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Geology and Physiography of the Continental Margin North of Alaska and Implications for the Origin of the Canada Basin

By

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Geology and Physiography of the Continental Margin
North of Alaska and Implications for the Origin of the Canada Basin

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ABSTRACT

The continental margin north of Alaska is of Atlantic type. It began to form probably in Early Jurassic time but possibly in middle Early Cretaceous time, when the oceanic Canada Basin of the Arctic Ocean is thought to have opened by rifting about a pole of rotation near the Mackenzie Delta. Offsets of the rift along two fracture zones are thought to have divided the Alaskan margin into three sectors of contrasting structure and stratigraphy. In the Barter Island sector on the east and the Chukchi sector on the west the rift was closer to the present northern Alaska mainland than in the Barrow sector, which lies between them. In the Barter Island and Chukchi sectors the continental shelf is underlain by prisms of clastic sedimentary rocks that are inferred to include thick sections of Jurassic and Neocomian (lower Lower Cretaceous) strata of southern provenance. In the intervening Barrow sector the shelf is underlain by relatively thin sections of Jurassic and Neocomian strata derived from northern sources that now lie beneath the outer continental shelf.

The rifted continental margin is overlain by a prograded prism of Albian (upper Lower Cretaceous) to Tertiary clastic sedimentary rocks that comprises the continental terrace of the western Beaufort and northern Chukchi Seas. On the south the prism is bounded by Barrow arch, which is a hingeline between the northward-tilted basement surface beneath the continental shelf of the western Beaufort Sea and the southward-tilted Arctic Platform of northern Alaska.

The Arctic platform is overlain by shelf clastic and carbonate strata of Mississippian to Cretaceous age, and by Jurassic and Cretaceous clastic strata of the Colville foredeep. Both the Arctic platform and Colville foredeep sequences extend from northern Alaska beneath the northern Chukchi Sea. At Herald fault zone in the central Chukchi Sea they are overthrust by more strongly deformed Cretaceous to Paleozoic sedimentary rocks of Herald arch, which trends northwest from Cape Lisburne. Hope basin, an extensional intracontinental sedimentary basin of Tertiary age, underlies the Chukchi Sea south of Herald arch.

SCOPE AND ACKNOWLEDGMENTS

This paper presents an overview of the physiography and geology of the Arctic continental margin of Alaska (Fig. 1) and discusses some implications of the data for the origin of this margin and the adjacent Canada Basin of the Arctic Ocean. Many of the interpretations presented are preliminary, and the paper does not attempt a comprehensive analysis of the features discussed. Some details can be found in Grantz et al. (1970a,1975) and Eittreim et al. (in press). Our data are mainly single-channel seismic reflection and sonobuoy refraction profiles obtained between 1969 and 1973 from U.S. Coast Guard icebreakers and a few of the multichannel CDP seismic reflection profiles obtained from the U.S. Geological Survey R/V _S.P. LEE_ in 1977 (Grantz et al., 1970b, 1971, 1972a, b, 1974, and 1975).

We are indebted to many U.S. Geological Survey colleagues for helping obtain the data presented, to the Coast Guard and the Naval Arctic Research Laboratory, Barrow, Alaska for logistic assistance, and to David W. Scholl, Leslie Magoon, David A. Dinter, and Irvin L. Tailleur for reviewing the manuscript and offering helpful suggestions. Olive T. Whitney prepared several of the illustrations. This report has not been reviewed

for conformance to stratigraphic nomenclature used by the U.S. Geological Survey.

PHYSIOGRAPHY

Major Features

The rim of the Arctic Basin in the western Beaufort and Chukchi Seas (see Fig. 2) consists of the narrow Western Beaufort Shelf, the broad Chukchi Shelf, and the Chukchi Continental Borderland. These face the Canada Basin (Fig. 3), which is that part of the deep Arctic Ocean basin that lies between the Lomonsov Ridge, eastern Siberia, and North America. The continental shelf in the western Beaufort and northern Chukchi Seas is a subsiding, prograding terrace dissected by submarine canyons. In contrast, the continental shelf in the central and southern Chukchi Sea is a submerged marine-cut platform eroded into the North American and Eurasian continents. Many of the geologic formations and structures that underlie these shelves are coextensive with formations and structures in northern Alaska. The bathymetrically complex Chukchi Continental Borderland (Fig. 2), which juts into the Canada Basin, is inferred to contain fragments of continental crust. The southern Canada Basin, which lies adjacent to Alaska, is floored by an abyssal plain in the west and a continental rise built out from the Canadian Arctic Islands and Mackenzie River Delta in the east.

Western Beaufort Shelf

The relatively narrow continental shelf of the western Beaufort Sea extends between the Mackenzie and Barrow Sea Valley, a distance of about 700 km (Figs. 1 and 2). The shelf is 70 to 120 km wide and extends seaward with a gentle gradient from barrier islands or low bluffs at the coast to a complex outer continental shelf break at depths of 200 to 800 m. East of 147° W. long (Figs. 2 and 15) the shelf consists of an inner section with a gradient of about 1 m/km that extends from shore to a slump-controlled break in slope near the 60-m isobath, and an outer section with a gradient of about 16 m/km that extends from the 60-m isobath to the outer shelf break. The steeper outer section is here named the Beaufort Ramp.

The inner Beaufort Shelf west of the Colville River is basically a wave-cut surface, although predominantly fine-grained Quaternary clastic sediments locally as much as 140 m thick have been deposited upon it. Rocks as old as Early Cretaceous are truncated at the base of the Quaternary cover. East of the Colville River, transportation and deposition of clastic sediment has been the dominant Neogene and Quaternary geologic process. Holocene sediment, dominantly lutite, has filled local depressions and smoothly prograded the continental shelf seaward. Sand and gravel occur in bars near shore, and scattered accumulations of relict gravel are found across the entire shelf (Barnes and Reimnitz, 1974). Rodeick (1974) suggests that most of the relict gravel, which is most abundant on the outer shelf, was derived from the underlying Gubik Formation (Quaternary) by erosion during the Holocene transgression. However, the gravel must also include dropstones from ice islands (tabular glacial icebergs from Ellesmere Island) that drift across the shelf.

Local relief on the Beaufort Shelf occurs at nearshore sand bars and ice gouges. Pleistocene glaciers (Fig. 2) apparently reached the shelf only east of Barter Island. The ice gouges are generally parallel to the coast and extend from nearshore to at least the 75 m isobath (Reimnitz and Barnes, 1974). Those related to the present stand of sea level are abundant to water depths of 30 m. The gouges are produced by grounding of deep-draft sea-ice pressure ridges and ice islands that are driven westward along the shelf by a wind-driven clockwise current, the Beaufort (Pacific) gyre of the Canada Basin. The deepest ice gouge measured north of Alaska is 5.5 m (Reimnitz and Barnes, 1974), but most are 1 to 3 m deep.

Chukchi Shelf

The Chukchi Shelf (Fig. 2) lies between Bering Strait on the south, Barrow Sea Valley on the east, and the longitude of Wrangel Island (180°) on the west. This broad shelf was eroded far into the continent and transects the principal mountain ranges of northern Alaska. Its north-south and east-west dimensions are both about 900 km. Although the shelf is characterized by low bathymetric gradients, underlying geologic control of its major physiographic features is evident. Hope Sea Valley-Herald Canyon, the largest sea valley system on the shelf, overlies Tertiary basins, and Herald and Hanna Shoals overlie structural highs that expose Paleozoic and Mesozoic rocks at the seabed. The shallow southern Chukchi Sea and Kotzebue Sound owe their shape and extent to Quaternary marine abrasion in the soft Tertiary strata of Hope basin (Fig. 3).

Bottom sediment in the Chukchi Sea is dominantly silt and very fine sand although sand and gravel occur near shore and on shoals. The sand and gravel on shoals may be lag deposits winnowed by ice gouging and currents (Toimil and Grantz, 1976). Gravel in the northern Chukchi Sea also includes glacial erratics dropped from ice islands. The Holocene sediment blanket on the Chukchi Shelf ranges in thickness from 0 to 12 m (Creager and McManus, 1967). On the southern Chukchi Shelf, much of this young sediment is from the Yukon River swept northward in the Alaskan Coastal Water, which flows north through Bering Strait (Nelson and Creager, 1977). Other sources are the Noatak and Kobuk Rivers and the smaller rivers that enter the Chukchi Sea north of Kotzebue Sound.

