchi basin

Stratigraphy

The sedimentary strata of northern Alaska and the United States Chukchi shelf are conveniently grouped into three regionally extensive sequences, The Franklinian, Ellesmerian, and Brookian, of contrasting lithology, tectonic character and hydrocarbon potential (Fig. 5). The Cambrian to Devonian Franklinian sequence, consisting of slightly to strongly metamorphosed sedimentary and some volcanic rocks, is inferred to constitute economic basement for the Chukchi shelf and the area of sale 85. 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, is a low-gradient surface that has remained remarkably stable beneath the North Slope of Alaska and the Chukchi shelf, and is the foundation for the potentially petroliferous strata in the area of sale 85. A lithologically diverse suite of clastic and carbonate sedimentary rocks, the Ellesmerian sequence, was deposited on the Arctic 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 sourceland that lay beneath and north of the outer part of the present continental shelf of the Beaufort and northeast Chukchi Seas. In a following section on the Hanna trough it is suggested that there may also have been a western sourceland for the Ellesmerian clastic strata of the United States Chukchi shelf. In the Chukchi shelf the main Ellesmerian sequence as developed on the western North Slope appears to be underlain with mild angular unconformity by a thick sedimentary unit that filled in structurally low areas of the Arctic Platform. This unit is referred to as the Eo-Ellesmerian sequence in this report.

Eo-Ellesmerian sequence: Structural sags and faulted depressions in the angular unconformity (the Arctic platform) at the top of the Franklinian sequence beneath the Chukchi shelf are filled with sedimentary prisms that coalesce at their edges to form a regional stratigraphic sequence of irregular outline and marked local variations in thickness. Figure 9, a structural contour map in isochrons of the base of this sequence, shows its distribution in the sale area and the local structural subbasins in which the sequence lies. The deepest of these subbasins, located about 50 km west of Icy Cape, contains up to 5 km of section on one seismic profile. These beds are closely related to the Ellesmerian sequence because they produce coherent seismic reflections over a large area and are only slightly more deformed than that sequence. However, there is commonly a low angle but pronounced angular unconformity between these rocks and the Ellesmerian beds, and in places fault-bounded prisms of these sediments appear to be overstepped by Ellesmerian strata. These strata are called Eo-Ellesmerian because of their structurally close, but unconformable relationship with the overlying Ellesmerian sequence.

The character of the Eo-Ellesmerian beds can only be inferred because they cannot be definitively correlated with outcrops or wells onshore. Further, they lie at subsurface depths that in places exceed 15 km, and they generally have only fair to poor seismic expression. Comparison with onshore seismic-stratigraphic and subsurface units recognized in the exploration of NPRA (Guldenzopf and others, 1980; and Alaska Geological Society, 1981) suggests two possible correlations for the Eo-Ellesmerian beds. The first is with the Wahoo Limestone (Upper Mississippian to Lower Permian) and overlying transition beds of the upper part of the Lisburne Group which occupy connected subbasins of limited extent in the western part of NPRA (Guldenzopf and others, 1980, Maps 3 and 4). The second is with the thick sequence of pre-Lisburne (Mississippian and perhaps Upper Devonian) Endicott Group clastics, mainly nonmarine and in part coal-bearing, of the northwest-elongate compound Ikpikpuk-Umiat basin of eastern NPRA. Seismic-reflection profiles suggest to C. E. Kirschner (unpublished data, 1982) that a wedge of Endicott clastics may also occur in Meade basin, which underlies western NPRA between about 158°-159° W. long and 69°30'-70°30' N. lat. The areal extent of the inferred Endicott beds in Meade basin is mmuch smaller than in the larger Ikpikpuk-Umiat basin to the east.

Correlation with the Lisburne is favored by the proximity of the Eo-Ellesmerian basin off Icy Cape to the upper Lisburne basins in western NPRA, but would require that the Lisburne basin become wider and deeper offshore. On a seismic profile 70 km northwest of Icy Cape the basal Eo-Ellesmerian beds rise from the deepest part of the subbasin there to the zone of truncation at the overlying unconformity. This geometry requires that if the Eo-Ellesmerian is upper Lisburne, the latter becomes 5 km thick beneath the Chukchi shelf. The thickest sections of the entire Lisburne Group on the North Slope and

Brooks Range are only 1 to 2 km (Brosgé and Tailleur, 1971, p. 79; Armstrong and Mamet, 1977). The isopach map of the Wahoo Limestone in western NPRA (Guldenzopf and others, 1980, Map 3) suggests, in part on speculative contours, that the Wahoo prism narrows westward near Icy Cape and that it may pinch out offshore rather than merge with the Eo-Ellesmerian prism.

In thickness and basin geometry the Eo-Ellesmerian prism more closely resembles the pre-Lisburne Endicott Group of the Ikpikpuk-Umiat basin and perhaps the Meade basin than the upper Lisburne basins of western NPRA. However, the Ikpikpuk-Umiat basin lies more than 200 km, and the small Meade basin at least 100 km east of the Eo-Ellesmerian prism, and no pre-Lisburne Endicott rocks have been reported from the westernmost North Slope. If the Eo-Ellesmerian beds are Endicott, rather than upper Lisburne, the Lisburne Group may be absent or have only a restricted distribution on the Chukchi shelf and the area of sale 85.

Ellesmerian sequence: The dominantly clastic Ellesmerian sequence of the western North Slope, which was derived from a northerly sourceland, extends offshore and underlies most, but not all, of the United States Chukchi shelf and the area of sale 85 (Figs. 5 and 6). Its structure and thickness in these areas are shown in Figures 10 and 11. Beneath the eastern part of the Chukchi shelf the sequence rests unconformably on the south-sloping Arctic platform and has the same general west strike, south dip, and southward increase in thickness that characterize it on the North Slope. In this area the sequence thickens from 0.1 sec (about 100-150 m) at a depth of about 1 sec (1 km) on the Barrow arch to about 2 sec (5 km) at a depth of 3 to a little more than 5 sec (6 to 11 km) in a southeast-striking structural low off Point Lay. This structural low merges with the Hanna trough, a north-striking structural low and sedimentary thick near 164° W. long. The base of the Ellesmerian sequence (top of Eo-Ellesmerian sequence) is more than 4.85 sec (10 km) deep, and the sequence is more than 3.0 sec (7.7 km) thick near 71°15' N. lat. A northward deepening, probably genetically related structural low north of 71°30' N. lat near 162° W. long contains a similar or greater thickness of Ellesmerian strata. West of Hanna trough the Ellesmerian sequence becomes progressively shallower and thinner. Beyond 167° W. long it is generally less than 0.5 sec (1.3 km) thick, and in places beyond about 168° W. lat it appears to be entirely absent. The decrease in thickness is both by stratal thinning and overlap, which suggest the possibility that a platform or sourceland lay to the west. On the other hand, sections of tentatively identified Ellesmerian rocks as thick as 2 sec (5.5 km) are preserved in fault blocks near Cape Lisburne, and these sections appear to extend west of the 0.5 sec isopach of the region north of the fault blocks. A strong seismic reflector of regional extent is interpreted to mark the top of the Ellesmerian sequence.

In the eastern part of the Chukchi shelf the reflectors correlated with the Ellesmerian sequence consist of an upper unit of relatively weak, less continuous reflectors and a lower unit that contains a number of strong reflectors of considerable lateral extent. A strong reflector which lies about 40% to 50% below the top of the Ellesmerian reflector packet on the seismic profiles marks the top of the lower subunit at many places north of the latitude of Point Lay. The relative thickness of the units changes markedly to the west, and in places one or both are entirely absent. Comparison with onshore data between Icy Cape and the Barrow area (Figs. 6 and 10) suggests that the upper unit consists of the Lower Cretaceous Pebble shale unit and the Jurassic-Lower Cretaceous Kingak Shale, which contains bodies of sandstone that form stronger reflectors in its lower part. The lower unit is thought to represent the Permian and Triassic Sadlerochit Group, the Triassic Shublik Formation and Sag River Sandstone, and perhaps beds of Jurassic sandstone in the lower part of the Kingak Shale. According to the regional time-depth function of Figure 7 the upper unit (Kingak Shale and Pebble shale is relatively thinner, and the lower unit relatively thicker offshore than beneath the western North Slope. The northern limits of key stratigraphic components of the Ellesmerian sequence in western NPRA, where there is a progressive south to north overlap of older by younger stratigraphic units, are shown in Figures 9 and 10. Seismic data indicate that the same progressive overlap occurs beneath the eastern Chukchi Sea.

Only the upper, mainly Pennsylvanian and Permian part of the Lisburne Group (Wahoo Limestone) is present beneath the western North Slope (Guldenzopf and others, 1980), and Figures 6 and 11 show that even that part of the group has only a limited distribution in the area. Indeed, a straightforward projection of the zero isopachs of upper Lisburne (Wahoo Limestone) rocks in western NPRA (Guldenzopf and others, 1980, Map 3) suggests that these rocks may wedge out entirely off Icy Cape. In support of this possibility, we have not recognized a strong low-frequency reflector that might correspond to the top of the Wahoo on our offshore profiles. A 0.2 to 0.4 km sag in the base of the inferred Ellesmerian seismic interval off Icy Cape contains no well-defined reflections and possibly corresponds to the interbedded limestone and shale that, according to Guldenzopf and others (1980, Map 4), forms the upper unit of the Lisburne Group in western NPRA. If the sag contains Wahoo Limestone, the limestone produces no strong seismic reflections there.

Lower Brookian sequence: The lower part of the Brookian sequence of the United States Chukchi shelf and sale 85 consists of a thick succession of seismic reflectors of weak to moderate strength that are interpreted to represent Cretaceous marine and nonmarine clastic sedimentary rocks of the Colville foredeep. Structural contours drawn at the base of the Brookian sequence on the eastern Chukchi shelf are shown in Figure 12. The sequence rests, typically by downlap, on a strong regional seismic reflector that is thought to mark the top of the Pebble shale unit (Neocomian), at the top of the Ellesmerian sequence. Comparison with onshore data (Molenaar, 1981; and Guldenzopf and others, 1980) suggests that the lower Brookian sequence of the Chukchi shelf consists of marine prodelta clastic deposits of the intertonguing Fortress Mountain and Torok Formations and nonmarine and shallow marine intradelta deposits of the Nanushuk Group (Figs. 5 and 6). The age of these units is Aptian(?), Albian, and possibly lowest Upper Cretaceous (Cenomanian). Paleocurrent data (Molenaar, 1981) suggest that these beds were derived from a sourceland that lay to the southwest. Near latitude 70° N. on the North Slope, and possibly in places in the western and northern parts of the sale area, the Albian beds are overlain by nonmarine and shallow marine intradelta deposits of the Colville Group (Upper Cretaceous). The Colville Group intertongues north and northeastward into marine prodelta deposits beneath the Beaufort and northern Chukchi shelves.

The lower Brookian sequence thickens north and south from a minimum of 0.25 to 0.67 sec (0.25 to 0.7 km) on the Barrow arch. On the eastern Chukchi Shelf the sequence thickens rather uniformly southward from the arch to a maximum of 3.7 sec (about 7.5 km) beneath the axis of the Colville foredeep between Icy Cape and Point Lay, in the southeastern part of the sale area. From this structural low and sedimentary thick the axis of the foredeep plunges southeastward beneath the foothills of the Brooks Range. Up-plunge, the axis merges with the north-trending Hanna trough in which the base of the Brookian sequence lies 2.4 to 3.0 sec (about 4 to 5.5 km) below sea level.

The thickness of the lower Brookian beds in the trough is reduced, however, by a buried canyon filled with a thick upper Brookian ("Tertiary") sedimentary prism (Figs. 4 and 14). West of Hanna trough and south of 71°30' N. lat, the Lower Brookian sedimentary sequence thins to less than 1.0 sec (about 1 km), but incomplete processing of the data in the southwest part of the sale area precludes determining whether or not it wedges out entirely. Northwest of Hanna trough the lower Brookian sequence thickens sharply as it drops into the North Chukchi basin, where the sequence is extensively deformed by listric normal faults of large displacement. The base of the unit lies more than 6 sec (about 12 km) below sea level, and is 4.5 km to perhaps 8.5 km or more thick, in this basin.

The lower Brookian sequence of the North Slope and eastern Chukchi Sea was derived from a sourceland that lay to the southwest and filled the Colville foredeep by progressive onlap against the Barrow arch to the northeast. The lower Brookian rocks also thicken into Hanna trough, which has somewhat less structural relief in the Brookian than in the underlying Ellesmerian rocks. The suggested, incompletely documented, westward reduction in the thickness of the lower Brookian sequence west of Hanna trough by stratal thinning, rather than by erosional truncation, suggests that a southwest sourceland or a structurally positive area lay to the west in early Brookian time.

Upper Brookian sequence: The Beaufort and northeastern Chukchi shelves north of Barrow arch, Hanna trough, the shelf west of Hanna trough north of the latitude of Icy Cape, and North Chukchi basin are underlain by an irregularly shaped body of young sedimentary rocks that form an important stratigraphic sequence in the northern half of the sale area. Structural contours at the base of this sequence are shown in Figure 14. These rocks are called the Upper Brookian sequence in this report. They overlie the lower Brookian rocks with angular unconformity, have relatively low seismic-reflection velocities, and constitute the youngest bedrock stratigraphic unit on the Chukchi shelf. From their stratigraphic position and relatively low seismic velocities we infer that they are largely or entirely of Tertiary age. While much of the section in the upper Brookian sequence can be traced into Tertiary beds of the Beaufort shelf and North Slope east of Harrison Bay, the basal contact or unconformity has not been tied to the Cretaceous-Tertiary boundary. For convenience we consider these rocks to be Tertiary in this report, but recognize that they may not include the lowest part of the Tertiary or, alternatively, that the lowest beds may be uppermost Cretaceous. Because the upper Brookian rocks are the highest stratigraphic sequence in the area and their upper beds lie at or close to the floor of the shallow Chukchi Sea, the structural contours on the base of the sequence in Figure 14 are essentially isopachs.

The upper Brookian rocks are as much as 2.0 sec (2.2 km) thick in the subbasin that overlies Hanna trough, 1.5 to 1.9 sec (1.6 to 2.1 km) thick in a filled channel that connects the subbasin with the North Chukchi basin, and more than 3.6 sec (5.6 km) thick in the North Chukchi basin itself. The morphology of the subbasin that overlies Hanna trough, and the fact that the subbasin is linked to the deep North Chukchi basin by a buried channel (Fig. 14), suggest that it is a filled submarine canyon tributary to the North Chukchi basin. In morphology and size the postulated submarine canyon resembles the modern Navarin and Zemchug canyons of the outer Bering shelf.

Low seismic velocities, the character of the Tertiary strata on the North Slope, and the geometry of the seismic reflectors suggest that the upper Brookian sequence of the Chukchi shelf is composed of clastic sediments. On the east side of the subbasin overlying Hanna trough the seismic reflectors are conformable with the basal unconformity. On the more steeply sloping west side of the basin, however, reflectors within the subbasin buttress against the basal unconformity and underlying basin slope. These relations suggest that the subbasin was filled from the east or southeast and that it was empty when sedimentation began. As the height of the west wall of the subbasin and the thickness of the buttressing beds is almost 1 sec (1 km), it is likely that much of the section in the subbasin is marine. The even thicker section in the North Chukchi basin presumably is also dominantly marine. As on the North Slope and Beaufort shelf, such marine beds would probably grade shoreward into nonmarine beds.

A sequence of sedimentary rocks that are correlative with the upper Brookian sequence of the northern Chukchi shelf, but occupy a separate basin 70 km to the south, underlie the southwest corner of the sale area. These rocks occur in Hope basin (Eittreim and others, 1978 and 1979) which contains more than 3 sec (4.1 km) of strata with low to moderate seismic velocities in the sale area. The seismic velocities, the character and age of sedimentary rocks exposed in the lowlands south and southeast of Hope basin, and the character of the seismic reflections (Eittreim and others, 1979) suggest that the basin is filled with nonmarine, and probably some estuarine and marine strata of Tertiary age. A lack of subsurface data leaves open the possibility that in places some Upper Cretaceous sedimentary rocks may also be present.

Structural Provinces

Most of the United States Chukchi shelf and the area of sale 85 is underlain by the Arctic platform (see section on "Stratigraphy", above), which has been remarkably stable since its development in Late Devonian-Early Mississippian time. The platform has been tilted and warped, but high-gradient folds have not been recognized and faults of significant displacement are common only in the western part of the sale area. Although structural gradients in the tilted and warped areas of the platform are very low, the affected areas are extensive and consequently the amplitude of the resultant deformation is large. Most of the major structural provinces in the area of sale 85, which are shown in Figure 16, are recorded in the morphology of the Arctic platform.

Barrow arch and Arctic platform east of Hanna trough: Beneath the United States Chukchi shelf east of Hanna trough, the Arctic platform slopes uniformly south-southwest with a gradient of about 2.5° from the crest of Barrow arch to the present structural axis of the Colville foredeep near Point Lay (Figs. 10 and 12). The sedimentary section on the platform near Point Lay consists of about 5.5 km of mainly clastic Ellesmerian strata and about 7.5 km of marine and nonmarine lower Brookian strata. Off Icy Cape a local basin of northeast strike contains about 1.7 sec (5 km) of Eo-Ellesmerian strata (Fig. 9). The northeast limit of these beds is not known. The Ellesmerian sequence thins northward by stratal thinning and progressive northward overlap of older by younger formations (Figs. 6, 9 and 10) and it is only 0 to 100 or 200 m thick on the crest of the arch. The lower Brookian sequence thins northward by the progressive northward downlap of foreset beds on its substrate and by erosion at the present land surface (Fig. 6). The foresets formed in a prograding prodelta that filled the Colville foredeep from the southwest. The sequence consists of the marine Torok Formation and the marine and nonmarine Nanushuk Group and is in places less than 0.25 sec (about 0.3 km) thick on Barrow arch.

Much of the Arctic platform east of Hanna trough and almost all of Barrow arch lies northeast of the area of sale 85. The arch itself, as expressed at the base of the Brookian sequence (Fig. 12), barely enters the sale area near 72° N. lat. A large fault near 162° W. long, which was observed on only one multichannel profile and therefore is of uncertain strike, may die out before it enters the sale area near 71° N. lat. The only significant deformational structures in the Arctic platform province within the sale area east of Hanna trough, other than the southwest tilt, are the detachment folds of the foreland fold belt structural province (Fig. 13).

Hanna trough: Downwarping and downfaulting of the Arctic platform from depths as shallow as 0.25 sec (0.3 km) on Barrow arch to depths as great as 4.85 sec (about 10 km) in the vicinity of 164° W. long, created the east flank of Hanna trough (Fig. 10). The change in structural level is largely accomplished by downwarping, but the major north-striking fault near 162° N. long forms the boundary of a northeast extension or subbasin of the trough near 71°40' N. lat. The west flank of the trough is a more gentle, westward rise in the Arctic platform. In contrast to the east flank of the trough, the Arctic platform in the axial region and west flank of the trough is in places folded and strongly faulted. The south end of the trough is placed where it changes trend from north-south to northwest-southeast off Point Lay. The north end lies beyond our multichannel profiles, but gravity data suggest that the trough or a related subbasin extends north-northeast to the north end of the sale area and beyond.

At least 0.4 sec (1 km) of Eo-Ellesmerian strata and more than 3 sec (7 to 8 km) of Ellesmerian strata were deposited in the deepest part of Hanna trough and its northeast extension, or subbasin (Fig. 11). The Eo-Ellesmerian beds were deposited in structural downwarps, in places faulted, in the Arctic platform. The overlying Ellesmerian strata of the trough are areally more extensive and somewhat less variable in thickness. In the west flank of Hanna trough the Ellesmerian strata thin westward by stratal thinning and overlap, suggesting that the region to the west was a structural high or platform, and perhaps a sourceland for Ellesmerian clastics. The Ellesmerian strata in the Arctic platform east of the trough, as discussed in a preceding section, thin toward a sourceland to the north by stratal thinning and progressive overlap. These stratigraphic relationships indicate that Hanna trough is a depositional basin as well as a structural trough (Fig. 11).

Hanna trough is also expressed in the thickness of the Brookian sequence and the structure of its basal contact (Fig. 12), but its flanks have very low gradients in these rocks and the structural relief is less than in the underlying Ellesmerian rocks. About 2.5 sec (4 km) of Brookian strata underlie the trough from where it becomes a north-trending feature west of Icy Cape to its merger with the North Chukchi basin near 72° N. lat. It is not known from present data whether or not an extension or subbasin of the trough, as expressed in Brookian rocks, also continues north-northeast into the northeast corner of the sale area, as is inferred from the Ellesmerian rocks. The lower Brookian sedimentary thick in Hanna trough formed in part by infilling an existing broad sag, and in part by post-depositional faulting and downwarping. Crustal loading by the underlying Ellesmerian sedimentary thick, Cretaceous uplift of Barrow arch and of the Arctic platform west of Hanna trough, and perhaps some differential compaction in Ellesmerian rocks all contributed to the structural relief of Hanna trough in lower Brookian rocks.

Upper Brookian strata filling a postulated submarine canyon are the highest sedimentary sequence in Hanna trough. The axis of the canyon fill and the channel connecting it to North Chukchi basin essentially coincide with the axis of the trough as defined by the base of the lower Brookian sequence (Fig. 12) even though these prisms are thought to have quite different origins. The coincidence suggests that the canyon began as a consequent drainage that followed a structurally generated topographic low along the axis of the Hanna trough after lower Brookian deposition ended. It also suggests that the branch canyon that trends northeast from the junction of the channel and the main canyon fill may likewise overlie a structural low in lower Brookian rocks. There are no multichannel profiles in this area, however, and the single channel profiles do not reveal whether a branch of Hanna trough indeed underlies the northeast branch of the canyon fill.

The maximum height of the west wall of the filled canyon is at least 1.25 sec (about 1.75 km), and the total thickness of the upper Brookian section is 2 sec (about 2.5 km). Thus most of the relief in these rocks is due to erosion and canyon filling, but some downwarping of strata into the basin added a small structural component to the present depth of the infilled canyon. Structural deformation may also have created the sill in the buried channel that appears to connect the filled canyon with North Chukchi basin. The top of the sill is 0.5 sec (about 0.75 km) higher than the deepest part of the filled canyon on our profiles, and creates an obvious difficulty for the canyon-fill hypothesis. The sill may be partly explained, however, by the large north-northeast-trending graben that obliquely crosses the channel near its junction with the North Chukchi basin. Isochrons on the base of the upper Brookian sequence (Fig. 14) indicate that the basal surface has been tilted east in the footwall of the fault on the east side of the graben. The tilt is interpreted to represent actual, as well as relative uplift of the footwall that contributed to the elevation of the adjacent sill. Additional relief on the sill was created by the syn- and post-upper Brookian downwarping of the canyon-fill subbasin that is recorded in post-canyon-fill strata.

Arctic platform west of Hanna trough: Westward shallowing of the Arctic platform, westward overlap of older by younger Ellesmerian beds, westward stratal thinning within the Ellesmerian and lower Brookian sequences, and extensive high angle normal faulting characterize the United States Chukchi shelf west of Hanna trough (Figs. 10 to 12). The platform (top of Franklinian basement) shallows from depths of 4.5 to 5.5 sec (about 9 to 12 km) at the axis of Hanna trough and Colville foredeep to less than 1 sec (about 1.0 to 1.25 km) in places near the west boundary of the sale area. As noted in a previous section, the westward overlap of older by younger Ellesmerian units against the westward-shallowing Arctic platform indicates that an Ellesmerian structural high and perhaps a sourceland lay to the west. In places the Ellesmerian rocks wedge out entirely in the western part of the sale area (Fig. 11) and the lower Brookian rocks thin to less than 1 km. The numerous normal faults west of Hanna trough are young features because they offset Brookian as well as Ellesmerian rocks and the underlying platform.

Upper Brookian rocks on the Arctic platform west of Hanna trough form a gently northward dipping and thickening sedimentary wedge that is broken by some large high angle normal faults (Fig. 14). In the sale area these rocks wedge out near 71°30' N. lat and thicken to about 2 sec (2.3 km) at the hinge line that separates the platform from the North Chukchi basin. The Brookian rocks are sufficiently shallow in many places to be mapped from single channel profiles. Accordingly, many structural features are shown within them on Figure 14 that could not be delineated in the older sequences. The large, north-northeast-striking graben near 166° W. long is one such feature. It has as much as 1.2 sec (about 1.4 km) of structural relief and a total sedimentary section, including overburden, that is 2 sec (about 2.3 km) thick. The graben is alined with the east end of North Chukchi basin and is possibly a fracture zone related to the opening of that basin.

Foreland fold belt of Colville foredeep: Large, high-amplitude detachment folds and thrust folds characterize the southeast part of the area of sale 85 between Icy Cape on the northeast and Cape Lisburne and Herald arch on the southwest (Fig. 13). The folds have flank dips of 1° to 15°, amplitudes of up to 1.2 km, wavelengths generally in the range of 10 to 30 km, and strike lengths of 10 to more than 120 km. They are the continuation of the foreland fold province of the north side of the Brooks Range, where they involve mainly lower Brookian, but apparently also Ellesmerian beds. The folds swing in strike from east-west on the western North Slope to west-northwest and northwest offshore. They die out about 70 km off Icy Cape and about 140 km off Cape Lisburne. Offshore, the folds appear to be restricted to the lower Brookian sequence and to die out abruptly at the top of the Ellesmerian sequence, probably in the Pebble shale unit of Neocomian age. Their geometry indicates that they are detachment folds in an allochthonous plate of a regional low-angle detachment fault system. Immediately above the detachment zone the cores of the folds contain thickened wedges of poorly reflective sediment, presumably tectonically mobilized shale. The folds become progressively more complex toward Herald arch, and near the arch they are thrust folds with cores that are appressed and contain upward steepening listric thrust faults that rise northeast from the detachment fault to the seabed. Northeast vergence and the southwest increase in structural complexity indicate that the folds and the upper plate of the detachment fault moved relatively from southwest to northeast. The folds appear to die out to the northwest by a decrease of displacement and shortening in the upper plate, rather than by extension of the basal detachment fault to the surface or its transformation into tear faults. However, some of our multichannel profiles in the fold belt are incompletely processed, and these conclusions are only tentative.

