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GEOLOGIC REPORT FOR THE CHUKCHI SEA PLANNING AREA, ALASKA

Regional Geology, Petroleum Geology, and Environmental Geology

by

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ABSTRACT

The Chukchi Sea Planning Area encompasses approximately 49,000 square miles of the northwestern Alaska continental shelf and is tentatively scheduled for public offering as Lease Sale 109 in early 1988. The planning area lies offshore of the National Petroleum Reserve in Alaska (NPRA), which provides geological and geophysical control for offshore interpretations. Three major stratigraphic sequences are recognized in northwestern Alaska: (1) the Franklinian sequence (Precambrian to Middle Devonian metasedimentary rocks), which comprises the acoustic and economic basement complex throughout most of northern Alaska; (2) the Ellesmerian sequence (Late Devonian to Early Cretaceous), which is composed of northerly sourced clastic and carbonate rocks; and (3) the Brookian sequence (Early Cretaceous to Tertiary), which comprises a clastic wedge that was shed generally northward away from the Brooks Range orogen. The Ellesmerian sequence is separated from the underlying basement by the Ellesmerian unconformity (EU) and from the overlying Brookian sequence by the Lower Cretaceous unconformity (LCU). Offshore, the Ellesmerian seismic sequence is subdivided into lower and upper parts by a Permian unconformity (PU). The Brookian seismic sequence is subdivided into lower and upper parts by the mid-Brookian unconformity (mBU) of Late Cretaceous(?) to Tertiary age.

Four major sedimentary basins are identified in the planning area: (1) the Ellesmerian-age depocenter informally termed the Central Chukchi basin, which forms a north-trending, offshore extension of the Arctic Alaska basin and contains up to 40,000 feet of layered carbonate and clastic strata; (2) the North Chukchi basin, which contains more than 45,000 feet of lower and upper Brookian clastic strata; (3) the Northern Hope basin, which contains up to 17,000 feet of Late Cretaceous(?) to Quaternary clastic deposits; and (4) the structural margins of the mid-Paleozoic Northeast Chukchi basin. In addition, the Central Chukchi basin contains two younger, superposed structural subbasins: (1) the Colville basin, which contains in excess of 20,000 feet of lower Brookian clastic deposits; and (2) the Northcentral subbasin, which contains up to 8,400 feet of upper Brookian stratified clastic rocks.

In addition to the major basins, tectonic provinces recognized in the planning area include the Late Devonian(?) to Cretaceous Chukchi platform in the west, the Arctic platform in the east, and the Late Cretaceous(?) to Tertiary North Chukchi high in the

northeast. Additional major structural features include the Late Devonian to Early Mississippian Barrow, Wainwright, and Northeast Chukchi fault zones; the Early to Late Cretaceous Fold and Thrust belt; the Late Cretaceous(?) to Tertiary Herald arch, Herald thrust fault, Hanna wrench-fault zone, and diapirs. Many local structural features are associated with the Hanna wrench-fault zone, including flower structures and tectonic sagging and upwarping.

The complex stratigraphic and tectonic histories, combined with numerous structural features, suggest a favorable environment for the generation, migration, and entrapment of hydrocarbons. Seismic extrapolations from wells in western NPRA indicate that known potential Ellesmerian and Brookian source rocks probably extend offshore, but these same wells predict a paucity of reservoir rock. Seismic interpretation suggests that reservoir sequences may have been deposited in source-proximal settings on the Chukchi platform. Reservoir quality of sandstones in the upper Brookian sequence offshore may be relatively high due to reworking of older sandstones of the underlying lower Brookian sequence. Of the three major seismic sequences in the planning area, the Ellesmerian sequence is considered the most prospective because it contains most of the major commercial hydrocarbon accumulations on the North Slope of Alaska.

The most prospective areas for the occurrence of large hydrocarbon accumulations are likely to be found along the margins of the Central Chukchi basin. The western margin, in particular, has high potential because of its proximity to the persistent tectonic highlands of the Chukchi platform. Furthermore, traps within Ellesmerian and lower Brookian strata on the Chukchi platform may not have been buried deeply enough to have become thermally overmature for the preservation of liquid hydrocarbons. Areally large stratigraphic traps are recognized along both margins of the Central Chukchi basin, in addition to broad domes, fault traps, and complex wrench-fault traps (flower structures). Traps associated with diapirism are found in the northern parts of the Chukchi platform.

Beneath the Northcentral subbasin, lower Brookian and older sequences are buried to sufficient depths to be thermally mature. Numerous fault traps and anticlinal features within the upper Brookian basin fill are associated with the Hanna wrench-fault zone, which crosses the Northcentral subbasin.

The thick Brookian sequence in the North Chukchi basin also exhibits possible trapping configurations that have potential for hydrocarbon accumulations. Other prospective areas include the margins of the North Chukchi high, where traps associated with thrust faults, normal faults, and folds are present in Ellesmerian and lower Brookian strata. The Fold and Thrust belt is considered to be only moderately prospective because the deformed lower Brookian strata appear to consist predominantly of thermally overmature shale. The Northern Hope basin is not considered prospective because small, shallow fault traps, which do not apear to have access to thermally mature strata, form the only identifiable prospects.

The seafloor of the planning area is characterized by a broad continental shelf that lies in water depths generally less than 200 feet and is slightly inclined to the north. The heads of three subsea valleys lie just within the northern and northeastern margins of the planning area. In the northern part of the planning area, the shelf is underlain by Pleistocene sediments that have been extensively channeled and subsequently filled. In the southern part, the shelf is formed by the seafloor subcrop of folded and truncated lower Brookian strata.

Geologic hazards to petroleum exploration and development include possible shallow gas, Quaternary faults (indicated by seafloor fault scarps), and ice gouging. Of all possible engineering constraints posed by the physical environment, however, the movement of sea ice is the most formidable. Pack ice covers much of the planning area for most of the year, and gouges in the seafloor produced by the grounding of bergs or ice islands pose a potential threat to bottom-founded or seafloor structures, such as drill-ship anchors, well heads, and pipelines.

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INTRODUCTION

This report is a summary of the regional geologic framework, hydrocarbon potential, and shallow geology of the Chukchi Sea (formerly Barrow Arch) Planning Area. It was prepared as part of the support documentation for Federal OCS Lease Sale 109, tentatively scheduled for early 1988. The report discusses previously undocumented regional geologic features and reviews and refines previously published concepts. The analysis is focused upon the petroleum potential of this remote but highly promising area. The discussion of offshore geology is based almost entirely on interpretations of high-quality common-depth-point (CDP) seismic reflection data collected by Western Geophysical Company (WGC) and Geophysical Service Incorporated (GSI), who have generously allowed us to use selected seismic lines to illustrate the regional geology of the Chukchi Sea Planning Area. The Chukchi Sea Planning Area is a frontier exploration province and remains completely untested by drilling. Publicly available well control is restricted to the western parts of the National Petroleum Reserve in Alaska (NPRA). Because of the remoteness of these wells, they are of limited use in providing regional stratigraphic control for our seismic interpretation. Major differences exist between the regional seismic stratigraphy and structure of the planning area and the onshore areas. Therefore, our analysis of the geology of this remote area remains somewhat speculative.

The Chukchi Sea Planning Area encompasses approximately 49,000 square miles (127,000 sq km) of the northwestern Alaska Chukchi Sea Outer Continental Shelf (fig. 1). The planning area is bordered on the southeast by the Alaska coastal 3-mile limit, and on the northeast by the 162 degrees west longitude and the 71 degrees north latitude lines and their intersection. The northern boundary is formed by the 73 degrees north latitude line, west to the U.S. - Russia Convention Line of 1867, which forms the western boundary. The southern boundary is a line extending west from Point Hope.

Based on projected industry interest and future technology development, the National Petroleum Council (1981) concluded that offshore exploration in the Arctic in the near future will be confined to the continental shelf where water depths are less than about 200 feet. Over 90 percent of the planning area lies on the continental shelf in water depths shallower than 200 feet. However, serious logistical and technological difficulties associated with the

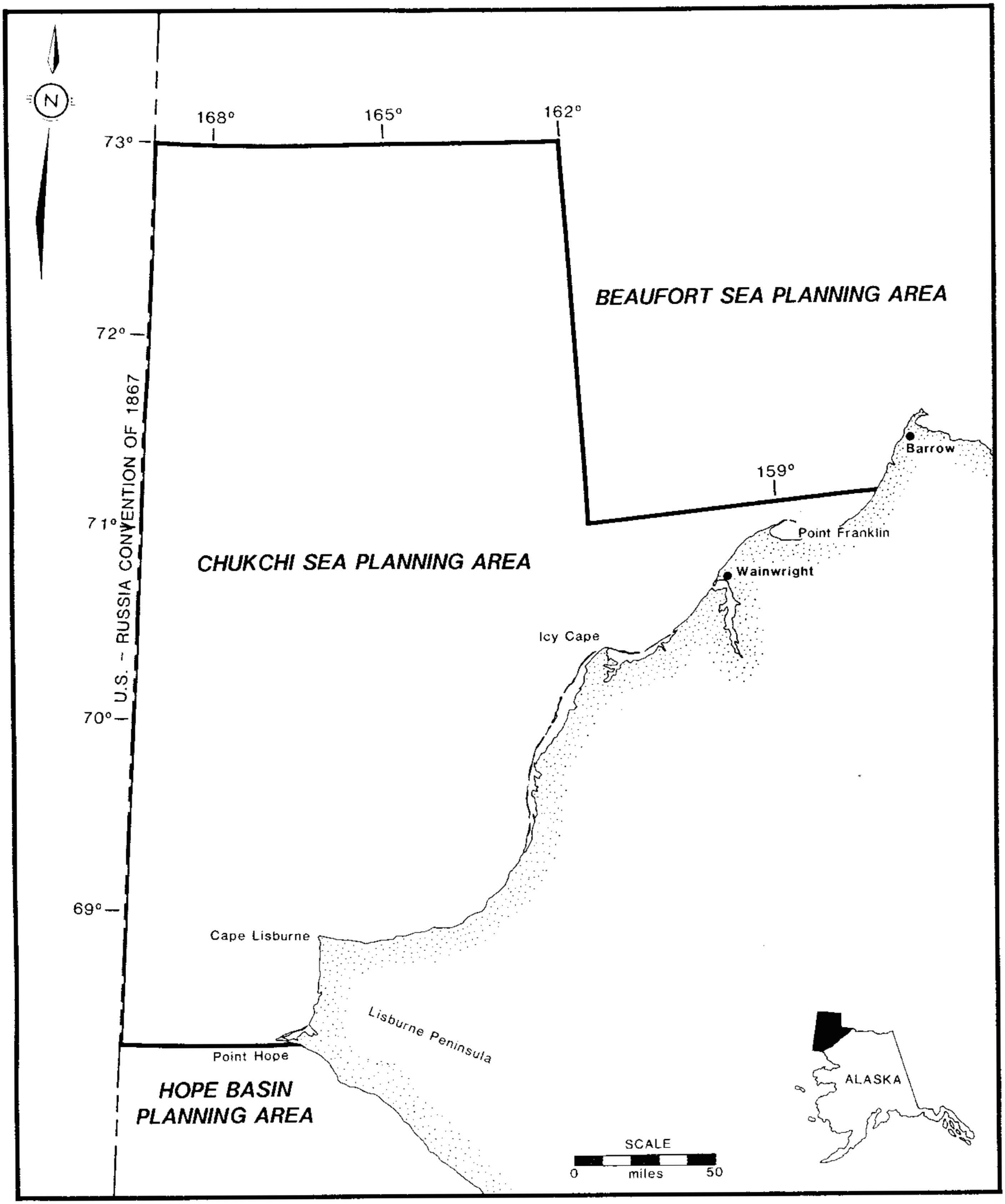

FIGURE 1. Index map for the Chukchi Sea Planning Area.

Arctic ice pack, which covers the area most of the year, and the great distances from shore-based staging areas, are major considerations that will affect the economic feasibility of petroleum exploration and development in the Chukchi Sea Planning Area.

Previous evaluations of the petroleum potential of the Chukchi Sea Planning Area have been made by the United States Geological Survey (USGS) and Minerals Management Service (MMS) (Grantz and others, 1982b; Grantz and May, 1984a; Cooke, 1985). Our recent studies of high-quality CDP data collected by industry have led to the identification of new major structural features and further delineation of previously described basins. We now recognize a great diversity and number of petroleum plays within the planning area, and conclude that there is high potential for the occurrence of significant hydrocarbon accumulations. The potential occurrence of unconventional hydrocarbon accumulations such as gas hydrates is not considered in this report, nor is the potential occurrence of economically significant nonenergy minerals such as gravel and placer metals.

This report identifies many new structural features and geologic trends which occur within regional tectonic settings that differ greatly from that of the North Slope. For that reason we have included a chapter that reviews the structure and tectonic framework of the North Slope. This review is also presented because traditional stratigraphic nomenclature is applied to the seismic sequences of the Chukchi Sea Planning Area, and because the evaluation of the petroleum source and reservoir potential of rocks in the planning area is based primarily on information projected from onshore wells.

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1. REGIONAL STRUCTURAL AND TECTONIC FRAMEWORK OF THE NORTH SLOPE

The geology of northwestern Alaska is dominated by several regional structural features that trend generally northwest (fig. 2). These are, from north to south, (1) the modern continental shelf break, (2) the Hinge Line fault zone, (3) the Barrow arch, (4) the Arctic platform, (5) the Foreland fold belt, (6) the Colville basin, and (7) the Brooks Range. These structural features are manifestations of tectonic events that affected the North Slope region in middle to late Paleozoic time and again in late Mesozoic to Cenozoic time. Evidence presented below in chapter 3 (Seismic Stratigraphy) and chapter 4 (Structural Provinces) indicates that these regional features change trend, structural expression, or are absent in parts of the Chukchi Sea Planning Area.

The Arctic platform is the oldest of the major regional features, consisting of Middle Devonian(?) or older metamorphic rocks that constitute acoustic and economic basement. These rocks underlie most of northern Alaska and are truncated at a low-relief unconformity (the Ellesmerian unconformity, or "EU") which slopes gently southward from the Barrow arch (fig. 3a). The Arctic platform is thought to have formed a broad shelf area on the northern flank of the late Paleozoic to Mesozoic Arctic Alaska basin (Brosgé and Tailleur, 1971), which deepened to the south toward the present Brooks Range. The basement rocks of the Arctic platform have been interpreted to be the southern extension of the orogenic terrane that existed north of the present Arctic coast (Drummond, 1974) prior to continental fragmentation in late Mesozoic time. In NPRA, the southern part of the Arctic platform is punctuated by local fault-bounded horsts and basins such as the Meade arch, the Meade basin, and the Tunalik basin (fig. 2). These features were formed by late Paleozoic faulting (Tetra Tech, 1982). The Arctic platform thereafter remained relatively stable (fig. 3a) until Early Cretaceous time, when an episode of continental rifting opened the Canada Basin along a rift near the present Beaufort Sea continental margin (Grantz and May, 1984b).

The Beaufort Sea continental margin was created by Atlantic-type seafloor spreading that began in Late Jurassic to Early Cretaceous time (Grantz and Eittreim, 1979). Grantz and May (1984b) and Craig and others (1985) have identified structural features and stratigraphic relationships that suggest a breakup history similar to the model for passive-margin evolution proposed by Falvey (1974). In

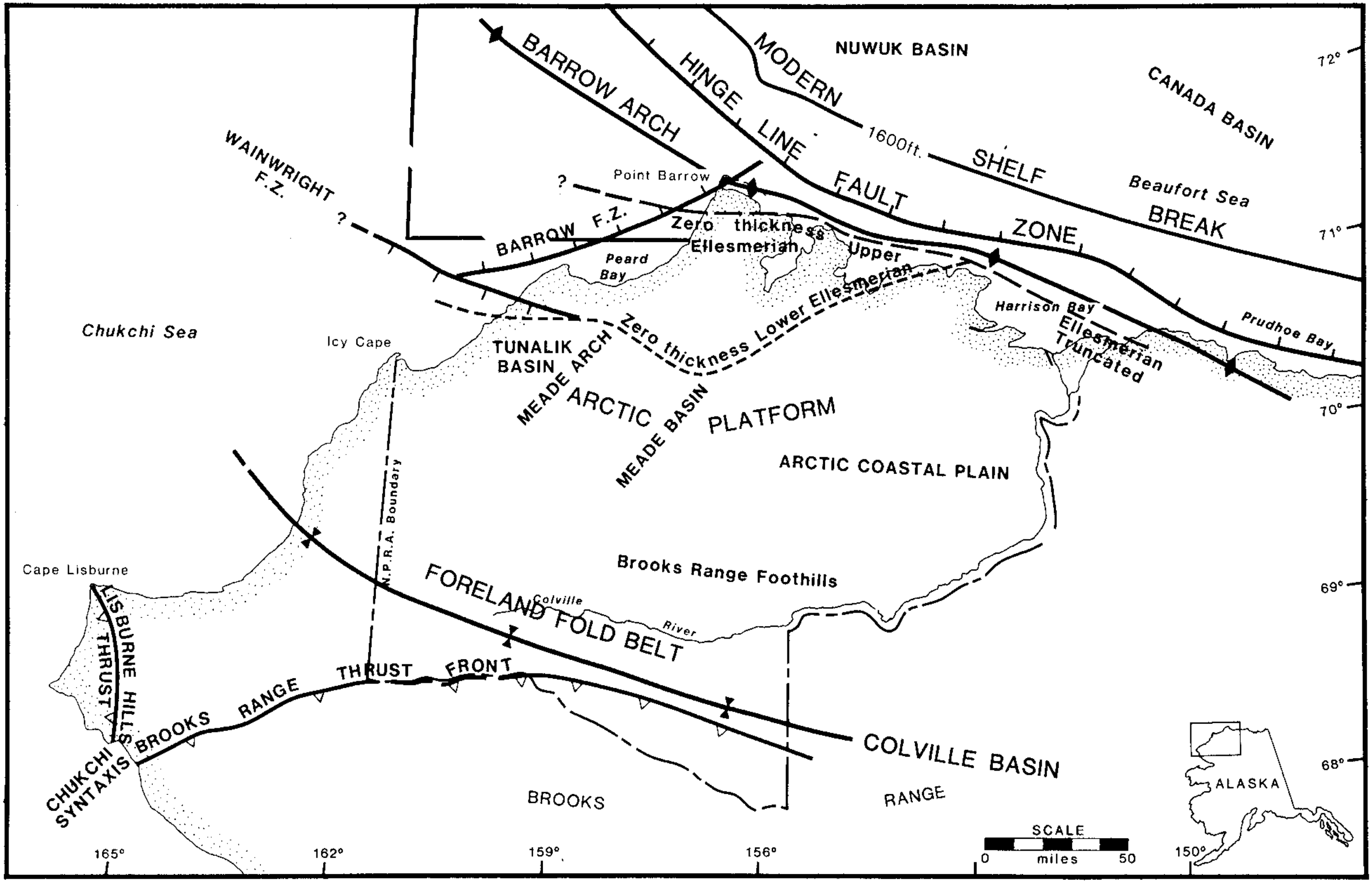
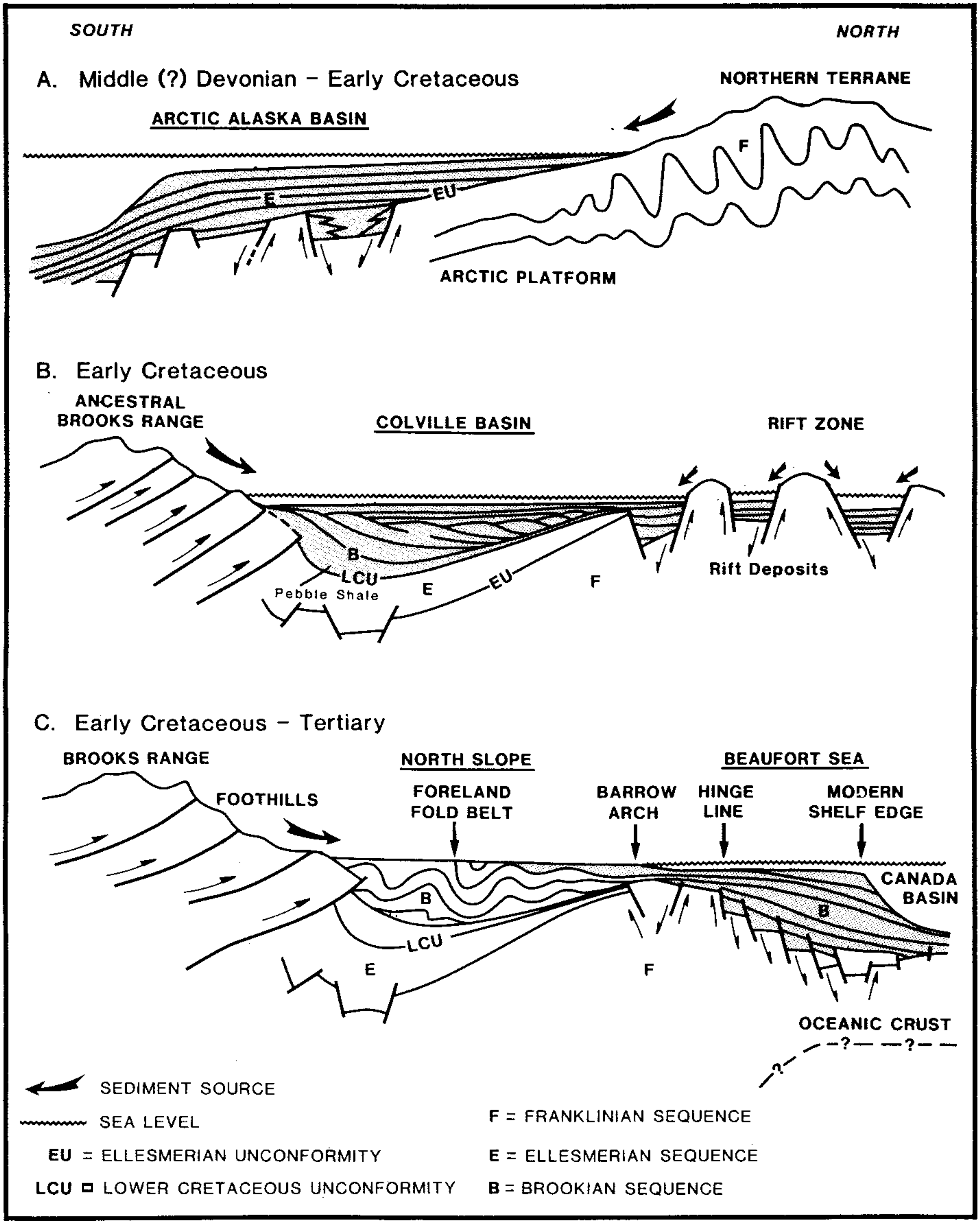


FIGURE 2. Major tectonic elements of northwestern Alaska and northeastern Chukchi shelf.



modified after Craig and others, 1985.

FIGURE 3. Schematic cross–section illustrating the geological evolution of northern Alaska. Shaded areas represent active depocenters during each major stage.

the context of the Falvey model, the pre-rift Lower Cretaceous unconformity (LCU), which truncates late Paleozoic to late Mesozoic strata on the northern Arctic platform, was apparently formed by regional uplift along the incipient rift zone. As the margin evolved, the northern part of the Arctic platform subsided as the Early Cretaceous rift widened (fig. 3b). Contemporary local grabens that formed along the rift are thought to have been filled with locally derived deposits correlative in age to basinal shales (Pebble Shale; fig. 3b) deposited to the south in the basal part of the Colville basin (Craig and others, 1985). The highly faulted crustal flexure on the northern edge of the present Arctic platform, termed the Hinge Line (Grantz and Eittreim, 1979), is a broad fault zone that may mark the transition from continental to oceanic crust at the former rift site (fig. 3c).

In contrast to the Early Cretaceous crustal extension in the north, which formed the Beaufort passive continental margin, the southern Arctic platform was subjected to contemporary crustal shortening that resulted in uplift of the ancestral Brooks Range and concomitant downwarping of a foredeep basin (Colville basin; fig. 3b). A major synorogenic clastic wedge prograded north and east from the Brooks Range into the Colville basin along the southern flank of the Arctic platform.

Early Cretaceous subsidence north of the Hinge Line fault zone and contemporary subsidence of the Colville basin formed a major intervening structural ridge termed the Barrow arch (Grantz and Eittreim, 1979) (fig. 3c). The Barrow arch generally trends parallel to, and lies south of, the Hinge Line fault zone, and is usually associated with a basement ridge on the faulted edge of the Arctic platform. However, as reported by Craig and others (1985), the Barrow arch does not coincide with structurally elevated basement rock beneath the northeastern Chukchi shelf.

The present Brooks Range was created by the continuation of northward-directed thrusting in Late Cretaceous to Tertiary time (fig. 3c). This tectonic front moved north through time, eventually deforming older synorogenic (Lower Cretaceous) sediments in the Colville basin. These strata were folded and thrust-faulted above a basal detachment zone to form the Foreland fold belt of the Brooks Range Foothills (fig. 2). Early Cretaceous to Tertiary sediments that were shed north from the Brooks Range overstepped the Barrow arch and accumulated as a thick clastic wedge in subsiding shelf-margin basins north of the Hinge Line fault zone (e.g., Nuwuk basin of Grantz and others, 1982b).

These regional structures can be traced northwestward from the Canadian border to about 162 degrees west longitude (fig. 2). The shelf break, Hinge Line fault zone, Barrow arch, and Brooks Range, however, do not extend into the Chukchi Sea Planning Area. Furthermore, the westward structural extensions of the Paleozoic Arctic platform, Cretaceous Colville basin, and the Foreland fold belt terminate in the eastern Chukchi Sea Planning Area. Offshore to the west of NPRA, late Paleozoic to Cenozoic structural ridges, fault zones, and sediment depocenters generally follow the north-south trends that typify the Chukchi Sea Planning Area. Structural features of the planning area were evidently formed by very different tectonic processes than the structures onshore and will be discussed in greater detail in chapter 4.

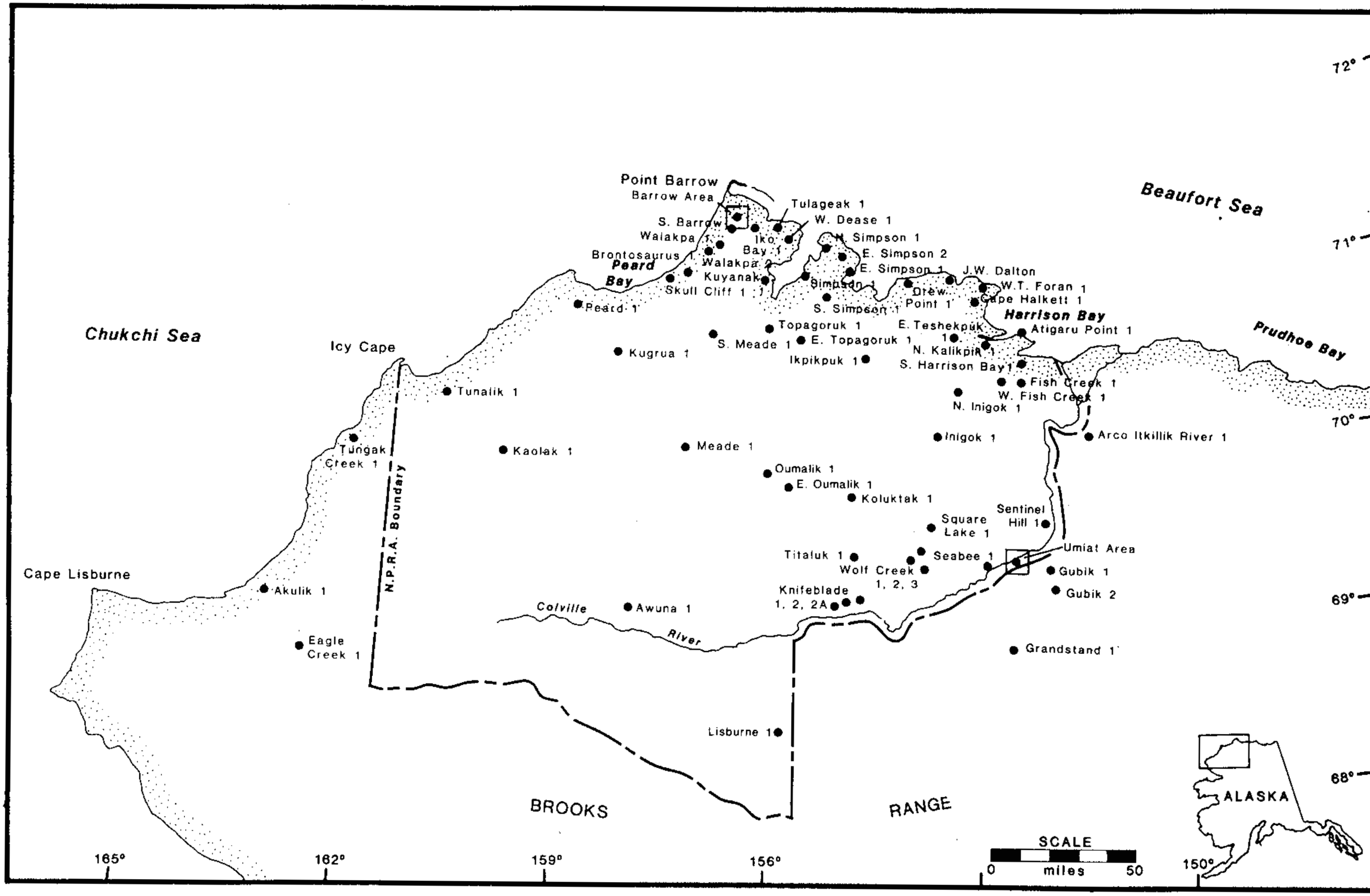
2. STRATIGRAPHY AND STRATIGRAPHIC TRENDS OF THE NORTH SLOPE

The stratigraphy of Arctic Alaska is documented by outcrop data from the Brooks Range, by information from public wells in NPRA and from numerous exploratory wells drilled by industry on the North Slope and in the Beaufort Sea (fig. 4). Three regional stratigraphic sequences are recognized in Arctic Alaska, recording three major phases of tectonic development and sedimentation. They are, from oldest to youngest, the Franklinian, Ellesmerian, and Brookian sequences (fig. 5) (Lerand, 1973; Grantz and others, 1982b). The Franklinian sequence is composed of Cambrian to Middle Devonian carbonate and clastic rocks which were metamorphosed and deformed during several early Paleozoic tectonic events, the latest of which occurred during Late Devonian to Early Mississippian time and correlates to the Ellesmerian orogeny in northern Canada (Churkin, 1973; Drummond, 1974). Metamorphic basement rocks, commonly referred to as the Franklinian basement-complex, may also include Precambrian rocks (Lerand, 1973; Norris, 1985). The Ellesmerian sequence overlies the Franklinian basement-complex above a major diachronous unconformity and consists of mildly deformed Late Devonian to Early Cretaceous marine shelf deposits (Brosgé and Tailleur, 1971; Dutro, 1981). The major North Slope oil production (Prudhoe Bay and Kuparuk fields) is from rocks of the Ellesmerian sequence (Jamison and others, 1980). The Ellesmerian sequence is overlain unconformably by Early Cretaceous to Holocene strata of the Brookian sequence. The Brookian sequence consists of deep-marine to nonmarine sediments deposited in a major synorogenic wedge that prograded north and east from the Brooks Range (Grantz and others, 1982b; Huffman and others, 1986; Molenaar, 1983).

FRANKLINIAN SEQUENCE

(PRECAMBRIAN TO MIDDLE DEVONIAN)

The Franklinian sequence in northern Alaska consists of mildly to strongly metamorphosed clastic, carbonate, and some volcanic rocks, and is generally considered to be economic basement (Carman and Hardwick, 1983; Grantz and others, 1982b). On seismic records, these rocks usually also represent acoustic basement (Tetra Tech, 1982). Franklinian rocks were deposited in and along the margins of a deep basin (the Franklinian geosyncline) that was located near the modern Arctic coast of North America (Drummond, 1974). Volcanic



base map after Tetra Tech (1982, fig. 2.)

FIGURE 4. Index map for well control in northwestern Alaska.

rocks and deep-marine flysch (now argillite) are more common in Franklinian rocks to the north and northwest, and shelf deposits (largely carbonates) are more common in the south and east (Churkin, 1973; Drummond, 1974).

Wells in the Prudhoe Bay area, east of NPRA, bottomed in steeply dipping argillite and graywacke containing graptolites of Ordovician to Silurian age (Carter and Laufield, 1975). These rocks probably represent the deep-water northern facies of the Franklinian sequence. Wells drilled in northern and western NPRA have encountered argillite basement rocks (Brosgé and Tailleur, 1971). In wells in northernmost NPRA (Barrow area) the Franklinian basement is described as dark-gray to black, low-grade metamorphic argillite with variable dips, displaying foliations, quartz-filled fractures and pyrite inclusions (Husky, 1983g; 1983h). On the basis of radiometric and fossil data, these rocks are considered to range in possible age from upper Precambrian to Silurian (Brosgé and Dutro, 1973). Southwest of Barrow, adjacent to the Chukchi Sea Planning Area, the basement penetrated in the Peard No. 1 well is described as sub-metamorphic siltstone and shale of unknown age (Husky, 1982a). In central NPRA, wells encountered steeply dipping meta-sedimentary rocks containing coarse-grained sandstones, shales, and coal seams (e.g., South Meade No. 1, Topagoruk No. 1, Ikpikpuk No. 1 (Husky, 1982b; Tetra Tech, 1982; Husky, 1983e)). A tentative age of Middle to Late(?) Devonian has been assigned to these rocks on the basis of plant fragments (Collins, 1961) and spores (Anderson, Warren and Associates in South Meade No. 1 report, Husky, 1982b).

On seismic profiles from NPRA, the top of acoustic basement is usually a prominent regional seismic reflection that generally correlates with the top of the Franklinian sequence in wells (Tetra Tech, 1982). The seismic reflection response to the top of acoustic basement in NPRA varies, depending both upon the acoustic properties of the rocks that compose it (which we assume to be relatively constant but which may be laterally variable), and, more importantly, upon the acoustic properties of the various stratigraphic units which unconformably overlie it. In northwestern NPRA, near the Peard No. 1 well, where Mesozoic-age Ellesmerian strata overlie the highly deformed Franklinian basement above a Permian unconformity (PU), the acoustic response is a high-amplitude reflection (plate 1). Beneath this reflection, the basement is acoustically incoherent, with local, discontinuous, steeply dipping reflections and abundant internal diffractions. Where overlain by Paleozoic-age Ellesmerian rocks, which have a relatively higher interval velocity than the Mezozoic Ellesmerian strata, the top of the acoustic basement has lower acoustic impedance contrast and is more difficult to identify (south of Wainwright fault zone; plate 1). Farther south, as shown on plate 1, acoustic basement appears to lie at depths below the base of the seismic reflection profile (6-second record length, >45,000 feet).

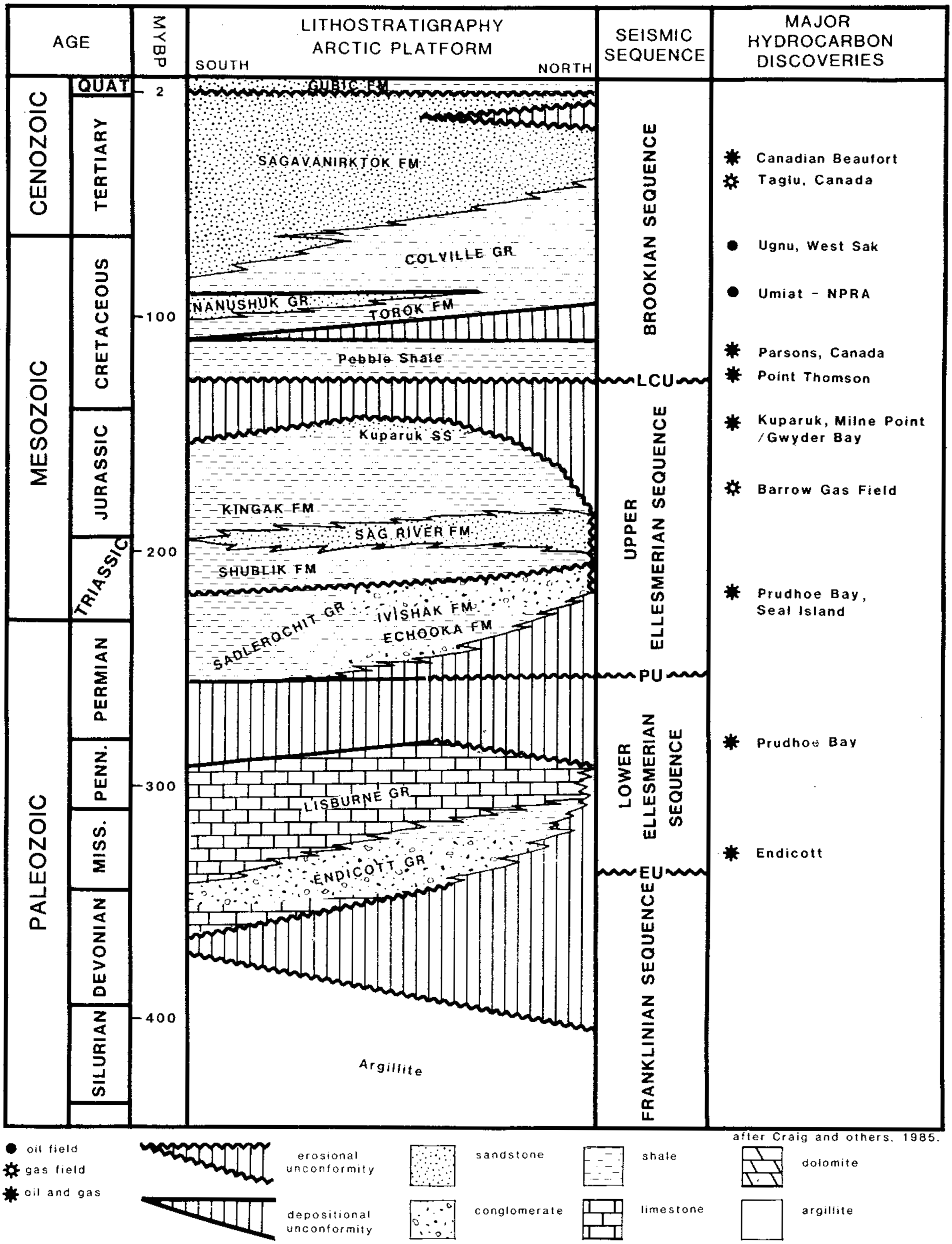


FIGURE 5. Generalized lithostratigraphic column showing the relationship of northern Alaska stratigraphic sequences to seismic sequences recognized in the Chukchi Sea Planning Area. Known petroleum reservoirs in northern Alaska and Canada are shown in right column.

ELLESMERIAN SEQUENCE

(LATE DEVONIAN TO EARLY CRETACEOUS)

Following the Ellesmerian orogeny, the Arctic platform was the site of repeated marine transgressions and regressions from Mississippian to Early Cretaceous time. These transgressive and regressive episodes resulted in cyclic deposition and erosion over large areas of the tectonically stable shelf. Ellesmerian rocks are exposed in the Brooks Range and Lisburne Peninsula and have been described by many investigators (Lathram, 1965; Brosgé and Tailleur, 1971; Brosgé and Dutro, 1973; Norris, 1973; Detterman, 1970; Detterman and others, 1975; Nilsen and others, 1982; Mull and others, 1982). Ellesmerian strata have been identified in the subsurface of the Arctic Coastal Plain (Brosgé and Tailleur, 1971; Morgridge and Smith, 1972; Jones and Speers, 1976; Carter and others, 1977; Bird and Jordan, 1977a; Jamison and others, 1980; Rockwell and Folk, 1980; Tetra Tech, 1982). Some seismic extrapolations of Ellesmerian stratigraphy into the offshore areas of the Chukchi and Beaufort Seas have been published by Grantz, Holmes, and Kososki (1975), Grantz and Eittreim (1979), Grantz and others (1982b), Grantz and May (1984a; 1984b), and Craig and others (1985).

In the Beaufort Sea, the traditional Ellesmerian sequence (fig. 5) has been subdivided by Craig and others (1985) into two informal seismic sequences which are bounded by regional unconformities and which exhibit unique seismic-stratigraphic characteristics. The informal subdivision of these workers is adopted in the following discussion.

The basal sequence (lower Ellesmerian sequence) is inferred to consist of Late Devonian to Mississippian marine and nonmarine clastic deposits conformably overlain by Mississippian to Pennsylvanian carbonate shelf deposits. The lower Ellesmerian strata overlie the Franklinian sequence above the diachronous Ellesmerian unconformity (Grantz and Eittreim, 1979; termed EU by Craig and others, 1985) in NPRA and the Beaufort Sea. The upper sequence (upper Ellesmerian sequence) is composed of Permian to Early Cretaceous carbonate shelf deposits and marine and nonmarine clastic deposits. The upper and lower Ellesmerian sequences are separated by a Permian unconformity (termed PU by Craig and others, 1985), which correlates with the basal Echooka unconformity in the Prudhoe Bay area (Jones and Speers, 1976). The top of the upper Ellesmerian sequence is truncated by erosional unconformities, represented by the Lower Cretaceous unconformity (LCU; Jamison and others, 1980), the Breakup unconformity (Craig and others, 1985), or correlative disconformities.

Lower Ellesmerian Sequence

(Late Devonian to Late Pennsylvanian)

The lower Ellesmerian sequence consists of Paleozoic sedimentary strata which are bounded by the EU at the base and by the PU at the top (fig. 5). In NPRA, the sequence generally consists of synorogenic to post-orogenic, coarse clastic deposits of the Endicott Group which grade upward into the carbonate platform deposits of the Lisburne Group (Tetra Tech, 1982).

Endicott Group

Rocks of the Endicott Group have been identified in several NPRA wells. The Husky Atigaru Point No. 1 well, in eastern NPRA (fig. 4), penetrated over 400 feet of Early Mississippian(?) sandstone, shale, conglomerate, and coal (Husky, 1983a). To the south, similar rocks were encountered in the West Fish Creek No. 1 well (Husky, 1983k). The Inigok No. 1, Ikpikpuk No. 1, and East Simpson No. 2 wells were drilled into Endicott rocks identified as Mississippian in age (Husky, 1983d; 1983e; 1983c). No known Endicott strata have been reported in wells drilled in western NPRA. However, lithologically similar but deformed Middle(?) Devonian clastic rocks, which appear to be part of the basement complex, were drilled in the South Meade No. 1 and Topagoruk No. 1 wells (Husky, 1982b; Tetra Tech, 1982), and may represent older but facies-equivalent Endicott strata below the EU. In addition, seismic reflection data suggest the presence of a thick (up to 9,000 feet) sedimentary section of lower Ellesmerian strata in the Meade and Tunalik basins beneath the strata penetrated in the Meade No. 1 and Tunalik No. 1 wells (Nilsen and others, 1982; Tetra Tech, 1982) (plate 1, southwest end). The deepest well, Tunalik No. 1, reached total depth after drilling 3,200 feet of Lisburne Group carbonates of Pennsylvanian age and did not reach Endicott Group or Franklinian basement rocks.

The diachronous Endicott Group generally is time-transgressive to the north, where Mississippian clastic rocks rest unconformably on basement, as seen in NPRA wells. In the Brooks Range, the Endicott Group consists of clastic deposits ranging in age from Late Devonian to Mississippian which disconformably overlie relatively undeformed Middle Devonian rocks (Nilsen and others, 1980; Nilsen and others, 1982). Along the margins of local basins on the Arctic platform, such as the Meade and Tunalik basins (fig. 2), lower Ellesmerian strata, possibly equivalent to the Endicott Group (Tetra Tech, 1982), appear to progressively onlap the reflector at the top of acoustic basement (plate 1). Near the Tunalik No. 1 well, the base of this sequence lies below the base of the seismic reflection profile (6 seconds, >45,000 feet). Along the Brooks Range, rocks of the Endicott Group outcrop discontinuously for over 600 miles (Nilsen and others, 1982), and thicknesses of up to 13,000 feet have been reported (Nilsen and others, 1980).

The Endicott Group is considered to be a Late Devonian to Early Mississippian offlap-onlap sequence, with two conglomerate units making up the middle, nonmarine part of the cycle (Nilsen and others, 1980). This delta-like clastic wedge was built southward from an orogenic belt that formed paleo-highlands north of the present northeastern Brooks Range and Arctic platform (Brosgé and Dutro, 1973).

Lisburne Group

The carbonate rocks of the Mississippian to Pennsylvanian Lisburne Group are exposed throughout the Brooks Range and on the Lisburne Peninsula as allochthonous thrust sheets (Armstrong and Mamet, 1977; Bird and Jordan, 1977a). Age-equivalent black shales and chert of the Kuna Formation crop out in the allochthons of the western Endicott and DeLong Mountains (Mull and others, 1982). Lisburne Group carbonate rocks have been penetrated in the subsurface by many wells throughout the Arctic North Slope area (Bird and Jordan, 1977a; Tetra Tech, 1982).

The base of the Lisburne Group conformably overlies the Endicott Group, where present; on northern parts of the Arctic platform, the Lisburne Group unconformably overlies basement (fig. 5). Younger strata overlap older strata to the north, with the base of the Lisburne Group becoming progressively younger northward on the Arctic platform. In the Brooks Range, the age of the base of the Lisburne Group ranges from late Early Mississippian to Late Mississippian (Armstrong and Mamet, 1977). In northern NPRA and over structural highs elsewhere on the Arctic platform, the base of the Lisburne Group generally ranges to Pennsylvanian in age (Bird and Jordan, 1977a).

The upper boundary of the Lisburne Group is time transgressive and coincides with the unconformity (PU) at the base of the upper Ellesmerian sequence throughout the northern Arctic platform (fig. 5). The upper part of the lower Ellesmerian sequence was removed by erosion on the PU throughout northern Alaska during Late Pennsylvanian to Early Permian time. The absence of Lisburne rocks in wells drilled in northern NPRA (the East Simpson Nos. 1 and 2, West Dease No. 1, Walakpa No. 1, and Peard No. 1 wells; Husky, 1983b; 1983c; 1983j; 1983l; 1982a) indicates that northern facies of the lower Ellesmerian either were not deposited or were completely removed by erosion at the PU. In this northern area, Permian and Triassic strata lie directly on basement, as illustrated on the northeast end of the seismic reflection profile shown in plate 1. Northward thinning and erosion of the Lisburne Group (and probably older strata) can also be seen on this seismic profile southwest of the Peard No. 1 well. Near the Tunalik No. 1 well, subparallel reflectors below the PU indicate the presence of a thick stratified sequence of Lisburne Group and probably older strata in the Tunalik basin (Tetra Tech, 1982). The zero-thickness edge of the lower Ellesmerian sequence (Lisburne Group), as mapped by Tetra Tech (1982) and shown in figure 2 and plate 1, lies mid-way between the Peard No. 1 and Tunalik No. 1 wells.

The Lisburne Group attains thicknesses of over 3,500 feet in the eastern Brooks Range and on the Lisburne Peninsula (Armstrong and Mamet, 1970; Armstrong and Mamet, 1977). It is over 4,000 feet thick in the subsurface of the eastern North Slope of Alaska (Bird and Jordan, 1977a). In western NPRA, the Tunalik No. 1 and Kugrua No. 1 wells penetrated over 3,200 feet and 1,400 feet of Lisburne Group strata, respectively, failing to reach older formations before drilling was abandoned (Husky, 1983i; 1983f). The Tunalik No. 1 well bottomed in Pennsylvanian-age rocks of the Lisburne Group after penetrating an 800-foot-thick sequence of interbedded basaltic flows (Husky, 1983i; Tetra Tech, 1982). This is the only known subsurface occurrence of volcanic rocks within the Lisburne Group.

The rocks of the Lisburne Group are predominantly detrital carbonates deposited in an open-marine to shallow-marine inner shelf environment (Armstrong and Mamet, 1977; Bird and Jordan, 1977a; 1977b). However, coeval deposits of the Kuna Formation (Mull and others, 1982), which contain black carbonaceous shales, black cherts, and fine-grained limestones, suggest a distal, euxinic environment of deposition for the Lisburne Group in the southwest.

Upper Ellesmerian Sequence

(Permian to Early Cretaceous)

The stratigraphy of the upper Ellesmerian sequence of northern Alaska is well documented. The terminology and stratigraphic nomenclature developed for these rocks in the Brooks Range (Leffingwell, 1919; Detterman, 1970; Brosgé and Tailleur, 1971) has been extended to correlative rocks in the subsurface of the Arctic North Slope (Kopf, 1970). The upper Ellesmerian sequence comprises, in ascending order, the Permian to Triassic Sadlerochit Group, the Triassic Shublik Formation, the Triassic to Jurassic Sag River Formation, and the Jurassic to Cretaceous Kingak Formation (fig. 5). Wells in western NPRA, including the Walakpa No. 1, Peard No. 1, Kugrua No. 1, and Tunalik No. 1 wells, have penetrated full or partial suites of the upper Ellesmerian sequence (Husky, 1983l; 1982a; 1983f; 1983i). Correlation of seismic data to these wells permits the extrapolation of these seismic units throughout NPRA (Rockwell and Folk, 1980; Tetra Tech, 1982) and offshore into the Beaufort and Chukchi Sea Planning Areas (Grantz and others, 1982b; Craig and others, 1985).

The strata at the base of the upper Ellesmerian sequence onlap the PU and generally become progressively younger to the north on the Arctic platform. The top of the Ellesmerian sequence is considered by most workers to be marked by the angular unconformity (LCU) at the base of the Pebble Shale unit (fig. 5) (Tetra Tech, 1982; Carman and Hardwick, 1983; Craig and others, 1985). Other workers place the top of the sequence at the top of the Pebble Shale unit (Molenaar, 1981; Grantz and others, 1982c). In this report we designate the LCU as the top of the upper Ellesmerian sequence, and include the Pebble Shale unit within the overlying Brookian sequence. Placing the Pebble Shale in the Brookian sequence is an arbitrary classification; it could have been placed, with as much justification, in the Ellesmerian sequence. It technically belongs to neither sequence (Carman and Hardwick, 1983; Craig and others, 1985) because the most common criterion for defining these two regional sequences is their sediment source direction (Ellesmerian from the north, Brookian from the south). The deposits of the Pebble Shale may have been derived, in part, from both directions, as well as from accumulations of pelagic sediment.

On the Barrow arch in northern NPRA, the LCU is a prominent erosional unconformity which has truncated the entire Ellesmerian sequence. In the South Barrow No. 16 well, the Pebble Shale unit lies directly on basement argillite (Husky, 1983h). Southward, toward the axis of the Colville basin, the LCU may grade into a depositional interface across which sedimentation was virtually continuous. Tetra Tech (1982) reports that the erosional surface correlative to the LCU in western NPRA, which they term the "Basal Pebble Shale unconformity," may lie within Early Cretaceous strata at the Tunalik No. 1 well.

The upper Ellesmerian sequence generally thins to the north by basal onlap on the PU and truncation of its top by the LCU. Wells in southern NPRA encountered thicker and more complete sections of upper Ellesmerian rocks (i.e., Inigok No. 1, 4,760 feet; Kugrua No. 1, 4,000 feet; Tunalik No. 1, 6,200 feet; Peard No. 1, 3,060 feet). In wells in northern NPRA, near the Beaufort coastline, the sequence is thinner, often incomplete, or absent (e.g., Walakpa No. 1, 1,560 feet; S. Barrow No. 13,300 feet; S. Barrow No. 16, missing (Tetra Tech, 1982)).

The acoustic appearance of the upper Ellesmerian sequence in western NPRA is illustrated in plate 1. The upper Ellesmerian sequence generally consists of continuous, relatively high-amplitude, broad-cycle-breadth reflections which exhibit a parallel to slightly divergent internal geometry to the southwest (basinward). In the lower part of the sequence (the equivalent of the Sadlerochit Group, and Shublik and Sag River Formations) the reflections are subparallel to each other and to the underlying lower Ellesmerian strata. The upper portion of the sequence (a Kingak Formation equivalent) contains widely spaced, southwardly inclined reflections which form progradational clinoforms that downlap underlying reflections at a low angle (plate 1; southwest end, at about 2.0 to 2.5 seconds).

On the Arctic platform, the upper Ellesmerian sequence is relatively undeformed, with isolated faults of post-Early Cretaceous age locally offsetting the sequence. Here, the primary deformation of the sequence consists of regional southward tilting and block-faulting (Grantz and May, 1984a; Craig and others, 1985). South of the Arctic platform, the upper Ellesmerian sequence was involved in the thrust faulting and folding in the Foreland fold belt and Brooks Range (Detterman and others, 1975).

The basal unit of the upper Ellesmerian sequence (fig. 5) is the Sadlerochit Group, which consists of the Permian Echooka Formation and the Early Triassic Ivishak Formation (Tetra Tech, 1982). In NPRA, the Echooka Formation is generally composed of carbonates and shales (Tetra Tech, 1982). Along the central Beaufort coast, the Ivishak Formation is composed of fluvial and deltaic sandstones and conglomerates; it forms the principal hydrocarbon reservoir in the Prudhoe Bay field (Jones and Speers, 1976). In northeastern NPRA, the Ivishak Formation grades into sandstone interpreted to be a strand-plain or offshore-bar deposit (Tetra Tech, 1982). The silt content generally increases to the south and west, and at the Tunalik No. 1 well, the Ivishak Formation is composed predominantly of siltstone.

The Middle to Late Triassic Shublik Formation in NPRA (fig. 5) consists of marine sandstones, shales, limestones, and calcareous to phosphatic mudstones, probably deposited in a marine shelf setting. At the Tunalik No. 1 well, the formation consists of 470 feet of organic-rich, calcareous siltstones and shales. Over structurally high areas, such as the Meade arch, the Shublik Formation contains abundant glauconitic sand and coquina. Detterman (1970) believes the Shublik Formation was deposited in a low-energy, moderate to deep (200 to 1,000 feet) marine environment.

The Late Triassic to Early Jurassic Sag River Formation varies from calcareous siltstone, shale, and silty fine-grained sandstone in the south (Inigok No. 1 and Tunalik No. 1 wells), to fine-grained glauconitic sandstone in the north (Peard No. 1, Kugrua No. 1, and Barrow No. 17 wells) (Tetra Tech, 1982). Sandstone development appears to be significant only in the north, near the paleosource area. This sandstone is interpreted by Tetra Tech (1982) as isolated offshore bar sand lenses.

In NPRA, the Early Jurassic to Early Cretaceous Kingak Formation consists of shales, siltstones, and sandstones. In northern NPRA, the Kingak Formation contains many unconformities and discontinuous sandstone bodies (Tetra Tech, 1982). These discontinuous sandstone bodies are considered by Tetra Tech (1982) to represent transgressive barrier-beach deposits which were localized on structural highs. Southward, toward the basin, the formation grades into an organic-rich facies with a predominantly silt and clay lithology which exhibits conformable internal relationships (Magoon and Claypool, 1984; Rockwell and Folk, 1980). Rockwell and Folk (1980) interpret internal clinoformal seismic reflections observed on seismic profiles to represent progradational surfaces that downlap intraformational unconformities within the Kingak Formation. Based on the geometry and distribution of reflections, Rockwell and Folk (1980) further suggest that these clinoformal reflections represent submarine fan deposits. An example of these low-angle dipping reflections can be seen below the LCU in plate 1 toward the southwestern end (between 2.0 and 2.5 seconds). The Tunalik No. 1 well penetrated nearly 3,500 feet of black, platy shale in the Kingak Formation (Banet, 1983). However, two units of fine- to very fine-grained sandstones were also penetrated: one was encountered at 12,510 feet below sealevel (bsl) and measured a total of 95 feet in thickness; the other was encountered at 10,900 feet bsl and measured a total of about 750 feet in thickness. Both sandstones produced minor gas shows (Tetra Tech, 1982).

The upper Ellesmerian sequence in western NPRA represents an overall transgressive marine sequence (Dutro, 1981). Nearshore and shoreline deposits are more common on the northern part of the Arctic platform and over structural highs, whereas coeval deposits in more southern parts of the Arctic Alaska basin exhibit more open-marine to deep-water facies.

BROOKIAN SEQUENCE

(EARLY CRETACEOUS TO PRESENT)

In western NPRA, the Brookian sequence (fig. 5) comprises a very large, thick, time-transgressive clastic wedge that was shed generally northward and eastward from the Brooks Range (fig. 3b). This wedge is composed of marine and nonmarine mudstone, siltstone, and sandstone deposited in a classic deltaic sequence containing bottomset, foreset, and topset facies. The Brookian sequence generally thins to the north over the Barrow arch (Molenaar, 1981) and then thickens into major shelf-margin basins north of the Hinge Line fault zone (Grantz and May, 1984a; 1984b; Craig and others, 1985). In eastern NPRA, the Brookian sequence also includes Late Cretaceous to Tertiary deltaic deposits that form an eastward continuation of the marine and nonmarine prograding clastic wedge. The traditional Brookian sequence in northern Alaska has been documented by Grantz and Eittreim (1979), Grantz and others (1982c), Grantz and May (1984a), and Craig and others (1985). Within the Chukchi Sea Planning Area, two distinct seismic sequences separated by a major unconformity or unconformities are recognized. We believe the lower sequence is correlative to the Lower Cretaceous Torok Formation and Nanushuk Group (fig. 5), which are widely exposed in the Colville basin area. This part of the sequence is here informally termed the lower Brookian sequence. The overlying sequence is recognized only in the northern parts of the Beaufort Sea and Chukchi Sea Planning Areas and cannot be directly traced onshore. We informally term this part the upper Brookian sequence and speculate that it is correlative to the Upper Cretaceous Colville Group and younger strata of eastern NPRA (fig. 5).

Lower Brookian Sequence

(Early Cretaceous)

Rocks of the lower Brookian sequence occur in all western NPRA wells. In ascending order, this sequence consists of the Pebble Shale unit, the Torok Formation, and the Nanushuk Group (fig. 5). In this report, the base of the lower Brookian sequence is defined as the Lower Cretaceous unconformity (LCU). In western NPRA, the top of the sequence is defined by the modern erosional surface; in eastern NPRA, the sequence is unconformably overlain by the Upper Cretaceous Colville Group. The LCU exhibits unfaulted, homoclinal dip to the south and southwest, toward the Colville basin, and ranges in depth from less than 3,000 feet over the Barrow arch to over 25,000 feet south of Point Lay (Molenaar, 1981). The LCU truncates underlying Ellesmerian rocks over large areas of the northern Arctic platform, but is traced southward into a conformable surface toward the axis of the Colville basin (Molenaar, 1981).

The thickest part of the lower Brookian section is located in the east-west-trending axis of the Colville basin north of the Brooks Range (fig. 2), where over 25,000 feet of strata are present. The sequence thins northward away from the Brooks Range, and has been further abbreviated by postdepositional uplift and erosion along parts of the Barrow arch (Molenaar, 1981). In the Barrow area, the lower Brookian sequence is less than 3,000 feet thick and lies unconformably on Paleozoic basement. South of Barrow, the Peard No. 1 well penetrated nearly 6,500 feet of lower Brookian rocks. About 60 miles to the southwest, the Tunalik No. 1 well encountered over 10,000 feet of lower Brookian strata (Husky, 1982a; 1983i; Tetra Tech, 1982). The thickness distribution of the lower Brookian deposits throughout the North Slope is controlled by the eastwardly trending Colville basin. Regional isopach trends extend into western NPRA and appear to continue westward into the Chukchi Sea Planning Area (Molenaar, 1981).

In some localities along the Barrow arch trend, lower Brookian rocks were uplifted and eroded. In the Barrow area, the Nanushuk Group is entirely breached and the underlying Torok Formation is exposed at the surface (Molenaar, 1981). To the south, the entire clastic wedge is gently folded in the Foreland fold belt province (fig. 2) and is progressively more intensely deformed toward the Brooks Range frontal thrust faults.

Using seismic data with well control, Molenaar (1981) and Tetra Tech (1982) have mapped units within the lower Brookian throughout NPRA. The lowermost unit (Pebble Shale) is generally thin, ranging from near 200 to 400 feet (usually within the width of the reflection-doublet associated with the LCU, as illustrated in plate 1). The Pebble Shale in northern NPRA is an organic-rich black shale containing minor amounts of sand and chert pebbles (Molenaar, 1981; Tetra Tech, 1982). This unit represents slow intermittent deposition for a long period of time, resulting in a condensed section of starved-basin shales.

Overlying the Pebble Shale unit is a thick succession of relatively moderate- to high-amplitude, broadly sigmoidal clinoforms and hummocky reflections that occur within a predominantly shale unit termed the Torok Formation. This unit comprises over half the total thickness of the lower Brookian section (plate 1). The internal, inclined reflections dip east-northeast and exhibit downlap against the Pebble Shale unit (Molenaar, 1981). The Torok Formation is composed of mudstone, shale, and some sandstone, deposited in a deep marine to shallow marine, prodelta to delta-front environment (Huffman and Ahlbrandt, 1978; Molenaar, 1981; 1983; Grantz and others, 1982c).

The uppermost unit of the lower Brookian sequence that can be recognized on seismic data is the deltaic topset strata of the Nanushuk Group (fig. 5). This unit is characterized by a series of parallel reflections having a relatively high-amplitude character but variable lateral continuity (plate 1). The Nanushuk Group consists

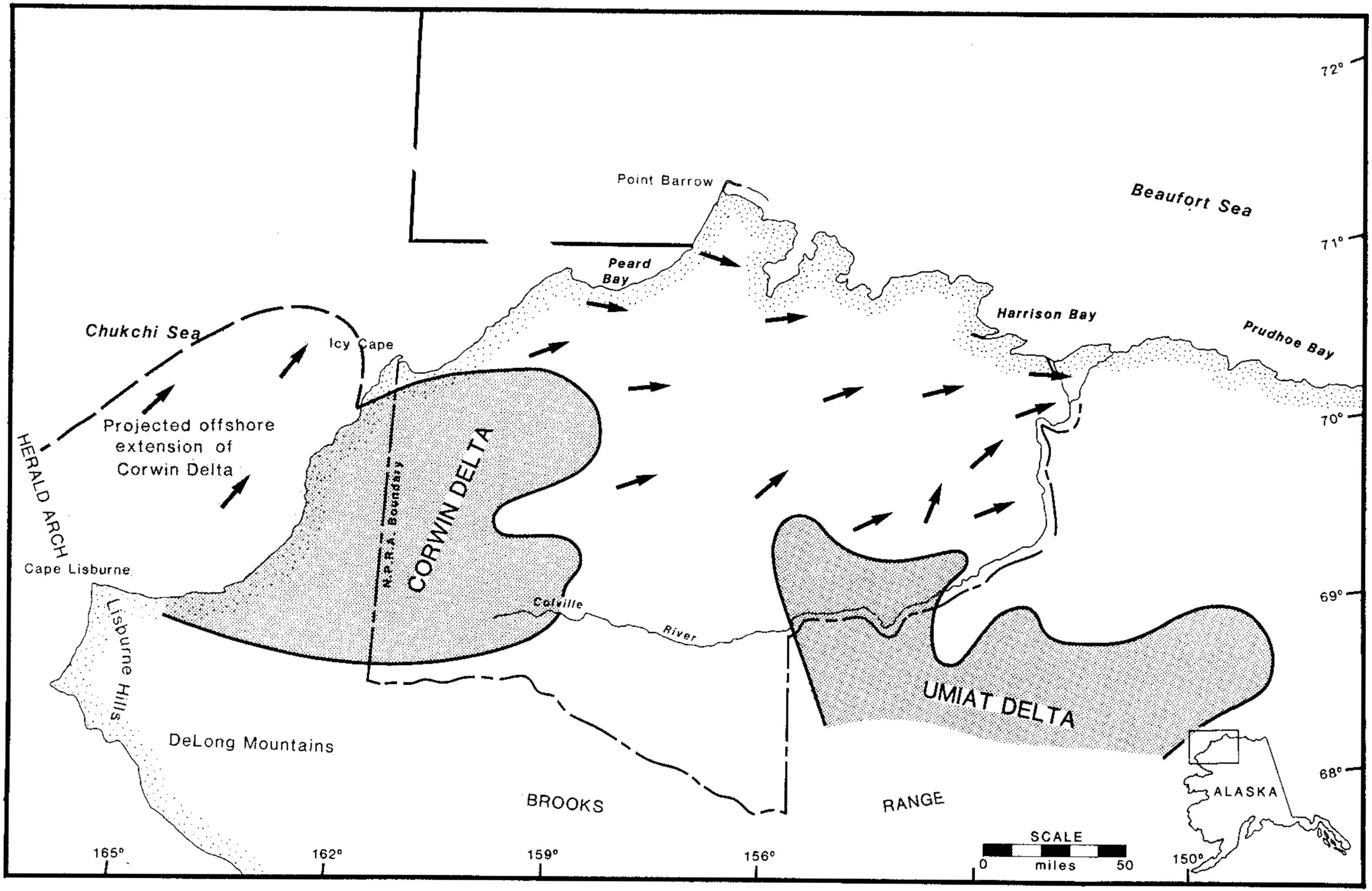


FIGURE 6. Major Early Cretaceous (Nanushuk Group) depocenters in the Colville basin. Diagram modified after Huffman and Ahlbrandt (1978).

of shales, sandstones, and some coal, which were deposited in a marginal marine to nonmarine delta-plain depositional environment (Ahlbrandt, 1979; Ahlbrandt and others, 1979; Bird and Andrews, 1979; Mull, 1979).