Small-scale bathymetric features on the Chukchi Shelf include nearshore sand bars, ice gouges, and large sediment dunes. Pleistocene glaciers reached

the shelf only near Chukotka and Kotzebue Sound (Figs. 1 and 2). Well-defined ice gouges have been found where the seabed is as deep as 60 m, but they are most abundant in depths of 25 to 40 m (Toimil, 1978). Most are 1 to 3 m deep. The deepest ice keels that have been measured in the western Arctic do not extend more than 50 m, and most do not extend more than 25 m below sea level. Thus the gouges found at depths of 60 m in the north-central Chukchi Sea were probably made prior to 3,000-4,000 years ago, when sea level was eustatically lower than at present. Sand waves with wavelengths as much as 400 m are common bottom features near Bering Strait, and sediment dunes as much as 15 m high and 250 m between crests occur near Barrow Sea Valley
Several short cores and sediment grabs from the dunes yielded only lutite.

Sea Valleys and Submarine Canyons

Several large sea valleys and canyons cut the Chukchi and Beaufort Shelves and slopes. Mackenzie Sea Valley, the largest, is the major conduit of detritus to the Canada Basin. Ice lobes and melt water of the Pleistocene Laurentide ice sheets were major factors in carving this sea valley (Fig. 2).

Barrow Sea Valley and Barrow Canyon

The axis of Barrow Sea Valley (Fig. 2) is incised into the northern Chukchi Shelf about 20 km off the northeast-trending Alaska coast north of Wainwright. It is a broad, flat-bottomed channel 200 km long and 2 to 8 km wide with an overall axial gradient of about 1 m/km. The east bank of the valley is higher than the west bank owing to preferential sedimentation on that side, but the gradient of the west bank is generally steeper. About 20 km south of the continental shelf break, the sea valley merges into Barrow Canyon. The canyon attains its maximum relief of 900 m where it crosses the projection of the shelf break. Its average axial gradient is 30 m/km but a steep upper segment slopes

48 m/km. A second canyon, comparable in relief to Barrow Canyon, lies 55 km to the east and a third, much smaller canyon lies 110 km to the east. The second, and possibly the third, appear to be abandoned extensions of the Barrow Sea Valley. These canyons may have been beheaded by the present Barrow canyon, which affords a more direct route from Barrow Sea Valley to the abyssal plain.

Although it is the only sizable sea valley entering the Canada Basin west of the Mackenzie, Barrow Sea Valley has only a modest sedimentary wedge and fan complex on the continental slope and rise. The volume of sediment in the wedge and fan is estimated to be of the order of $10^4 km^3$, compared to roughly $3x10^5 km^3$ for the Mackenzie Cone, suggesting that Barrow Sea Valley has not been a major sediment conduit to the basin. Additional Barrow Sea Valley-derived sediment underlies the abyssal plain, and some is stored on the continental shelf.

The Barrow Sea Valley heads on the northeast Chukchi Shelf, which receives sediment only from relatively small streams with a total drainage area of approximately 35,000 km^2. The only large sediment sources in the Chukchi Sea are the Kobuk and Noatak Rivers, which drain about 100,000 km^2 of northwest Alaska, and the Alaskan Coastal Water, which introduces silt-laden Yukon River water via Bering Strait. These sources are semi-isolated from the Barrow Sea Valley by Herald Shoal and its extension to Cape Lisburne. In contrast, the Mackenzie Sea Valley receives sediment from the 2,000,000-km^2 Mackenzie River drainage.

Barrow Sea Valley is thought to have been incised into the shelf and slope by subaerial streams during Pleistocene regressions in sea level and by the northeast-flowing Alaskan Coastal Water during interglacial times. Barrow Canyon is presumed to have been cut by turbidity currents. The principal in fluence of the Alaskan Coastal Water may have been as a source of clastic sediment for the turbidity currents and for the submarine fan complex at the mouth of the canyon. The Alaskan Coastal Water flows northeast along the coast from south of Cape Lisburne to north of Point Barrow and its axis follows the Barrow Sea Valley. Presumably the current is held against the coast by the Coriolis effect. Garrison and Becker (1976) argue, on the basis of physical oceanographic data, that this canyon also acts as a conduit for exchange of water masses between the Chukchi Shelf and the Canada Basin. They postulate that cold saline water generated on the shelf in winter drains north into the deep basin, and that under certain barometric conditions deep Canada Basin water wells up onto the shelf via the sea valley.

Hope Sea Valley and Herald Canyon

The Pleistocene and early Holocene Noatak and Kobuk Rivers crossed the Chukchi Shelf via Hope Sea Valley and Herald Canyon (Creager and McManus, 1965). According to these workers, this sea valley system (Fig. 2) consists of a series of channels interrupted by areas of deltaic deposition representing still stands during Pleistocene sea-level fluctuations. Bering Strait Sea Valley (Hopkins et al., 1976), which flows north through Bering Strait, may be a tributary of Hope Sea Valley that was similarly modified by deltaic deposition. Because the deltaic areas lack clearly defined channels, the axis of the sea valley system is difficult to map. Herald Canyon (Fig. 3) apparently enters Canada Basin at the Chukchi Abyssal Plain between 170° and 180° W. (Beal, 1969). This plain, a perched basin at about 2,200 m depth, may have received much of its sedimentary fill from the Noatak and Kobuk Rivers and northern Chukotka via the Hope Sea Valley-Herald Canyon drainage system during Pleistocene glacial maxima.

Hanna Sea Valley

Hanna Sea Valley (Fig. 2), a broad, east-northeast-trending feature north of Hanna Shoal, may be an abandoned late Pleistocene course of the Hope-Herald Sea Valley system. The Noatak-Kobuk effluent and an ancestral northeast-flowing Alaskan Coastal Water, if it existed during the late Pleistocene, must have flowed west of then-emergent Herald Shoal to reach the Arctic Basin. The current may have been deflected northeast and held against the north side of Herald and Hanna Shoals by the Coriolis effect. Hanna Sea Valley might have been related to this postulated current much as Barrow Sea Valley appears to be related to the present northeast-advecting Alaskan Coastal Water.

Chukchi Continental Borderland

The Chukchi Borderland (Figs. 2 and 3), 400 km wide and 600 km long, extends northward from the Chukchi Shelf between 160° and 170° W. long (Beal, 1969; Hunkins et al., 1962). The borderland consists of a cluster of shallow, flat-topped plateaus and ridges with an intervening deep basin, Northwind Abyssal Plain, and sea valleys. Chukchi Cap (Fig. 3), the largest high-standing plateau in the borderland, has flat shelves at 270 m and 400 to 500 m below sea level and rises locally to 246 m below sea level. The east margin of the borderland is the Northwind Escarpment, a steep continental slope that abuts the deep Canada Basin at depths near 3,900 m. Gentler slopes, irregular in plan, characterize the other margins. Bathymetry and geophysical characteristics (Shaver and Hunkins, 1964) suggest that the high-standing parts of the borderland consist of continental crust.

Continental Shelf Break and Beaufort Ramp

The shelf break in the Chukchi and western Beaufort Seas (Fig. 2) has large regional variations in character and depth that reflect the interplay between tectonic processes and Quaternary sedimentation and slumping (Fig. 17). The main (outer) shelf break lies at headwalls of submarine slumps on the continental slope. Its depth is 200 to 300 m near 150° W., 450 m near 160° W., and about 800 m at 139° W. long.

The Beaufort Ramp, a transition zone between the low-gradient inner shelf and the continental slope, is the product of Neogene (Quaternary?) subsidence and folding. Its inner edge, near the 60 m isobath, lies at or seaward of the crests of broad mid-shelf arches and anticlines expressed in Neogene beds. The slope of the ramp and the dip of the underlying strata are generally similar, about 0.5 to 1.5°, which suggests that the strata and seabed were tilted together. The fold crests apparently acted as dams behind which shelf sediments ponded and smoothed the seabed of the inner shelf, but sediment also overtopped the fold crests and prograded a Quaternary sedimentary wedge seaward at the head of the ramp. Headwalls of bedding plane slides developed within this wedge determine the specific position of the inner shelf break.