The faulted, folded, and therefore structurally thickened lower Brookian prism is 2 sec to more than 3.6 sec (about 2.8 to 7.3 km) thick in the fold belt. Beneath this prism and its basal detachment fault lies 0.5 to more than 2 sec (about 1 to more than 5 km) of Ellesmerian section (Figs. 10 and 11). Near Cape Lisburne, tentatively identified Ellesmerian and older rocks are broken by a system of large normal faults whose trends and structural effects are presented conjecturally in Figures 10 and 11. These faults, and the faulted blocks of Ellesmerian(?) and older rocks, terminate upward at the low-dipping detachment surface at the base of the folded Brookian sequence. The Ellesmerian(?) rocks in the fault blocks range in thickness from a feather edge between Franklinian and Brookian rocks near Cape Lisburne to a little more than 2 sec (about 5.5 km) in the next fault block to the north.

Herald arch overthrust: A belt of perched acoustic basement which trends northwest from Cape Lisburne to the west boundary of the sale area has been named Herald arch. The belt of acoustic basement lies between the folded lower Brookian rocks of the Colville foredeep to the northeast, which it overlies structurally, and the young sedimentary rocks of Hope basin, which overlie it depositionally. On profiles situated 20 to 30 km northwest of Cape Lisburne a reflector inferred to be the base of the lower Brookian rocks can be traced southwestward at least 15 km beneath the perched (overthrust) acoustic basement (Fig. 12). No reflectors were recognized, however, that represented the lower Brookian rocks themselves.

The perched acoustic basement is tentatively interpreted to be the upper, allochthonous plate of a large overthrust fault system that dips southwest at a low angle from the north side of Herald arch. The folded lower Brookian rocks below the overthrust fault are thought to form a lower allochthonous plate that in turn rests on the detachment fault discussed in the preceding section. It is likely that the lower Brookian rocks extend considerably farther than 15 km southwest beneath the acoustic basement of the upper allochthonous plate, and it is possible that a significant area and thickness of Ellesmerian rocks also underlies the lower allochthonous plate and its basal detachment fault. The Tertiary Hope basin, which overlies the upper allochthonous plate west and south of Cape Lisburne, is thought to post-date the thrust faulting because it unconformably overlies an interpreted extension of the Herald arch and fault zone south of Point Hope.

Shallow seismic refraction measurements obtained with the multichannel streamer permit the perched acoustic basement to be divided into two domains of shallow bedrock (0 to 0.5 km deep) that have contrasting compressional wave seismic velocities (Vp) (see Figs. 12 and 13). In the northern domain Vp ranges from 3.1 to 4.0 km/sec; in the southern domain it ranges from 3.7 to 7.3 km/sec. These velocities, several dredge and dart core samples, and projection of onshore geologic boundaries suggest that the domain of lower Vp consists mainly of strongly deformed lower Brookian and perhaps upper Ellesmerian (post-Lisburne) sedimentary rocks. They also suggest that the domain of higher Vp contains, in places, Lisburne, Endicott, and Franklinian rocks and that Ellesmerian rocks may be more common in this domain than Brookian rocks.

Hope basin: A Tertiary sedimentary prism characterized by irregular basement topography, broad tectonic warps, and high angle normal and a few high angle reverse faults, but lacking compressional folds, underlies the southwest corner of the area of sale 85 (Fig. 14). The prism occupies Hope basin, which contains mainly or entirely Tertiary sedimentary rocks. Tectonic warping in mid-Tertiary time created two sedimentary subsequences within the basin. Both subsequences are irregular in thickness due to strong basement relief, faulting, and warping. The older, "Paleogene" subsequence is more uniform in regional distribution, and has a greater volume than the younger, "Neogene" sequence. Each sequence has a maximum thickness of more than 2 km, but the "Neogene" beds are present in significant thickness only in a triangular subbasin south of Point Hope.

Economically significant thicknesses of Hope basin sediment, about 1 km or more, occupy most of a region about 80 x 90 km in extent in the southwest corner of the sale area. This region, which lies off the coast between Cape Lisburne and Point Hope, is bounded on the east and northeast by a large normal fault zone. The Hope basin section is as much as 3 sec (about 4.4 km) thick in the sale area off Point Hope and thickens southward to a maximum thickness of 3.5 sec (about 5.6 km) south of Point Hope. The area of relatively thick Hope basin section in the sale area consists mainly of the "Paleogene" subsequence. The "Neogene" subsequence in the sale area is a sedimentary wedge that is generally less than 0.5 km, and in a small area a little more than 1 km thick, that onlaps Herald arch to the north.

North Chukchi basin: A tectonic hinge line at which the dip of Ellesmerian and Brookian beds, and the thickness of the lower Brookian sequence increase to the north and west marks the south and east boundaries of North Chukchi basin (Figs. 4, 10, 12, and 14). The position of the hinge line is imperfectly defined by three multichannel profiles (Fig. 1). The profiles demonstrate that the northwest corner of the sale area is underlain by the North Chukchi basin but they do not adequately relate the hinge line to the lower Brookian isochrons.

The base of the Brookian sequence deepens, and the sequence thickens, from 2 to 3.5 sec (about 2.5 to 5.5 km) on the Arctic platform near the hinge line to more than 6 sec (12 km) on our northernmost multichannel lines in the basin in the sale area. Most of the increase in thickness is in the lower Brookian sequence but some of it, especially in the east end of the basin, is in upper Brookian rocks. The former attains a thickness of at least 7 km, and the latter of at least 5 km in the basin. On one line near the eastern margin of the basin about 4 km of Ellesmerian rocks are seen to underlie the lower Brookian beds.

Contrasting structural deformation in the tentatively identified lower and upper Brookian sequences of North Chukchi basin suggests the mode of origin and general age of the basin. The lower Brookian rocks are broken by numerous listric normal faults which are commonly antithetic and bound rotated fault blocks. Although the seismic records are not unequivocal on the point, the faults appear to extend into pre-Brookian rocks at moderate angles of dip. The faulting and rotation produced a structurally and paleomorphologically complex seabed surface that was smoothed soon after deformation by sedimentary infilling of the structurally produced low spots and erosion of the high spots. The smoothed seabed was then covered by the only slightly faulted basin fill sequence contoured in Figure 14. Both the infilling sedimentary rocks and the subsequent basin fill are thought to belong to the upper Brookian sequence.

Crustal stretching related to the initial stages of sea floor spreading according to the model of Montadert and others (1979), as observed in the Bay of Biscayne, is thought to have induced the pervasive listric normal faulting and fault block rotation that characterize the lower Brookian sequence in North Chukchi basin. Stretching, expressed in the upper crust as listric normal faulting and block-fault rotation, resulted in crustal thinning, subsidence of the sea floor over the thinned crust, and formation of the basin. Initiation of basin subsidence coincided with the development of the listric faults in post-lower Brookian, pre-upper Brookian time. Faulting was in part older than, and in part coeval with deposition of the lenticular sedimentary sequence that smoothed the block-faulted sea floor. If our correlation of the youngest sedimentary sequences of North Chukchi basin as lower and upper Brookian is correct, the basin originated in latest Cretaceous or earliest Tertiary time.

Several diapirs observed on single channel seismic-reflection profiles intrude the sedimentary rocks within or adjacent to North Chukchi basin. Two of the diapirs were actually traversed, and three others are inferred from localized uplifts in otherwise flat-lying upper Brookian beds (Grantz and others, 1975 and 1981). The diapirs are piercement structures that rise to within 100 m of the sea bed. The best-studied is about 2 km in diameter and extends at least 3 km beneath the sea bed. Low sonobuoy velocities, apparent lack of strong gravity or magnetic anomalies, and regional stratigraphy suggest that the diapirs are probably shale rather than salt, gypsum or igneous rock. On the basis of single channel data the diapirs are tentatively interpreted to originate in the lower Brookian or possibly the upper Ellesmerian sequence.

PETROLEUM POTENTIAL

Assessment of the petroleum potential of an extensive frontier area such as that of sale 85 on the basis of a reconnaissance seismic-reflection network and a few dredge samples, but no subsurface information, must necessarily be generalized, speculative and incomplete. Nevertheless the seismic data, augmented by the extrapolation of the results of geologic and petroleum exploration in NPRA and the North Slope, permit a preliminary evaluation of the petroleum potential and relative prospectivity of various parts of the sale area. The assessment is relatively more objective in the eastern part of the sale area, which lies near the western part of the partially explored NPRA, than elsewhere. The potential of areas like Hanna trough and North Chukchi basin, which have no close analogs onshore, is highly speculative. A synopsis of general lithologic conditions relevant to the petroleum potential of the western North Slope, taken mainly from K. J. Bird (oral communication, 1982), C. E. Kirschner (unpublished data, 1982), Bird (1981), Carter and others (1977), Guldenzopf and others (1980), and Bird and Andrews (1979) is presented in a following section as a necessary first step in evaluating the potential of the sale area.

A preliminary petroleum prospectivity map of the sale area is presented in Figure 16. For convenience in discussion, the structural provinces of the sale area are also shown. Most of the area is considered prospective because it can be inferred from seismic data to be underlain by a significant thickness of Ellesmerian and Brookian sedimentary rocks. Part of the area is probably underlain by a significant thickness of these rocks, but the seismic data are inadequate to demonstrate this. A small area at the western boundary of the sale area, incompletely outlined by our reconnaissance seismic network, is not prospective because the sedimentary section there is too thin. The minimum thickness of sedimentary rock that is prospective is estimated to be no less than 1 km. This thickness was chosen because it was judged that, barring a truly exceptional discovery, oil and gas pools at shallower depths would require too many costly production platforms for their development to be economically viable. Prospectivity in Figure 16 is based on sedimentary thickness alone because our data are inadequate to make meaningful judgments on the quality of source and reservoir rocks, reservoir seals, and stratigraphic traps in the sale area, let alone thermal history and timing and pathways of hydrocarbon migration.

Western North Slope

Strata: The general subsurface stratigraphy and structure and the location and stratigraphic position of oil and gas pools and shows in test wells and seeps in NPRA west of Dease Inlet (Fig. 3) are shown in Figures 1, 6 and 15. The mid- and Upper Permian Echooka Formation (basal Sadlerochit) and all formations from the Shublik (Middle Triassic) to the Nanushuk (Albian and Cenomanian(?)) have yielded shows of oil or gas in test wells. However, neither the Lisburne Group (Pennsylvanian and Permian in the western North Slope) nor the Lower Triassic Ivishak Formation (lower Sadlerochit), penetrated in fewer wells than younger rocks, have encountered oil or gas to date in wells west of Dease Inlet. These stratigraphic units do, however, contain oil or gas shows in test wells east of Dease Inlet and they contain the major oil and gas accumulations at Prudhoe Bay. The hydrocarbon occurrences west of Dease Inlet include structurally trapped, subeconomic gas pools in Lower Jurassic sandstones in the South Barrow and East Barrow fields, which lie 15 to 20 km south of Point Barrow, and it is believed that additional small accumulations of similar type are likely to occur in the vicinity (Lantz, 1981). Sands of similar age may also form small pools in combination stratigraphic-structural traps at the Iko Bay-1 and Walakpa-1 wells, 30 to 35 km southeast and southwest of Point Barrow, but these occurrences have not been adequately evaluated (Bird, 1981; C. E. Kirschner, unpublished data, 1982). Pre-Lisburne (Endicott Group) and post-Nanushuk (Colville Group and Sagavanirktok Formation) sedimentary strata have not been encountered in test wells west of Dease Inlet even though many of the wells were drilled to basement.

In general, reservoir quality is better in the Ellesmerian shelf and shelf basin deposits than in the Brookian sequence. The Ellesmerian sandstones become thicker, coarser in grain size and cleaner to the north, toward their sourceland, and most of them shale out southward in an east-trending zone across central NPRA. Reservoir quality in the Brookian rocks is harder to characterize. The Brookian sequence consists of thick deltaic deposits that filled a foredeep and they were deposited much more rapidly than the Ellesmerian rocks. The best reservoirs may be expected in the paralic and shallow marine facies of the intradelta, and in submarine fan turbidites at the base of prodelta slopes.

Geochemical studies at the Prudhoe Bay field (Seifert and others, 1979) indicate that the oil there was derived from the Shublik Formation, Kingak Shale and Pebble shale unit, which correlates well with the occurrence of oil and gas shows in western NPRA (Fig. 15). The lack of oil and gas shows in the Lisburne rocks of western NPRA may be because permeability pathways have not connected them with petroleum source beds, or because they consist of the non-dolomitic light-colored Wahoo Limestone rather than the vuggy, dolomitic, dark-colored and shaly Alapah Limestone that contains the major Lisburne reservoirs at Prudhoe Bay. It is not certain, however, that the prospects drilled in western NPRA were traps at the Lisburne level. Thermal alteration studies on the Inigok-1 well, in eastern NPRA, indicate that the Endicott and Lisburne Group rocks are apt to be post-mature and gas prone below 3,600 m on the Arctic platform (Magoon and Claypool, 1982). These rocks lie at similar or greater depths in western NPRA where the thermal maturity of the surface formations, as estimated from vitrinite reflectance studies (L. B. Magoon and G. E. Claypool, unpublished data, 1982), tends to be even higher than at Inigok-1.

The Lower Triassic Ivishak Sandstone of the Sadlerochit Group, the main reservoir at Prudhoe Bay, is represented by lutite in NPRA west of about 157° W. long (Guldenzopf and others, 1980). The only significant sandstone in the Sadlerochit Group of western NPRA occurs as a 30-km-wide band in the Upper

Permian Ikiakpaurak Member of the Echooka Formation (Guldenzopf and others, 1980). This sandstone produced minor gas shows in the Peard-1 well. It is about 50 to 60 m thick in the Peard-1 and Kugrua-1 wells and extends from a pinchout about 10 km north of Wainwright to a shaleout several kilometers south of the Tunalik-1 well. It is separated from the source rocks of the Shublik Formation by the Kavik Shale and the lutite facies that constitutes the Ivishak Sandstone in western NPRA. Therefore the gas shows may have originated in the adjacent shales of the Sadlerochit Group.

The Middle and Upper Triassic Shublik Formation and Sag River Sandstone, which are reservoirs for oil and gas at Prudhoe Bay, are possibly more prospective than the Sadlerochit in western NPRA and the eastern Chukchi shelf. These units produce oil and gas shows in test wells west of Dease Inlet and they contain sandstones that are in contact with the Shublik Formation and Kingak Shale, which contain petroleum source rocks. Sandstone in the Shublik occurs in a west-southwest-striking belt 40 or more km wide that onlaps Barrow arch on the north and shales out a few kilometers north of the Kugrua-1 and Tunalik-1 wells. Sand-shale ratios in the Shublik are highest in western NPRA, and reach values of 5.0 and 5.1 in the Walakpa-1 and Peard-1 wells, where the formation is about 90 m thick. The overlying Sag River Sandstone, mainly a lutite in western NPRA, is 30 to 40 m thick and contains sandy bar-like complexes of unknown extent at the Peard-1 and Kugrua-1 wells (Guldenzopf and others, 1980). Good prospects may also be found in the Kingak Shale, a westerly thickening Jurassic and Neocomian lutite that ranges in thickness from 500 m to more than 1,000 m in western NPRA. The Kingak, a source rock at Prudhoe Bay, contains several sandstone units west of Dease Inlet, and some of these contain subeconomic or incompletely evaluated gas pools at the South Barrow and East Barrow fields and the Walakpa-1 and Tunalik-1 test wells. The sandstones may include transgressive nearshore and offshore bar-like deposits and deep water turbidites (Guldenzopf and others, 1980), appear to have been derived from northerly and northwesterly sources, and in general become more abundant to the west, toward the area of sale 85. In western NPRA the Kingak is truncated by the unconformity at the base of the upper Neocomian Pebble shale unit, which may serve as both a source rock and reservoir seal for hydrocarbon deposits in Kingak sandstones in contact with the unconformity. In addition to serving as a possible source rock and seal, several thin sand bodies in the Pebble shale unit may also have reservoir potential. One such sand body in the Peard-1 well, where the Pebble shale unit is 116 m thick, is inferred to extend into the sale area north of Icy Cape (Guldenzopf and others, 1980).

The Brookian rocks encountered in test wells in western NPRA were derived from source lands that lay to the south and southwest. They fill the Colville foredeep and consist of the interfingering Fortress Mountain and Torok Formations and the partly interfingering, partly overlying Nanushuk Group of Albian and Cenomanian age. The intradeltaic Nanushuk and the prodeltaic Torok both have shows of oil and gas in western NPRA. The shows in the Torok west of Dease Inlet are from foreset and bottomset turbidite and submarine fan deposits (C. E. Kirschner, unpublished data, 1982). The Nanushuk Group contains several small oil and gas fields in eastern NPRA. Gas and oil shows are common in the Nanushuk, and it contains a small gas field (Meade) west of Dease Inlet. South of Point Lay the Nanushuk is dominantly nonmarine and contains thick coal beds, and it thins and becomes increasingly paralic and shallow marine to the northeast. The paralic and shallow marine conditions should improve reservoir quality in that direction. Accordingly, the Nanushuk is expected to be gas-prone and contain less capable reservoirs to the southwest, and to be more likely to contain oil and have more capable reservoirs to the north or northeast. An oil seep from Nanushuk rocks at Skull Cliff, about 50 km southwest of Barrow (McKinnery and others, 1959), supports this contention. The Chevron Oil Company's Akulik-1 test well, located 8 km inland between western NPRA and the Chukchi Sea 110 km east of Cape Lisburne, tested the Nanushuk intradelta facies and perhaps the Torok-Fortress Mountain Formations near the sale area. Projections from offshore (Fig. 12) and NPRA (Bird and Andrews, 1979) suggest that at total depth (5,190 m) the well was still in these lower Brookian (Albian) rocks. The results of this test and of another Chevron well (Eagle Creek-1, T.D. 3,650 m) 50 km to the southeast have not been announced, but both wells were plugged and abandoned. The Union Oil Company Tungak Creek-1 well, which tested the same rocks 35 km northeast of Point Lay, was suspended in March, 1982, at a depth of 2,503 m.

<u>Thermal maturation</u>: Vitrinite reflectance data and the rank of coal in test wells and outcrops provide some insight into the thermal history and possible stage of hydrocarbon generation and preservation in the sedimentary rocks of western NPRA, but they do not reveal whether the affected rocks actually

generated oil or gas. Some of the vitrinite reflectance data are reported by Magoon and Claypool (1979 and 1982), and we are grateful for the use of additional unpublished data by these workers. Data on coal rank was taken from Barnes (1967) and Conwell and Triplehorn (1976). Relation of coal rank to stages of hydrocarbon generation is from Héroux and others (1979), but we follow Magoon and Claypool (1982) in using vitrinite reflectance values of 0.6 and 2.0 for the top and base of the liquid window--the zone of oil and gas condensate generation.

Vitrinite reflectance data indicate that equivalent stages of thermal maturation become shallower from eastern and central to western NPRA, suggesting more uplift on the west (Magoon and Claypool, 1979). The data also suggest that the top of the liquid window (the highest rocks that have experienced a thermal history capable of generating oil) lie about 0.3 to 1.0 km below the surface in western NPRA between the latitude of Point Lay and the Peard-1 well (Fig. 1). The rank of outcropping Albian coal beds in this area is subbituminous, which corresponds to the zone of wet gas generation above the liquid window. North of Peard-1, the deepest prospective strata on basement are at the top of, or above the liquid window, in the overlying zone of wet gas generation. The base of the liquid window between the latitudes of Point Lay and Peard-1 in western NPRA, as interpreted from vitrinite reflectance measurements, lies 2.3 to 3.4 km below the surface in the three wells that reached the underlying zone of overmature rocks. One test well and the rank of outcropping Albian coals suggests that surface rocks beneath the foothills of the Brooks Range south of the latitude of Point Lay are in the liquid window, and that the base of the liquid window lies about 2.0 km below the surface. The rank of Endicott Group coal beds on the Lisburne Peninsula suggests that the Paleozoic rocks of the western Brooks Range and the upper allochthon of Herald arch are overmature for oil and gas condensate, and that former hydrocarbon liquids in these beds would now be dry gas. The vitrinite reflectance values also suggest that in the eastern half of the sale area upper Paleozoic and Triassic strata are overmature from Icy Cape or Wainwright south, and that lower Brookian and older strata are overmature from the general latitude of Point Lay south.

Area of Sale 85

Arctic platform east of Hanna trough: The petroleum potential of the Arctic platform structural province (area 1 in Table 1 and Fig. 16) is much like that of western NPRA, which it adjoins. Offshore seismic data and projection of onshore stratigraphy and thermal maturation data suggest that in area 1 sandstones from the Permian and Triassic Sadlerochit Group to the lower part of the Albian Nanushuk Group may be in contact with adequate source rocks and could contain significant pools of oil and, especially, gas. To date, only some subeconomic or inadequately evaluated gas deposits have been found in the adjacent onshore. Subsurface data (Guldenzopf and others, 1980; and C. E. Kirschner, unpublished data, 1982) suggest, however, that sandstone beds in the Middle Triassic to Lower Cretaceous Shublik, Sag River, Kingak and Pebble shale units, which locally attain significant thickness in western NPRA, may be thicker, more numerous and perhaps better reservoirs in area 1. If structural traps exist in this area, they are very low amplitude and have not been recognized on our reconnaissance seismic network. Stratigraphic traps caused by permeability gradients or shale oversteps at one of several unconformities in the section possibly occur. If present, such traps could be very large because of the uniform but low regional dip. Eo-Ellesmerian and Lisburne strata, if present in area 1, are probably overmature and at best would contain dry gas.

Hanna trough: Economically significant oil and gas deposits could be present in Hanna trough (area 2 in Table 1 and Fig. 16) because the trough contains a very thick section of sedimentary rocks with possible oil traps in some large basement-involved folds and locally numerous faults and rotated fault blocks. In addition to the area shown in Figure 16, the trough may extend into the northeastern corner of the sale area, north of 72° N. lat, but we have no multichannel seismic data there, and our discussion is confined to the area south of 72° N.

If the thermal history of the sedimentary rocks in Hanna trough is similar to that found in Tunalik-1 well, the Eo-Ellesmerian and most of the Ellesmerian section is overmature and could only contain dry gas. Ellesmerian and Brookian strata thicken into Hanna trough (Figs. 9-12), but the nature of any accompanying facies changes is conjectural. The marked thickening of Ellesmerian beds into the trough (Fig. 11) suggests that it may there be a basinal facies, perhaps dominated by lutite and possibly containing turbidite beds. Although these thickened deposits are probably themselves now overmature they could have generated oil or gas at an earlier time that migrated out of the trough into possible reservoirs on the flanks, where subsequent thermal alteration was less intense.

The presence of westward-increasing amounts of sandstone of north and northwest provenance in the Shublik-Pebble shale interval in western NPRA suggests that the broad crestal region of the Barrow arch east of Hanna trough was a sourceland for detrital sediment through late Ellesmerian time. This sourceland might also have furnished reservoir sands to the upper Ellesmerian section of Hanna trough. Most of the upper Ellesmerian rocks are probably in the liquid window in most parts of Hanna trough.

The thickening of the lower and upper Brookian sequences into Hanna trough (Figs. 12 and 14) may have also created conditions favorable for the generation and entrapment of oil and gas. Free-wheeling extrapolation of thermal conditions and facies patterns from western NPRA suggests that part to all of the lower Brookian sequence in Hanna trough is in the liquid window and that in places the section probably contains paralic and shallow marine beds that could include winnowed sands. In addition, the deeper parts of the fill in the upper Brookian canyon (Fig. 14) might also be in the upper part of the liquid window, but we have no thermal data from which to judge whether this is indeed the case. The upper Brookian canyon fill and the adjacent wall rocks could contain hydrocarbon traps where reservoir sands or sealing shale beds of the fill are in contact with source beds or sands of the lower Brookian sequence in the canyon walls. An analogous feature appears to have localized the subeconomic Simpson oil field (Bird, 1981), 85 km east of Barrow, where oil in the Nanushuk Group is trapped at an up-dip seal formed by Upper Cretaceous sedimentary rocks in Simpson canyon (C. E. Kirschner, unpublished data, 1982). Faults and rotated fault blocks, which are locally numerous in the canyon fill, may have created structural traps in both the lower and upper Brookian beds.