In western NPRA, the bottomset-foreset-topset geometry of the lower Brookian sequence outlines a long, eastwardly prograding, river-dominated delta known as the Corwin delta (Ahlbrandt and others, 1979). Based on paleocurrent directions and mineralogic associations, the Corwin delta (fig. 6) is inferred to have had a south to southwestern source terrane near the present DeLong Mountains, Lisburne Hills, and offshore Herald arch (Grantz and others, 1982b; Bird and Andrews, 1979, Huffman, 1979; and Bartsch-Winkler and Huffman, 1980). The Corwin delta prograded east along the axis of the Colville basin. Nanushuk Group rocks in the Corwin delta are characterized by a low sand content (generally less than 20 percent), which is probably due to the long distance from the source and the abundance of labile constituents (argillite, carbonate, etc.) in its provenance (Bartsch-Winkler and Huffman, 1980). The presence of low-angle prodelta foresets in seismic data, abundant matrix material in sandstones, and the apparent absence of sediment reworking by marine processes are indicative of a low energy, shallow water, and probably river-dominated deltaic environment (Huffman and others, 1986).

Upper Brookian Sequence

(Late Cretaceous to Present)

From Early to Late Cretaceous time the Barrow arch deflected the prograding Brookian delta complex easterly along the axis of the Colville basin (Molenaar, 1981). Eastern parts of the delta complex in the Colville basin are younger and include strata of the Late Cretaceous Colville Group and Tertiary strata of the Sagavanirktok Formation (fig. 5). Offshore of western NPRA in the Beaufort Sea, Late Cretaceous to Tertiary sediments overtopped the Barrow arch and accumulated in great thicknesses in major basins north of the Hinge Line fault zone (fig. 2) (Grantz and May, 1984b; Craig and others, 1985). Grantz and others (1982c) and Craig and others (1985) have reported thicknesses of over 35,000 feet for the Late Cretaceous to Tertiary sediments in the basins north of the Hinge Line fault zone in the Beaufort Sea. The upper Brookian seismic sequence beneath the Beaufort continental shelf is composed of basinward-divergent, relatively high-amplitude continuous reflections, which form a northward-thickening wedge. These Late Cretaceous to Tertiary regressive deposits are age equivalent to the Colville Group and Sagavanirktok Formation of eastern NPRA and tentatively correlated to the isolated upper Brookian sequence offshore in the Chukchi Sea Planning Area (discussed in detail below).

3. SEISMIC STRATIGRAPHY OF THE CHUKCHI SEA PLANNING AREA

The following discussion of seismic stratigraphy is based primarily on our interpretation of high-quality CDP seismic reflection data which were acquired by WGC and GSI between 1980 and 1984. The data bases for these surveys (including 1985 and 1986 data) are shown in figures 7 and 8. Selected regional profiles from these surveys will be referred to throughout the report (plates 2 through 9; locations shown in fig. 71). Sonobuoy refraction data of Houtz and others (1981) were used to construct subregional time-depth curves (fig. 9). These curves appear on regional time maps and were used on the interpreted seismic lines for conversion from time to depth. Sonobuoy velocities are supplemented in the report by interval velocity ranges for selected seismic sequences which were calculated from stacking velocity data supplied by WGC Velans and GSI Velscans. Figure 10 shows the location and general age of the three major sedimentary basins contained in the Chukchi Sea Planning Area: the North Chukchi, Central Chukchi, and Northern Hope basins. In addition, a fourth paleo-basin, termed the Northeast Chukchi basin by Craig and others (1985), is shown because its structural margins extend into the eastern part of the Chukchi Sea Planning Area..

Each of these basins extends outside the planning area: The Northern Hope basin (Tertiary) is a continuation of the Hope basin, and the North Chukchi basin (Early Cretaceous to Tertiary) extends northwestward for an unknown distance into Russian waters. The Central Chukchi basin ("Hanna Trough" of Grantz and Eittreim, 1979) is a northward-trending continuation of a late Paleozoic depocenter--the Arctic Alaska basin of Brosgé and Tailleur (1971). Superposed upon the Central Chukchi basin are two distinct younger subbasins: (1) the western extension of the Early Cretaceous Colville basin in the south, and (2) a southern subbasin of the North Chukchi basin, informally termed the "Northcentral subbasin," in the north (fig. 10). Although the term "Hanna Trough" of Grantz and Eittreim (1979) correctly defines the general location of a composite of the major sedimentary basins, we prefer not to adopt this term because it is too broad to properly delineate the complex depocenters in the central Chukchi Sea Planning Area. The Northeast Chukchi basin (pre-Mississippian) lies almost entirely within the western part of the Beaufort Sea Planning Area. It is discussed in this report because three of its structural boundaries lie within the Chukchi Sea Planning Area (the Barrow and Wainwright fault zones along the south,

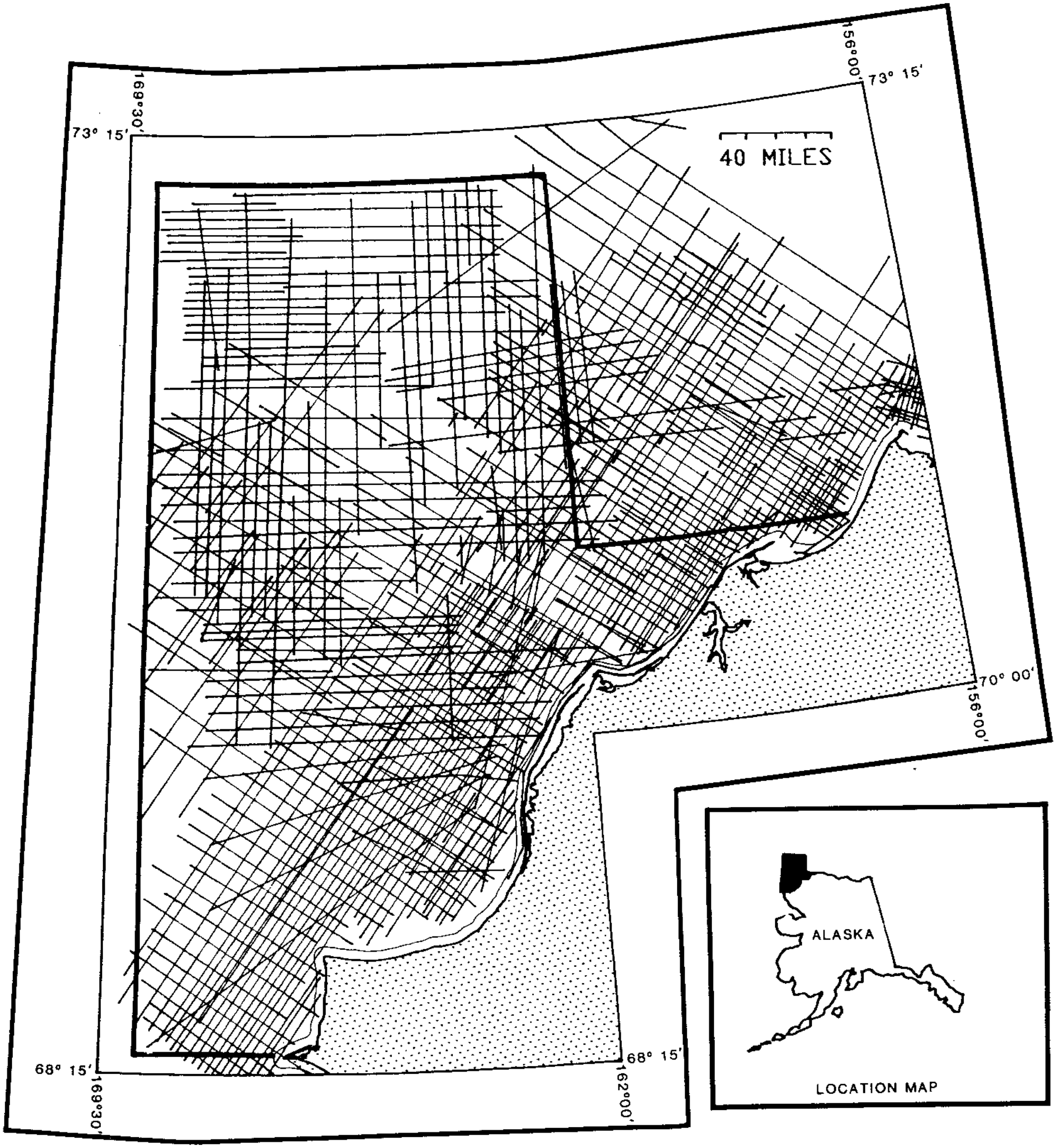


FIGURE 7

WESTERN GEOPHYSICAL COMPANY DATA COVERAGE (1980-1986)
IN CHUKCHI SEA PLANNING AREA AND ADJOINING AREAS
OF THE CHUKCHI SHELF

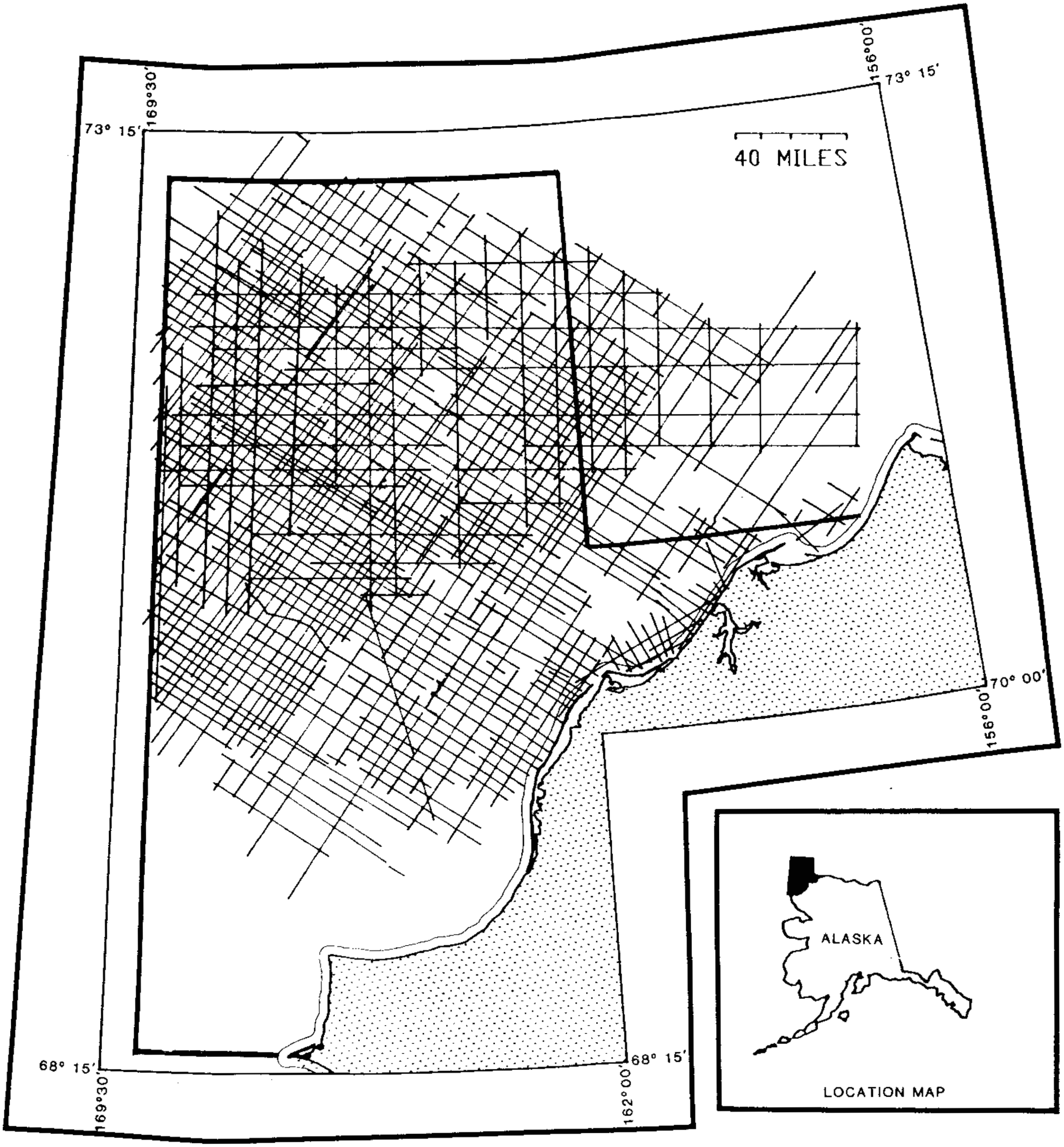


FIGURE 8

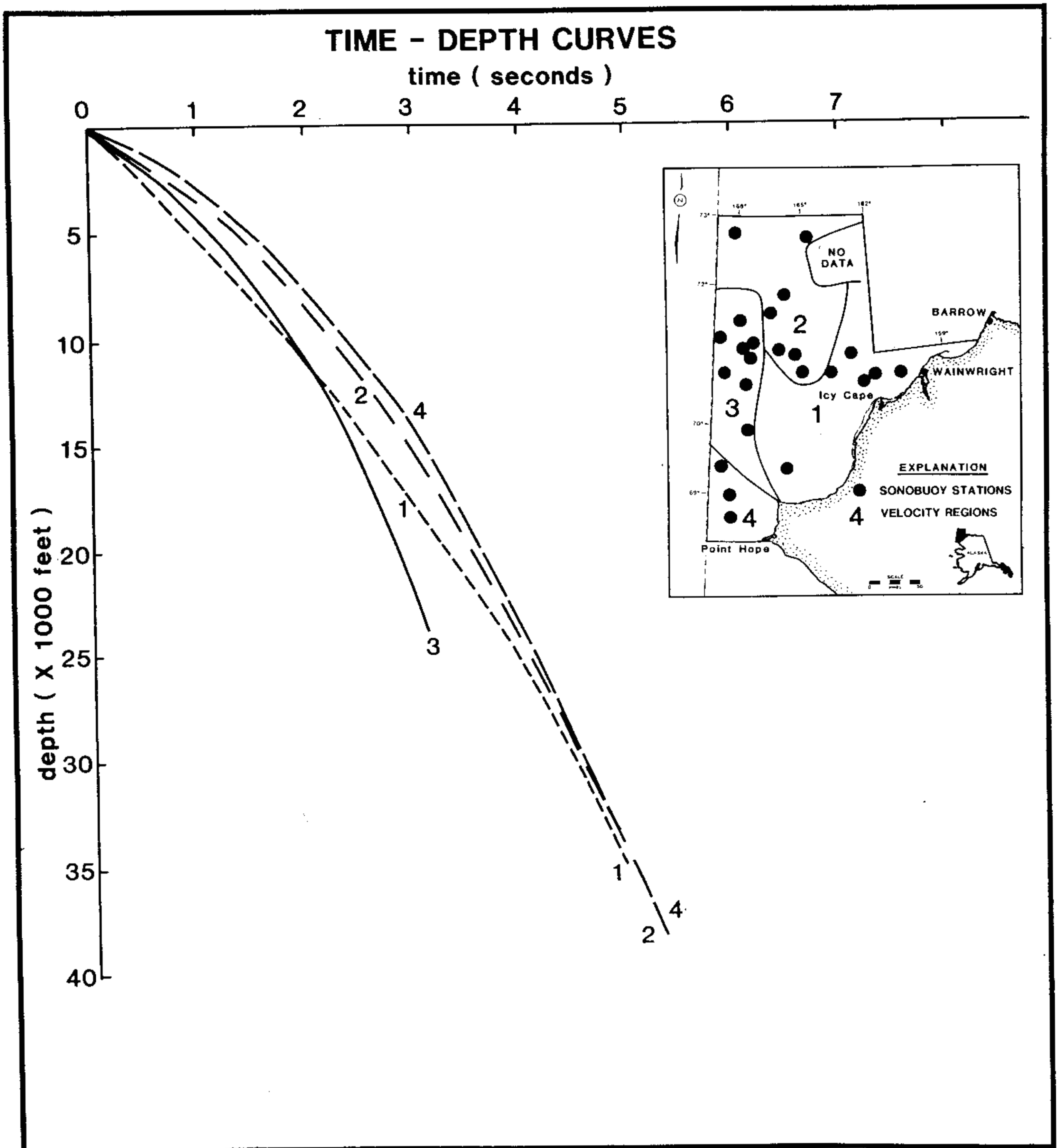
GEOPHYSICAL SERVICE INC. DATA COVERAGE (1982-1986) IN CHUKCHI SEA PLANNING AREA AND ADJOINING AREAS OF THE CHUKCHI SHELF and a broad, north-trending fault zone, here informally termed the "Northeast Chukchi fault zone," on the west).

Onshore seismic stratigraphy has been correlated to lithostratigraphy of exploratory wells throughout NPRA (Tetra Tech, 1982). Direct seismic ties can be established between western NPRA and the adjoining eastern part of the Central Chukchi basin (Craig and others, 1985) (plates 1 and 2). This correlation becomes less reliable with increasing distance from onshore well control. Geologic factors complicating the direct offshore correlation of regional seismic sequences include: (1) abrupt changes in thickness, distribution, and facies which affect the reflection character of correlative seismic sequences; and (2) structural complexity caused by several episodes of regional deformation, including syndepositional and postdepositional extensional faulting, compressional folding, thrust faulting, and wrench tectonics.

The strata of the Northeast Chukchi basin, North Chukchi basin, Northcentral subbasin, and Northern Hope basin are not exposed in outcrop onshore and have not been penetrated by any wells. The interpretations presented here are based entirely upon seismic reflection data and are, therefore, somewhat speculative. However, comparative analyses of the structural and seismic-stratigraphic histories of these untested areas and the documented geology of western NPRA permits the formulation of a conceptual model for basin development in the Chukchi Sea Planning Area. The following sections will discuss each of the major seismic-stratigraphic units of the planning area, their acoustic character, their continuity between basins, and their inferred relationship to the major seismic-stratigraphic sequences recognized in NPRA.

ACOUSTIC BASEMENT

The term "acoustic basement" is used to describe the rocks exhibiting little or no internal reflection coherency which lie below the base of the lowest resolvable seismic-stratigraphic sequence. The top of acoustic basement is commonly characterized by a relatively high-amplitude, broad-cycle-breadth seismic reflection which represents a major angular unconformity or nonconformity that probably separates highly deformed rocks from overlying, relatively undeformed sedimentary sequences. Because the internal seismic characteristics of the acoustic basement are poorly resolved, and because several provinces are isolated by major structural boundaries, the acoustic basement in these provinces may be composed of rocks of highly variable age and diverse lithologies. For example, acoustic basement may include rocks no younger than mid-Paleozoic in the offshore extension of the Arctic platform and on the Chukchi platform, but may include rocks as young as Cretaceous in the North Chukchi High, the Herald arch, and the Northern Hope basin (fig. 11). For the purposes of this study, acoustic basement is a purely structural unit which carries no firm implications for stratigraphic age of the deformed rocks which compose it.



Plotted from an average of refraction data for each region, using data of Houtz and others (1981)

FIGURE 9. Curves for conversion of two—way travel time to depth for major velocity regions in the Chukchi Sea Planning Area.

Some wells in northwestern NPRA provide control for the interpretation of acoustic basement on seismic records in the adjacent eastern Chukchi Sea Planning Area east of the Barrow fault zone. However, basement lies beyond readily drillable depths onshore in the Tunalik basin near the Tunalik No. 1 well (plate 1), offshore south of the Wainwright fault zone (plate 2), and west of the Northeast Chukchi fault zone (plates 3 and 4). South of the Wainwright fault zone, acoustic basement lies below the base of seismic records (>6 seconds), and it is not a mappable horizon to the west in the axial regions of the Central Chukchi basin. Farther west, the basement complex rises from depths greater than 45,000 feet in parts of the Central Chukchi basin to less than 5,000 feet over the Chukchi platform near the western boundary of the planning area (fig. 12). Locally, along the margins of the Central Chukchi basin, acoustic basement is directly overlain by Mesozoic Ellesmerian and Brookian strata, whereas in the central portions of the basin it is overlain by Paleozoic units of the lower Ellesmerian sequence.

The acoustic basement in the Northern Hope basin (fig. 13) lies at depths generally shallower than 15,000 feet (3.0 seconds), and its age and lithology are unknown. Two wells drilled by Socal in the southern part of Hope basin near Kotzebue penetrated Paleozoic basement consisting of marbles and schists (Turner and Olson, 1978). Along the northern margin of Hope basin, deformed lower Brookian strata may be locally incorporated into acoustic basement of the Herald arch. Therefore, the age of acoustic basement may vary from Paleozoic to Lower Cretaceous. The acoustic basement was block-faulted during early Cenozoic(?) time and is overlain by Tertiary strata (Grantz and Eittreim, 1979).

In the northwestern part of the planning area, acoustic basement is downwarped into the North Chukchi basin along a flexure-zone to depths greater than 40,000 feet (below the base of 6.0-second reflection records). The acoustic basement in the North Chukchi high, located in the northeastern portion of the planning area, lies at depths typically less than 5,000 feet. The deformed rocks of the acoustic basement complex in the North Chukchi high include Paleozoic Ellesmerian to Cretaceous lower Brookian strata, which are overlain by relatively undeformed upper Brookian strata.

ELLESMERIAN SEQUENCE

Strata identified as equivalent to the Ellesmerian sequence in the planning area form a seismic sequence that exhibits highly variable stratigraphic geometry and seismic reflection characteristics. Stratigraphic relationships within this seismic sequence are interpreted to differ from those within the Ellesmerian sequence in NPRA and the Beaufort Sea. This may be the result of the combined effects of (1) a conspicuous change in trend of the Ellesmerian depocenter from predominantly east-west onshore to more northerly offshore, and (2) a significantly different tectonic setting in the Chukchi Sea Planning Area.

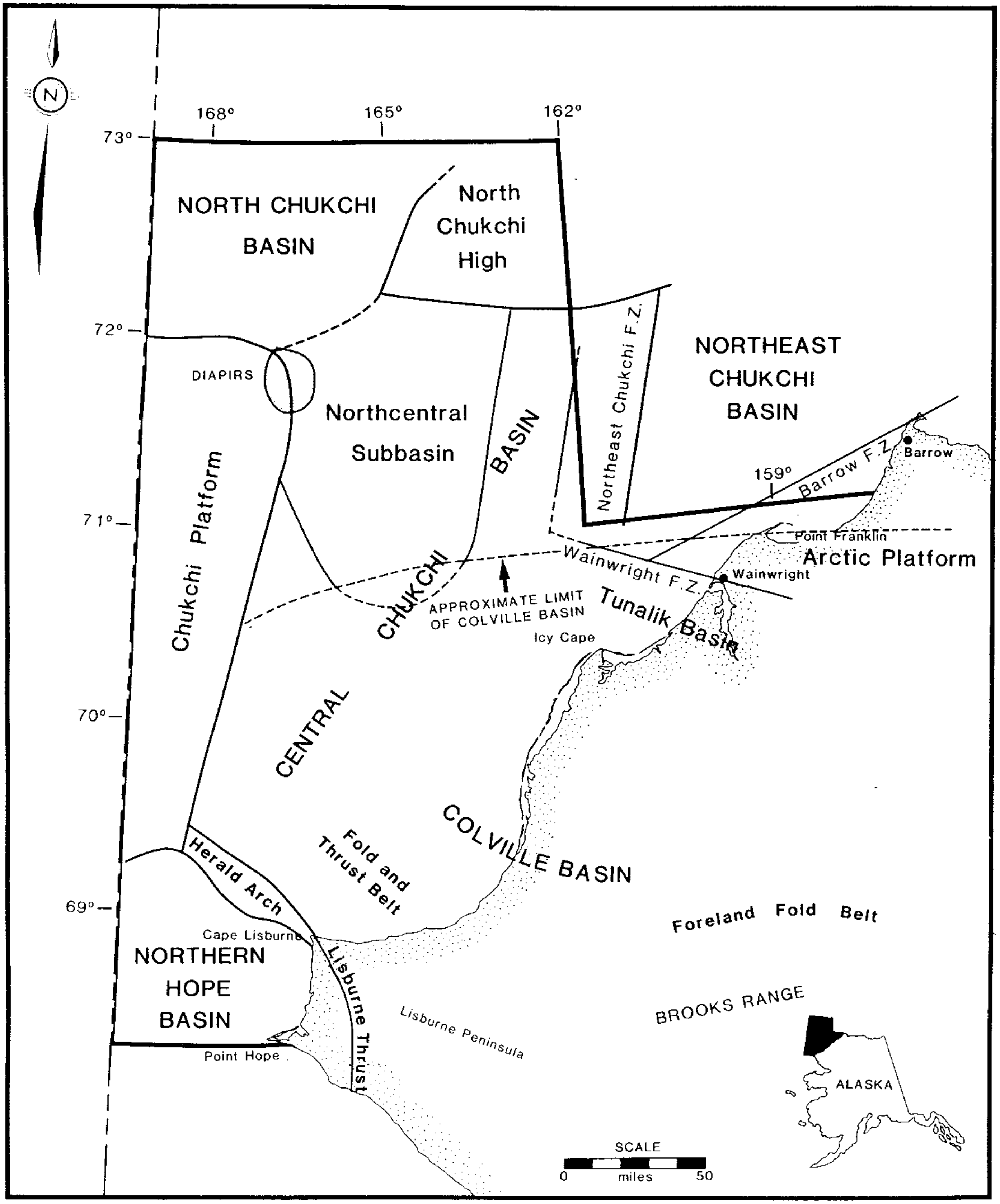


FIGURE 10. Major structural provinces and sedimentary basins of the Chukchi Sea Planning Area and adjoining parts of the Chukchi shelf.

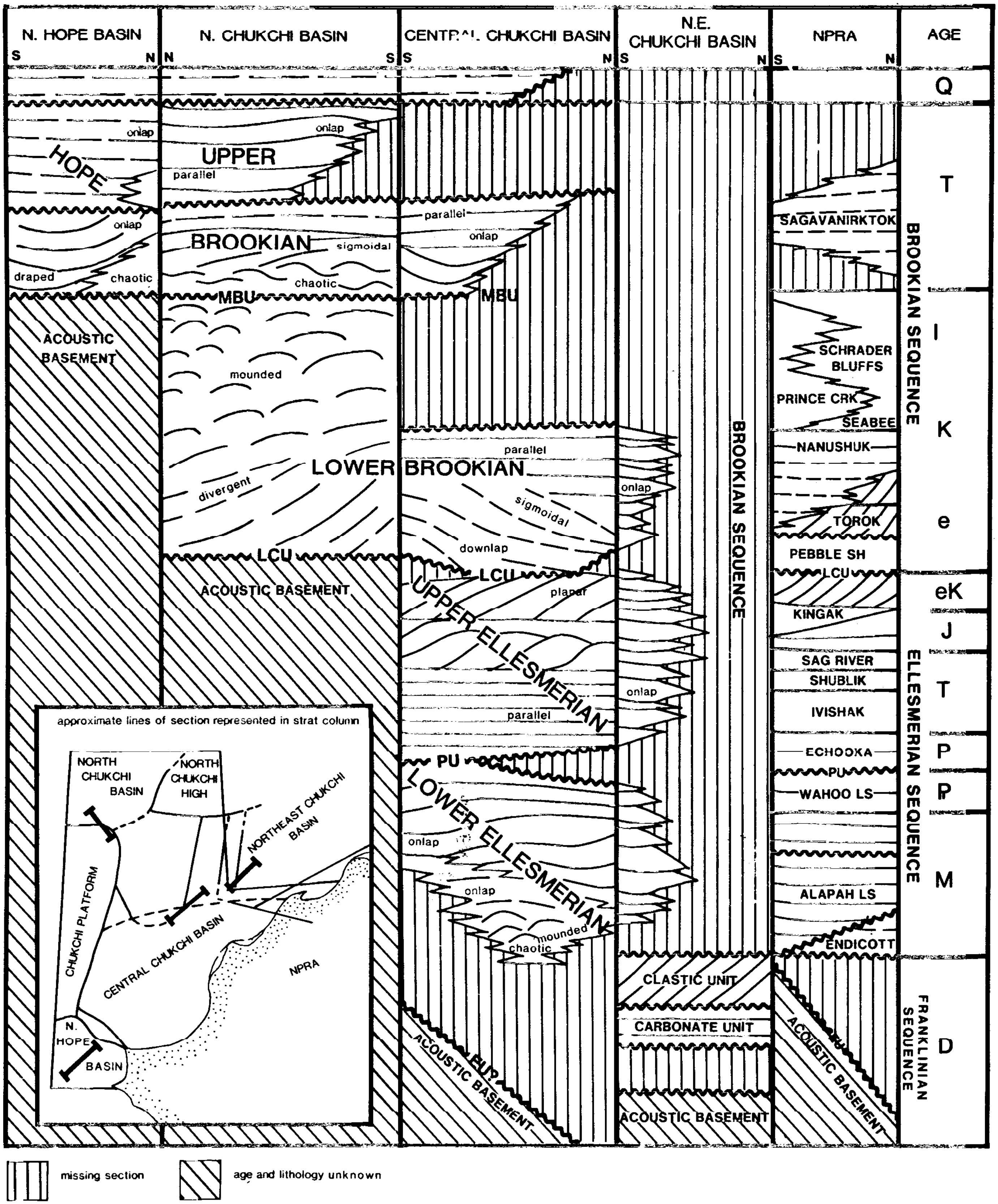


FIGURE 11. Seismic stratigraphic correlation chart, showing generalized reflection characteristics and geometry of seismic sequences in northern Alaska and the Chukchi Sea Planning Area.

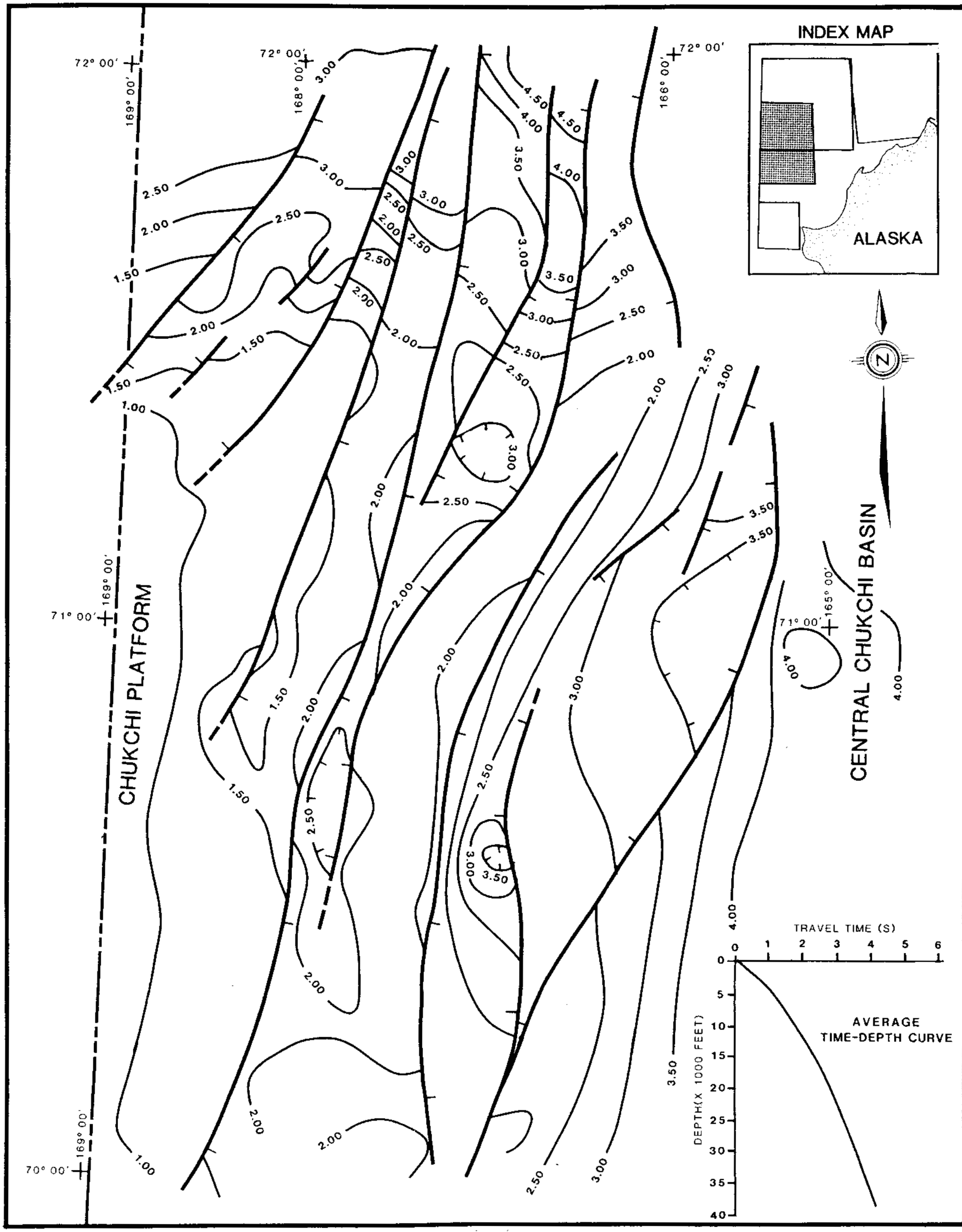


FIGURE 12. Structure map on the top of acoustic basement, Chukchi platform. Contour interval in 0.50 seconds of two—way travel time.

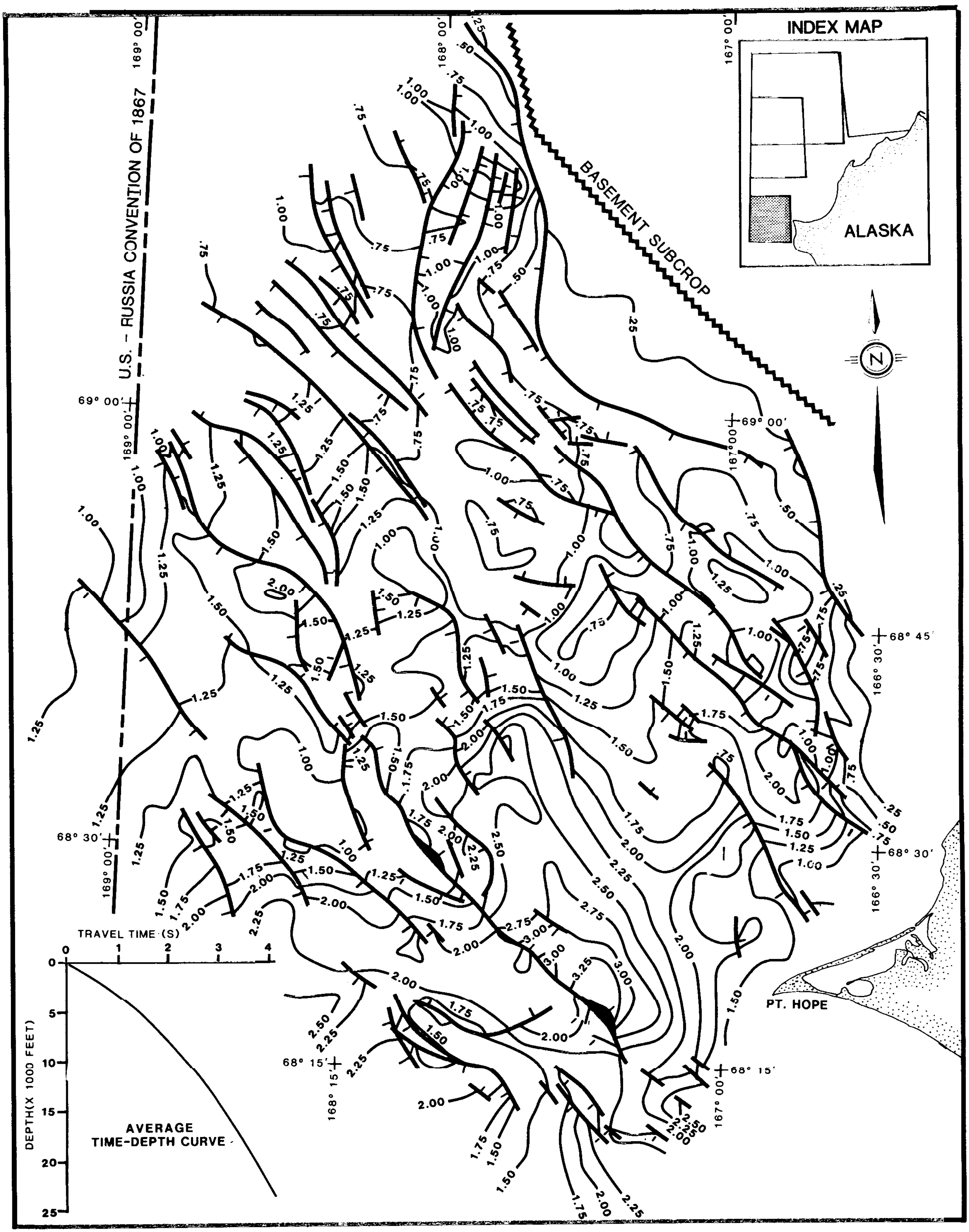


FIGURE 13. Structure map of the top of acoustic basement in the Northern Hope basin. Contour interval in 0.25 seconds of two-way travel time.

The geology of the southeastern part of the Chukchi Sea Planning Area and western NPRA are similar, and offshore seismic extrapolation from onshore control is unhampered by faults or zones of complex deformation. An example of this seismic character correlation can be seen by comparing the seismic reflection profiles in plates 1 and 2. In offshore areas (plate 2), as onshore (plate 1), the Ellesmerian sequence is bounded at its top by a prominent reflection doublet correlative to the LCU. The base corresponds to the lowermost reflection which approximates the top of acoustic basement, which is below the base of seismic reflection profiles (6.0 seconds, or 45,000 feet) in the Tunalik basin.

The western edge of the Central Chukchi basin is characterized by thinning of the Ellesmerian sequence, where individual units progressively onlap the basement surface of the Chukchi platform. In addition, Ellesmerian units are extensively truncated by the LCU (plate 5). The original westward extent of the late Paleozoic basin is obscured on the Chukchi platform by subsequent erosion or deep subsidence of Ellesmerian strata. However, based on onlap relationships and interstratal thinning, it appears that the Chukchi platform existed as a structural high during Ellesmerian time.

The southern extent of Ellesmerian strata in the Central Chukchi basin is obscured by Late Cretaceous to Early Tertiary thrust faulting along the northern edge of the Herald arch. However, apparent thinning of Ellesmerian units toward the Herald arch suggests that a structurally positive feature existed in that area when these units were deposited. This thinning is illustrated on the northeastern end of the seismic reflection profile in plate 8, where relatively undeformed subthrust units of the Ellesmerian sequence gradually thin to the south.

The northern extent of the Ellesmerian sequence is unknown because Late Cretaceous(?) to Tertiary deformation and subsidence have obscured stratigraphic relationships in deep sequences in that area. In the northeastern part of the planning area, lower Brookian and older strata are folded and uplifted along high-angle reverse and normal faults in an area of complex uplift and wrench tectonics termed the North Chukchi high. To the northwest, seismic identification of the extent of Ellesmerian strata is obscured beneath the thick Brookian sequence in the North Chukchi basin.

The Tunalik No. 1 well provides control for the correlation of a mid-Ellesmerian unconformity (PU) which is mappable as a regional seismic reflection. The PU seismic marker serves as a practical and geologically significant boundary for the separation of the traditional Ellesmerian sequence into two informal sequences: the lower Ellesmerian sequence and the upper Ellesmerian sequence.

Lower Ellesmerian Sequence

Control

The lower Ellesmerian sequence is considered to include all sedimentary strata which lie between the PU and acoustic basement (fig. 11). The Tunalik No. 1 well penetrated over 3,200 feet of lower Ellesmerian rocks but never reached their base. In the vicinity of the Tunalik well, and westward into the offshore area, acoustic basement appears to lie below the base of the seismic profiles (6.0 seconds, or 45,000 feet). This is illustrated on the southwestern half of the seismic sections in plates 1 and 2.

Bounding Surfaces

Eastern margin (Central Chukchi basin). On the northern part of the Arctic platform (fig. 2), the PU surface generally slopes southwest away from the vicinity of the Wainwright fault zone, where it overlies acoustic basement at about 10,000 feet (plate 1, northeast end). The surface of the PU plunges into the Central Chukchi basin south of the Tunalik No. 1 well, where it lies at a depth of over 20,000 feet (plate 1). Offshore, the PU surface also slopes gently southwest, toward the Central Chukchi basin (plate 2). On the northeastern end of plate 2, the PU lies directly on Paleozoic rocks of the Northeast Chukchi basin (Craig and others, 1985) at a depth of approximately 3,000 feet, but descends southwest to a depth of over 25,000 feet beneath folded lower Brookian strata in the axis of the Cretaceous Colville basin. Along the western margin of the Northeast Chukchi fault zone (fig. 10), the PU lies above a seismically chaotic zone which may represent a more highly deformed stratigraphic equivalent of the lower Ellesmerian sequence (plate 3). From this area, the PU dips southwest into the axial portion of the Central Chukchi basin (plate 3, southeastern end; plate 4, northeastern end). The PU cannot be reliably traced into the northeasternmost portion of the planning area, where pre-upper Brookian strata are highly deformed and are rendered seismically incoherent by wrench tectonics (plate 6, southeast half).

The base of the lower Ellesmerian sequence on the eastern side of the Central Chukchi basin is difficult to identify on seismic records, and its interpretation is not controlled by well data. Where possible, we have placed the base of the lower Ellesmerian sequence at the top of the lowest continuous seismic reflection. On seismic data this surface appears as a relatively high-amplitude reflection that is down-faulted to the south along the Wainwright fault zone and lies below a seismically chaotic interval that grades laterally southward into stratified reflections of the lower Ellesmerian seismic sequence in the Central Chukchi basin (plate 2). In a local Ellesmerian basin (Tunalik basin) south of the Wainwright fault zone, this high-amplitude reflection is faulted below the base of the seismic panels (plate 2). An acoustic basement reflection is present below the lower Ellesmerian sequence along the northeastern margin of the Central Chukchi basin west of the Northeast Chukchi fault zone (plate 3, southeast end; plate 4, northeast end; plate 6, southeast end).

Central area (Central Chukchi basin). The PU generally passes from an angular unconformity at the margins of the Central Chukchi basin into a minor disconformity between essentially parallel strata in the axial parts of the basin. In these deeper areas, the PU lies at depths exceeding 20,000 feet, but it rises over 10,000 feet in structural elevation to the east and west toward the basin margins (plates 2, 4, and 5). The PU is characterized by a high-amplitude and broad-cycle-breadth reflection in the basin area and by progressive truncation of underlying reflections toward the basin margins. The high-amplitude reflection recognized elsewhere at the base of the Ellesmerian sequence is, in many areas of the Central Chukchi basin, obscured by deformation across structural highs and by extreme burial depth in the intervening lows.

Western margin (Central Chukchi basin). On the western margin of the Central Chukchi basin, thinning of the lower Ellesmerian sequence appears to be caused by a combination of basal onlap against underlying basement of the Chukchi platform and erosional truncation by the PU (plate 5). Similar onlap/truncation thinning of the lower Ellesmerian sequence is observed in the southwest near the Herald arch (plate 8; northeastern end). The PU surface lies at depths of approximately 10,000 feet (2.0 seconds) in the Chukchi platform area, where it onlaps and directly overlies acoustic basement (plate 5, northwestern part). The top of acoustic basement on the flanks of the Chukchi platform is characterized by a continuous, high-amplitude, broad-cycle-breadth reflection. Along the eastern edge of the Chukchi platform, the entire Ellesmerian section is locally truncated by the LCU over a major north-trending basement ridge, which is formed by an eastwardly tilted horst block (plate 5). West of this basement ridge, outliers of Ellesmerian strata, possibly including the PU horizon, are preserved in a large half-graben that parallels the western side of the horst block (plate 5, central portion).

Thickness and Distribution

The maximum thicknesses of lower Ellesmerian strata in the depocenters of the Central Chukchi basin exceed those observed onshore. Much of this additional thickness occurs at the base of the sequence. This suggests the presence of a significant proportion of Endicott Group age-equivalent or older rocks. There is seismic evidence for the existence of these strata but no direct well control for their identification or even for the delineation of the base of the Lisburne Group. The upper part of the lower Ellesmerian sequence is correlated to the Lisburne Group at the Tunalik No. 1 well (plates 1 and 2).

The eastern parts of the Central Chukchi basin contain thick deposits of lower Ellesmerian sediments. These sediments attain thicknesses greater than 30,000 feet in the Tunalik basin south of the Wainwright fault zone (plate 2). Northward along the eastern margin of the Central Chukchi basin, the lower Ellesmerian sequence exceeds 20,000 feet in thickness in a subbasin located west of the Northeast Chukchi fault zone (fig. 14; plate 3, southeastern half; plate 4, northeastern half; and plate 6, southeastern half). Lisburne Group age-equivalent strata thin updip to the northeast by a combination of onlap and erosional truncation. Near the northwestern end of plate 3, these lower Ellesmerian sequence reflections thin by onlap on a possible basement high. In the axial parts of the Central Chukchi basin, local fault-bounded subbasins contain up to 20,000 feet of strata that appear to be equivalent to the "Eo-Ellesmerian" strata described by Grantz and others (1982b) (plate 4, southwestern end; plate 5, southeastern end). Although these lower Ellesmerian subbasins in the Central Chukchi basin are partially separated from each other by uplifted fault blocks, they appear to contain correlative seismic stratigraphic units.

The lower Ellesmerian section thins west toward the Chukchi platform by a combination of basal onlap on the acoustic basement and truncation at internal and overlying unconformities (plate 5). The lower Ellesmerian sequence is locally truncated by the LCU over a north-trending basement ridge (plate 5). West of this ridge is a prominent linear asymmetric graben (fig. 12) that contains an outlier of Ellesmerian strata up to 5,000 feet thick. This outlier may be correlative to either the lower or the upper Ellesmerian sequence, or both (plate 5, northwest of center). This interpretation implies that the westward distribution of Ellesmerian deposits extends, at least some distance, onto the Chukchi platform and into the North Chukchi basin. South, along the strike of the graben, the relief on the bounding faults is less, and depositional continuity from the Central Chukchi basin onto the southern part of the Chukchi platform is preserved (fig. 15). Here the bounding faults appear to be predominantly lower Ellesmerian in age. In figure 15, lower Ellesmerian sequence strata onlap the southeastern side of the bounding horst. Upper Ellesmerian and possibly some lower Ellesmerian strata appear to overlap the horst and can be traced directly into the Chukchi platform area. In the southwest, near the Herald arch, the lower Ellesmerian sequence thins to approximately 2,000 feet beneath the Cretaceous rocks of the Fold and Thrust belt before it is truncated at the Herald thrust (fig. 10; plate 8, northeastern end).

Acoustic Character

<u>Eastern margin</u>. The lower Ellesmerian sequence varies greatly in acoustic character on seismic reflection records. On the eastern side of the Central Chukchi basin, along the Wainwright and Northeast Chukchi fault zones, the lower part of this sequence is characterized by discontinuous, poorly resolved to incoherent seismic reflections. Reflections in this sequence have distinct mounded configurations along the downthrown sides of these major fault zones (east-central parts of plates 2 and 3, and northeastern part of plate 4). In plate 2, a seismically chaotic zone grades basinward from the Wainwright fault zone into continuous, broad-cycle-breadth reflections that diverge to the southwest. Plate 3 shows an example of a similar

relationship in the area west of the Northeast Chukchi fault zone: discontinuous, chaotic, and possibly mounded reflections on the southeastern end of the panel appear to grade westward (basinward) into a distinctly layered sequence that here contains internal angular unconformities. These relationships are also observed in plate 4, which is located west of the Northeast Chukchi fault zone, although here the gradation from chaotic (northeast end, below 2.5 seconds) to layered reflections (southwest end) is partially obscured by later wrench-fault deformation. The seismically chaotic or mounded zone that lies west of the Northeast Chukchi fault zone trends northeast, parallel to the fault zone. In the northeastern part of the planning area, the lower part of the lower Ellesmerian sequence is characterized by a complex reflection geometry consisting of predominantly westward-dipping and overlapping lens-shaped seismic packages (plate 6, southeast end). These features are seen in the same relative stratigraphic and structural position on other seismic lines in the area. Interval velocities vary greatly in the chaotic to mounded seismic facies of the lower Ellesmerian sequence because of variable dips, seismic incoherency, and the generally great depths at which the features lie; the interval velocities are, therefore, considered to be unreliable.

A half-graben filled with a wedge of acoustically well stratified lower Ellesmerian rocks that contains several intrasequence unconformities is recognized along the downthrown side of the Northeast Chukchi fault zone, near the border of the Beaufort Sea Planning Area (fig. 14). The wedge geometry and multiple internal unconformities may indicate that graben subsidence and eastward tilting were syndepositional.

Along the eastern margin of the Central Chukchi basin, the upper part of the lower Ellesmerian sequence (Lisburne Group equivalent) is characterized by subparallel, relatively high-amplitude, broad-cycle-breadth reflections. These reflections are moderately continuous and exhibit lateral reflection terminations similar to those observed within the Lisburne carbonates in western NPRA (compare plates 1 and 2). Reflections that are seismically equivalent to the Lisburne Group converge to the north where they onlap the underlying zone of chaotic reflections in the vicinity of the Wainwright fault zone. Lisburne-equivalent strata pinch out to the northeast and do not extend onto the Northeast Chukchi basin "plateau" (plate 2, central portion).

The southwestern half of the seismic profile in plate 2 shows local northeastward-dipping reflections beneath the Lisburne seismic-equivalent strata (below 4.0 seconds). In the central portion of plate 3, the reflections of the upper part of the lower Ellesmerian sequence unconformably truncate underlying steeply southeastward dipping reflections of the lower part of the sequence. The orthogonal profiles in plates 2 and 3 both exhibit westward apparent dips in the lower Ellesmerian sequence, indicating that the true dip of the PU and underlying Lisburne reflections is generally to the west in the eastern part of the basin. Interval velocities

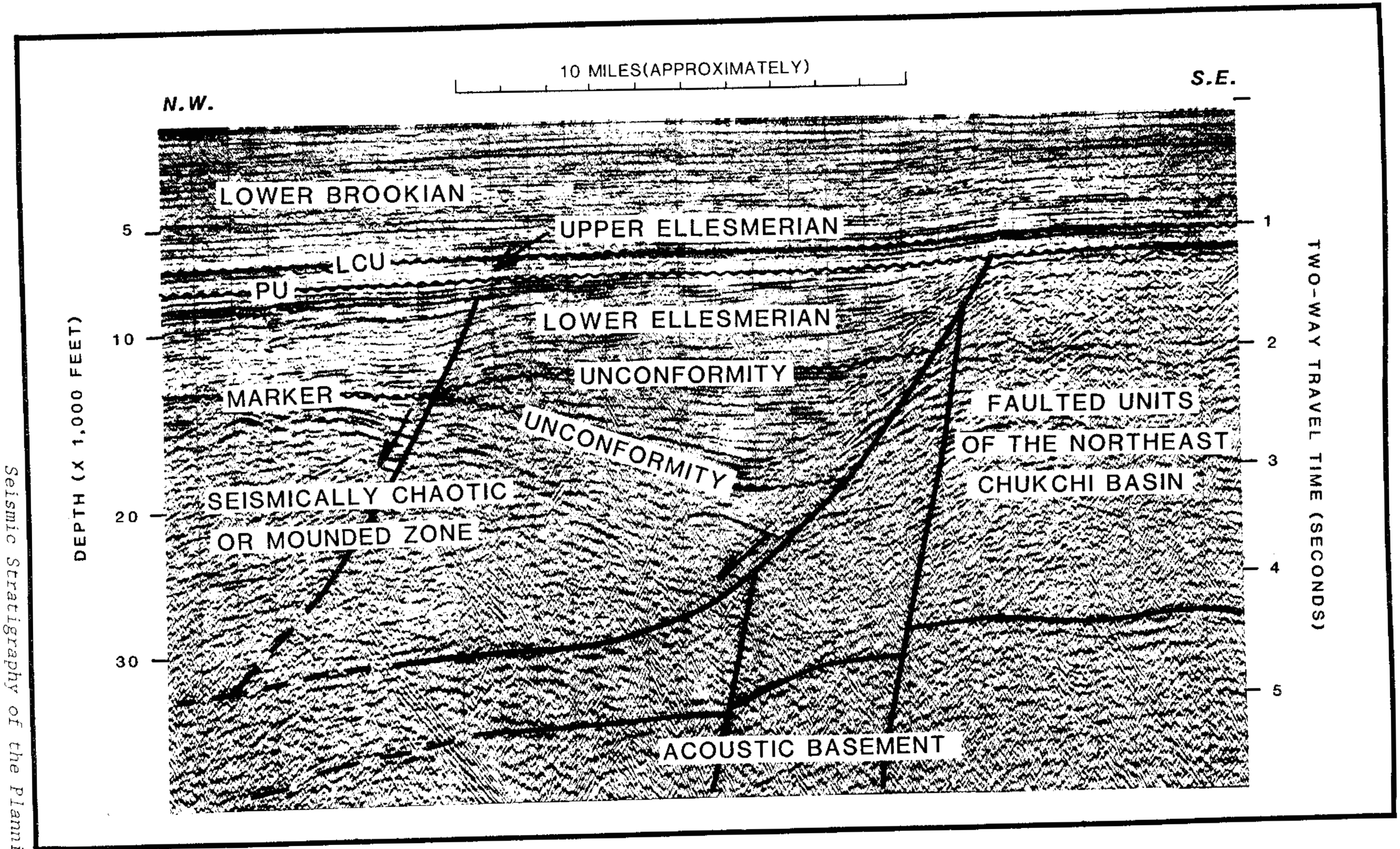


FIGURE 14. Graben filled with wedge of lower Ellesmerian (Endicott–equivalent?) strata along the Northeast Chukchi fault zone. See figure 71 for location of seismic panel. Data courtesy of Western Geophysical Company.

calculated from WGC Velans in this area show an average of about 17,500 feet/second in the inferred Lisburne section.

Central area and western margin. Well-stratified reflections occur within the lower Ellesmerian sequence in the deep axial portion of the Central Chukchi basin, as illustrated on the southwestern end of the seismic reflection profile in plate 4, below 3.8 seconds, and in the southeastern end of plate 5, below about 4 seconds. The lower Ellesmerian reflections are relatively high-amplitude, continuous, and coherent events. Angular relationships between reflection sets suggest the presence of local angular unconformities in the deeper parts of the basin.

The half-graben west of the basement ridge in plate 5 contains a wedge of high-amplitude, continuous reflections beneath the LCU that have a similar seismic character to both the upper and lower Ellesmerian seismic sequences on the eastern side of the block. The interval velocities derived from WGC Velans for this sequence indicate a range from 15,000 feet/second for the upper part of the section to about 17,500 feet/second for the lower part. These interval velocity ranges are similar to velocities obtained for lower Ellesmerian strata on the eastern side of the ridge, suggesting further that grabens on the Chukchi platform may contain some lower Ellesmerian rocks in their deeper parts.

Provenance and Depositional Setting

Based on preserved thickness distributions and depositional geometries, it appears that the source terrane for the lower Ellesmerian sequence in the Central Chukchi basin was located primarily northeast and east of the basin. However, seismic stratigraphic evidence suggests that a contemporary provenance existed to the west and southwest in the general areas of the Chukchi platform and modern Herald arch (fig. 16). The reflections from within the block-faulted, axial portion of the Central Chukchi basin exhibit internal unconformities and variable dip directions, indicating possible local, intrabasinal sources for sediment during early stages of basin development (plates 2, 3, and 4).

In Mississippian time, prior to the deposition of the Lisburne Group, the Northeast Chukchi basin (a relict Devonian(?) depocenter) was elevated and formed a high-relief structural plateau that bordered the eastern margin of the Central Chukchi basin along the Northeast Chukchi and Wainwright fault zones (figs. 10, 14, and 16; plate 2, northeastern part). On the western side of the basin, the Chukchi platform formed what appears to have been a low-relief basement high which was locally disrupted by horsts and grabens (fig. 15; plate 5, northwestern part). The intervening Central Chukchi basin was block faulted into locally deep basins and basement highs (plates 3, 4, and 5). Large volumes of clastic sediment (possibly equivalent to the Endicott Group) were shed from both the west and east into the Central Chukchi basin (fig. 16; plate 2, northeast-dipping and southwest-dipping reflections). The seismically chaotic zone in the lower Ellesmerian sequence near the Northeast Chukchi and

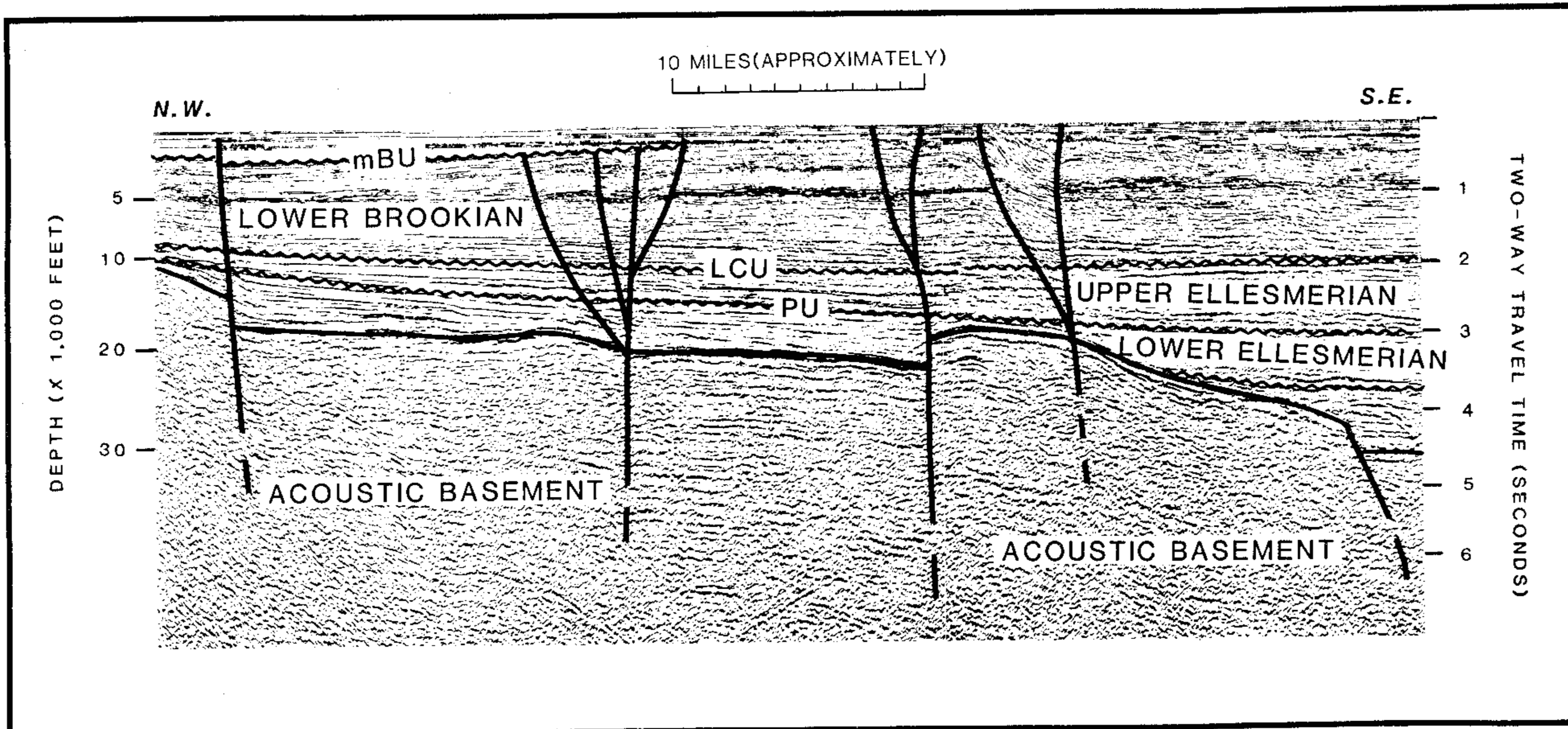


FIGURE 15. Seismic profile illustrating the structure of the western margin of the Central Chukchi basin and the adjoining Chukchi platform. See figure 71 for location of seismic panel. Data courtesy of Western Geophysical Company.

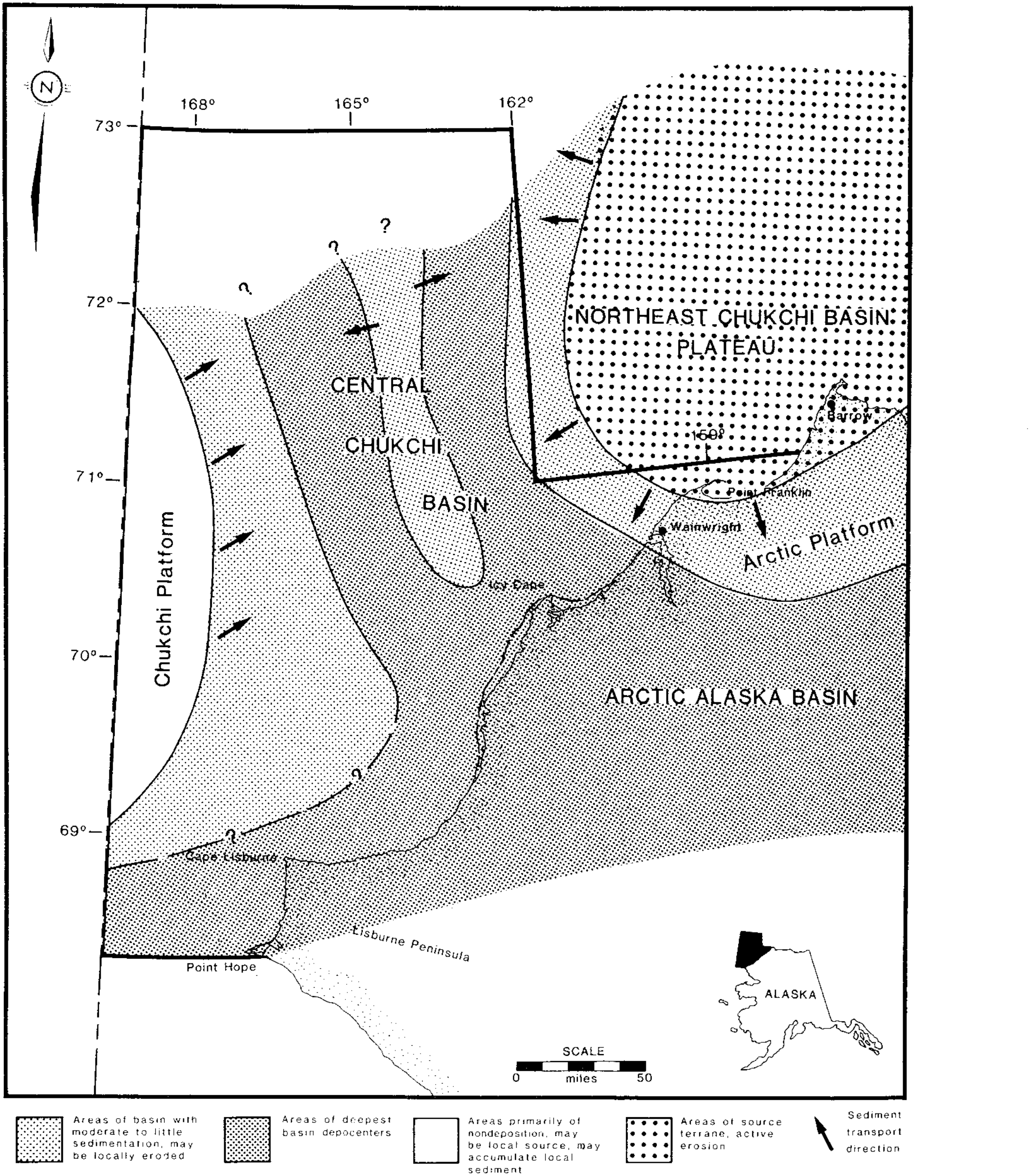


FIGURE 16. Inferred paleogeography and depositional trends for the lower Ellesmerian seismic sequence.

Wainwright fault zones may be caused by a combination of dense faulting and structural localization of slope deposits shed from the adjacent Northeast Chukchi basin "plateau" (fig. 14; plate 2). As previously noted, the central part of the Central Chukchi basin may have had local sediment sources from intrabasinal basement highs.

In Mississippian to Pennsylvanian time, marine transgression extended Lisburne-age sedimentation onto the broad, low-relief shelf of the Arctic and Chukchi platforms. Lisburne-equivalent strata in the south and southwestern parts of the Central Chukchi basin may contain higher proportions of black shales and cherts similar to the Lisburne Group known from exposures on the Lisburne Peninsula (Mull and others, 1982). The black shales found in these exposures are thought to represent a deep-water, euxinic, sediment-starved depositional environment (Armstrong and Mamet, 1970). Along the western margin of the Central Chukchi basin, low-relief, fault-bounded basins (fig. 15) may have ponded sediment in restricted-basin facies settings.