On some of our seismic profiles (Fig. 15), pre-Quaternary beds beneath deeper parts of the Beaufort Ramp are truncated at or near the seabed, even though parts of the ramp are deeper than 800 m, well below the deepest Pleistocene regression. This truncation of bedding indicates that the ramp was once above wave base and subsequently subsided and tilted seaward. The outer shelf break along the Beaufort Ramp increases in depth from 200 to 300 m near 150° W. to 830 m near 139° W. long (Fig. 16), a rate of about 1.2 m/km. Deepening of the shelf break corresponds closely with the easterly increase in thickness of the sedimentary prism of the Mackenzie Cone and Canada Continental Rise. Eastward deepening of the shelf break and northward tilting of the Beaufort Ramp may therefore be an isostatic subsidence due to crustal loading by sediment on the cone and rise. This hypothesis is supported to some extent by the pocket of earthquakes reported at the head of the Mackenzie Cone and Canada Rise by Wetmiller and Forsyth (1978). These workers suggest (p. 15) that the earthquakes "are possibly related to isostatically uncompensated loads of recent sediments."

Alaska Continental Slope and Northwind Escarpment

The continental slope north of Alaska follows a gentle arc from the Mackenzie Sea Valley to the Chukchi Borderland (see Fig. 2). Its junction with the continental rise lies at depths of 1,100 to 2,000 m and its average slope ranges from 4° to 12°, with local steep pitches of 16°. The steep, nearly linear slope along the east face of the Chukchi Borderland, the Northwind Escarpment (Figs. 2 and 3), has slopes as steep as 23° (Fisher et al., 1958). Numerous slumps, landslides, and incised channels characterize the Alaska Continental Slope. The largest slide masses head at or near the shelf break. Along many crossings the vertical drop at the headwall of these slides is 900 to 1,200 m, and head-to-toe length of some large slides exceeds 35 km. Slumps and irregular prograded sedimentary wedges similar to these surficial features also occur within the Tertiary section beneath the outermost Western Beaufort Shelf (see Fig. 13B, C).

Seismic and bathymetric profiles show that many canyons incise the Alaska Continental Slope. Some appear to be slump scars; others contain bedded sediments, are bordered by levees, and appear to be turbidity current channels. In these channels the upper surface of the sedimentary fill is commonly tilted up toward the eastern bank owing to the Coriolis effect on the depositing current.

Canada Continental Rise and Abyssal Plain and Alaska Continental Rise

The Canada Abyssal Plain, which underlies the western two fifths of the Canada Basin, is about 3,700 m to more than 4,000 m deep (Fig. 2). Its smooth floor and sparsity of abyssal hills indicate that it overlies a thick sedimentary fill. The Canada Continental Rise underlies the eastern three fifths of the basin. It is about 3,700 m deep at its gradational boundary with the abyssal plain on the west and slopes gently upward toward the Arctic Islands and Mackenzie Delta, where it abuts the continental slope between the 1,400- and 1,800-m isobath. Its morphology indicates that the Canada Rise is underlain by a thick sedimentary fill derived in large part from the Mackenzie Valley and Arctic Islands. Because these areas were covered by the Laurentide ice sheet, it is likely that glacial detritus constitutes a major part of the sedimentary fill beneath the Canada Rise. The rise is as much as 500 km wide from the continental slope to the 3,700-m isobath; the other rises fringing the Canada Basin, including the Alaska Rise, are much narrower. Sedimentation on the Canada Rise has thus overwhelmed that on the Alaska Rise, and its sediments abut, or lap onto, the surface of the Alaska Rise (Fig. 2). As the Canada Abyssal Plain adjoins the Alaska Rise at depths as great as 4,000 m, and the upper part of the Canada Rise laps onto it at depths of 1,400 to 1,800 m, sedimentation on the Canada Rise has reduced the vertical relief of the eastern part of the Alaska Rise and Slope by more than 2,200 m. Concomitantly, the width of the Alaska Rise narrows from about 100 km near 150° W. long to a wedge edge near Herschel Island. Westward, the Alaska Continental Rise wedges out again at the base of the steep Northwind Escarpment, where terrigenous sedimentation was slight. In places the escarpment appears, on reconnaissance charts, to plunge directly to the Canada Abyssal Plain. The disparity in size between the Canada Rise and the other continental rises of the Canada Basin demonstrates that the Arctic Islands and Mackenzie Valley were much more important sources of late Cenozoic detritus to the Canada Basin than northern Alaska and the Chukchi Shelf.

Smooth slopes and gentle gradients characterize the Alaska Continental Rise. Gradients range from 0.9° to more than 2.2°. Bedding in the underlying sediment is generally parallel to the seabed and presumably consists of turbidity current and disaggregated slide deposits. Channels and levees can be seen on bathymetric profiles and, vaguely, on bathymetric charts of the Alaska Rise. A few refraction measurements and estimates of sediment thickness beneath the nearby Canada Basin and Western Beaufort Shelf (Fig. 5) suggest that sediment beneath the Alaska Rise may be 4 to 8 km thick. Because it borders an Atlantic-type margin, the structural simplicity observed in its upper beds is inferred to characterize the entire Alaskan Rise sedimentary prism. However, many large diapiric folds deform the Alaska Rise and Slope east of 146° W. long.

REGIONAL STRATIGRAPHY AND TECTONIC SETTING

The geologic formations of northern Alaska and vicinity are divided conveniently into four tectonic-stratigraphic sequences (Franklinian, Ellesmerian, Brookian, and Hope basin) that correlate well with the major geologic events of the region. The character of these sequences is shown in Figure 4A-B, and their distribution in Figures 5, 6, 8, and 9. The Franklinian, Ellesmerian, and Brookian sequences were defined by Lerand (1973) from rock sequences in the Arctic Archipelago of Canada and the Brooks Range of Alaska. The Hope basin sequence is defined here from the Tertiary Hope basin of the southern Chukchi Sea. The onshore stratigraphic and structural data presented in this paper include data and concepts from Alaska Geological Society (1971, 1972, 1977); Anonymous (1970); Armstrong and Bird (1976); Beikman and Lathram (1976); Bird (1978); Brosgé and Tailleur (1971); Campbell (1967); Chapman and Sable (1960); Detterman et al. (1975); Jones and Grantz (1964); Kameneva (1977); King (1969); Lerand (1973); Martin (1970); Norris (1977); Tailleur and Brosgé (1970); Tailleur et al. (1972); U.S. Geological Survey (1978); and Young et al. (1976).

Franklinian Sequence and Precambrian Rocks

Basement for standard seismic reflection and sonobuoy refraction surveys in northern Alaska and its continental shelves occurs within the Franklinian sequence or, in places, Precambrian rocks. The Precambrian rocks are mainly slate, phyllite, schist, gneiss, marble, and metavolcanic rock. The Franklinian sequence was named for the Franklinian geocyncline of the Arctic Archipelago. In the archipelago the sequence is of Middle Cambrian to Devonian age and was derived mainly from northern sources. Its southern facies are mainly carbonate. In northern Alaska the Franklinian sequence consists of generally strongly deformed Cambrian to Devonian miogeoclinal and eugeoclinal rocks (Fig. 4A -B) strongly disrupted by thrust faults in the Brooks Range and in the Seward and Chukotsk Peninsulas. In places the sequence is mildly metamorphosed, and locally it is intruded by plutonic rocks. It is thought to extend seaward to the continental slope, and it may underlie the Chukchi Borderland.