Arctic platform west of Hanna trough: The westward thinning and shallowing of Ellesmerian and Brookian strata in area 3, the Arctic platform west of Hanna trough (Table 1 and Fig. 16) suggest that a structural high or former sediment sourceland lay to the west. If it did, these rocks could contain good reservoir beds analogous to the north-sourced sandstone and conglomerate beds that are productive at Prudhoe Bay and elsewhere on the North Slope. Hydrocarbon fluids could have entered these beds from interlayered source beds or migrated into them from shales that might lie downdip, in Hanna trough. It is probable that much of the Ellesmerian and lower Brookian section in the eastern part of area 3 is in the liquid window, but extrapolating thermal conditions this far offshore from the North Slope is probably speculative at best. If source and reservoir beds are present in area 3, the presence of numerous normal faults, some folds and possibly up-dip pinchouts may provide traps, but our seismic lines are too widely spaced to demonstrate whether closed structures are present. The eastern and central parts of area 3 are much more prospective than the western part, where the total post-Franklinian sedimentary section thins to less than 1 km.

Foreland fold belt: Extrapolation of thermal maturation data from the western North Slope indicates that the top of the liquid window in the foreland fold belt (area 4 in Table 1 and Fig. 16) is at the surface, or has been removed by erosion, from approximately the latitude of Point Lay south. North of Point Lay, the top of the window deepens to about 1 km opposite the northern part of area 4. Data from the Tunalik-1 and Awuna-1 wells in NPRA (L. B. Magoon and G. E. Claypool, personal communication, 1982) indicate that the vertical height of the liquid window at the latitude of area 4 is about 2.0 to 2.5 km. These data suggest that most of the Ellesmerian sequence and the lower part of the lower Brookian sequence in the broad structural low off Point Lay are overmature and could now contain only dry gas. All or most of the lower Brookian sequence, on the other hand, is within the liquid window and could have generated and preserved oil and gas condensate.

Broad folds and fault blocks in the Ellesmerian strata below the detachment fault that underlies area 4 offer possible structural traps for gas, but the extrapolation of stratigraphic trends from western NPRA suggest that adequate reservoirs may be absent. The numerous large detachment folds and thrust folds in the lower Brookian rocks that constitute the upper plate, above the detachment fault, are probably the most prospective structures in area 4. Thrust faults, however, disrupt the cores of many of the folds in the central and southern parts of area 4 and may reduce their capacity to hold hydrocarbon fluids. The folds may also be largely within the Nanushuk intradelta and have relatively poorer prospects for oil and for winnowed sandstones of paralic and neritic facies than eastern and north central NPRA, where the Nanushuk contains several small oil and gas fields.

Herald arch overthrust: Brookian rocks in the Herald arch overthrust belt (area 5 in Table 1 and Fig. 16) are probably too strongly deformed by listric thrusts and thrust folds, related to the underlying detachment fault zone, to have significant petroleum potential. Extrapolation of onshore data indicates that the underlying and overlying Ellesmerian rocks are overmature for hydrocarbon liquids in the southeastern part of area 5, and the overlying Ellesmerian rocks are probably too strongly thrust-faulted to be prospective. If Ellesmerian rocks are present beneath the detachment fault zone in the northwest part of area 5, where the Brookian sequence is thinner, they may have escaped deep burial and overmaturation and be comparable in potential to the Ellesmerian rocks of area 3, the Arctic platform west of Hanna trough.

Hope basin: Thermal maturation in Hope basin (area 6 in Table 1 and Fig. 16) is not known, but an estimate for the geologically analogous Norton basin by Fisher (1982) suggests that the liquid window in Hope Basin may lie between about 2.5 or 3.0 km and 5.0 km below the seabed. As Hope basin is as deep as 4.4 km in the sale area near Point Hope, and locally as deep as 5.6 km farther south, the lower third of the basin fill may be within the liquid window. Adequate structural traps and reservoir sands may well be present in Hope basin, but the quality of source rocks is problematical. Meager marginal outcrops and two test wells at the head of Kotzebue Sound suggest that nonmarine rocks are prominent, possibly dominant, in the basin. Marine facies can be inferred for the center of the basin, but their presence has yet to be demonstrated. In light of the youthfulness of the basin (much of the fill is interpreted to be Neogene), and the nonmarine character of the marginal outcrops, Hope basin may be gas prone. However, the possibility that oil was also generated cannot be ruled out.

North Chukchi basin: It is inferred that both the lower and upper Brookian sequences of the North Chukchi basin (area 7 in Table 1 and Fig. 16) contain a substantial or dominant component of marine sedimentary rock, and therefore source beds for oil and gas are likely to be present. Strong reflectors in both sequences suggest further that many sandstone and perhaps conglomerate beds that could serve as reservoirs may also be present. This interpretation is supported by the observed westward thinning of Brookian sedimentary units on the Arctic platform west of Hanna trough. A sourceland in that direction would have been much closer to the basin than the Brooks Range sourceland for Brookian clastics on the North Slope, and could have resulted in the delivery of coarser and more abundant detritus to the basin. The numerous listric normal faults and rotated fault blocks that characterize the lower Brookian sequence in the North Chukchi basin may form large structural traps. Their prospectivity is greatly enhanced by the locally thick, early post-faulting infilling sedimentary unit that unconformably overlies it. The infilling unit has weaker seismic reflectors than the sequences that lie above and below, and probably contains more shale. The unit could have served as a seal for hydrocarbon fluids in the underlying faulted rocks, and also as a hydrocarbon source rock. Where the infilling unit is absent, the base of the upper Brookian sequence unconformably overlies the faulted beds and may have placed sealing beds and possible reservoir beds across truncated sandstones and shales of the lower sequence. The upper Brookian rocks offer possible traps against small normal faults, in a few very low amplitude folds (closure not demonstrated), against possible up-dip permeability barriers or pinch-outs, and around shale(?) diapirs.

Assessment of the petroleum potential of North Chukch basin is particularly sensitive to its thermal history and the hydrocarbon maturation stage of its sedimentary rocks. In the absence of actual data, we have estimated the position of the liquid window according to two quite different models that may be appropriate for the extensional, and therefore probably high heat-flow, North Chukchi basin. If the basin developed by crustal thinning over a new spreading center, as postulated in a preceding section, the method of Royden and others (1980) for very high heat-flow rifted margins can be applied. This method suggests that the liquid window in the basin might lie about 1.7 to 3.5 km subsea. If the estimates derived by Fisher (1982) for the assumed moderately high heat-flow extensional, epicontinental Norton basin are used, the liquid window might lie about 2.8 to 5.0 km subsea. Both models suggest that the liquid window intersects the structurally important boundary between the extensively faulted lower Brookian and the little-faulted upper Brookian sequences. If the Norton basin model or one that assumes a less intense thermal history is realistic, then a substantial part of the faulted lower Brookian section and perhaps the deepest part of the little-faulted upper Brookian section are in the liquid window. If the rift model is appropriate, most of the lower Brookian sequence and the deepest parts of the upper Brookian section are overmature, and the liquid window encompasses the lower part of the upper sequence and the structurally highest parts of the lower sequence. The Norton basin or "cooler" models would thus place substantially more of the very prospective block-faulted lower Brookian sequence in the liquid window than the rift model. However, even the rift model places a large volume of lower Brookian rocks at the margins of the basin in the liquid window and the overmature rocks could contain substantial deposits of dry gas. In addition, some faults cut both the lower and upper Brookian sequences and these might have provided pathways for the migration of hydrocarbon fluids out of the lower sequence into higher reservoirs before the lower sequence became overmature.

Relative prospectivity of the structural provinces: Ranking the relative petroleum potential of the seven structural provinces of the sale area is in part an assessment of a reconnaissance data set, and in part a prediction of what more complete data sets will reveal. Subsurface information in areas 2, 3, and 7 are especially needed. From the perspective of a preliminary evaluation of our reconnaissance data, and ignoring the extremely difficult logistic and engineering problems posed by the Arctic climate and polar ice pack, the Arctic platform east of Hanna trough (area 1), Hanna trough (area 2), the Arctic platform west of Hanna trough (area 3), and the North Chukchi basin (area 7) are tentatively estimated to have a potential for significant deposits of oil or gas. Drilling targets, however, will be hard to define in large parts of these areas. Exploration in western NPRA suggests that in at least the eastern part of area 1 the potential may be greater for gas than for oil. The Foreland fold belt (area 4) and the northern tip of Hope basin (area 6) are estimated to have modest potential for significant deposits of oil and gas, and they may be gas-prone. Structural complexity and estimated thermal conditions suggest that most of the Herald arch overthrust belt (area 5) has a low potential for significant deposits of oil or gas. The northwest part of area 5 may have some potential in Ellesmerian rocks beneath the overthrust faults, but our data are inadequate for assessment.

RESOURCE ASSESSMENT

The planning area for proposed sale 85 includes portions of four different geologic provinces used by the Geological Survey in their unpublished oil and gas estimates for the Alaska Outer Continental Shelf. Most of the Central Chukchi Province is included, as well as half of the North Chukchi Province and small portions of the Beaufort Shelf and Hope Provinces. However, much of the included North Chukchi and Beaufort Shelf areas have water depths greater than 200 ft (61 m). Based on information published by the National Petroleum Council (1981), resources are not considered recoverable with present technology in seas with Arctic pack ice where water depths are greater than 200 ft. The included portion of the Hope Province is small and has a predominantly thin sedimentary section, and the estimated oil and gas resources are negligible.

After consideration of the boundary problems, it is estimated that the economically recoverable resources in the planning area are approximately the same as the unpublished Geological Survey estimates for the Central Chukchi Province, shown in Table 2. Federal lands beyond the three-mile limit are estimated to contain 95 percent of the total oil and gas resources in the Central Chukchi. These estimates of economically recoverable resources do not include any resources in water depths greater than 200 ft. Even in shallow water depths, the estimates of economically recoverable resources have a high level of uncertainty because the technology and costs of producing oil and gas in areas of Arctic pack ice are speculative.

Estimates in Table 2 are probability estimates of "more than" quantities associated with given probabilities of occurrence. Both conditional and unconditional estimates are given. The conditional estimates are of those quantities that may be present, assuming that commercial quantities do exist. The unconditional estimates are of those quantities that may be present when the chance of finding commercial hydrocarbons is included. There may be considerable risk in finding commercial hydrocarbons in frontier areas such as the Central Chukchi and a marginal probability is assigned to express this risk.

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.

Table 2.--Estimates of total undiscovered oil and gas, Central Chukchi Province[1,2]

	95th Fractile[3]	5th Fractile[4]	Mean	Marginal Probability
Oil (Billions of barrels)				
Conditional	0.74	9.43	3.52	0.39
Unconditional	0	6.30	1.37	--
Associated Dissolved Gas (TCF)[5]				
Conditional	1.11	14.14	5.28	0.39
Unconditional	0	9.45	2.06	--
Non-Associated Gas (TCF)[5]				
Conditional	2.06	22.43	8.61	0.37
Unconditional	0	14.74	3.18	--
Aggregated Gas (TCF)[5]				
Conditional	1.41	22.73	8.45	0.62
Unconditional	0	19.37	5.24	--

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

[2]Federal lands beyond the three-mile limit are estimated to contain 95 percent of these resources.

[3]It is estimated that there is a 95 percent probability that more than the stated amounts of oil and gas are present.

[4]It is estimated that there is a 5 percent probability that more than the stated amounts of oil and gas are present.

[5]TCF, trillion cubic feet.

ENVIRONMENTAL CONSTRAINTS TO PETROLEUM DEVELOPMENT

First-order environmental constraints to the engineering of structures on the Chukchi continental shelf are those posed by mobile sea ice and its interactions with the seabed and the coastline. Although the activity and effects of sea ice on the Beaufort shelf to the northeast are more intense and pervasive in a general way than on the Chukchi shelf, it may well be that sea ice will present equally difficult engineering hazards in the Chukchi Sea. This is owing to the fact that much of the area prospective for petroleum in the Chukchi Sea lies far from shore in areas where the movement of polar pack ice is erratic and not routinely predictable. Moreover, pipelines to shore from these remote sites would traverse terrains influenced by strong currents, extensive scoring of the seafloor by deep ice-ridge keels, and in places rapid coastal modification.

Second-order, but still important environmental constraints to engineering include shallow free-gas deposits, unconsolidated sediment, strong currents and storm waves, longshore sediment transport and migration of sand waves, river flooding, storm surges along the coastline, and instability of coastal bluffs. Earthquakes and young, shallow faults are uncommon within the lease sale area, and should pose no particular problems. Little is presently known of the distribution of subsea permafrost in the Chukchi Sea, or of potential slope instability near the shelf break. Based partly on theoretical grounds and partly on experience gained in the Beaufort Sea, these phenomena are tentatively judged to pose a limited and local hazard to engineering structures in the Chukchi Sea.

Coastal physiography

The Alaskan mainland between Cape Lisburne and Point Barrow slopes generally northward. The southern part of the mainland is hilly, whereas the northern part is a gently sloping coastal plain. The edge of the mainland, which faces the open sea in some places, and lagoons, bays or barrier spits elsewhere, is commonly marked by cliffs or bluffs that tend to gradually decrease in height northward (Hartwell, 1973). Barrier islands and spits are extensive along the Chukchi Sea coast from Point Barrow to the Point Lay area and form major capes at Point Barrow, Point Franklin, and Icy Cape. Nearshore, in depths less than 25 m, shore-parallel shoals are developed off the capes, and actively migrating longshore bars form adjacent to the beaches.

Surficial distribution of bedrock

Paleozoic and Triassic rocks which form the sea cliffs from Cape Lisburne south along the Lisburne Peninsula are believed to extend offshore and lie at or within a few meters of the seabed along a roughly northwest-trending structural high known as Herald arch (Fig. 4). Northeast of Herald arch to approximately the latitude of Wainwright, folded Cretaceous intradelta deposits lie at or near the seafloor and crop out in the lower parts of the coastal seacliffs. Consolidated bedrock also lies near the seabed between Wainwright and Barrow. Unconsolidated Quaternary sediment thicker than 5 to 10 m probably occurs only in North Chukchi and Hope basins (Fig. 4) and as channel fill in paleovalleys that were cut into the shelf during Pleistocene sea level lowstands.

Sea ice zonation

In favorable years, the southern margin of the Arctic polar ice pack in the Chukchi Sea retreats to an average position between latitudes 72° and 73° N. during the latter part of August and September (Fig. 2). Even in less favorable seasons the shelf is mostly ice-free as far north as latitudes 70° to 71° N during these months, and a coastal lead allowing sea passage around Point Barrow into the Beaufort Sea is usually open during late summer. By November the pack ice has generally drifted south and west to about the latitude of Icy Cape, and by mid-January pack ice has effectively covered the entire Chukchi shelf, although leads exist intermittently throughout the winter (Toimil, 1978). The pack ice consists mainly of first and multiyear floes averaging 2 to 4 m thick, but also incorporates deep-keeled pressure ridges and ice island fragments (Grantz and others, 1982). Ahlnas and Wendler (1980) and Shapiro and Burns (1975) report episodic movement toward and through Bering Strait during the winter and early spring. Movement shifts to the north and west later in the season (Shapiro and Barry, 1978). Breakup begins in May, typically with the development of a shore lead, coincident with the Alaska Coastal Current by early June. Northward retreat continues throughout the summer.

Ice gouges

Although the interaction of sea ice with the seabed of the continental shelf has been extensively studied in the Beaufort Sea, relatively little work has yet been completed in the Chukchi Sea. The only comprehensive report to date is by Toimil (1978), which is based on analysis of 1,800 km of fathometer and side-scan sonar records collected by the U.S. Geological Survey in 1974. The summary and map presented here (Fig. 17) modify and extend Toimil's work on the basis of preliminary interpretations of an extensive network of high-resolution seismic reflection (Uniboom) records collected by the U.S. Geological Survey in 1977, 1978, and 1980 (Fig. 1).

Toimil (1978, and unpublished data, 1982) concluded that the density of ice gouges in the eastern Chukchi Sea increases in a rough way with increasing latitude, increasing slope gradients, and decreasing water depth. Unlike the Beaufort shelf, however, where sea ice annually scores the seabed to varying degrees in shore-parallel zones restricted to quite predictable ranges of water depths (e.g., Reimnitz and others, 1978), the floor of the eastern Chukchi Sea is quite patchily scored. Dense concentrations of deep gouges occur, in places, directly adjacent to regions of sparse, shallow gouges at similar water depths (Fig. 17). Except near shore from about Point Lay to Point Barrow, where gouge azimuths trend rather consistently northeast, subparallel to the coastline and to the Alaska Coastal Current, gouge orientations are widely spread and many older gouges are crossed at high oblique angles by newer ones (Fig. 18). Despite the local and regional patchiness of concentration and incision depth, however, several useful generalizations may be made concerning the intensity of ice scoring in the eastern Chukchi Sea.

Rex (1955) recognized ice gouges with 1 to 3 m relief on the shelf near Point Barrow. He noted that the relief was best developed in a zone between the 6- and 30-m isobaths nearly coinciding with the areal occurrence of modern sea ice pressure ridges. Toimil (unpublished data, 1982) reports gouge densities in excess of 50/km in water depths of 20 to 35 m almost ubiquitously along the coast from near Point Hope to Point Barrow. Inshore of the 20-m isobath, the inner shelf is normally covered by floating shorefast ice which thickens to about 1.3 to 2.0 m before breakup in the spring (Toimil, 1978). North of Point Lay sparse gouges that were subparallel to the coast were noted between the 35- and 45-m isobaths. Possibly gouges in this zone, as well as inshore, are annually reworked and partially erased by the Alaska Coastal Current.

Nearly all of the mobile sea ice transient through the Chukchi Sea during winter months enters from the northeast via the Beaufort Sea. According to Toimil (unpublished data, 1982):

> "Prevailing winter winds from the northeast cause an overall southward drift of the polar ice pack, against generally north-flowing currents, from its summer position northwest of Point Barrow."

As a result, as recognized by Toimil, highest gouge densities occur on the northeast flanks of topographic highs, notably Hanna and Herald Shoals (Figs. 3 and 17). It is not surprising, given the source of the ice, that depth limits of ice scoring in the northeast Chukchi Sea are similar to those in the Beaufort Sea. Shallow, sparse, apparently modern ice gouges have been routinely noted in water as deep as 62.5 m near the Beaufort shelf break north of Alaska (Grantz and others, 1982). Similarly, shallow solitary gouges in water as deep as 64.5 m occur in the northeast Chukchi Sea east of Hanna Shoal. Pressure ice-ridges with drafts this deep probably form primarily offshore of the stamukhi zone (zone of grounded ice ridges) in the Beaufort Sea, but may also form in situ east of Hanna Shoal, where westward-drifting polar pack ice piles up against an icefield that typically grounds annually on Hanna Shoal (Toimil and Grantz, 1976). Large and thick tabular ice bergs that are episodically calfed from the Ward Hunt ice field of northern Ellesmere Island also ground and gouge the sea bed on the northern Chukchi shelf.

Hanna Shoal, which rises to within 25 m of present sea level some 130 km NNW of Point Franklin, is pervasively scored. The shoal, and probably the ice field often grounded there, apparently serve as an important bifurcating obstruction to pack ice drifting westward and southward onto the shelf. To the north and southeast of the shoal there are dense gouge concentrations, whereas in its lee to the southwest, gouges are sparse and very shallow (Fig. 17). On the north flank of Hanna Shoal in a roughly east-west trending zone between about the 40- and 52-m isobaths, there are random dense gouge concentrations. Out to about the 47- or 48-m isobath, gouges are seldom incised deeper than about 2 m. Beyond this, out to about the 52-m isobath, gouges as deep as 3 to 4 m are common. Gouges are extremely sparse and shallow beyond about the 54-m isobath, and are thought to be absent in water deeper than 62 to 65 m.

Barrow Sea Valley provides a conduit for southward movement of pack ice that has been shunted to the south of Hanna Shoal. In a northeast-southwest trending region on the north bank of the valley a dense concentration of gouges less than about 2.0 m deep occur between water depths of roughly 40 and 47 m, which is similar to the depth of gouges on the north flank of Hanna Shoal. Dense concentrations of gouges as deep as 5.0 m occur in water some 48 to 55 m deep, and shallower, sparser gouges occur in deeper water (Fig. 17).

Except in the coastal zone, gouges on the central Chukchi shelf appear to decrease in density southwestward toward the north flank of Herald Shoal, where there are moderate concentrations of gouges less than about 1.5 m deep in water depths of about 35 to 45 m. This southwest decrease in observed gouge density is probably due in part to the occurrence of relatively hard Cretaceous bedrock at or near the seabed south of about the latitude of Point Franklin (Fig. 17). That is, the seafloor in this area may be intensely scraped, but have few marks to show for it. The crest of Herald Shoal displays no typical gouges, probably for a similar reason. Bedrock is exposed at the seabed on the shoal and the surface of the shoal typically has undulating, irregular relief of about 1 to 3 m, probably owing to ice-push processes. Gouges are sparse or absent south of Herald Shoal, which presumably shields most of Hope basin to the south from encroachment of deep-draft pressure-ice keels.

In summary, the Alaskan Coastal Current divides the Chukchi shelf north of about Cape Lisburne into two broad sea ice provinces. In the coastal region southeast of the current, ice-pressure ridges that probably formed _in situ_ seaward of the annual shorefast ice densely score the seabed between about the 20- and 35-m isobaths (Fig. 19). Pipelines crossing this zone will probably need to be buried some 2 to 3 m beneath the seabed. Such excavation may be quite difficult owing to the occurrence of bedrock at or near the seafloor in most of the coastal zone from Point Hope north to about Point Franklin.

Northwest of the Alaskan Coastal Current, winter sea ice on the Chukchi shelf is probably mostly composed of polar pack ice drifting south and west from the Beaufort Sea and the Arctic Ocean under the influence of prevailing winter winds from the northeast. Hanna Shoal apparently bifurcates the ice into two streams. The northern stream drifts roughly westward along the shelf break and the southeastern stream continues its southwesterly drift toward Herald Shoal. Both streams apparently contain ice with keels deep enough to substantially score the seabed at depths in excess of 55 m. Herald Shoal apparently blocks most of the deep-keeled ice from further southward drift into Hope basin.

Effects of sea ice on beaches and the near shore

The movement of sea ice into shallow water and onto the beaches is probably the most severe environmental hazard along the Chukchi Sea coast. Kovacs and Sodhi (1980) have summarized ice effects on beaches. The nearshore ice is more affected by currents in the Chukchi Sea than in the Beaufort Sea, and ice-push and ice-override seem to be more severe problems on the beaches of the Chukchi Sea (Barry and others, 1979; Shapiro and Barry, 1978; Stringer 1978). The movement of ice onto the beaches has caused damage at Barrow several times during the last several decades (see, for example, Hume and Schalk, 1964; Rex, 1964; Shapiro and others, 1979). Similar problems can be expected farther south along the Chukchi Sea coast, where much less information is available. Ridges of beach sediment formed by ice-push are as high as 4 m in the vicinity of Barrow (Hume and Schalk, 1964), and barriers have locally been overridden by ice (Shapiro and others, 1979). Ice has sometimes been pushed up against cliffs, forming ramps that extend to heights of as much as 10 m above sea level (Duguid, 1971).

The zone of shorefast ice is relatively protected from moving sea ice, but the zone of grounded ice ridges (the stamukhi zone) is a zone of intense gouging of the seafloor (Fig. 19). In the Beaufort Sea, where the stamukhi zone has been most intensively studied, this zone occurs at water depths of 10 to 20 m, to as much as 40 m in late winter (Barnes and Reimnitz, 1974; Reimnitz and others, 1978). The intensity of ice ridging in the Chuckchi Sea over a period of several years has been mapped by Stringer (1978). Ridging in the Chuckchi Sea seems to occur at water depths similar to those in the Beaufort Sea and is expecially intense along lines passing close to the major capes (Fig. 19).

Subsea permafrost

Prior to about 10,000 years ago, during the last glacial sea-level lowstand, most of the present Chukchi and Beaufort shelves were exposed subaerially to frigid temperatures and ice-bonded permafrost probably aggraded downward in the sediments to depths exceeding 300 m. Reflooding of the shelf exposed these sediments to saline water at temperatures above the freezing point and much of the permafrost has probably warmed and remelted. Depending on such parameters as pore water, salinity, original thickness and temperature of the subaerial permafrost, and the insulating effect of Holocene muds, fully ice-bonded permafrost may or may not be encountered at depth offshore.

Surficial development structures may be less sensitive to the presence of permafrost in the Chukchi Sea than in the Beaufort Sea owing to the widespread occurrence of consolidated bedrock at or near the seabed over much of the shelf. Overpressured gas trapped in pockets in permafrost at depth, however, might pose blowout problems during drilling.

The distribution of relict and modern permafrost in the nearshore zone of the Alaskan Chukchi coastal region is presently unknown. Along the innermost Beaufort shelf, which is probably partly analogous, Sellman and Chamberlain (1979) report that 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 bottomfast 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.

Nearshore permafrost is most likely to occur in areas where coastal erosion is rapid. Because the rates of coastal erosion are typically less in the Chukchi Sea than in the Beaufort Sea, nearshore permafrost may not be as common in the Chukchi Sea (Harper, 1978).

Shallow free gas deposits

Shallow free gas has accumulated in several geologic environments beneath the shelf of the eastern Chukchi Sea (Fig. 20). In most cases the gas probably originates in surficial sediment as a product of bacterial metabolism of organic constituents (biogenic origin). In some cases the gas may have migrated to the surface from hydrocarbon deposits in underlying sedimentary strata (thermogenic origin). Wherever it occurs, shallow gas must be considered a potential engineering hazard to petroleum exploration structures founded on the seabed. Such gas can inhibit the normal consolidation of accumulating sediment, leading to abnormally low shear strengths. In addition, gas pockets might cause blowouts during drilling.