Upper Ellesmerian Sequence

Control

The upper Ellesmerian seismic sequence in the eastern Chukchi Sea Planning Area correlates readily to wells in western NPRA (Tetra Tech, 1982; Grantz and others, 1982b; Craig and others, 1985). Onshore wells have penetrated complete sections of this sequence and provide lithologic and seismic control for the interpretation of the sequence offshore. However, extrapolation of well ties farther than 100 miles west of Wainwright and 60 miles west of Icy Cape is frustrated by stratal disruption in wrench-fault zones.

Bounding Surfaces

The upper Ellesmerian seismic sequence comprises all strata which overlie the PU and lie beneath the LCU (fig. 11). Offshore from NPRA, the PU surface slopes gently southwestward (about 2 degrees) toward the axis of the Central Chukchi basin (plate 2). In the northeastern part of the Central Chukchi basin, the PU slopes more to the west (plates 3 and 4). The PU is clearly an angular unconformity in the structurally high areas along the eastern margin of the Central Chukchi basin, where it truncates more steeply dipping reflections within the underlying lower Ellesmerian sequence (plate 2, northeastern half; plate 3). In the deeper areas of the basin, the PU separates parallel reflections and here may represent a depositional interface or disconformity (plate 2, southwest end). Along the western margin of the Central Chukchi basin, the PU surface slopes to the east, toward the basin axis. The PU is more steeply inclined than the LCU and is truncated by the LCU on the Chukchi platform (plate 5).

Offshore from the Arctic platform, the slope of the LCU forms three separate southwestward-dipping homoclinal segments separated by narrow hinge zones (plate 2). The northernmost slope-segment

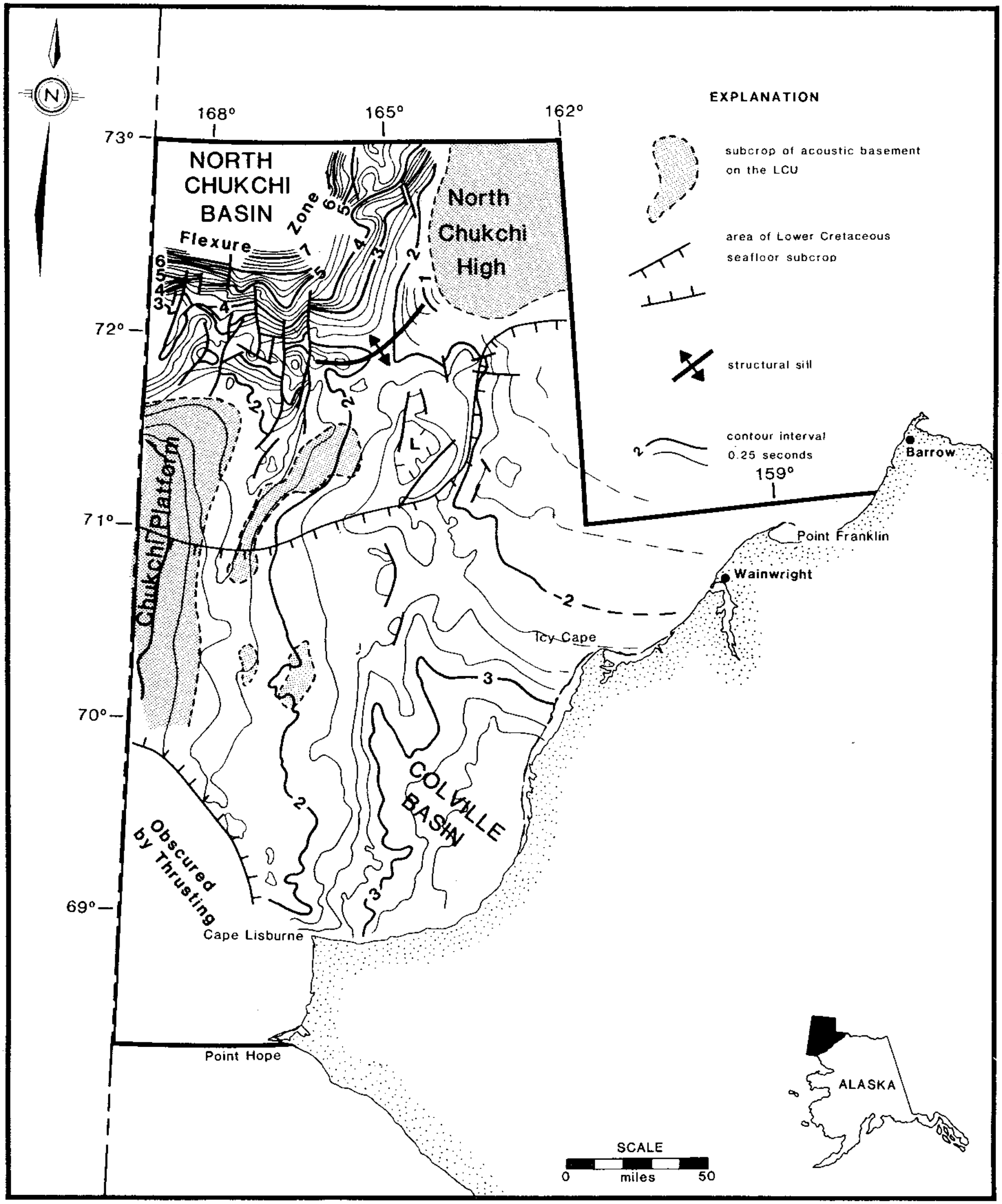


FIGURE 17. Structure map of the Lower Cretaceous unconformity in the Chukchi Sea Planning Area. Contours represent two—way travel time.

overlies the Northeast Chukchi "plateau," where the LCU is virtually flat and completely truncates underlying, upper Ellesmerian strata. Here, the LCU lies at a depth less than 3,000 feet (plate 2, northeastern end). South of a gentle flexure above the inactive Wainwright fault zone, the LCU dips toward the Central Chukchi basin at a constant angle of slightly greater than 1 degree and diverges from the underlying, more steeply dipping PU (plate 2, central portion). The third slope-segment formed by the LCU begins at a second gentle hinge zone where the dip abruptly doubles (to about 3 degrees). Southwest of this zone, the LCU and PU converge (southwestern end of plate 2). These segments of different slope angles may represent primary dip, possibly controlled by gentle basin structuring. In the interior of the basin, the LCU appears to be a depositional interface or disconformity rather than an erosional unconformity. The LCU corresponds to an easily recognized basin-wide high-amplitude reflection.

At the western margin of the Central Chukchi basin, the LCU appears to lie directly on basement at a depth of about 8,500 feet (1.6 seconds) over an eastward-tilted horst (plate 5, central portion). In the graben to the west of the horst in plate 5, the LCU overlies possible upper Ellesmerian strata. Farther west (plate 5), the LCU again lies directly on basement of the Chukchi platform.

In the southcentral part of the planning area, the PU and LCU appear to converge to the southwest beneath the deformed lower Brookian strata of the Fold and Thrust belt (northeastern end of plate 8).

Thickness and Distribution

Strata of the upper Ellesmerian seismic sequence can be traced from the Arctic platform on the east to the Chukchi platform on the west. They can also be traced to the north as far as the southern boundary of the North Chukchi basin and the North Chukchi high and to the south beneath the folded lower Brookian strata of the Cretaceous Colville basin. In the central and northern parts of the Central Chukchi basin, the sequence is thickest along the axis of the basin. In the southern part of the basin, the isopach maximum does not coincide with the basin axis, but lies along the northeast flank of the basin. The upper Ellesmerian sequence displays less regional variation in thickness than the overlying Brookian or the underlying lower Ellesmerian sequences.

In the eastern part of the Chukchi Sea Planning Area, seismic data indicate that the upper Ellesmerian sequence thins to the northeast by a combination of depositional onlap and erosional truncation. It is completely absent due to truncation at the LCU over the northern parts of the Northeast Chukchi "plateau" (plate 2). The thickness of the sequence increases to a maximum of about 8,000 feet just south of the Wainwright fault zone, then, as noted above, thins southwest toward the main axis of the Central Chukchi basin.

Along the profile in plate 4, the upper Ellesmerian sequence thickens from about 2,500 feet at the northeast end to an apparent maximum of nearly 9,500 feet at the feature identified as the "Wainwright dome." South of the dome, the sequence gradually thins to about 8,500 feet at the end of the record. In the northeastern part of the planning area, near the North Chukchi high, the upper Ellesmerian sequence is about 6,000 feet thick (plate 6, southeastern end). Within the North Chukchi high, the sequence is too highly deformed to reliably identify in seismic data.

Westward of the northern and central axial parts of the Central Chukchi basin, the upper Ellesmerian sequence thins from a maximum of approximately 8,000 feet to a truncation edge (at the LCU) on uplifted basement blocks of the Chukchi platform (plate 5). Up to 8,000 feet of pre-Lower Cretaceous strata, consisting at least in part of the upper Ellesmerian sequence, are locally preserved as an outlier in a graben on the Chukchi platform (plate 5).

Acoustic Character

The acoustic character of the upper Ellesmerian sequence is relatively similar across most of the planning area. The seismic sequence is generally composed of continuous, slightly divergent to parallel, relatively high-amplitude, broad-cycle-breadth reflections. However, there are some noteworthy areal variations in the acoustic details of the upper Ellesmerian sequence.

Along the eastern side of the Central Chukchi basin, basal reflections onlap the PU and are successively overlapped eastward by overlying reflections (plates 2 and 4). North and east of the Wainwright and Northeast Chukchi fault zones, upper Ellesmerian reflections are progressively truncated updip by the LCU (plates 2 and 4). Internal reflections in the upper part of this sequence are locally shingled and inclined toward the Central Chukchi basin (plate 2). This particular internal configuration of reflections has been reported for the Kingak Formation in parts of NPRA (Molenaar, 1981) where much of the upper part of the Kingak Formation is Neocomian in age.

Interval velocities calculated from WGC Velans and GSI Velscans typically range from 10,000 to 15,000 feet/second within the upper Ellesmerian seismic sequence. Sonic-log-derived interval velocities from NPRA wells show similar average values for the upper Ellesmerian sequence at similar burial depths.

Provenance and Depositional Setting

The thickness distribution and stratigraphic relationships within the upper Ellesmerian sequence in the Central Chukchi basin suggest the presence of source terranes northeast and west of the basin. The stratal thinning to the northeast over the unified structural block formed by the Arctic platform and the Northeast Chukchi basin "plateau" suggests that this area, or areas farther north, formed a northeastern source terrane for upper Ellesmerian

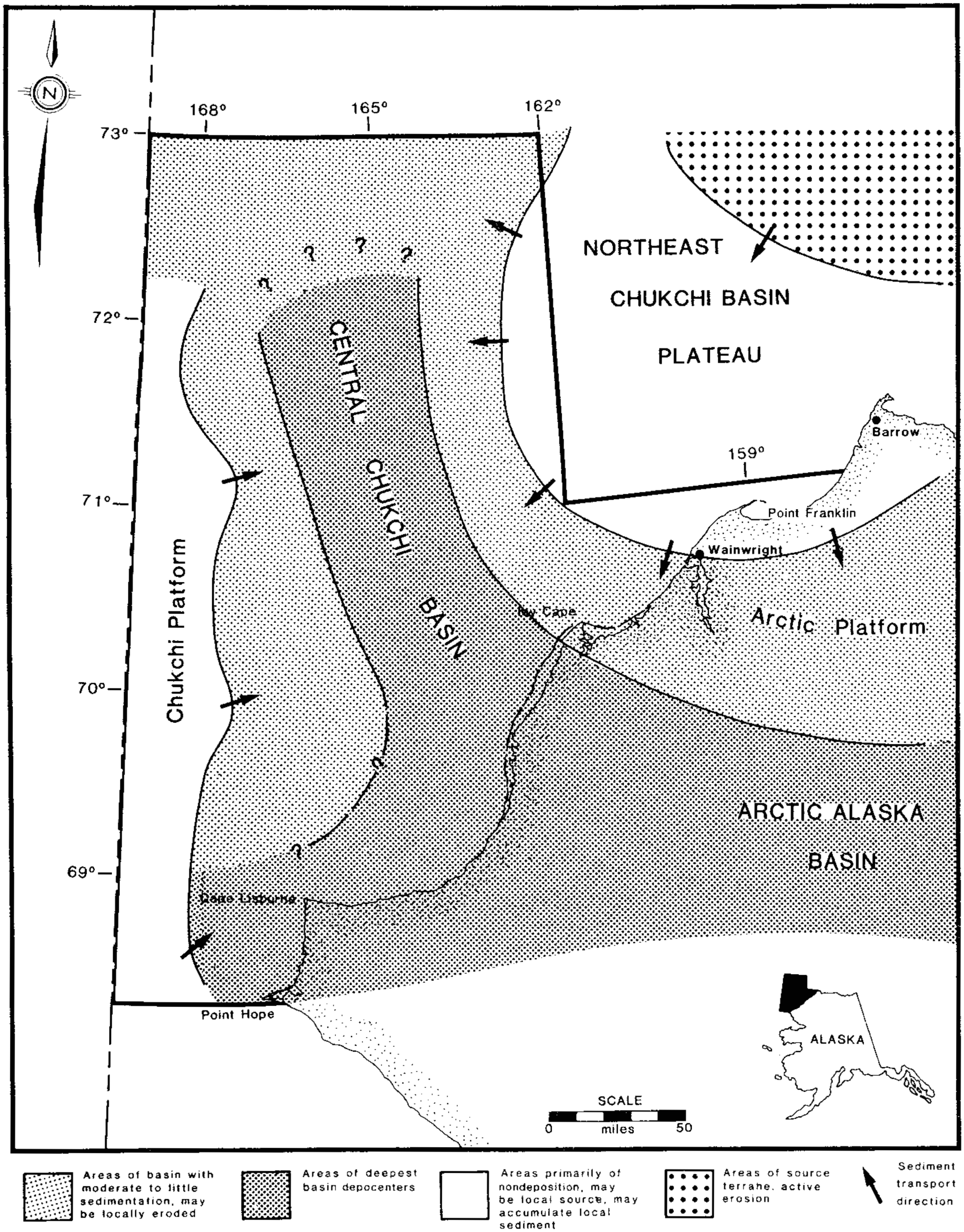


FIGURE 18. Inferred paleogeography and depositional trends for the Upper Ellesmerian seismic sequence.

sediments. Offshore of NPRA, the zero-thickness edge of the upper Ellesmerian sequence swings to the north, paralleling the margin of the Central Chukchi basin, which also indicates that a structurally high area existed to the east or northeast and possibly served as a source of sediment for this depositional area (fig. 18). In the southern part of the Central Chukchi basin, isopach maxima of the upper Ellesmerian sequence do not correspond to the axis of the basin. This is apparently due to a local thickening of the uppermost part of the sequence, possibly the Kingak Formation. The thickness may reflect the configuration of a Jurassic-Cretaceous deltaic system which invaded the basin from the north. The upper part of the upper Ellesmerian sequence thins toward the basin axis, and the Kingak-equivalent sequence there may represent distal, deep-water bottomset sediments.

On the western margin of the Central Chukchi basin, the westward thinning by onlap and by truncation at internal and overlying unconformities points to a western source area on or west of the Chukchi platform. At the southwestern margin of the Central Chukchi basin, high-quality seismic reflection data identify pinch-outs, thinning, and erosional truncations, which may suggest a provenance to the southwest.

Following the PU erosional event across the Arctic Platform and much of the planning area, the Permian sea transgressed the margins of the Central Chukchi basin, and strata equivalent to the basal members of the Sadlerochit Group were deposited. In the planning area, the lithology of this part of the sequence is unknown. A general marine regression of Triassic age is documented on the North Slope by the deposition of marginal-marine to nonmarine clastic deposits of the Ivishak Formation. Proximal fluvial-deltaic sandstones of the Ivishak Formation form the principal reservoir at the Prudhoe Bay field (Jones and Speers, 1976). At the Tunalik No. 1 well, however, this sequence is largely shale and siltstone, and probably represents age-equivalent strata deposited nearer to the basin axis. However, sandy facies may have been deposited in more proximal settings elsewhere along the eastern margin, and, conceivably also along the western margin of the Central Chukchi basin. Subsequently, the highly organic limestones and shales of the Triassic Shublik Formation were deposited throughout NPRA and presumably also in the Central Chukchi basin.

The Late Triassic to Early Jurassic deposits of the Sag River Formation consist of very fine grained, glauconitic sandstones. In NPRA, the Sag River sandstones accumulated as "isolated bar-like" bodies on the margin of the Arctic Alaska basin (Tetra Tech, 1982). Equivalent deposits may also be found on the margins of the Central Chukchi basin. In NPRA, the Sag River Formation grades upward into the marine shales of the Jurassic to Early Cretaceous Kingak Formation (Molenaar, 1981; Tetra Tech, 1982). Age-equivalent seismic strata on the east side of the Central Chukchi basin appear similar to the Kingak Formation on seismic reflection profiles from NPRA, and also exhibit shingled clinoforms which suggest lateral progradation of a delta-like system.

The generally uniform character of most of the upper Ellesmerian sequence suggests that it was deposited in a broad, low-relief, relatively simple basin. The overall geometry of the upper Ellesmerian seismic sequence in the planning area indicates that it was deposited in a north-trending trough-like basin with a southern axis curving to the east (fig. 18). The thick deposits in the north-trending part of the basin may consist of relatively shallow-water marine to nonmarine sediments that were derived from both the Arctic platform to the east and the Chukchi platform to the west. In the southern part of the basin, the sediments are probably more similar to the distal-facies rocks prevalent in the upper Ellesmerian sequence in NPRA.

BROOKIAN SEQUENCE

The Brookian sequence records a major change in regional tectonics of northern Alaska which resulted in a reversal of provenance direction and a great increase in the volume and rate of sedimentation. The traditional Brookian sequence of the North Slope is divided in the Chukchi Sea Planning Area into three major seismic sequences which can be separated on the basis of their geographic locale, relative age, sedimentary environment, and provenance. The first two sequences are informally termed (1) the "lower" Brookian, sequence, primarily of Lower Cretaceous age, and (2) the "upper" Brookian sequence, primarily Upper Cretaceous(?) to Tertiary in age. We identify the geographically isolated Tertiary to Quaternary clastic fill of the Northern Hope basin as a third, separate sequence, probably equivalent to the upper Brookian sequence.

Lower Brookian Sequence

Control

This sequence corresponds to the Pebble Shale, Torok Formation, and Nanushuk Group of western NPRA (Molenaar, 1981; Tetra Tech, 1982) (fig. 11). All wells in western NPRA encountered rocks of the lower Brookian sequence. Along the Chukchi coast, at the Peard No. 1 and Tunalik No. 1 wells, the lower Brookian sequence ranges in thickness from 6,500 to over 10,600 feet (Tetra Tech, 1982). Lower Brookian rocks are exposed in thrust-related folds of the Brooks Range Foothills and underlie the Arctic Coastal Plain (fig. 2). They have also been recognized in the continental-margin basins of the Beaufort shelf (Grantz and Eittreim, 1979; Craig and others, 1985).

Bounding Surfaces

The base of the lower Brookian sequence is defined by the LCU, which lies at the base of the Pebble Shale unit (fig. 11). This surface is seismically traceable as a high-amplitude reflection across the region, except in the Northern Hope basin, where the LCU is absent, and in the North Chukchi basin, where the LCU lies below the base of seismic reflection profiles (fig. 17). The regional characteristics of the LCU have been described in a preceding section.

Lower Brookian rocks subcrop at the seafloor in the eastern part of the planning area (parallel to the coast), in the southern part (Fold and Thrust belt), and in the western part (Chukchi platform). Over much of the northern parts of the planning area, the top of the lower Brookian sequence is an angular unconformity at the base of the upper Brookian sequence; this unconformity is informally termed the middle Brookian unconformity (mBU) (figs. 11 and 19). The mBU corresponds to a variable-amplitude seismic reflection that commonly truncates underlying lower Brookian reflections and is onlapped by reflections of the upper Brookian sequence. The mBU is readily recognized in the Northcentral subbasin, where reflections on either side of the interface exhibit angular discordance (plate 5). The mBU rises steeply from a depth of 8,400 feet in the axis of the Northcentral subbasin to a subcrop at the seafloor at the subbasin margins. North of the Chukchi platform and Northcentral subbasin, the mBU generally dips from 2 to 5 degrees northwestward into the North Chukchi basin (plate 7). On the North Chukchi high, the mBU truncates deformed lower Brookian and older rocks (plate 6) and is, in turn, truncated at the seafloor over parts of the structure.

A contour map (in time) of the mBU surface is presented in figure 19. This map includes the Northcentral subbasin, the North Chukchi basin, and the northern part of the Chukchi platform (fig. 10). Plate 5 illustrates the seismic character of the LCU and mBU from the Northcentral subbasin to the Chukchi platform.

Thickness and Distribution

The lower Brookian sequence attains maximum thicknesses primarily in two Early Cretaceous depocenters: the Colville basin in the south and the North Chukchi basin in the north (fig. 10). The part of the structure map in figure 17 that lies within the lower Brookian seafloor subcrop belt essentially isopachs the lower Brookian sequence. The sequence exceeds 20,000 feet in thickness in the Colville basin between Cape Lisburne and Point Lay. The lower Brookian clastic wedge in the Colville basin thins northward and westward onto basement highs (Arctic and Chukchi platform areas, respectively). In the second basin in the northern part of the planning area, the lower Brookian sequence thickens abruptly northward from about 2,000 feet on the northern part of the Chukchi platform (plate 7, southwest end) to over 35,000 feet (>6 seconds) in the North Chukchi basin. No northern limit to the North Chukchi basin can be identified with present data coverage. The seismic correlation of the sequence between these two major depocenters is dependent on the interpretation of a comparatively thin (less than 5,000 feet) section across a structurally complex area between the two basins. Over the northern parts of the Chukchi platform, the mBU and LCU are separated by a thin (3,500 feet) section of lower Brookian strata, which rest directly on acoustic basement (plate 5, northwestern end; plate 7, southwestern end).

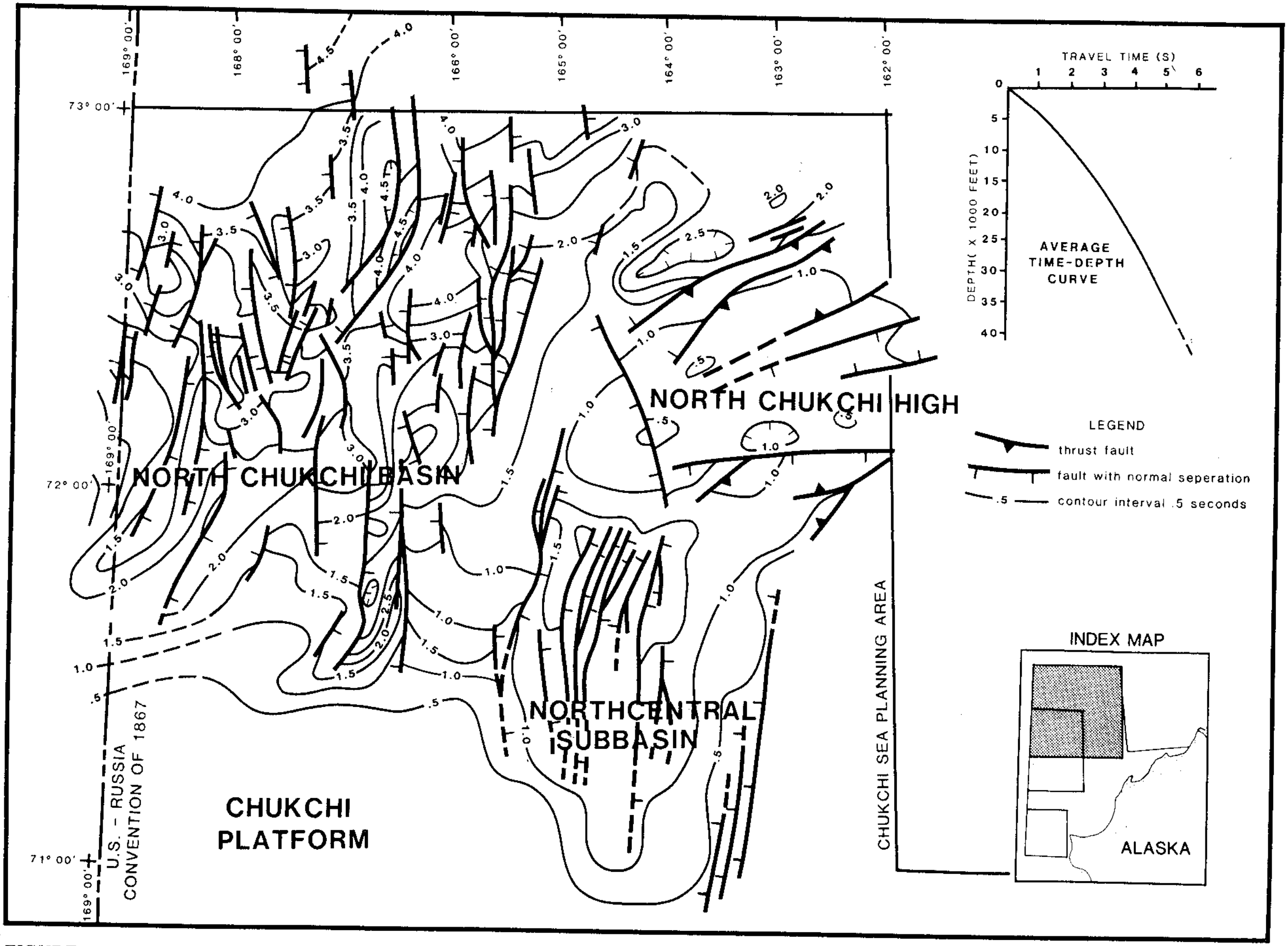


FIGURE 19. Structure map of the mid–Brookian unconformity (mBU) in the Northcentral subbasin and the North Chukchi basin.

Acoustic Character

The two primary depocenters (Colville basin and North Chukchi basin) contain lower Brookian sequences with contrasting acoustic characteristics and reflection geometry. In the Colville basin, the lower Brookian seismic sequence is a southward-thickening wedge consisting of two major seismic facies. The lower facies is composed of moderate-amplitude, broad-cycle-breadth, laterally continuous reflections generally arranged in low-angle, northeastwardly prograding clinoforms which downlap a reflection doublet above the LCU (plate 2, southwest end). This clinoformal facies correlates with the Pebble Shale unit and Torok Formation at the Tunalik No. 1 well (plate 1), and represents the bottomset, prodelta, and delta front facies of the lower Brookian deltaic system (plates 2 and 4). The clinoformal seismic facies is overlain by a seismic facies consisting of subparallel, generally moderate- to high-amplitude, narrow-cycle-breadth, laterally discontinuous reflections. This upper "undaformal" or topset seismic facies is correlative with the Nanushuk Group penetrated by the Tunalik No. 1 well (plate 1) and represents the delta plain facies of the lower Brookian deltaic system. Over the northern and western flanks of the Colville basin, the entire lower Brookian sequence thins and consists primarily of parallel to subparallel, continuous, broad-band-width reflections (plate 5; plate 6, southeast end; plate 7, southwest end).

From the northern margin of the Colville basin, the thin undaformal facies of the lower Brookian seismic sequence thickens abruptly at the flexure-zone which bounds the North Chukchi basin, and a lower clinoformal facies is not conspicuously developed (plate 7). At the flexure-zone, the seismic sequence consists of generally northward (basinward) diverging, moderately continuous seismic reflections that become relatively flat lying and parallel in the basin (plate 7, northeast end).

Provenance and Depositional Setting

Progradational clinoforms in the Colville basin exhibiting initial northeastward dip within the lower Brookian sequence (plates 2 and 4) indicate a source terrane to the southwest near the present position of the Herald arch. The Chukchi platform on the west and the Arctic platform on the northeast apparently formed broad highs upon which only thin lower Brookian strata were deposited and subsequently preserved. In the North Chukchi basin, the sediments of the northward-thickening lower Brookian sequence are inferred to have been derived predominantly from a southerly direction. Some lower Brookian sediment in the North Chukchi basin may have been derived locally from the northern part of the Chukchi platform (fig. 20).

Our studies of regional seismic data suggest a depositional model for the lower Brookian sequence in the southern part of the planning area that is similar to models proposed for the Colville basin by Grantz and Eittreim (1979), Molenaar (1981), and Tetra Tech (1982). The lower Brookian sequence in western NPRA, and probably in the southcentral part of the planning area, from the base to the top,

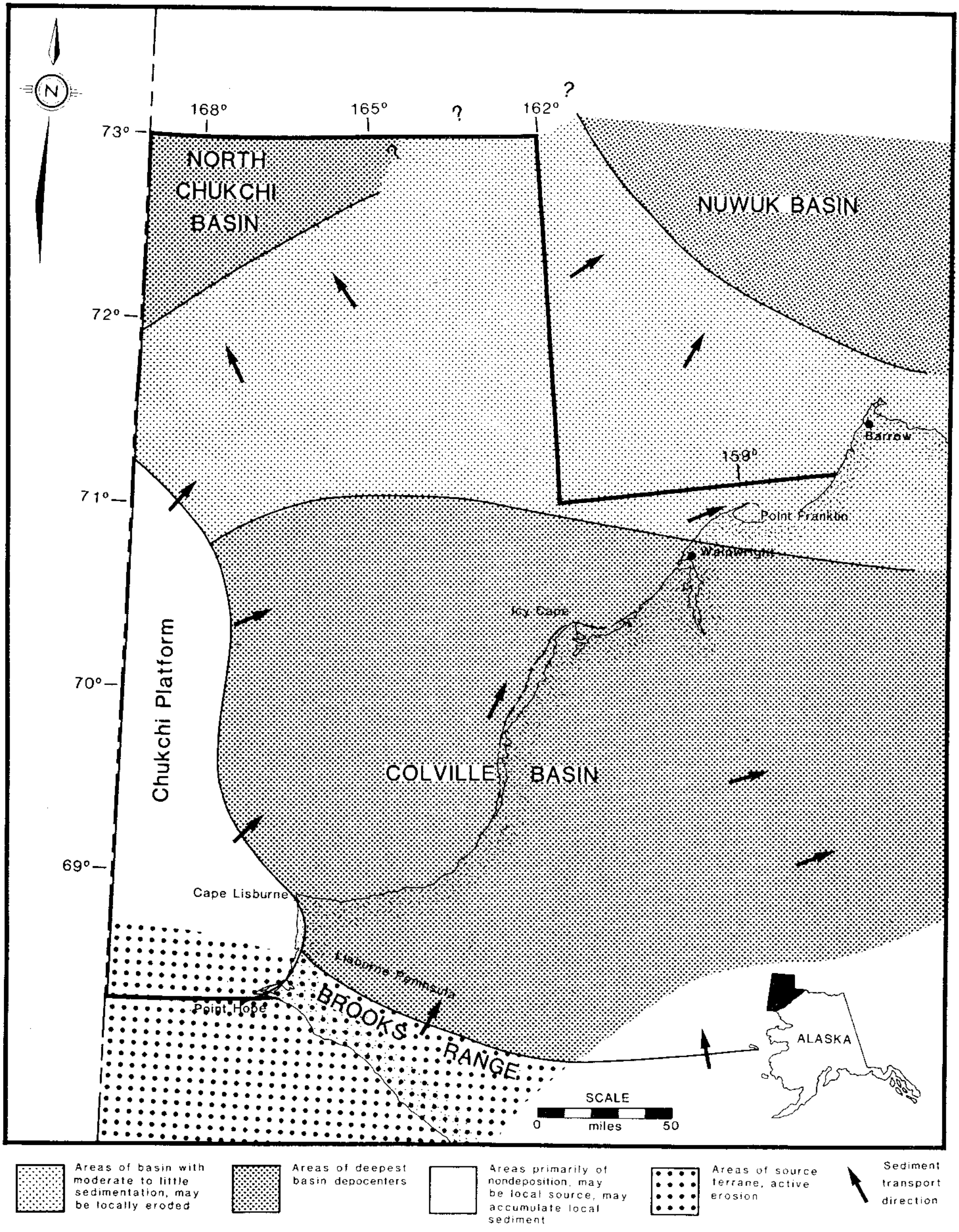


FIGURE 20. Inferred paleogeography and depositional trends for the Lower Brookian seismic sequence.

consists of basinal muds or clays (Pebble Shale unit) overlain by a thick section of delta front and prodelta shales that exhibit low-angle, sigmoidal clinoforms (Torok Formation). The clinoformal unit is overlain by a delta plain unit of fluvial and marginal marine sandstones, shales, and coals (Nanushuk Group). This lithologic succession characterizes the lower Brookian sequence and represents a prograding delta complex (Molenaar, 1981). Ahlbrandt (1979) and Ahlbrandt and others (1979) conclude that this sequence formed as an eastwardly prograding, low-energy, river-dominated delta, which they termed the Corwin delta (fig. 6). The eastwardly elongate configuration of the Corwin delta, and the fact that the sandstone in the sequence is dominated by fine- to very fine-grained clasts (Bartsch-Winkler, 1979), respectively, indicate that deposition was focused along the east-trending axis of the Colville basin, at a significant distance from the source terrane (fig. 20).

The thin, horizontally stratified deposits of the lower Brookian seismic sequence in the northern area of the Colville basin may represent a delta plain sedimentary facies or topset seismic facies of the prograding delta system. These possible fluvial to shallow marine strata were deposited on the Pebble Shale seismic unit or, locally, directly on the LCU. The thick, marine, clinoformal unit (prodelta-delta front facies) found elsewhere in the Colville basin appears to have graded north and west into topset facies on the Chukchi platform.

The northern parts of the Colville basin may have been bypassed by large volumes of sediment which were ultimately deposited in the Nuwuk basin along the Chukchi-Beaufort continental margin and in the North Chukchi basin (fig. 20). The undaform or topset facies of the lower Brookian sequence in the northern parts of the Colville basin appears to grade laterally to the north into a thick sequence of northward-diverging strata that filled the subsiding North Chukchi basin.

Upper Brookian Sequence

Control

The geographically isolated upper Brookian seismic sequence in the Chukchi Sea Planning Area is recognized only in seismic reflection data. No direct well control exists for this sequence. The North Chukchi basin is similar in magnitude and timing of subsidence and in general structure to the Nuwuk basin of the Beaufort shelf, as described by Craig and others (1985). However, no seismic correlations have been made between the two basins because, within the area of present data coverage, they are structurally separated by the North Chukchi high (fig. 10) and may have had quite different depositional histories.

Bounding Surfaces

The upper Brookian sequence consists of all sedimentary strata which lie between the seafloor and the middle Brookian unconformity (mBU) (fig. 11). The mBU is an angular unconformity over structural highs at the margins of the North Chukchi basin and the Northcentral subbasin (plate 7, southwest end; plate 6, northwest end; plate 5, central part). In the deeper parts of the North Chukchi basin and Northcentral subbasin, the mBU is identified as the interface where upper Brookian strata onlap structurally tilted strata of the lower Brookian sequence (plates 5 and 7). The mBU is highly faulted and abruptly rises to the seafloor along the margins of a major wrench-fault zone on the eastern margin of the Northcentral subbasin (plate 3). The southern margin of the Northcentral subbasin is generally not defined on CDP seismic reflection profiles because the mBU rises gently to a zone (above 1 second) where it is obscured by strong seafloor-multiple reflections. The seafloor subcrop of the mBU on the Chukchi platform, as mapped in figures 17 and 19, was instead identified and located using high resolution seismic reflection data.

Thickness and Distribution

In addition to the two primary depocenters (the North Chukchi basin and the Northcentral subbasin), upper Brookian strata were deposited over the northern parts of the Chukchi platform and over the North Chukchi high. The structural configuration of the mBU (and, essentially, the seismic thickness (in time) of the upper Brookian sequence) in the northern part of the planning area is shown in figure 19. Strata in the axis of the Northcentral subbasin reach a maximum thickness of 8,400 feet (2.0 seconds). At the northern end of the Northcentral subbasin, the mBU rises over a northeast-trending structural sill at a depth of about 3,000 feet (1.0 second; fig. 19). Convergence of reflections toward the sill and truncation of strata at the seafloor over the crest of the sill imply syndepositional and post-depositional uplift. This sill marks the boundary between the Northcentral subbasin and the North Chukchi basin.

Areas of maximum thickness of upper Brookian strata on the northeastern part of the Chukchi platform and western part of the Northcentral subbasin commonly coincide with isopach maxima for older sequences within fault-bounded grabens (plate 5, center and southeastern part). This suggests reactivation of the faults during upper Brookian (Late Cretaceous(?) to Tertiary) time. On the northwestern part of the Chukchi platform, the thick upper Brookian section does not correspond to older grabens (plate 5, northwest end). On the Chukchi platform the sequence gradually thins southward, eventually terminating at a seafloor subcrop of the mBU. The upper Brookian sequence attains thicknesses of up to 25,000 feet (4.5 seconds) in the North Chukchi basin (fig. 19; plate 7).

Acoustic Character

The acoustic character of the upper Brookian sequence varies regionally. In the Northcentral subbasin, the upper Brookian sequence is characterized by laterally continuous reflections of narrow- to intermediate-cycle-breadth. These reflections converge toward the basin flanks and generally exhibit a parallel geometry in

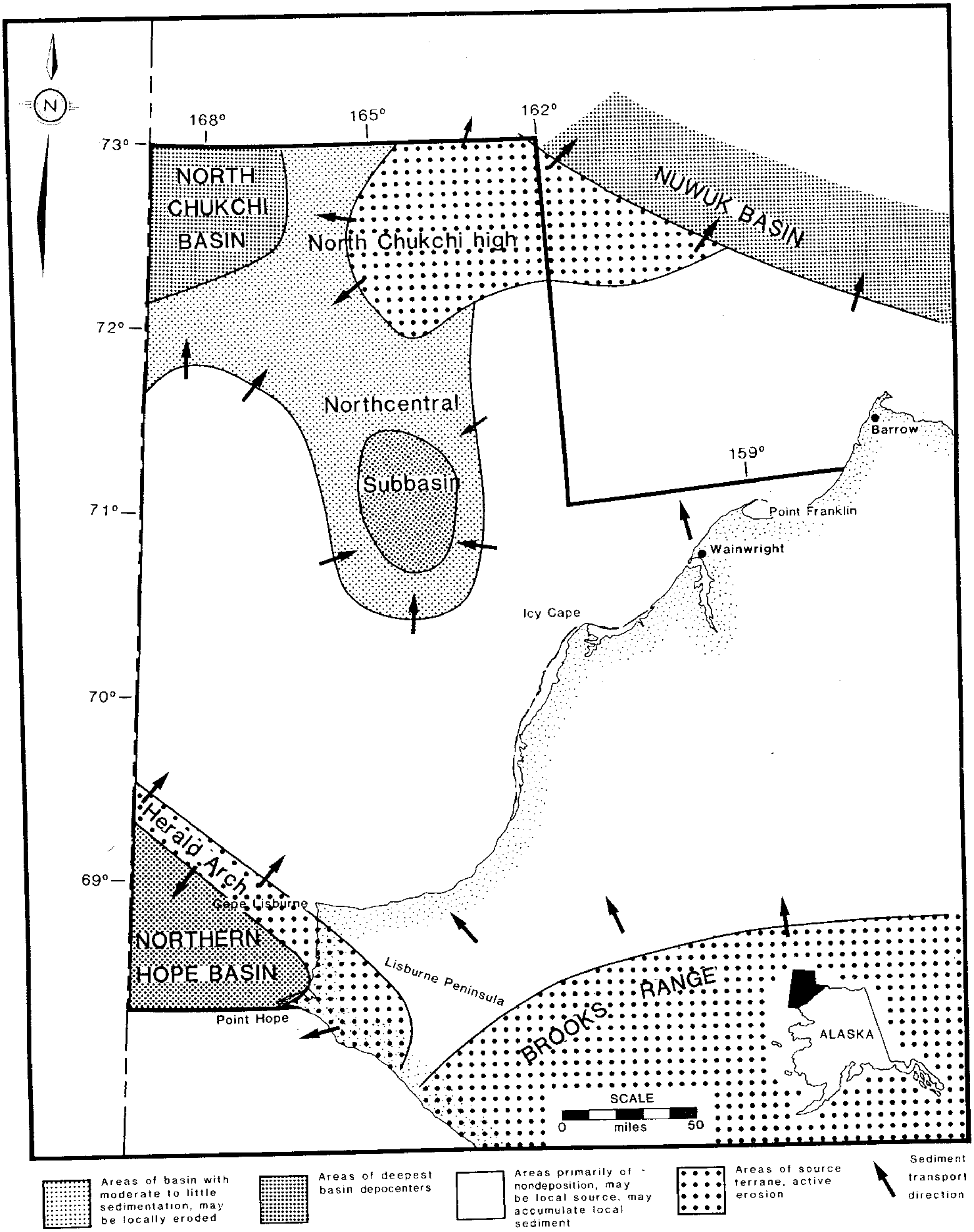


FIGURE 21. Inferred paleogeography and depositional trends for the Upper Brookian seismic sequence.

the basin. The upper Brookian sequence on the northern part of the Chukchi platform commonly consists of a uniformly thickening wedge of parallel to slightly divergent, intermediate- to broad-cycle-breadth, laterally continuous reflections that dip toward the North Chukchi basin (plate 5, northwest end). In the North Chukchi basin, the sequence is composed of laterally continuous reflections which gradually diverge and dip into the basin. Thin clinoformal facies are recognized locally in the lower part of the upper Brookian sequence in the North Chukchi basin (plate 7).

Provenance and Depositional Setting

Upper Brookian sediments were derived primarily from the Brooks Range and the Herald arch areas to the south of the main depocenters (fig. 21). Sediments deposited in the Northcentral subbasin were probably derived, in part, from adjacent uplifts along active wrench-fault zones. Possible local source areas for the upper Brookian sequence in the Northcentral subbasin are the Fold and Thrust belt, the Chukchi platform, and the North Chukchi high (fig. 21).

The upper Brookian sequence generally lacks the suite of seismic facies (bottomset, clinoformal or foreset, and topset or undaformal) typical of the deltaic systems that are so conspicuously developed in the lower Brookian sequence of the Colville basin. The upper Brookian sequence is overall most similar in seismic appearance to the topset (fluvial-deltaic) seismic facies of the lower Brookian sequence and may have formed in a similar depositional setting.

In the North Chukchi basin a prominent unconformity is present within the upper Brookian sequence (plate 7). This unconformity separates a lower sequence which contains progradational clinoforms and, in places, shows poor acoustic resolution, from an upper sequence which consists of acoustically well resolved, evenly stratified, subparallel reflections (plate 7; fig. 11).

Hope Basin Sequence

Control

The strata of this basin have been partially tested by the Socal Nimiuk Point No. 1 and Cape Espenberg No. 1 wells, which were drilled in the southern Hope basin over 150 miles southeast of the Chukchi Sea Planning Area. These wells encountered nearly 4,000 feet of Pleistocene marine and glacio-fluvial sediments overlying middle to late Tertiary marine deposits ranging from approximately 1,300 to 2,000 feet in thickness. The middle to late Tertiary deposits overlie older volcanic and nonmarine volcaniclastic rocks, possibly of Eocene age, that range from 1,000 to 3,000 feet in thickness (Larson and Olson, 1984). This Tertiary section unconformably overlies Paleozoic schists and metamorphosed carbonate rocks. However, these wells tested the Kotzebue basin, which is partially isolated from Hope basin by a major tectonic feature known as the Kotzebue arch (Grantz and others, 1975). This fact, coupled with the remoteness of the wells, makes it difficult to reliably extend this control into the Chukchi Sea Planning Area.

Bounding Surfaces

The Hope basin sequence is bounded on the top by a Pleistocene erosional surface at the present seafloor (fig. 11). The sequence lies on acoustic basement above a major unconformity throughout the basin. A contour map (in time) on the top of acoustic basement is presented in figure 13. This figure also illustrates the thickness and gross distribution of the Hope basin sequence. The acoustic basement is extensively fragmented by high-angle faults that trend generally northwest, parallel to the Herald arch.

Thickness and Distribution

Seismic reflections of the Hope basin sequence onlap the southern flank of the Herald arch and do not extend into the Central Chukchi basin (fig. 13). South of the zero-thickness edge, the sequence fills local fault-bounded basins (plate 8) that formed on the back (south) side of the Herald thrust sheet. In the planning area, these basins contain from 3,000 feet (1.0 second) to 17,000 feet (3.25 seconds) of strata inferred to be Cenozoic in age.

In the Chukchi Sea Planning Area, the Hope basin sequence exhibits internal seismic characteristics that allow the separation of the sequence into two units, as illustrated in plate 8. The lower unit is confined to local grabens and is highly faulted. In the northern part of the basin, the lower unit makes up most of the total thickness of the sequence. The southwestern end of plate 8 shows the distribution of the lower unit in these grabens. The graben on the flank of the Herald arch contains about 3,500 feet of the unit, and the graben at the southwest end of the profile contains over 5,000 feet. The upper unit unconformably overlies the lower unit, is sparsely faulted, and thickens gradually to the south from a zero-edge at the Herald arch to about 3,000 feet at the southwest end of plate 8.

Acoustic Character

The lower unit of the Hope basin sequence (fig. 11) contains reflections which diverge strongly into the grabens and onlap flanking structural highs. Local, seismically chaotic zones near graben margins grade laterally and up-section into relatively high-amplitude, broad-cycle-breadth reflections. A reflection event at the base of the upper unit corresponds to an apparent disconformity over the grabens and an angular unconformity on the flanks and crests of local basement blocks. This surface dips at a low angle to the southwest and forms the base of a southwestward-thickening wedge that is composed of parallel to slightly divergent, narrow-band-width, relatively low amplitude, and moderately continuous seismic reflections. Interval velocities of the Hope basin sequence are typically low, ranging from approximately 5,500 to

10,800 feet/second (Grantz and Eittreim, 1979), suggesting that these are young clastic deposits which have not been deeply buried.

Provenance and Depositional Setting

The northward thinning and onlap of sediments deposited in the northern portion of Hope basin suggest a provenance to the north, in the vicinity of the Herald arch. However, a significant contribution from local sources (basement uplifts) adjacent to grabens is also possible. The fill in these grabens may be largely fans or deltas and may be represented by the chaotic acoustic character of the lower seismic unit (plate 8). Following the cessation of fault movements and the development of a regional unconformity, the evenly-stratified deposits of the upper unit were laid down, possibly in a shallow marine shelf environment. The westernmost Brooks Range probably also formed a source for sediment in the Hope basin (fig. 21).

4. STRUCTURAL PROVINCES OF THE CHUKCHI SEA PLANNING AREA

The larger and more conspicuous structural provinces in the Chukchi Sea Planning Area were identified and named by Grantz and others (1975); Grantz and Eittreim (1979); Grantz and others (1982b); and Grantz and May (1984a, 1984b). The major features recognized in these studies include the offshore extension of the Arctic platform, the offshore extension of the Foreland fold belt, the "Hanna trough," the Herald arch, the Herald thrust, the Hope basin, the Chukchi platform, and the North Chukchi basin. The present report adopts most of this terminology. However, in this report we refer to the Hanna trough as the Central Chukchi basin. We prefer to abandon the term Hanna trough because it unites three areally coincident structural basins of Ellesmerian and Brookian age which formed at different times in highly contrasting settings. Instead, we propose the term Central Chukchi basin to describe the larger structural basin of Mississippian to Early Cretaceous age. In turn, the Central Chukchi basin is structurally overlain by two distinct, younger subbasins formed by Cretaceous and Tertiary subsidence (fig. 10). These are (1) the westward, offshore extension of the Early Cretaceous Colville basin; and (2) the Late Cretaceous(?) to Tertiary Northcentral subbasin. The Northcentral subbasin was identified by Grantz and May (1984a) as a possible submarine canyon tributary to the North Chukchi basin. We instead propose that this depression is the result of structural subsidence.

The area shown by Grantz and others (1982b) as the offshore extension of the Arctic platform coincides with the southwest margin of the structural block containing the Northeast Chukchi basin (fig. 10). Grantz and others also identified the general location and northward trend of a fault zone along the northeastern border of the Chukchi Sea Planning Area (Grantz and others, 1975; 1982b). This fault zone was also recognized by Craig and others (1985) and is here informally termed the Northeast Chukchi fault zone (fig. 10). Craig and others (1985) identified several features that extend from the Beaufort Sea Planning Area into the eastern Chukchi Sea Planning Area. These features are the Barrow fault zone, the Northeast Chukchi basin, and the North Chukchi high (fig. 10). Fault zones which truncate the Northeast Chukchi basin (Barrow fault zone on the south and east, and the Northeast Chukchi fault zone on the west) are found within the Chukchi Sea Planning Area. A southeast- trending fault zone which truncates the Barrow fault zone and forms the north boundary of the Tunalik basin near the settlement of Wainwright is here informally termed the Wainwright fault zone (fig. 10). Additional significant structural features that we describe include the Hanna wrench-fault zone and an area containing abundant diapirs in the northern part of the Chukchi platform (figs. 10 and 22).

HERALD ARCH

The Herald arch is a structural ridge created by a northwest-trending thrust sheet which can be traced into exposures of highly deformed Paleozoic and Mesozoic rocks on the Lisburne Peninsula (Grantz and others, 1975) (fig. 22). The highly deformed Ellesmerian clastic and carbonate rocks exposed in the Lisburne Hills (Lathram, 1965) may constitute the acoustic basement of the Herald arch offshore. The frontal thrust of the Herald arch is termed the Herald thrust fault (plate 8; fig. 22) and appears to be an offshore extension of the thrust fault system that lies at the northern front of the Lisburne Hills. Holmes (1975) estimates a dip angle for the Herald thrust fault of 8 to 10 degrees to the southwest, and a minimum lateral displacement of 12 miles northeastward.

Acoustic basement subcrops at the seafloor along the Herald arch but is unconformably onlapped by Late Cretaceous(?) to Tertiary rocks (Grantz and Eittreim, 1979) of the Northern Hope basin (plate 8; fig. 13). The Herald thrust truncates lower Brookian strata, and imbricate thrust sheets carrying acoustic basement have overridden thrust-cored detachment folds in lower Brookian rocks in the Colville basin along the northern front of the Herald arch (plate 8). The northwesterly trend of these detachment folds is nearly orthogonal to the east-west fold trend in the Foreland fold belt (Grantz and Eittreim, 1979) (fig. 22). The northwesterly trending Herald/Lisburne Hills thrust fault system and associated fold belt truncate, and appear to overprint, the dominantly west-trending Brooks Range thrust system and Foreland fold belt (Martin, 1970; Grantz and others, 1975). The onshore intersection of the two thrust fault systems has been termed the Chukchi syntaxis (Grantz and others, 1975). This feature is believed to have formed by the cross-cutting of the older Brooks Range thrust system by a later episode of eastward-directed overthrusting along the Herald arch (Martin, 1970).

The present site of the Herald arch was a structurally positive area from possibly Early Mississippian to Early Cretaceous time, as suggested by southward thinning of Ellesmerian strata by truncation and onlap toward the Herald arch in the Central Chukchi basin (plate 8, northeast end). This area was actively uplifted in the Early Cretaceous, during the initial formation of the Brooks Range, and probably formed a provenance for the northeastwardly prograding lower Brookian clastic wedge in the Colville basin (Bird and Andrews, 1979; Bartsch-Winkler and Huffman, 1980).

To the northwest, the Herald arch intersects the southern part of the Chukchi platform. At this juncture the Herald thrust system may terminate at strike-slip faults which dissect the Chukchi platform. This proposed relationship implies that the Herald thrust

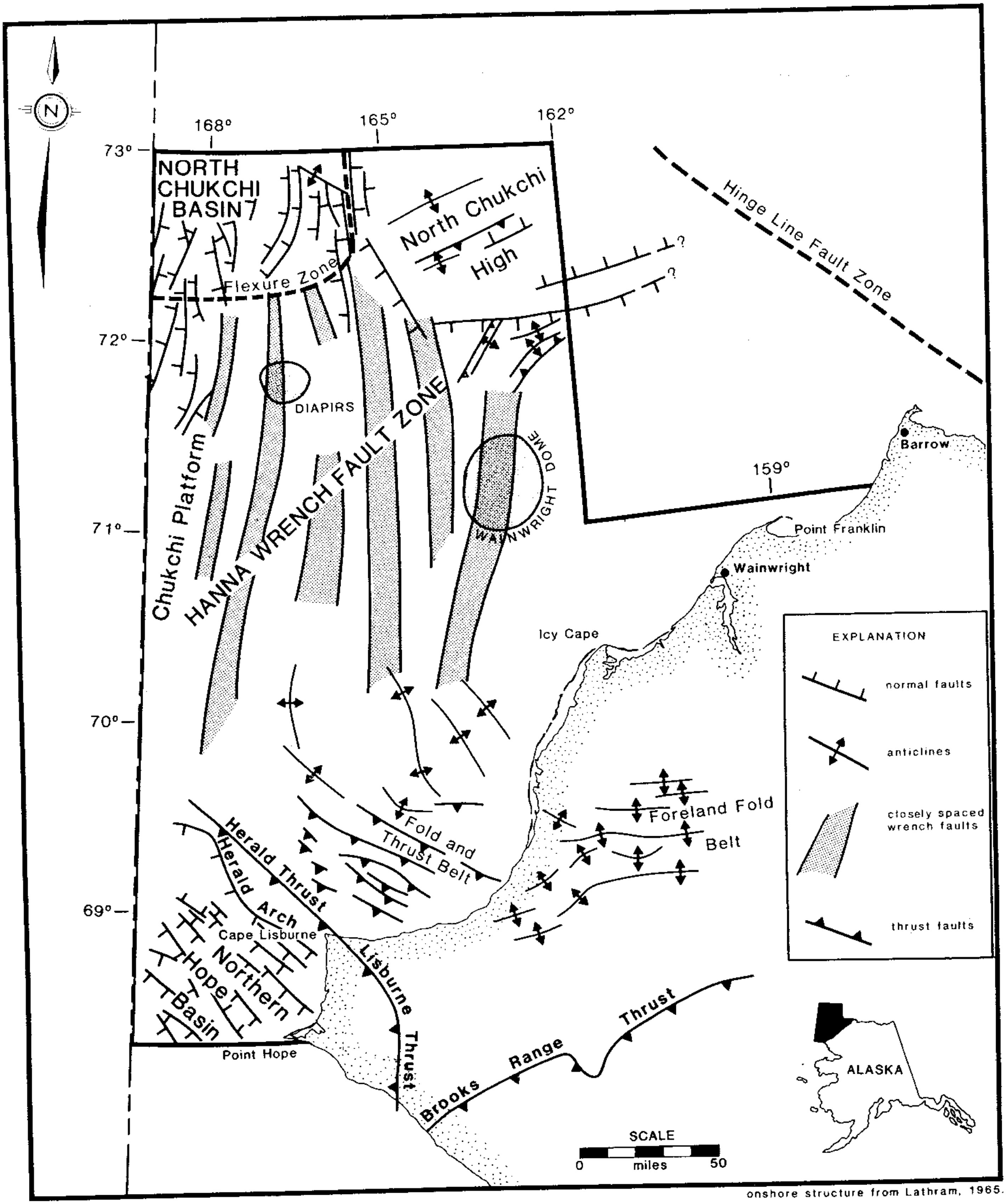


FIGURE 22. Early Cretaceous to Tertiary tectonic elements of the Chukchi Sea Planning Area and contiguous areas.

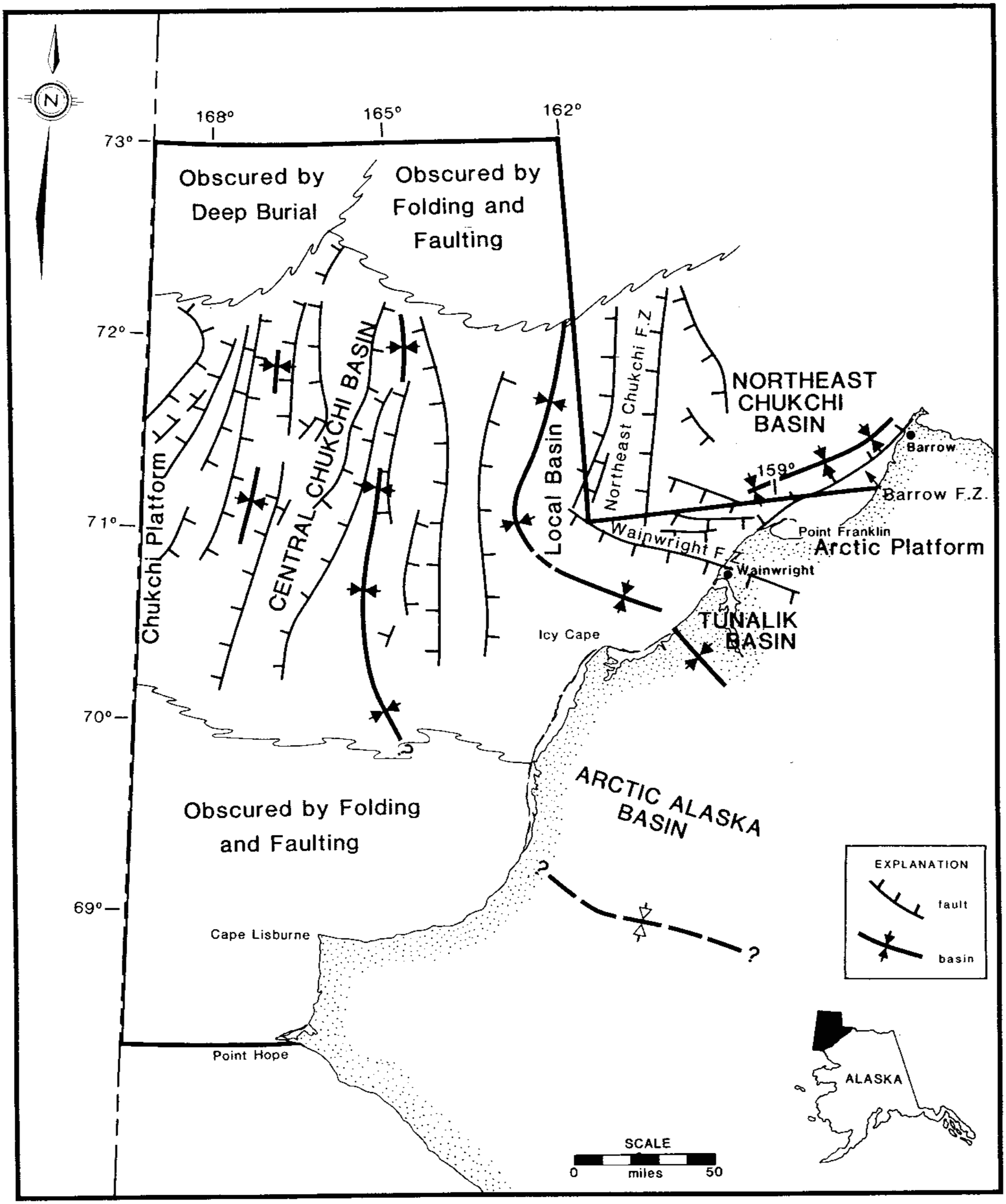


FIGURE 23. Paleozoic tectonic elements of the Chukchi Sea Planning Area and contiguous areas.

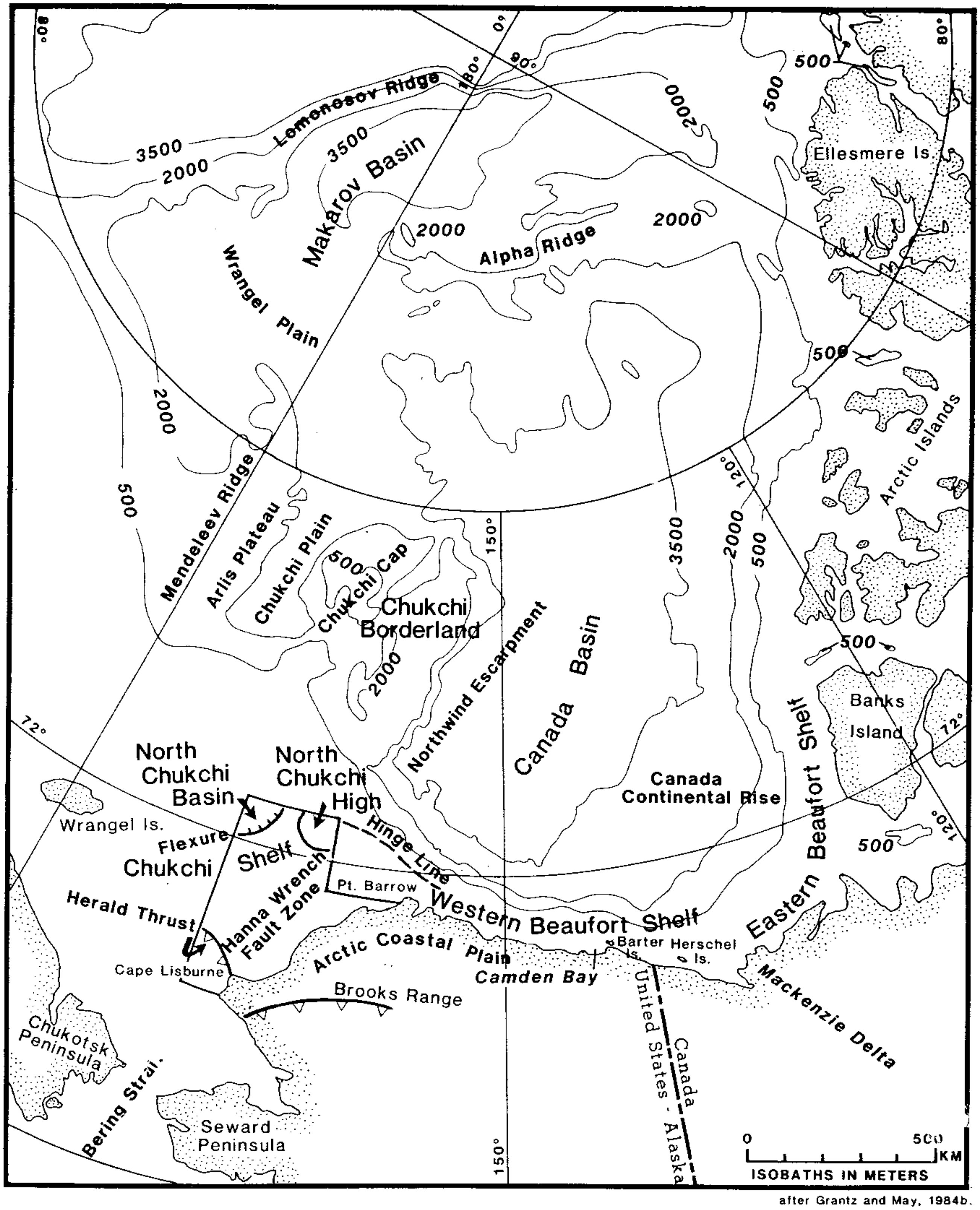


FIGURE 24. Late Cretaceous to Tertiary tectonic features of the Chukchi Sea Planning Area and major physiographic features of the Arctic Ocean.

system may be part of a larger wrench tectonic system that has controlled contemporary subsidence of the Northcentral subbasin and deformation along the Hanna wrench-fault zone.

CHUKCHI PLATFORM

The western part of the planning area is underlain by a broad basement high termed the Chukchi platform (Grantz and May, 1984a). Seismic stratigraphic relationships suggest that this area was a structural high which formed the western margin of the Central Chukchi basin during accumulation of the Ellesmerian sequence (Early Mississippian to Early Cretaceous). The Chukchi platform persisted as a structurally positive block during deposition of the lower Brookian sequence, but its northern part was subsequently down-dropped during deposition of the upper Brookian sequence (plate 5, northwestern end).

The Chukchi platform trends generally north-northeast from the Herald arch to the North Chukchi basin (fig. 10). The top of acoustic basement on the platform gradually slopes beneath the northward-thickening lower Brookian clastic wedge to an abrupt termination at the west-trending flexure-zone along the southern margin of the North Chukchi basin (plate 7; fig. 12). The Chukchi platform is segmented by a set of lengthy, north-trending faults that extend from their apparent southern intersection with the Herald arch to their northern intersection with the North Chukchi basin flexure-zone. The throw on these high-angle faults generally increases to the north as they approach the flexure-zone (fig. 12). A tilted horst that formed primarily during Ellesmerian time is illustrated in figure 15. This feature is a southern counterpart to the tilted horst shown in plate 5. The graben in figure 15 is overlapped by Ellesmerian strata and exhibits primarily pre-upper Ellesmerian offset with some reactivation during or following Brookian sedimentation.

The Ellesmerian-age faults in the northern parts of the Chukchi platform were reactivated in Late Cretaceous(?) to Early Tertiary time as wrench faults. Evidence for this hypothesis is shown in plate 5, where faults that bound grabens which formed in pre-LCU time now also extend upward to form domal or basinal features in the overlying Brookian sequence(s). These fault complexes closely resemble wrench-fault structures which are termed "flower structures" (Harding, 1985). These wrench-fault features are common throughout the northern parts of the Chukchi platform. The lower Brookian sequence overlying the wrench zone along the horst in plate 5 shows localized stratal variation that suggests it was a former basin that was subsequently structurally inverted. This is suggested by the observation that strata thin on the flanks of the uplift but thicken over the crest of the uplift.