Arctic Platform and Ellesmerian Sequence

The Franklinian rocks were strongly deformed and truncated by regional erosion during the Late Devonian-Early Mississippian Ellesmerian (Antler) orogeny, creating a stable shelf, the Arctic platform of northern Alaska. The platform maintained a remarkable stability for 200 million years, from Early Mississippian to Cretaceous time. During this interval a diverse suite of mature marine and nonmarine clastic and carbonate rocks, the Ellesmerian sequence, was deposited on the platform. The sequence is named for the Ellesmerian orogeny. It is typically exposed in the Sverdrup basin of the Arctic Archipelago, where it consists of Mississippian to Jurassic rocks of mainly easterly and southerly provenance. In northern Alaska, however, the Ellesmerian sequence, which is also called the Arctic Alaska basin (Tailleur and Brosgé, 1970), was derived mainly from northerly source terranes. Its constituent rock units (Fig. 4A-B) in general thin, coarsen, and lap toward this source terrane, which is called Barrovia (Tailleur, 1973). On the Barrow arch Mississippian to Jurassic beds of the sequence thin to a wedge edge owing in part to sedimentary thinning and in part to erosional truncation, and they are overstepped by the Neocomian "Pebble Shale." This shallow-water organic shale is the youngest unit in northern Alaska with a northern source. Outcrops of Jurassic and Neocomian strata in northern Yukon Territory and on the Arctic Coastal Plain of northeastern Alaska (Young et al., 1976; and Reiser et al., 1978) and the interpreted presence of 1,800 m of Kingak Shale (Jurassic and Lowest Cretaceous) beneath the Beaufort Shelf north of Yukon Territory (Norris, 1977) suggest that the Jurassic and earliest Cretaceous strata of these areas become shalier to the north and are of southern provenance. In northern Yukon Territory the Kingak Shale oversteps Mississippian to Triassic beds of northerly provenance lower in the Ellesmerian sequence.

The boundary between the Ellesmerian and overlying Brookian sequence, according to Lerand (1973, p. 373), could be placed either at the oldest beds (Middle Jurassic) that received sediment from southern sources or at the youngest beds (Neocomian) that received sediment from northern sources. Lerand arbitrarily placed the boundary at the base of the Cretaceous. In this report the boundary is placed between the "Pebble Shale"-Kongakut Formation (Neocomian) of northern provenance and the Torok Formation-Nanushuk Group (Albian) of southern provenance beneath the Arctic Coastal Plain, northern Arctic Foothills, and Chukchi and Western Beaufort Shelves of northern Alaska (Figs. 2 and 4A-B). In the southern Arctic Foothills and northern Brooks Range the boundary is placed between Upper Triassic beds of northern provenance and Middle Jurassic tuffaceous sandstone to Neocomian (Okpikruak Formation) turbidite of southern provenance. Since the boundary lies at the top of the

"Pebble Shale" over most of northern Alaska and its continental shelves, the term Brookian in this report refers to post-Neocomian rocks unless otherwise specified. The character of the Jurassic and Neocomian beds of northern provenance suggests that the northern source terrane was then senescent.

Colville Foredeep and Brookian Sequence

The long period of tectonic quiescence recorded by the Ellesmerian sequence ended during Jurassic and earliest Cretaceous time, when deformation began that created the Brooks Range orogen along the southern part of the Arctic platform. Paleozoic and Mesozoic rocks were thrust northward onto the southern part of the platform and created a southward deepening, asymmetric foreland basin, the Colville foredeep, north of the ancestral Brooks Range. The load of the thrust sheets and of the Jurassic and Cretaceous sedimentary rocks subsequently deposited in the foredeep caused it to deepen and broaden and tilted the Arctic platform southward. Concomitantly, southern sources first supplemented, then supplanted northern sources of sediment to the newly formed basin.

The oldest strata deposited in the Colville foredeep were Middle Jurassic tuffaceous beds and Upper Jurassic to Neocomian turbidites of southern provenance now exposed in the northern Brooks Range and adjacent foothills. These are coeval with condensed shale and coquinoid shale deposited on an intrabasin high and with euxinic basin and shelf deposits of northern provenance (Jones and Grantz, 1964) in the upper part of the Ellesmerian sequence to the north. Higher beds of the foredeep--namely Albian, Upper Cretaceous, and Tertiary strata of the Brookian sequence, all of southern provenance--extend from the Brooks Range across the entire Arctic platform to the Western Beaufort Shelf.

The Cretaceous sedimentary rocks of the Colville foredeep exceed 6,000 m in thickness on the south, where they consist mainly of turbidites and paralic-deltaic wedges. These strata thin northward to about 500 m to 2,000 m where they onlap Barrow arch. The Cretaceous beds on the arch, and probably on the Chukchi Shelf, are of paralic and neritic to upper bathyal facies. In northwestern Alaska and on the Chukchi Shelf, they include deltaic deposits with thick coal beds. In the northern Chukchi Sea and the Canning-Sagavanirktok Rivers area, wedges of northward-thickening Tertiary sedimentary strata overlie the Cretaceous rocks of the northern part of the Colville foredeep and Barrow arch. Nonmarine facies in the Tertiary and Cretaceous sequences appear to give way northward to marine facies, and the northward prograded sedimentary strata beneath the Western Beaufort Shelf are probably mainly marine. However, some nonmarine beds of both sequences reach the coast and appear on seismic records to extend offshore. Seaward, the prograded Brookian-equivalent beds thicken from about 500 to 2,000 m on the Barrow arch to more than 6,000 m in places on the outer shelf.

Cessation of sedimentation from northern terranes that geographically occupied the present area of the southern Canada Basin argues for a rifted origin of the Canada Basin. Tailleur (1969, 1973) suggests, in addition, that the early phase of the Brooks Range orogeny was produced along the leading edge of the southward-rotating northern Alaska plate in response to opening of the Canada Basin. However, Late Jurassic to mid-Cretaceous Brooks Range tectonic events are generally similar and synchronous with those in the Cordillera south of Alaska. Accordingly, we believe that the ancestral Brooks Range and its structures are a foreland thrust belt related to a broader subduction and collision zone between crustal plates of the Pacific region and the North American plate. Opening of the Canada Basin possibly increased the rate of subduction south of the Brooks Range, but any specific effects of this increased rate in the geologic record have not been documented.

Hope Basin Sequence

The young sedimentary rocks of Hope basin in the southern Chukchi Shelf have not been dated, and their correlation with the bedded rocks of adjacent land areas is conjectural. Outcrops of late Neogene marine sedimtary rocks along the margins of the basin (Hopkins and MacNeil, 1960; Belevich, 1969) and scattered outcrops of Paleogene and Neogene nonmarine sedimentary rocks on the northern Seward Peninsula and in the Selawik Lowland (Hudson, 1977; Patton and Miller, 1968) belong to formations that probably extend into Hope basin. Nonmarine rocks of Late Cretaceous or early Tertiary age on the eastern Seward Peninsula (Sainsbury, 1976) possibly also extend into the basin. Hope basin sequence was deposited in local intracontinental basins south of the Brooks Range, and is tectonically distinct from the Brookian sequence of northern Alaska.

GEOLOGY

Structural Provinces

The continental shelf and slope of the western Beaufort and northern Chukchi Seas is underlain by a thick prism of Cretaceous to Quaternary, and locally Jurassic, sedimentary strata that prograded seaward on a subsiding shelf. A thick correlative sedimentary sequence also underlies the adjacent continental rise and abyssal plain of the Canada Basin. In two places the prograded prism widens into sizable sedimentary basins. A southwestward bend of the Barrow arch in the northern Chukchi Sea creates an embayment wherein lies the North Chukchi basin (Fig. 3), which is filled with inferred Cretaceous, Tertiary, and perhaps older sedimentary rocks; and differential subsidence between Harrison Bay and Camden Bay has produced the Cretaceous and

Tertiary Camden basin (Fig. 5). This basin underlies both the continental shelf and a large area of coastal plain near the Colville and Sagavanirktok Rivers.

The central and southern Chukchi Shelf is dominated structurally by two positive (anticlinorial) and two negative (synclinorial) tectonic elements (Figs. 3 and 8-10). The positive elements, which bring Paleozoic rocks close to the surface, are the Barrow and Herald-Wrangel arches. The negative elements are the Colville foredeep, which contains thick accumulations of Jurassic, Cretaceous and locally Tertiary sedimentary rocks, and Hope basin, which is filled with Tertiary sedimentary strata. The basement underlying the Colville foredeep is the Ellesmerian sequence. In Hope basin basement is the Precambrian to Lower Cretaceous rocks which trend toward it from the western Brooks Range and Chukotsk Peninsula.

Barrow Arch

Barrow arch is the dominating structure of the Western Beaufort and northern Chukchi Shelves. Emerging near the Canning River from beneath a thick Tertiary section in the Camden Bay area, its crest (Figs. 3, 5, 7, 8, 10, and 11C) follows the coast westward to Barrow, then cuts seaward to 70° N., 160° W. in the northern Chukchi Sea. From here the arch turns southwest and persists as a more complex, but still broad structure to its termination in the west near the crosscutting Herald fault zone.