Inferred high concentrations of shallow free gas have been mapped in Pleistocene channel fills in North Chukchi basin, in a broad WNW-trending belt along the center of Hope basin, in Cenozoic sediment offshore of Point Franklin (north of Wainwright), and in scattered accumulations near the shelf break both east and west of Barrow Sea Valley (Fig. 20). The accumulations are delineated on high-resolution (Uniboom) seismic reflection profiles (Fig. 1). 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 20 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 not marked 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 impedance contrast at its basal interface.

Earthquakes and surficial faulting

Seismic data recorded by the Worldwide Network and summarized by Meyers (1976), indicate that extreme northwestern Alaska and the adjacent Chukchi shelf, including the proposed oil and gas lease area, have been historically aseismic. Earthquakes of magnitudes as great as 6.9 to 7.3 have, however, occurred adjacent to the lease area on the south. Figure 21, an isoseismal map from Meyers and others (1976), shows that the southern portion of the lease area may thus be subject to earthquake intensities of I-V (modified Mercalli scale).

Normal faults and monoclines offset the erosional surface at the base of thin, inferred Holocene deposits no more than 3 or so meters in the part of Hope basin that lies within the proposed lease sale area. These features are inferred to strike roughly northwest, subparallel to the basin margin, and to be minimally active, if at all. Similar, but sparser features offset probable Pleistocene beds in parts of North Chukchi basin, but data are presently insufficient to map their extent.

Distribution, texture, and thickness of unconsolidated sediment

As previously discussed, only a thin blanket of unconsolidated sediment, probably averaging about 2 to 5 m thick, overlies well-indurated bedrock over much of the Chukchi shelf. Exceptions occur within the North Chukchi basin, where there are several northwest-thickening layers of probable Quaternary sediment, and in Hope basin. Within Hope basin in the lease sale area west of Cape Lisburne, Holocene and/or late Wisconsin sediment is as thick as 11 m (McManus and others, 1969). The surficial sediment texture maps of McManus and others (1969) are reproduced in Figs. 22, 23, 24, and 25 of the present report.

Substantial gravel accumulations occur close to shore at Cape Lisburne, where bedrock beachcliffs are the probable primary source, and on the east flank of Herald Shoal, where bedrock is exposed at the seabed (Fig. 22). Sand is concentrated beneath the main course of the Alaska Coastal Current from Point Hope north and northeast to the head of Barrow Sea Valley off Point Franklin, and on Herald and Hanna Shoals (Fig. 23), where currents and deep sea ice keels resuspend the sediment and winnow out finer materials (Toimil and Grantz, 1976). Percentages of silt-size grains are highest west of Lisburne Peninsula and on the central Chukchi shelf northwest of Icy Cape, where current velocities of the bifurcated Alaskan Coastal Current have diminished to the extent that such grains may be deposited from suspension (Fig. 24). Their probable primary source is the Yukon River (McManus and others, 1969). Clay occurs in substantial concentrations only on the northernmost Chukchi shelf (Fig. 25), where ice-rafted sediment contributions were probably important during late Wisconsin/early Holocene time, and may be significant even now. Figure 26 summarizes the present sedimentary environments within lease sale area 85.

The beaches and barriers along the Chukchi Sea are composed, at least in the few places where they have been sampled, of sand and gravel (Short, 1979). The thickness of unconsolidated sediment beneath the barriers is not known, but the extensive migration of tidal inlets documented by Short (1979) suggests that the thickness is commonly as great as the depth of the inlets, or about 10 m (Fig. 27).

Paleochannels

Filled Pleistocene paleochannels and paleovalleys as deep as 50 m beneath the present seafloor north of Herald Arch are clearly delineated on high-resolution (Uniboom) seismic reflection profiles (Fig. 28). Data coverage is presently insufficient to map the continuity and distribution of these features; however, they may serve as important sources of gravel in the event that artificial islands are constructed on the northern Chukchi continental shelf.

Currents, waves and storms

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. 29).

Tides are small in the Chukchi Sea, and the tidal range along the eastern coast is generally less than 30 cm. Tides are of the semi-diurnal type (Creager, 1963, Wiseman and others, 1973), and tidal waves move from north to south (Coachman and Aagaard, 1974). Tide-generated currents can be expected to be of limited velocity along the open coast. Within lagoons and embayments, however, higher velocities are common. Tide-generated currents are reported up to 204 cm/sec within the tidal passes east of Barrow (Rex, 1955). Similar velocities can be expected within the tidal passes along the coast of the Chukchi Sea.

Storms during the summer months usually result in winds from the southwest that move across the Chukchi Sea (Wiseman and Rouse, 1980). Resulting stormwaves and storm-generated currents may erode and scour the sea floor as well as result in intense sediment transport on the shelf and on shoals.

Wind-generated currents are extremely variable both in velocity and in direction of movement for 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 (Hufford, 1977). The wind-generated currents generally follow the bottom contours (Wiseman and others, 1973). 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, 1974, Coachman and others, 1976). The current bifurcates at Cape Lisburne, one branch flowing northwest and the other branch flowing to the northeast parallel to the coast (Fig. 29). The current varies in width and can be as narrow as 20 to 37 km (Aagaard and Coachman, 1964; Hufford, 1977). Velocities of the coastal current vary from 50 cm/sec near Cape Lisburne (Sharma, 1979) to 51 to 87 cm/sec south of Icy Cape (Ingham and Rutland, 1972), to 55 cm/sec north of Wainwright (Hufford, 1977). Surface velocities of up to 200 cm/sec and mid-depth velocities of 70 cm/sec are reported north of Wainwright (Hufford, 1977). Near the head of Barrow Sea Valley northwest of Wainwright and west of the Alaska Coastal Current a returning southwest-directed current is reported with surface velocities of 80 cm/sec (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. Episodes of strong southward-flowing currents off Cape Lisburne during winter (Fig. 30) are reported by Coachman and Aagaard (1981).

Longshore sediment transport

The direction of longshore sediment transport, as indicated by the migration of tidal inlets and the orientation of nearshore bars, is towards the major capes and away from the centers of intervening embayments (Short, 1975, 1979). In other words, the capes represent convergences of longshore transport and the centers of the embayments represent divergences. Rates of longshore sediment transport are poorly known; Short (1979) estimates them to be in the range of 5,000 - 25,000 m^3/yr. Hume and others (1972), have estimated a rate of 9,000 m^3/yr at Barrow. The directions and rates of longshore sediment transport should be determined more precisely and taken into account when any harbor facility along the Chukchi Sea coast is designed.

Sandwaves

There are few data on seafloor modification, erosion, and rates of sediment transport for the Chukchi shelf. Limited data nearshore in depths ranging from 2 to 15 m show numerous shore-parallel, small-scale asymmetric sand waves resulting from wave-generated and storm-generated currents. Based on limited data from widely spaced track lines, the wave-generated shore-parallel sand waves occur along the coast where the water is less than 15 m deep and the influence of the northward-flowing Alaska Coastal Current is diminished.

Limited data on the presence of actively northward-migrating bedforms on the seafloor suggest that a zone of scouring and formation of current-dominated bedform fields occurs at depths of at least 15 to 30 m. Such features develop in a zone parallel to the coast seaward of the wave-dominated, shore-parallel bedforms and represent northward sediment transport by the Alaska Coastal Current.

Linear, northeast-trending, parallel shoals generally occur off the capes and also reflect northward sediment transport by the Alaskan Coastal Current. The shoals range in depth from approximately 6 to 22 m and rise to 3 m depth off Icy Cape. The shoals probably form as a result of repeated ice gouging, ice pushing and bedform migration. Actively northward-migrating bedform fields with relief as great as 2.5 m cover the shoals. The sand waves result in upward-building and northward migration of the shoals along Icy Cape. Seaward of the Icy Cape shoal bedforms as high as 3 m are reported (Moore, 1964).

Biological communities

Kelp and red algae have been identified locally from the shallow nearshore region northeast of Peard Bay (Fig. 27). The biota, dominated by kelp, is described by Mohr and others (1957). The algal beds occur at depths of 8 to 15 m and extend parallel to shore. Algal communities may also be found in the shallow nearshore zone of the coastal region where gravel or bedrock crops out east of Cape Lisburne and possibly east of Icy Cape.

Coastal erosion and deposition

The cliffed sections of the Chukchi Sea coastline were formed by erosion. The barrier islands and spits, in contrast, are depositional features. Some of the barrier islands are known to be migrating landward by erosion on their seaward sides, overwash across their crests, and deposition on their lagoonal sides. Rates of coastal erosion have been measured rather precisely in the cliffed section of coastline between Barrow and Peard Bay; here, the erosion rate averaged 0.31 m/yr in the period 1949-1976 (Fig. 27, and Harper, 1978). Studies in the section between Icy Cape and Barrow suggest that the erosion rate is locally as great as 2 to 6 m/yr. Erosion rates have not been measured south of Icy Cape, but Short (1979) has presented evidence that some sections of the barriers are retreating. The tidal inlets that cut through the barriers tend to migrate in the direction of longshore transport by erosion on the downdrift margin and deposition on the updrift margin of the inlet. Short (1979) has estimated that the average rate of inlet migration is 20 m/yr.

Although deposition is seldom as much of a hazard as erosion, shoaling of harbor areas or channels can create significant logistic or engineering problems. On the Chukchi Sea coast, deposition associated with inlet migration and the landward migration of barrier islands would need to be studied before coastal engineering developments were started.

Storm surges

Storm surges pose an erosional hazard as well as a flooding hazard to coastal areas. Several storm surges have caused severe coastal erosion at Barrow during the last several decades (see, for example, Hume and Schalk, 1967). Observations of spindrift lines and other features along the Chukchi Sea coast south of Barrow (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. Surges reach as high as 3 to 3.5 m above sea level at Barrow and elsewhere along the Chukchi Sea coast (Aagaard, 1978) and can cause extensive overwash across the barriers.

Tsunamis, which pose hazards similar to those posed by storm surges, have not been recorded from the Chukchi Sea coast. Their occurrence there is improbable.

River flooding

River flooding in the Arctic takes place before ice breakup along the coast, and flooding onto coastal ice can pose an erosional hazard where river water finally breaks through the ice and scours the seafloor. River flooding onto ice in the Chukchi Sea is largely restricted to lagoonal areas and is not as significant a hazard as in the Beaufort Sea (Short and Wiseman, 1975; Barry and others, 1979).

Slope instability in coastal zone

Landsliding can be expected on any of the sea cliffs along the Chukchi Sea coast and occurs very commonly where the cliffs are cut into unconsolidated sediment, as in the section between Peard Bay and Barrow. Such cliffs are unstable due to thermal erosion of ice-bonded sediment. Slope instability is not known in the lagoons, on the barriers, or on the nearshore shelf, and is not expected in most places because slope gradients are low. However, slumping could conceivably occur along the steep margins of tidal inlets that cut deeply through the barriers, and along the slopes of Barrow Sea Valley.

Petroleum seeps

Heavy petroleum seeps from Cretaceous bedrock on the beach at Skull Cliff, about 50 km southwest of Barrow. An analysis of petroleum from this site is reported by McKinnery and others (1959).

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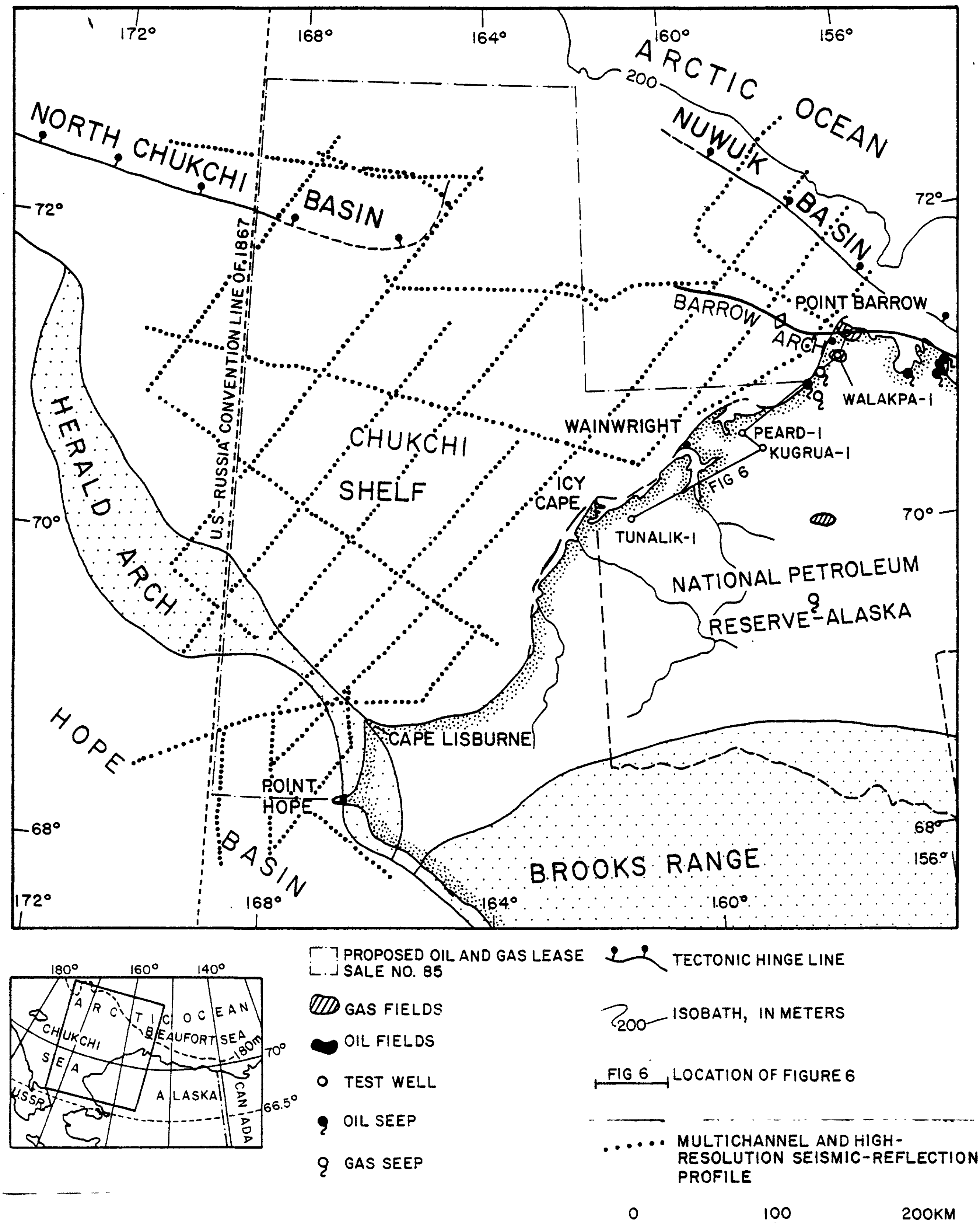


Figure 1.--Map of central and northern United States Chukchi Sea and vicinity showing major geologic features, petroleum development, oil and gas seeps, proposed oil and gas lease sale no. 85, and seismic-reflection profile data base.

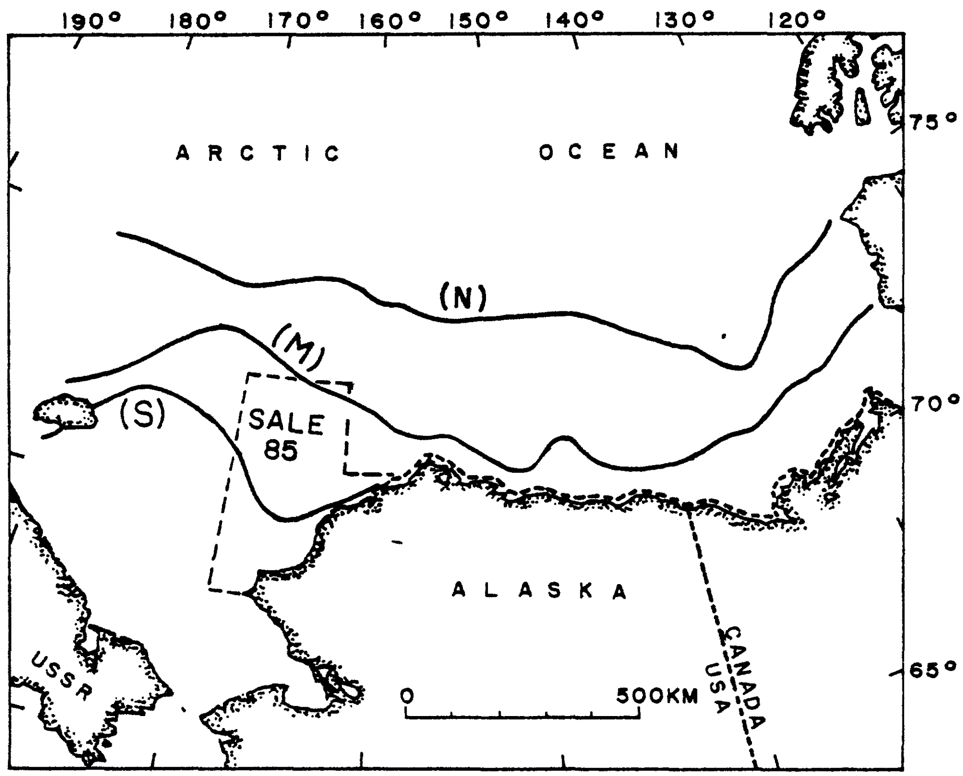


Figure 2. Most northerly (N), most southerly (S), and median (M) position of the southern edge of the Arctic ice pack north of Alaska during the usual period of maximum retreat, September 16 to 30, based on data from 1954 through 1970 (after Brower and others, 1977).

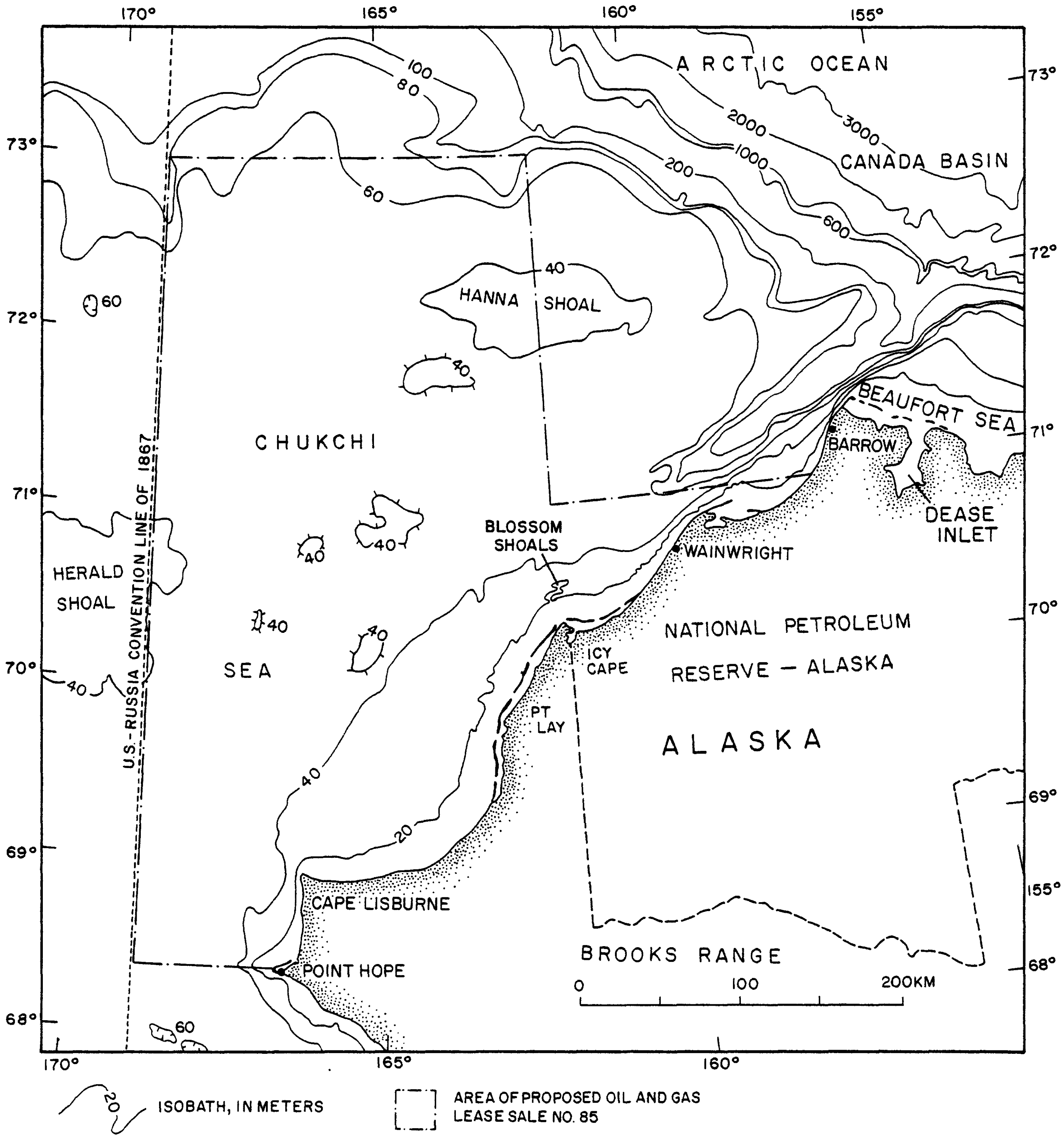


Figure 3.--Bathymetric map of central and northern United States Chukchi Sea showing location of proposed oil and gas lease sale no. 85.

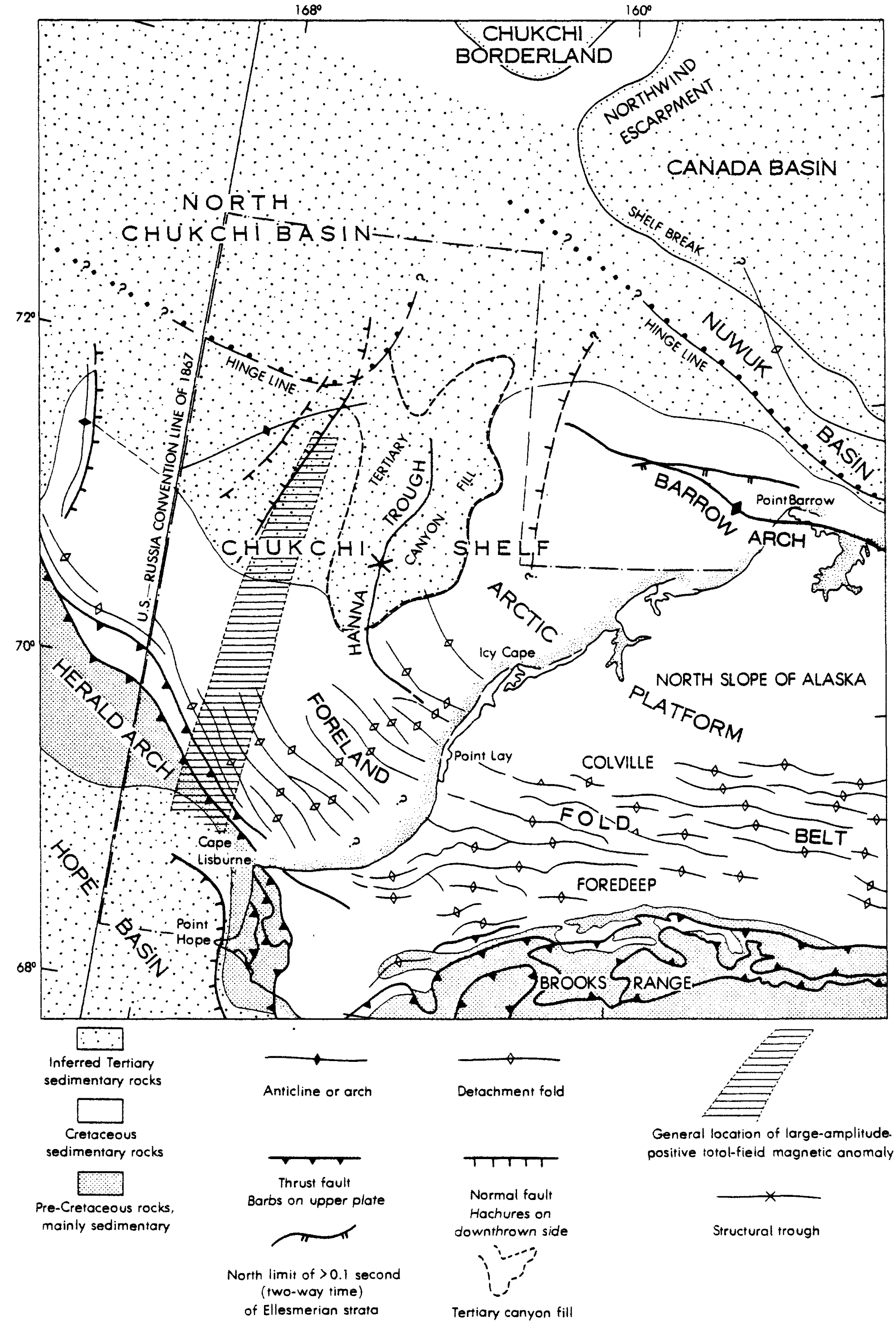


Figure 4.--Preliminary tectonic map of the United States Chukchi shelf and vicinity.