Diapirs and associated structures which disrupt Cretaceous through Tertiary strata have been identified on several seismic lines in the northern parts of the Chukchi platform. Late-stage piercement

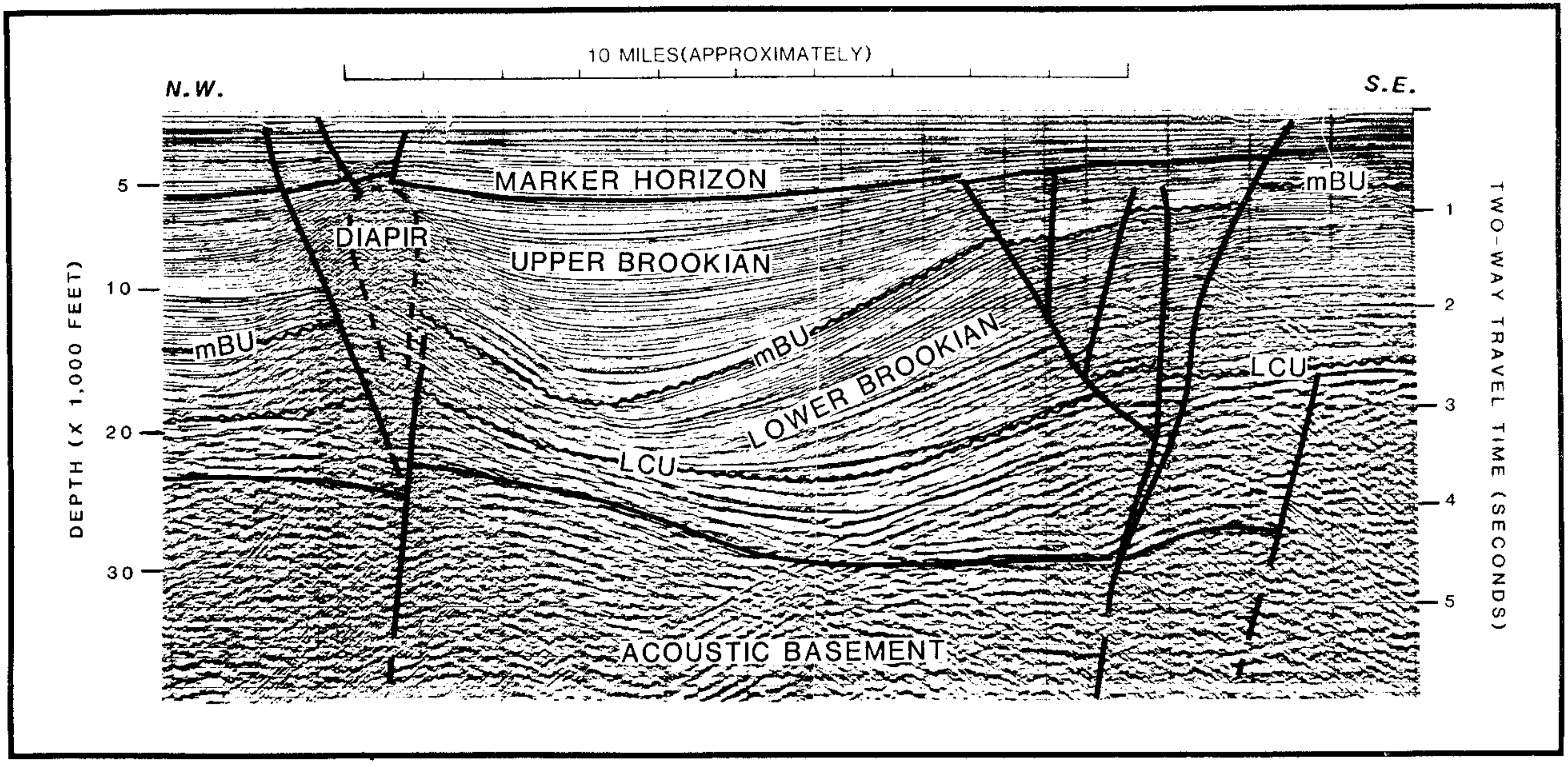


FIGURE 25. Tilted graben and piercement diapir on northern part of the Chukchi platform. See figure 71 for location of seismic panel. Data courtesy of Geophysical Service, Inc.

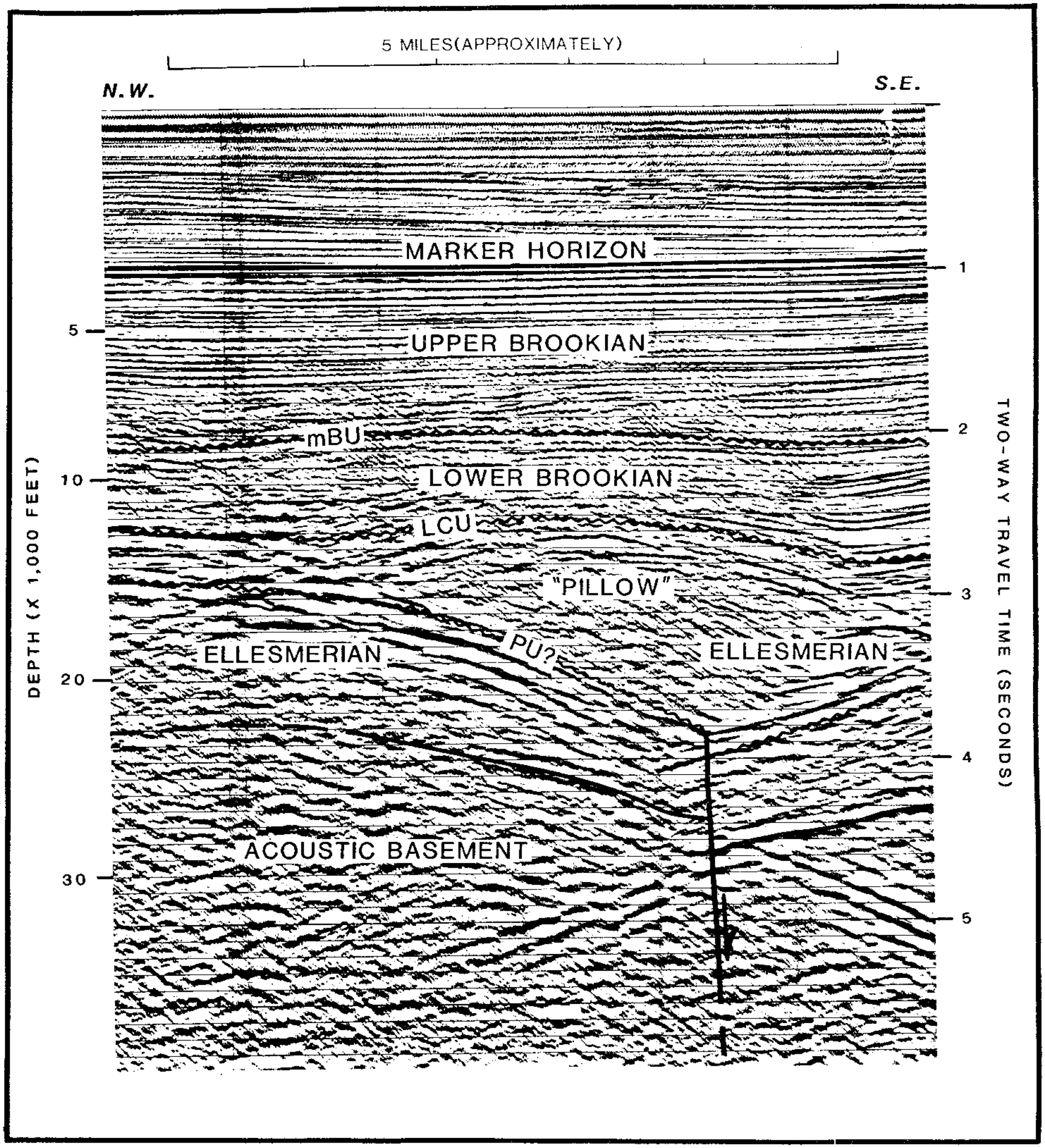


FIGURE 26. Incipient diapir or "pillow structure" in graben on the northern part of the Chukchi platform. See figure 71 for location of seismic panel. Data courtesy of Geophysical Service, Inc.

structures as well as incipient diapir mounds (figs. 25 and 26) are recognized in seismic data. Structures commonly associated with diapirism, such as collapse and compaction features that are related to withdrawal, are also widely recognized. In addition, faulting, flexing, and drape of strata over diapirs are also present. The diapiric structures are generally found above a deeply buried graben filled with Ellesmerian strata. This feature is a northern extension of the graben located west of the tilted horst block in plate 5. Seismic reflection mapping suggests that this graben is filled with upper and possibly lower Ellesmerian strata, which appear to form the source for the diapiric material.

Several stages of diapirism are present, from the initial formation of incipient diapirs (fig. 26) that appear similar to "salt pillows" described from the North Sea by Owen and Taylor (1983), to piercement structures that have risen very near the seafloor (fig. 25). The movement of mobile material may have occurred in multiple pulses during Brookian sedimentation. This is suggested by the presence of stratal thinning within the upper Brookian sequence adjacent to diapirs (fig. 25), and by the apparent ponding and thickening of upper Brookian sediments in sag areas on the flanks of the diapir (fig. 25). The pillow structure illustrated in figure 26 domes up the LCU and some of the overlying lower Brookian strata, but does not disturb strata in the upper Brookian sequence. This suggests that the formation of this structure began and ended in Cretaceous time.

The Chukchi platform is bounded on the east by a tilted horst which is inclined to the east beneath the Ellesmerian strata of the Central Chukchi basin (plate 5; fig. 12). This horst coincides with a linear positive magnetic high reported by Grantz and Eittreim (1979).

CENTRAL CHUKCHI BASIN

The Central Chukchi basin is a north-trending structural basin that began to form in Early Mississippian or earlier time by subsidence on bounding fault systems (fig. 23). The Central Chukchi basin continued to subside and receive Ellesmerian or equivalent sediments through Early Cretaceous time. At least 30,000 feet of Ellesmerian strata are present in the axial parts of the basin.

The Central Chukchi basin is bounded by the Northeast Chukchi and Wainwright fault zones on the east and by the Chukchi platform to the west (fig. 23). The boundary fault systems and intrabasinal faults were locally reactivated in Early Cretaceous time and again in Late Cretaceous to Tertiary time, particularly in the northern and western parts of the basin. Many of these faults may form the master fault systems in the Late Cretaceous(?) to Tertiary Hanna wrench-fault zone. In the southwestern part of the basin, the older faults associated with basin development retain some of their original displacement. This is illustrated in figure 15, where the fault on the west side of the tilted basement horst exhibits only minor wrench-related offset of the post-lower Ellesmerian sequences, but clearly bounds a graben filled with lower Ellesmerian strata. Wrench structures are abundantly present in figure 15, demonstrating that later shear movements extended this far south in the Central Chukchi basin. In areas of wrench-faulting within the basin, thick sections of Ellesmerian and Brookian strata are often flexed upward above wrench faults, although graben-like structures are also locally associated with the wrench faults.

Colville Basin

The southern parts of the Central Chukchi basin are obscured by the thick Lower Cretaceous deposits of the lower Brookian sequence in the Colville basin (fig. 17). This basin is an offshore extension of the foredeep basin (Colville trough, or Colville basin) that parallels and lies north of the Brooks Range (figs. 2 and 22). Offshore, these strata thin to the west over the Chukchi platform and to the north toward the North Chukchi basin flexure-zone. In the axial parts of the Colville basin, the thick lower Brookian sequence was detached from the underlying Ellesmerian strata and tectonically thickened by folds and thrust faults (plates 2 and 8) associated with the formation of the Herald arch.

The Fold and Thrust belt lies within the Colville basin north of the Chukchi syntaxis and the Herald arch. Nearshore, the deformational trend is similar to that described from outcrop and seismic data in the Foreland fold belt in southwestern NPRA (Lathram, 1965; Molenaar, 1981), suggesting that these structures were formed prior to deformation on the Herald thrust by the same northward-directed movements associated with the formation of the Brooks Range. To the west, folds trend more northerly, parallel to the younger Herald thrust. Folding is most intense to the south, where breached anticlines are locally cored by mobile shale. Seismic reflection data reveal numerous imbricate thrust faults (plate 8) which are rooted in a decollement near the base of the Brookian sequence. The intensity of deformation decreases to the north, and Brookian strata are undisturbed in the vicinity of the Tunalik No. 1 well (plate 2). To the west toward the Chukchi platform, the deformation of the thinner Brookian section is characterized by less folding and more high-angle reverse faulting, locally with associated back-thrusts. To the west and north, the faults of the Fold and Thrust belt are terminated by north-trending wrench faults which dissect the Chukchi platform (fig. 22).

Northcentral Subbasin

This subbasin is structurally superposed on the northern part of the Central Chukchi basin and was formed by Late Cretaceous(?) to Tertiary subsidence, probably related to movement on the Hanna wrench-fault zone (fig. 22). The subbasin is oriented roughly north-south and merges to the north with the North Chukchi basin. The Northcentral subbasin contains up to 8,400 feet (2 seconds) of upper Brookian strata that are partly correlative to the upper Brookian seismic sequence of the North Chukchi basin. This subbasin apparently did not exist during the initial formation of the North Chukchi basin, but after the subbasin began to subside, it was connected to the North Chukchi basin via a northwest-trending trough. Later uplift of a structural sill across this trough partially separated the basins. The structural sill is conjectured to have been uplifted late in the accumulation of upper Brookian strata (middle to late Tertiary(?)), roughly coeval to wrench deformation in the adjoining Chukchi platform and North Chukchi high.

The Northcentral subbasin appears to have formed by renewed post-lower Brookian downwarping of the old Central Chukchi basin. Syndepositional movement on wrench-fault zones during upper Brookian sedimentation suggests that subsidence of the subbasin was contemporary with activity on the major wrench zones in the western part of the Chukchi Sea Planning Area. Evidence for wrench-fault-related subsidence includes the observation that upper Brookian strata thin or thicken abruptly off the flanks of the wrench-fault structures (plates 3 and 9). Wrench-fault deformation locally persisted into post-upper Brookian time within the Northcentral subbasin, as illustrated by the flower structures in the upper Brookian Sequence in plate 5. The deformation of the youngest upper Brookian strata shows that wrench-faulting probably continued until at least late Tertiary time. High-resolution seismic data (plate 9, USGS line) identify offsets of near-seafloor reflections, and locally, seafloor fault-scarps over major wrench-fault zones in the Northcentral subbasin (Part 3, Quaternary Geology, fig. 50). This suggests that some of the wrench-fault zones have remained intermittently active to Quaternary time.

The wrench-fault zones which penetrate this subbasin are oriented roughly north-south and are part of a larger shear zone termed the Hanna wrench-fault zone. The relationships between the wrench-fault zones and sedimentation in the Northcentral subbasin provide important data on the age of activity on the Hanna wrench-fault zone, which elsewhere appears to involve primarily lower Brookian or older strata.

NORTH CHUKCHI BASIN

The North Chukchi basin is located in the northwestern part of the planning area (fig. 10). The basin contains up to 45,000 feet of Brookian sediment (>6.0 seconds). Ellesmerian strata may be present beneath this thick sequence but are not recognized in seismic reflection data. Upper Brookian strata attain thicknesses of up to 25,000 feet (4 seconds) in the basin (plate 7) and thin toward the south to about 5,000 feet (1.5 seconds) where the basin merges with the Northcentral subbasin through a narrow trough that lies between the northern Chukchi platform and the North Chukchi high (fig. 19).

The northern part of the Chukchi platform and western side of the North Chukchi high are downwarped along a broadly curved flexure-zone. The structure of the flexure-zone is illustrated in plates 6 and 7 and in the LCU structure map in figure 17. The slope of the LCU in the western part of the flexure-zone (plate 7; fig. 17) ranges from 7 to over 11 degrees northward. In the interior parts of the basin, the LCU descends below 45,000 feet and cannot be recognized in seismic reflection data. Along the north-facing part of the flexure-zone, some faults that offset the LCU trend parallel to the flexure-zone, but most faults strike to the north, parallel to the major fault systems in the Central Chukchi basin and the Chukchi platform. The pattern of faulting in the overlying upper Brookian sequence is shown in the structure map of the mBU (fig. 19). The west-trending part of the flexure-zone and parallel faults which displace the LCU appear to pre-date the north-trending faults which dominate the structure of the younger units in the North Chukchi basin. All faults in the North Chukchi basin appear to exhibit primarily normal displacement and do not show any of the characteristic features related to wrench-faulting so widely associated with faults in the Chukchi platform (plate 7).

On the eastern side of the North Chukchi basin, the flexure-zone trends north-northeast, and the LCU and mBU surfaces slope to the west away from the North Chukchi high (fig. 17). The flexure-zone extends northward out of the planning area. Its northern extent is not known. Rocks below the LCU on the eastern margin of the North Chukchi basin consist of undeformed Ellesmerian strata in the south and acoustic basement (possibly highly deformed Ellesmerian strata) in the north. The uplift of the North Chukchi high and formation of the eastern side of the flexure-zone postdates the initial (lower Brookian) subsidence of the North Chukchi basin. This can be inferred from the presence of folded lower Brookian strata in the basin near the North Chukchi high (plate 7, northeast end). The thinning of upper Brookian strata along the eastern margin of the North Chukchi basin in the vicinity of the North Chukchi high implies subsidence on this limb of the flexure-zone before or during upper Brookian deposition. The slope of the top of the acoustic basement on the eastern part of the flexure-zone locally exceeds 10 degrees but is generally less steep than the western limb of the flexure-zone (fig. 17). Faults along the eastern side of the North Chukchi basin are oriented north-south, parallel to the flexure-zone, following the general trend of faults which displace upper Brookian strata along the western margin of the North Chukchi basin.

The relationship of the North Chukchi flexure-zone to a similar flexure along the Beaufort margin (Hinge Line fault zone) described by Grantz and May (1984b) and Craig and others (1985) is unclear. The Hinge Line fault zone is a feature of regional extent that consists of a system of down-to-the-north normal faults which lie south of and parallel to the modern northern Alaska continental margin. The Hinge Line is thought to coincide approximately with the transition zone between the continental crust of the Arctic platform and the transitional to oceanic crust underlying the Canada Basin (Craig and others, 1985) (fig. 24). The Hinge Line fault zone trends northwest out of the Beaufort Sea Planning Area into parts of the Chukchi shelf which lie north of the Chukchi Sea Planning Area. The Hinge Line appears to intersect or to be truncated by a major north-northeast-trending linear seafloor scarp called the Northwind

Escarpment, which forms the eastern physiographic margin of the Chukchi borderland (fig. 24). No seismic data are available to map these features in the area of their mutual intersection; therefore, their relationships to each other and to the North Chukchi basin flexure-zone remain unknown. The southern projection of the Northwind Escarpment can be traced into the area of the North Chukchi high, and although its trend is generally parallel to the west-facing flank of the North Chukchi high, the two segments are apparently of opposite structural relief.

NORTH CHUKCHI HIGH

The northeastern part of the planning area is occupied by a broad, faulted uplift termed the North Chukchi high (figs. 10 and 22). The North Chukchi high is flanked on the west and northwest, across the flexure-zone, by the North Chukchi basin. It is bordered on the south by the Central Chukchi basin and the superposed Northcentral subbasin. To the southeast, the complex structures which characterize the North Chukchi high are gradually attenuated and cannot be traced into the relatively undeformed strata of the Northeast Chukchi basin. Ellesmerian and lower Brookian rocks within the area of the uplift are intensely deformed, and complexly faulted folds can be recognized on seismic reflection profiles along the northern and southern margins (plate 6). Within the central parts of the North Chukchi high, lower Brookian and older sequences are so highly deformed that no coherent reflections are present, and much of the substrate beneath the mBU resembles "acoustic basement" (plates 6 and 7). This structural complex is unconformably overlain by up to 3,500 feet (1.0 second) of relatively undeformed upper Brookian strata which gradually thicken into the flanking North Chukchi basin (plate 6). The base of the upper Brookian seismic sequence (mBU) subcrops at the seafloor near the southeastern margin of the North Chukchi high (plate 6).

As noted above, along the margins of the North Chukchi high are found generally east-northeast trending zones of complex faulting and folding in the lower Brookian and older sequences (plate 6). The northern margin exhibits a zone of broad folds that are offset by reverse and normal faults (plate 6). This northern fold belt appears to extend an unknown distance westward across the flexure-zone beneath the upper Brookian sequence into the North Chukchi basin (fig. 22), as folded lower Brookian strata are also observed below the mBU at the northeast end of plate 7. The southern structural boundary of the North Chukchi high in the Chukchi Sea Planning Area is characterized by tight concentric folds and associated thrust faults as well as a west-trending normal fault zone that exhibits high-relief, down-to-the-south displacement (fig. 22). Although data coverage is sparse on the North Chukchi high, preliminary mapping along the southern boundary suggests that the east-trending folds and thrust faults are truncated by closely-spaced post-upper Brookian faults which may merge southward with the wrench faults which cross the Northcentral subbasin. However, the older east-trending folds may be mechanically related to an earlier phase of wrench deformation which antedated and/or accompanied formation of the Northcentral subbasin.

Preliminary mapping indicates that folds on the northern margin of the North Chukchi high and individual faults within the uplifted area trend east to northeast. Within the Beaufort Sea Planning Area to the east, folds are less well resolved in seismic data, and the North Chukchi high structural complex is highly dissected by steeply dipping faults which may parallel the older Northeast Chukchi fault zone (Craig and others, 1985, plate 3). The structural complex appears to extend northeast to an intersection or truncation at a north-trending zone of Late Cretaceous(?) to Tertiary faulting, which extends north to the Hinge Line fault zone (fig. 22). The western margin of the North Chukchi high is drawn at a zone of north-trending, high-angle, normal faults along the eastern limb of the North Chukchi basin flexure-zone (fig. 22).

Although relatively undeformed strata of the upper Brookian sequence unconformably overlie the highly deformed older sequences in the central part of the North Chukchi high, close inspection of the reflection profile in plate 6 reveals that the thin upper Brookian sequence is cut by numerous, closely spaced faults (interpretations not shown). These high-angle faults are not associated with any obvious wrench structures, exhibit only small vertical displacements, and extend very near to the seafloor. It is not known at present whether these faults are the manifestation of wrench tectonics on the North Chukchi high or are caused by an unrelated late-stage extensional event.

WAINWRIGHT FAULT ZONE

The northeastern boundary of the Central Chukchi basin is formed by a major set of normal faults termed the Wainwright fault zone (figs. 10 and 23). The Wainwright fault zone trends west-northwest for approximately 45 miles across the eastern part of the Chukchi Sea Planning Area and extends onshore into NPRA in the vicinity of the village of Wainwright. Net vertical displacements of up to 20,000 feet, down-to-the-south, have occurred across this fault zone (plate 2). Most faults do not extend above the Permian unconformity (PU) and are, therefore, pre-Permian in age. The apparent thinning of lower Ellesmerian strata (Endicott and Lisburne Group equivalents) toward the fault zone from the Central Chukchi basin suggests syndepositional movement on this fault zone. However, some faults show modest warping of the PU (plate 2) and may have been reactivated during basin subsidence associated with upper Ellesmerian sedimentation. The Wainwright fault zone appears to truncate the older(?), northeast-trending Barrow fault zone, which forms the eastern margin of the Northeast Chukchi basin (figs. 10 and 23).

Onshore, the Wainwright fault zone separates uplifted acoustic basement (argillite(?)) of the Arctic platform from the deep Ellesmerian Tunalik basin to the south (plate 1). Offshore, the fault zone forms a boundary between the gently inclined Ellesmerian strata of the Central Chukchi basin to the south and the broadly folded lower Ellesmerian strata of the Northeast Chukchi basin (conjectured to be Late Devonian or older; Craig and others, 1985) to the north (plate 2). The Wainwright fault zone is generally 10 to 20 miles wide and is characterized by discontinuous reflections or a seismically chaotic appearance. This fault zone is apparently truncated or joined to the northwest by the Northeast Chukchi fault zone, which separates the northeastern part of the Central Chukchi basin on the west from the Northeast Chukchi basin to the east (fig. 23).

NORTHEAST CHUKCHI FAULT ZONE

The Northeast Chukchi fault zone is a wide, faulted flexure which juxtaposes Late Devonian or older strata of the Northeast Chukchi basin against Mississippian to Permian units of the lower Ellesmerian seismic sequence in the Central Chukchi basin. The fault zone extends approximately 100 miles from its juncture with the Wainwright fault zone northward to where it is disrupted by complex Late Cretaceous(?) to Tertiary faulting on the southern margin of the North Chukchi high (fig. 10). The Northeast Chukchi fault zone, although reactivated by Late Cretaceous(?) to Tertiary faulting in the Beaufort Sea Planning Area, appears to extend northward to a truncation at the Hinge Line fault zone (K. W. Sherwood, personal commun., January 1987).

In the Chukchi Sea Planning Area, the fault zone is locally 40 miles wide and, like the Wainwright fault zone, is characterized by a seismically chaotic appearance on seismic reflection profiles (plate 3). Much of the lower Ellesmerian seismic sequence in the vicinity of the fault zone also shows poor acoustic stratification. Relative displacement is down-to-the-west and varies in magnitude along the strike of the fault zone. Displacements are generally greatest along the southern parts of the fault zone where up to 25,000 feet (5.0 seconds) of vertical throw is postulated. In contrast, along more northern parts of the fault system, slightly over 10,000 feet (2.0 seconds) of apparent displacement is observed.

Major fault displacements within the Northeast Chukchi fault zone most likely occurred prior to and concurrent with the deposition of strata equivalent to the Endicott and Lisburne Groups. This hypothesis is supported by the association of the fault zone with grabens which are filled with acoustically well stratified reflections from strata tentatively assigned to the lower Ellesmerian(?) seismic sequence. Figure 14 presents a CDP seismic reflection profile across one of these grabens. The graben fill is characterized by the presence of several internal unconformities which document periodic movement on the bounding faults to the east and tilting of strata within the graben. Local minor offset of the PU suggests that this fault zone, like the Wainwright fault zone to the south, was also locally reactivated during subsidence of the Central Chukchi basin associated with upper Ellesmerian sedimentation (plates 3 and 4).

HANNA WRENCH-FAULT ZONE

In the central and western Chukchi Sea Planning Area there are numerous structural features commonly associated with wrench tectonics. These features are distributed in north to northeastwardly trending zones, which are herein collectively termed the Hanna wrench-fault zone (fig. 22). The Hanna wrench-fault zone is over 100 miles wide and is recognized in the Central Chukchi basin, the North Chukchi high, the Northcentral subbasin, and the Chukchi platform structural provinces (fig. 22). Wrench-faulting is absent in the extreme eastern parts of the planning area near NPRA (fig. 22; plate 2). The easternmost strand of the Hanna wrench-fault zone lies about 60 miles west of Icy Cape and extends from the North Chukchi high south to an intersection with the northwesterly trending structures of the Fold and Thrust belt. The Hanna wrench-fault zone extends into the Chukchi platform, but its western extent is unknown, partly because wrench features are less well developed in the thin Brookian strata overlying acoustic basement in the western parts of the Chukchi platform. The wrench-fault zone is obscured in the south by the northwesterly trending folds and thrust faults in the lower Brookian rocks of the Colville basin. The Hanna wrench-fault zone does not extend south of the Herald arch. No obvious wrench features are recognized within the North Chukchi basin or along its southern margin. However, the eastern margin of the North Chukchi basin (west-facing flank of the North Chukchi high) may have been formed, in part, by wrench-faulting. This is suggested by the parallelism between the Hanna wrench-fault zone and the faults associated with the eastern part of the flexure zone (fig. 22).

The type of structural features produced by wrench-faulting may depend on the thickness, burial depth, and lithology of the rocks involved, as well as the amount of displacement on the faults. The intensity of deformation varies throughout the planning area. Although the structural styles associated with wrench deformation vary areally and individual faults may have been active at different times, the wrench-related features generally fall into four main categories: (1) structural sags or depressions found in areas of the Northcentral subbasin and northern parts of the Chukchi platform; (2) broad structural uplift (e.g., North Chukchi high); (3) local structural doming in strata above and between wrench zones (e.g., "Wainwright dome"); and (4) local, highly faulted structural sags and uplifts respectively termed negative and positive flower structures.

Although we adopt the terms "negative" and "positive" flower structures following the usage of Harding (1985), we are presently unable to show that the development of these features was controlled primarily by the angle of incidence between laterally moving blocks, resulting in "divergent" or "convergent" resolved stresses, in the manner hypothesized by Harding (1985). The vertical transformation of deformational style within the flower structures may also be affected by the change in mechanical properties of rocks that differ in burial depth and lithology. We use these terms in a purely descriptive sense to aid in categorizing the different structural expressions of wrench-faulting observed in the Chukchi Sea Planning Area.

In cross section, flower structures appear as features in which a single master fault or fault zone splays upward into numerous, diverging dendriform strands. Typically, little or no vertical offset or deformation of strata is observed at the structural level of the master fault zone. However, faults in the splay zone exhibit significant vertical displacements, showing both normal and reverse separations. This outwardly enigmatic observation is the result of small vertical offset on the master fault, whose primary lateral displacement is resolved at shallower levels along numerous splay faults into complex horizontal, vertical, and oblique components which were formed in local environments of compression, extension, and shear. In addition, juxtaposition of different thicknesses of the same seismic unit on opposite sides of the fault zone locally imparts a contradictory sense of apparent displacement of strata at different levels on the same fault trace. This may result from horizontal displacement of lenticular seismic units or abrupt stratigraphic thinning of a unit across the fault zone.

Negative flower structures are characterized by a shallow graben or synform bounded by upward-spreading fault strands rooted in a master fault (Harding, 1985). Negative flower structures are common along the southeastern edge of the Hanna wrench-fault zone. In this area, wrench-fault features typically consist of a zone of closely spaced faults across which down-to-the-west displacement of the Brookian sequence has occurred. The CDP seismic reflection profile in plate 9 shows a traverse across the eastern edge of the Hanna wrench-fault zone and clearly illustrates the main characteristics of negative flower structures in the Chukchi Sea Planning Area. The fault traces generally begin at depth as a single master fault or fault zone which branches upward into a system of anastomosing splay faults that complexly offset the Brookian sequence and bound a shallow structural depression. Contradictory magnitudes and senses of vertical displacement of strata along individual faults are observed in cross section. Locally, only minor vertical offset of deeper strata by the master faults is observed. Commonly, shallow, high-angle splay faults in the Brookian sequence curve at depth to a low-angle intersection with the master fault. Some of these splay faults that curve at depth locally serve as a sole fault which truncates the downward extension of other high-angle faults. Similar negative flower structures occur along the southeastern edge of the Hanna wrench-fault zone. These north-south-trending features can be traced south into the Colville basin where they intersect northwesterly trending folds of the Fold and Thrust belt (fig. 22). Structural trends within the Fold and Thrust belt swing more northerly near the intersection with the eastern side of the wrench zone (fig. 22).

Positive flower structures are encountered farther north along the eastern margin of the Hanna wrench-fault zone. Positive flower structures typically consist of a shallow antiform displaced by upward-diverging strands of a wrench fault (Harding, 1985). An excellent example of a positive flower structure is illustrated in the CDP profile of figure 27. The seismic reflection profile is from the northeastern margin of the Hanna wrench-fault zone and shows an oblique northeast-southwest crossing of the structure. Note that the base of the deformed zone (LCU) is relatively undisturbed except for minor displacements on a few discrete faults. These faults branch upward into numerous splays along which disruption of Brookian strata has occurred. Many of these splay faults appear to have a normal sense of displacement, but some appear to have a reverse throw.

The most conspicuous attribute of this flower structure is the broad upwarping of Brookian strata over the master fault zone (fig. 27). The structure is also illustrated in plate 3, but here it is traversed at nearly 90 degrees to its strike. In this view, the antiform shows the same complex displacements of the Brookian strata on upward-branching splay faults. This feature forms the eastern structural boundary of the Northcentral subbasin and the Hanna wrench-fault zone. The mBU at the base of the upper Brookian sequence appears to truncate some faults and tilted lower Brookian strata on the western flank of the flower structure, indicating that the feature formed, in part, before deposition of the upper Brookian sequence. However, upper Brookian strata are domed up and the mBU subcrops at the seafloor over the crest of the flower structure, suggesting growth of the feature following deposition of the upper Brookian sequence (Late Cretaceous(?) to Tertiary). The general distribution of these flower structures and zones of closely spaced faults are mapped in figure 22.

Other features commonly associated with wrench tectonics are formed by local doming or warping of strata above, between, or adjacent to wrench faults. Some of these features exhibit apparent two-way structural closure at various stratigraphic levels. Examples of these features are illustrated in the CDP profile of plate 9, where broad structural upwarping is observed in upper and lower Ellesmerian rocks between two master faults at the center of the seismic reflection profile. Higher in the section, between two flanking flower structures, another structurally positive feature can be seen in the lower Brookian sequence near the center of the profile at about 1.6 seconds. Faulting does not appear to extend upward through the warped surface. On plate 4, the LCU is domed up above what appears to be a positive flower structure at depth. This feature, informally termed the Wainwright dome (plate 4), is areally large (over 1,000 square miles) and exhibits structural relief of several thousand feet. The doming of the LCU appears to be the result of the local thickening of the underlying Kingak Formation combined with the structural uplift caused by wrench-faulting. Strata directly beneath the domed surface are parallel to the upper surface, but appear to terminate by downlap laterally against a horizontal substrate tentatively identified as a Jurassic unconformity. It is not clear whether the Kingak Formation was thickened tectonically, such as by flowage of mobile material toward the apex of the dome during the wrenching episode, or if it represents a depositional mound, or lastly, perhaps a local basin that was subsequently uplifted and inverted. Orthogonal lines

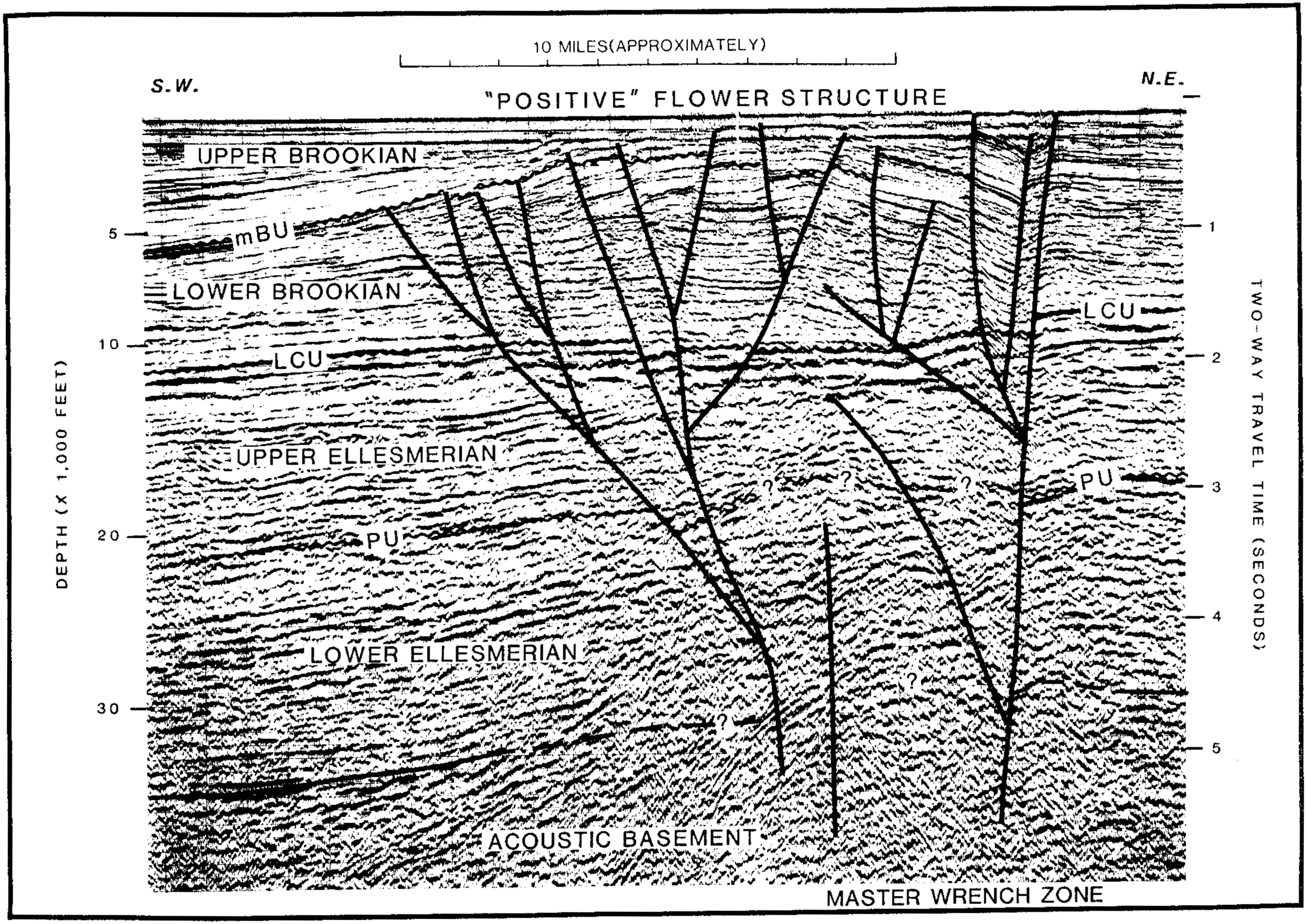


FIGURE 27. Positive flower structure in complex wrench zone along northeast flank of Northcentral subbasin. See figure 71 for location of seismic panel. Data courtesy of Western Geophysical Company.

through the Wainwright dome show that it has four-way structural closure.

The eastern part of the Hanna wrench-fault zone extends northward into a zone of intense deformation characterized by folding and thrust faulting near the southern margin of the North Chukchi high. Preliminary mapping of these zones of "box" folding and southward-directed thrusting (plate 6) suggest that they trend northeast and oblique to the wrench-fault zones (fig. 22). However, these features extend into the North Chukchi high and there intersect or join easterly trending structures (fig. 22). The relationships of these folds and thrust faults to orthogonal features in the North Chukchi high remain uncertain because of sparse data coverage. The deformational event which formed the North Chukchi high postdates the deposition of the lower Brookian sequence, but antedates or was coeval with the formation of the mBU and deposition of the upper Brookian sequence. It is not known at present whether this major deformational event antedated the initiation of movement on the Hanna wrench-fault zone or was directly related to it. Although deformation in both provinces appears to be roughly synchronous, they have contrasting styles and trends and may have formed at different times by completely independent structural mechanisms.

Wrench faults and related features are also found to the west across the Central Chukchi basin, the Northcentral subbasin, the northern part of the Colville basin, and the Chukchi platform. In many of these areas, the master faults that control the wrench deformation appear to be reactivated older faults (compare figs. 22 and 23). On the Chukchi platform, as illustrated in plate 5, the older, pre-Brookian faults that bound horsts and grabens have been reactivated as wrench zones and have localized the formation of flower structures in the lower and upper Brookian sequences. The wrench faults become more sparse to the west, and associated structures are less complex, suggesting that the magnitude of wrench-fault displacement diminishes to the west (plate 5).

5. SUMMARY OF THE GEOLOGIC HISTORY

Several periods of deformation, ranging in age from Late Devonian(?) to present, are represented in the Chukchi Sea Planning Area. The unique structures formed during these tectonic episodes have overprinted each other. In Late Devonian(?) to Early Mississippian time, large-scale subsidence of the Central Chukchi basin occurred and was accompanied by basinward tilting of the flanking basement platforms (Chukchi and Arctic platforms). Active faulting along the eastern margin of the Central Chukchi basin (the Wainwright and Northeast Chukchi fault zones) and along intrabasinal faults formed local depocenters for the accumulation of up to 35,000 feet of Mississippian (or older) through Pennsylvanian clastic and carbonate strata of the lower Ellesmerian sequence. Less dramatic sagging of the Central Chukchi basin continued from Permian to Early Cretaceous time and created the depocenter for the accumulation of up to 10,000 feet of predominantly clastic shelf deposits assigned to the upper Ellesmerian seismic sequence. In Early Cretaceous time, the Brooks Range began to rise in the south and a foredeep basin (Colville basin) formed at the Brooks Range front. Up to 20,000 feet of lower Brookian rocks accumulated in this basin. The Colville basin was terminated in the western Chukchi Sea Planning Area against the structurally high Chukchi platform. Early Cretaceous seafloor spreading northeast of the planning area created the Nuwuk basin along the Beaufort shelf and may have led to subsidence of the North Chukchi basin along the flexure zone. Over 35,000 feet of lower Brookian clastic sediments shed from the south formed a wedge which thickens northward into the North Chukchi basin.

Continued northward thrusting along the Brooks Range tectonic front in Early to Late Cretaceous time expanded the zone of deformation northward into the Colville basin and formed west-trending detachment folds and thrust faults in the strata of the lower Brookian sequence. Late Cretaceous(?) deformation in the northern part of the planning area created east-trending fault and fold structures in the area of the North Chukchi high as well as the north-trending eastern limb of the North Chukchi basin flexure-zone. Roughly coeval deformation formed the north-trending Hanna wrench-fault zone and the northwest-trending Herald thrust to the south. This Late Cretaceous(?) deformational episode tilted and uplifted rocks over much of the planning area, except the North Chukchi basin, and created the widespread mid-Brookian unconformity (mBU). Late Cretaceous subsidence of the Northcentral subbasin and the North

Chukchi basin created depocenters for the accumulation of up to 8,400 and 25,000 feet of upper Brookian strata, respectively. Strike-slip shear movements across broad areas of the planning area during the Cenozoic formed flower structures and other wrench features, chiefly in Brookian strata and in local faulted uplifts of Ellesmerian strata. Broad, coeval uplift of the North Chukchi high and parts of the adjacent Chukchi platform formed a structural sill between the Northcentral subbasin and the North Chukchi basin. Continued upper Brookian sedimentation in the North Chukchi basin was accompanied by the growth of diapirs and diapiric structures. In late Cenozoic(?) time, the North Chukchi basin was filled and fault activity subsided. Late Cretaceous to Tertiary extensional faulting occurred throughout the Northern Hope basin south of the Herald arch and created local basins for the accumulation of up to 17,000 feet of clastic sediments. In Quaternary time, the Brooks Range was glaciated and a lower sea level exposed the Chukchi shelf to subaerial erosion and an episode of extensive fluvial-channel cutting.

Although the complex structural and stratigraphic history of these provinces may frustrate preliminary geologic analyses, the polycyclic tectonic history of this region may eventually prove to be favorable for the occurrence of large hydrocarbon accumulations. An abundance of petroleum exploration plays is present, and offshore provinces contain untested potential source and reservoir rocks ranging in age from Devonian(?) to Tertiary. All of the offshore provinces in the Chukchi Sea Planning Area contain hydrocarbon plays which differ from those previously tested by onshore exploration. Subsequent sections of this report will summarize what is known about potential source and reservoir rocks of NPRA, and their possible relationship to significant plays and recognized traps in the offshore provinces of the Chukchi Sea Planning Area.

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6. EXPLORATION HISTORY

The first permit for seismic exploration in the Chukchi Sea Planning Area was issued in 1969. Since then, oil industry groups have collected approximately 58,126 line miles of CDP seismic reflection data. In addition, 4,295 line miles of high-resolution seismic reflection data (HRD), and 28,015 line miles of aeromagnetic and shipborne gravity data have been collected. The U.S. Geological Survey (USGS) collected approximately 10,000 line miles of shallow seismic data between 1969 and 1980. In the past few years, industry has shown increasing interest in this area, as suggested by the fact that over 50 percent of the existing data coverage has been acquired since 1984. In the 1986 permit year, industry acquired an additional 15,500 line miles of CDP data and 10,000 flight-line miles of aeromagnetic data. All of industry's exploration efforts, however, have been limited to geophysical exploratory work; no plans presently exist for a Continental Offshore Stratigraphic Test (COST) well.

In 1923, by Executive Order of President Warren G. Harding, an area occupying more than one-third of the Alaskan North Slope was designated as Naval Petroleum Reserve No. 4 (NPR-4) (fig.4). Its original purpose was to serve as an emergency oil reserve for the Navy. Surface geological studies, initiated in 1904 by the USGS, represented the only exploratory activities in the area until 1944. From 1944 to 1953, the U.S. Navy, with assistance from the USGS, conducted the first major geological and geophysical exploratory program (PET-4) for the purpose of evaluating the hydrocarbon potential of the reserve. During this program, 45 shallow core test wells and 36 deep test wells were drilled (Tetra Tech, 1982). Minor oil accumulations were discovered at Umiat, Fish Creek, and Cape Simpson. Gas was discovered at the South Barrow, Gubik, Meade, Square Lake, and Wolf Creek well sites (fig. 4). No further drilling was conducted until the U.S. Navy began its second exploratory program in 1974. At this time, political events (the 1973 oil embargo) and the discovery of a giant oil field in 1968 at Prudhoe Bay, just 50 miles to the east of NPR-4, mandated exhaustive evaluation of the reserve. Between 1974 and 1977, four additional test wells were drilled in the Barrow area, along with seven test wells in northeastern NPR-4 (Tetra Tech, 1982). All the wells failed to yield commercial quantities of oil or gas, but most contained minor oil shows. When the U.S. Navy ceased its exploration activities in 1977, it had collected a total of 11,100 line miles of seismic reflection data, nearly 400 seismic refraction profiles, gravity data from over 36,000 stations, and 12,600 flight-line miles of aeromagnetic data (Tetra Tech, 1982). In addition, a total of 47 deep test wells had been drilled.

In 1977, NPR-4 was transferred from the U.S. Navy to the U.S. Department of the Interior and renamed the National Petroleum Reserve in Alaska (NPRA). The Department's mission was to conduct detailed studies which would pinpoint areas of hydrocarbon potential and to make recommendations to Congress for possible competitive leasing. The USGS assumed responsibilty for the exploration program and continued to explore and evaluate hydrocarbon resources. Under contract to the USGS, Husky Oil NPRA Operations drilled an additional 28 exploratory wells, some of which yielded oil and gas shows. Geophysical Service Inc. (GSI) collected about 8,000 line miles of seismic reflection data between 1977 and 1981. Between 1982 and 1984, a total of four competitive oil and gas lease sales were held, netting total high bids of less than $100 million dollars. Because of poor industry response to these lease offerings, no future lease sales are presently scheduled.

ARCO Alaska, Inc., recently drilled the first industry wildcat well, Brontosaurus No. 1 (fig. 4) in the northwest portion of the reserve, 30 miles south of Barrow. However, test results do not appear to have been encouraging, because the well was subsequently plugged and abandoned. The results of this well have not yet been made public.

Three exploratory wells have been drilled on native corporation lands west of NPRA. These include the Chevron Eagle Creek No. 1 and Akulik No. 1 wells, and the Unocal Tungak Creek No. 1 well (fig. 4). All information on these wells is on file with the State of Alaska under "indefinitely confidential" status and, therefore, is not available for integration into the present study. All three wells were drilled during the period 1978 to 1982, and were plugged and abandoned.

Several attempts have been made to offer the Chukchi Sea Planning Area for competitive leasing. The first lease sale (No. 85) was originally planned for July 1984, but was delayed until February 1985. Further delays have caused the sale to be tentatively rescheduled for early 1988 as Sale No. 109.

7. SOURCE ROCKS AND INFERRED MATURATION HISTORY

The evaluation of source rock potential in the Chukchi Sea Planning Area is derived from the seismic extrapolation of known source sequences from onshore wells in western NPRA (fig. 4) into the offshore. It is recognized, however, that seismically traceable, equivalent sequences offshore may have formed in depositional or organic facies settings much different from those of known source sequences onshore. Furthermore, the extrapolation of maturity data from onshore control is of necessity based upon assumptions about the relationship of thermal maturity to depth. This relationship may not remain constant, but may change profoundly in provinces with different thermal regimes or burial histories offshore. For these reasons, conclusions drawn in the following analysis must be considered somewhat speculative.

The following discussion of source rock potential relies heavily on geochemical and thermal maturation data published by Magoon and Bird (1986) in their analysis of 63 wells located across the western North Slope (fig. 4). The three key oil-prone source bed formations recognized on the North Slope are the Pebble Shale, the Shublik Formation, and the Kingak Formation (fig. 5). Seismically-equivalent strata occur offshore, and these are emphasized in this analysis of potential source rocks. Existing data indicate that the rest of the stratigraphic column consists of formations which contain kerogen typically associated with gas, and for this reason, the discussion of these formations is brief.

ACOUSTIC (ECONOMIC) BASEMENT

Acoustic basement in NPRA is composed chiefly of early Paleozoic metamorphosed argillite and graywacke (Franklinian sequence; fig. 5). OC (total organic carbon) values for the sequence average 2.0 weight percent (OC is used here in the same sense as the more familiar "TOC," as defined by Hunt (1979)). The ratio of extractable C_{15+} (heavy) hydrocarbon content (HC) to organic carbon content (OC) is used to determine the ability of a rock unit to generate oil. On figure 28, the lower line represents an HC/OC value of 0.007, and is defined as the lower limit of petroleum source rocks (Hunt, 1979). The upper line represents an HC/OC value of 0.05 and separates inferred indigenous hydrocarbons from migrated, expelled, or reservoired hydrocarbons (Magoon and Bird, 1985). The HC/OC

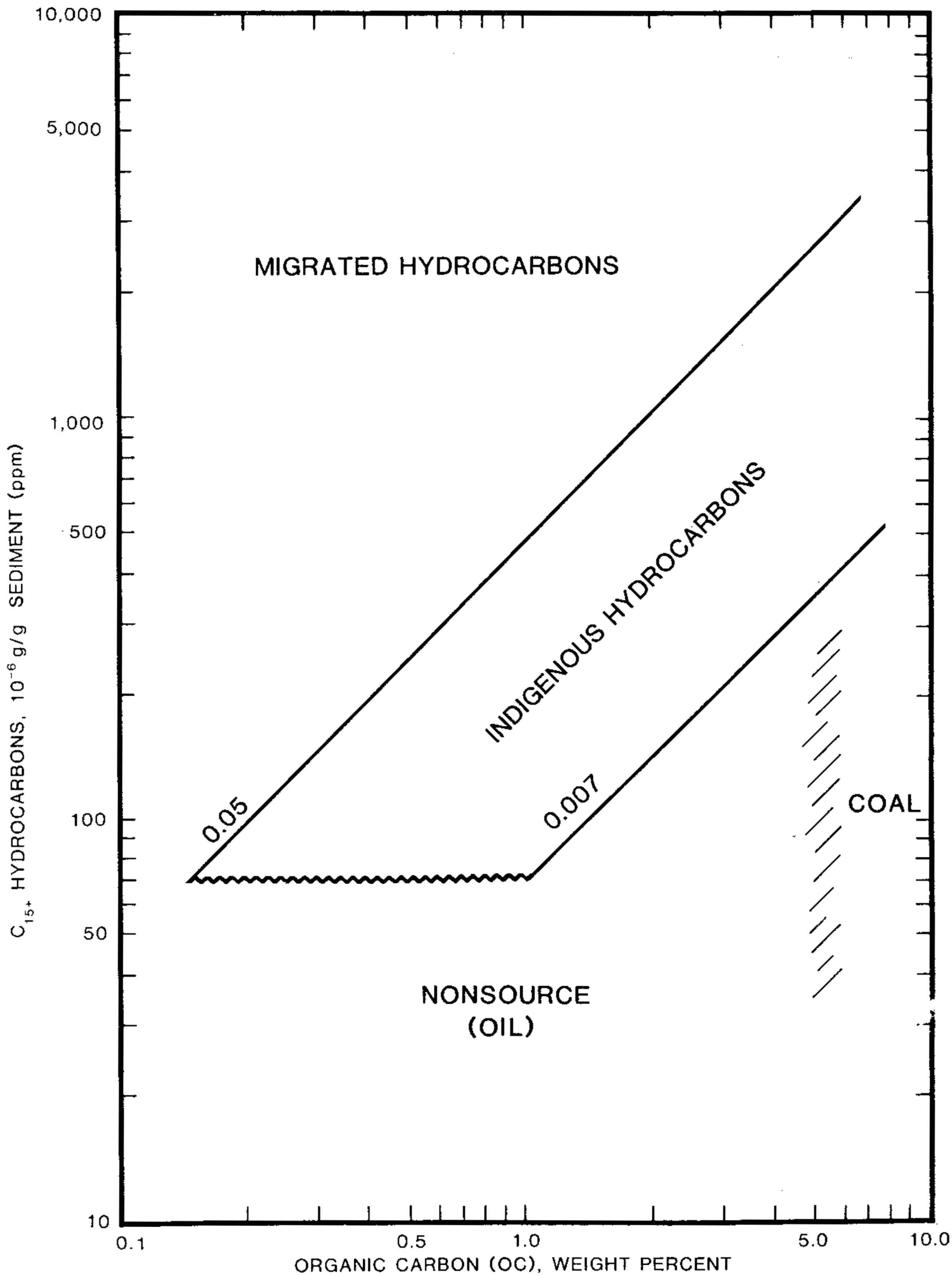


FIGURE 28. Plot for separation of indigenous and migrated hydrocarbons in rock samples. General ratios for nonsource rocks and coals are also shown. Diagram after Magoon and Bird (1985), as modified after Hunt (1979, fig. 7—1).

values for the basement lie between 0.007 and 0.05 percent, which are considered acceptable values for source rock (fig. 28) (Magoon and Bird, 1986; Hunt, 1979). However, Magoon and Bird (1986) feel that the high thermal maturity of the metamorphosed Franklinian basement rocks (in NPRA) probably destroyed any hydrocarbons generated prior to the deposition of the overlying Ellesmerian sequence, beginning in Late Devonian time.

ENDICOTT GROUP

The Late Devonian to Mississippian Endicott Group (fig. 5), at the base of the Ellesmerian sequence, is composed of carbonates and clastic lithofacies which contain intermittent coal beds. It has not been penetrated in any wells in western NPRA, but seismic data show the presence of a thick sequence of strata underlying the Lisburne Group in the Tunalik, Meade, and Central Chukchi basins which may be stratigraphically equivalent to the Endicott Group. In central and northeastern NPRA, the Endicott Group contains coal and interbedded shales which are regarded by Magoon and Bird (1986) as gas prone.

LISBURNE GROUP

A seismic sequence which may be stratigraphically equivalent to the Lisburne Group occurs offshore in the Chukchi Sea Planning Area. Onshore, this Mississippian to Pennsylvanian carbonate sequence (fig. 5) contains minor interbedded sandstone and shale. OC values for rocks in this sequence range from 0.15 to 0.40 percent, below the widely accepted minimum requirement of 0.4 to 0.5 percent for a clastic potential source rock (Hunt, 1979). However, Hunt (1979) indicates that as little as 0.30 percent OC may be sufficient for fine-grained carbonate rocks to be considered potential sources. Therefore the low OC values obtained from Lisburne Group rocks may not eliminate it as a potential source sequence. HC/OC values suggest, however, that the Lisburne Group is generally a nonsource.

Magoon and Bird (1986) consider vitrinite reflectance values (R_o) unreliable in carbonates, but R_o values for clastic units above and below the Lisburne Group indicate extrapolated R_o values in excess of 1.5 percent for the Lisburne Group over most of NPRA. An R_o range of 0.6 to 1.35 percent is generally considered to bracket the zone of oil generation and destruction (Hunt, 1979).

Magoon and Bird (1986) suggest that higher organic contents may occur elsewhere within the Lisburne Group as a consequence of facies changes downdip (basinward) from the Tunalik No. 1 well. In the Brooks Range, dark shales in the Lisburne Group are considered to be compositionally favorable, though overmature, source rocks (Bird and Jordan, 1977a). The discovery of solid bitumen in pores within the Lisburne Group in outcrop (Kleist and others, 1984) in the foothills of the central Brooks Range and in wells near the Brooks Range may also support the concept of the occurrence of basinal-facies Lisburne source beds to the south. Although these source beds are now overmature, it is possible that hydrocarbons might have been generated at an earlier time and then migrated updip to traps to the north within thermal regimes favorable for the preservation of oil. On persistent structural highs, such as the Chukchi platform, Lisburne-equivalent beds may not have been as deeply buried as those in NPRA and could yet form an active or potential source.

SADLEROCHIT GROUP

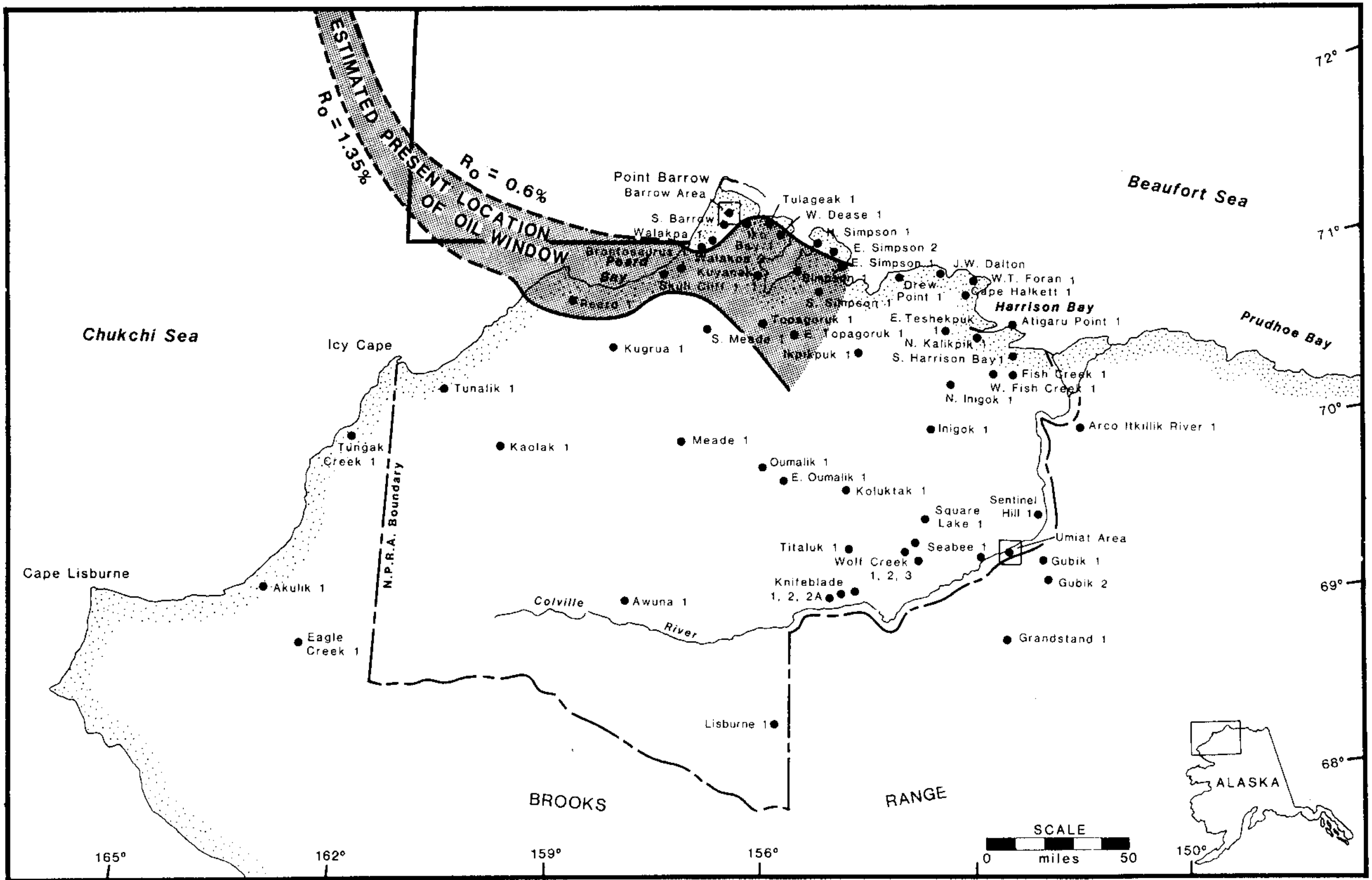
The Permian to Triassic Sadlerochit Group (fig. 5) is composed of alluvial to nearshore marine sandstone, conglomerate, and shale which grade southward to a sequence dominated by marine, fine-grained sedimentary rocks (Jones and Speers, 1976). OC values of shales within this sequence range between 0.5 and 1.0 percent (Magoon and Bird, 1986) and indicate poor to fair source rock potential. HC/OC ratios for several specimens from 14 NPRA wells are above 0.05, suggesting that migrated hydrocarbons are locally present (fig. 28) (Magoon and Bird, 1986). Vitrinite reflectance values range from 0.6 to 4.15 percent, with the higher values associated with more deeply buried strata to the south in the Colville basin (fig. 2). The maximum R_o value of 4.15 percent is found at the Tunalik No. 1 well (fig.4).

Magoon and Bird (1986) feel that the nonmarine to transitional marine environment of deposition for the shales in the lower part of the Sadlerochit Group was not conducive to the preservation of hydrogen rich organic matter. They classify the Sadlerochit Group as a nonsource to poor source rock, based on low values for organic carbon and hydrocarbon content, and in areas where R_o exceeds 2.0 percent, regard it as only a potential source for gas.

SHUBLIK FORMATION

The Triassic Shublik Formation (fig. 5) consists of marine limestone, sandstone, siltstone, phosphatic shale, and calcareous shale (Magoon and Bird, 1986). OC values for this formation may range up to 3.25 percent, but average about 1.30 percent in wells in northern NPRA. Average OC values increase southward, up to 2.7 percent, with increasing shale content. Magoon and Bird (1986) classify this formation as a good source rock because the majority of the HC/OC values (Magoon and Bird, 1985, fig. 6D) cluster near the 0.05 line. In western NPRA, amorphous-herbaceous kerogen content ranges from 20 percent in the south up to 50 percent in the north, which suggests that the formation becomes more oil prone northward.

Vitrinite reflectance values generally increase southward from 0.6 percent near Barrow to 3.4 percent at the Tunalik No. 1 well, where the Shublik Formation is overmature. Favorable values for OC, vitrinite reflectance, and amorphous-herbaceous kerogen content make the Shublik Formation a good potential source rock onshore in northern NPRA. An offshore projection, along depth contours, of the present-day maturation zone corresponding to the oil window (R_o = 0.6



base map after Tetra Tech (1982, fig. 2.)

FIGURE 29. Offshore projection (along modern depth contours) of the oil window for the Shublik Formation, based upon vitrinite reflectance data from wells in NPRA.

to 1.35 percent) for the Shublik Formation in western NPRA is shown in figure 29. This map suggests that there is only a narrow corridor within which the Shublik Formation now lies within the oil-generating zone in the northern part of the Chukchi Sea Planning Area. South of this corridor, where the Shublik Formation is more deeply buried, the formation is probably too mature to be considered a potential source for oil. However, the Shublik Formation in these areas may have served as a past source for oil earlier in the subsidence history of the Central Chukchi basin.

SAG RIVER FORMATION

The Triassic Sag River Formation (fig. 5) is a glauconitic, shallow marine sandstone with minor amounts of shale. OC values range from 0.31 to 1.06 percent, indicative of fair source rock potential. HC/OC values place it in the fair-to-good source range (Magoon and Bird, 1986, fig. 15). Vitrinite reflectance values point to a thermal history resembling that of the Shublik Formation.