East of 160° W. long the Barrow arch trends westerly, is only slightly asymmetric (steeper flank north), and has low flank dips and generally simple structure (Fig. 10). West of 160° W. long, the arch trends southwest and the northwest flank is considerably steeper than the southeast flank (Fig. 7). The northwest flank west of 160° W. long contains large normal faults and is parallel to a strong gravity gradient that strikes northeast. Free-air anomaly values descend from 50 mgal over the arch to 0 to -10 mgals over the North Chukchi basin. These features suggest that the northwest flank of the Barrow arch may have resulted from truncation of the Arctic platform west of 160° W. long by a northeast-striking structure related to formation of the North Chukchi basin.

The Barrow arch is the broad structural culmination of the rifted and southward-tilted Arctic platform of northern Alaska. Crustal heating associated with the initial Jurassic and Early Cretaceous rifting of the Canada Basin is thought to have uplifted and tilted the northern part of the platform to the south along the arch (Rickwood, 1970). The south tilt is also partly Mississippian to Jurassic paleoslope and partly tilt produced by Cretaceous loading of the southern part of the Arctic platform by nappes and voluminous detritus from the nascent Brooks Range. The north flank of the arch is the modified rift scarp reduced in relief by down-to-the-north normal faulting, Jurassic and Early Cretaceous erosion, and regional post-rift subsidence. Such subsidence, commonly observed along rifted continental margins (see, for example, Watts and Ryan, 1976) may be a consequence of post-rift cooling of the crust beneath the rifted zone and subsequent sedimentary loading on and near the newly created continental margin. These processes are thought to have shifted the crest of the Barrow arch south by 50 to 100 km to the vicinity of the present coastline from an original position beneath the continental slope (Fig. 5).

Arctic Platform and Colville Foredeep

Between Cape Lisburne and Barrow, the bedded rocks of northern Alaska trend northwest beneath the Chukchi Sea. Here the Ellesmerian and Brookian rocks are limited on the southwest by the Herald arch and fault zone and thin northward toward the Barrow arch. Our seismic data do not show to what extent

Ellesmerian strata continue across the crestal zone of the arch to underlie the North Chukchi basin. Brookian rocks do extend across the Barrow arch and dominate the sedimentary prisms of the Western Beaufort Shelf and North Chukchi basin.

A sedimentary sequence at least 3 km thick designated "E-Fr" on cross section Figure 10 has been recognized in the northeastern Chukchi Sea, although its extent has not been determined. The sequence is interpreted to be overlain by Albian or older Early Cretaceous rocks in the north and by Mississippian beds low in the Ellesmerian sequence in the south. It yields seismic interval velocities (preliminary) of 5.0 km/sec or more and rests on bedded rocks with preliminary interval velocities of 6.0 km/sec or more. The sequence is tentatively postulated to be either a local thickening of Lower to mid-Mississippian clastic sedimentary rocks (Endicott Group) at the base of the Ellesmerian sequence or beds in the upper part of the Franklinian sequence that are structurally more orderly than the Ordovician and Silurian argillite and graywacke found in boreholes in northern Alaska (Carter and Laufeld, 1975). The Endicott Group is represented in the subsurface of northern Alaska by more than 550 m of conglomerate and sandstone of the Itkilyariak Formation, Kekiktuk Conglomerate, and Kayak Shale. These beds rest with angular unconformity on the strongly deformed Ordovician and Silurian beds.

In northwestern Alaska, the Ellesmerian sequence thickens from a wedge edge in the crestal region of the Barrow arch to at least 4,000 m, and perhaps more than 8,000 m, in the southern part of the North Slope and the western Brooks Range (Fig. 4A). Offshore, single-channel seismic reflections and sonobuoy refractions were received from the Ellesmerian rocks only north of Icy Cape (unit J-M in Fig. 10). In this area their seismic velocity is about

3.7 to 4.3 km/sec, and they consist of a gently south-dipping, southward-thickening packet of strong reflectors. An interpretation of the structure of these rocks in the eastern Chukchi Sea, which is speculative south of 70°50' N. lat, is presented in Figure 10.

The Brookian sequence of northwest Alaska consists of delta front foreset beds and shallow marine and paralic topset clastic beds and coal, all of southerly source and late Early Cretaceous (Albian) age. Tertiary beds of the Brookian sequence overlie the crestal zone of the Barrow arch and the northern part of the Arctic platform everywhere except in the region between 153° W. and 158° W. long (Figs. 5 and 8). The Brookian sequence, thinned by erosion, is 400 to 600 m thick and of Albian age in the vicinity of South Barrow gas field, on the crest of the Barrow arch. Southward, as noted previously, it thickens to at least 6,000 m near the Brooks Range. Northward, beneath the Western Beaufort Shelf, the Brookian sequence contains Cretaceous and Tertiary beds and thickens to at least 6,000 m.

The Cretaceous rocks of the central Chukchi Shelf have stratigraphic features, interpreted from seismic reflection profiles, that permit some of them to be correlated with subsurface strata of northern Alaska as described, for example, by Brosgé and Tailleur (1971), and Woolson (1962). On the Chukchi Shelf a thick seismic unit with irregular weak to moderately strong reflectors and many north or northeasterly dipping clinoform beds is well developed north of the foreland folds of the southern part of the Colville foredeep (Fig. 8). This unit is correlated with the Torok Formation of Albian age, a thick lutaceous unit containing turbidite beds. An overlying unit typified by strong parallel reflectors underlies the region of the foreland folds. It is correlated with the paralic and deltaic Albian and Cenomanian(?) Nanushuk Group, which consists of sandstone, lutite, conglomerate, and coal. West of the foreland folds lies an extensive terrane characterized by weak reflectors, small irregular folds, and poor seismic penetration. This terrane also has a relatively high positive free-air gravity anomaly (see Ruppel and McHendrie, 1976). Taken together, these features suggest that the terrane of weak reflectors is structurally elevated lutite low in the Brookian sequence (Torok Formation) or high in the Ellesmerian sequence ("Pebble Shale" or Kingak Shale).

Structurally the rocks of the Colville foredeep beneath the eastern Chukchi Shelf resemble those onshore. North of Icy Cape they are almost unbroken by faults or folds and dip gently and uniformly south. South of Icy Cape they are folded into long, east-west-striking anticlines and broad, shallow synclines (Fig. 8). The amplitude and tightness of folding increase to the south, and the southern folds show thrusting, incipient core diapirism, and northern vergence--features that indicate relative northward movement of the upper beds. Detachment in these foreland folds is inferred to occur within the early Albian Torok Shale and the youngest rocks affected are the Nanushuk Group of Late Albian age (see Woolson, 1962; Chapman and Sable, 1960). Apparently related structures in the Ogotoruk Creek area, southeast of Point Hope, appear to trend westward beneath Paleogene(?) strata in Hope basin. The detachment folds are therefore inferred to have formed during Laramide (Late Cretaceous-early Tertiary time. Along the Herald arch and fault zone, which bound deposits of the Colville foredeep on the southwest, the detachment folds are intersected obliquely by large thrust-folds (elongate folds with thrust-faulted cores) of the Herald fault zone (Fig. 8). These folds and related faults extend farther west than the detachment folds and appear to be younger.

Herald and Wrangel Arches

Herald arch, the dominant structural feature of the central Chukchi Sea, is a belt of strongly reflective rock 20 to 100 km wide that trends N 50° w. from Cape Lisburne toward Herald Island (Figs. 3, 8, and 9). Near 70° 30' N. lat, 173° W. long the arch merges with a zone of north-south structures that connect it with the broad zone of shallow acoustic basement called Wrangel arch (Figs. 3 and 8). Because the Brooks Range and Wrangel Island are underlain by similar rocks of the Ellesmerian and Franklinian sequences (Kameneva, 1977), Herald and Wrangel arches are thought to form a structural connection between the two areas. Wrangel arch resembles Barrow arch because it is underlain by similar correlatives of the Franklinian and Ellesmerian sequences and bounds the North Chukchi basin on the south (Figs. 3 and 8). Unlike Barrow arch, but similar to Herald arch, it is bounded on the north by south-dipping reverse faults.