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 northeastward 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. Shallow- to deep-marine clastic rocks in the east.	
MESOZOIC	CRETACEOUS	LOWER	BROOKIAN	NANUSHUK GROUP (W. North Slope)	0-3,300+	Marine and nonmarine shale, siltstone, sandstone, coal, conglomerate, and bentonite.	
MESOZOIC	CRETACEOUS	LOWER	BROOKIAN	TOROK FORMATION	200-1,200+; 400-3,000	Marine shale, sandstone, and siltstone turbidites.	
MESOZOIC	CRETACEOUS	LOWER	BROOKIAN	FORTRESS MT. FM. (W. North Slope)	1000-3,000	Marine shale, sandstone, and conglomerate.	
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, shale. Local volcanic rocks.	
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 5.--Generalized stratigraphy of northern Alaska and adjacent continental shelves.

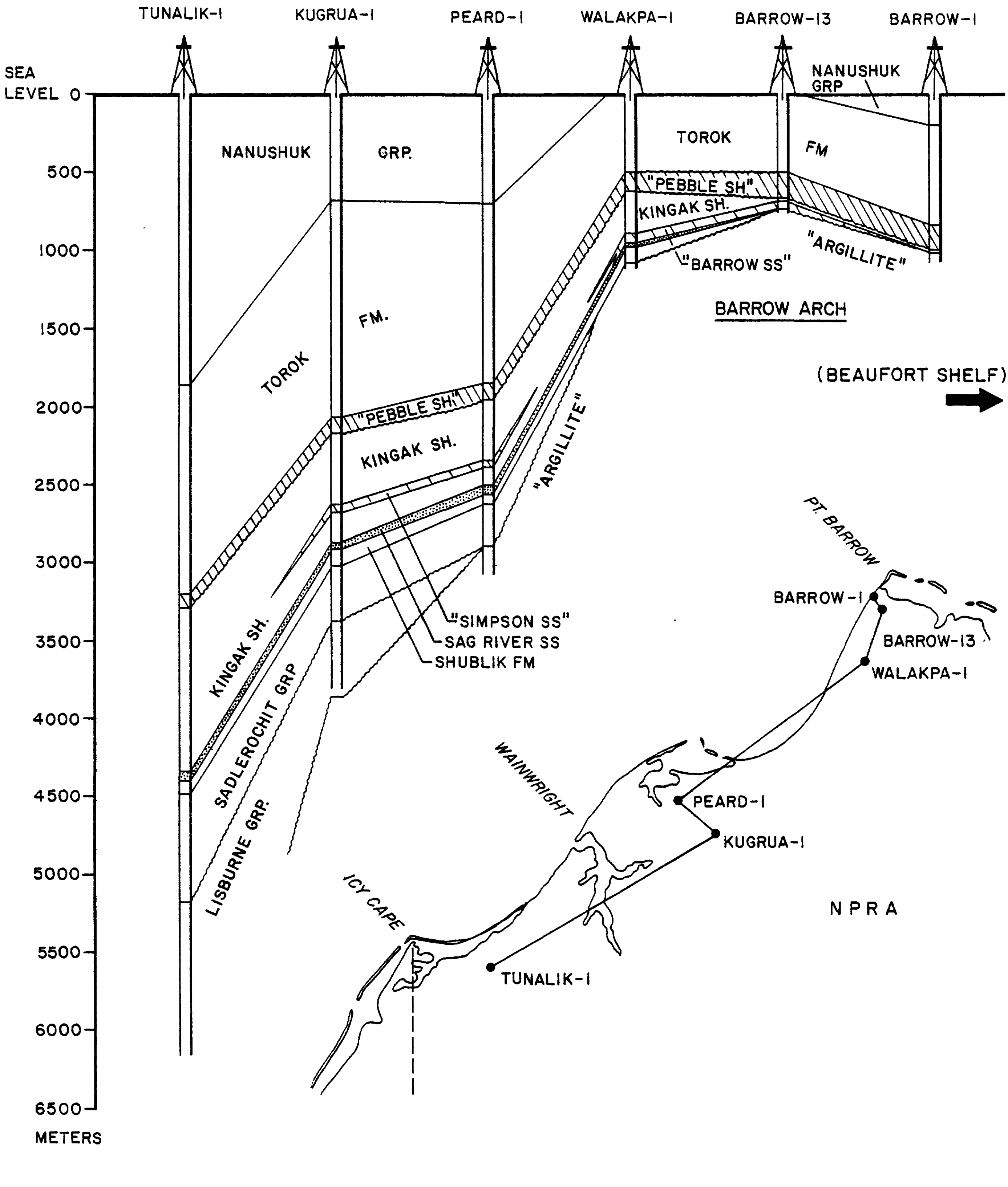
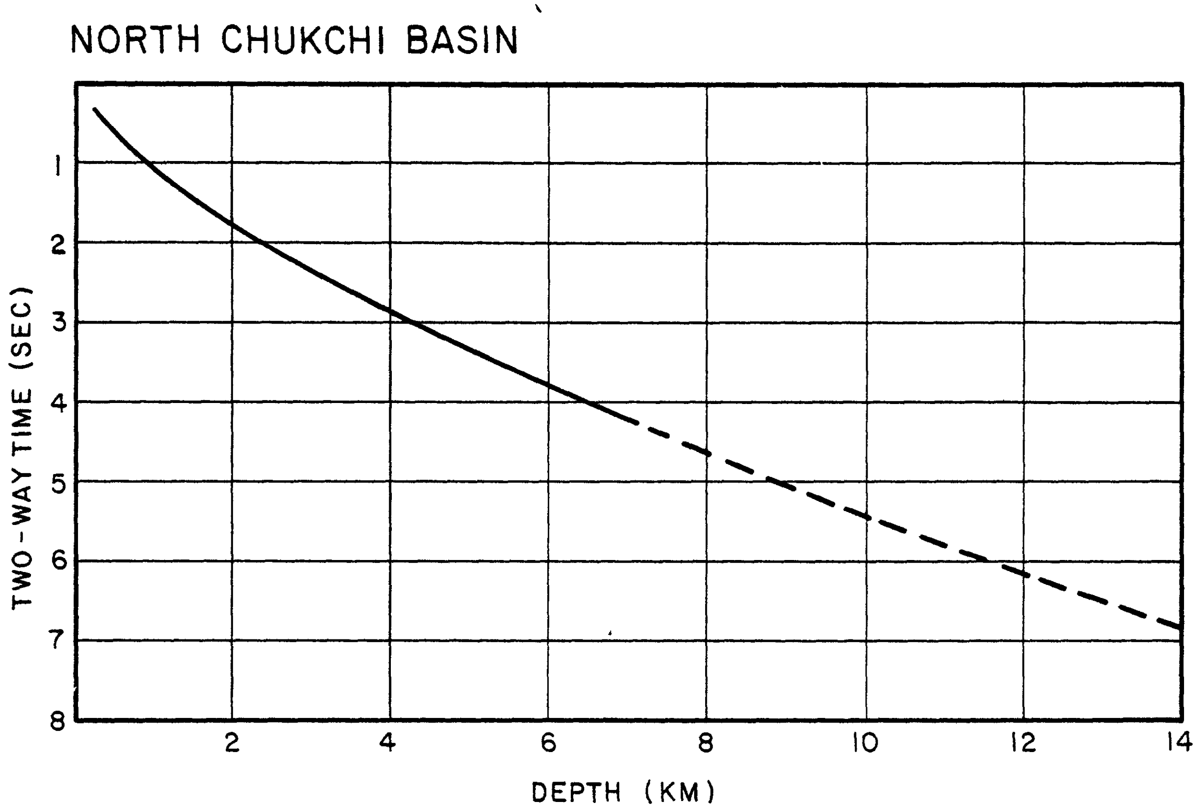


Figure 6.--Geologic cross section based on correlated test wells in National Petroleum Reserve in Alaska that lie near the northern Chukchi Sea. Data from Bird, 1982. See Figure 1 for location.



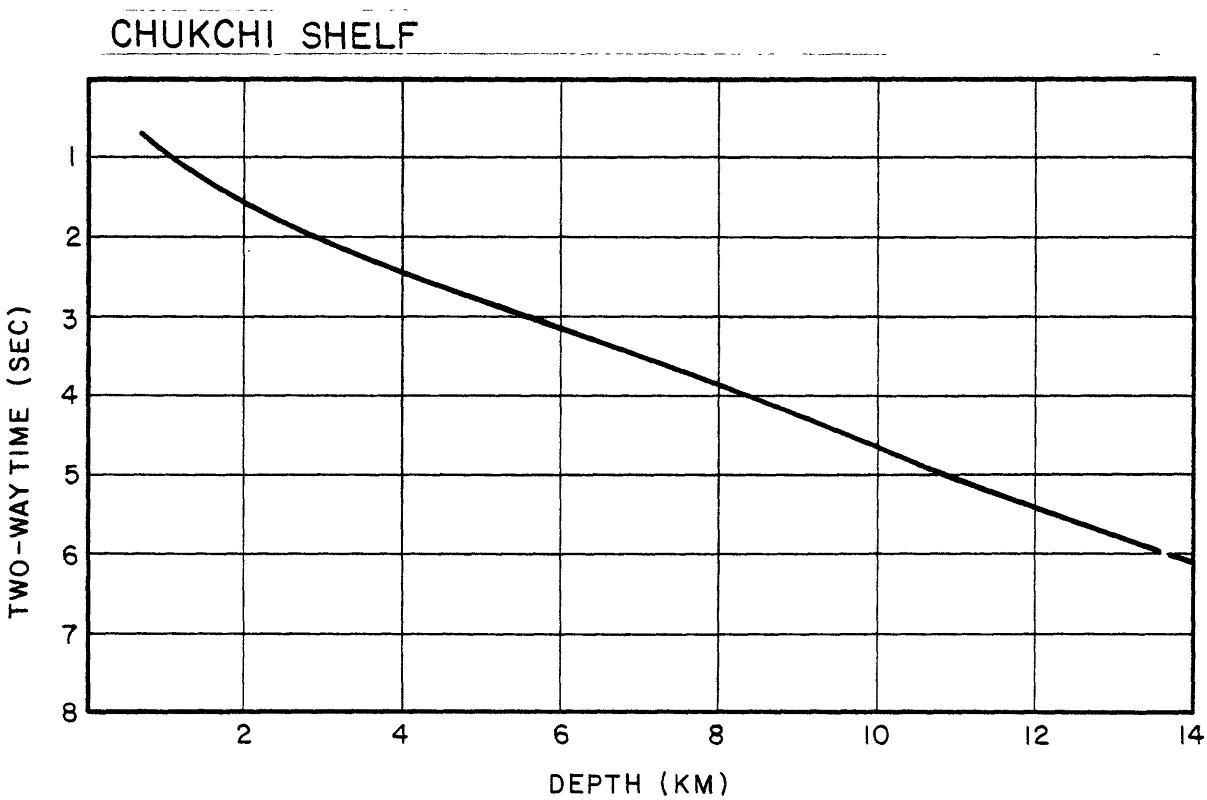
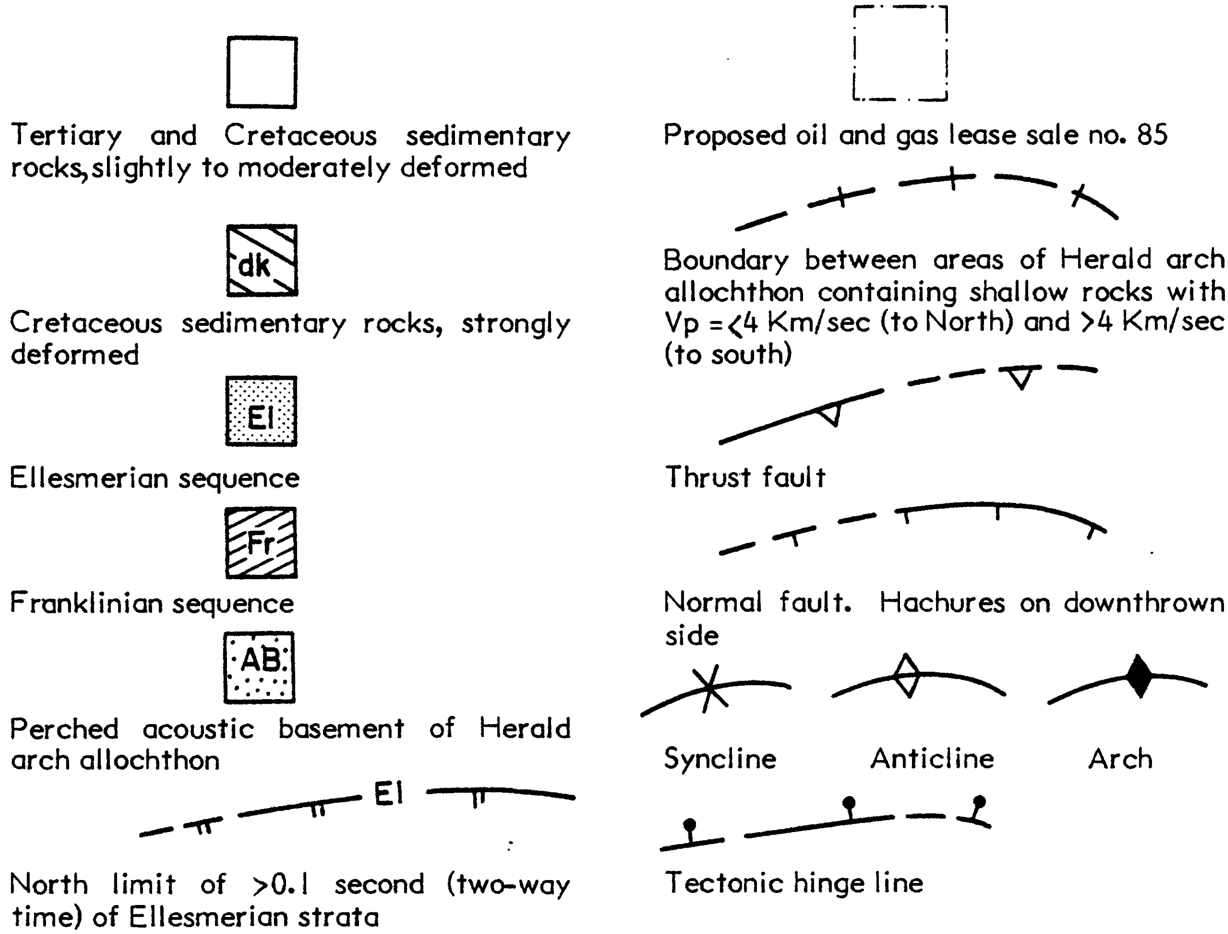


Figure 7.--Generalized average seismic-reflection time as a function of depth for the Chukchi shelf and North Chukchi basin, derived from seismic-stacking-velocity measurements. The curve for the North Chukchi basin also approximates conditions in the northern part of Hope basin



Note--All geologic lines, including isochrons and isopachs, on Figures 8 to 14 are solid where interpolated between adequately distributed control points, dashed where extrapolated beyond adequate control, dotted where speculative, queried where doubtful.

Figure 8.--Explanation of map symbols in Figures 9 to 14 and 16.

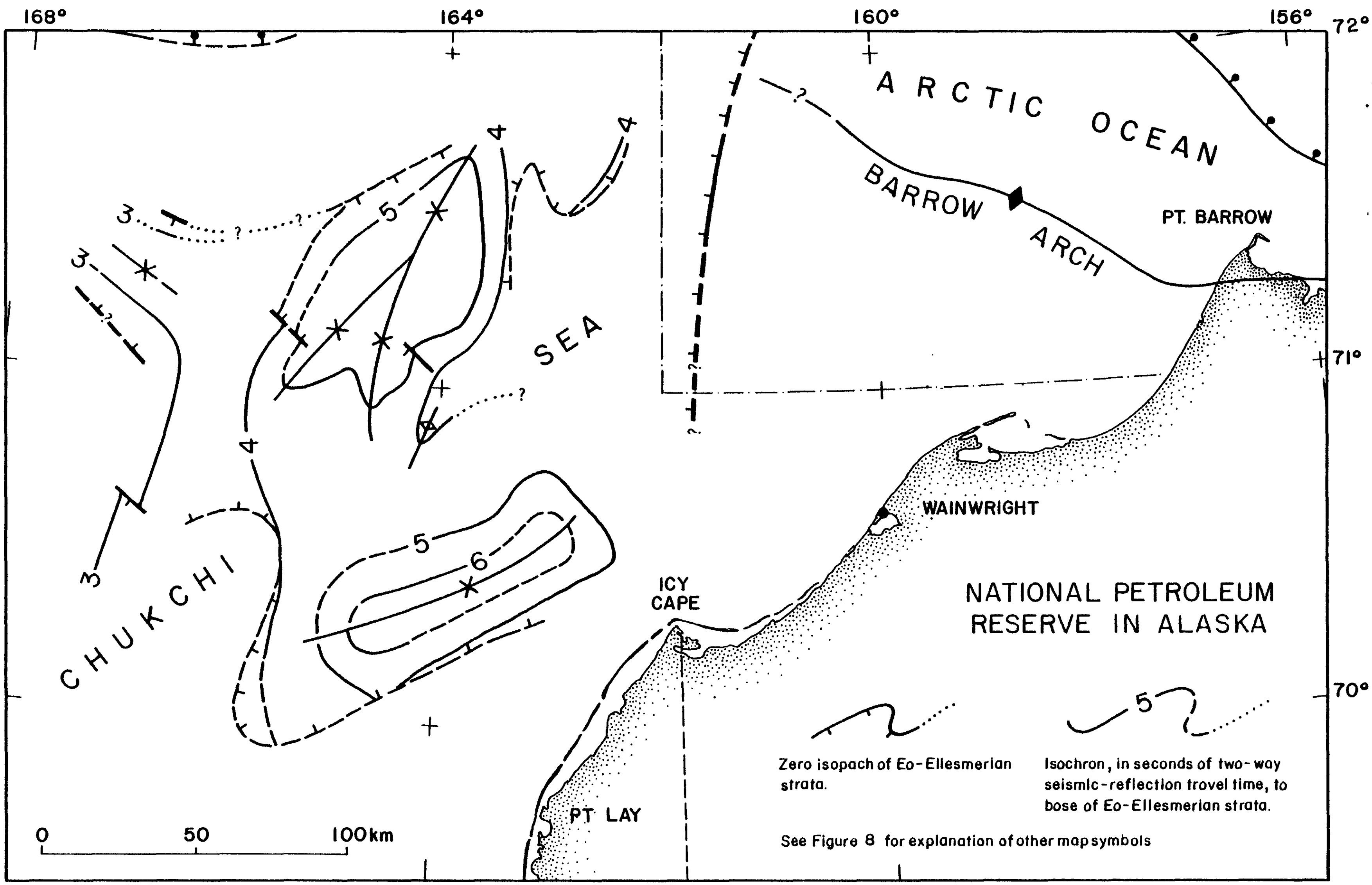


Figure 9.--Isochrons on base of Eo-Ellesmerian strata, top of Franklinian sequence, beneath the northern part of the United States Chukchi shelf. The northeast limit of the Eo-Ellesmerian sedimentary prism was not recognized on the seismic-reflection profiles.

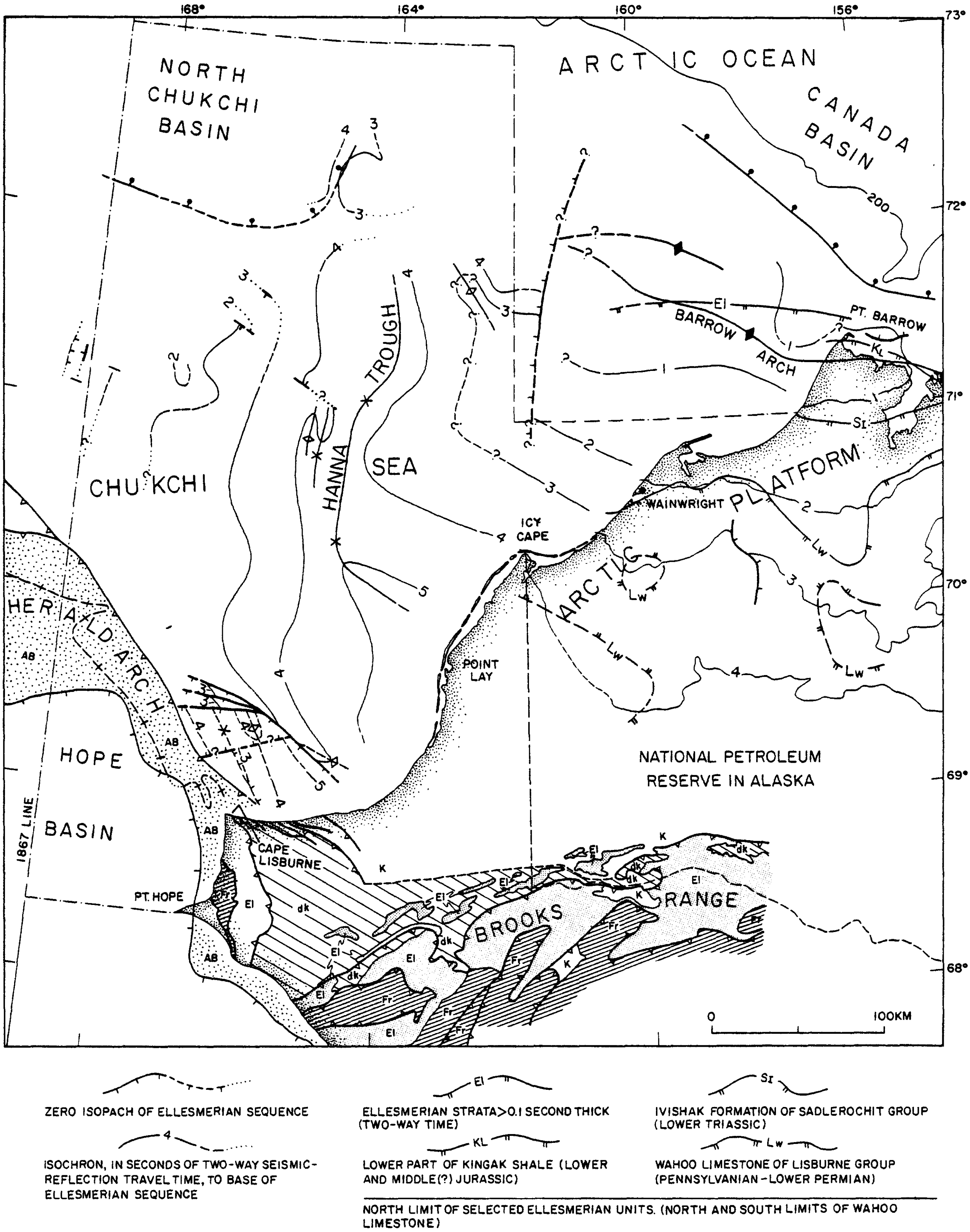
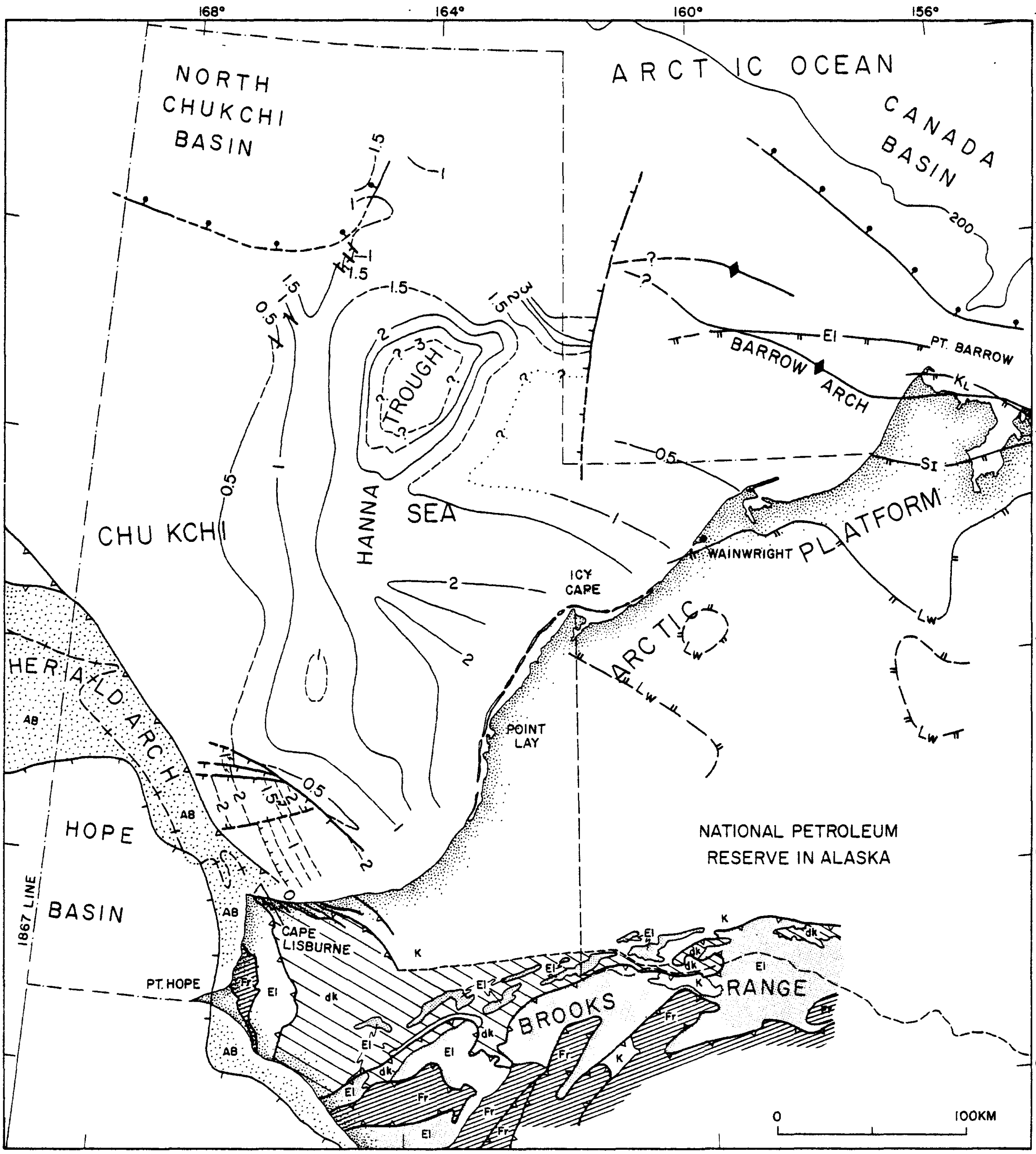


Figure 10.--Isochrons on base of Ellesmerian sequence beneath the United States Chukchi shelf. Onshore isochrons from Miller and others (1979), onshore limits of selected Ellesmerian stratigraphic units from Guldenzopf and others (1980).