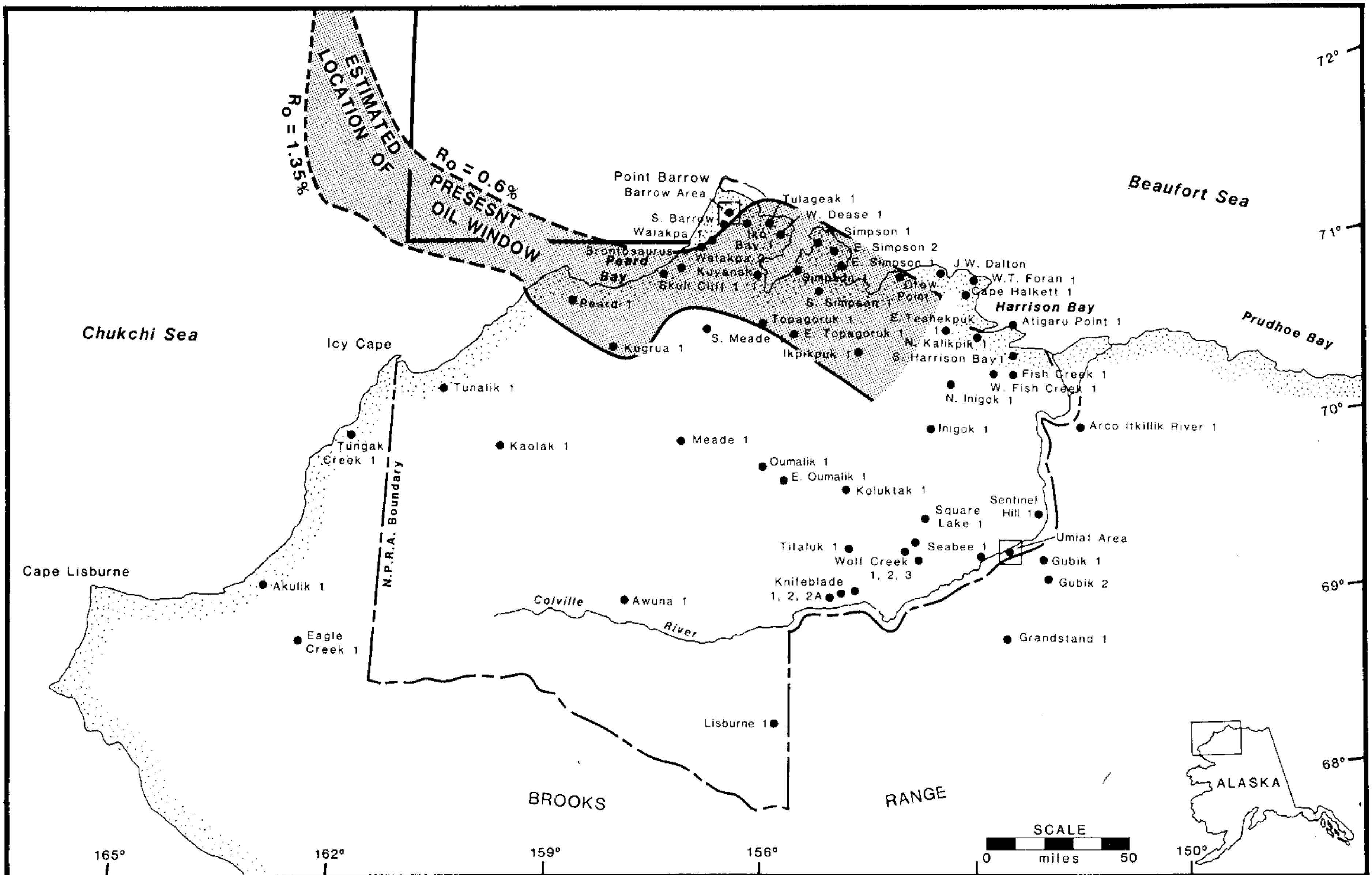
KINGAK FORMATION

The Jurassic Kingak Formation is a marine shale with minor amounts of siltstone and sandstone. OC values for this sequence range from 0.90 to 1.20 percent. The HC/OC values are indicative of a good source rock, with high HC values ranging from 200 to 600 parts per millon (ppm) (Magoon and Bird, 1986). Morgridge and Smith (1972) obtained an OC value of 1.9 percent and an HC value of 660 ppm for Kingak shales at Prudhoe Bay. Amorphous-herbaceous kerogen content ranges from 40 percent in central NPRA to 70 percent in northernmost NPRA.

Vitrinite reflectance values increase from 0.5 percent in the north to 2.0 percent in the south, reflecting increasing thermal maturity southward into the Colville basin. Projections of the modern depths for the oil window, based on vitrinite reflectance values of the Kingak shale in NPRA, into the offshore area are shown in figure 30. These projections identify a narrow corridor on the northeast flank of the Central Chukchi basin where the Kingak Formation is sufficiently mature for the generation of oil. Presumably, this zone migrated northward toward its present location as the Central Chukchi basin subsided during Cretaceous time.

PEBBLE SHALE

The Lower Cretaceous Pebble Shale (fig. 5) is a marine shale with minor sandstone beds. OC values for this sequence are high, ranging southward from 1.6 up to 3.2 percent (Magoon and Bird, 1986). Morgridge and Smith (1972) obtained OC values up to 5.4 percent and HC values as high as 3,000 ppm, which are indicative of good source rock potential for liquid hydrocarbons. Amorphous-herbaceous kerogen



base map after Tetra Tech (1982, fig. 2.)

FIGURE 30. Offshore projection (along modern depth contours) of the oil window for the Kingak Shale, based upon vitrinite reflectance data from wells in NPRA.

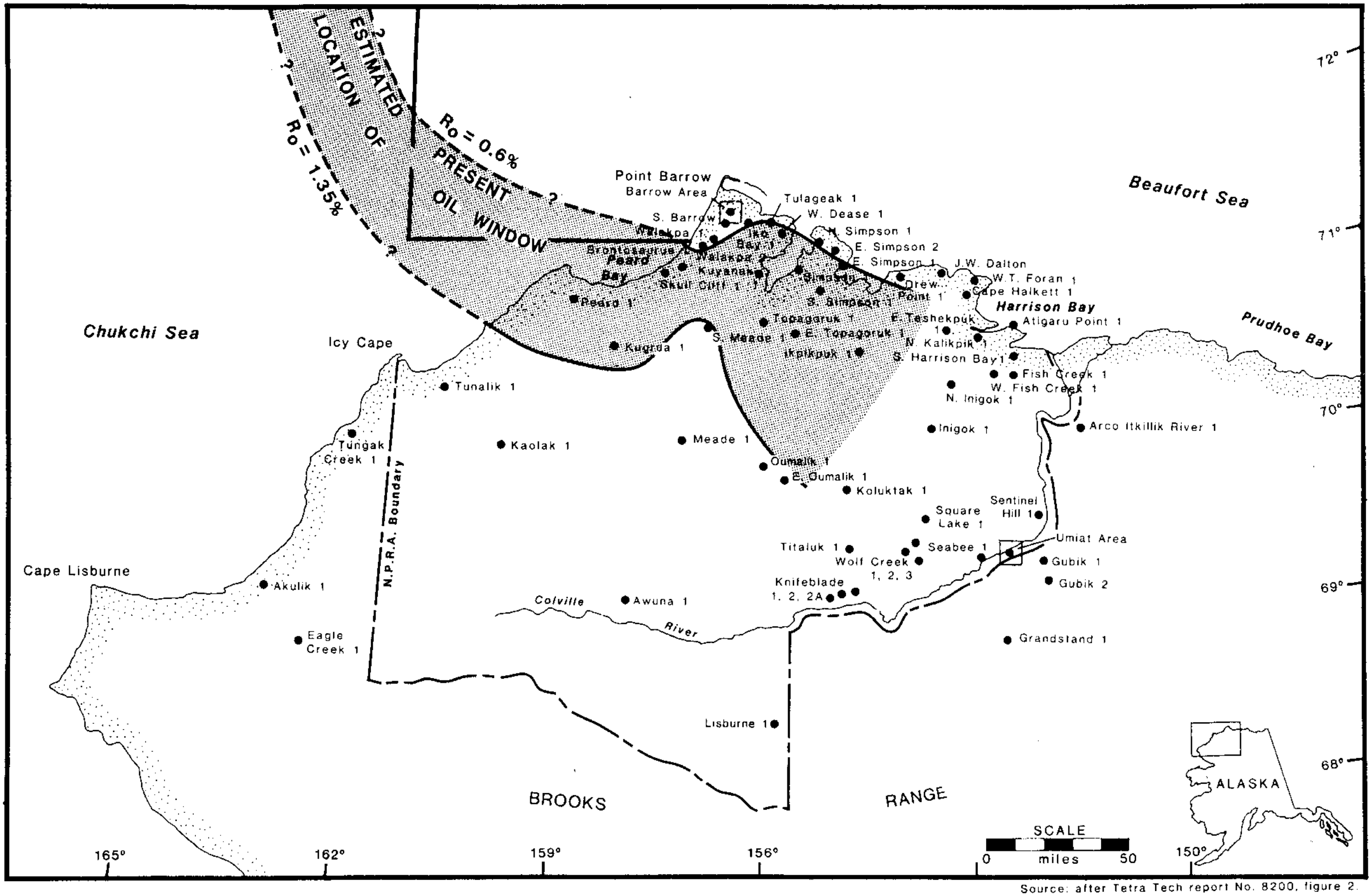


FIGURE 31. Offshore projection (along modern depth contours) of the oil window for the Pebble Shale, based upon vitrinite reflectance data from wells in NPRA.

content is high, ranging from a high of 80 percent in northern NPRA to a low of 40 percent in the south.

Vitrinite reflectance values increase southward from 0.6 to 2.0 percent, indicating sufficient thermal maturity for oil generation within the area of well control. The presence of high organic carbon content and a mature oil-prone kerogen type make the Pebble Shale a good potential source for oil in NPRA as well as in the Chukchi Sea Planning Area. Projections offshore of the depths corresponding to the present-day oil window, as bracketed by vitrinite reflectance data in western NPRA, are presented in figure 31. These data identify a narrow zone in which the Pebble Shale is presently sufficiently mature to generate oil. During Early Cretaceous time, this zone probably was located far south of its present location and migrated northward during the subsidence of the Colville basin.

TOROK FORMATION

The Lower Cretaceous Torok Formation (fig. 5) consists of moderate to deep marine shale and siltstone with minor amounts of sandstone (Molenaar, 1981). Average OC values for this sequence range from 0.6 percent in the north to 1.4 percent in the south. HC/OC values for this sequence fall between 0.007 and 0.05, sufficiently high to classify the Torok Formation as a potential source rock. Amorphous-herbaceous kerogen content ranges from 40 to 60 percent, increasing southward. On the basis of elemental analyses, Magoon and Bird (1986, fig. 7a) consider the Torok Formation to be gas-prone. However, it is possible that in different organic facies settings offshore in the Chukchi Sea Planning Area (such as the North Chukchi basin), a more oil-prone kerogen assemblage may have been preserved within the Torok Formation shales. Vitrinite reflectance values at the base of the formation increase southward from 0.6 to 2.0 percent. Available data on patterns of thermal maturity suggest that all of the Torok Formation in the southwestern part of NPRA is probably thermally overmature (Magoon and Bird, 1985, fig. 13). However, the maximum burial depths of the Torok Formation in offshore areas (such as the Chukchi platform) may have been less than those attained onshore, and correlative strata in different provinces offshore may not be thermally overmature.

NANUSHUK GROUP

The Lower Cretaceous Nanushuk Group (fig. 5) is a sequence of fluvial-deltaic to shallow marine deposits consisting of sandstone, siltstone, shale, conglomerate, and coal (Molenaar, 1981). OC contents may range from 2.0 to 10.0 percent, with the higher values related to coal content. HC/OC values reflect the presence of coal in many samples, but indicate good petroleum source rock potential for some shales (Magoon and Bird, 1986). Magoon and Claypool (1979) state that amorphous and herbaceous kerogen together make up at least 50 percent of the total kerogen content. Throughout NPRA, the maximum measured value for vitrinite reflectance at the base of the

Nanushuk Group is 0.9 percent (Magoon and Bird, 1986). The Nanushuk Group appears to have sufficient organic carbon content and thermal maturity to be considered a potential source rock for oil.

COLVILLE GROUP

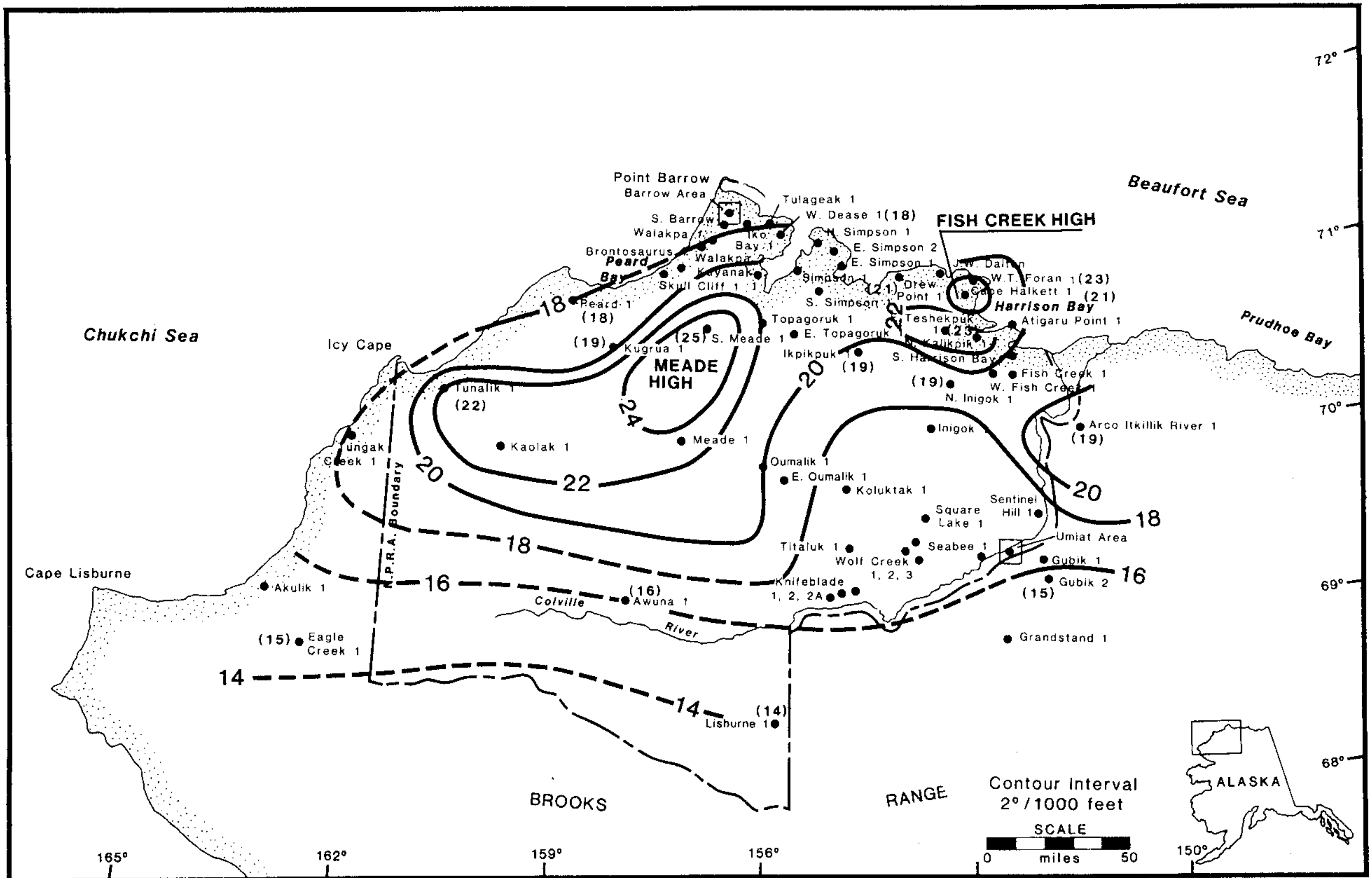
The Upper Cretaceous Colville Group (fig. 5) consists of shale, siltstone, sandstone, conglomerate, coal, and bentonite. Outcrops in isolated outliers in western NPRA indicate a fluvial facies for these rocks. These rocks cannot be traced directly offshore into the Chukchi Sea Planning Area. The upper Brookian seismic sequence of the North Chukchi basin and the Northcentral subbasin may be time equivalent to the Colville Group. Onshore, these rocks have a high organic carbon content due to the presence of coal. In NPRA, vitrinite reflectance values are everywhere less than 0.6 percent, insufficiently mature to form an active source. Offshore, particularly in the North Chukchi basin, upper Brookian strata are buried at depths exceeding 25,000 feet, and should be sufficiently mature to form active sources provided appropriate organic compositions are present.

8. GEOTHERMAL GRADIENTS OF WESTERN NPRA AND CHUKCHI SHELF

The only available source of geothermal data for the Chukchi shelf is that obtained from exploratory wells in NPRA. Though sparse, this onshore data base is sufficiently extensive to permit the speculative extrapolation of onshore thermal data into geologically similar offshore provinces on the Chukchi shelf. In eastern and southeastern NPRA, geothermal gradients appear to decrease southward as depth to basement increases (fig. 32). Elsewhere, the map distribution of geothermal gradients indicates that the highest gradients typically correspond to tectonic highs--the Meade arch, the Wainwright arch, Fish Creek platform, and Simpson shelf (fig. 32). The highest measured geothermal gradient in NPRA is 25 ^{o}F/1,000 feet (46 ^{o}C/km) at the South Meade No. 1 well (figs. 32, 33). This high gradient could be caused by an anomalous heat supply from relatively young intrusive rocks at depth (Blanchard and Tailleur, 1982a). Geothermal gradients from wells in westernmost NPRA range from 17.6 ^{o}F/1,000 feet (31 ^{o}C/km) at the Peard No. 1 and Walakpa wells (Blanchard and Tailleur, 1982a), increasing southward up to 21.6 ^{o}F/1,000 feet (39 ^{o}C/km) at the Tunalik No. 1 well (Blanchard and Tailleur, 1982b) (figs. 32, 33).

We hypothesize that the geothermal gradients in areas of ancient and persistent structural highs, like the Chukchi platform, may be comparable to those found on the Arctic platform (fig. 2) of westernmost NPRA. If so, the average geothermal gradient on most of these parts of the Chukchi shelf may range from approximately 18 ^{o}F/1,000 feet (30 ^{o}C/km) to 20 ^{o}F/1,000 feet (35 ^{o}C/km). Extrapolation of values from onshore parts of the Tunalik/Colville basins in southern NPRA into the geologically similar Central Chukchi/Colville basins suggests that an average geothermal gradient of 16 ^{o}F/1,000 feet (28 ^{o}C/km) probably typifies the latter province and other provinces characterized by high rates of Cretaceous or Tertiary subsidence and sedimentation.

Based on the observations above, and on relationships between modern geothermal gradients and thermal maturity (as defined by R_o) for rocks of Cretaceous age (after Dow, 1977), approximate depth intervals for oil generation zones in the planning area can be estimated (table 1).



modified after Blanchard and Tailleur (1982a, fig. 21).

FIGURE 32. Map of modern geothermal gradients in NPRA wells.

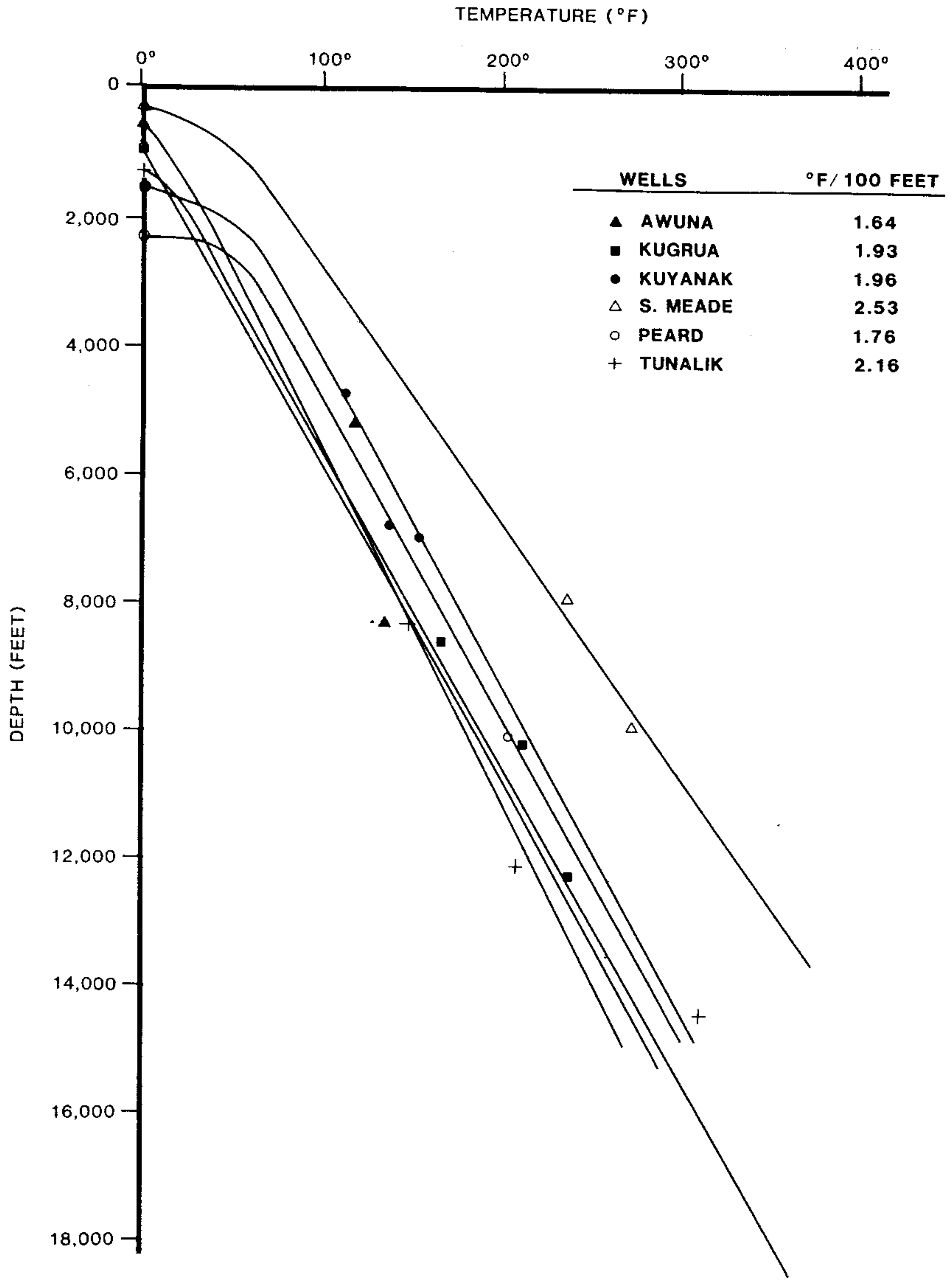


FIGURE 33. Geothermal gradients for 6 wells in western NPRA. Data reinterpreted from Blanchard and Tailleur (1982b).

Table 1. Estimated depth intervals of oil generation zones for the major provinces within the Chukchi Sea Planning Area.

Province	Estimated Geothermal Gradient (°F/100 ft)	Oil Generation (0.6% R_o @183 °F)	Oil Floor (1.35% R_o @244 °F)	Wet Gas Floor (2.00% R_o @275 °F)
Colville basin	16.0	11,400 ft	15,300 ft	17,200 ft
Central Chukchi basin	"	"	"	"
Fold and Thrust belt	"	"	"	"
North Chukchi basin	"	"	"	"
Northcentral subbasin	"	"	"	"
North Chukchi high	"	"	"	"
Northern Hope basin	"	"	"	"
Northeast Chukchi plateau	18.0 to 20.0	9,150 ft to 10,200 ft	12,200 ft to 13,600 ft	13,800 ft to 15,300 ft
Chukchi platform	"	"	"	"
Herald arch	"	"	"	"

9. OIL WINDOW

Magoon and Bird (1986) use vitrinite reflectance values of 0.6 to 2.0 percent to define the liquid window, corresponding to the limits for the initial generation and preservation of oil or condensate. Oil generation is depleted at about 1.3 percent R_o, and condensate at about 2.0 percent R_o (Hunt, 1979). Worldwide, sedimentary rocks within the catagenic stage of petroleum generation, from 0.6 to 2.0 percent R_o, contain 91 percent of the liquid hydrocarbons and 82 percent of the gas (Hunt, 1979).

Thermal maturity data for wells in western NPRA (from Magoon and Bird, 1986) are summarized in figures 34 and 35. Figures 29, 30, and 31 illustrate the approximate onshore and offshore locations of the present-day oil windows for each of the three major source rock formations in NPRA, as obtained from extrapolation of vitrinite reflectance data. At the Tunalik No. 1 well, all units below the Pebble Shale appear to be overmature (>2.0% R_o; fig. 34). The top of the oil window at Tunalik No. 1 lies high in the stratigraphic sequence, extending across the lower half of the Nanushuk Group (fig. 34). At the Peard No. 1 and Kugrua No. 1 wells, the oil window lies at greater depths and encompasses all units from the Sadlerochit Group up through the Torok Formation (fig. 34). The presence of anomalously shallow maturity values at the South Meade No. 1 well is believed to reflect local Cretaceous uplift on the Meade Arch and unusual geothermal conditions at that site (Magoon and Bird, 1986). At the Walakpa No. 2 well, all the sedimentary units are immature and lie above the oil window (fig. 34). In western NPRA, the top of the oil window ranges from about 2,400 to 4,500 feet below the surface (fig. 34), while the base of the oil window lies between 5,800 and 11,200 feet.

In wellbores in western NPRA, a significant discrepancy exists between oil window depths defined by vitrinite reflectance data (fig. 34) and those projected from modern geothermal gradients (fig. 33). At most localities, the oil windows defined by R_o values are significantly shallower. At the Tunalik No. 1 well, for example, the oil window as defined by vitrinite reflectance data lies between 2,400 and 8,500 feet (Magoon and Bird, 1986); but the oil window, as estimated from the modern geothermal gradient (22 ^oF/1,000 feet (40 ^oC/km)), should lie between 9,159 and 12,200 feet.

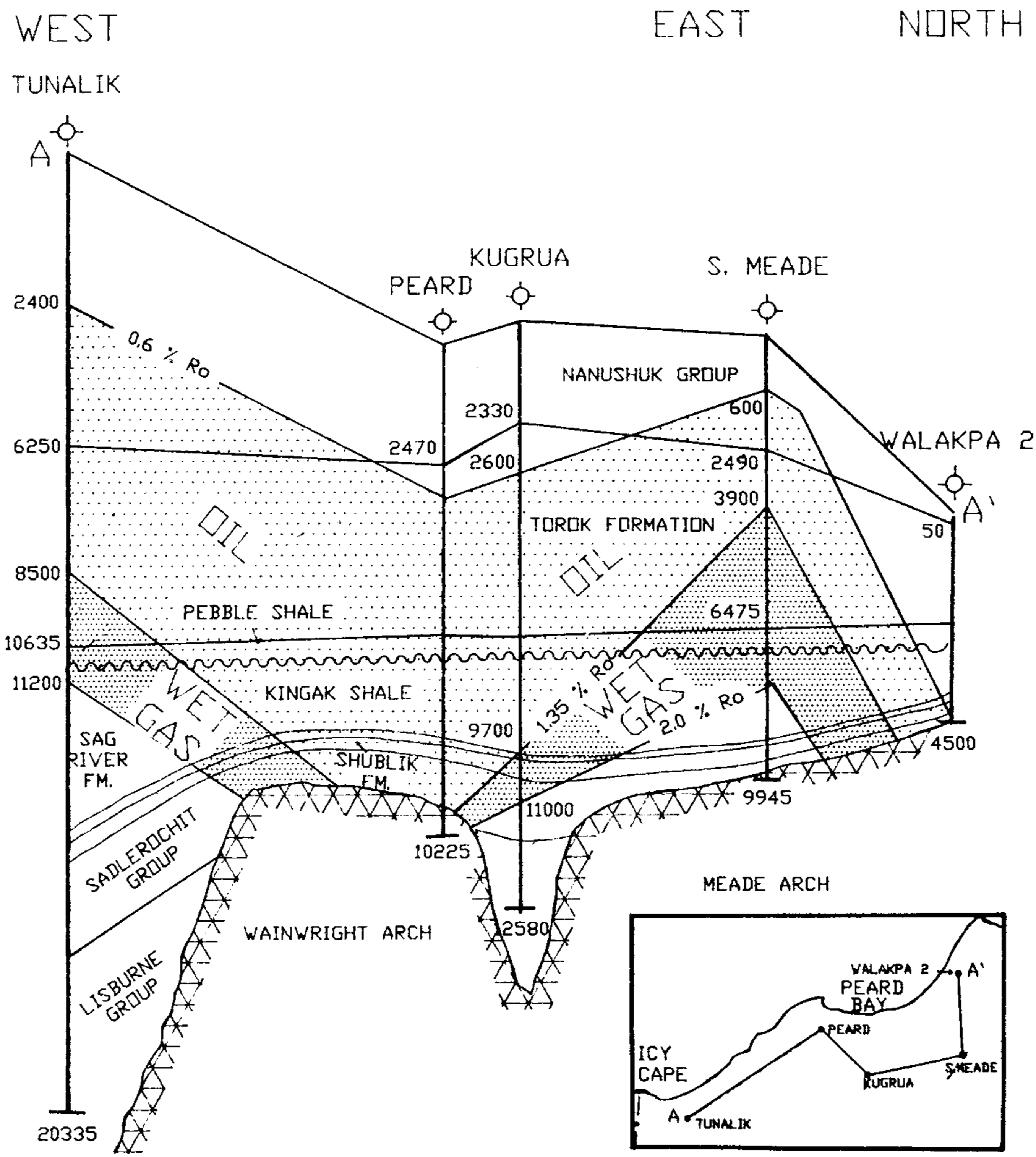


FIGURE 34. Cross section showing variation in depth of oil window in 5 wells in northwestern NPRA. Adapted from Magoon and Bird(1986, figs. 4,5). Posted depths are in feet.

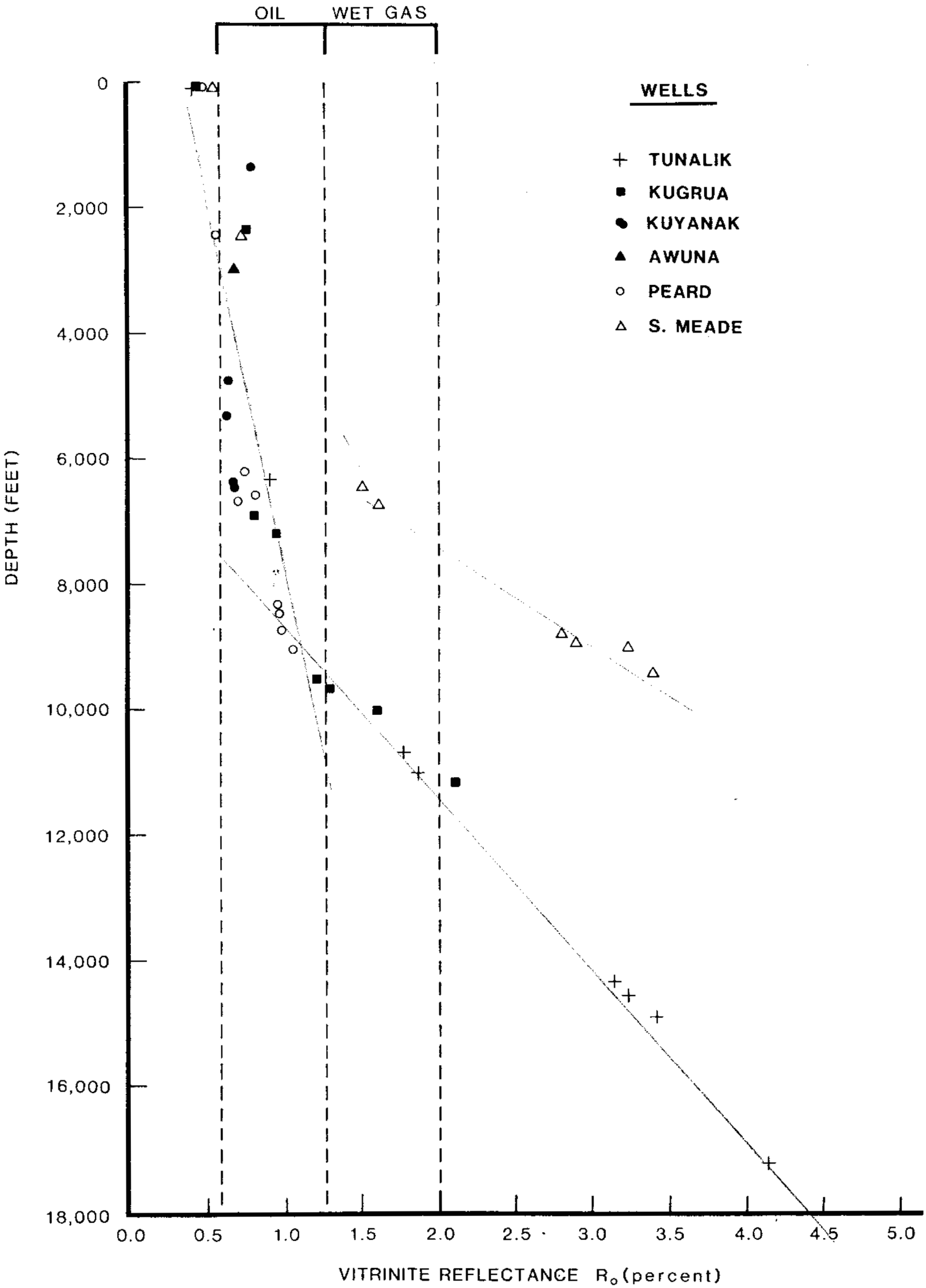


FIGURE 35. Vitrinite reflectance data for 6 wells in western NPRA. Diagram adapted from Magoon and Bird (1986).

The discrepancy between oil window depths defined by vitrinite reflectance and those defined by modern geothermal gradients may result from either or both of the following processes: (1) geothermal gradients were much higher in the past than at present; or (2) much of the area was once more deeply buried and has since been uplifted, and the overlying rocks have been removed by erosion. The second process is probably the more significant, as the Nanushuk Group has clearly been breached over the northernmost parts of the Arctic platform (Molenaar, 1981). Therefore, R_o data are probably more appropriate for predicting modern-day oil window depths in the parts of the planning area where seismic studies suggest complex burial histories comparable to that of western NPRA.

The potentially active oil-generating zones projected into the Chukchi Sea Planning Area in figures 29, 30, and 31 are based upon the assumption that the relationships between depth and maturity found in onshore wells can be extended into offshore areas. These oil-generating zones presumably were once located closer to the axis of the Colville basin, but migrated northward to their present location as the basin subsided during the Early Cretaceous. Oil expelled from a zone at any time might have migrated updip (northward) and might have lodged in any traps which existed there. This oil could still be preserved, provided that the traps were not later overrun by the northward-sweeping oil window and the oil contained within them thermally destroyed.

Because the geological development (and therefore perhaps geothermal histories) of the nearshore Central Chukchi and the Colville basins (figs. 2, 10) are probably similar to that of western NPRA, the oil window in these offshore areas may also lie at anomalously shallow depths, 2,400 feet to 8,500 feet, comparable to those documented by onshore well control (i.e., Tunalik No. 1).

Seismic studies (chapter 3, Seismic Stratigraphy) suggest that the Chukchi platform (fig. 10) is an ancient and persistent structural high. Although it is overlain by a sequence of lower Brookian strata, it does not appear to have been a foredeep and may not have been subjected to the history of deep burial and subsequent uplift experienced by strata of the Colville basin. If so, the strata of the Chukchi platform may now lie at the maximum burial depths achieved during the subsidence history of that area. If this is the case, then inference of oil window depths from regional geothermal gradients (chapter 8, Geothermal Gradients) in this area may provide a more reasonable estimate of the maturity regime. Figure 12 shows that basement lies at depths less than 15,000 feet (2.5 seconds) over much of the Chukchi platform. A reasonable range of geothermal gradients, 18 to 20 °F/1,000 feet (30 to 32 °C/km), inferred on geological grounds for this area, yields a liquid window in the depth range from 9,150 to 15,300 feet. This indicates that very little of the stratigraphic sequence on the Chukchi platform lies below the oil window. The perhaps unique subsidence history of the Chukchi platform may make it one of the most prospective parts of the planning area.

10. POTENTIAL RESERVOIR ROCKS

Assessments of the presence and quality of potential reservoir rocks in the Chukchi Sea Planning Area must rely upon the offshore extrapolation of reservoir units known from onshore well control. Stratigraphic units equivalent to those having attractive reservoir properties in NPRA would logically be the most likely to contain reservoir units in the eastern part of the Chukchi Sea Planning Area. Carter and others (1977) suggest that the most attractive known reservoir rocks in northern Alaska are part of the Ellesmerian sequence, which was derived from a northern source area. These include the Endicott Group, Lisburne Group, Sadlerochit Group, and Kuparuk River Formation, all of which are oil productive or potentially productive in the Prudhoe Bay area east of NPRA. In the central part of the Chukchi Sea Planning Area, the Ellesmerian sequence appears to have been derived from both northeastern and western source terranes which flanked the Central Chukchi basin (figs. 16, 18).

Within the southerly derived Brookian sequence, sandstones occur locally at the base of the Pebble Shale (e.g., Kuyanak and Walakpa sands) and form potential reservoirs in northwestern NPRA and probably in the nearby Chukchi shelf area. Near the top of the lower Brookian sequence, the Nanushuk Group (fig. 5) contains sandstones which may form potential reservoirs offshore. Nanushuk Group sandstones are known to contain noncommercial accumulations of oil and gas near Umiat (fig. 4) in the Foreland fold belt north of the Brooks Range. The upper Brookian seismic sequence (fig. 11) in the northern part of the Chukchi Sea Planning Area is inferred to contain sands which may be comparable to the oil-bearing West Sak and Ugnu sands of the Colville Group and sandstones within the Tertiary Sagavanirktok Formation west of Prudhoe Bay.

ENDICOTT GROUP (LATE DEVONIAN to LATE MISSISSIPPIAN)

In northern Alaska, the Endicott Group consists of Late Devonian low-grade metasedimentary rocks (Brooks Range) to clastic rocks of Early to Late Mississippian age (Arctic platform) (Tetra Tech, 1982). In NPRA, the Endicott Group (fig. 5) is subdivided into two formations: the basal Kekiktuk Formation and the overlying Kayak Formation (Tetra Tech, 1982). No Endicott rocks have been penetrated by any wells in western NPRA. However, some wells in eastern NPRA (Inigok No. 1, Ikpikpuk No. 1) have encountered sandstones which appear to be part of the Endicott Group. These sandstones, however, were determined to be of poor reservoir quality because of low porosities resulting from extensive cementation.

At the Endicott field near Prudhoe Bay, hydrocarbons occur within Mississippian fluvial sandstones of the Kekiktuk Formation (Behrman and others, 1985). Kekiktuk sandstones here are not as thoroughly cemented as those found in NPRA (Craig and others, 1985). Porosities average 20 percent (Alaska Oil and Gas Conservation Commission, 1984) and permeabilities range up to 1,100 millidarcys (Behrman and others, 1985). Reservoir sands within the Endicott Group are compositionally very mature and exhibit a secondarily enhanced pore network (Behrman and others, 1985).

Although no Endicott Group rocks have been penetrated in western NPRA, thick sequences of pre-Lisburne strata are observed in seismic data in the Tunalik and Meade basins, offshore in the Northeast Chukchi basin (Craig and others, 1985) and in the Central Chukchi basin (fig. 10). These strata may be age equivalent in part to the Endicott Group. Because of the lack of direct well control, it is not possible to evaluate the reservoir potential of these possible Endicott-equivalent strata at this time.

LISBURNE GROUP (LATE MISSISSIPPIAN to EARLY PERMIAN)

The Lisburne Group (fig. 5) consists mainly of carbonates deposited in a southward-deepening shelf bordering an ancient northern highland area (Bird and Jordan, 1977a, b). Lisburne carbonates occur throughout most of northern Alaska and are oil productive at Prudhoe Bay. In the Chukchi Sea Planning Area, seismic sequences equivalent to the Lisburne carbonates (fig. 11) can be traced into the Central Chukchi basin (fig. 10).

In the eastern North Slope at Prudhoe Bay, Bird and Jordan (1977a, b) have divided the Lisburne Group into three informal lithological units: a lower limestone, a medial dolomite, and an upper limestone. At Prudhoe Bay, most of the Lisburne hydrocarbons are contained in thin dolomitic interbeds within the upper limestone unit (Bird and Jordan, 1977a, b).

Bird and Jordan (1977a, b) identify three potential reservoir facies in the Lisburne Group in Prudhoe Bay and nearby areas: dolomite, oolitic grainstone, and sandstone. The most prospective reservoir rock in terms of net thickness, areal extent, and predictability appears to be a microdolomite (10 to 30 microns crystal size) of intertidal to supratidal (sabkha) origin. It occurs throughout the Lisburne Group, but is most common in the medial dolomite unit (Bird and Jordan, 1977a, b). Average porosities from wells at Prudhoe Bay range from 10 to 15 percent, with maximum values of 27 percent. Intergranular porosity enhanced by vugs and vertical fractures increases reservoir permeability. Bird and Jordan (1977a, b) suggest that porosities could increase to the north toward the paleohighlands. Oolitic grainstone occurs throughout the Lisburne

Group, mostly in the upper limestone unit. The open-framework packing observed by Bird and Jordan (1977a, b) shows signs of high initial porosity before the introduction of calcite cement. This rock type could be a good reservoir under conditions favoring preservation of initial porosity or where secondary leaching has removed intergranular cement.

A significant thickness of sandstone in the dolomite and upper limestone units is present in two wells near Prudhoe Bay, the Hamilton Brothers Milne Point No. 1 and the PLAGHM Beechey Point No. 1 (Bird and Jordan, 1977a, fig. 6). Bird and Jordan (1977a, b) postulate that larger areas of sandstone may extend offshore, representing a "nearshore fringe" of clastic sediment bordering the paleolandmass to the north.

However, the Lisburne Group is relatively nonporous and does not appear to form a prospective reservoir sequence in southern NPRA or in the Brooks Range (Tetra Tech, 1982). In the Lisburne No. 1 well (fig. 4), the Lisburne carbonates contain no intergranular porosity because the pores are filled with calcite and quartz. Porosity development and reservoir quality in the Lisburne Group in NPRA are quite poor, and the unit is not considered a primary reservoir objective. In offshore areas, however, lap-out edges, as observed in seismic reflection data on the flanks of the Chukchi platform and the northern and southern margins of the Central Chukchi basin (figs. 10, 12), may be associated with sequences of proximal clastics or dolomitic carbonates which may form potential reservoir rocks.

IVISHAK SANDSTONE (TRIASSIC)

The Ivishak Sandstone, the uppermost formation of the Sadlerochit Group (fig. 5), is composed of interbedded conglomerate, sandstone, and siltstone, and is the main hydrocarbon-bearing reservoir in the Prudhoe Bay field (Morgridge and Smith, 1972; Tetra Tech, 1982).

In the Prudhoe Bay area, Jones and Speers (1976) interpret the depositional setting of the Ivishak Sandstone to be that of a braided stream-delta complex. The Ivishak Sandstone is a major North Slope reservoir because of its thickness, its areal extent, and its excellent reservoir characteristics. The sandstones and conglomerates are poorly cemented and contain little matrix, possibly a result of winnowing and reworking by stream and current action at the time of deposition. Individual sandstone bodies are laterally continuous and are not separated by numerous or thick mudstone intervals. The average sandstone/shale ratios within the Prudhoe Bay field are greater than 0.9. Porosities range up to 30 percent and permeabilities average 1 darcy (Jones and Speers, 1976).

In northwestern NPRA, Tetra Tech (1982) interprets the Ivishak Sandstone to be a strandplain-offshore bar complex. Sandstone/shale ratios within the Ivishak Sandstone decrease toward the southwest as the sequence is increasingly dominated by a siltstone and shale lithofacies. West of the Meade arch (fig. 2), the sandstone content of the Ivishak Sandstone decreases until it is composed almost entirely of siltstone at the Tunalik No. 1 well (Tetra Tech, 1982). The highest values for sand content and porosity occur along the northeast coast through Smith Bay and Harrison Bay and south of the Barrow arch (fig. 2). In this area, porosity values for sandstones decrease southward because of increased secondary cementation (Tetra Tech, 1982).

The best reservoir rocks in the Ivishak sequence in NPRA occur in the northeastern corner and just south of the Barrow arch (fig. 2). This area was apparently adjacent to the northern source area, where a higher energy, proximal, deltaic environment facilitated formation of a more favorable reservoir rock facies.

Seismic studies suggest that strata equivalent to the Ivishak Sandstone (fig. 11) can be traced across wide areas of the Central Chukchi basin, the Chukchi platform, and perhaps over the Northeast Chukchi plateau (fig. 10). However, because the Ivishak Sandstone becomes increasingly silty westward across NPRA, there is a low probabilty of it forming a viable reservoir offshore in the axial parts of the Central Chukchi basin. Nevertheless, because the Ivishak Sandstone represents a regional regressive event, equivalent strata in source-proximal settings on the Chukchi platform along the western margin of the Central Chukchi basin could contain prospective reservoir facies.

SAG RIVER FORMATION (LATE TRIASSIC to EARLY JURASSIC)

The Sag River Formation (fig. 5) is divided into a shale and a sandstone member. The sandstone member constitutes a minor hydrocarbon reservoir in the Prudhoe Bay field (Barnes, 1985). It is a fine-grained, well-sorted, glauconitic, quartzose sandstone (Tetra Tech, 1982) which appears to become siltier and finer grained to the south and west. Jones and Speers (1976) suggest that the Sag River sandstone may have been deposited as a barrier beach complex which prograded over the underlying shallow marine sediments of the Shublik Formation (fig. 5). It exhibits the best reservoir qualities in the northeastern part of the Prudhoe Bay field, where porosities as high as 20 percent and permeabilities as high as 70 millidarcies are developed along its contact with the LCU.

In NPRA, the Sag River sandstone appears to be present only in the northern part of the reserve, where it occurs as a series of thin overlapping bars (Tetra Tech, 1982). These sand bodies tend to thicken and develop more porosity as they stack together northward. The formation ranges in thickness along the Barrow arch from approximately 50 feet at Prudhoe Bay to 70 feet near Point Barrow. Overall porosity values in NPRA are fair (>10%), and all the wells in northwestern NPRA have penetrated Sag River sandstones, with at least some intervals exhibiting porosity values greater than 16 percent, although permeabilities are typically quite low (20 millidarcies). However, the presence of abundant detrital matrix coupled with pore occlusion related to diagenetic cements and compaction has severely impaired reservoir quality in the Sag River sandstones (Barnes, 1985).

The Sag River sandstone contains oil shows at numerous localities, has yielded oil on drill stem tests, and produces oil in some wells in the Prudhoe Bay field. However, the Sag River Formation is not generally considered an attractive objective on the North Slope or in the Beaufort Sea Planning Area because of the poor overall reservoir quality of the formation and its limited thickness (Craig and others, 1985).

The Sag River sandstones in northwestern NPRA may extend offshore into the northern parts of the Chukchi Sea Planning Area as part of the seismically traceable upper Ellesmerian sequence (fig. 11). There, these sands might conceivably become thicker, cleaner, and more porous in different facies settings more proximal to the source areas. The strata equivalent in age to the Sag River Formation are therefore considered a potential reservoir objective in the northern and possibly western parts of the Chukchi Sea Planning Area (Chukchi platform; fig. 10). In the axis of the Central Chukchi basin, available well data suggest that strata equivalent to the Sag River sandstone will be dominated by shale.

PEBBLE SHALE SANDSTONES (EARLY CRETACEOUS)

At several localities across the North Slope of Alaska, sandstones are found beneath the Pebble Shale and directly overlying the LCU, at the base of the Brookian sequence (fig. 5). A mixed informal nomenclature has been applied to these sandstones, generally reflecting the particular well in which the sandstones were encountered. In western NPRA, examples include the "Walakpa" and "Kuyanak" sandstones. These sandstones are typically only a few tens of feet in thickness, whereas stratigraphically equivalent sandstones (Point Thomson sandstones) in the eastern North Slope occur in isolated bodies greater than 300 feet in thickness. This suggests that the depositional settings for these sandstones vary widely and are areally quite discrete.

Porosities in the Pebble Shale sandstones in northwestern NPRA range from 16 to 22 percent, generally increasing northward (Tetra Tech, 1982). A core of the Walakpa sandstone yielded an average porosity of 18 percent and an average permeability of 49 millidarcies (Husky, 19831). With the exception of locally developed thick sandstone bodies in the eastern North Slope, we consider the Pebble Shale sandstones to be too thin to form a significant reservoir formation in most onshore areas or offshore in the Chukchi Sea Planning Area. However, it remains possible that a significantly thicker sand with attractive reservoir properties could have developed in different facies settings offshore in the Chukchi Sea Planning Area. For this reason, we presently regard the base of the lower Brookian seismic sequence as a potential reservoir horizon.

LOWER BROOKIAN SANDSTONES (EARLY CRETACEOUS)

The Nanushuk Group is a regressive sandstone and shale sequence that includes marine, transitional, and nonmarine intervals (fig. 5) (Ahlbrandt and others, 1979). It is the most widely distributed sandstone-bearing sequence in NPRA and corresponds to the upper "topset" facies of the lower Brookian seismic sequence mapped in the planning area (fig. 11). The sequence extends into the offshore Colville basin and into the Fold and Thrust belt, which is the offshore extension of the Foreland fold belt containing the Umiat and Gubik accumulations (figs. 4, 10).

Sandstones of the Nanushuk Group have been classified by Ahlbrandt (1979) as litharenites. These sandstones contain abundant ductile rock fragments, which have deformed during compaction, thereby reducing intergranular pore space. The introduction of diagenetic cements has also adversely impacted reservoir quality. The source terranes for the western Nanushuk Group are believed to be the western Brooks Range, the Lisburne Peninsula, and a highland in the present area of the Herald arch (fig. 6). These terranes, composed predominantly of low-grade metamorphosed shales, limestones and mafic-igneous rocks, yielded sediments relatively poor in quartz. Porosities in Nanushuk Group sandstones in NPRA are low, ranging from 0.4 to 15.6 percent. The sand/shale ratio and reservoir quality improve to the east in the Umiat area (fig. 4) because of a greater influx of coarse detrital-bearing quartz into the Umiat deltaic system north of the Endicott Mountains (fig. 4) (Mull, 1979).

Mull (1979) suggests that the overall prospects for the occurrence of a major oil accumulation in the Nanushuk sandstones in western NPRA are poor because sandstone porosities are generally too low. The low permeability, limited thickness, and poor lateral continuity of Nanushuk sandstones in the western North Slope also severely constrain formation productivity and the potential size of traps (Mull, 1979).

Offshore in the Chukchi Sea Planning Area, we conjecture that the reservoir potential of Nanushuk Group-equivalent strata in the lower Brookian seismic sequence (fig. 11) is most likely poor on the grounds that these rocks are probably no different from the lithic-rich sandstones exposed onshore in the western part of the Nanushuk deltaic system. However, it is equally possible that Nanushuk-equivalent sandstones in the lower Brookian sequence offshore were derived from unidentified quartz-rich provenances farther west and were subjected to high-energy marine reworking at the margins of delta complexes not yet identified or correlated to the North Slope. Such circumstances would almost certainly lead to the development of more attractive potential reservoir sequences. For these reasons, we do not entirely rule out sandstones of the Nanushuk Group as potential exploration objectives in the Chukchi Sea Planning Area.

UPPER BROOKIAN SANDSTONES (LATE CRETACEOUS(?) to TERTIARY)

Late Cretaceous to Tertiary fluvial-deltaic sandstones occur along the Beaufort shelf (Craig and others, 1985) and east of Harrison Bay on the North Slope (Grantz and May, 1984a). Many wells which have penetrated this sequence have encountered numerous thick, porous sandstones which exhibit minor oil staining and other shows. However, the only known accumulation within these sandstones is found west of Prudhoe Bay, where large volumes of heavy oil occur in the Upper Cretaceous West Sak and Ugnu sands (Jamison and others, 1980). Porosities for the nearshore-marine West Sak sands average 29 percent, with permeabilities averaging about 500 millidarcys (Jamison and others, 1980). A pilot study presently in progress is testing the feasibility of using enhanced recovery techniques for extraction of hydrocarbons from this accumulation.

In NPRA, minor noncommercial amounts of oil and gas have been reported in sands of the Upper Cretaceous Colville Group at Umiat (figs. 4, 5) (Tetra Tech, 1982). Fluvial-deltaic sands in the upper topset facies of the Brookian sequence are regarded by Craig and others (1985) as the primary reservoir objectives in the Nuwuk and Kaktovik basins. Thick sequences of porous sandstone and conglomerate with favorable reservoir properties have been encountered within this interval by numerous wells along the Beaufort coast.

Offshore, in the Chukchi Sea Planning Area, strata of the upper Brookian seismic sequence (fig. 11) fill the North Chukchi basin and the Northcentral subbasin (fig. 10). As previously suggested on the grounds of acoustic character (chapter 3, Seismic Stratigraphy), this seismic sequence may include fluvial-deltaic sands similar to those of the Colville Group and the Sagavanirktok Formation known from northern Alaska. In addition, the sediments in the Northcentral subbasin of the Chukchi Sea Planning Area may have been derived, in part, from the reworking of Nanushuk Group-equivalent clastics, further increasing the potential for the development of favorable reservoir characteristics. For these reasons, we regard the upper Brookian sequence in the North Chukchi basin and the Northcentral subbasin as a reasonably attractive potential reservoir objective.

11. HYDROCARBON PLAY CONCEPTS AND TRAPS

The regional geologic structure and stratigraphy of the Chukchi Sea Planning Area are highly complex and a great diversity of potential hydrocarbon traps are present. Analysis of seismic reflection data indicates that both structural and stratigraphic traps abound. The following discussion of play concepts is organized around the major structural provinces of the planning area, which are unified by common stratigraphic histories, structural development, and trap types (fig. 10).

NORTHERN HOPE BASIN

The only identifiable potential trapping structures in the Northern Hope basin (fig. 10) are fault traps (fig. 36a). However, the shallow burial depths (ranging up to 17,000 feet but generally less than 10,000 feet) and the youth of the sediments in this basin suggest that they are probably thermally immature (table 1) and consequently may not have generated thermogenic hydrocarbons.

HERALD ARCH and HERALD THRUST ZONE

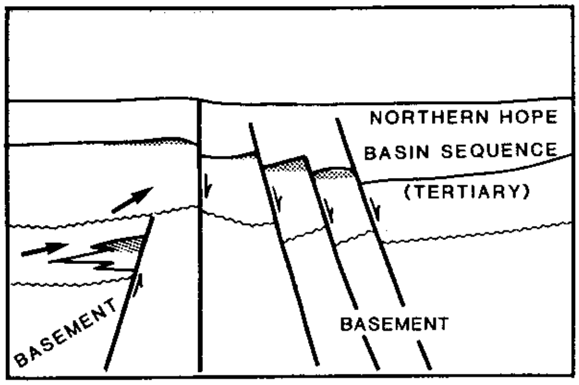
At the southwest boundary of the Central Chukchi and Colville basins, along the Herald thrust (fig. 10), folds and thrust faults in lower Brookian units have created potential hydrocarbon traps (fig. 36b). Lower Brookian units in the vicinity of the Herald thrust are very highly deformed and are probably not prospective. On the Herald arch, Ellesmerian sequences are inferred to be highly deformed and to form acoustic basement. They are therefore considered unprospective.

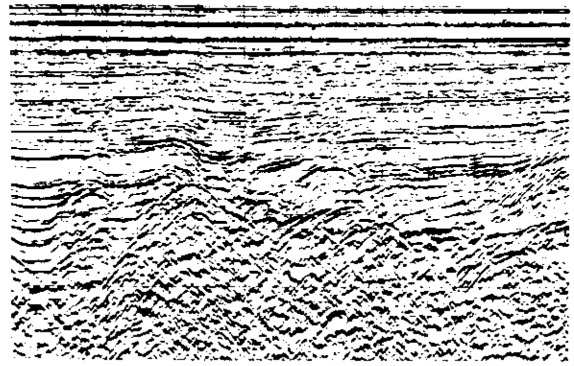
CHUKCHI PLATFORM

The Chukchi platform (fig. 10), which lies west of the Central Chukchi basin, appears to have been a source area for late Paleozoic to Mesozoic Ellesmerian sediments in the western parts of the Central Chukchi basin. In parts of the basin which fringe this source terrane, proximal clastic sequences, possibly capable of forming significant reservoir formations, may have been deposited.

NORTHERN HOPE BASIN:

(A)



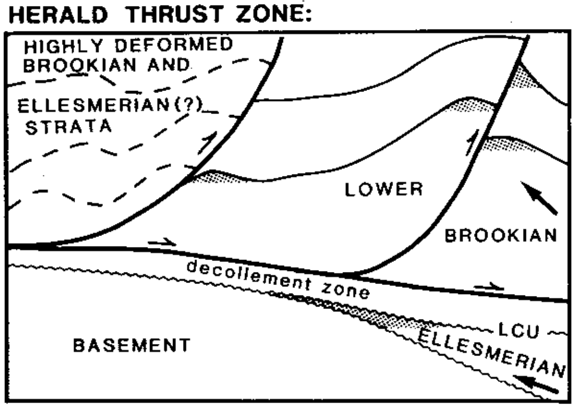


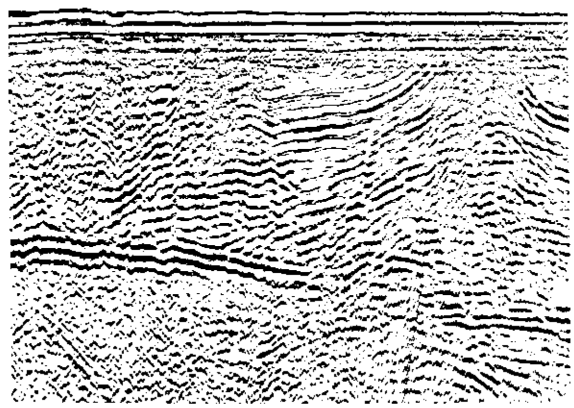
(Data courtesy of Western Geophysical Company)

Fault traps in Northern Hope Basin sequence.

HERALD THRUST ZONE:

(B)





(Data courtesy of Western Geophysical Company)

Traps in folds and at thrust faults, and stratigraphic traps in the subthrust sequence.

FIGURE 36. Play concepts and potential traps in Tertiary(?) strata in the Northern Hope basin and in Brookian and Ellesmerian strata in the Herald thrust zone. Large arrows denote potential migration paths. Shaded areas represent potential hydrocarbon accumulations.

Potential hydrocarbon-bearing features on the Chukchi platform include stratigraphic traps, graben fault traps, diapir-related traps, and pillow structures (figs. 37, 38).

Although stratigraphic traps related to facies changes are difficult to recognize on seismic reflection profiles, the geologic setting suggests that they may be widespread along the eastern edge of the Chukchi platform. Unrecognized traps may include those formed by seals resulting from updip shale-outs or diagenetically caused permeability changes. Updip truncations of tilted strata at unconformities within the Ellesmerian sequence are widely recognized in seismic data in this area (fig. 37a) and form some of the largest prospects on the Chukchi platform.

The half-grabens developed on the eastern edge of the Chukchi platform (fig. 10) are inferred from seismic interpretation to contain rocks of the Ellesmerian sequence. Potential hydrocarbon traps are found along the margins of these grabens where strata are truncated updip and juxtaposed against acoustic basement along the block-bounding faults (fig. 37b). Ellesmerian strata appear to have been preserved as outliers within the grabens and subsequently sealed beneath thick Brookian shales.

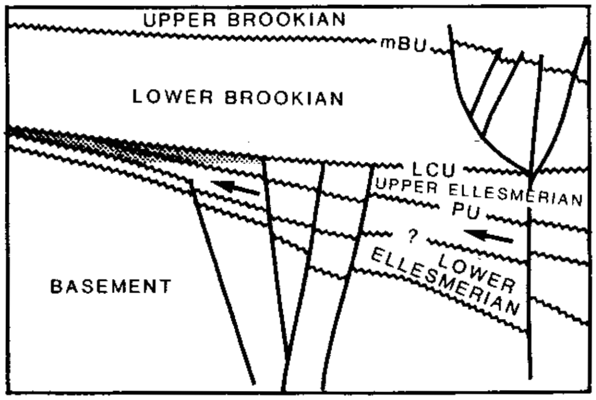
Diapiric structures are observed locally in the northern part of the Chukchi platform at the margin of the North Chukchi basin (figs. 10, 25). Many types of hydrocarbon traps are associated with diapiric structures, and some of these are illustrated in figure 38a. Potential hydrocarbon traps widely associated with these diapirs are as follows:

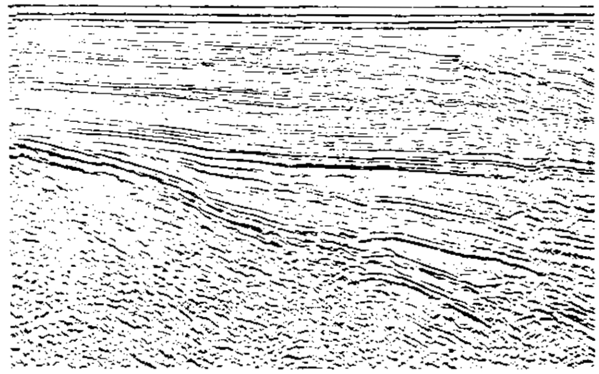
1. simple domal anticline draped over the diapir
2. graben fault traps in the extended strata over the diapir
3. syndiapiric flank sands--either (1) truncated updip at the outer wall of the diapir, (2) pinched out updip near the diapir, or (3) unconformably truncated on the flank of the diapir
4. fault traps on the flank of the diapir, associated with uplift of the diapir

Pillow structures, which are common to diapiric provinces (Owen and Taylor, 1983), have also been identified on seismic reflection data in the northern part of the Chukchi platform (fig. 10), as illustrated in figures 26 and 38b. Such structures are widely known to form prolific potential traps because they are areally large and only drape, but are not pierced by, underlying diapiric masses (Harding and Lowell, 1979).

Seismic stratigraphic relationships (discussed in chapter 3, Seismic Stratigraphy) suggest that the Chukchi platform has been a persistent structural high since the time of deposition of lower Ellesmerian strata. Accordingly, this area may not have experienced the history of deep burial, high thermal maturation and subsequent uplift found in the Colville and Central Chukchi basins. Therefore, the rocks may not be thermally overmature, and as discussed above

A

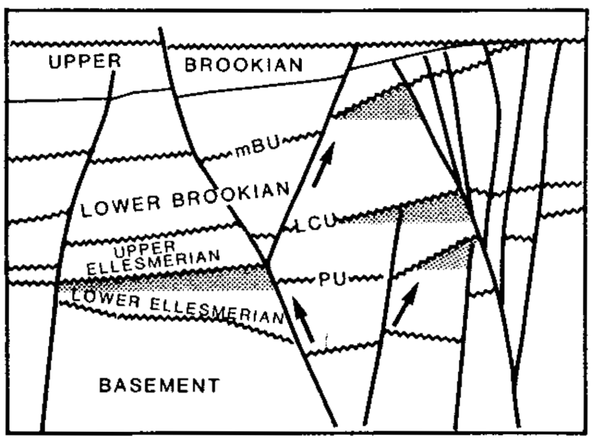


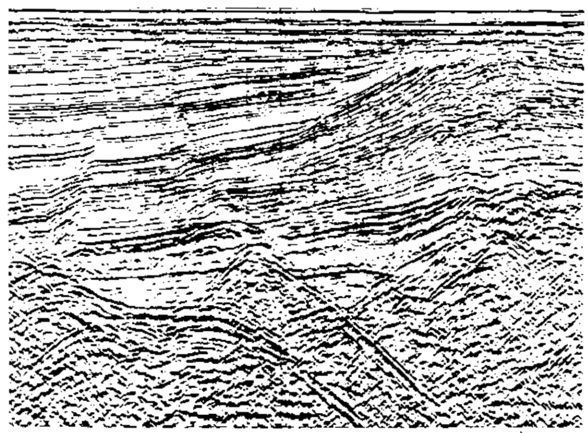


(Data courtesy of Western Geophysical Company)

Potential traps associated with unconformities and pinch-outs at onlap edges in upper and lower Ellesmerian strata along the eastern margin of the Chukchi platform.

B



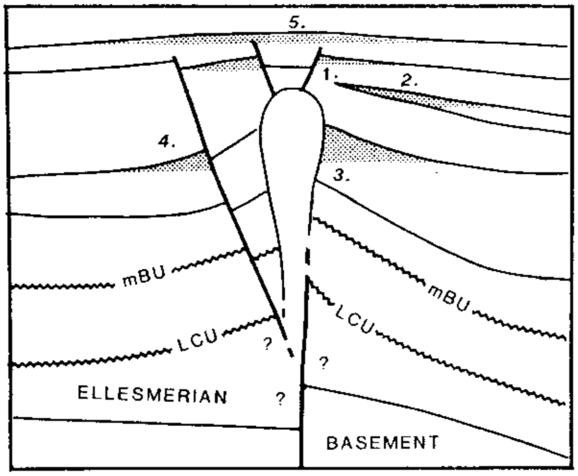


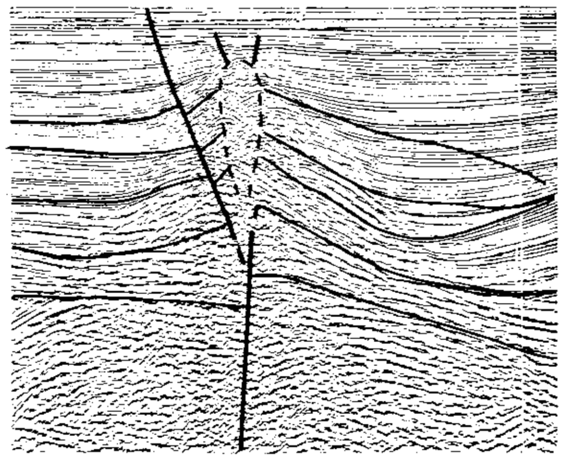
(Data courtesy of Western Geophysical Company)

Potential fault traps at margins of Ellesmerian grabens and fault traps in wrench fault zones along reactivated graben-bounding faults.

FIGURE 37. Play concepts and potential traps in Ellesmerian and Brookian strata on the Chukchi platform. Large arrows denote potential migration paths. Shaded areas represent potential hydrocarbon accumulations.