The strongly reflective rocks in Herald arch are onlapped from the south by Tertiary rocks in Hope basin. The south-dipping unconformity at the base of the Tertiary rocks constitutes the south flank of the arch. The north flank is formed by the northeast-verging, northwest-striking Herald fault zone, which brings the strongly reflective rocks of the arch against well-bedded, less strongly reflective rocks of the Colville foredeep.

The character of "acoustic basement" in Herald and Wrangel arches can be inferred from outcrops on Lisburne Peninsula and Wrangel Island, a reported occurrence of Jurassic(?) plutonic rocks on Herald Island (N. A. Bogdanov, oral communication, 1970), and three dredge hauls taken from the north side of Herald arch near 70°N. lat, 168° to 170° W. long by the University of Washington (Fig. 8). The dredge samples are predominantly well-indurated graywacke sandstone and siltstone (Platt, 1975) that most resemble Lower Cretaceous graywacke and shale in the western Brooks Range and Lisburne Peninsula, but a positive correlation could not be made. On the northeast side of the arch, "acoustic basement" produces scattered, dismembered patches of steeply dipping but coherent reflectors suggesting strongly deformed bedded rocks (dK? on Figs. 8, 9, and 10). The strongly deformed beds of Lower Cretaceous graywacke and shale in the western Brooks Range and Lisburne Peninsula (dK in Figs. 8 and 9), which strike northwest from the north side of Cape Lisburne into the area of "dismembered" reflectors, could produce this observed acoustic pattern. "Acoustic basement" southwest of the belt of dismembered reflectors has few internal reflectors and is inferred to comprise lower Ellesmerian clastic and carbonate rocks and strongly deformed Franklinian clastic rocks (Iviagik Group of Martin, 1970) as crop out on the Lisburne Peninsula. Limited acoustic data over the Wrangel arch suggest that a similar boundary may underlie its northern part.

Herald and Wrangel Fault Zones

Herald and Wrangel arches are bounded on the north by the Herald and Wrangel fault zones (Figs. 8 and 9). Although both fault zones exhibit reverse slip and border the north sides of similar large belts of acoustic basement, they appear to differ in character and age. Herald fault zone consists of several thrust folds and faults that dip southwest at low angles (about 15°?). The thrust folds are best developed at the southeast end of the fault zone where they involve well-bedded competent rocks interpreted to represent the Cretaceous Nanushuk Group. Northwestward the dip of the fault zone becomes difficult to map, but may be steeper, and the large thrust folds along the northeast side of the fault zone diminish in amplitude and apparently lack thrust-faulted cores. This difference in structural response may correspond to a change in lithology. Seismic reflections suggest that northwestward from Cape Lisburne the rocks of the Colville foredeep probably change from well-bedded sandstone and lutite of the Nanushuk Group in the region of the foreland folds to harder, poorly bedded rocks belonging to the older Torok or Kingak Shales farther west. Alternatively, the fault style may change from dominantly easterly directed low-angle reverse slip near the Lisburne Peninsula to moderate or high-angle reverse slip with a large component of strike-slip west of 169° W. long for reasons not directly related to lithology.

Offshore the Herald fault zone separates moderately deformed Cretaceous sandstone and lutite to the northeast and more strongly deformed Cretaceous clastic rocks to the southwest (Figs. 8 and 9) and strikes toward a similar contact on the north side of the Lisburne Peninsula. A more important break, however, may lie to the southwest, between the area of acoustic basement with many bedding traces (Cretaceous(?) map unit dK?) and acoustic basement with few bedding traces (pre-Cretaceous(?) map unit pK). This boundary strikes toward a southwest dipping thrust-fault zone on the Lisburne Peninsula between Ellesmerian carbonates to the west and deformed younger rocks, mainly Cretaceous shale and graywacke to the east. Herald fault zone is younger than the Nanushuk Group strata (Albian), which it offsets, and older than the Paleogene(?) beds in Hope basin, which overlie it. Wrangel fault zone, in contrast (Figs. 8, 11A, B), separates presumed Paleogene and (or) Cretaceous strata in the North Chukchi basin from strongly reflective rocks in the Wrangel arch. A younger Tertiary unit, perhaps Neogene, overlies the fault zone and is not deformed. The fault zone may therefore be Late Cretaceous or early Tertiary, but definitive evidence for the age of the limiting rocks is lacking. Although it was seen on only a few profiles, the fault appears to be a steep south-dipping reverse fault with a number of splays on the north side (Figs. 11A , B). The splays bound subsidiary upthrown fault slivers that resemble horsts on seismic sections.

Chukchi Syntaxis

The Chukchi syntaxis (Tailleur and Brosgé, 1970) is the right-angle junction of the westerly striking thrust faulted Paleozoic and Triassic terrane of the Brooks Range with the north and northwest-striking Lisburne Hills and Herald arch (Fig. 3). Tailleur and Brosgé suggest that the Lisburne Hills and Herald arch are a simple extension of the Brooks Range structural trend that was rotated into its present position, relative to the Brooks Range, by oroclinal bending at the Chukchi syntaxis. In this model, Herald fault zone is a seaward extension of the frontal thrust faults of the Brooks Range beyond a relatively minor kink at the Lisburne Peninsula. Grantz et al. (1970a) consider the Herald arch and fault zone to be the leading edge of an easterly directed, somewhat younger thrust fault system that crosscuts the Brooks Range and its thrusts. In this case, the Chukchi syntaxis was created by the superposition of the Herald fault zone across the western Brooks Range and the detachment folds that lie in front of it.

The Herald fault zone trends across the detachment folds of the Colville foredeep at an angle of 45°, yet there appears to be no faulting between the outer thrust folds of the fault zone and the intersected detachment folds (Figs. 8 or 9, and Grantz et al., 1970a). These relations are most simply explained if the Herald fault zone and its inferred onshore extension, the thrust fault system that bounds the east side of the Lisburne Hills, postdate and are superimposed across the detachment folds (see also Chapman and Sable, 1960; and Martin, 1970). The suggested superposition could have created the Chukchi syntaxis. Additional evidence bearing on the origin of the syntaxis comes from paleomagnetic poles in Mississippian (lower Lisburne Group) beds on the Lisburne

Peninsula and in the western Brooks Range (Newman et al., in press). Preliminary data suggest that these poles have a common orientation even though they occur on both flanks of the syntaxis. This result is difficult to reconcile with the orocline hypothesis but it is at least compatible with the superposition hypothesis for the origin of the syntaxis. The age of the syntaxis is Late Cretaceous or early Tertiary since Albian strata are strongly deformed in its core and its apex is blanketed by Paleogene(?) beds in Hope basin.

Hope Basin

Hope basin (Figs. 9 and 10) lies between the presumed Paleozoic rocks of the Herald arch to the northeast and the Paleozoic and Precambrian rocks of Seward and Chukotsk Peninsulas to the southwest. It overlies strongly deformed Lower Cretaceous (Albian) and older rocks (Campbell, 1967) of the Brooks Range orogen. Low seismic velocities (V_p = 1.7 to 3.3 km/sec), the age of the underlying rocks, and the character and age of nearby onshore sedimentary basins suggest that Hope basin is filled with Tertiary and possibly some Upper Cretaceous sediments. A series of basement ridges subdivides the basin into a number of east-west troughs in which sediment thicknesses locally exceed 3,000 m. The largest of the basement ridges is Kotzebue arch, a structural high that trends westerly across the southern part of the basin (Fig. 9). This arch, which appears to have existed since the early Tertiary, is overlain by several hundred meters of Tertiary sediments. The smaller ridges that lie between the Kotzebue and Herald arches are more deeply buried. Kotzebue arch is alined at Cape Krusenstern with the east and east-northeast-trending Igichuk Hills, which may be its onshore extension. Indeed, an easterly-striking positive linear gravity anomaly along the arch (Ostenso, 1968) trends onshore and follows the western Igichuk and Kiana Hills to the Kobuk River near Kiana (Barnes, 1976), 150 km inland.