ISOPACHS, IN SECONDS OF TWO-WAY SEISMIC-REFLECTION TRAVEL TIME, OF THE ELLESMERIAN SEQUENCE (MISSISSIPPIAN TO NEOCOMIAN) SEDIMENTARY ROCKS.

El — ELLESMERIAN STRATA >0.1 SECONDS THICK (TWO-WAY TIME)

SI — IVISHAK FORMATION OF SAOLEROCHIT GROUP (LOWER TRIASSIC)

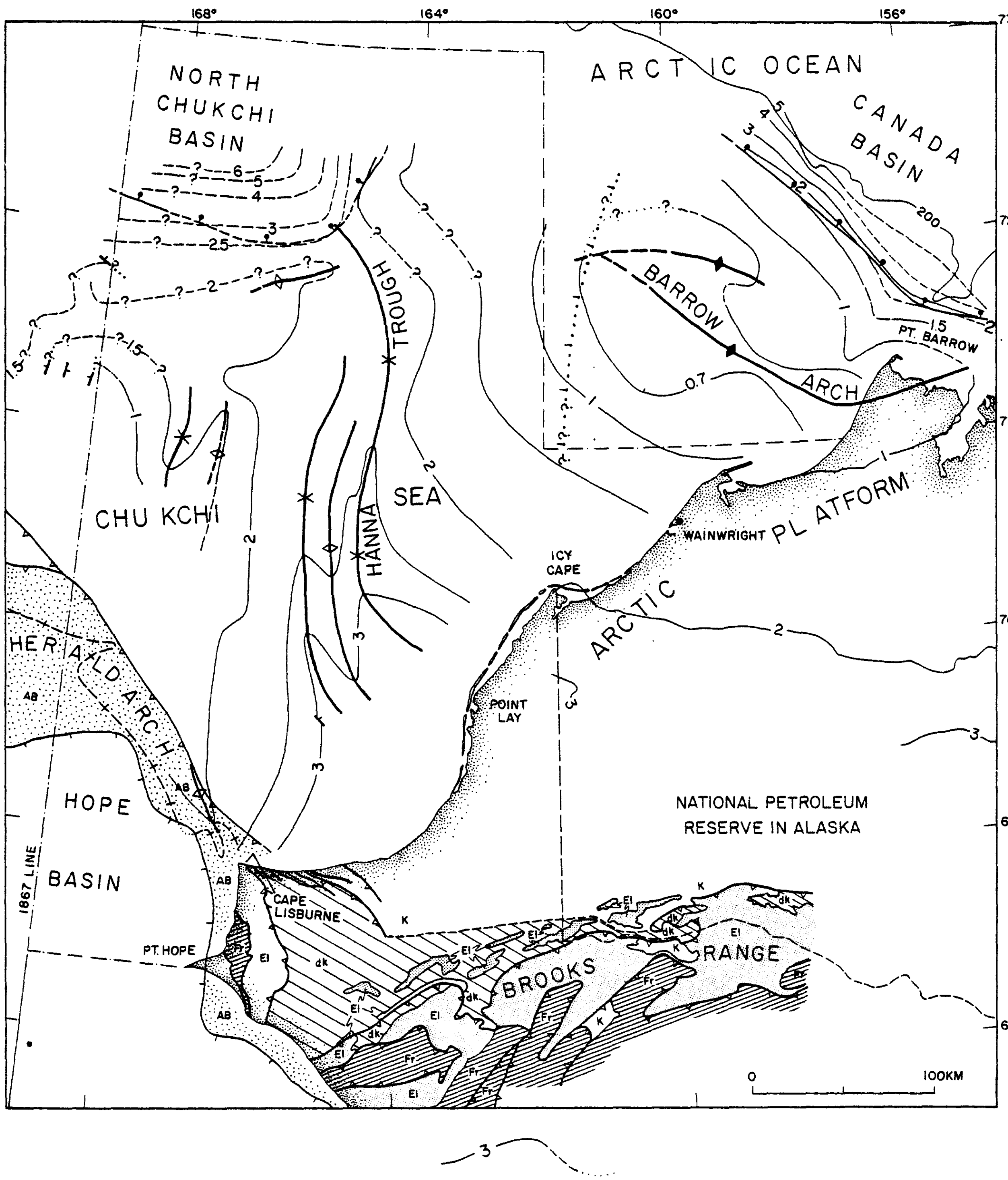
KL — LOWER PART OF KINGAK SHALE (LOWER AND MIDDLE (?) JURASSIC)

LW — WAHOO LIMESTONE OF LISBURNE GROUP (PENNSYLVANIAN-LOWER PERMIAN)

NORTH LIMIT OF SELECTED ELLESMERIAN UNITS. (NORTH AND SOUTH LIMITS OF WAHOO LIMESTONE)

SEE FIGURE 8 FOR EXPLANATION OF OTHER MAP SYMBOLS

Figure 11.--Isopachs, in seconds of two-way seismic-reflection time, of the Ellesmerian sequence beneath the United States Chukchi shelf.



ISOCHRONS, IN SECONDS TWO-WAY SEISMIC-REFLECTION TRAVEL TIME, TO BASE OF BROOKIAN SEQUENCE (BASE OF TOROK-FORTRESS MOUNTAIN FORMATION)

SEE FIGURE 8 FOR EXPLANATION OF OTHER MAP SYMBOLS

Figure 12.--Isochrons on base of lower Brookian sequence (Torok-Fortress Mountain Formation) beneath the United States Chukchi shelf. Onshore data from Miller and others (1979).

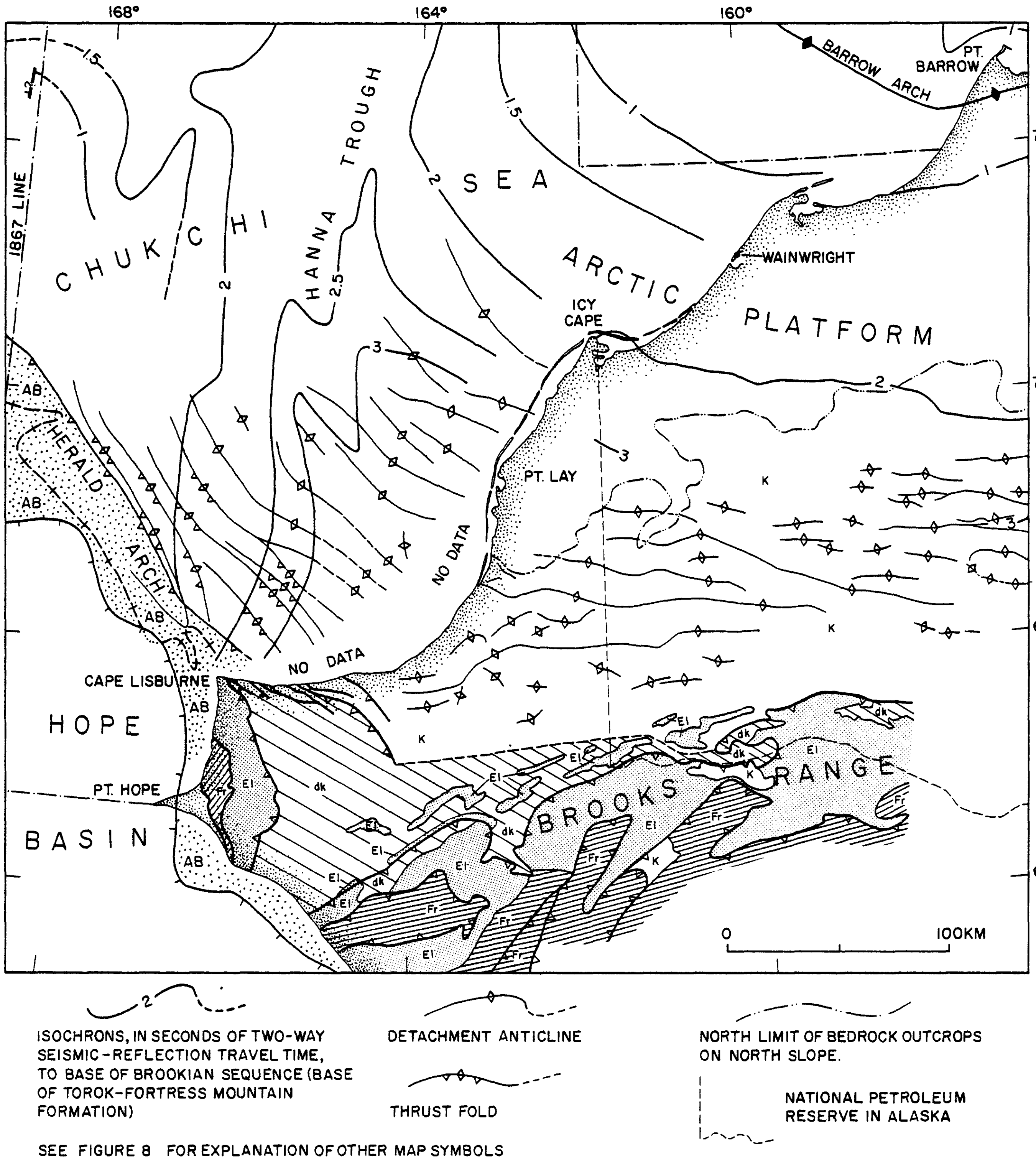


Figure 13.--Detachment folds and thrust folds in Cretaceous sedimentary rocks of the Colville foredeep on the United States Chukchi shelf and western North Slope. Some of the more southerly structures mapped as detachment folds on the North Slope are probably also thrust folds. Beneath the Chukchi shelf the folds are detached at or close to the base of the Torok-Fortress Mountain Formation, which is contoured in isochrons. Onshore isochrons from Miller and others (1979); onshore folds from Lathram (1965).

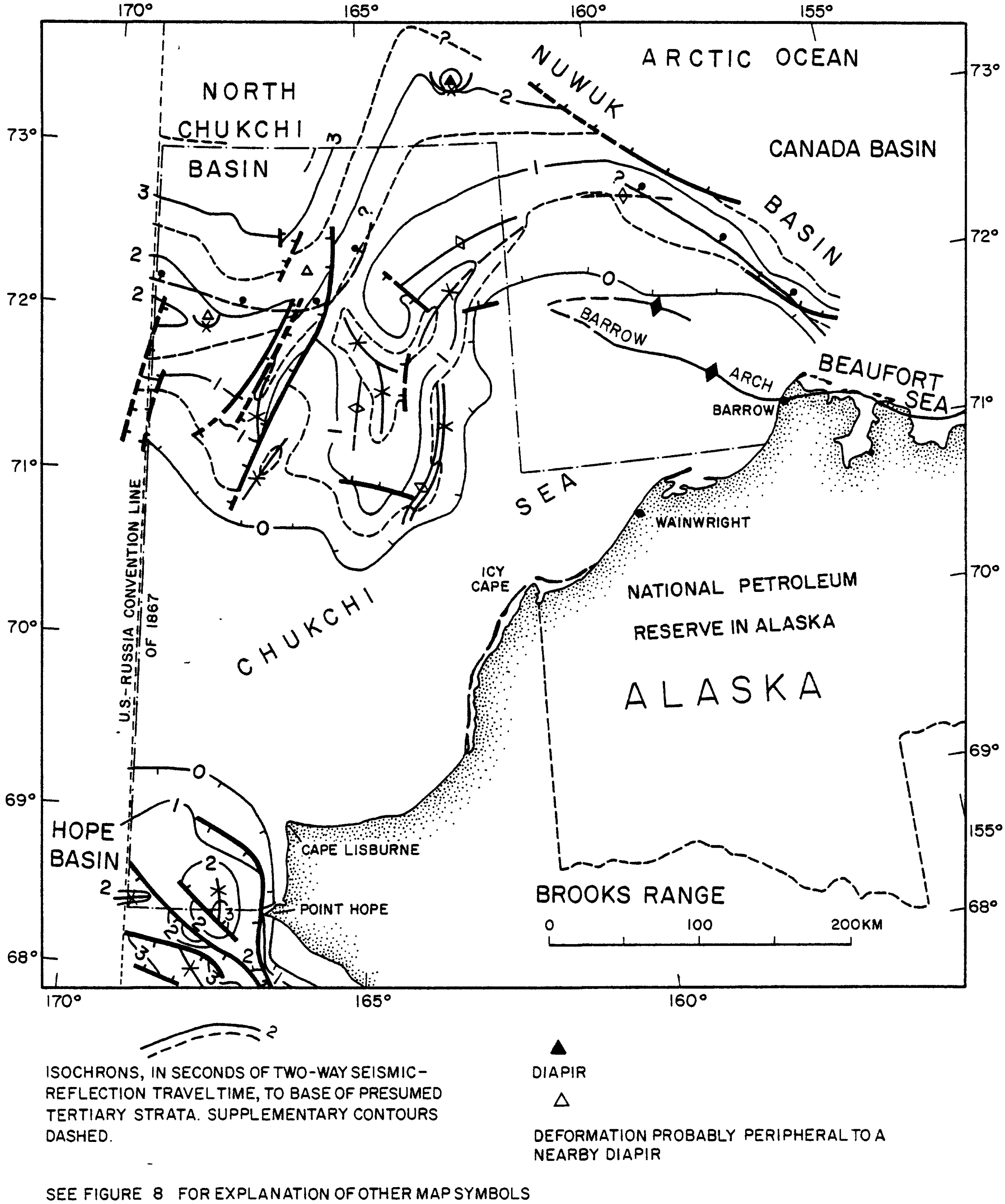


Figure 14.--Isochrons on base of upper Brookian (presumed Tertiary) strata in part of Hope basin and the northern United States Chukchi Sea, including part of North Chukchi and Nuwuk basins. Isochrons north of the multichannel lines (Fig. 1) are based only on shallow-penetration single channel seismic-reflection profiles, and are speculative

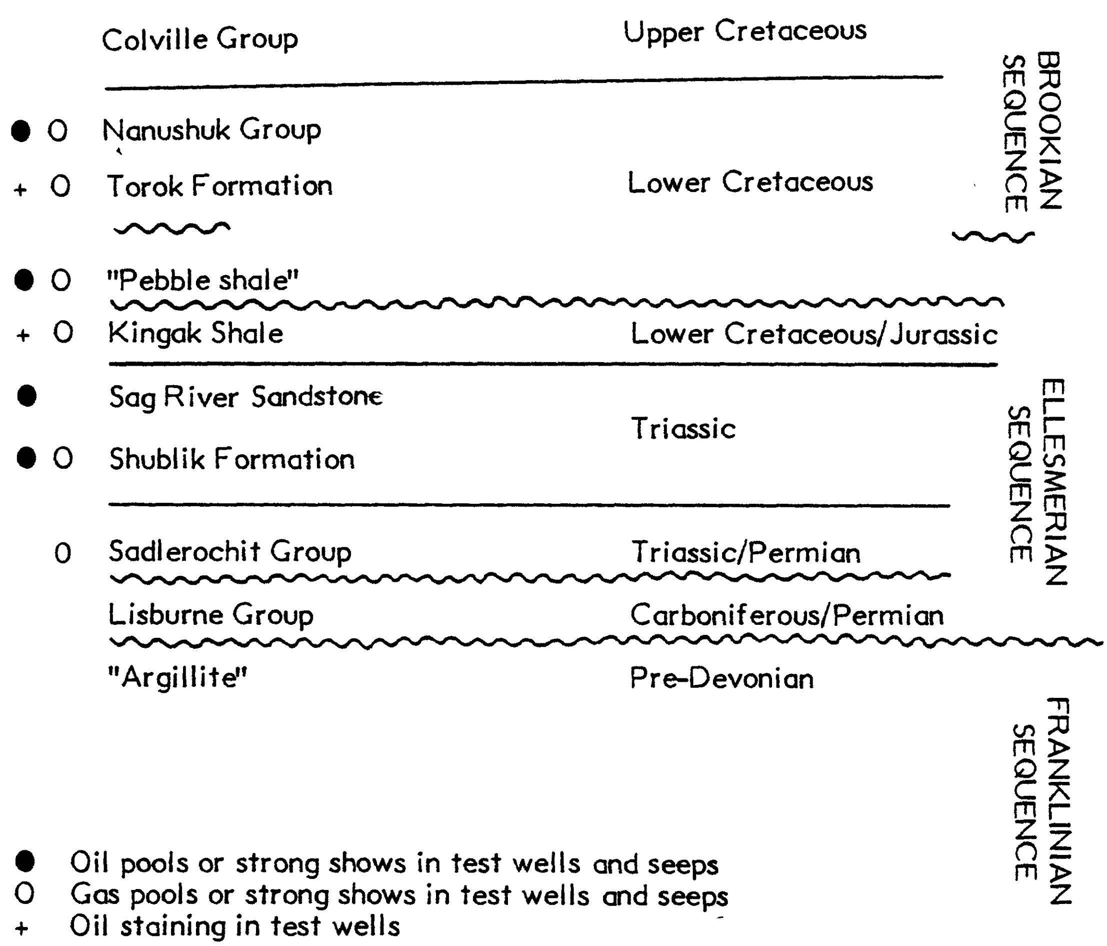


Figure 15.--Generalized stratigraphic column beneath the Arctic coastal plain of northwestern Alaska west of Dease Inlet showing position of oil and gas pools, strong shows of oil and gas, and oil staining encountered in test wells and seeps. (Data from Alaska Geological Society, 1981; Bird, 1982; and Kenneth J. Bird, personal communication, 1982.

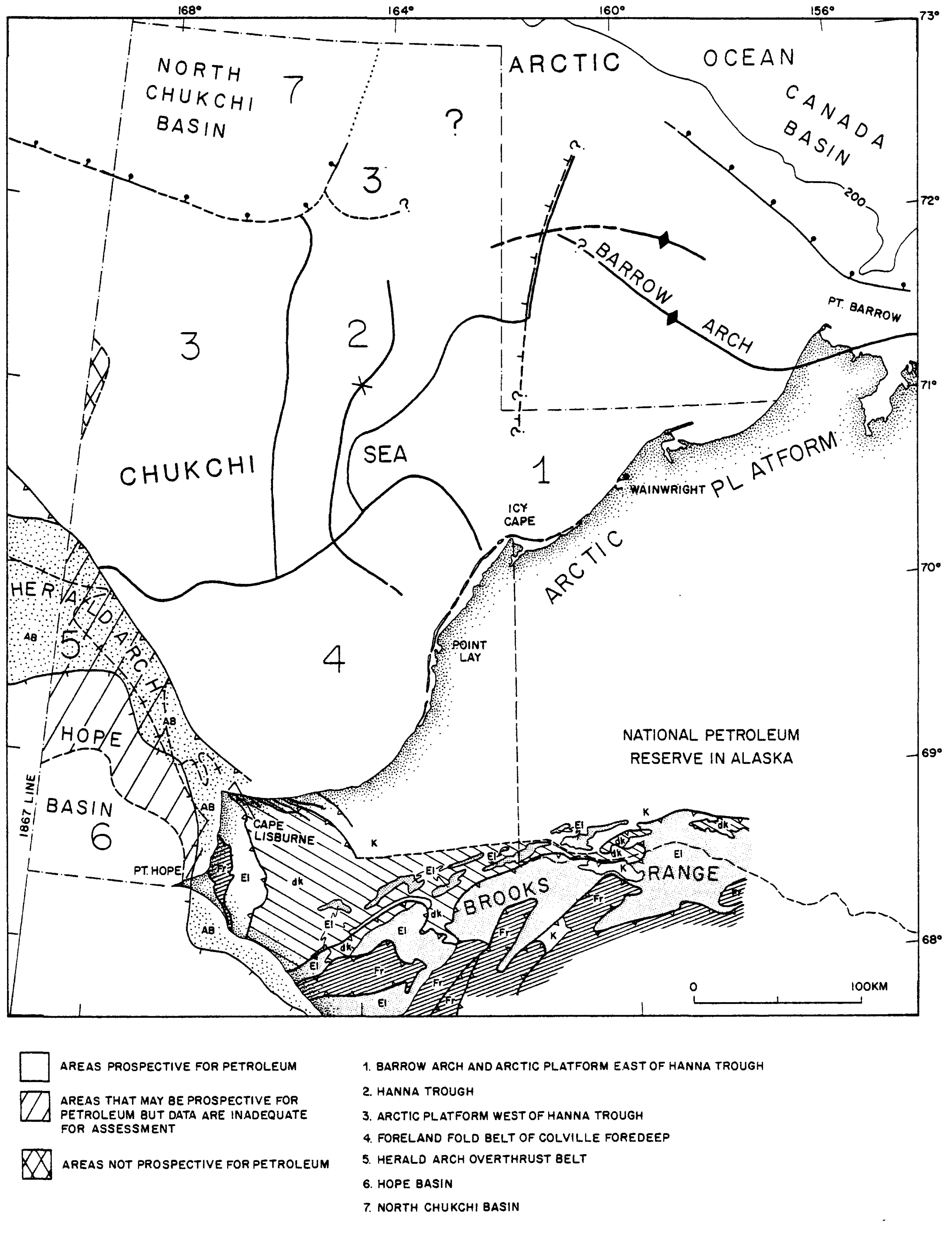


Figure 16.--Structural provinces and areas prospective for petroleum in proposed oil and gas lease sale no. 85.

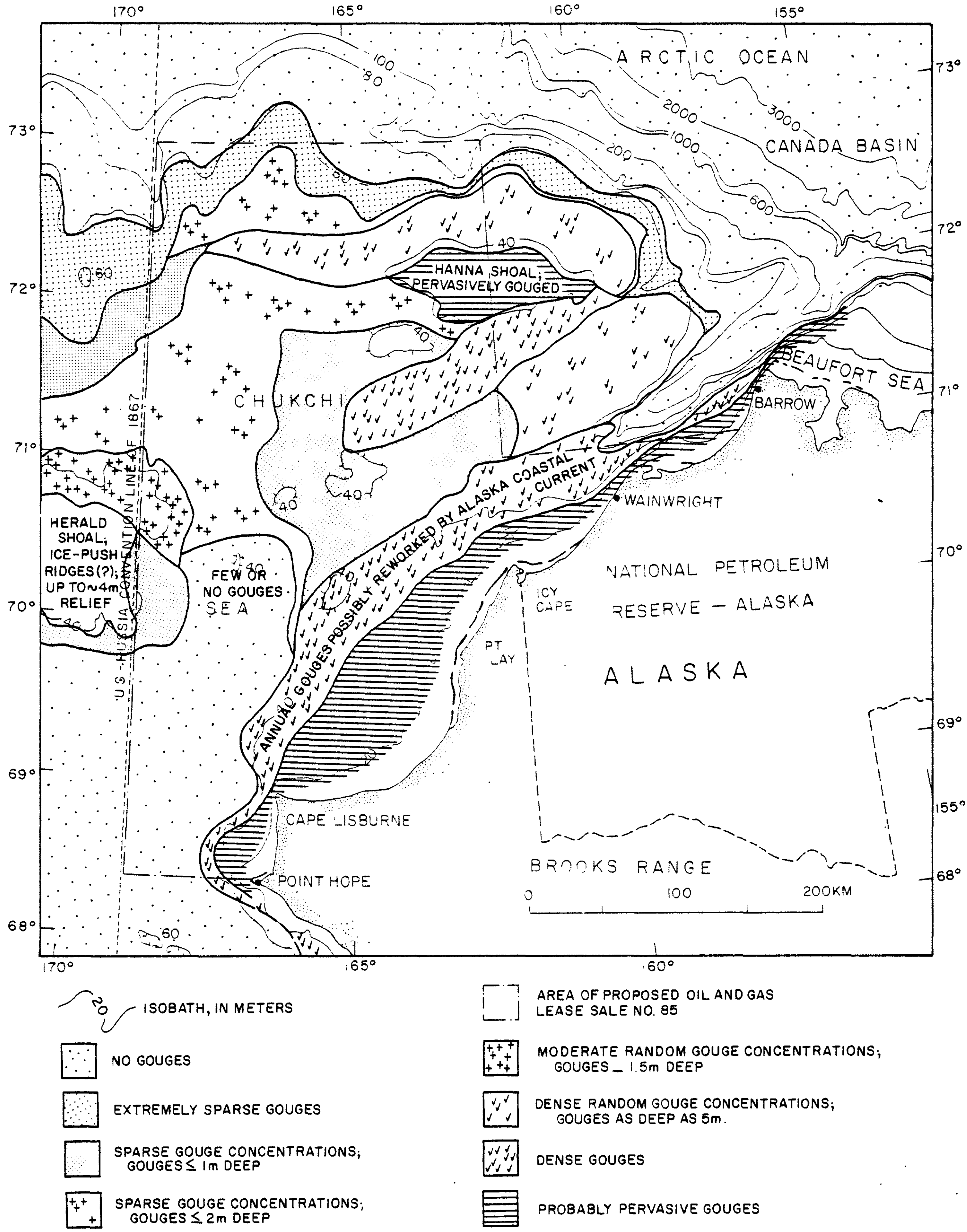


Figure 17.--Distribution of ice gouges on the seabed of the Chukchi Sea.