(A)



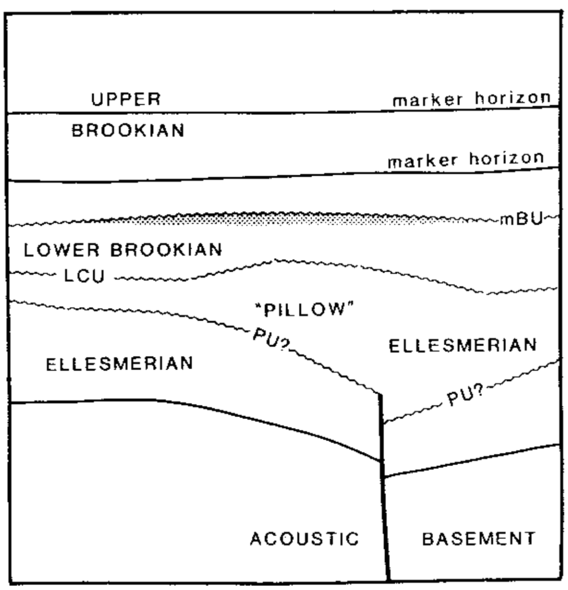


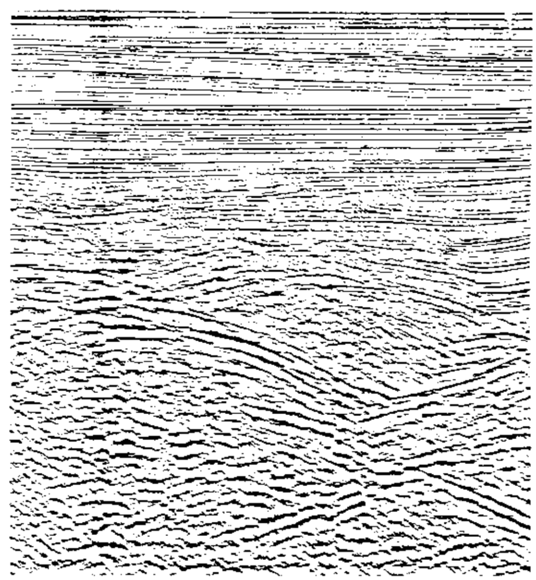
(Data courtesy of Geophysical Service, Inc.)

Diapir structure with various types of hydrocarbon traps:

1. **fault traps along graben over dome.**
2. **flank sand pinchout and sand lens**
3. **tilted strata truncated at wall of diapir.**
4. **fault trap**
5. **domed strata over diapir**

(B)





(Data courtesy of Geophysical Service, Inc.)

Potential traps in broadly domed strata over pillow structure.

FIGURE 38. Play concepts and trapping mechanisms in Ellesmerian and Brookian strata affected by diapirism in the northern part of the Chukchi platform. Large arrows denote potential migration paths. Shaded areas represent potential hydrocarbon accumulations.

(chapter 9, Oil Window), most of the prospective structures are conjectured to lie in or above the oil window.

CENTRAL CHUKCHI PROVINCE

Colville Basin and Fold and Thrust Belt

In the Fold and Thrust belt, located near the axis of the Colville basin north of the Herald thrust (fig. 10), the most prevalent potential traps are anticlines involving the lower Brookian sequence (fig. 11). Seismic reflection data (plates 2, 8) show the folds to be completely detached above a decollement zone from underlying, undeformed Ellesmerian strata. The faulted anticlines appear to be thrust faulted with axial shale cores (fig. 39a). The simple anticlinal structures (fig. 39b) also contain shale cores and, because they appear to be unfaulted, are probably the most prospective structures in the Fold and Thrust belt. Strata equivalent to the basal Brookian Pebble Shale source sequence (fig. 5) may be present offshore in the Fold and Thrust belt. However, this unit and deeper Ellesmerian potential source rocks are overmature in the nearest control well to the north (Tunalik No. 1) and were probably once even more deeply buried in the Fold and Thrust belt. In summary, the features in the Fold and Thrust belt may be prospective if the following conditions have been met:

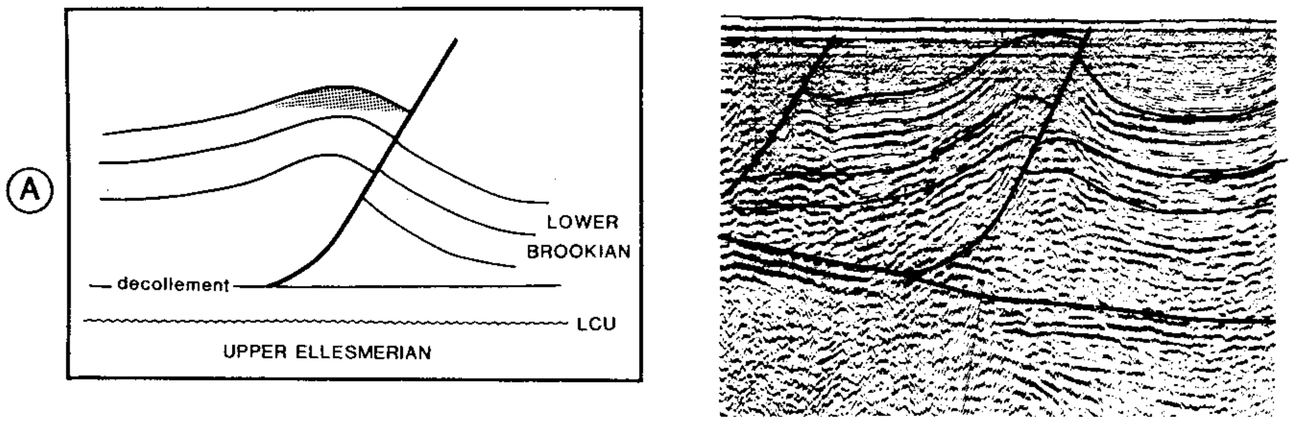
1. Brookian and upper Ellesmerian sequences have not been as deeply buried as their counterparts in the northern parts of the Colville basin (Tunalik No. 1 well), such that maturity values at the level of mappable traps do not exceed the base of the oil window (2.0% R_o).

2. Deformation in the Fold and Thrust belt occurred prior to significant oil generation, providing suitable structures for for the entrapment of upwardly migrating hydrocarbons.

3. A porous sandstone reservoir facies is present within the lower Brookian sequence, interbedded with shales which may serve as seals.

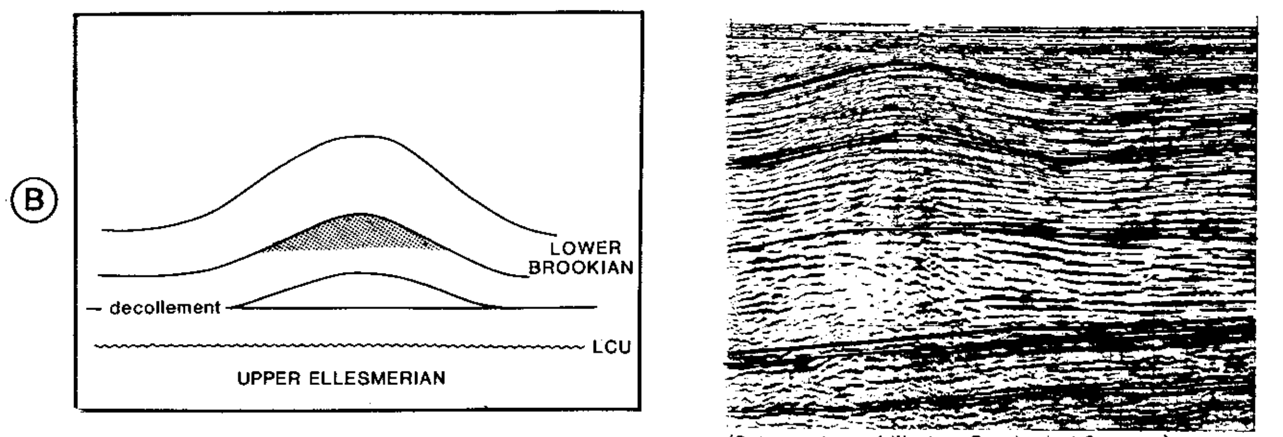
Central Chukchi Basin

The principal concern in the evaluation of the hydrocarbon potential of both the Colville and the Central Chukchi basins or of traps along their margins is the burial history of potential source rocks within the basins. Present-day burial depths for seismic reflectors equivalent to the Pebble Shale appear to range from about 10,000 to 20,000 feet beneath the Colville basin. Banet (1983) places the oil window at the Tunalik No. 1 well (fig. 4) in the depth interval from 3,300 to 10,500 feet. At the well, the oil window lies above the Pebble Shale and the rocks are overmature (Banet, 1983). Although Magoon and Bird (1986) identify a different interval for the oil window in the same well (fig. 34), their data also confirm a



(Data courtesy of Western Geophysical Company)

Faulted anticlinal traps in detached folds within Lower Brookian strata.



(Data courtesy of Western Geophysical Company)

Simple anticlinal traps in detached folds within Lower Brookian strata.

FIGURE 39. Play concepts and potential trapping mechanisms in lower Brookian strata in the Fold and Thrust belt and Colville basin. Shaded areas represent potential hydrocarbon accumulations.

thermally overmature condition for the Pebble Shale and underlying Ellesmerian sequences.

Northeast Chukchi Fault Zone

Half-grabens are present along the northeastern margin of the Central Chukchi basin within the Northeast Chukchi fault zone (figs. 10, 14; plate 3). These half-grabens are filled with acoustically well stratified sediment which is similar in seismic character to lower Ellesmerian Endicott Group rocks identified in well data and seismic reflection profiles in NPRA (fig. 5). Potential traps may be found where reservoir strata within these inferred Endicott Group rocks are truncated updip at faults on the east flanks of these grabens (fig. 40a). However, as discussed above, the thermal maturity of Ellesmerian strata in these grabens and adjacent parts of the Central Chukchi basin may be too great for the preservation of oil.

Wainwright Fault Zone

Updip fault truncations of south-dipping strata are the only seismically discernible potential traps in the Wainwright fault zone (fig. 10; plate 2). These occur in the lower Ellesmerian sequence (fig. 11) where potential reservoir rocks are truncated updip to the north against individual strands of the Wainwright fault system (fig. 40b). Shales in the upper Ellesmerian sequence overlying the Permian unconformity (PU) could serve as a regional seal (fig. 40b). However, onshore data suggest that the strata beneath the PU in this area are probably thermally overmature for the preservation of oil.

Northcentral Subbasin

The Northcentral subbasin (fig. 10) is superimposed on the northern portion of the Central Chukchi basin (plate 5). This basin contains up to 8,400 feet of upper Brookian strata which unconformably overlie the lower Brookian and Ellesmerian seismic sequences. Most of the Ellesmerian sequence (fig. 11, plate 5) is probably thermally overmature, since geothermal gradients from onshore wells (chapter 8, Geothermal Gradients) suggest that the oil window in the Northcentral subbasin ranges across the approximate depth range of 11,000 to 15,000 feet. This places the lower Brookian sequence and a portion of the upper Ellesmerian sequence within the oil-generating window. The upper Brookian sequence (fig. 11) has not experienced the complex burial history of the older sequences, suggesting that potential oil accumulations may have been preserved.

The upper Brookian sequence in the Northcentral subbasin is highly disrupted by wrench faults which form part of the broader Hanna wrench-fault zone (figs. 10, 22). Many diverse kinds of structural and stratigraphic traps are associated with these major features, and these are described in the section which addresses the Hanna wrench-fault zone. No well or outcrop control exists for the upper Brookian seismic sequence (fig. 11) in the Chukchi Sea Planning Area. Regional considerations suggest that it is probably a

NORTHEAST CHUKCHI FAULT ZONE:

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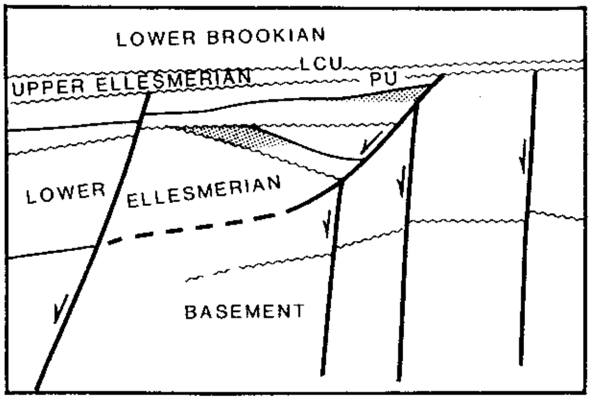
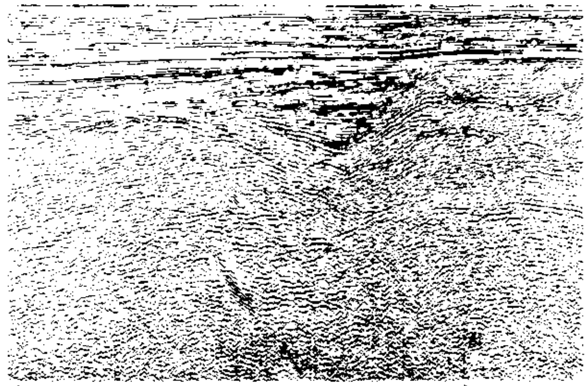
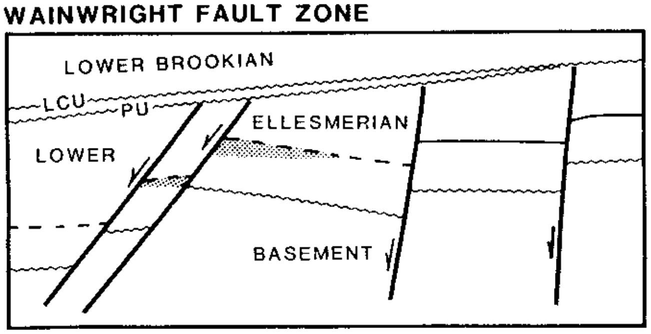


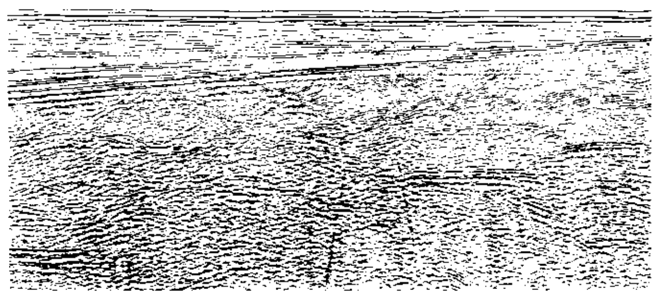


(Data courtesy of Western Geophysical Company)

Fault traps and stratigraphic traps along margins of half-grabens filled with lower Ellesmerian (Endicott Group?) rocks along the Northeast Chukchi fault zone.

WAINWRIGHT FAULT ZONE





(Data courtesy of Western Geophysical Company)

Ⓑ

Fault traps in tilted blocks of lower Ellesmerian strata along the Wainwright fault zone.

FIGURE 40. Play concepts and potential traps in Ellesmerian strata along fault systems which bound the Central Chukchi basin. Shaded areas represent potential hydrocarbon accumulations.

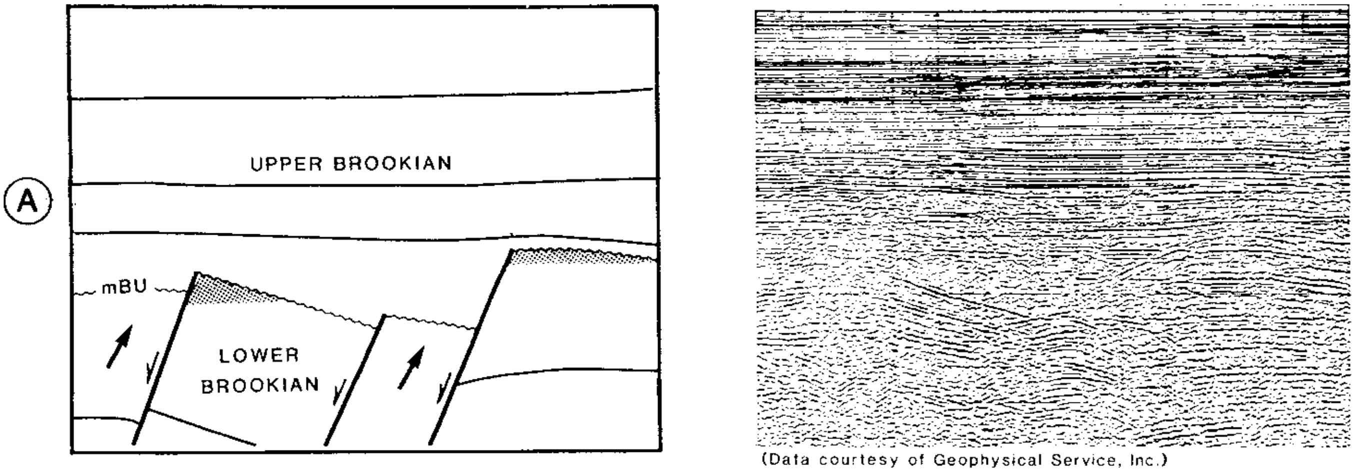
sand-shale sequence, possibly similar to Upper Cretaceous and Tertiary sequences known from the eastern North Slope. We can only speculate that attractive reservoir beds may be present in the observable structures of the Northcentral subbasin.

NORTH CHUKCHI BASIN

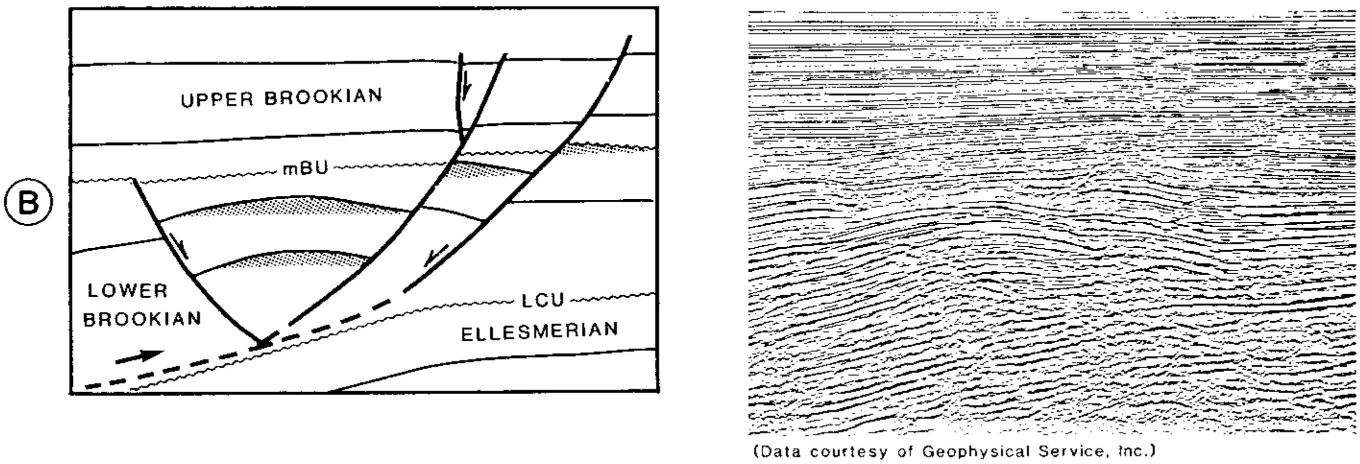
Using seismic reflection and refraction data, Grantz and others (1975) estimated that the North Chukchi basin (fig. 10) contains more than 6.0 km (19,700 ft) of strata of probable Cretaceous and Tertiary age. They suggest that two sequences are present, including more than 4.0 km (13,200 ft) of Neogene(?) strata and more than 2.0 km (6,500 ft) of Cretaceous(?) and/or Paleogene strata. These two major stratigraphic sequences are separated by a conspicuous angular unconformity. Grantz and others (1975) considered deeper sequences to be masked by multiples. In our data, we recognize two principal seismic sequences above acoustic basement in the North Chukchi basin (fig. 11). The lower sequence, termed the lower Brookian seismic sequence, is considered to be primarily Early Cretaceous in age and ranges up to 30,000 feet in thickness. The lower Brookian sequence was down-faulted and tilted along a flexure-zone into the North Chukchi basin during the early phase of basin subsidence and subsequently unconformably overlain (at the mBU) by the upper Brookian seismic sequence. The upper Brookian sequence is conjectured to range from Late Cretaceous to Tertiary(?) in possible age and ranges up to 25,000 feet in thickness in the remote, northwestern extremity of the planning area.

The burial history of the lower Brookian sequence in this area is unknown, and may not parallel that of the lower Brookian sequence in the Colville basin. Seismic reflection data clearly show that these strata have not been subjected to the regional folding and thrusting which characterizes the lower Brookian sequence in the southern part of the Colville basin. However, folds in the lower Brookian sequence in the North Chukchi basin have been recognized on seismic reflection data west of the North Chukchi high (plate 7). The upper Brookian sequence appears to have accumulated continuously in most areas with little structural disruption since the formation of the basal unconformity (mBU) (fig. 11) which separates it from the lower Brookian sequence. We cannot evaluate the presence of potential source or reservoir strata in either of these sequences. However, it is probably reasonable to assume that some of the large volume of sediments in this basin have experienced, and presently occur within, thermal environments appropriate for the generation and expulsion of hydrocarbons. Since the major, seismically recognizable traps in the basin began to form early in the development of the basin, they may have had timely access to migrating hydrocarbons.

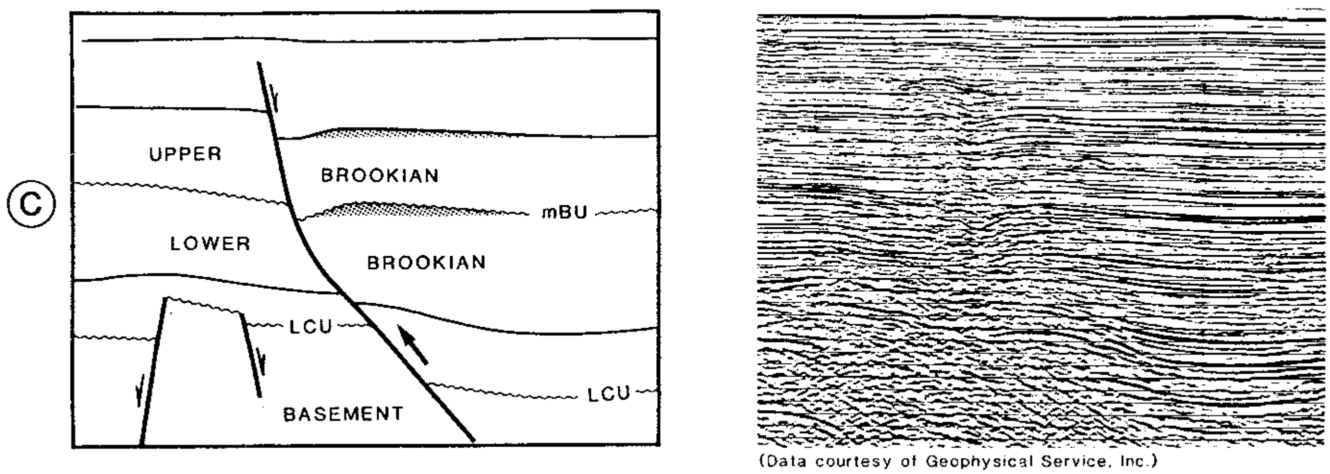
Although upper Brookian strata extend as a thin, onlapping sequence into adjacent structural provinces, the margin of the North Chukchi basin proper is considered to coincide with a major flexure-zone (fig. 22; plate 7) along which much of the basin subsidence has occurred. This flexure-zone trends east along the northern edge of



Traps in rotated fault blocks of Brookian strata.



Traps in Lower Brookian strata in anticlines and rotated blocks associated with listric fault systems.



Traps in Upper Brookian strata in rollover anticlines associated with listric fault systems.

FIGURE 41. Play concepts and potential trapping mechanisms in Brookian strata of the North Chukchi basin. Large arrows denote potential migration paths. Shaded areas represent potential hydrocarbon accumulations.

the Chukchi platform and the Northcentral subbasin, and then turns abruptly north to pass along the west margin of the North Chukchi high (fig. 22). Potential hydrocarbon traps observed in the North Chukchi basin appear to be primarily those structures related to movements along the flexure-zone, but may also be associated with folds near the North Chukchi high and with younger north-south-trending faults which overprint the older features. Potential traps include:

1. East-west-trending faults which are most conspicuous along the southwest and southeast margin of the North Chukchi basin and which offset basement and lower Brookian strata. These faults appear to be related to initial basin subsidence.

2. North-trending normal faults which offset strata of the upper and lower Brookian sequence throughout the basin and which may have overprinted the flexure-zone faults (fig. 41a).

3. Gentle rollover folds associated with listric faults which cut primarily lower Brookian strata in the southeast corner of the basin (fig. 41b, 41c). Locally, these faults appear also to extend upward into the upper Brookian sequence.

4. Folds in lower Brookian strata near the western margin of the North Chukchi high (plate 7). Traps also may occur where strata within these folds are breached at the mBU.

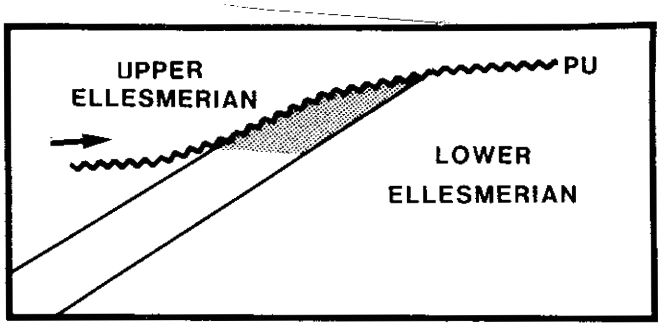
In all of the above-mentioned fault traps, the faults themselves could have influenced hydrocarbon accumulation by serving as either conduits or barriers to hydrocarbon migration. Grantz and May (1984a) suggest that the prospectiveness of these traps may be enhanced by the presence of locally thick, unfaulted upper Brookian strata overlying them. This would indicate that no recent activity has occurred along the faults to disrupt oil accumulations which may have been lodged earlier in strata truncated at the faults.

NORTHEAST CHUKCHI PLATEAU

Stratigraphic traps form the principal hydrocarbon plays in the very small portion of the Northeast Chukchi plateau which extends into the Chukchi Sea Planning Area (fig. 10). Stratigraphic traps which may be present in this region are described as follows:

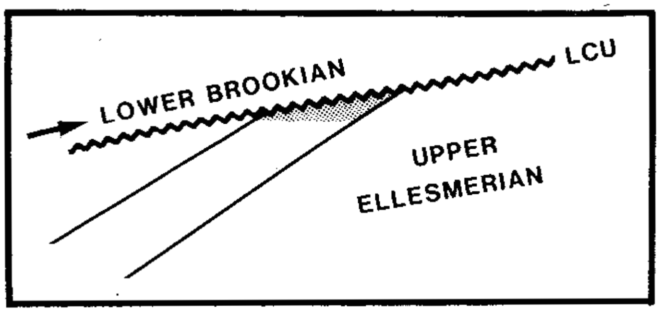
1. Unconformable truncations of lower Ellesmerian clastic reservoir strata at the PU may form traps where sealed by impermeable shales in the upper Ellesmerian (fig. 42a). These strata are folded and tilted in certain parts of the basin, with some anticlinal features present. Shales of the basal lower Brookian sequence (Pebble Shale), the upper Ellesmerian sequence (Shublik and Kingak Formations), or deeper lower Ellesmerian strata, may provide hydrocarbon sources for these traps.

A.



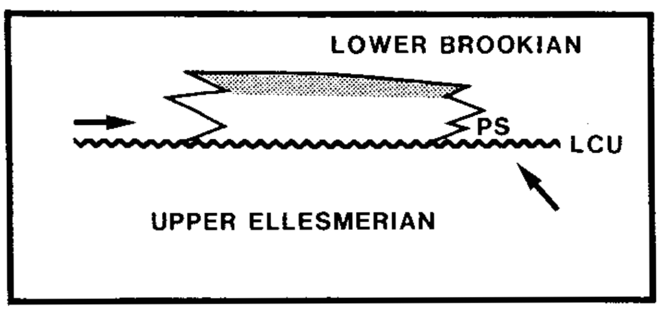
STRATIGRAPHIC TRAPS WITHIN LOWER ELLESMERIAN STRATA WHERE TRUNCATED AT THE PU.

B.



STRATIGRAPHIC TRAPS WITHIN UPPER ELLESMERIAN STRATA WHERE TRUNCATED NORTHWARD AT THE LCU.

C.



LATERALLY SEALED SANDSTONE LENSES AT THE BASE OF THE PEBBLE SHALE (PS) ON THE LCU.

FIGURE 42. Schematic diagrams illustrating play concepts and potential trap configurations in Ellesmerian and Brookian strata in the Northeast Chukchi basin. Shaded areas denote potential hydrocarbon accumulations. Large arrows denote potential migration paths.

2. Upper Ellesmerian reservoir sands truncated updip to the north by the LCU, with the overlying Pebble Shale serving as a potential source and seal. The underlying Kingak and Shublik Formations form additional or alternative sources (fig. 42b).

3. Lenses of sand at the base of the Pebble Shale enclosed laterally by shales serving simultaneously as source and seal (fig. 42c).

As discussed above, well-known potential Brookian and upper Ellesmerian source beds (Pebble Shale, Kingak Formation, and Shublik Formation) (fig. 11) can be seismically traced into this area. Using thermal maturity data from NPRA, nearly coincident "corridors" of thermal maturity corresponding to the oil window for these units are inferred to lie now along the boundary between the Northeast Chukchi plateau and the Central Chukchi basin (chapter 7, Source Rocks). This implies that deeper strata, such as the lower Ellesmerian sequence in both basins, are probably overmature. The Brookian and upper Ellesmerian source beds are relatively overmature for their present burial depths, which suggests a prior history of deeper burial followed by uplift and erosion of at least several thousands of feet of overlying strata. The patterns of thermal maturity within these rocks were probably determined during an earlier period of deep burial related to subsidence of the Colville basin and Early Cretaceous deposition of the lower Brookian sequence. Early in this period of subsidence, as noted previously, the oil corridors probably were located nearer the axis of the Colville basin and subsequently migrated northward as the basin subsided. Oil expelled from the oil corridors would have migrated updip into earlier-formed (pre-LCU) traps along the flank of the Northeast Chukchi plateau. Any early oil accumulations which formed south of the present-day southern margins of the oil corridors have probably been destroyed by thermal degradation of the oil. However, similar accumulations north of the same margins may be preserved.

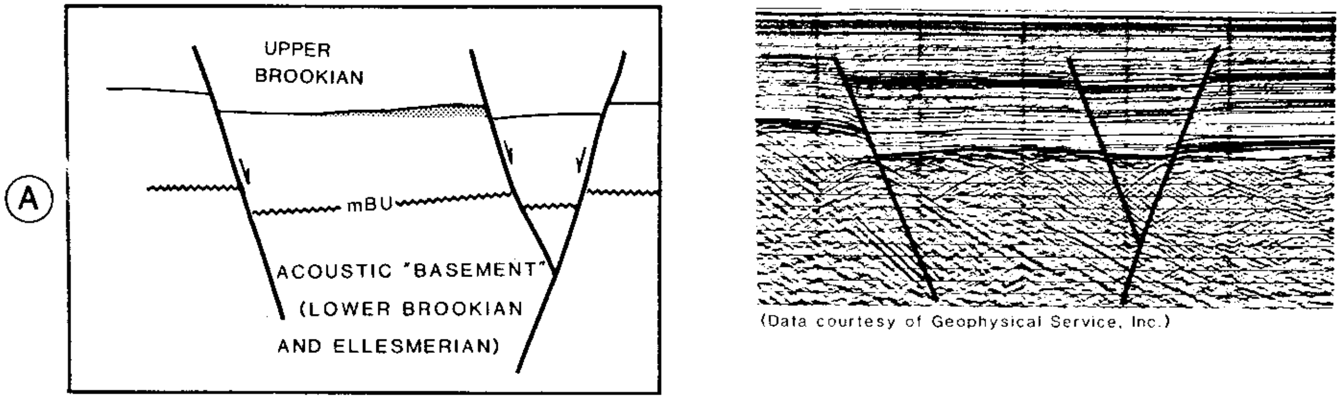
NORTH CHUKCHI HIGH

The North Chukchi high, located in the northeast portion of the planning area (fig. 10), appears to have been initially formed by Late Cretaceous to Early Tertiary folding and(?) wrench faulting. Potential hydrocarbon traps identified in seismic reflection data include:

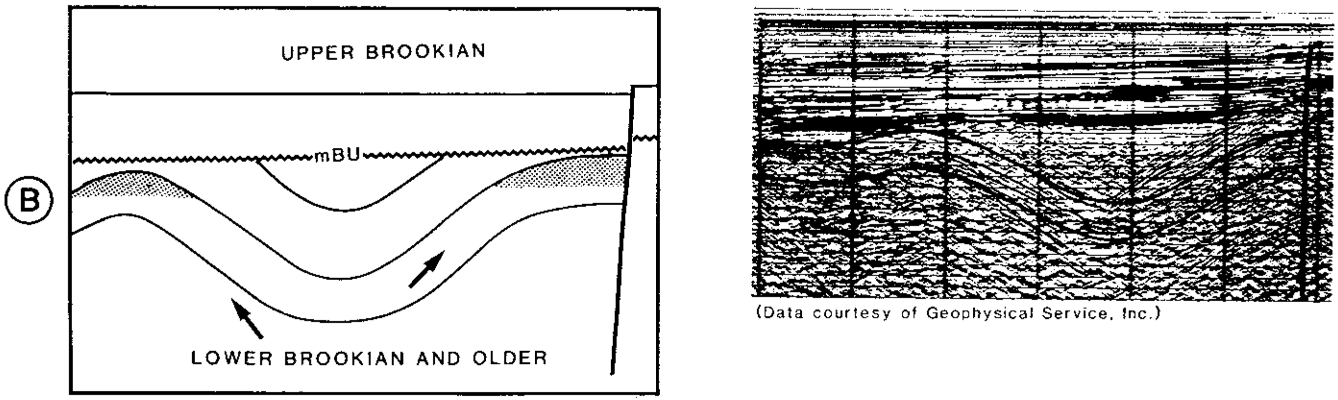
1. Apparent normal faults associated with the Hanna wrench-fault zone in which upper Brookian reservoir strata are juxtaposed against impermeable older strata (fig. 43a).

2. Box folds and reverse faults which deform Ellesmerian and lower Brookian strata, most prominent in the southern part of the North Chukchi high (fig. 43c; plate 6).

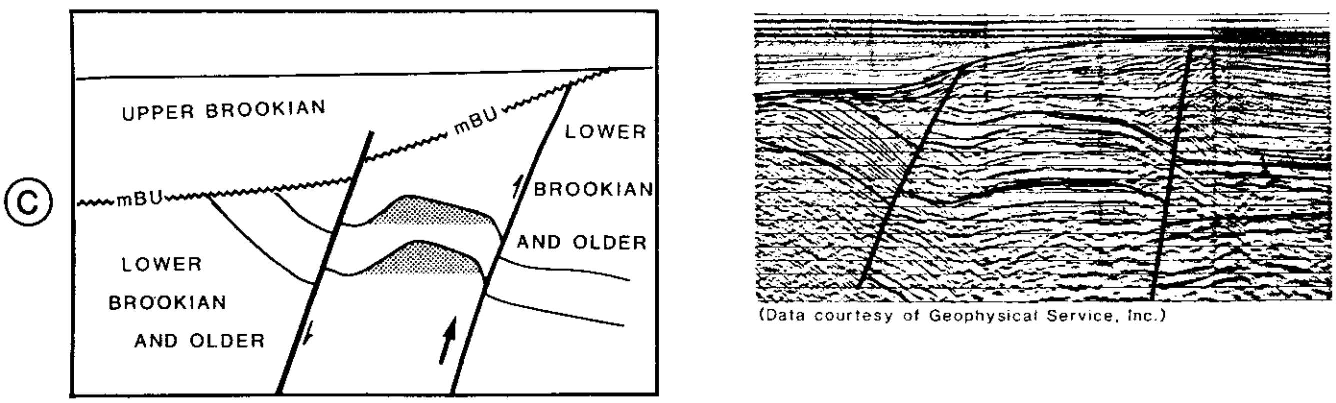
3. Broad folds within lower Brookian or Ellesmerian strata



Fault traps in Upper Brookian strata in the central part of the North Chukchi High.



Broad folds in Brookian(?) and older strata along the western boundary of the North Chukchi High.



Box fold traps in Ellesmerian and Lower Brookian (?) sequences along the southern margin of the North Chukchi High.

FIGURE 43. Play concepts and trapping mechanisms in Ellesmerian and Brookian strata in the structural complex which underlies the North Chukchi high. Large arrows denote potential migration paths. Shaded areas represent potential hydrocarbon accumulations.

(below the mBU) along the northwestern margin of the North Chukchi high (fig. 43b; plate 6).

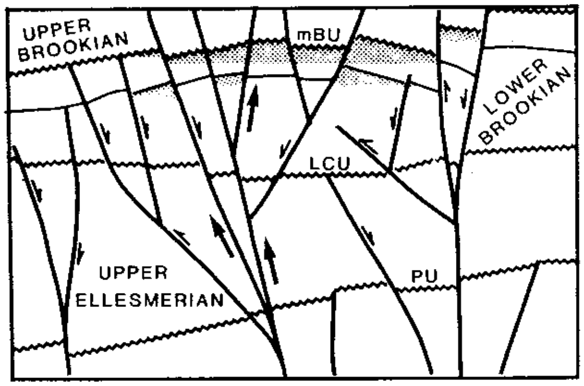
Our projections of thermal maturity for the Pebble Shale, Kingak Formation, and Shublik Formation suggest that they are thermally mature to overmature in the North Chukchi high. However, the maturity of these units onshore was determined during burial beneath lower Brookian sediments. Since traps on the North Chukchi high formed after lower Brookian sedimentation, probably after the hydrocarbons had migrated out of the source beds, they are considered to have a low probability of containing hydrocarbons sourced from the Pebble Shale or older strata. Potential sources within the Brookian sequence, however, cannot be ruled out, and these may have contributed hydrocarbons to the complex array of structures on the North Chukchi high.

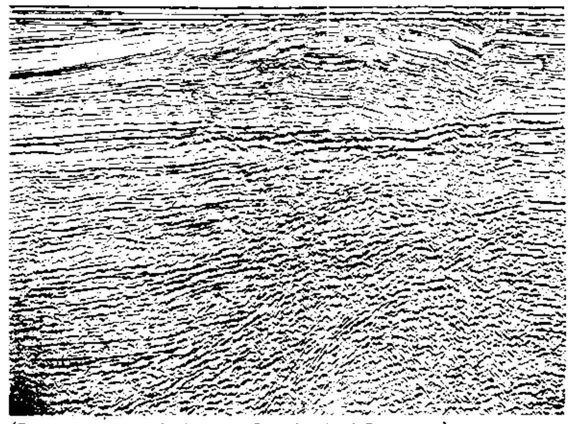
HANNA WRENCH-FAULT ZONE

The Hanna wrench-fault zone (fig. 22) is the youngest tectonic element in the planning area and overprints several established geologic provinces, including the North Chukchi high, the Northcentral subbasin, the Central Chukchi basin, and the Chukchi platform (fig. 10). Faulted grabens and uplifts have formed in narrow, north-trending zones above basement-controlled faults with little or no apparent vertical displacement of the basement. These structural features are believed to reflect wrench movement in the basement rocks. Faulted antiforms, synforms, and local domal features related to the wrench zones are probably the most prospective structures in the Hanna wrench-fault zone.

Examples of the kinds of features commonly found in individual wrench-fault zones in the Hanna system are illustrated in figures 44 and 45. In some areas of the Hanna wrench-fault zone are found gentle, unfaulted anticlines which straddle the fault zone and which contain potential reservoir strata of the Brookian sequence. Because of their relatively uncomplicated structural styles, these structures may be the most prospective of the wrench-related features. In other areas, however, the anticlines are fragmented by numerous faults. In such structures, many small faults splay upward from a single basement fault, forming a dendritic pattern. These structures are termed positive "flower" structures (fig. 27). Conversely, large-scale grabens dissected by dendriform faults which converge at depth are termed negative "flower" structures. In some zones, the strata have been severely disrupted and fragmented by dense arrays of complex faults. In these structures, individual traps are likely to be small because of the close spacing of faults. Potential traps in the Hanna wrench-fault zone include both positive and negative flower structures, which typically involve both upper and lower Brookian sequences (figs. 44a, 44b). Potential traps also occur where passive anticlinal features are developed between flanking negative flower structures (fig. 44b).

A

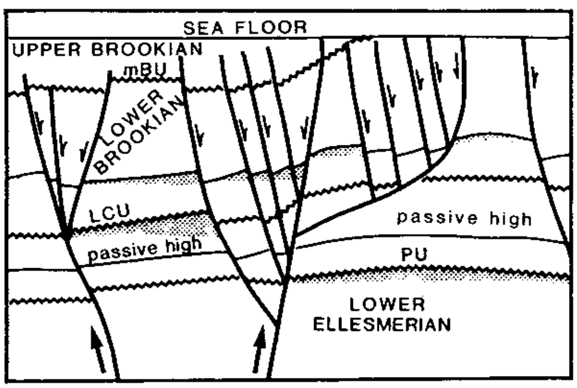


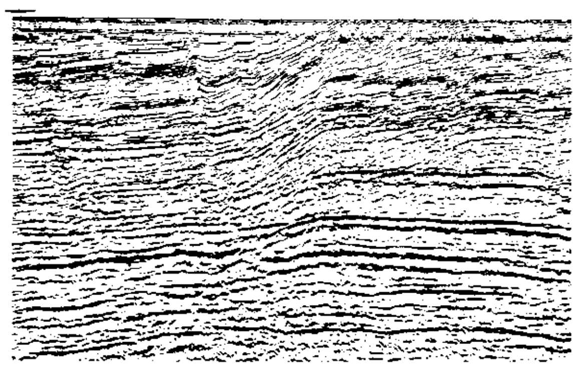


(Data courtesy of Western Geophysical Company)

Potential traps in faulted anticlinal features associated with positive flower structures in the Brookian sequence overlying wrench fault systems.

B

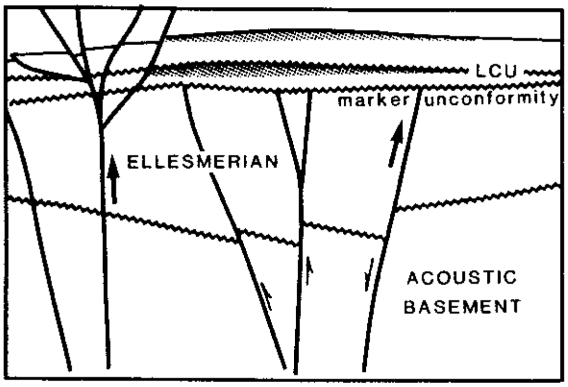


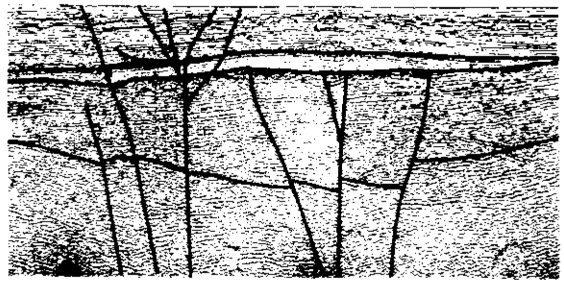


(Data courtesy of Western Geophysical Company)

Potential traps in broad highs formed passively between flanking negative flower structures, and fault traps in negative flower structures above wrench faults.

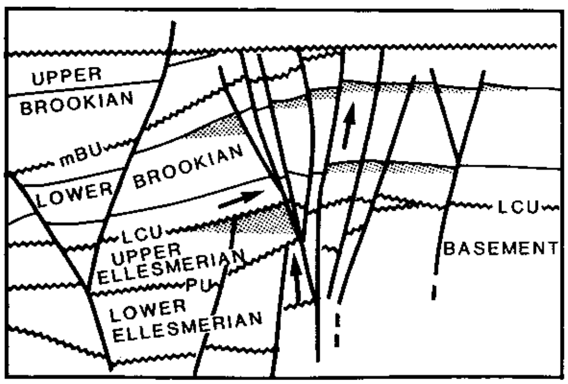
FIGURE 44. Play concepts and potential traps associated with the Hanna wench—fault zone. Large arrows denote potential migration paths. Shaded areas represent potential hydrocarbon accumulations.

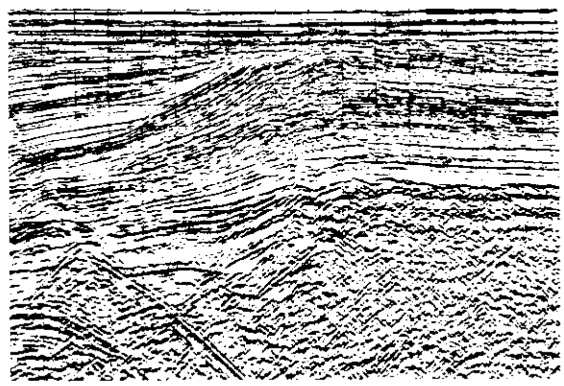




(Data courtesy of Western Geophysical Company)

Domed strata above wrench fault zone.





(Data courtesy of Western Geophysical Company)

Fault traps associated with wrench faults formed by reactivation of older basement faults on the Chukchi platform.

FIGURE 45. Play concepts and potential trapping mechanisms associated with parts of the Hanna wrench–fault zone. Large arrows denote potential migration paths. Shaded areas represent potential hydrocarbon accumulations.

Additional prospective traps identified on seismic reflection data are positive structural inversions in Ellesmerian and Brookian rocks (fig. 45a, plate 4). These structural inversions, as discussed previously (chapter 4, Structural Provinces), were formed by the local uplift and doming of unfaulted strata above, between, or adjacent to wrench faults. In seismic cross section these structures consist of a foundation of planar strata which lie beneath a domal feature. The internal configuration of these structures consists of a lenticular body of reflections which appear to downlap the underlying planar reflections outward from the center. According to Harding (1985), the "anticlines" in the strata draped over positive structural inversions are attractive potential hydrocarbon traps. This is primarily because the areal extent of these folds is commonly larger than conventional compressional structures and provides large closures that are not dependent on sealing faults.

In the southern parts of the Hanna wrench-fault zone on the Chukchi platform (figs. 10, 22), some simple anticlinal and faulted anticlinal traps occur in rocks of the Ellesmerian and Brookian sequences, both of which may contain potential reservoir and source rocks. On the Chukchi platform, positive flower structures are widely developed in lower and upper Brookian strata over reactivated faults which bound older, pre-wrench grabens (plate 5). Extensional displacement on these faults apparently was initiated during deposition of the lower Ellesmerian sequence and largely ceased prior to the LCU erosional event. These faults appear to have been more recently reactivated as individual strands of the Hanna wrench-fault zone (fig. 45b). The potential for hydrocarbon accumulations in the deformed Brookian strata could conceivably be enhanced because of access via faults to Ellesmerian source rocks which contact the faults at greater depth.

12. SUMMARY OF THE PETROLEUM GEOLOGY

The assessment of petroleum potential for a frontier area as large and structurally complex as the Chukchi Sea Planning Area is necessarily somewhat speculative. The only available well control consists of remote onshore wells in western NPRA. These wells are of limited value and provide lithologic control only in the nearshore portion of the planning area. However, seismic data and offshore extrapolations of the geologic information derived from these onshore wells provide a means to formulate a preliminary assessment and ranking of the relative prospectiveness of the various structural provinces. This ranking, and the chief concepts which justify the ranking, are briefly summarized as follows:

1. Chukchi platform.

It is an ancient high overlain by near-source Ellesmerian sedimentary rocks, which elsewhere across northern Alaska form, in part, attractive reservoir sequences. The fact that the Chukchi platform has been a persistent high suggests the rocks were probably not buried deeply enough to become overmature. Faulting of the platform occurred prior to Brookian sedimentation, so potential hydrocarbon traps were present before major subsidence and thermal heating coincidental with lower Brookian sedimentation. The Chukchi platform also contains numerous younger but equally prospective structures such as diapirs and wrench structures related to the Hanna wrench-fault zone.

2. North Chukchi basin.

The two principal seismic sequences in the basin, the lower and upper Brookian sequences, do not appear to have experienced the deep burial, intense deformation and subsequent uplift which characterize stratigraphically equivalent strata in the southern Colville basin and therefore cannot be justifiably inferred to be similarly overmature. Potential hydrocarbon traps began to form during the early phase of basin subsidence and may have had access via deep faults to hydrocarbons migrating upward from greater depths within the basin.

3. North Chukchi high.

The late timing of the intense deformation of the Ellesmerian and lower Brookian strata suggests that most recognizable traps formed after lower Brookian sedimentation had buried older strata so deeply that they had become thermally overmature. Because of the intense deformation, most traps are small and difficult to map with existing seismic reflection data. Later disruption by faults associated with the Hanna wrench-fault zone may have destroyed any pre-existing hydrocarbon accumulations.

4. Northcentral subbasin.

The upper Brookian sequence is disrupted by numerous wrench structures which would form attractive hydrocarbon traps. Lower Brookian strata within the basin have been buried deep enough to have experienced thermal conditions favorable for the generation and expulsion of hydrocarbons. However, most of the deeper Ellesmerian strata are probably overmature.

5. Fold and Thrust belt.

The onshore counterparts of the Ellesmerian seismic sequences are overmature and have unfavorable reservoir characteristics. The offshore Ellesmerian-equivalent sequence in the Fold and Thrust belt appears to have been even more deeply buried and is therefore probably not prospective. The folded lower Brookian sequence onshore contains poor reservoir rocks and generally lean, gas-prone source rocks.

6. Northeast Chukchi plateau, Central Chukchi basin, and Wainwright and Northeast Chukchi fault zones.

As discussed previously (chapter 11, Hydrocarbon Play Concepts and Traps), the basal Brookian and upper Ellesmerian source beds appear to have been so deeply buried that any hydrocarbons generated were probably destroyed by thermal degradation as basinal subsidence proceeded, unless they migrated updip into the western part of the Beaufort Sea Planning Area. Therefore, these provinces are considered to have generally poor hydrocarbon potential within the Chukchi Sea Planning Area.

7. Northern Hope basin.

Although many fault traps are present, shallow burial depths in most of the basin and the youth of the sediments (upper Tertiary(?)) suggest that the sedimentary section is probably thermally immature and therefore not prospective for hydrocarbon generation and entrapment.

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13. BATHYMETRY

The Chukchi Sea Planning Area lies within a broad, low-relief continental shelf which is gently inclined to the north (fig. 46). Approximately 80 percent of the planning area lies in water depths of between 100 and 200 feet. Deeper water areas are restricted to three subsea valleys that impinge upon the shelf from the continental slope. Two broad, unnamed subsea valley heads incise the shelf in the northwestern and northeastern parts of the planning area, and the head of the large Barrow Sea Valley extends southwest into the extreme eastern part of the planning area. Nearshore areas which are shallower than 120 feet exhibit complex bathymetry characterized by ridges and troughs (fig. 46). Farther offshore, water depths are less than 80 feet on the Herald Shoal in the west, on a small unnamed seafloor high in the center of the planning area, and on the Hanna Shoal in the northeast (Grantz and others, 1982b).

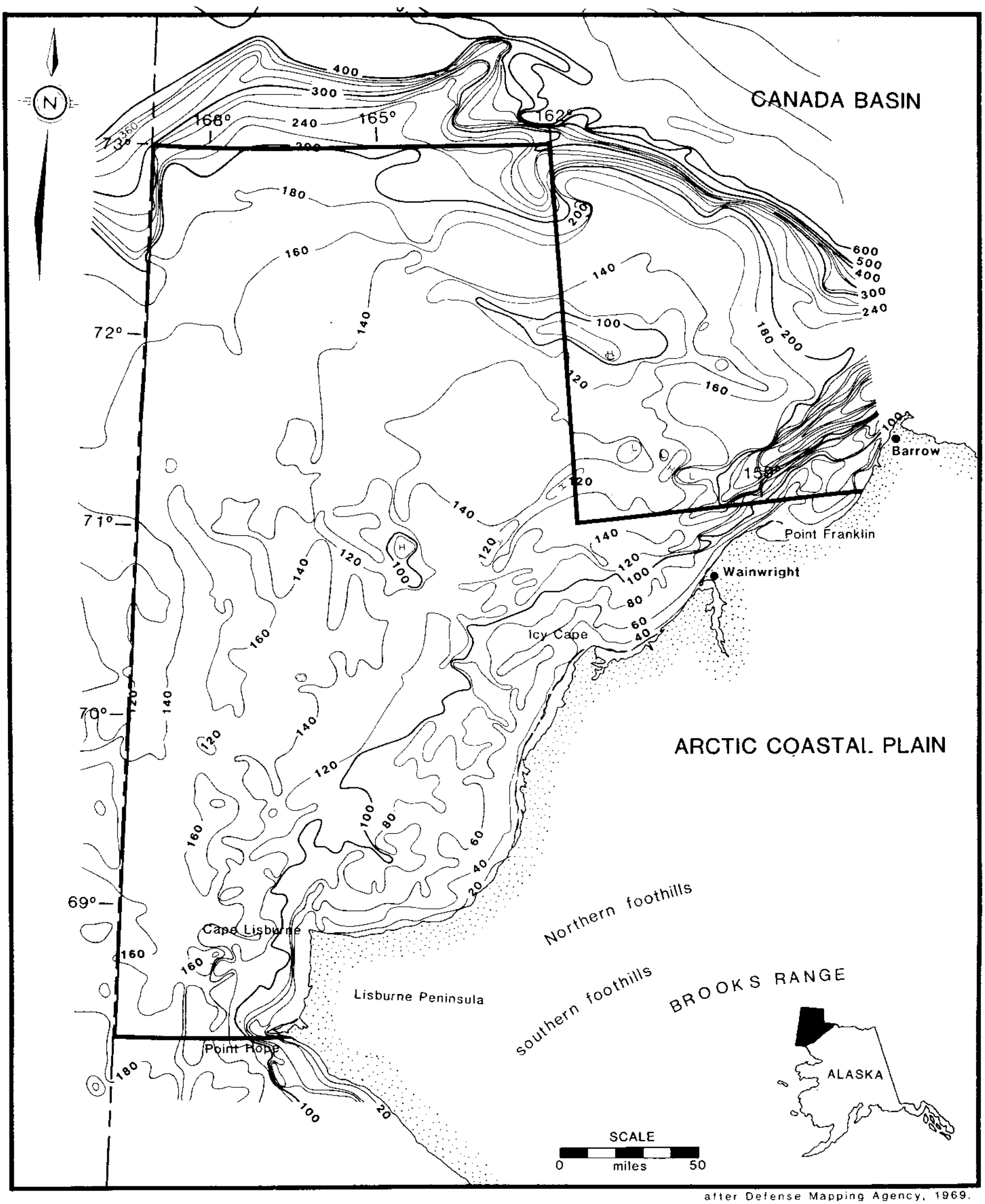


FIGURE 46. Bathymetry of Chukchi shelf, in feet. Contour interval is 20 feet.

14. COASTAL PHYSIOGRAPHY

Major west-trending physiographic provinces of the Arctic North Slope (Foothills and Coastal Plain) intersect the Chukchi coastline and influence the coastal profile as a function of the nature of the rocks exposed at the shoreline. The southern Foothills are predominantly composed of erosion-resistant Paleozoic and Mesozoic metamorphic rocks, and the northern Foothills are formed of less deformed Cretaceous shales and sandstones (fig. 47). The Coastal Plain is composed of silt and decreases in relief to the north, away from the Foothills. The southern part of the Coastal Plain consists of a relatively thin blanket of silt which overlies Cretaceous bedrock, but which thickens considerably northward toward the Beaufort coast. Hartwell (1973) has divided the northwestern Alaska coast, from Point Hope to Point Barrow, into four geographic regions based upon the presence of similar coastal features and their vertical relief (fig. 47):

SOUTHERN FOOTHILLS

The shoreline in this region is characterized by steep sea cliffs formed in Paleozoic bedrock of the Lisburne Hills. These cliffs reach a maximum relief of 850 feet at Cape Lisburne and are generally fronted by narrow beaches. At Point Hope, nearly continuous sand-and-gravel barrier islands outline the broad Kukpuk river delta.

NORTHERN FOOTHILLS

Like the southern Foothills region, the shore is characterized by sea cliffs. But here the cliffs are lower (245 feet maximum) because of the erosion of less resistant Cretaceous bedrock. No offshore barrier islands or large river outlets are present along this segment of coastline.

FOOTHILLS SILT SURFACE OF THE COASTAL PLAIN

Nearly continuous sea cliff exposures of Cretaceous bedrock with relief of 13 to 45 feet characterize this region. The northern part of this region is fronted by nearly unbroken barrier islands with

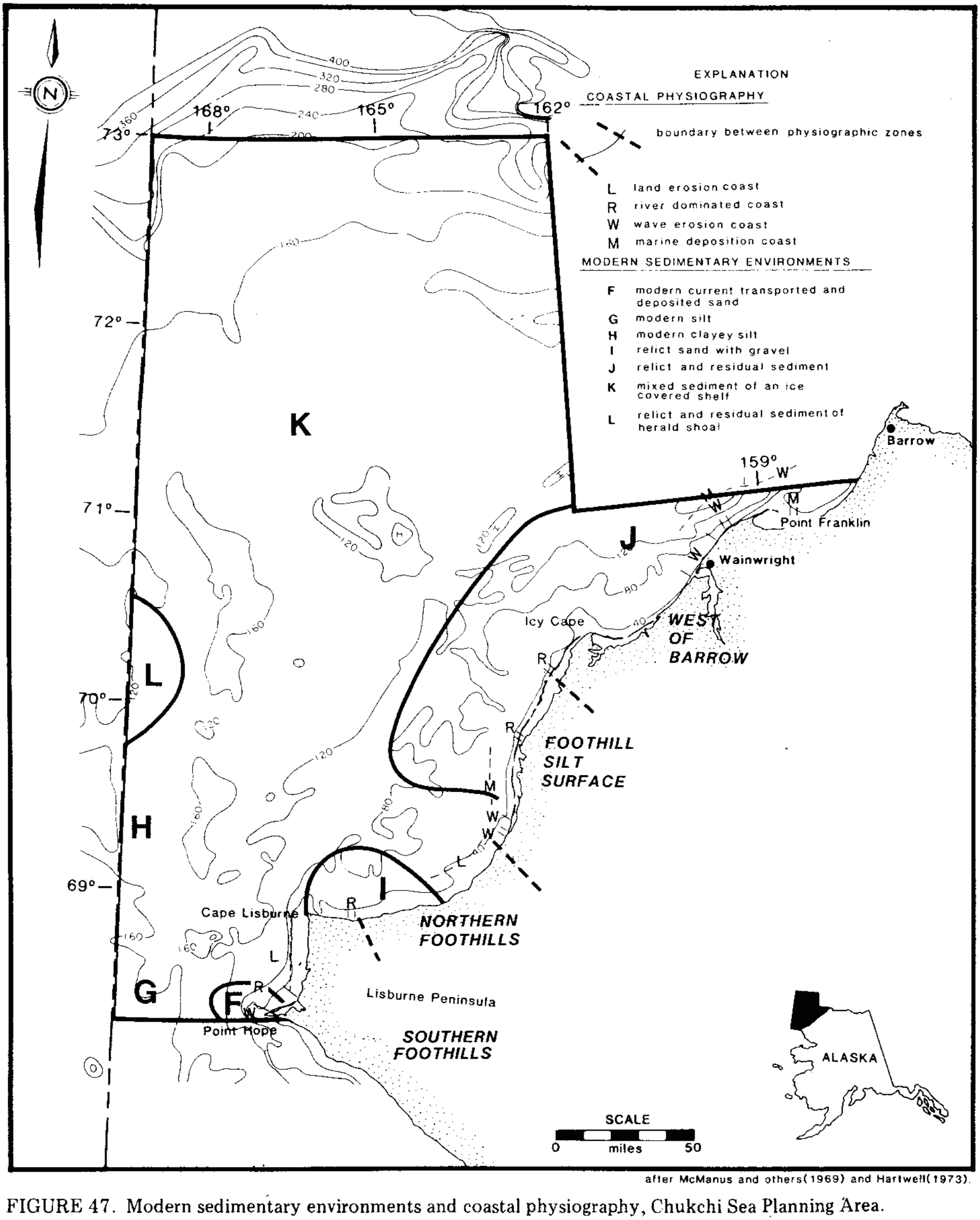


FIGURE 47. Modern sedimentary environments and coastal physiography, Chukchi Sea Planning Area.

less than 10 feet of relief. These islands enclose the shallow Kasegaluk Lagoon, which is as wide as 4.5 miles.

COASTAL PLAIN WEST OF POINT BARROW

This region is characterized by nearly continuous sea cliffs up to 40 feet high cut into perennially frozen or ice-rich sediments. Near Icy Cape and Point Franklin, offshore barrier islands front the coast, enclosing shallow lagoons. Elsewhere the cliffs are abutted by narrow beaches.

Hartwell (1973) further categorizes the coastline into two main coastal classes: primary coasts, shaped largely by terrestrial processes; and secondary coasts, shaped largely by marine processes. Each of these two classes is divided into two types based upon whether it is predominantly influenced by erosion or deposition (fig. 47).

PRIMARY COASTS

Land Erosion (L)

The coast is shaped by subaerial erosion and partially drowned by rising sea level. This type is characterized by a nearly straight coastline with steep sea cliffs formed in bedrock. Relief on these cliffs may reach hundreds of feet. In some places the cliffs are fronted by barrier deposits and protected from the open ocean.

River Dominated (R)

This type of coast is due to river deposition at the shoreline. Fluvial-deltaic deposits consist of sedimentary lobes separated by multiple braided river channels with steep banks. Dune fields are present on some deltas where sedimentary deposits are not vegetated. Some segments of this type of coast are fronted by nearshore barrier islands and relief is generally less than 15 feet.

SECONDARY COASTS

Wave Erosion (W)

These coastlines, which are directly exposed to open ocean, are rare (fig. 47). They are characterized by sea cliffs, generally less than 35 feet high, cut into perennially frozen bedrock and ice-rich sediments. The cliffs are undergoing active erosion or are in near-equilibrium condition and may have a narrow beach at their base.

Marine Deposition (M)

This type is similar to wave erosion coasts (W) in that the coasts are eroded by waves and currents, but here marine deposition is more evident. These are fronted by barrier islands and spits that generally follow the coastal trend but are separated from the mainland by a relatively narrow body of water (less than 3 miles). The barrier islands protect the coast from the pack ice, waves, and currents of the open ocean. Spits are common and partially deflect river courses where they meet the coast. Relief on these coasts is generally less than 15 feet.

15. SEAFLOOR GEOLOGY

BEDROCK SUBCROPS

During Pleistocene low-sea-level stillstands, a large portion of the Chukchi shelf was subaerially exposed (Hopkins, 1967). Over large parts of the planning area the seafloor is barren of significant sediment cover. The seafloor bedrock subcrops occur in two belts--one that trends northwest and overlies the Herald arch, the Fold and Thrust belt (fig. 48), and the southern part of the Chukchi platform (fig. 49); and another that is wider and trends northeast, parallel to the coast. In the central part of the planning area over the Northcentral subbasin, folded Late Cretaceous to Tertiary strata may compose the bedrock subcrops (fig. 50; also see fig. 70 for the location of the reflection profiles). However, the majority of the bedrock breached at the seafloor in the planning area is composed of Lower Cretaceous strata in the Fold and Thrust belt (fig. 48) and the Colville basin (figs. 10, 49). Mesozoic and possibly some Paleozoic bedrock lie at or near the seafloor along the crest of the Herald arch along the southwest margin of the subcrop belt (Grantz and others, 1982b).

QUATERNARY SEDIMENTS

Quaternary sediment cover is thin, generally 6 to 30 feet, across most of the central Chukchi shelf (Grantz and others, 1982b). The thickest Pleistocene deposits are found in the North Chukchi and Northern Hope basins, where they may exceed 100 feet in thickness. In addition, throughout the northern part of the planning area, Pleistocene paleochannel-fill attains thicknesses locally exceeding 100 feet (figs. 49, 51, and 52). Offshore from Wainwright, more than 75 feet of probable Pleistocene sediments fill the offshore extension of the Kuk River channel (Phillips and Reiss, 1984). Phillips and Reiss (1984) also documented the occurrence of up to 45 feet of possible Holocene sediment within the sandbanks of the Blossom Shoals off Icy Cape.