During Neogene time, a deep, east-west elongate sub-basin developed in eastern central Hope basin north of Kotzebue arch. The axis of the sub-basin is defined by a thickening of the sedimentary section above a key regional seismic reflector which is believed to approximate the Neogene/Paleogene boundary. Subsidence of the sub-basin was accommodated by numerous antithetic and normal faults (Fig. 10), and the arch itself was concurrently uplifted several hundred meters. Between Point Hope and Cape Krusenstern the Neogene sub-basin is bounded by normal faults parallel to the coast that also form the western boundary of the De Long Mountains and the western Brooks Range. The northern boundary of the sub-basin is a series of monoclines and normal faults that bring older rocks to the surface in Herald arch. Westward, the Neogene sub-basin gradually diminishes in depth, and near 171° W. long its ridge and trough structures die out entirely.

An episode of volcanic and tectonic activity strongly affected the Seward Peninsula and lower Kobuk Valley beginning in late Miocene time. Plio-Pleistocene basalts flooded a large area south of Kotzebue Sound and tectonic warping and faulting offset Miocene gravels and Pleistocene glacial deposits. These displacements were accompanied by the formation of sizable nonmarine sedimentary basins and by block faulting in and adjacent to the Kigluaik and Bendeleben Mountains of the Seward Peninsula and the Waring Mountains of the lower Kobuk Valley (Hudson, 1977; Patton, 1973). This tectonism may also have been responsible for the Neogene subsidence, arching, and faulting in Hope basin.

Hope basin developed in two steps. A Neogene sub-basin less than 100 km wide resulting from late Tertiary extensional tectonism formed within a broader mid-Tertiary or Paleogene basin more than 200 km wide that was produced by Late Cretaceous-Early Tertiary subsidence. Regional onshore stratigraphy suggests that both basins consist at least partly, and perhaps largely, of nonmarine rocks. However, a few marginal outcrops of Neogene marine strata and the periodic migration of Neogene marine faunas across Bering Strait (Hopkins, 1967) indicate that some marine beds must occur in the Neogene sub-basin, which subsided rapidly. In both the older and younger basins marine rocks may replace nonmarine rocks away from shore.

North Chukchi Basin

The North Chukchi basin (Grantz et al., 1975, p. 687-690) underlies the northern Chukchi Shelf between the western Barrow and Wrangel arches on the east and south and the Chukchi Continental Borderland on the north (Fig. 3). The westerly extent of the basin is not known.

The North Chukchi basin contains a thick prograded sequence of Brookian clastic sedimentary rock. Our seismic reflection data and a long refraction line by Hunkins (1966) indicate that the total section is more than 6 km thick (Figs. 8 and 11). Seismic profiles show that some beds in the basin onlap the Barrow arch on the south, but we lack data from their contact with the Chukchi Borderland to the north. Although both nonmarine and marine beds occur in the Brookian sequence in northwest Alaska, the equivalent rocks in the North Chukchi basin are probably mainly, and perhaps entirely marine. The basin fill can be divided into two to four stratigraphic packets on the basis of unconformities seen on single-channel seismic reflection profiles. Sonobuoy refraction velocities and correlations with the stratigraphy of northern Alaska suggest that these units are Neogene, Paleogene, Cretaceous and pre-Cretaceous.

Strata in the southern part of the North Chukchi basin dip as much as 15° northerly. Basinward, to the north, dips decrease to between 0° and 1° northerly. The absence of beds with a southerly dip component, even on lines near 74° N. lat within 50 km of the Chukchi Borderland, suggests that the North Chukchi rocks were deposited on thinned continental or oceanic crust rather than in a subsiding intracontinental basin. If so, these rocks may onlap high-standing blocks of pre-Cretaceous (Franklinian(?)) rocks in the Chukchi Borderland.

Well-developed diapirs (Figs. 5 and 8) pierce Tertiary beds in the North Chukchi basin to within a few tens of meters of the seabed (Grantz et al., 1975, p. 689-693). Low sonobuoy velocities, apparent lack of strong gravity or magnetic anomalies (Fig. 12), and regional stratigraphy suggest that the diapirs are probably shale, rather than salt, gypsum, or igneous rocks. Possibly the diapirs consist of soft Jurassic(?) or Lower Cretaceous prodelta shale, an early deposit in the basin subsequently deeply buried by rapidly deposited slope, shale, or deltaic sediment. Such shale, being weak and of relatively low density, might have risen buoyantly toward the seabed under the load of thick overlying sediments, piercing and bending the adjacent beds upwards in the process. Five diapirs (two crossings, three near-misses) have been identified in the basin to date. The best studied is about 2 km in diameter and extends to 3 km or more beneath the seabed. Judging from the number found and the density of our line coverage, something like 30 or 40 diapirs may be present.

Western Beaufort Shelf Sedimentary Prism

Sediments

A relatively narrow northward-prograded sedimentary prism consisting primarily of Brookian rocks underlies the continental terrace of the western Beaufort and northeast Chukchi Seas (Fig. 3). Between the North Chukchi basin and Camden Bay, the prism overlies Franklinian rocks on the north flank of the Barrow arch. Beneath the southern part of the shelf, the sequence includes locally thick sections of upper Ellesmerian Jurassic and Neocomian beds of northern provenance (Fig. 13B) and, in places near shore, the northern wedge edges of pre-Jurassic Ellesmerian formations. Between Harrison and Camden Bays the Tertiary beds of the Brookian sequence thicken and extend more than 100 km inland to form the Camden basin.

West of Harrison Bay the sedimentary prism consists mostly of Lower Cretaceous marine rocks with a Tertiary wedge of unknown character beneath the outer shelf and slope. The thickness of this sequence is 1 to 3 km near the coast and 6 to 8 km beneath the outer shelf. Between Harrison and Camden Bays, however, the prism consists mainly of Upper Cretaceous and Tertiary beds, with the Tertiary becoming dominant near Camden Bay. Here the prism is 3 to 6 km thick at the coast and 6 to 8 km thick on the outer shelf. Onshore correlatives of these rocks are both marine and nonmarine. The lower part of the Tertiary and probably the upper part of the Upper Cretaceous section in the Camden embayment contain coal beds (Alaska Geological Society, 1977). Both the Tertiary and Cretaceous beds are presumed to become more marine and finer grained seaward.

East from Camden Bay, Jurassic and Neocomian deposits as well as later Cretaceous and Tertiary deposits crop out on the Arctic Coastal Plain and are interpreted to project offshore beneath the Western Beaufort Shelf. Dark-gray Kingak Shale with Middle Jurassic (Bajocian) marine fossils (Reiser et al., 1978) crops out on the coastal plain 30 km southeast of Barter Island. The outcrops are surrounded by Early Cretaceous (Neocomian) and Late Cretaceous (Turonian) marine shale. Farther east, Norris (1977) interprets about 1,800 m of Kingak Shale (Jurassic and lowest Cretaceous) to extend northward beneath the Beaufort Shelf from outcrops near the Yukon coast, where the formation overlaps pre-Ellesmerian rocks. The outcrops of Kingak Shale near Barter Island lie 30 km north of the easterly projection of the truncation edge (zero isopach) of the northward-thinning Kingak Shale. This isopach trends from near Barrow on the west to the eastern Sadlerochit Mountains, 50 km south-southwest of Barter Island. Thus, a thick and extensive section of the Jurassic Kingak Shale appears to be included at the base of the Western Beaufort Shelf sedimentary prism beneath the shelf to the east, but not to the west, of eastern Camden Bay.

Structure

The Western Beaufort Shelf contains three terranes of contrasting geologic structure. In the first structural terrane, which extends from Camden Bay to the Alaska-Yukon boundary, the inner half of the shelf is underlain by two large, compound structural arches or anticlines and several much smaller anticlines (Figs. 5 and 13A). The largest arch exceeds 200 km in length and 10 to 15 km in width; its maximum amplitude exceeds 4 km. The arches and anticlines are subparallel to the adjacent arcuate coastline and to long, large-amplitude onshore folds, such as Marsh anticline, that lie in front of the northward salient of the Brooks Range in northeasternmost Alaska and northern Yukon Territory. The folds terminate along the projection of the structural front which bounds the west face of this salient (Fig. 5). This feature was informally named the Shaviovik Front by the late Sankey L. Blanton (oral communication, 1977). The outer half of the shelf in the first terrane is underlain by a monocline that dips seaward subparallel to the seabed out to the main shelf break, where the beds are dropped by slumping onto the continental slope.