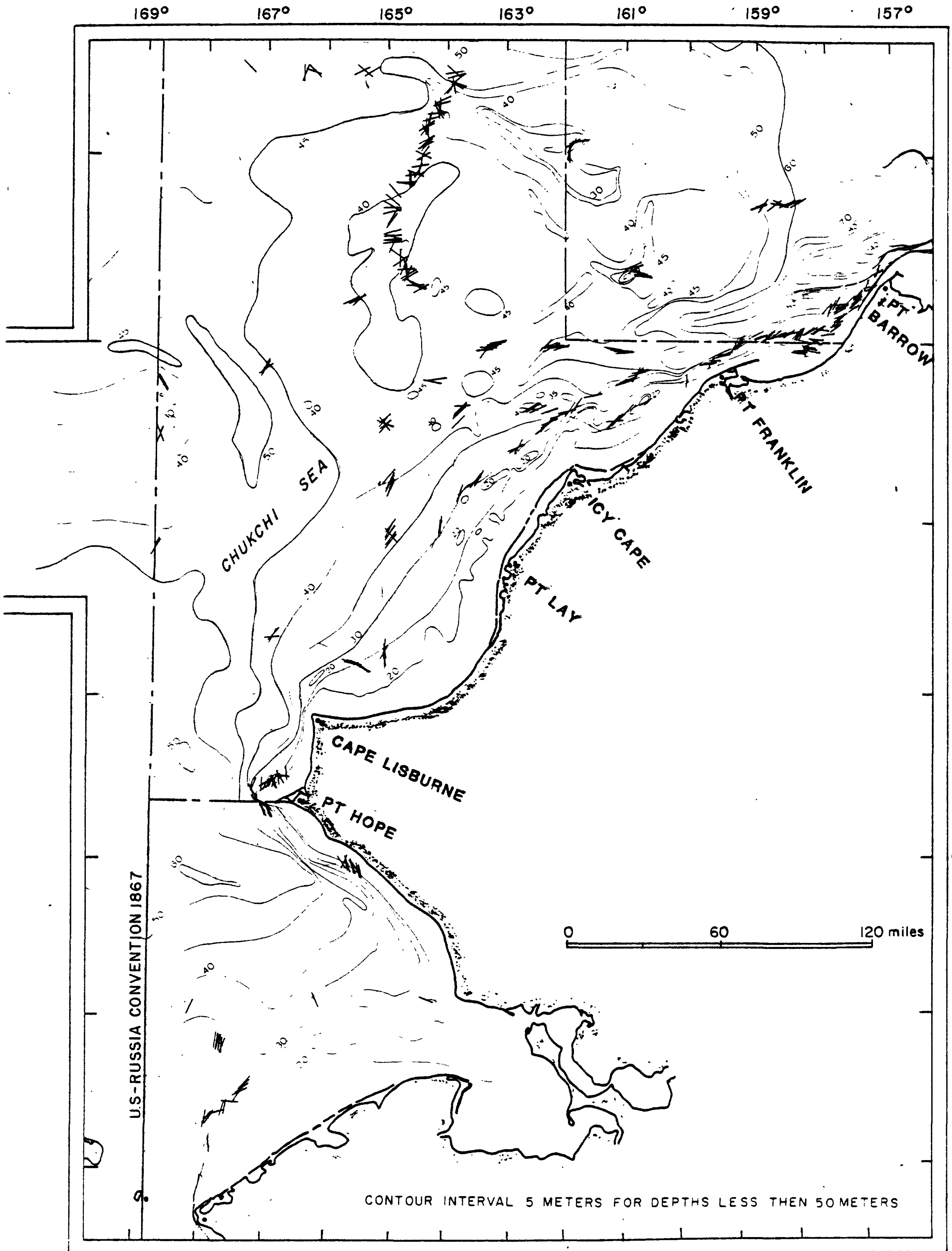


Figure 18.--Dominant ice gouge azimuths on the seabed of the Chukchi Sea (from Toimil, L. J., Reimnitz, E., and Grantz, A., unpublished data).

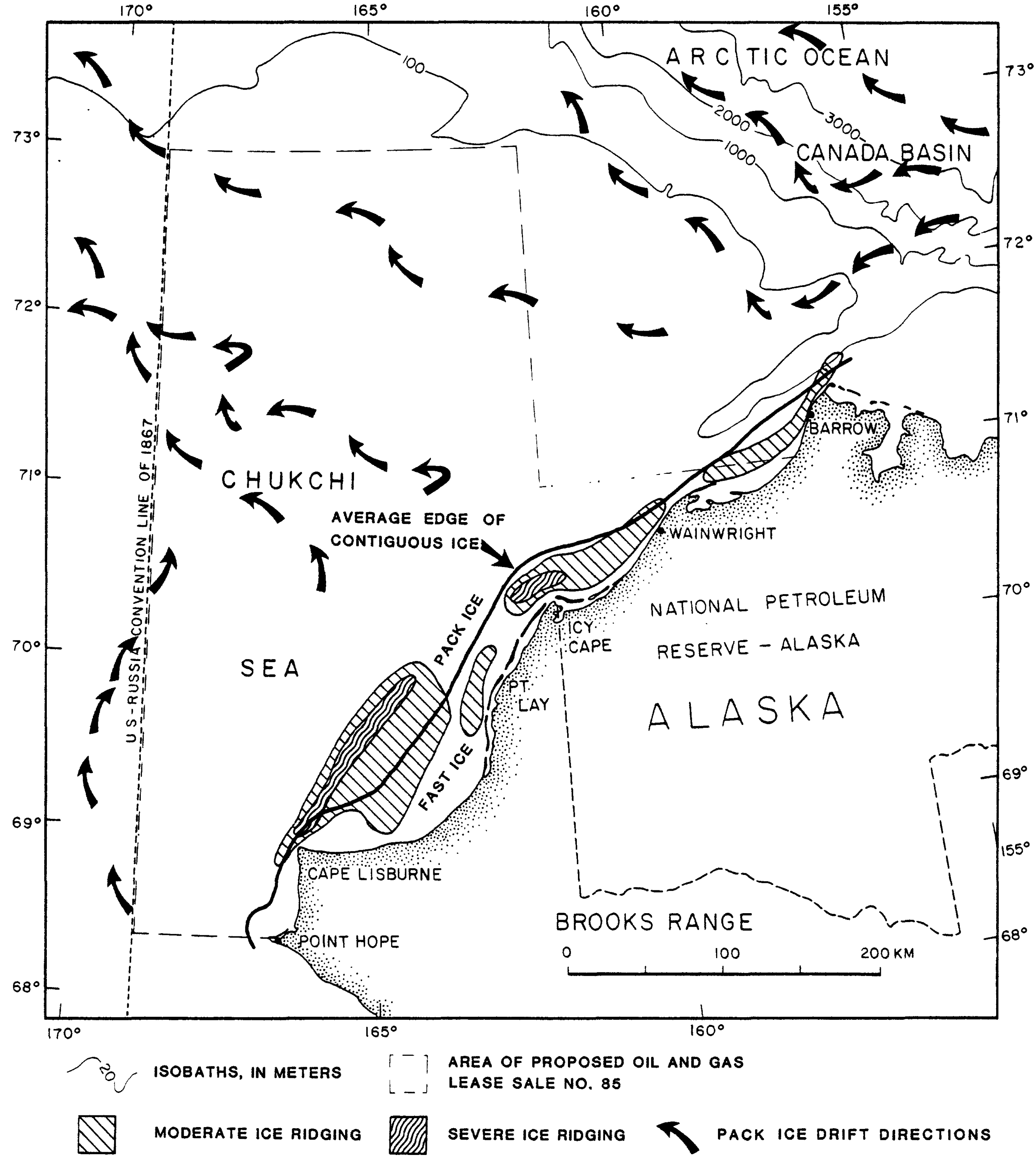


Figure 19. Coastal ice zonation, areas of ice ridging and direction of pack ice movement. The contiguous ice boundary represents the seaward boundary of stationary ice (fast ice). The areas of ice ridging represent regions of ice groundings and correspond to the stamukhi zone (data from Stringer, 1978). Drift direction of pack ice determined by monitoring buoys from March to September.

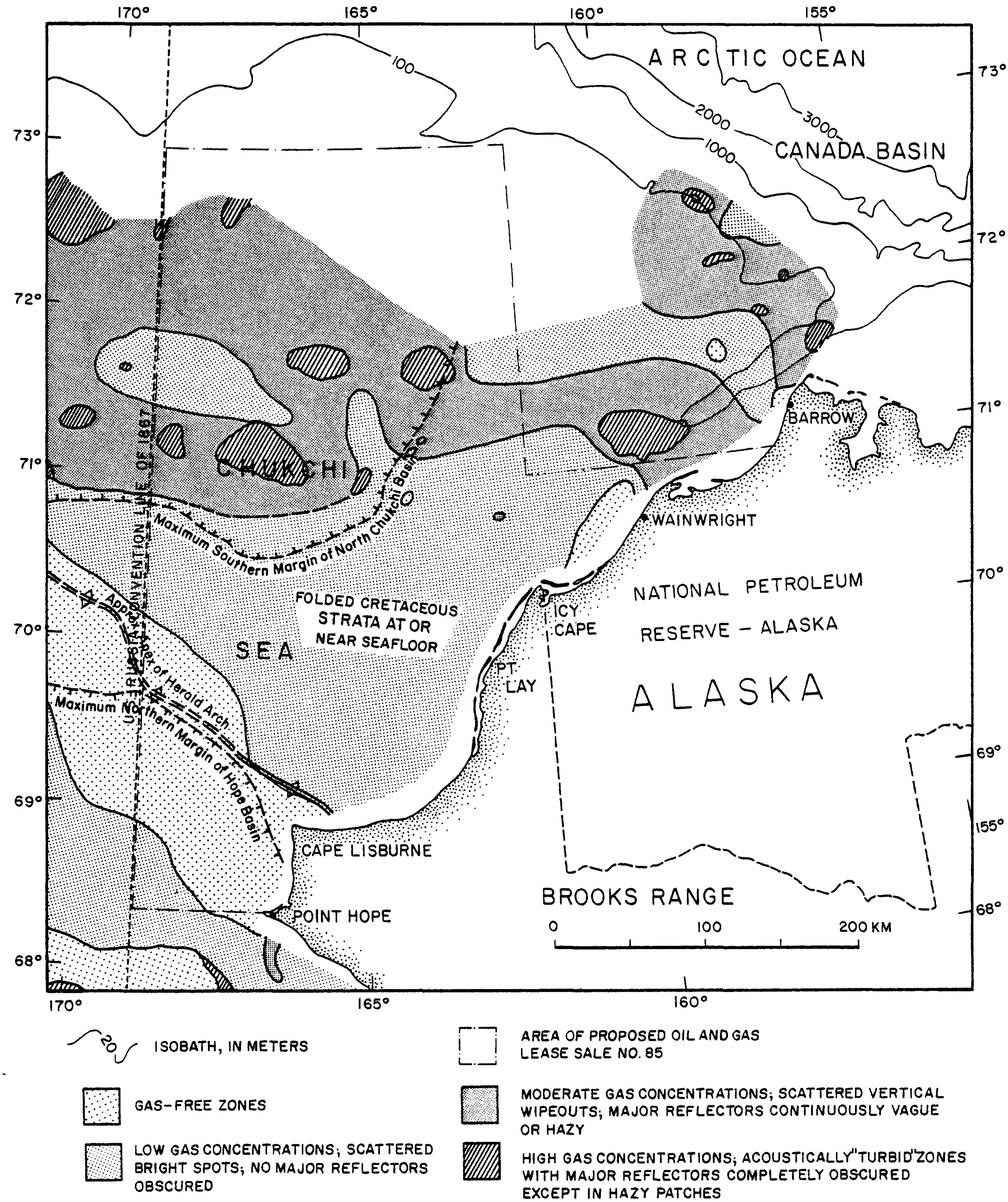


Figure 20.--Distribution of inferred shallow (down to 100 m subseabed) free gas concentrations in the Chukchi Sea. Interpretations are based on the occurrence of acoustic "turbidity" on high-resolution (Uniboom) reflection seismic profiles shown in Figure 1

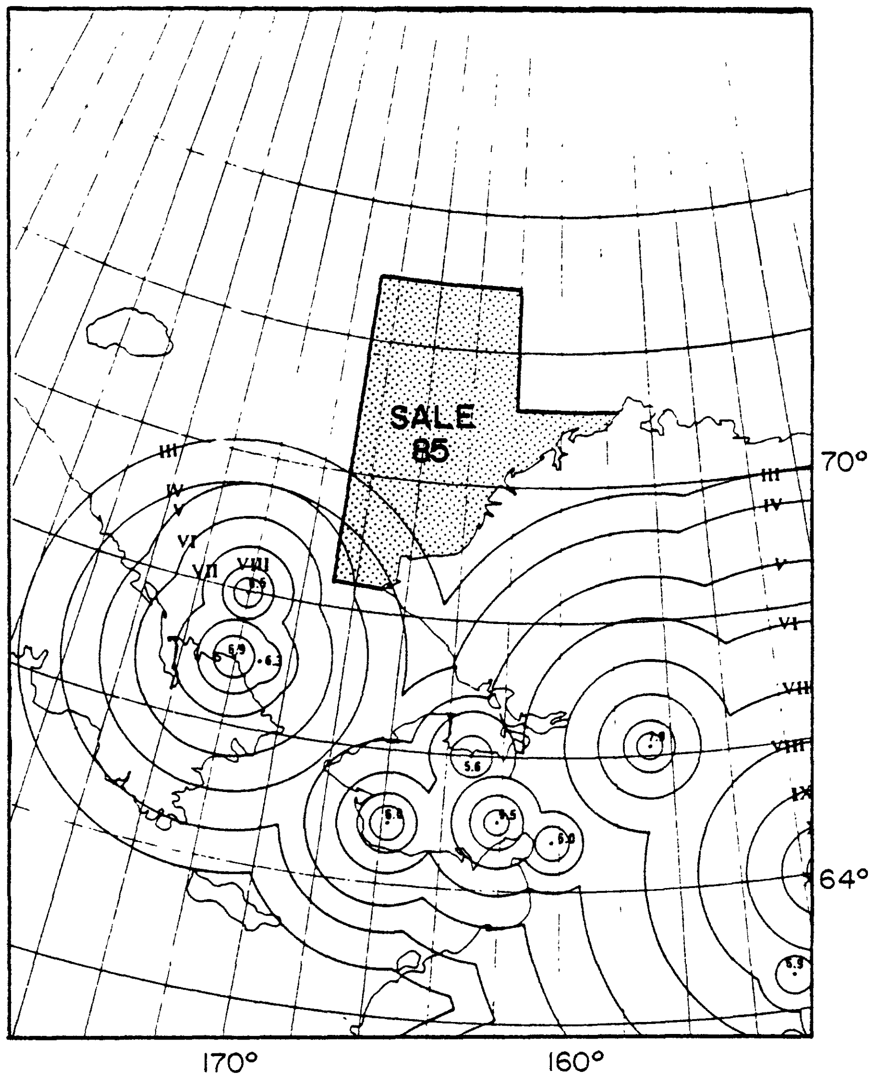


Figure 21.--Isoseismal map showing projected maximum intensities of major earthquakes in northwestern Alaska through 1974 (from Meyers, 1976).

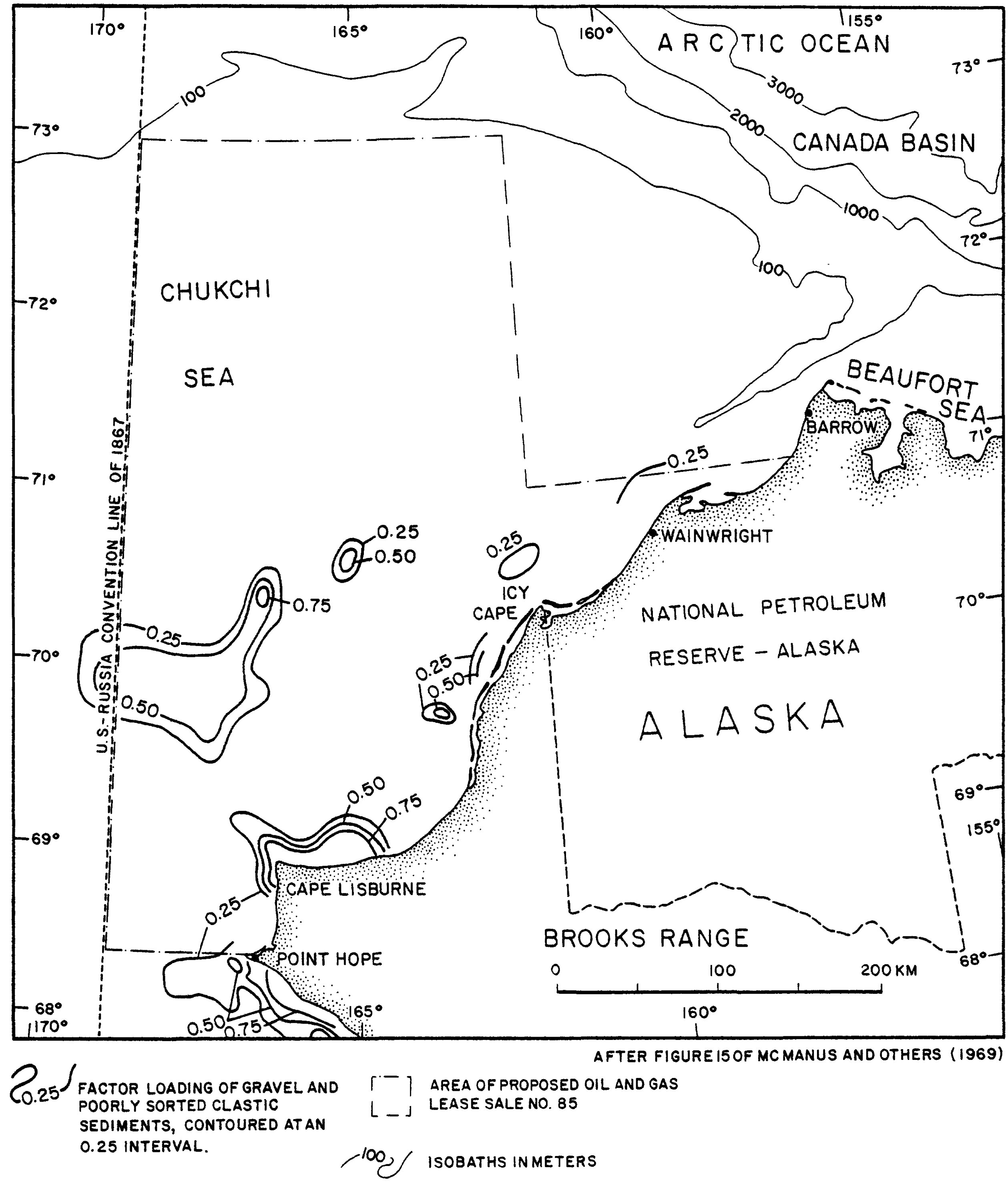


Figure 22.--Distribution of surficial gravel on the Chukchi seafloor (from McManus and others, 1969). High values indicate high gravel concentrations

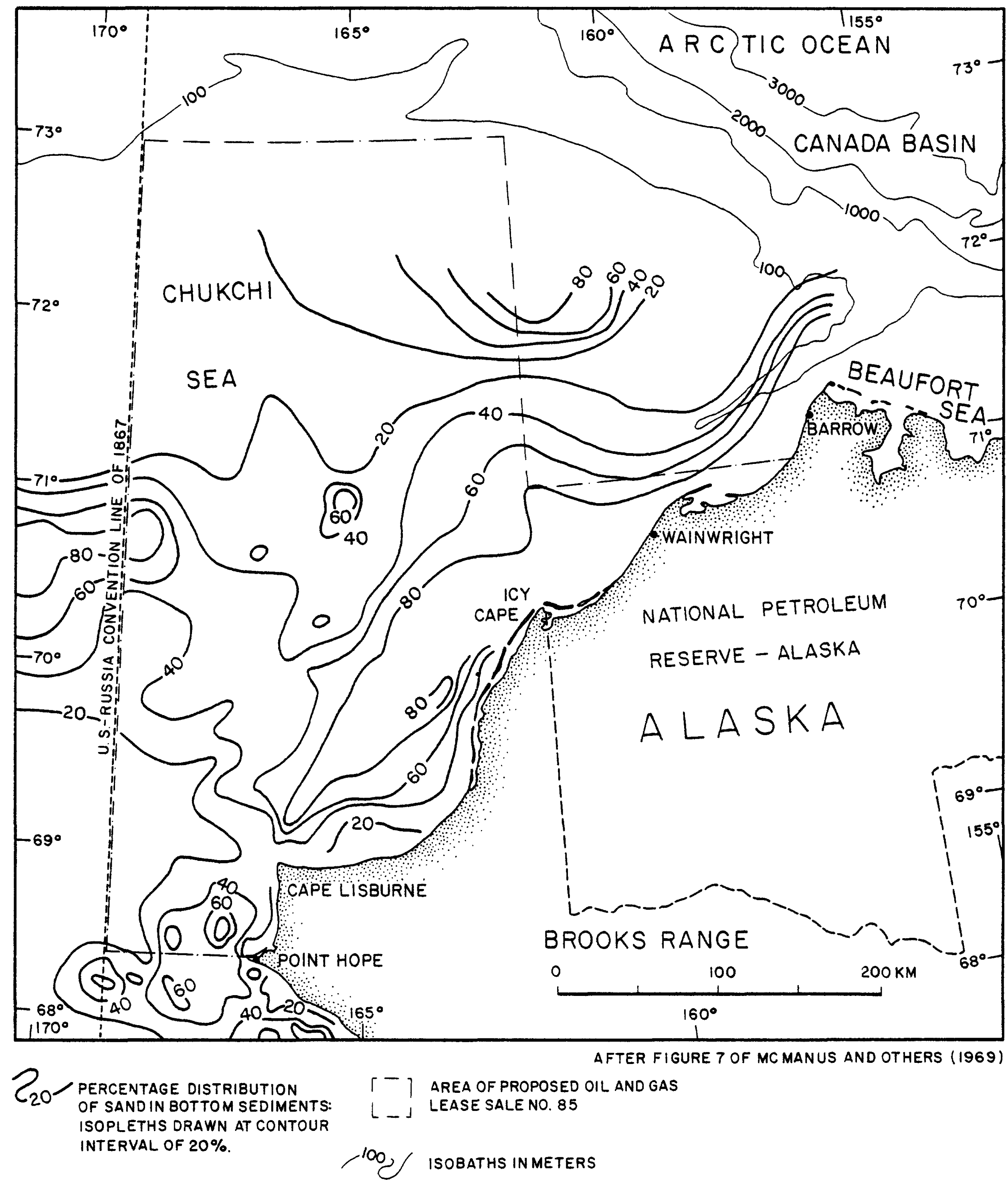


Figure 23.--Distribution of surficial sand on the Chukchi seafloor (from McManus and others, 1969).