SURFICIAL SEDIMENTS

McManus and others (1969) classified and mapped sediments mantling the seafloor on the basis of grain characteristics and depositional processes (fig. 47). The distributions of clay, silt, sand, and gravel in the surficial sediments is shown in figures 54,

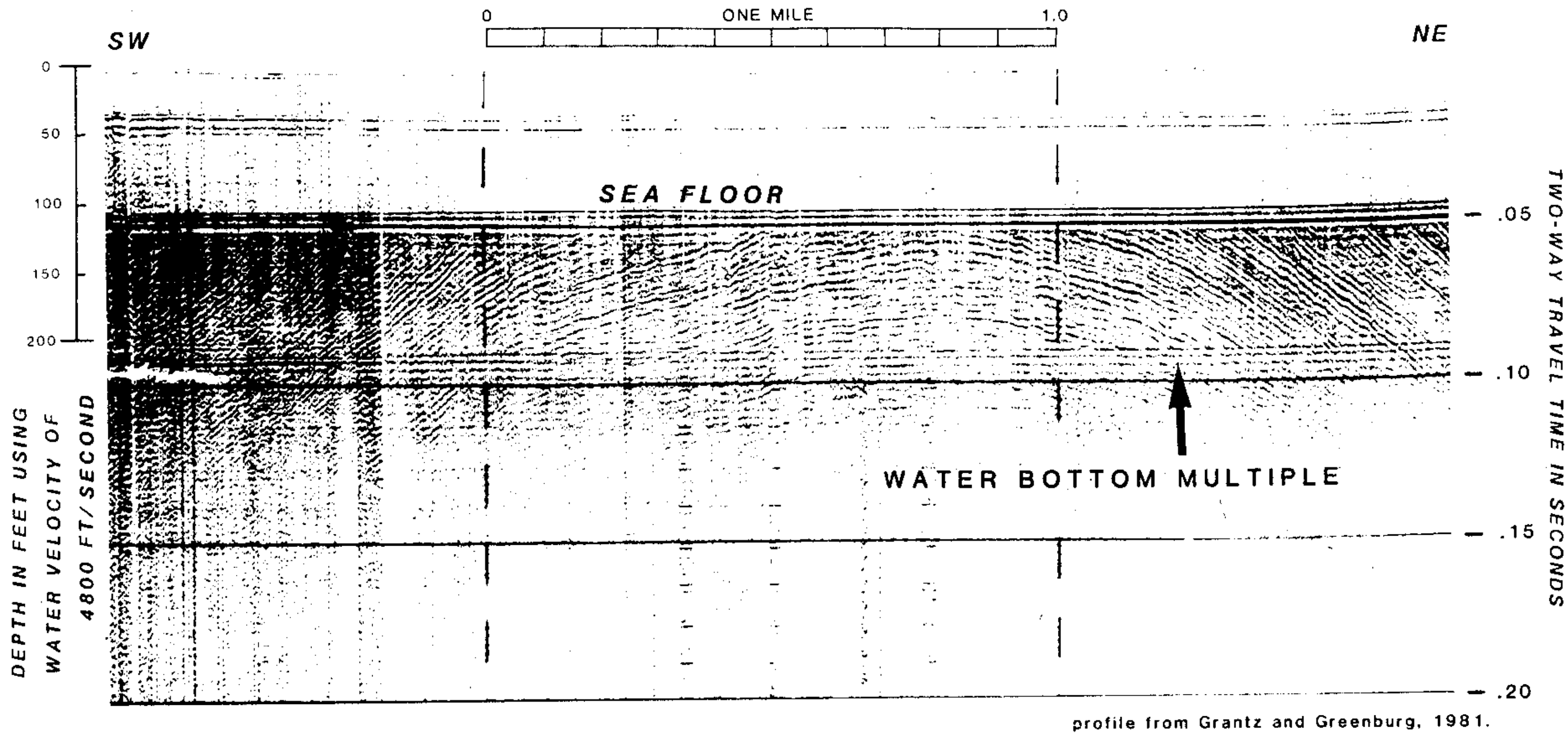


FIGURE 48. Segment of USGS Uniboom line 803, showing folded Cretaceous(?) strata subcropping at the seafloor north of the Herald Arch. See figure 70 for location of profile.

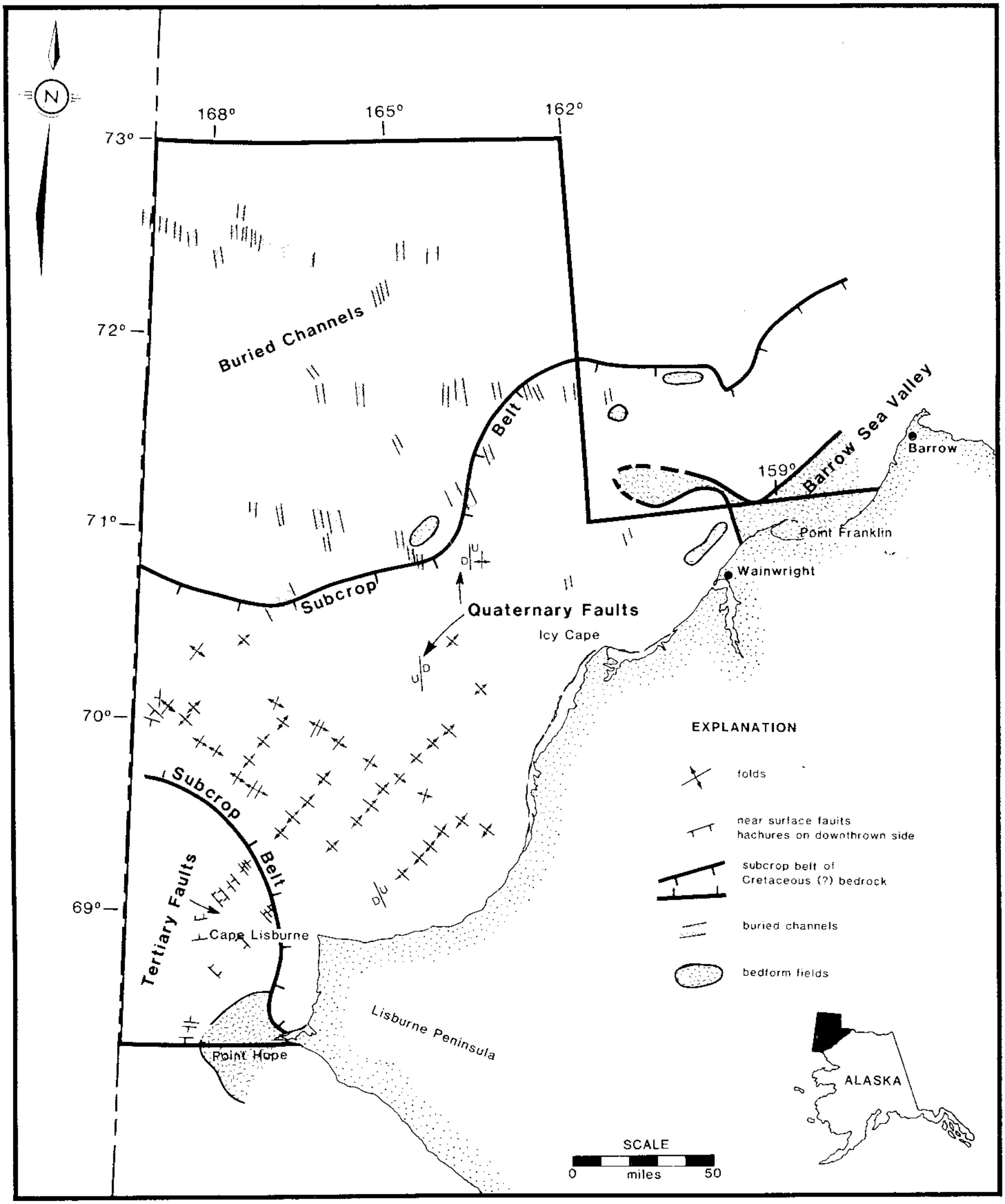


FIGURE 49. Surficial geologic features of the Chukchi shelf.

55, 56, and 57. Silt and clay mantle most of the Chukchi shelf (figs. 54 and 55) and are considered to be modern sediment derived from the Yukon and other rivers that has been carried north by the Alaska Coastal Current (fig. 53) (McManus and others, 1969). These sediments are generally poorly sorted, homogeneous, and exhibit an absence of layering due to bioturbation (fig. 47, environments "G", "H", and "K"). The highest concentrations of silt and clay are found west of Cape Lisburne and in the central Chukchi shelf (figs. 54 and 55).

The surface distribution of sand in the planning area is shown in figure 56. The highest sand concentrations occur typically along the course of the northeastward-flowing Alaska Coastal Current and over the shoals. Modern sand deposits off Point Hope are shaped by currents into asymmetric bedforms (fig. 59) and are considered by McManus and others (1969) to have been derived from the nearby sea cliffs (fig. 47, environment "F"). Many of the areas of high sand concentration correspond to areas of asymmetric bedforms (figs. 49 and 56). Some of the concentrations of sand over the shoals and along the coast may be residual or relict (McManus and others, 1969) (fig. 47).

The distribution of gravel shown in figure 57 is expressed as a statistical function ("factor loadings") which is related to the percentage of clay/silt/sand/gravel and to various grain-size parameters (McManus and others, 1969). The higher values correspond to higher gravel concentrations. The highest gravel concentrations occur on the Herald Shoal and along the coast, particularly north of the Lisburne Penninsula (figs. 57, 47, environments "I", "J", and "L"). The high gravel content of surface sediments adjacent to the coast and on the Herald and Hanna Shoals reflects residual or relict sediments. North of the Lisburne Peninsula, the relict sand and gravel (figs. 56 and 57) are believed to be winnowed, submerged shoreline deposits (McManus and others, 1969). On the Hanna Shoal, the sediments are considered to be lag deposits left by the winnowing of the fine fraction by currents after they are resuspended by ice gouging of the seafloor (Toimil and Grantz, 1976).

16. MIGRATING BEDFORMS

Asymmetric bedform features occur in the Chukchi Sea Planning Area in water depths ranging from less than 50 feet to approximately 200 feet and at distances of up to 100 miles from the coastline (fig. 49). Because of the asymmetric profile of the bedforms, it is assumed that they are actively migrating in the direction of their steep face.

In the southeastern part of the planning area, small, asymmetric sand waves trending generally parallel to the shoreline are found in water depths of less than 50 feet (Grantz and others, 1982b). These bedforms are probably intermittently activated by currents and waves associated with storm events, and are apparently unaffected by the northward-flowing Alaska Coastal Current which passes farther west (fig. 53).

Larger shore-parallel shoals in water depths between about 20 and 70 feet generally occur off the capes. Grantz and others (1982b) believe that asymmetric bedforms as high as 8 feet on these shoals reflect northeastward sediment transport by the Alaska Coastal Current. Northwardly migrating sandwaves between Wainwright and Peard Bay have been documented by Phillips and others (1982).

Phillips and Reiss (1984) have mapped a group of features termed the Blossom Shoals north of Icy Cape and have concluded that they are formed in a complex hydrodynamic regime which produces northeastwardly migrating sandwaves in the southern part of the shoals and westerly migrating sandwaves in the northern part. The sandwaves in the southern part of Blossom Shoals appear to migrate in response to the northeastwardly flowing Alaska Coastal Current, whereas the sandwaves in the northern part of the shoals migrate under the influence of a westerly flowing counter-current or eddy off the main Alaska Coastal Current.

The sand from Blossom Shoals is carried along the course of the Alaska Coastal Current and is deposited in a shore-parallel sand field near the head of Barrow Sea Valley (fig. 49, west of Wainwright). This sand field contains northeastwardly migrating bedforms in water depths ranging from 24 to 60 feet.

Bedforms offshore from Point Hope occur in water depths over 180 feet and exhibit wave heights of over 20 feet and wavelengths of nearly 5,000 feet. These bedforms are asymmetric to the south (fig. 59), suggesting southward migration. However, because sediment transport off the Lisburne Peninsula is generally believed to be predominantly influenced by the northeastward-flowing Alaska Coastal Current, the southward asymmetry of the bedforms illustrated in figure 59 is anomalous. These bedforms may be the result of a local eddy or counter-current associated with the main Alaska Coastal Current, which causes a southerly back-flow through this area. Alternatively, these features might have formed in a southern extension of a seasonal southerly flow regime that has been observed in the winter around Cape Lisburne (Coachman and Aagaard, 1981).

An additional area of asymmetric bedforms occurs on the central shelf (fig. 49) northwest of the bedrock outcrop belt. The uniboom line illustrated in figure 58 shows two sandwaves, in water depths over 150 feet, with wavelengths of approximately 2,000 feet and wave heights of approximately 10 feet. These features are located farther offshore than any other previously reported seafloor bedforms in the Chukchi Sea Planning Area.

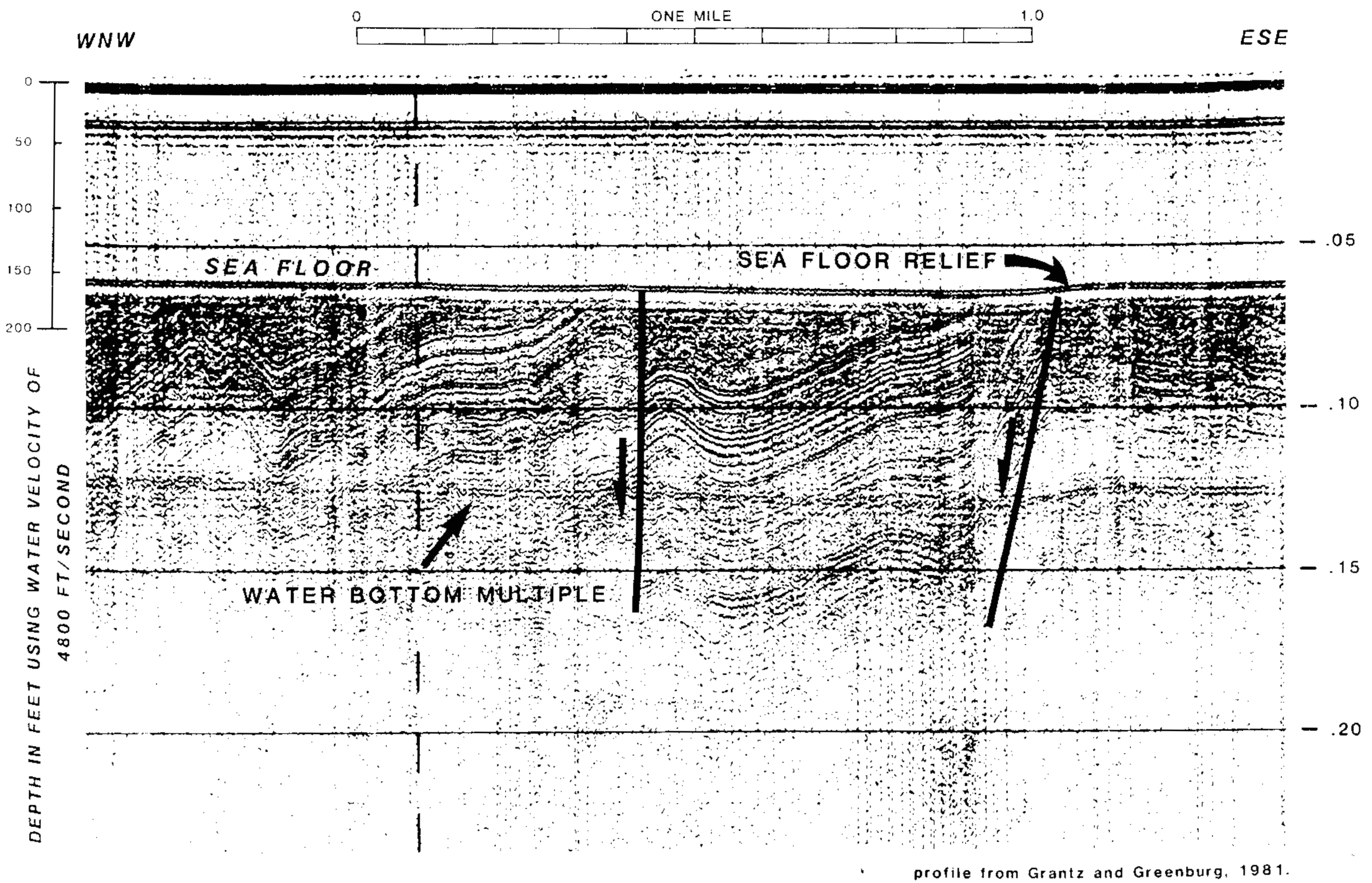


FIGURE 50. Segment of USGS Uniboom line 823, showing a fault scarp (or a fault—line scarp ?) on the seafloor above a strand in a wrench fault zone. See figure 70 for location of profile.

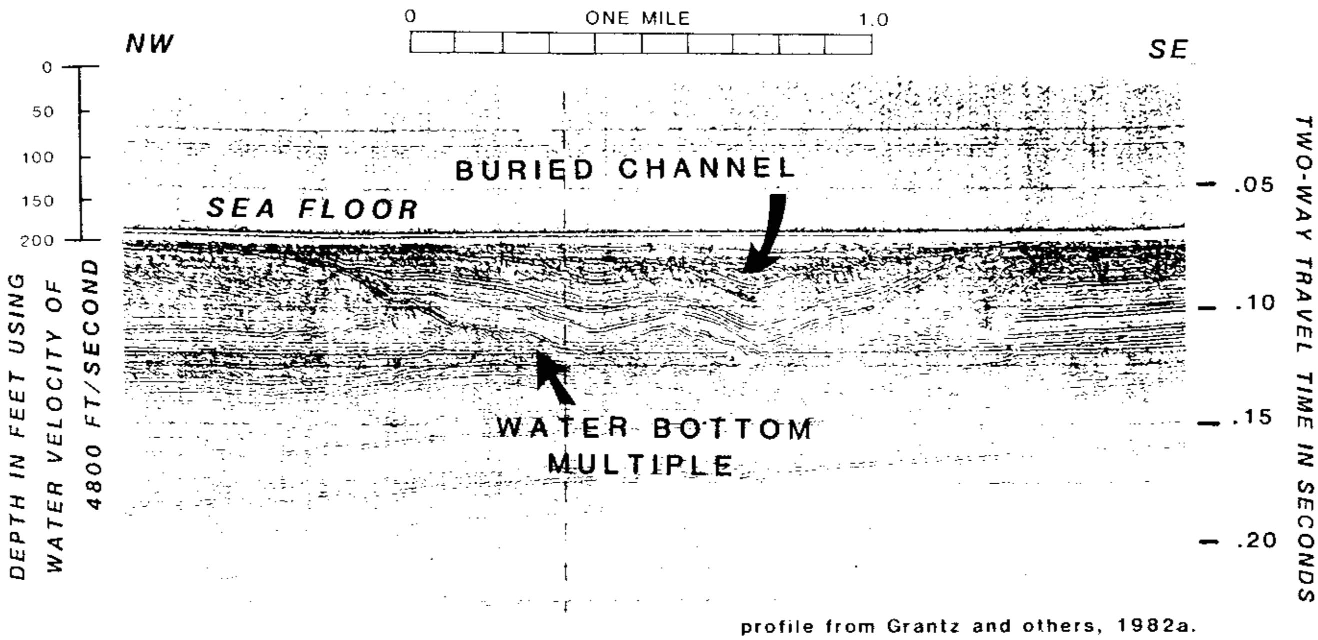


FIGURE 51. Segment of USGS Uniboom line 012, showing a filled paleochannel west of the Barrow Sea Valley. See figure 70 for location of profile.

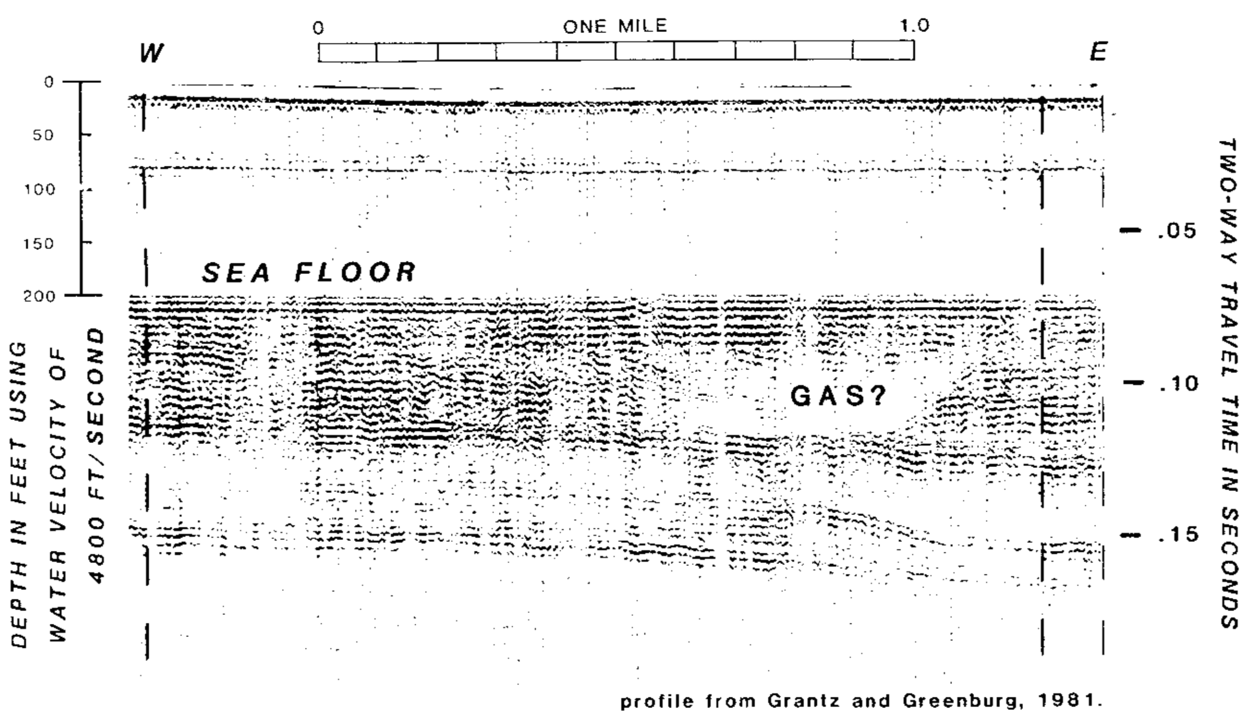
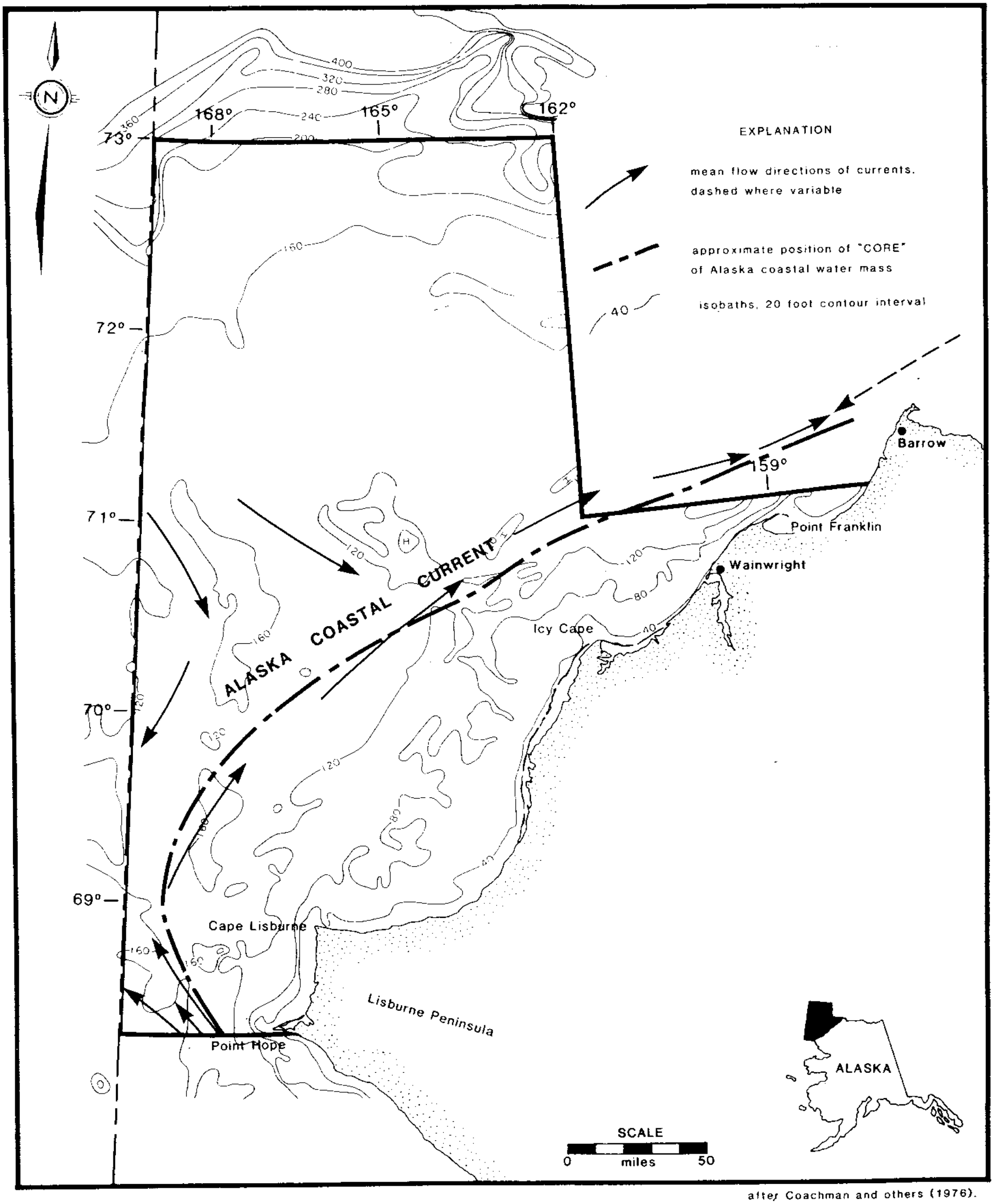
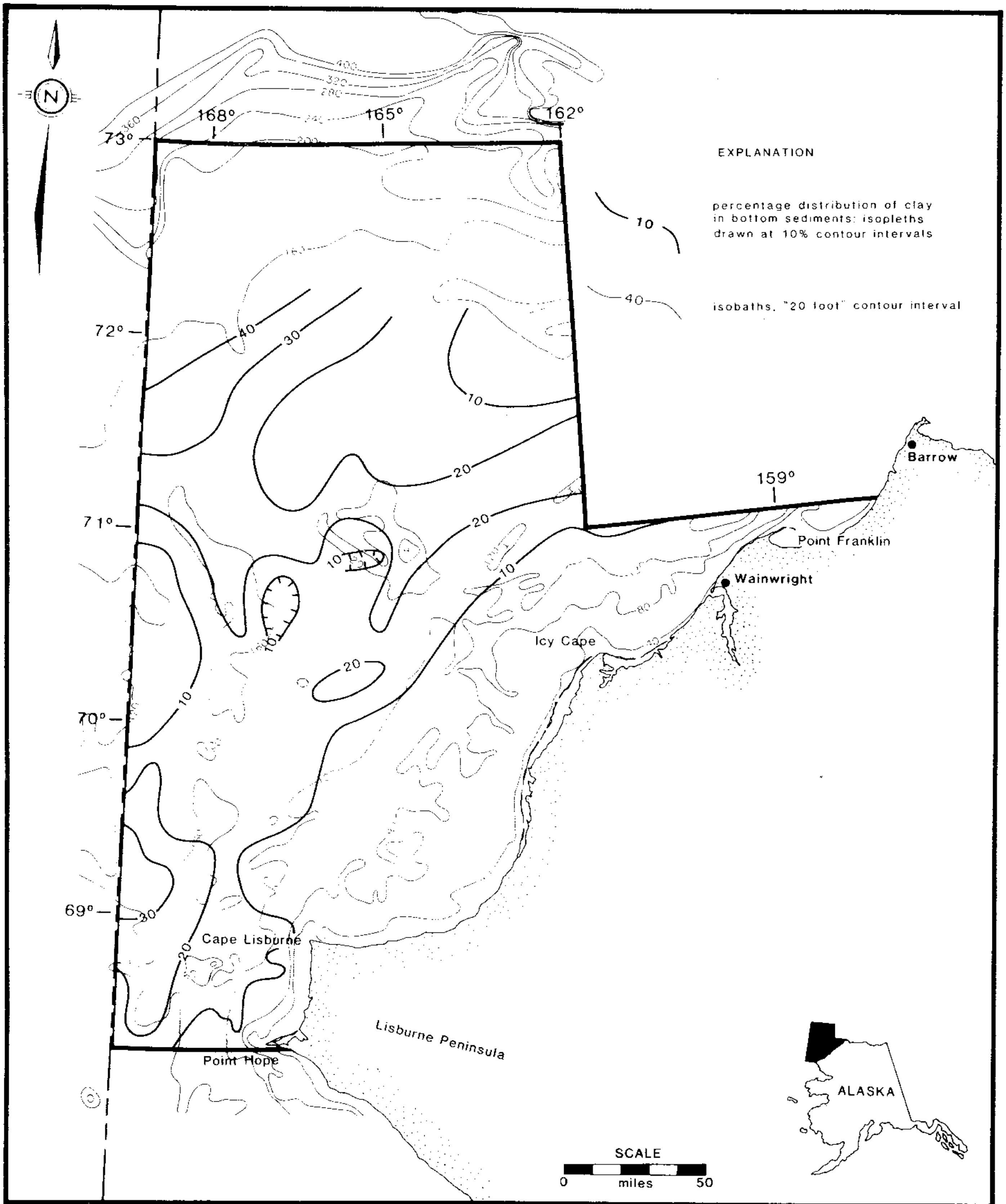


FIGURE 52. Segment of USGS Uniboom line 809, showing a filled paleochannel with acoustic absorption possibly related to free gas. See figure 70 for location of profile.



after Coachman and others (1976).

FIGURE 53. Bottom currents on the Chukchi shelf.



after McManus and others (1969).

FIGURE 54. Clay fraction (in percent) of surficial sediments in the Chukchi Sea Planning Area.

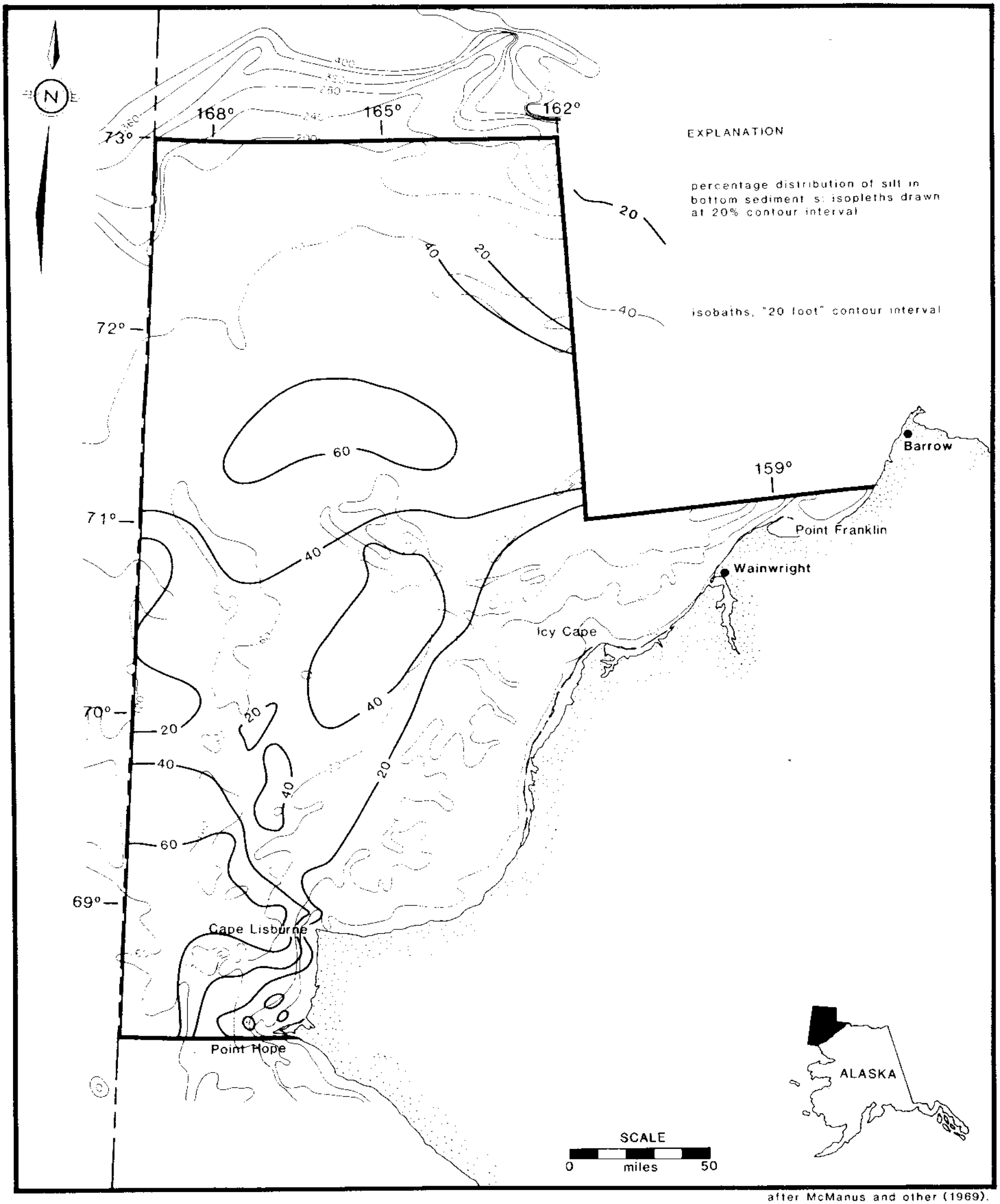
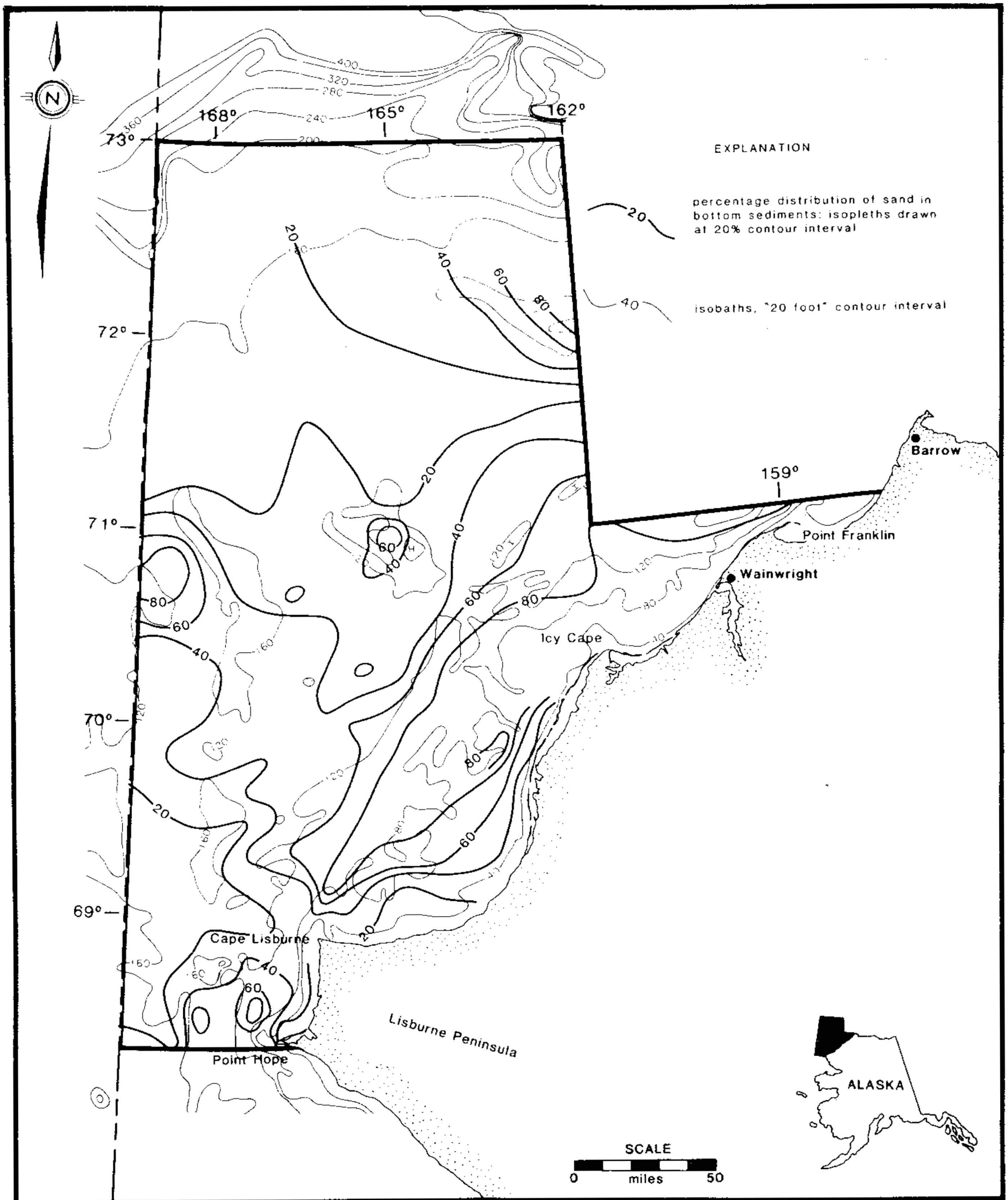


FIGURE 55. Silt fraction (in percent) of surficial sediments in the Chukchi Sea Planning Area.



after McManus and others (1969).

FIGURE 56. Sand fraction (in percent) of surficial sediments in the Chukchi Sea Planning Area.

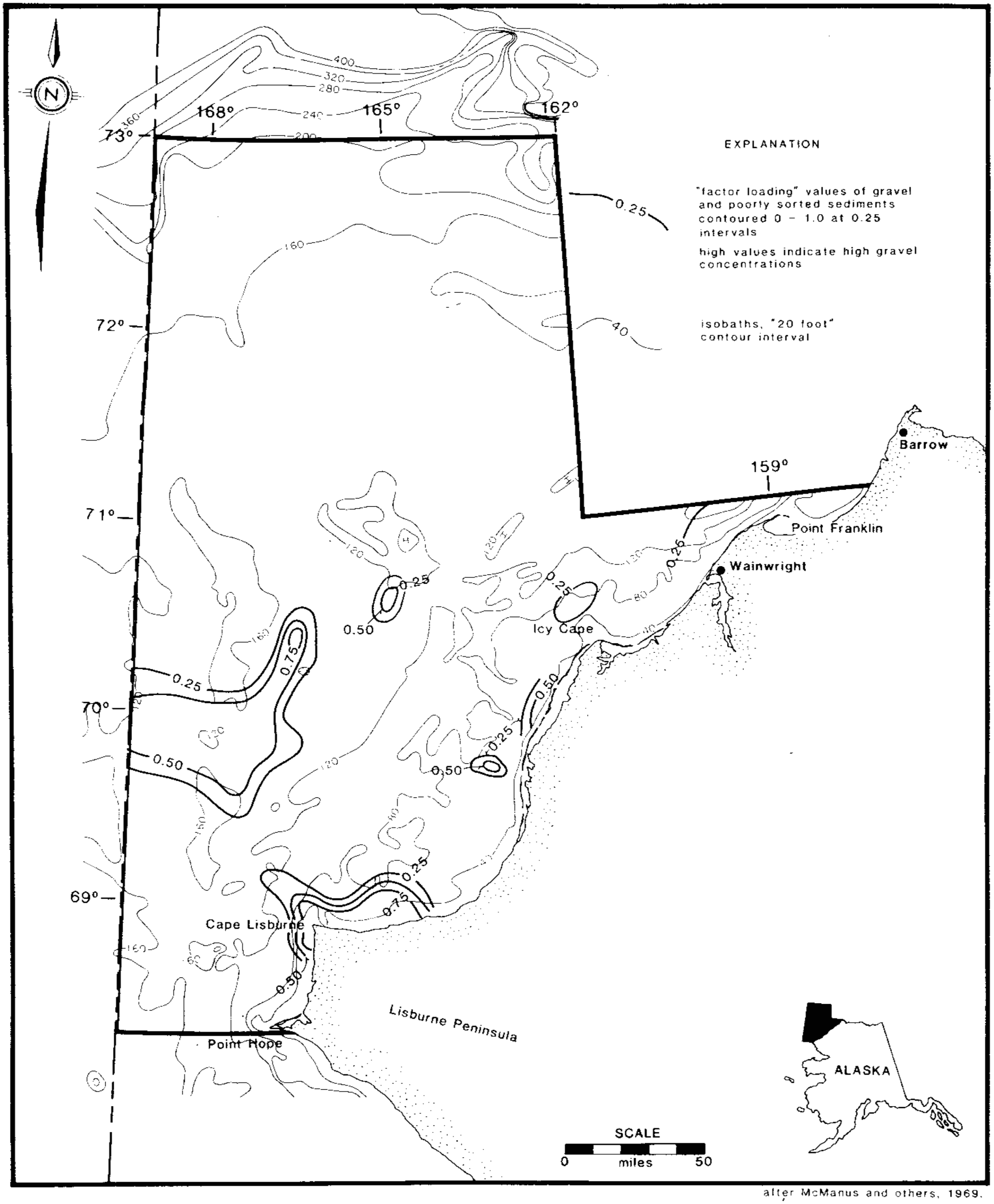


FIGURE 57. Distribution of gravel in surficial sediments of the Chukchi Sea Planning Area.

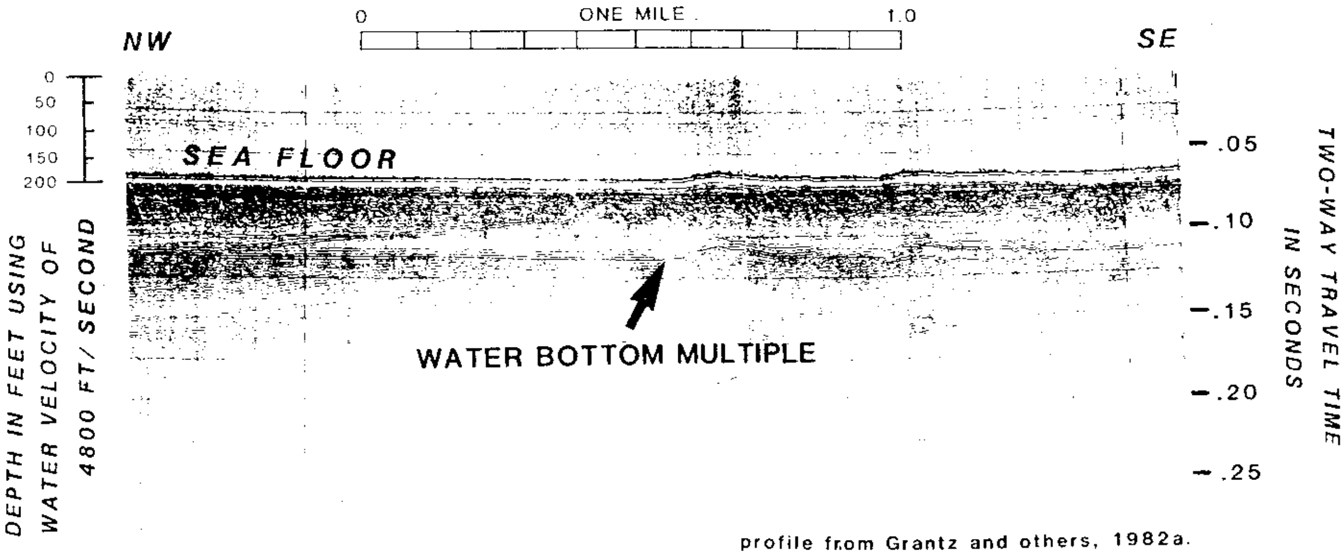


FIGURE 58. Segment of USGS Uniboom line 012, showing northwest facing asymmetric bedforms located northwest of Icy Cape. See figure 70 for location of profile.

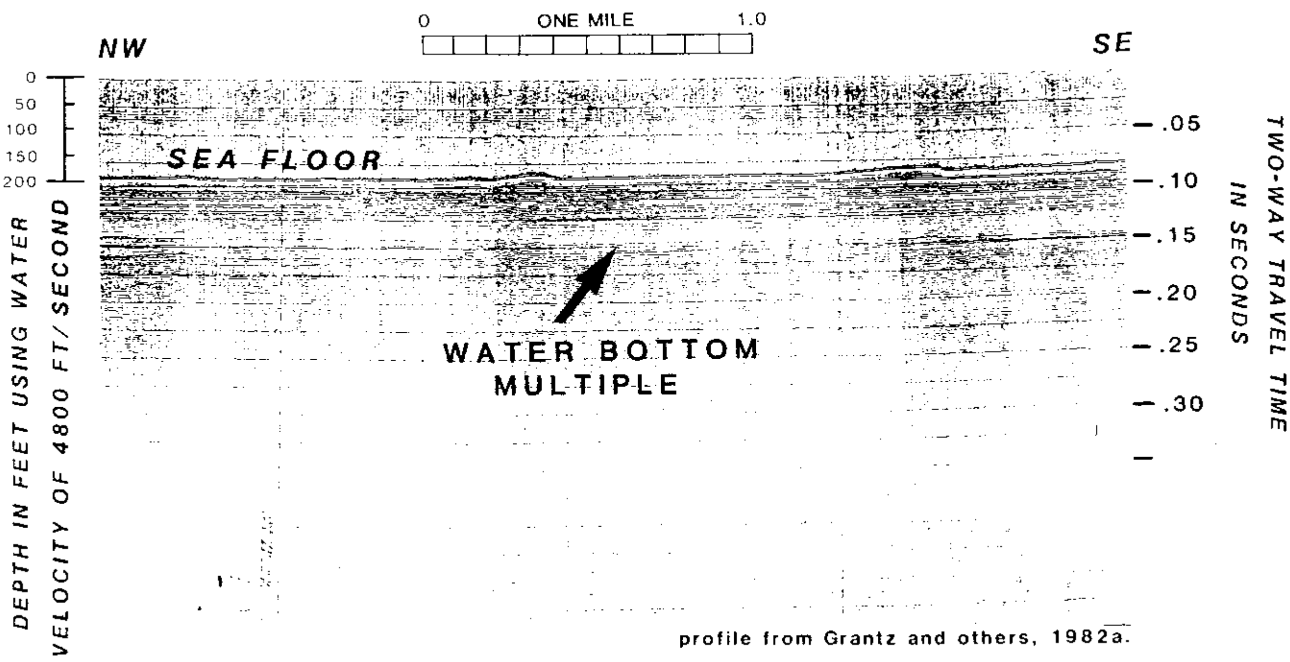


FIGURE 59. Segment of USGS Uniboom line 013, showing southeast facing asymmetric bedforms located west of Point Hope. See figure 70 for location of profile.

17. ICE GOUGING

The Arctic ice pack covers much of the Chukchi shelf for 7 to 10 months each year (fig. 60). In the planning area, grounded sea ice produces nearly ubiquitous but variable (in terms of density, morphology, and orientation) ice gouging of the seafloor (fig. 61).

Ice gouges are linear to curvilinear furrows produced by the dragging of an ice keel along the sea bottom. Gouges may be several miles long, 2 to 12 feet deep (fig. 62), and hundreds of feet wide. The morphology of individual gouges depends on factors such as the shape of the ice keel, the type and thickness of the seafloor sediment, the type of driving force on the ice, and the relative age of the feature.

Multi-keeled pressure ridges produce numerous parallel gouges. Tabular ice bodies may produce broad, flat, and shallow ice gouges. Ice gouges in a hard bottom exhibit a rough and irregular appearance on side-scan sonograph records (Toimil, 1978). Gouges in soft, unconsolidated sediments appear smooth on sonographs and are usually modified by wave and current action.

The distribution and density of ice gouging in the Chukchi Sea were evaluated by Toimil (1978) on the basis of nearly 6,000 track-line miles of side-scan sonar and fathometer data. Generally, ice gouge density increases with latitude and seafloor slope angle, but decreases with increasing water depth. Toimil also observed that certain ice gouge characteristics were generally restricted to specific water depth intervals (fig. 63). Gouges in water depths below 115 feet tend to be wider, deeper, larger, more linear, and have a lower density than those in shallower water (fig. 62). Ice gouging is most pervasive along the eastern flank of the Barrow Sea Valley and northeast flank of Hanna Shoal (fig. 61). Toimil and Grantz (1976) investigated a bergfield at Hanna Shoal and determined that ice gouging has modified the texture of the sedimentary substrate by disturbing and resuspending the finer fraction. Winnowing leaves the coarser fraction as a lag deposit. Similar lag deposits have been reported on the Herald Shoal by McManus and others (1969).

The relative age of ice gouging is determined from the superposition of gouges and recent sedimentary structures. Toimil (1978) identified "fresh-looking" ice gouges (current ripples

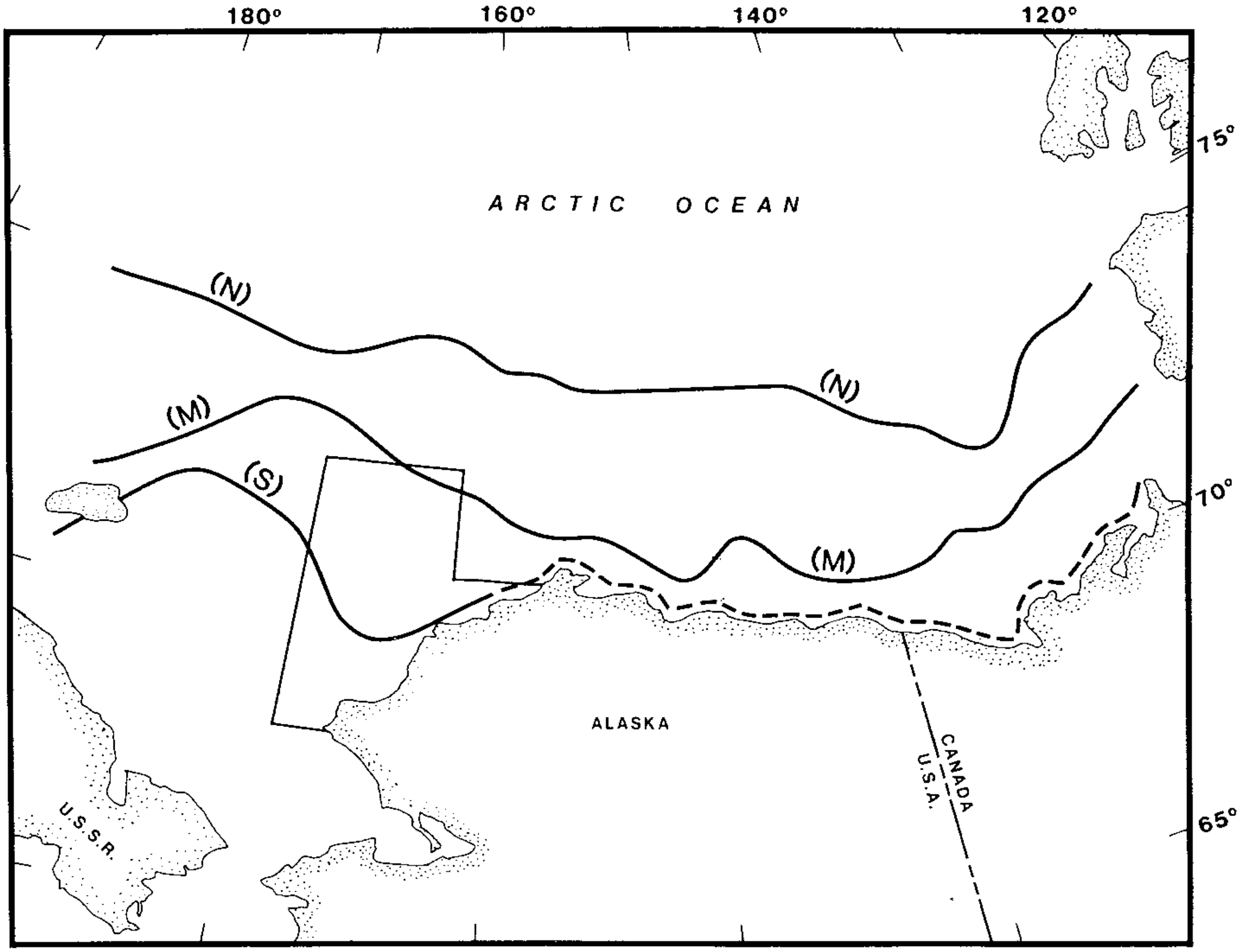
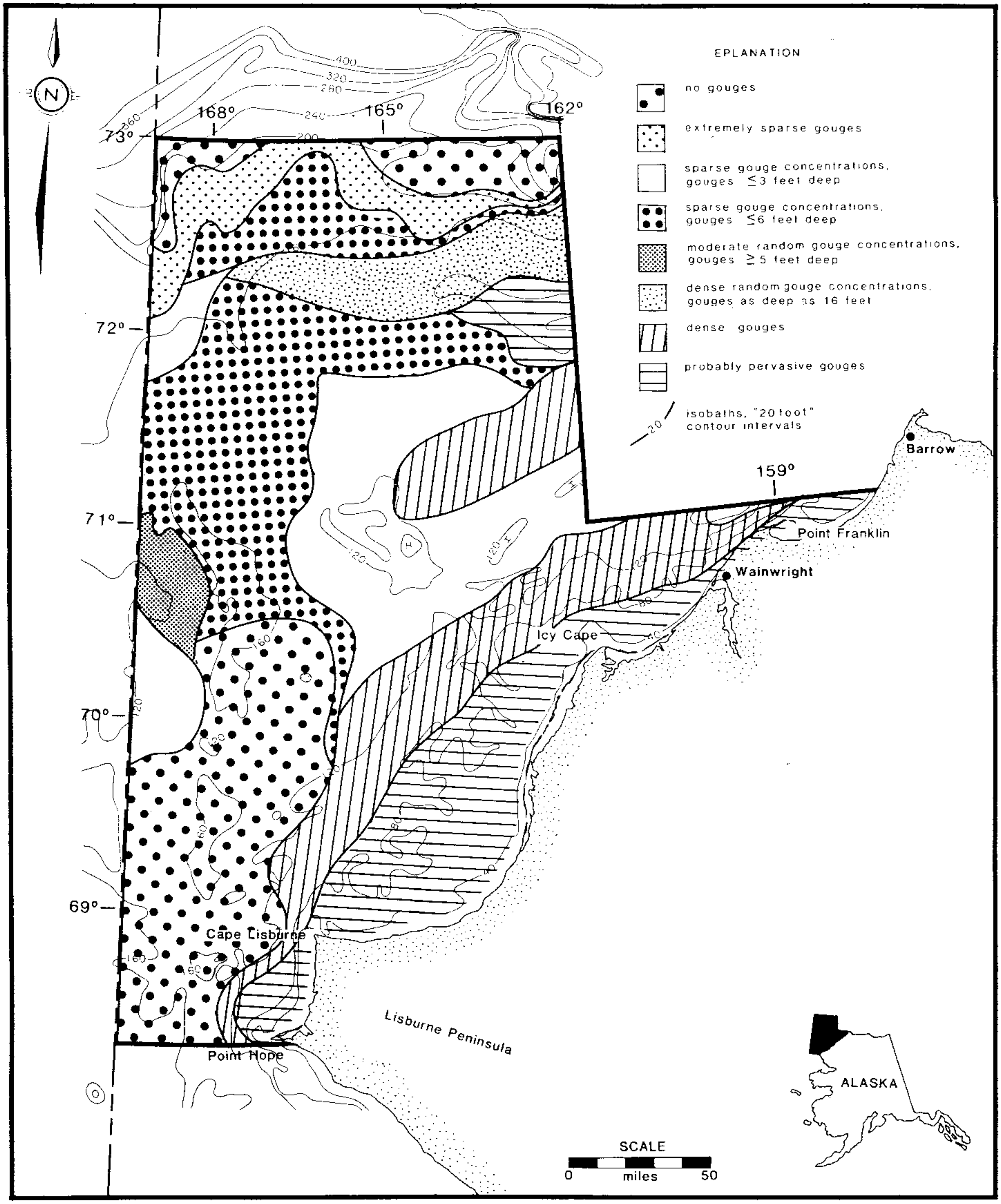


FIGURE 60. Most northerly (N), most southerly (S), and median (M) positions of the southern edge of the Arctic ice pack, September 16 to 30. Diagram after Grantz and others (1982b) as adapted from Brower and others (1977). The positions are based on data from 1954 through 1970.



after Grantz and others, 1982b, fig. 17.

FIGURE 61. Distribution of ice gouge densities in the Chukchi Sea Planning Area.

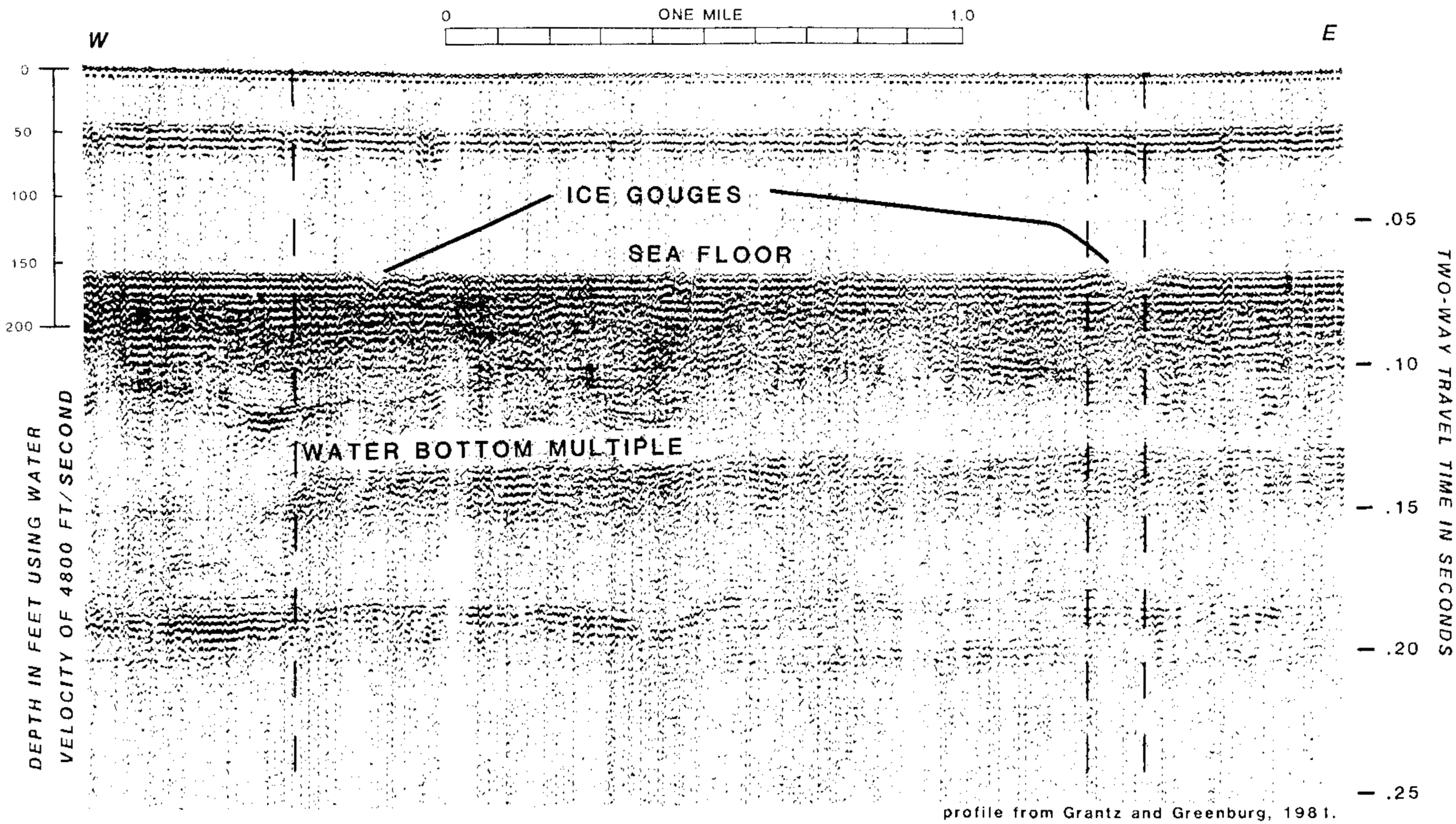


FIGURE 62. Segment of USGS Uniboom line 809, showing character of ice gouges in area of sparse gouges. See figure 70 for location of profile.

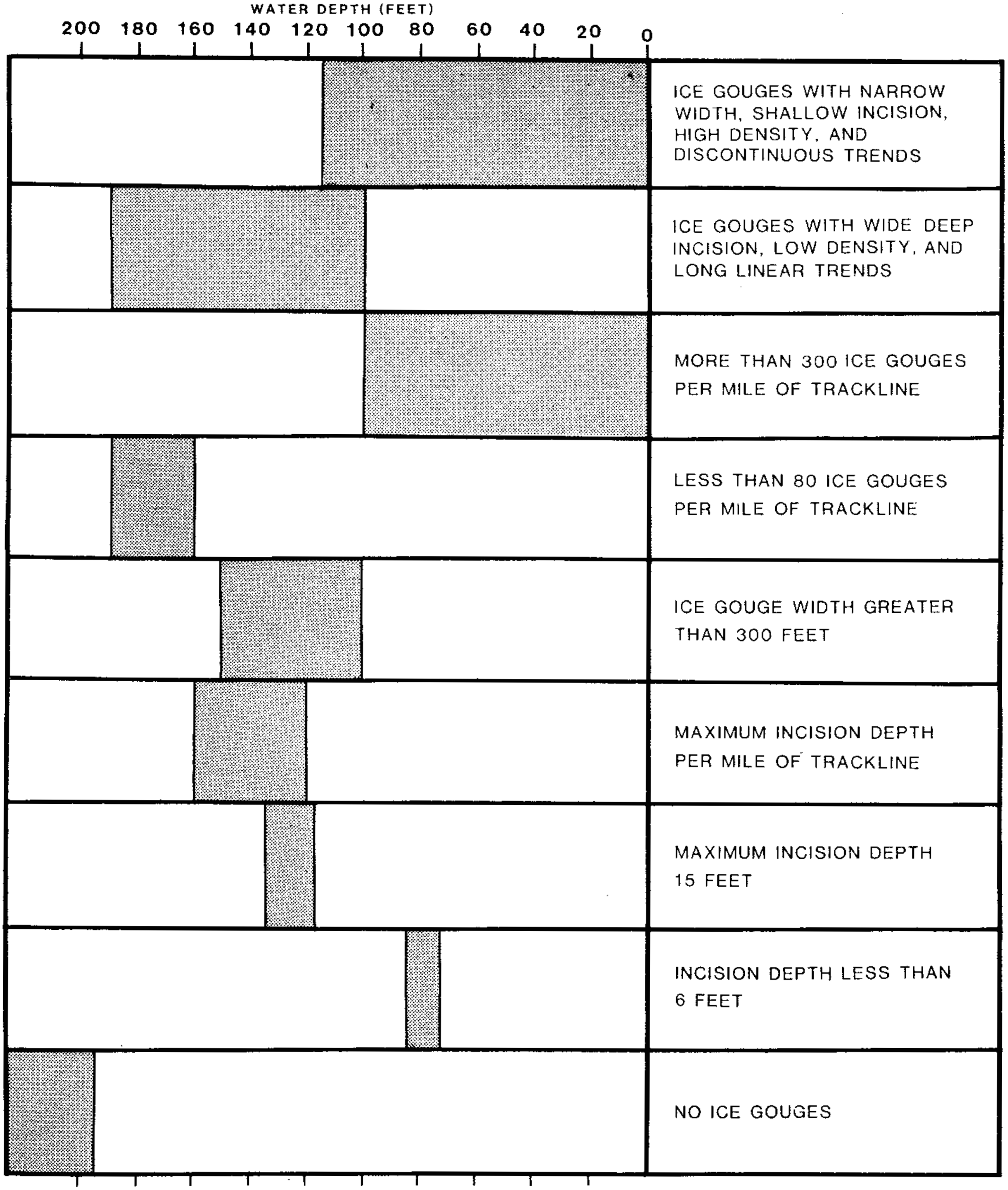


FIGURE 63. Associations of ice gouge characteristics with water depths (summarized from Toimil, 1978)

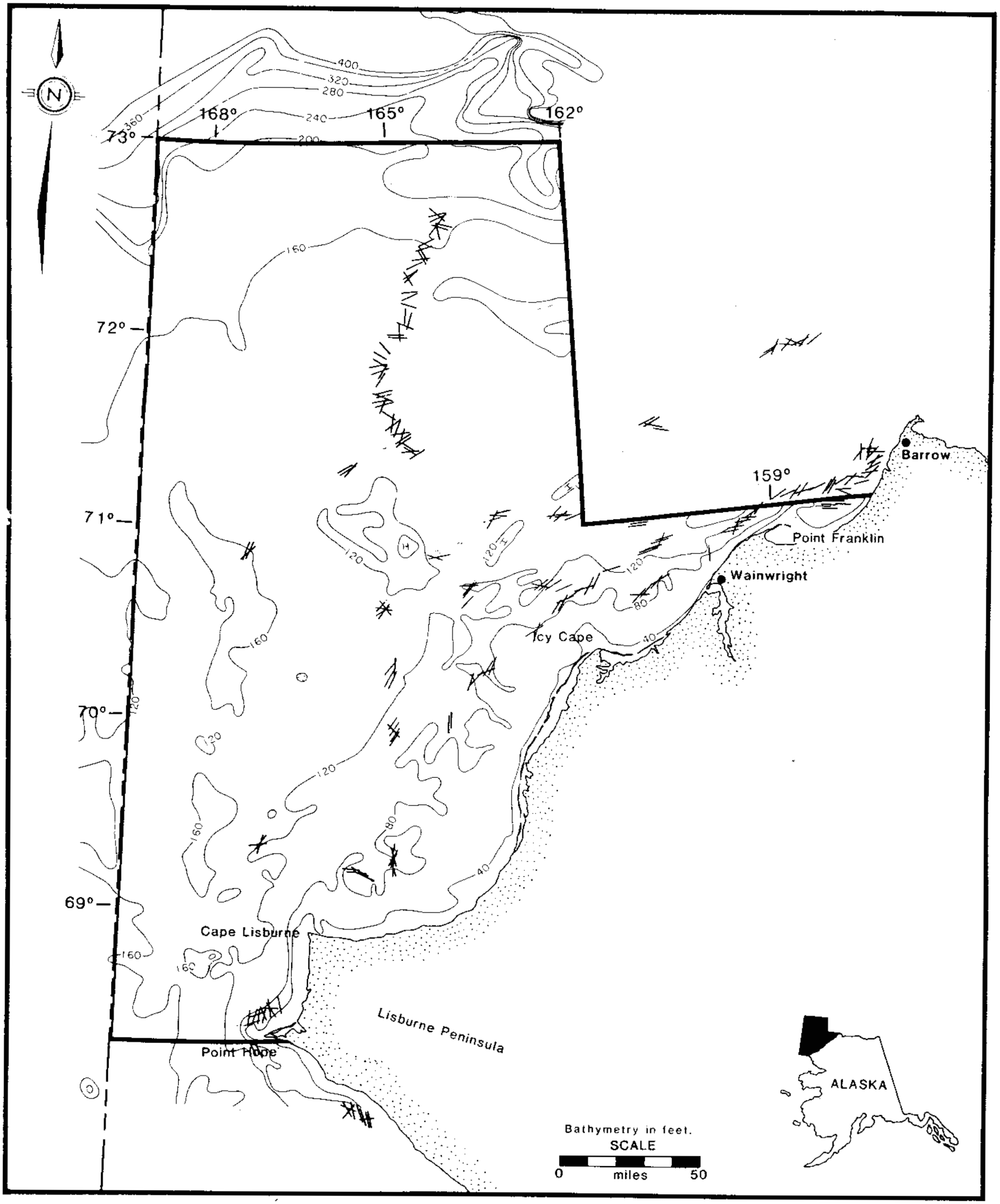


FIGURE 64. Areal variation in dominant azimuths of ice gouges on the seabed of the Chukchi shelf (from Grantz and others, 1982b, fig. 18).

adjacent to but not within the gouges) in 141 feet of water and considered these to be the deepest water modern gouges in the Chukchi Sea. However, in the northern part of the planning area, ice gouges that appear to be recent (based on the sharpness and depth of furrows) are found in 160 feet of water (fig. 62).

Ice gouge trends show no preferred regional orientations (fig. 64). This may be because of the variable wind patterns and complex current circulation on the shelf. Locally, gouging is roughly parallel to bathymetric contours, especially in areas of steep slope gradient and on the northwest side of shoals on the inner shelf. Gouge trends become more scattered with distance from the coast.

18. SHALLOW GAS

Areas of acoustic anomalies typical of interstitial or free gas at shallow depths (less than 1,000 feet) have been mapped from high-resolution seismic reflection data by Grantz and others (1982b) and by the present authors (fig. 65). In the northern part of the planning area and east-central shelf, acoustic "turbidity" or "wipe-out" zones are found in paleochannels of Pleistocene age. These anomalies might be due to the presence of unconfined shallow gas of biogenic origin (fig. 52). No acoustic anomalies identified on high-resolution profiles were recognizable on CDP seismic reflection profiles through the same location.

In the Northern Hope and North Chukchi basins, acoustic anomalies have been identified on seismic reflection profiles within possible Tertiary strata. The anomalies are typically characterized by acoustic "wipe-outs," or zones of attenuated seismic signal, which commonly exhibit "pull-down" of reflections at their margins (figs. 66 and 67). These anomalies may represent the presence of either biogenic or thermogenic gas. Depending on their burial depth, trapping mechanism, and the presence or absence of an effective seal, some accumulations could be overpressured.

Acoustic anomalies mapped in shallow Cretaceous strata are not as well defined on seismic reflection profiles as those found in younger strata. In the belt of Cretaceous bedrock that lies between the Tertiary pinch-out lines of the North Chukchi and Northern Hope basins (fig. 65), the acoustic anomalies are often manifested as amplitude-enhanced reflections (bright-spots) (fig. 65). These features are possibly caused by the entrapment of gas in a porous unit below a shallow sealing layer. The gas reduces the velocity of the porous layer and enhances the acoustic impedance at the interface between the gas-bearing and sealing layers. Some anomalies in this area exhibit acoustic "turbidity" or "wipe-out" similar to features seen on profiles through younger strata in areas to the north and south (fig. 68).

Anomalies identified within Cretaceous rocks in the subcrop belt, although they are generally poorly defined on reflection profiles and appear to be less abundant than in younger strata, are probably more likely to represent shallow thermogenic gas. Support for this speculation is provided by the presence of large accumulations of thermogenic gas in correlative Cretaceous rocks

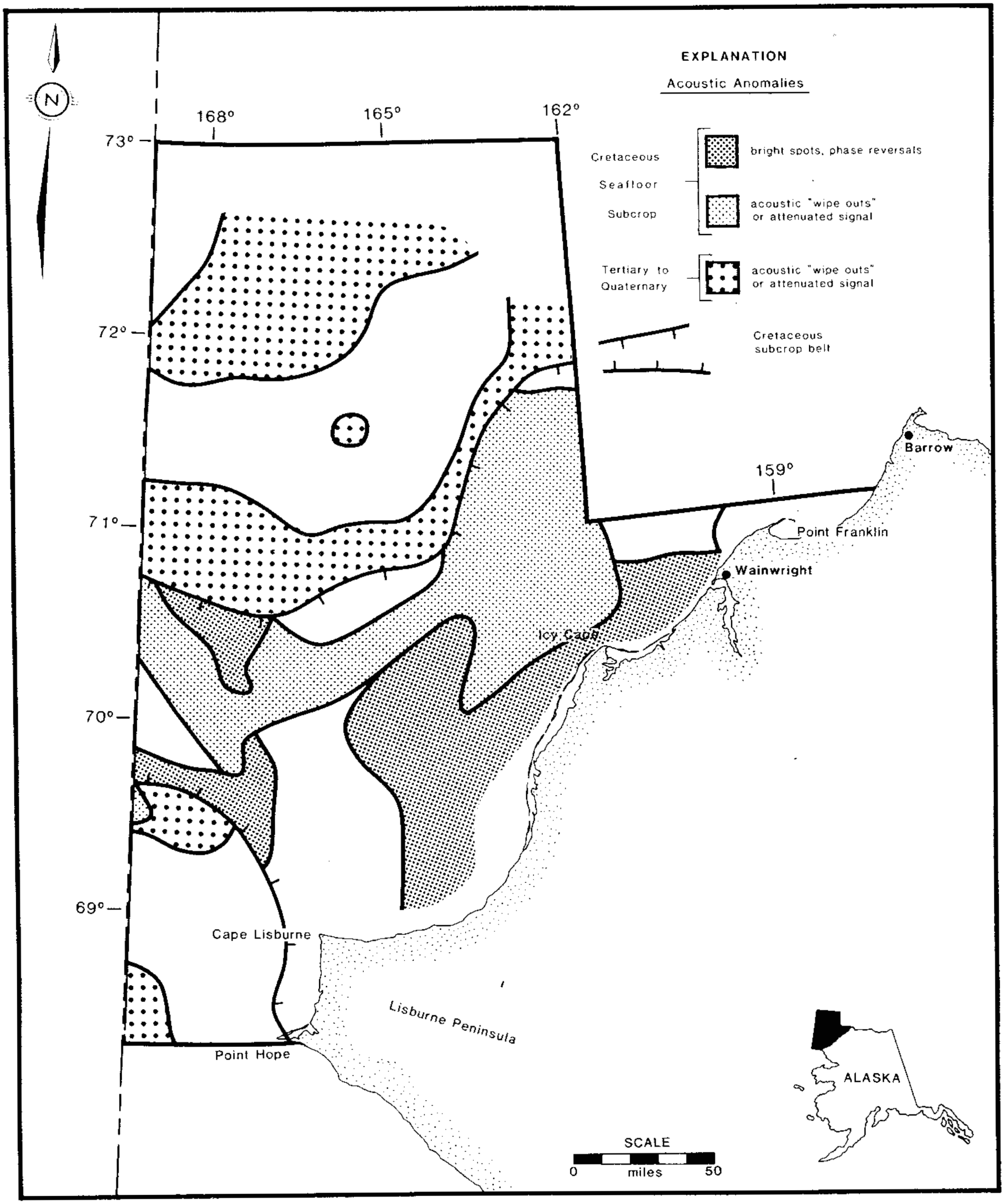


FIGURE 65. Distribution of near—surface acoustic anomalies possibly related to shallow gas.

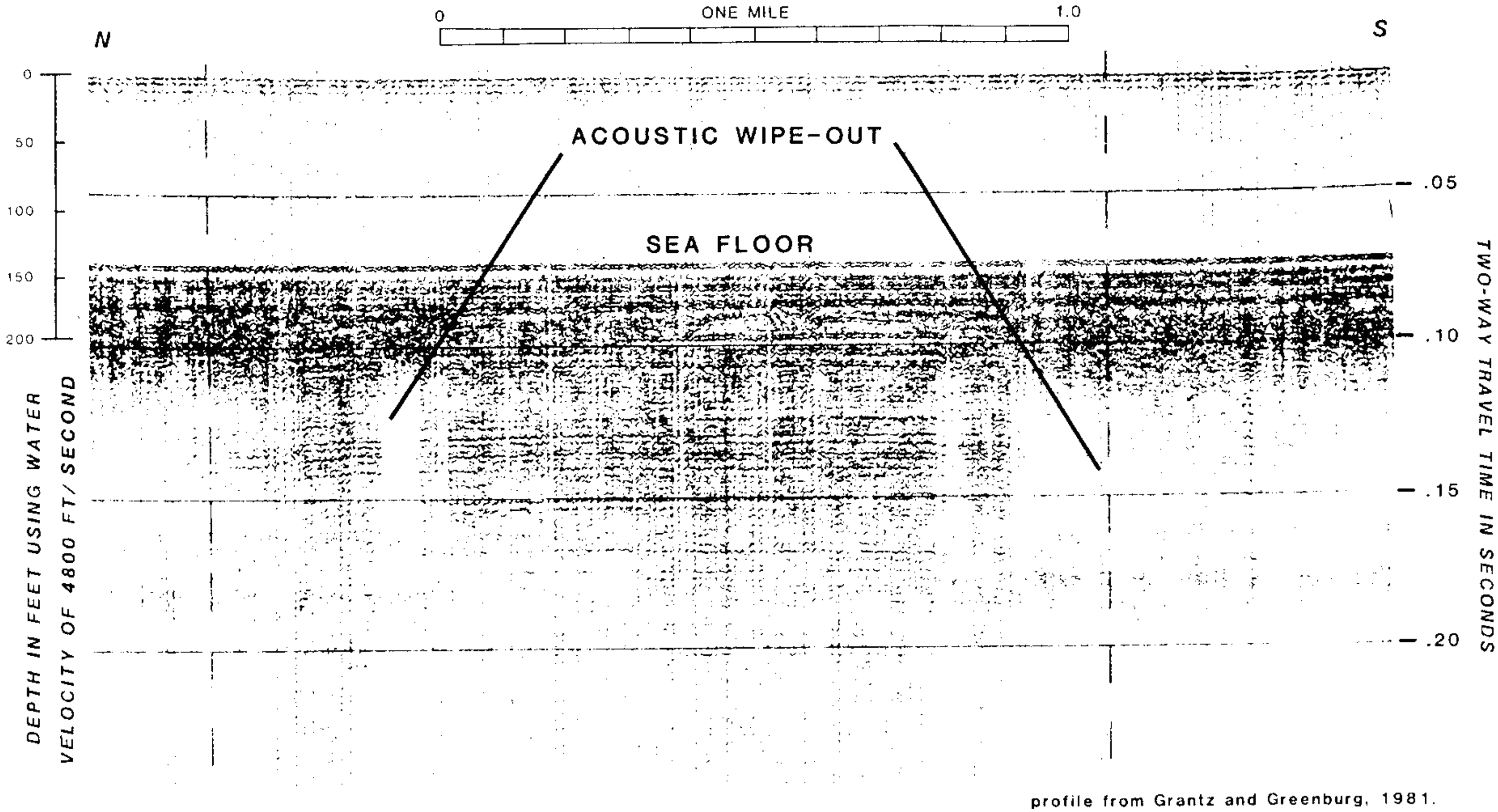


FIGURE 66. Segment of USGS Uniboom line 826, showing wipe—out or acoustic absorption due to shallow free gas in Northern Hope basin. See figure 70 for location of profile.

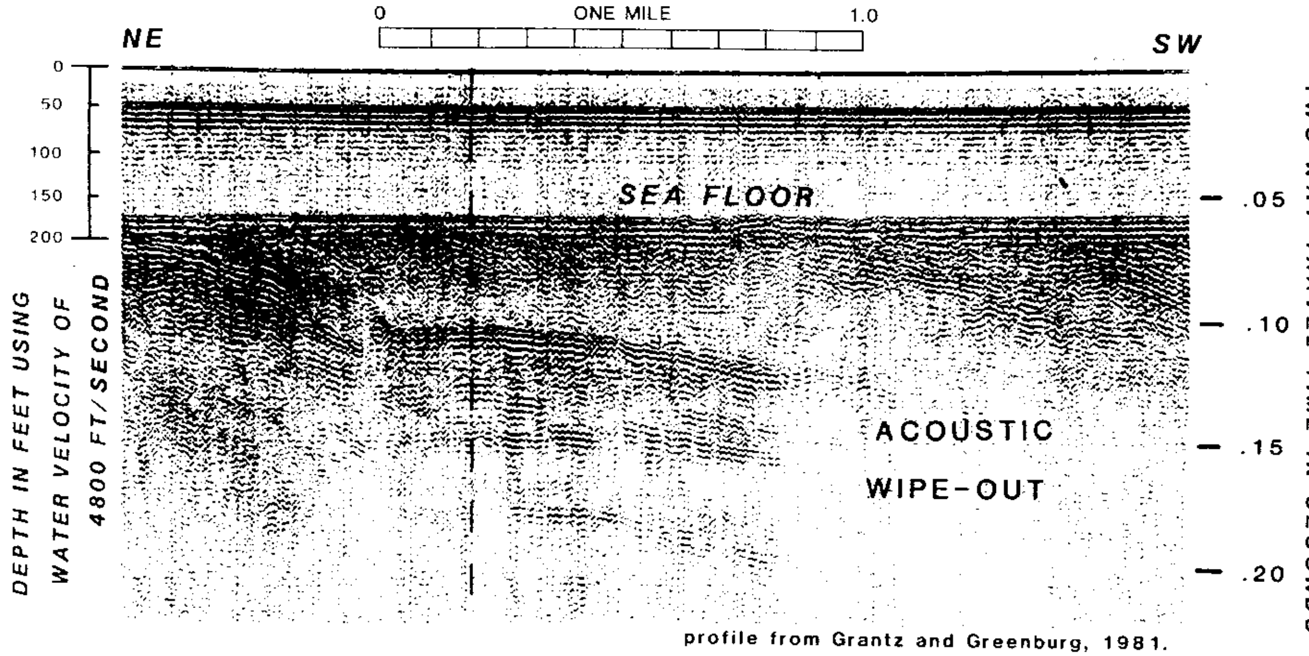


FIGURE 67. Segment of USGS Uniboom line 806, showing acoustic wipeout possibly related to presence of shallow, free gas. See figure 70 for location of profile.

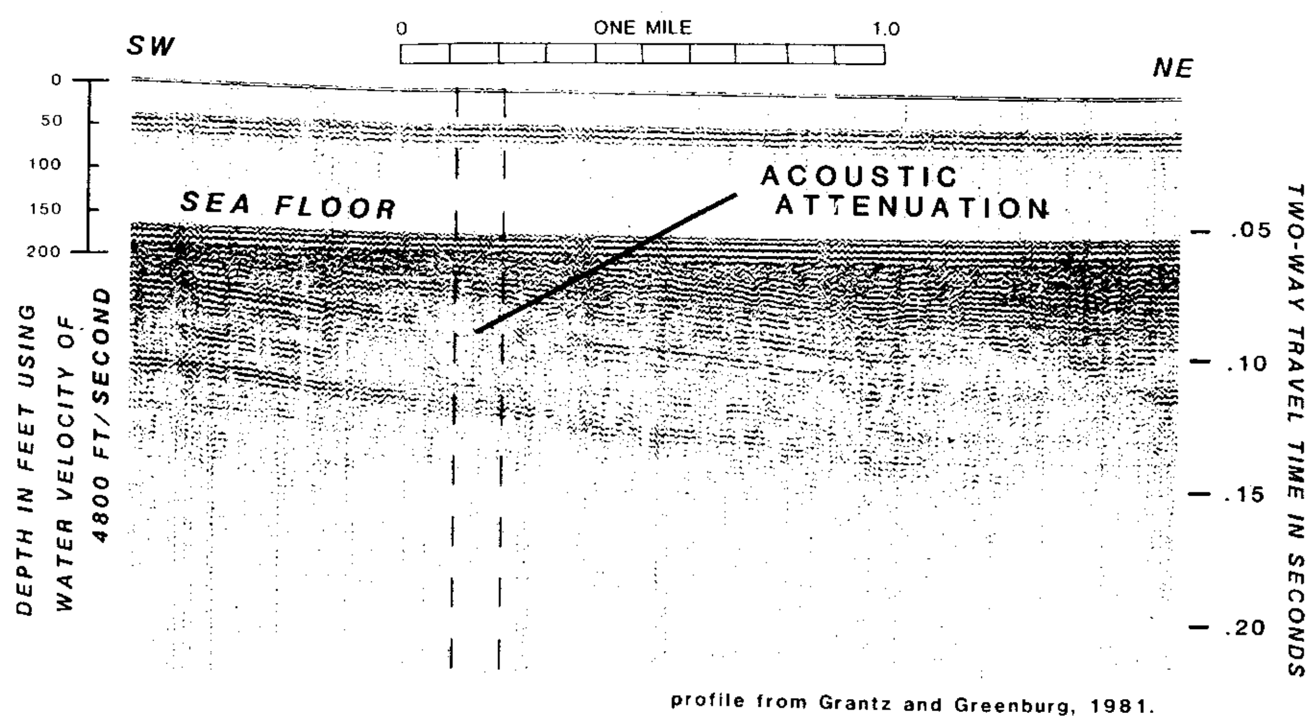


FIGURE 68. Segment of USGS Uniboom line 806, showing acoustic attenuation possibly related to presence of shallow free gas. See figure 70 for location of profile.

onshore in NPRA. Offshore, this gas may be trapped near the seafloor in dipping strata sealed by Quaternary sediments, in the apexes of anticlines, or adjacent to faults.

19. SEISMICITY AND RECENT FAULTING

The Chukchi Sea Planning Area has no historical record of seismicity (Meyers, 1976). Projected maximum intensities (modified Mercali scale) of major earthquakes that occurred in northwestern Alaska between 1786 and 1974 are displayed in figure 69. This isoseismic map shows that a 6.9 (Richter) magnitude tremor on the north coast of the Chukotsk Peninsula of Siberia could generate a maximum intensity of IV on the Modified Mercalli scale in the southwestern corner of the planning area, over 600 miles away.

Evidence for Quaternary faulting has been reported by Grantz and others (1982b) in the North Chukchi and Northern Hope basins. Offsets are no more than 10 feet. In many cases, the scarps appear to be covered by Holocene deposits, which suggests that these faults are minimally, if at all, active (Grantz and others, 1982b). However, seafloor offsets caused by fault displacement have been identified by the present authors in the southwestern part of the planning area near the Herald arch and in the central part of the planning area associated with the Hanna wrench-fault zone (fig. 49).

The USGS uniboom profile in figure 50 shows a 10-foot offset of the seafloor on one of the faults in the wrench zone. The generally flat-lying beds of the western side appear to have been uplifted relative to the folded beds of the eastern side. These faults originally formed in Tertiary time and appear to be primarily Tertiary in age, as illustrated by their simple offset of Cretaceous and older strata and their profound influence on the distribution and thickness of Tertiary sedimentation (plate 9). The offset of the present-day seafloor suggests that the wrench faults have been active into Quaternary time. However, it remains possible that the seafloor offset shown in figure 50 could be caused by Quaternary differential erosion of strata juxtaposed across the fault zone, and the apparent seafloor offset might actually be a fault-line scarp formed along an inactive fault.

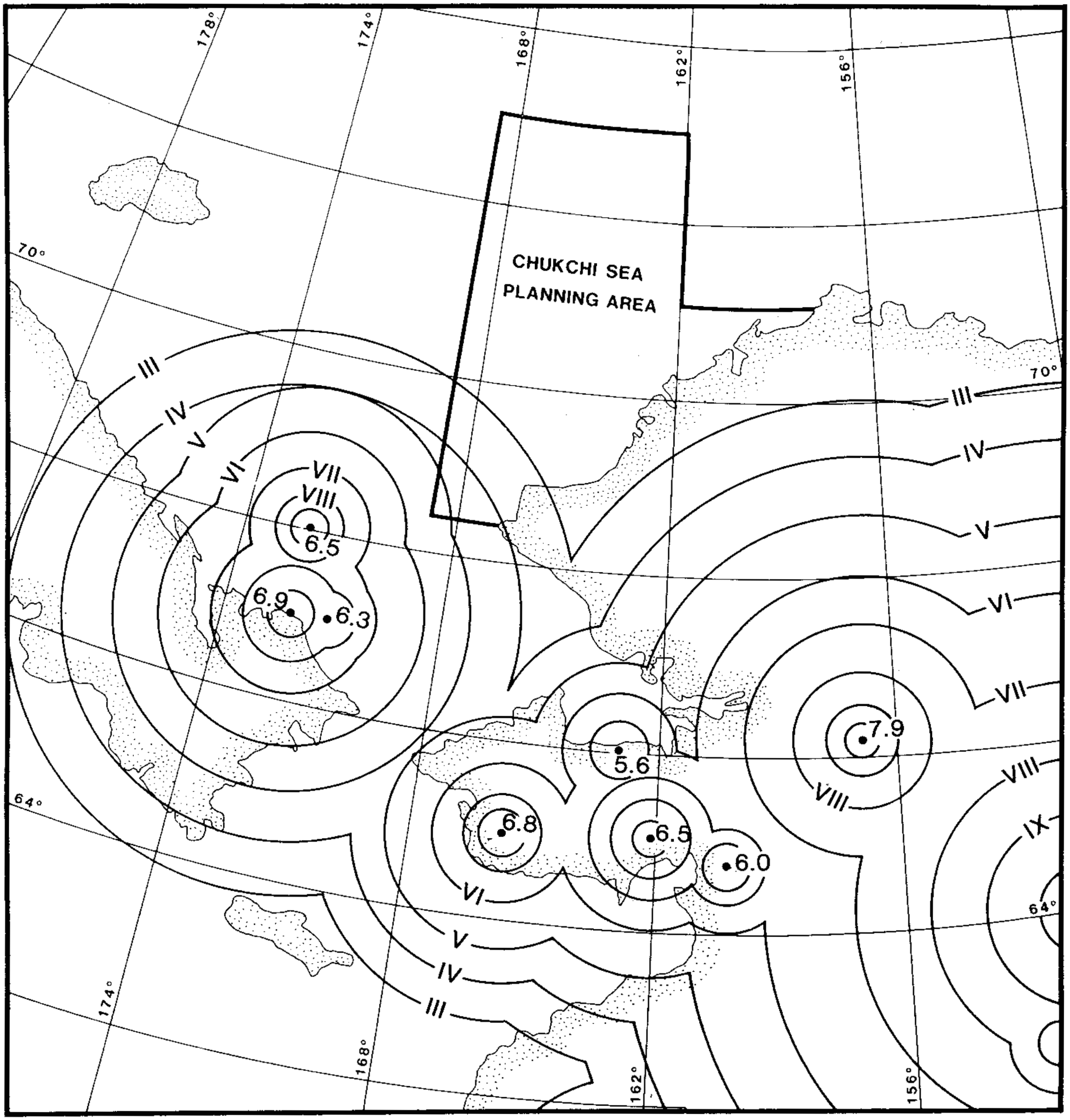


FIGURE 69. Projected maximum intensities (modified Mercalli scale) for major earthquakes in northern Alaska during the period 1786 to 1974 (from Grantz and others, 1982b, fig. 21, as adapted after Meyers, 1976).

20. SUBSEA PERMAFROST

The distribution and occurrence of permafrost along the coast of the Chukchi Sea is poorly documented. The presence of extensive subsea permafrost on the Beaufort shelf (Craig and others, 1985) suggests that some subsea permafrost may be present along the northwest coast of Alaska. However, no anomalous near-surface seismic velocities that would indicate the presence of ice-bonded sediments have been reported. The near-surface consolidated rock present throughout much of the Chukchi shelf may have inhibited the development of permafrost during lowered sea level (Grantz and others, 1982b). Another explanation for the apparent lack of relict permafrost offshore is that it was melted by the relatively warm currents moving north from the Bering Sea.

21. SUMMARY OF POTENTIAL GEOLOGIC HAZARDS

Hazards to exploration and development activities in the Chukchi Sea Planning Area are posed by virtually every element of the natural conditions. Extreme cold, high winds, winter darkness, and remoteness combine to make the Chukchi Sea Planning Area a hazardous and challenging environment for petroleum-related industrial activity. In order of relative severity, the key considerations are summarized as follows:

1. Pack ice: Although strictly an environmental phenomena, the most formidable engineering constraint and potential hazard in the planning area is that presented by moving masses of sea ice. Platforms must be built to withstand the crushing forces of pack ice, or designed to divert moving ice away from the structure. Summer seasonal drilling from anchored vessels is an alternative approach to the sea ice problem that is particularly applicable to exploration programs.

2. Ice Gouging: In the Chukchi Sea Planning Area, where ice covers the sea for 7 to 10 months a year (fig. 60), ice-seabed interactions pose the most dynamic geologic hazard to any permanent seafloor installations related to hydrocarbon development activities on the continental shelf. Deep draft keels of free-floating ice bergs and ice islands produce gouges in the seafloor and will require that pipelines be buried below the local maximum incision depth. Burial of pipelines will be difficult in areas with thin or no unconsolidated sediment cover.

3. Shallow Gas: The existence of gas at shallow depths can reduce the sediment shear-strength by increasing pore pressure and reducing frictional contact between framework grains. This situation may pose engineering problems for the placement and stability of bottom-founded structures. The presence of overpressured gas at shallow "open-hole" (before conductor) depths (generally 0 to 1,000 feet) in a well could precipitate gas flow to the surface and associated hazards to surface facilities.

4. Migrating Bedforms: Current-induced shifting of surface sediment may require engineering design to prevent the undermining of bottom-founded structures. Pipelines laid on or buried in migrating bedform fields may become unsupported and fail unless special design modifications are implemented.

5. Modern Seismicity: Ground shaking during a major earthquake can seriously affect bottom-founded structures and might cause consolidation problems in artificial gravel islands used as drilling platforms. Surface faulting may disrupt buried pipelines and damage drilling structures.

CONCLUSIONS

The intent of this geologic report is to evaluate the hydrocarbon potential of the Chukchi Sea Planning Area in preparation for its first public lease offering as OCS Sale No. 109. We have based our conclusions upon our analysis of regional structure, stratigraphy, and potential geologic hazards, as determined from available geological and geophysical data. Our analysis concludes that it is probable that major petroleum accumulations exist in the Chukchi Sea Planning Area. Several factors contribute to this conclusion.

Known reservoir and source rocks within the Ellesmerian and Brookian sequences are seismically traceable offshore into the eastern part of the Chukchi Sea Planning Area. On the basis of regional considerations, the best source rocks in the planning area are probably seismic units equivalent to the Shublik Formation, the Kingak Formation, and the Pebble Shale. All of these units onshore offer favorable organic compositions, and where not overmature, probably form viable source rocks in offshore areas. Unidentified liquid-prone source rocks may also be present offshore in the lower Brookian sequence, or in the upper Brookian sequence in the North Chukchi basin.

Upper Brookian sandstones, if present at all, are postulated to have been derived, in part, from the reworking of Nanushuk Group-equivalent clastics. These sediments should be compositionally and texturally more mature than the Nanushuk Group sandstones, and may offer more favorable reservoir characteristics. Well data from western NPRA indicate a lack of attractive reservoir formations in the Ellesmerian sequence. However, seismic sequences equivalent to the Ellesmerian sequence can be seismically traced into a proximal setting near seismically identifiable lapout edges on the eastern margin of the Chukchi platform. In this setting, the Ellesmerian strata may contain potential reservoir formations, as found in source-proximal settings along the Beaufort coast of Alaska.

The complex tectonic history and stratigraphy of the Chukchi Sea Planning Area has resulted in the formation of a variety of potential hydrocarbon traps. The most prospective areas for the generation and entrapment of hydrocarbons are probably the margins of the Central Chukchi basin, especially the western margin, along the Chukchi platform. This is because the Chukchi platform is considered to have been a persistent tectonic high which did not share the history of deep burial and overmaturation observed in equivalent rocks in the nearest onshore well control. The types of potential hydrocarbon traps identified here include subunconformity truncation traps, graben fault traps, diapirs, and wrench structures related to the Hanna wrench-fault zone. More subtle stratigraphic traps related to abrupt facies changes may also be present.

The North Chukchi basin contains many fault traps related to basin subsidence along the bounding flexure zone. Anticlinal structures have been identified locally in the lower Brookian sequence in what appears to be fold belt in the northern parts of the basin.

The North Chukchi high is not considered highly prospective because the fault and fold traps appear to have been formed after lower Brookian sedimentation and thus after deep burial and maturation of known source rocks in the Ellesmerian sequence and the lower part of the Brookian sequence.

Prospective traps are common in the Northcentral subbasin, where numerous wrench structures disrupt upper Brookian strata. The lower Brookian sequence appears to have been buried sufficiently deep to be thermally mature. However, most of the Ellesmerian rocks lie below projected oil window depths and are most likely overmature.

One of the least prospective areas is considered to be the Fold and Thrust belt, where the Ellesmerian rocks are most likely overmature and well data indicate poor reservoir formations in the lower Brookian sequence. The Northern Hope basin is also considered to be relatively unprospective because most potential traps are associated with thin sequences of young (upper Tertiary(?)) strata which are probably thermally immature.

Potential geologic hazards in the Chukchi Sea Planning Area include migrating bedforms, shallow gas accumulations, ice gouging of the seafloor, and Quaternary faulting. There appears, however, to be a low probability for a large-scale seismic event and there is no evidence for subsea permafrost. The most formidable obstacle to exploration and development is that posed by the extensive ice pack which covers much of the planning area for most of the year.

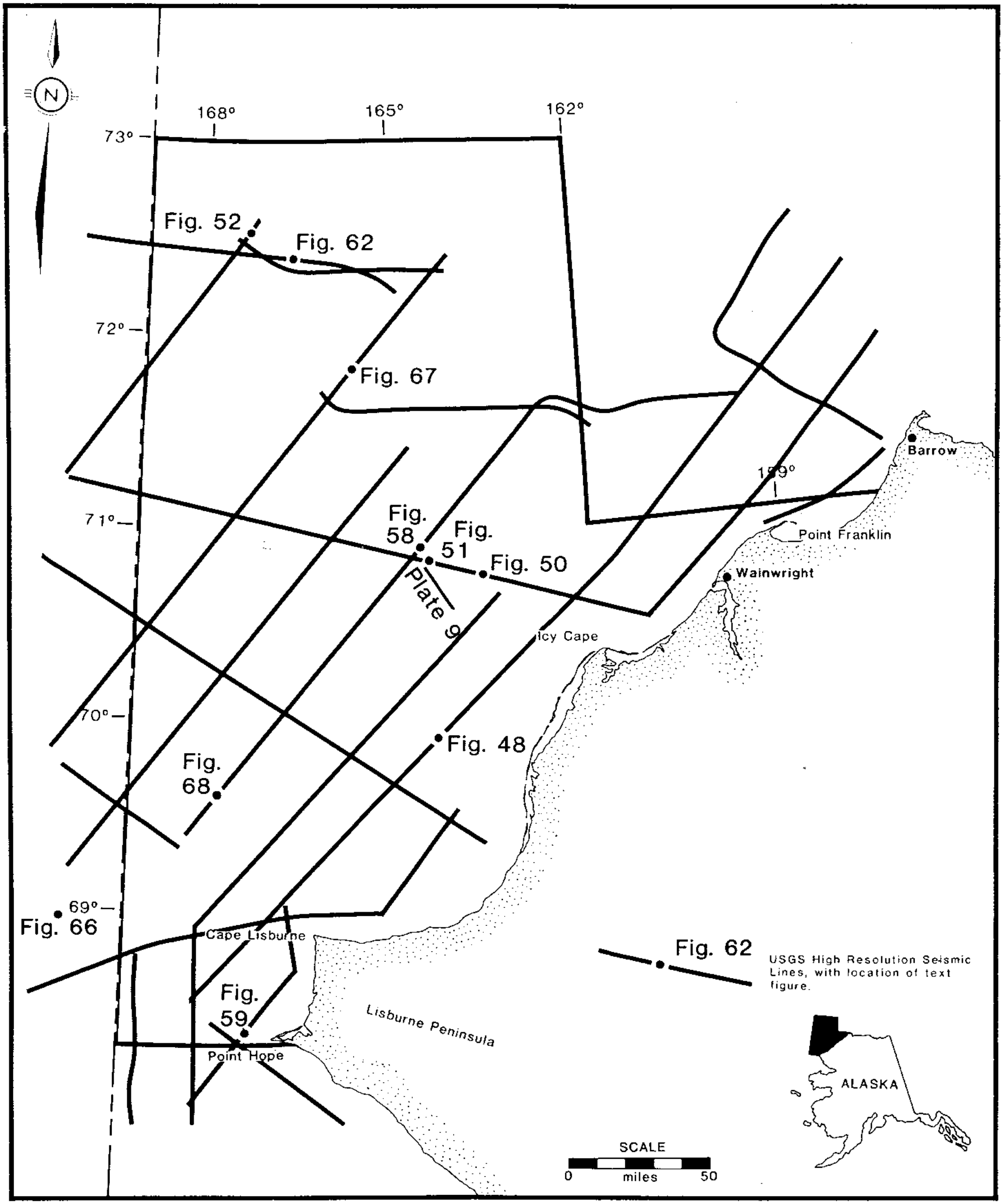


FIGURE 70. Index map showing segments of U.S.G.S. uniboom profiles illustrated in figures.

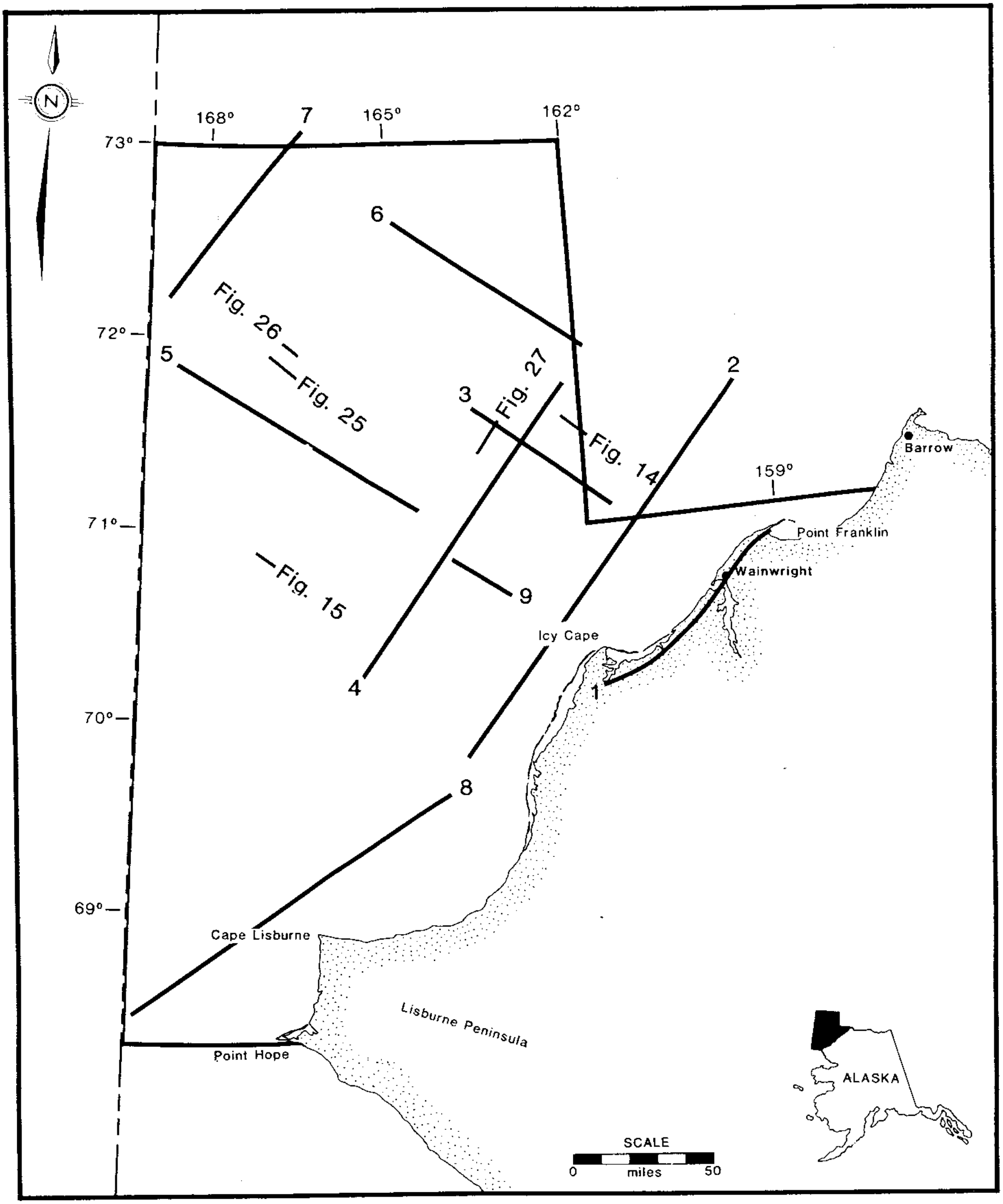


FIGURE 71. Index map showing locations of CDP seismic profiles shown in plates (1 to 9) and figures.

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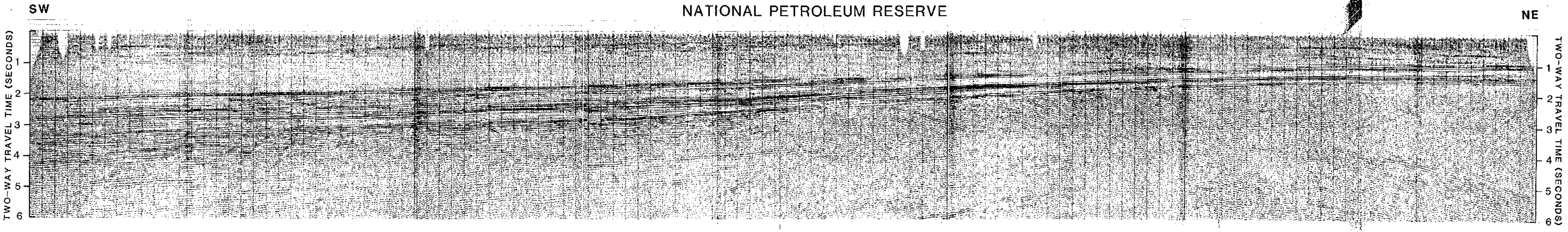


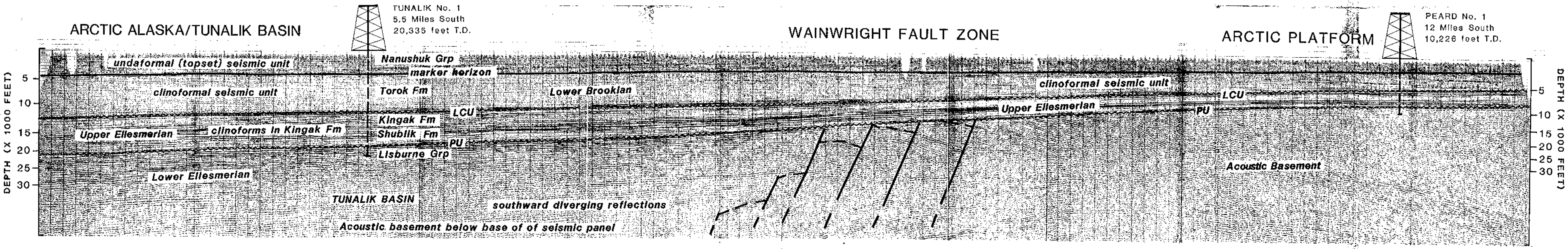
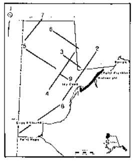


PLATE 1. Representative unmigrated seismic profile illustrating the geology of the Arctic Alaska or Tunalik basin, the Wainwright fault zone, and the Arctic Platform in the western part of the National Petroleum Reserve in Alaska. See figure 71 for location of profile. Data courtesy of Husky - Geophysical Service Inc. Line 125-76.

10 Miles



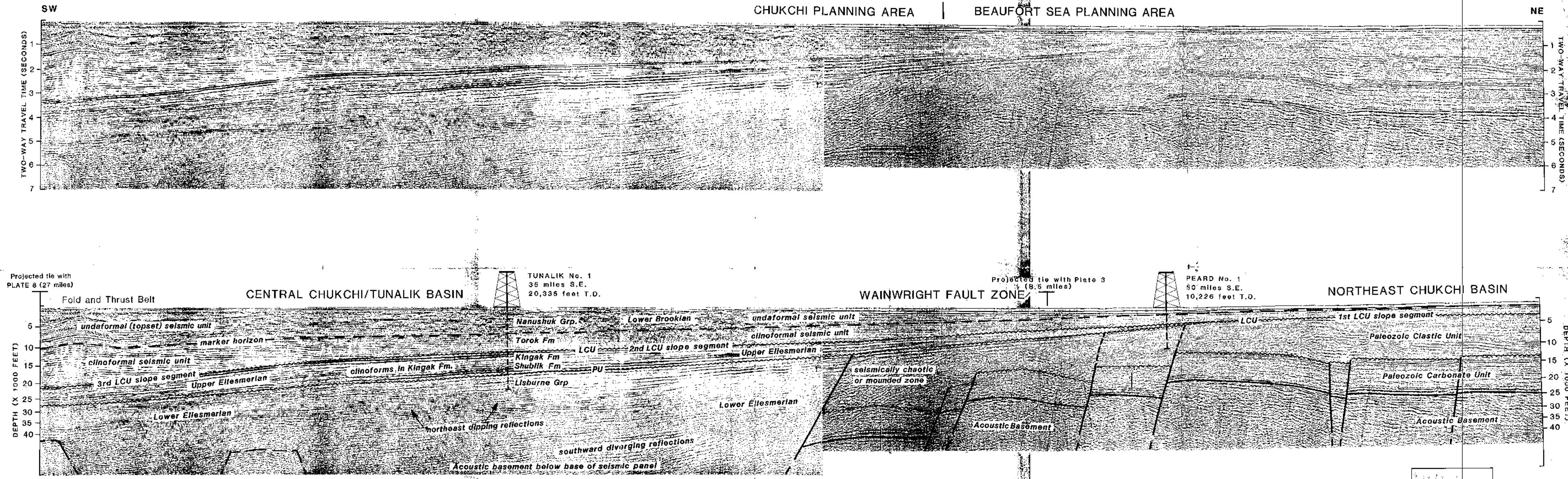
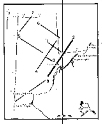


PLATE 2. Representative unmigrated seismic profile illustrating the geology of the Fold and Thrust belt, the Central Chukchi basin, the Wainwright fault zone, and the Northeast Chukchi basin. Seismic data courtesy of Western Geophysical Company.

10 Miles



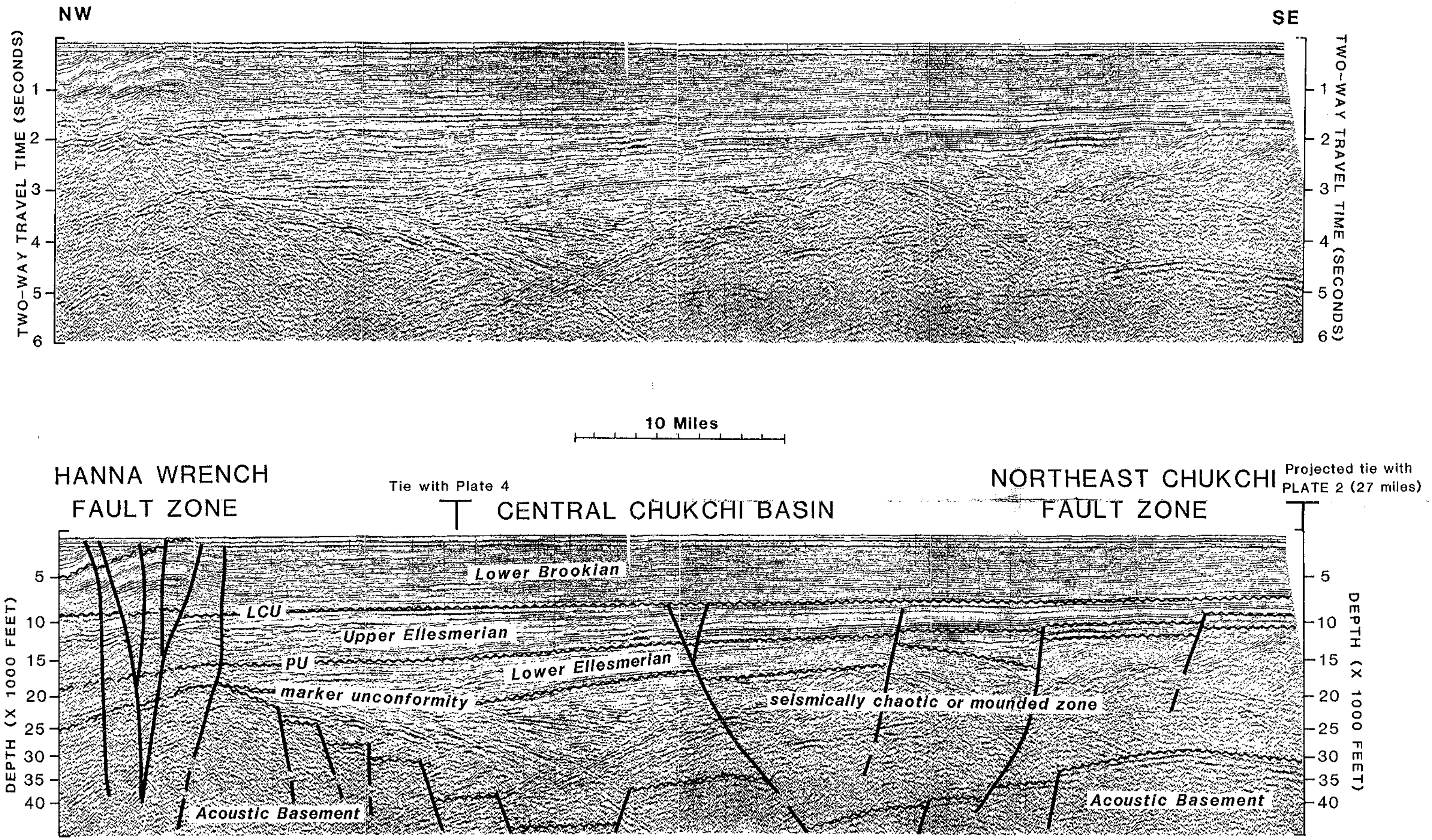
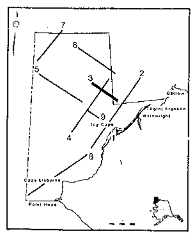


PLATE 3. Representative unmigrated seismic profile illustrating the geology of the northeastern part of the Central Chukchi basin in the area of the Northeast Chukchi fault zone and the Hanna wrench fault zone. Seismic data courtesy of Western Geophysical Company.



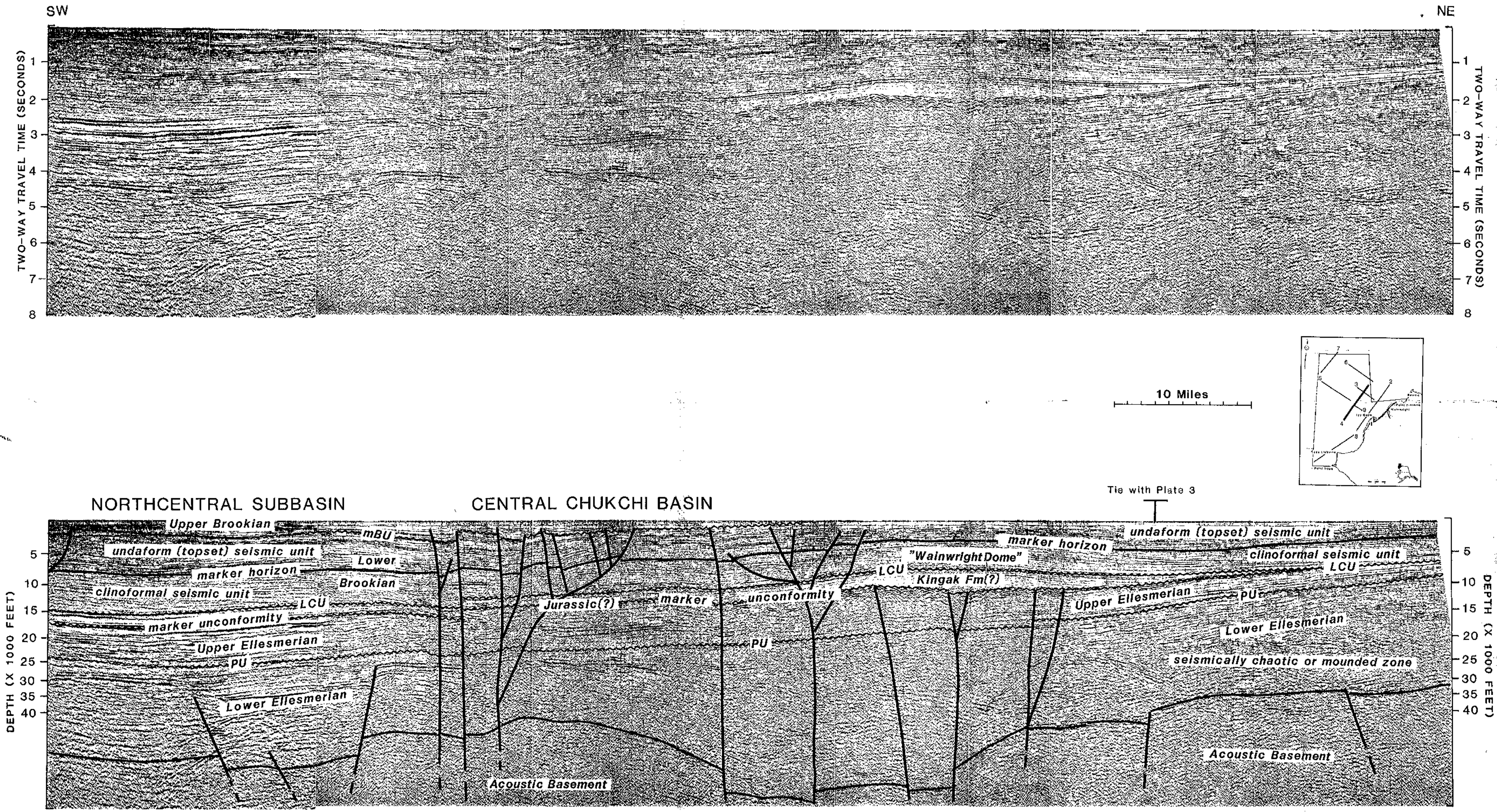


PLATE 4. Representative unmigrated seismic profile illustrating the geology of the northern part of the Central Chukchi basin and the southern part of the Northcentral subbasin where dissected by north-trending strands of the Hanna wrench fault zone. Seismic data courtesy of Western Geophysical Company.

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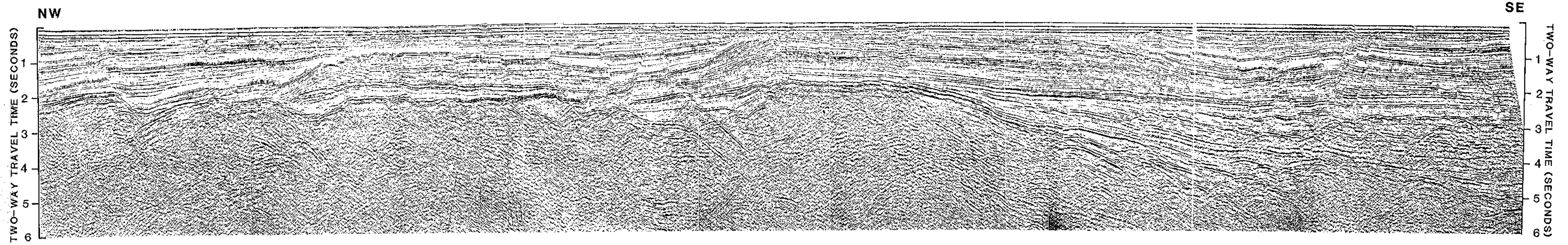


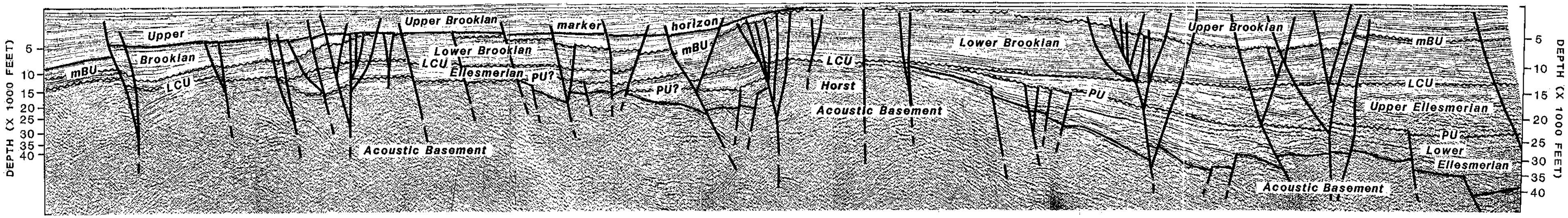
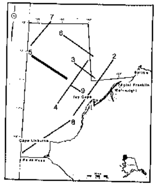


PLATE 5. Representative seismic profile illustrating the geology of the Chukchi platform , Central Chukchi basin, and Northcentral subbasin where dissected by strike-slip fault systems of the Hanna wrench fault zone. Unmigrated seismic data courtesy of Western Geophysical Company.

10 Miles



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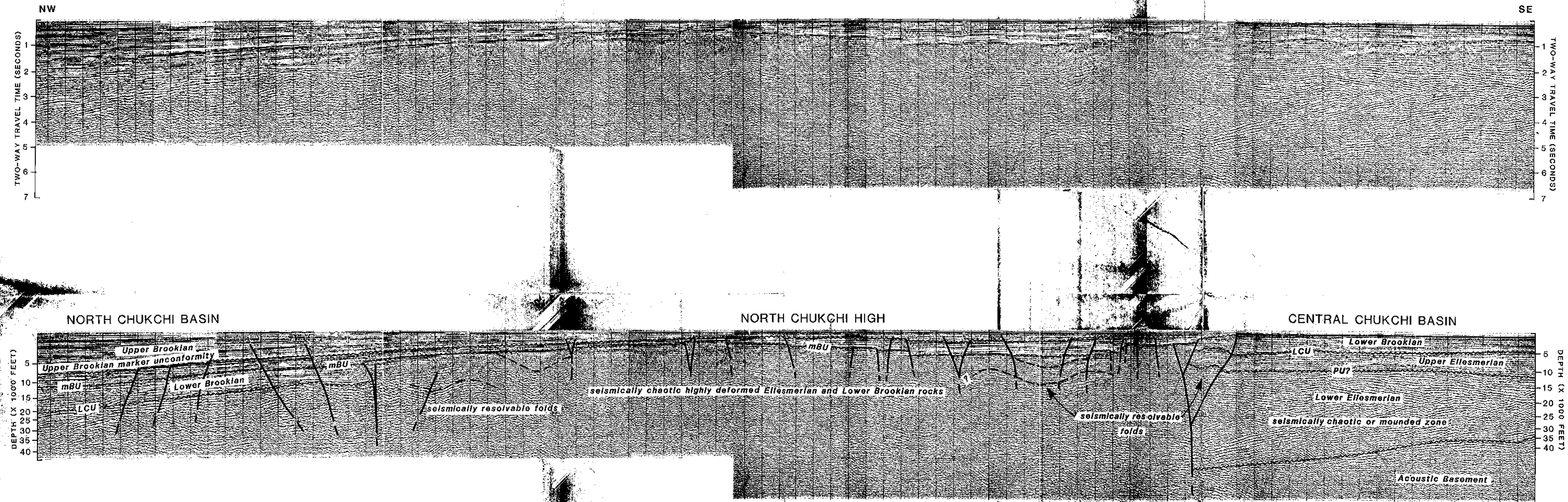
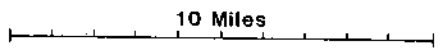
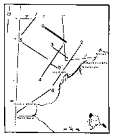


PLATE 6. Representative unmigrated seismic profile illustrating the geology of the northeastern part of the North Chukchi basin, the North Chukchi high, and the northern end of the Central Chukchi basin. Seismic data courtesy of Geophysical Service, Inc.





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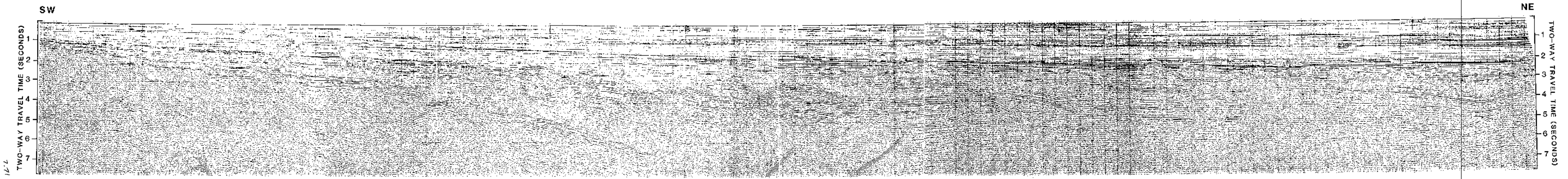


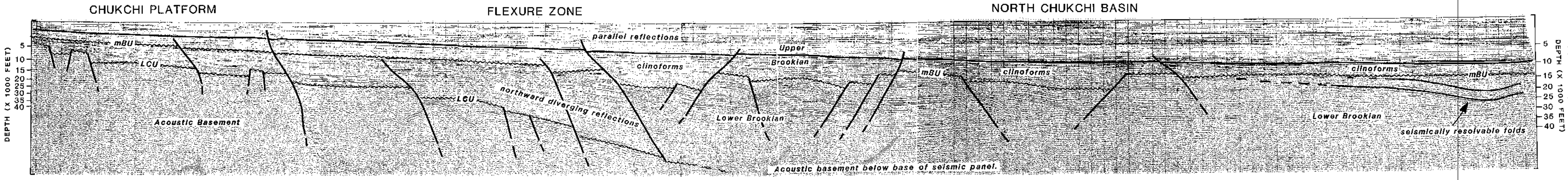
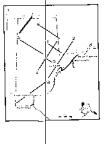


PLATE 7. Representative seismic profile illustrating the geology of the northern part of the Chukchi platform, the flexure zone which bounds the North Chukchi basin, and the central part of the North Chukchi basin. Seismic data courtesy of Geophysical Service, Inc.

123 mi.

10 Miles



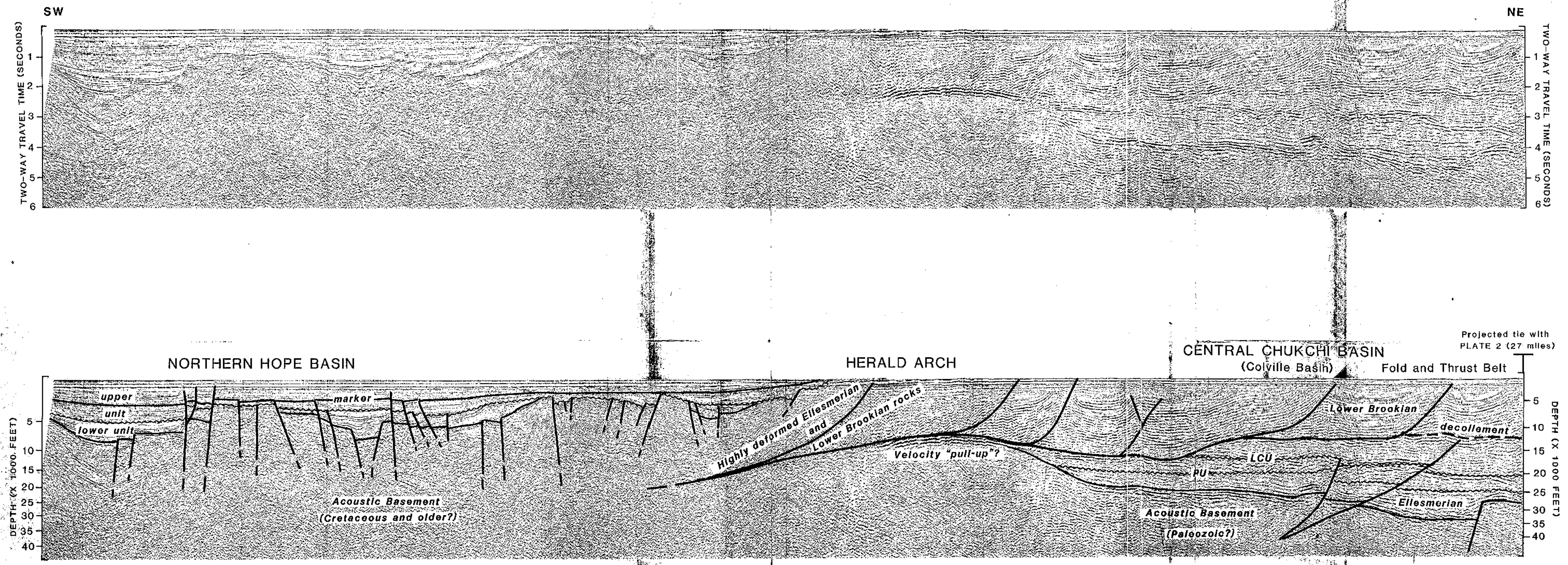
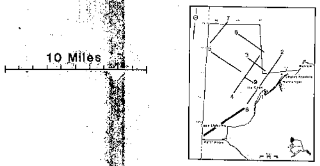
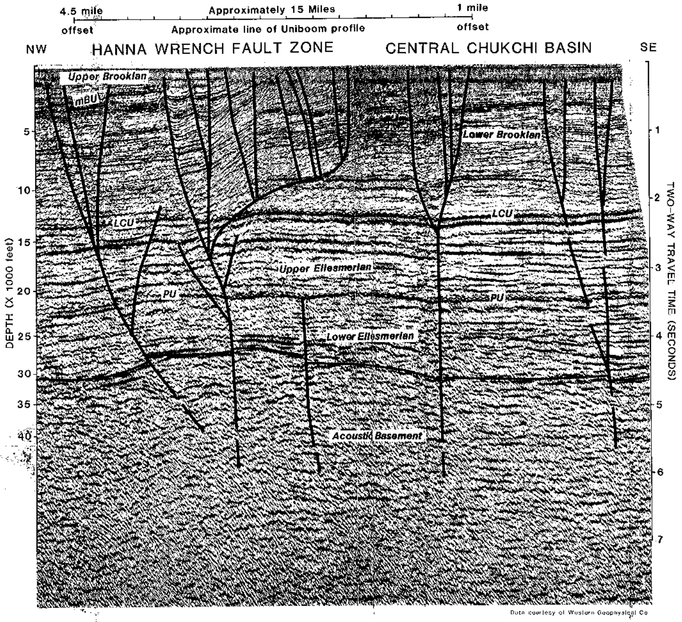
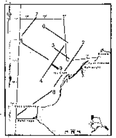


PLATE 8. Representative seismic profile illustrating the geology of the Northern Hope basin, Herald Arch, Herald thrust and the Fold and Thrust belt in the southern part of the Colville basin. Data courtesy of Western Geophysical Company.







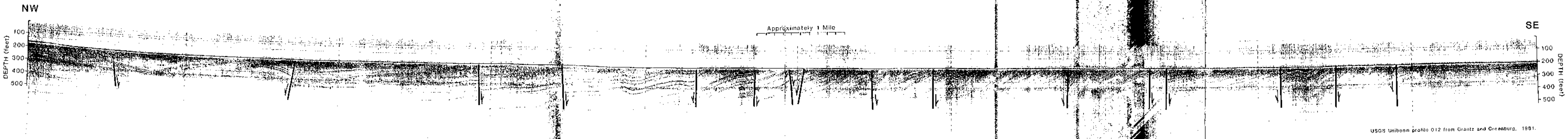


PLATE 9. CDP panel and parallel Uniboom line illustrating the geologic structure at deep and shallow levels in the Hanna Wrench fault zone.