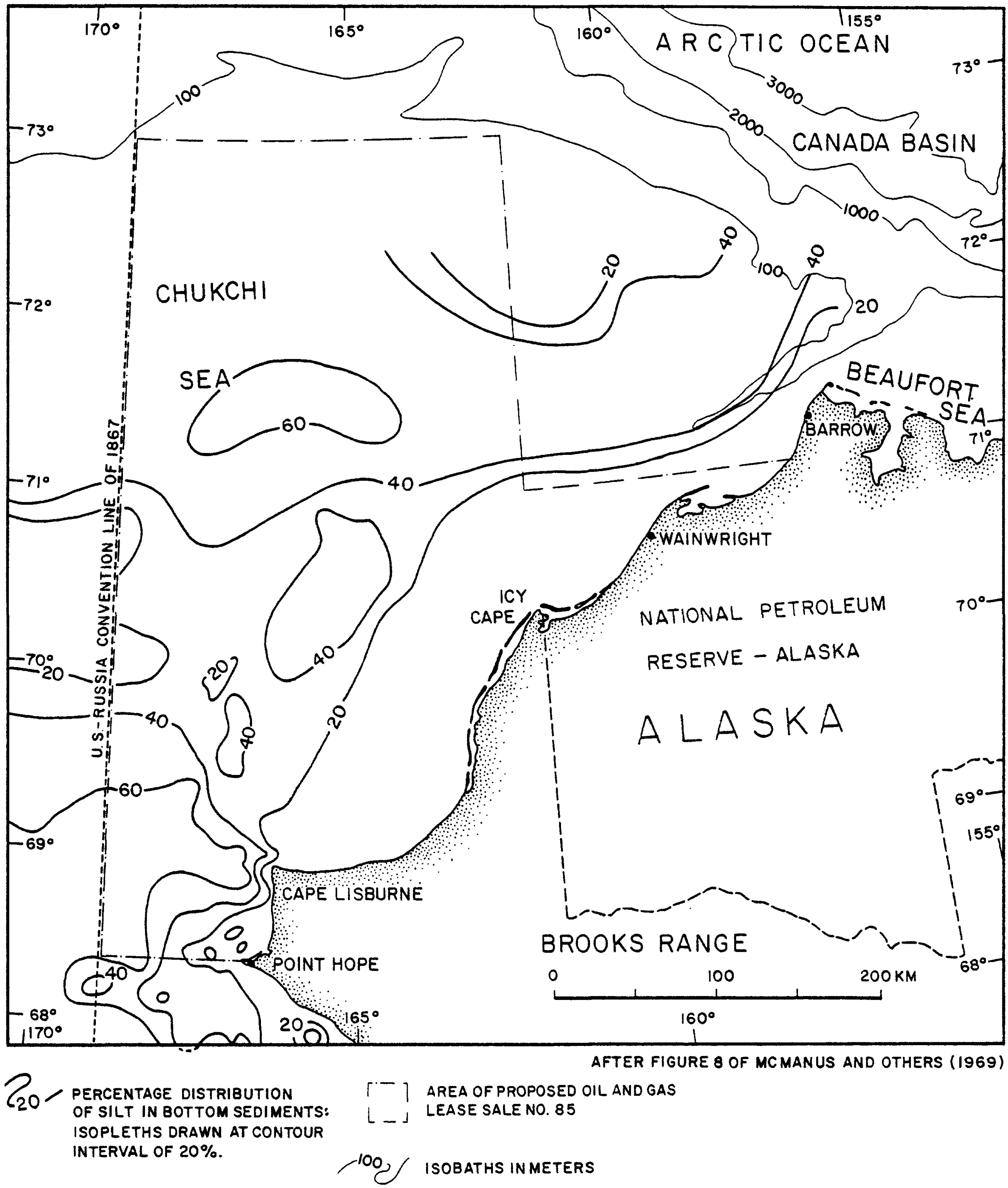


Figure 24.--Distribution of surficial silt on the Chukchi seafloor (from McManus and others, 1969).

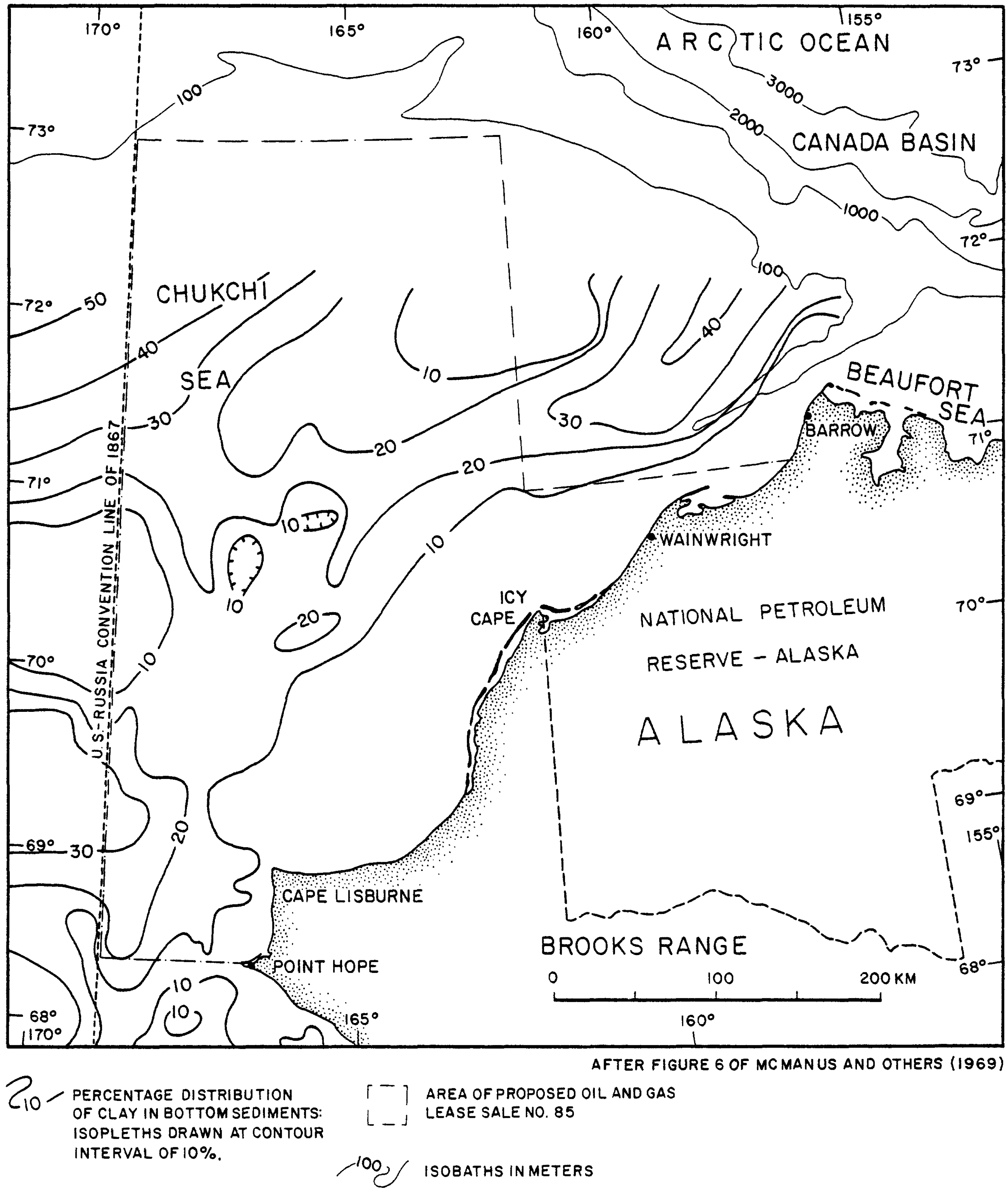


Figure 25.--Distribution of surficial clay on the Chukchi seafloor (from McManus and others, 1969).

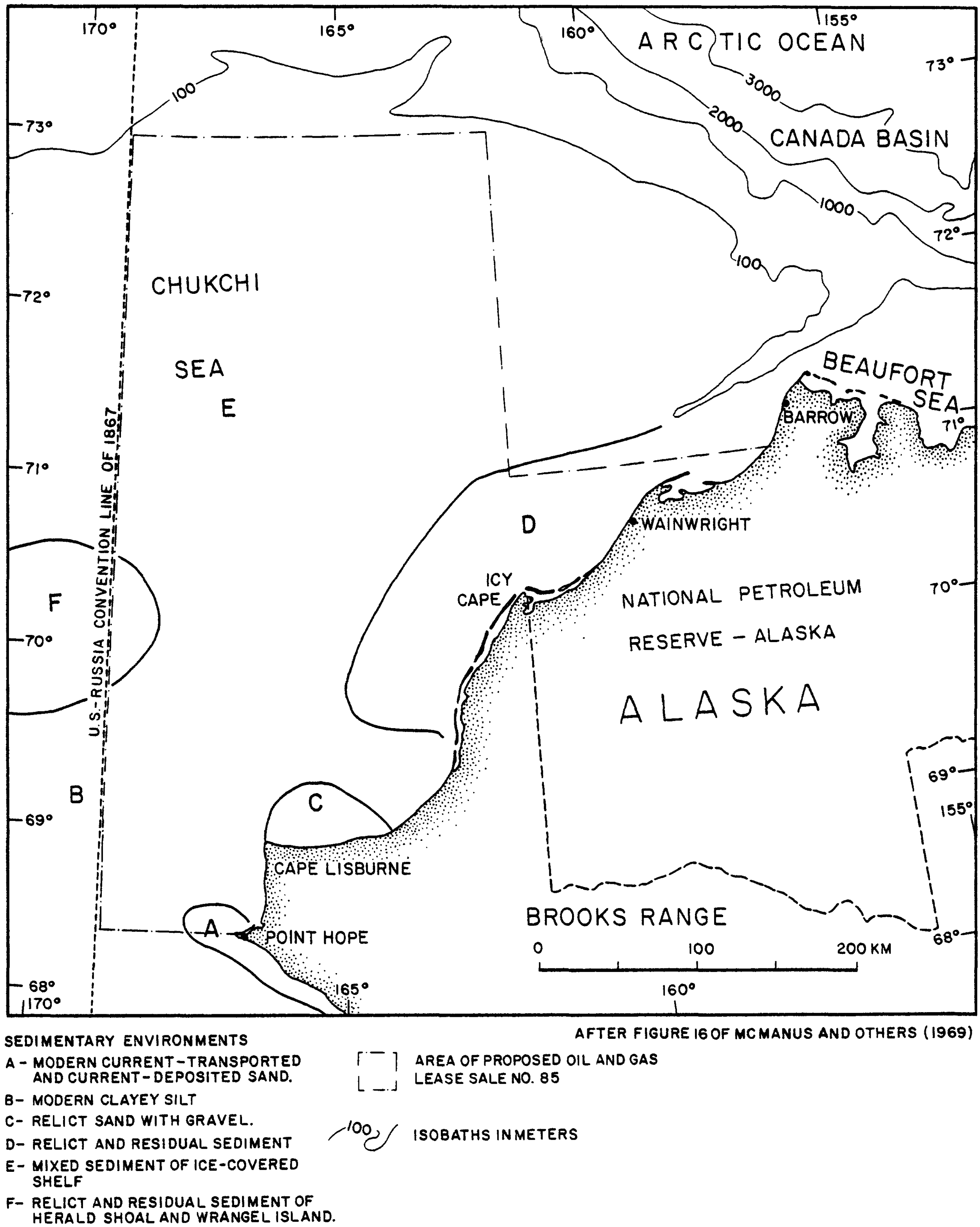


Figure 26.--Sedimentary environments of the Chukchi Sea (from McManus and others, 1969).

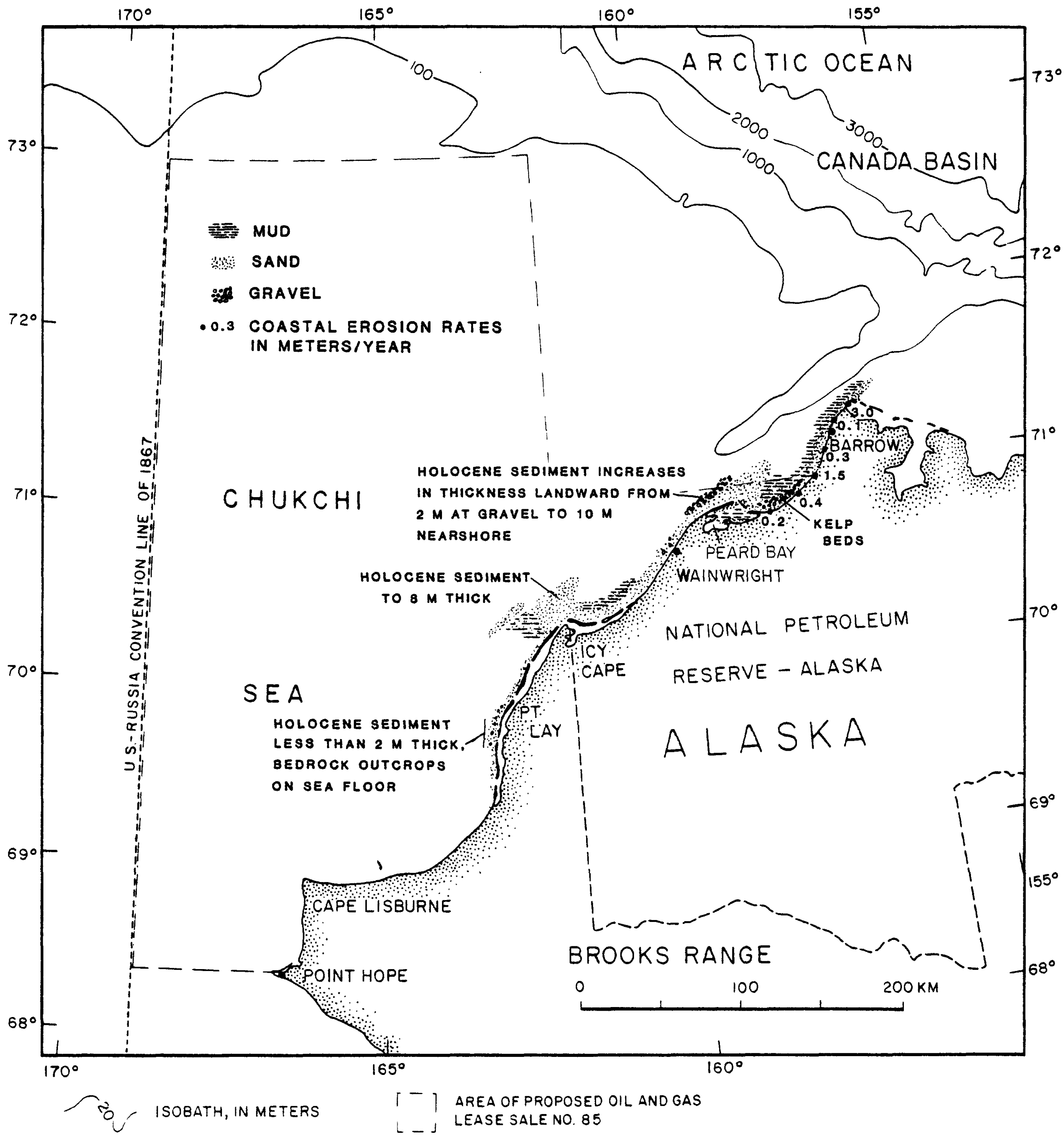


Figure 27. Nearshore character of surficial sediments and coastal erosion rates. The Holocene sediment increases in thickness toward the barrier islands. Coastal erosion rates are low, averaging 0.3 m per year for the area south of Barrow; data are lacking for the rest of the coastal regions, but these can be expected to have similar erosion rates.

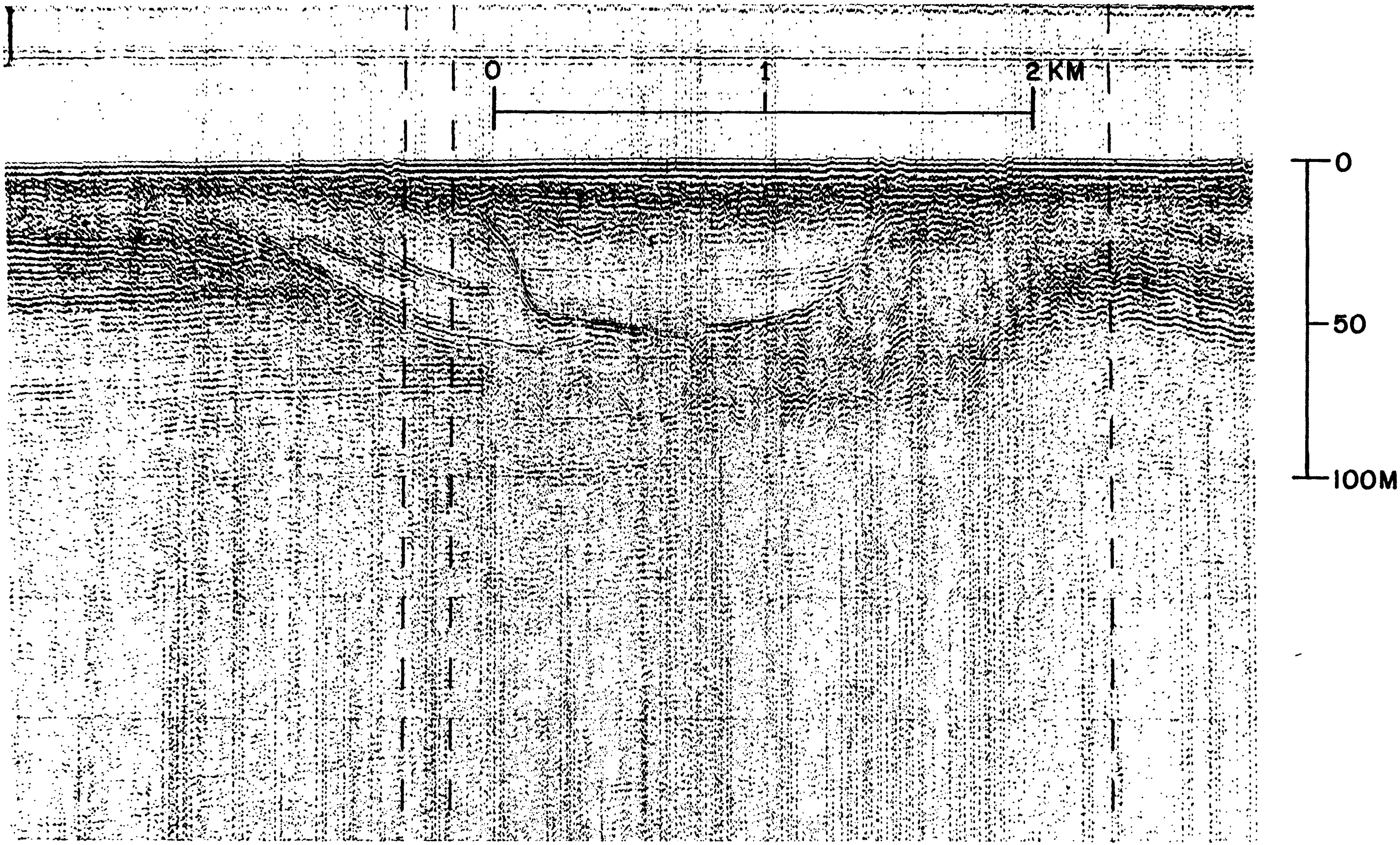


Figure 28.--High-resolution (Uniboom) seismic-reflection record of a large, typical paleovalley on the Chukchi shelf. Such features are numerous in some areas, and may serve as gravel sources.

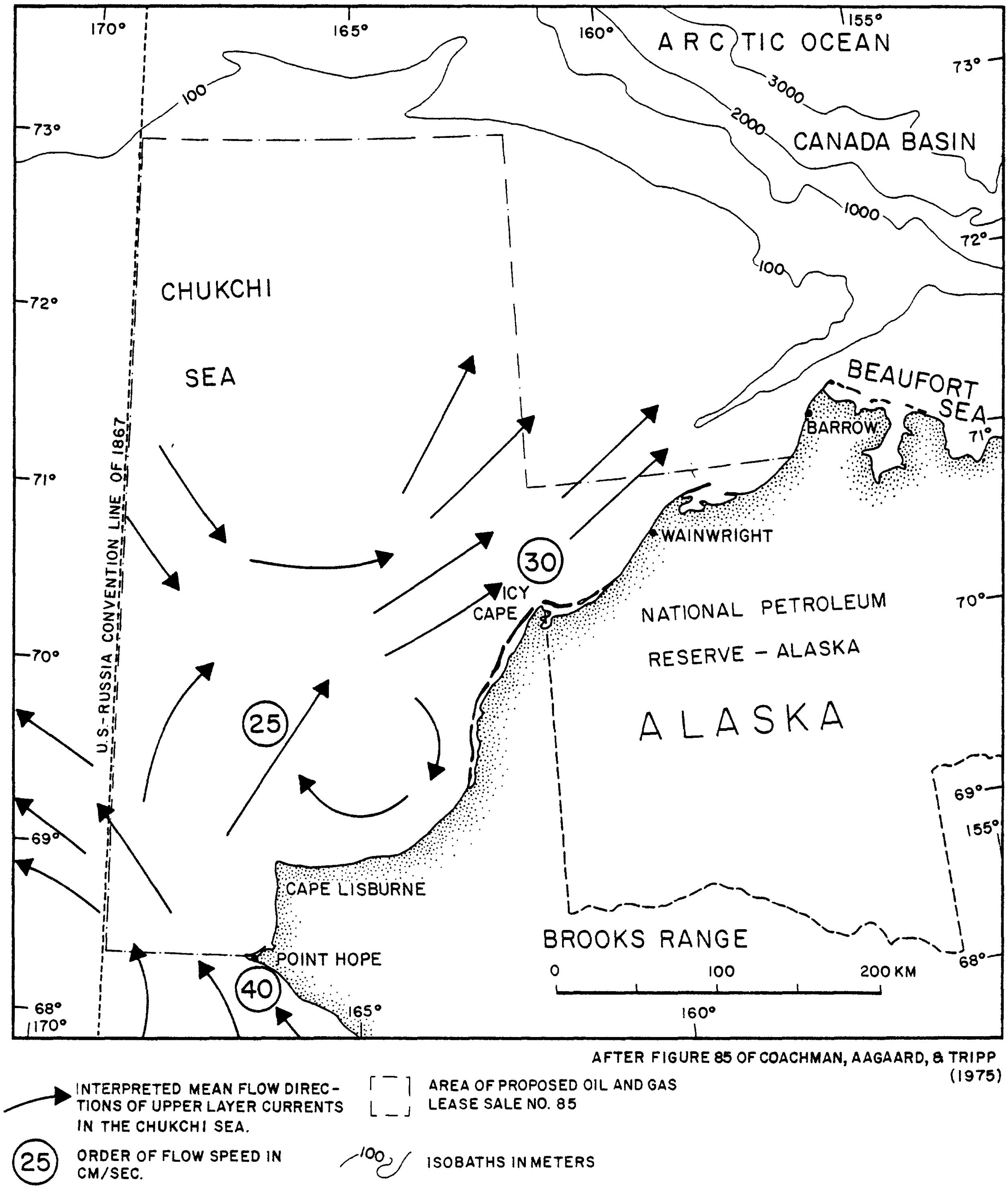


Figure 29.--Upper layer currents in the north Chukchi Sea (from Coachman and others, 1975).

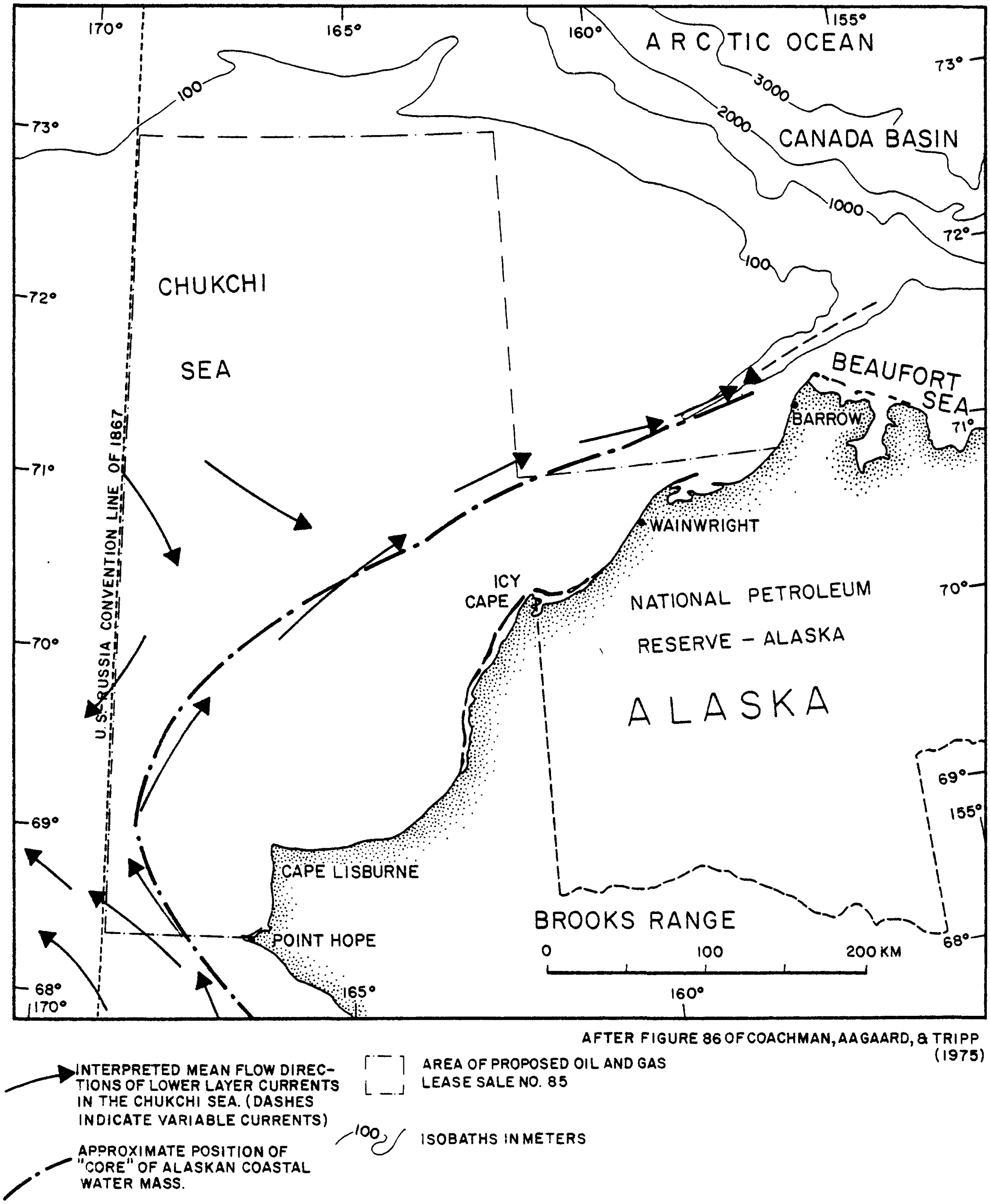


Figure 30.--Lower layer currents in the north Chukchi Sea (from Coachman and others, 1975).