The crests of the large arches are underlain at depths as shallow as 0.5 km by strata with seismic velocities of 3.5 km/sec or more, which are appropriate for the Cretaceous and Jurassic clastic sedimentary rocks of the region. Preliminary interpretations of CDP seismic sections indicate that in places the arches also contain south-dipping reverse faults that, on one seismic line, apparently dip about 15° S (Fig. 13A). The folding is as young as Neogene, and locally Quaternary, since beds of these ages are affected in Marsh anticline, which underlies the Arctic Coastal Plain near Camden Bay.

The arches and associated folds are somewhat similar in geometry and tectonic position to the long, west-trending, décollement-related thrust-folds of the Colville foredeep north of the Brooks Range and west of the Shaviovik Front, although the folding occurred at very different times in these two areas. The eastern folds are thought to be related to Neogene uplift and northernward translation of the northeast salient of the Brooks Range, whereas the folds of the Colville foredeep are related to Laramide (Cretaceous and early Tertiary) uplift and relative northward translation of the Brooks Range west of the Shaviovik Front. A Laramide age is inferred because the thrust folds deform Albian and Upper Cretaceous beds north of the Brooks Range and are in turn deformed in the Chukchi syntaxis, which is onlapped by Paleogene(?) beds in Hope basin.

The northern, and apparently larger, of the offshore arches dies out near western Camden Bay. Off Canning River, 15 km west of our westernmost crossing of this structure, only down-to-the-basin normal faults with displacements of 100 or 200 m are seen on seismic profiles. Shallow water limited our profiles here to the outer two-thirds of the continental shelf, so we have no data as to whether the southerly arch or related structures continue westward on the inner shelf.

The second structural terrane of the Western Beaufort Shelf, which lies offshore between the Canning River and Cape Halkett, is characterized by a monocline that dips typically 20 to 60 m/km seaward (Fig. 13B). This feature is broken on the inner and mid-shelf by small down-to-the-basin normal faults that are more or less parallel to the shelf edge. The faults become more numerous toward the shelf edge, where large down-to-the-basin gravitational failures dominate the structure.

The third structural terrane lies west of Cape Halkett. Here normal faults are prominent and a long structural high (Fig. 13C) underlies the outermost shelf. The sedimentary section beneath the outer shelf contains intraformational slumps and growth faults at least as far west as 160° W. long (Figs. 10 and 13C). The outer shelf structural high is syn- and post-depositional, and it therefore did not serve as a dam which trapped the deposits of the Western Beaufort Shelf sedimentary prism. The high is 20 to 25 km wide and extends as a continuous or semicontinuous feature from western Harrison Bay to at least 160° W., a distance of 350 km (Figs. 5 and 7). Its amplitude is typically 0.3-0.5 km at depths of about 1 km, and in places as much as 1.5 km at depths of 1.5 to 2.0 km. Preliminary interpretation suggests that the feature was produced by rotation along normal or growth faults (Fig. 13C) during Late Cretaceous and Tertiary time. On one CDP seismic section the growth fault dips about 50° N. and displacement is down to the north about 1.5 km. An analogous but smaller and discontinuous feature, locally obscure, extends from Harrison Bay to Camden Bay.

Block Glides

The surface of the outermost continental shelf between 155° W. long on the east and beyond 158°30' W. long on the west is broken by multiple open cracks that deepen seaward toward the shelf break (Figs. 2 and 14). Water depth in the affected areas is 70 to at least 350 m. Similar features buried beneath Holocene sediment and low scarps border the zone on the south. The cracks and associated features are thought to be the result of Holocene block gliding. The affected sediments are flat lying, as much as 140 m thick, and readily penetrated by low-energy acoustic signals. They probably consist of poorly consolidated Quaternary deposits. Reflection characteristics and the ability to support deep open cracks suggest that the upper part of the section, which is well bedded, consists of lutite and fine sand. The lower part is more homogeneous and probably lutite, except for intervals characterized by broken, irregular reflectors. These intervals are inferred to be slip zones over which the large blocks bounded by the observed cracks glide toward the shelf break. The gentle seaward dip of the slip zones, about 1°, and the inferred parallelism of the slip zones and bedding suggest that the slippage occurs within beds that are weak or susceptible to liquefaction. The block-glide terrane is adjacent to Barrow Sea Valley and the northeast-flowing Alaskan Coastal Water, which may be supplying sediment in the silt and very fine sand grades typical of liquefiable sediments.

The open cracks are commonly as deep as 8 m to 17 m, and one exceptional crack is 37 m deep. Downward, they persist as filled cracks and closed fractures to depths of 40 or 50 m, and locally to 75 m below the seabed, ending at the inferred slip zones. The cracks are typically alined subparallel to the shelf break and spaced 100 m to 500 m apart. Their spacing in general decreases seaward. The fact that many of the cracks are unfilled indicates that the block gliding is still an active, or potentially active, process. Three lower-level slip zones and glide sheets have been recognized in places beneath the active, or quasi-active surficial glide sheet on high-resolution seismic records.

Bedding Plane Slides

A mosaic of bedding plane slides similar in origin and character to the block glides underlies the upper half of the Beaufort Ramp between 148° W. long and the Mackenzie Sea Valley, a distance of about 300 km (Figs. 2 and 15). The slides are 10 to 43 km long in the direction of slip and 70 to 230 m thick.

The dip of the basal slip planes is typically 0.5° to 1.5°. The slides occur in a downslope-thinning prograded wedge of Quaternary(?) sediment beneath the upper Beaufort Ramp seaward from the crestal zones of mid-shelf anticlines. Over most of their length the upper parts of the slide masses are slabs of soft sediment broken by many extensional fractures. The lower beds appear on seismic profiles to be churned and dismembered. Variation in thickness of the slides of about 20 to 50 percent, caused by internal flowage in the lower beds, is superimposed upon a general downslope thinning of the wedge of sediment in which the slides developed.

At the landward margin of the Beaufort Ramp, near the 60-m isobath, the slides are bounded by well-defined slip-plane scarps and pull-apart grabens. The slide toes are usually low bulges that merge with the gently sloping seabed. Presumably, the slip planes dissipate their displacement downslope mainly by internal distortion within the lower part of the slide. The slip planes are subparallel to bedding, a geometry that suggests the shearing occurred in relatively weak or sensitive strata. Estimates of the horizontal slip at the head of well-developed slides range from 0.2 to 2.3 km, with a median value of about 1 km.

Near 145° W. long the lower 15 km of the slide is only 20 to 30 m thick and consists of surficial sediment with well-developed bedding that is parallel to the seabed and the slide plane. This thin part of the slide is characterized by numerous extension cracks 0.25 to 1.5 km apart, measured down the slope, and closely resembles the block glides west of 151° W. long. The thin slide extends to the shelf edge, where it slumps down the upper continental slope.

According to Hopkins (1973), sea level in the Bering Sea dropped to about 130 m below the present level during the penultimate Pleistocene regression, approximately 125,000 years ago, and to 90 to 100 m below present sea level during the maximum late Wisconsin regression, approximately 15,000 to 20,000 years ago. The heads of the bedding-plane slides, now lying at depths of 57 to 70 m (Fig. 15), were thus emergent during the Pleistocene regressions in sea level. Emergence, which increased the gravitational load on the sediment at the head of the ramp by removing the buoyant support of the upper part of the water column, is thought to have triggered the bedding-plane slides. Grabens and scarps at the head of the slides and the lack of evidence for undercutting at the toes support this hypothesis. The apparent morphologic youthfulness (i.e., roughness) of the slides suggests that they moved during or after the maximum late Wisconsin regression rather than during the older, penultimate regression some 110,000 years earlier. Superimposed multiple slip planes observed within the slide masses on some of our high-resolution seismic profiles suggest the possibility that the remnants of older slides, perhaps related to older regressions, may be present beneath the inferred late Wisconsin slides.

Diapiric Folds Beneath the Continental Rise

Diapiric folds disrupt bedding in the sedimentary rocks of the lower Alaskan Continental Slope and Rise and adjacent parts of the Canada Rise east of 146° W. long (Figs. 5, 13A and 17). The folds are 5 to 10 km apart along lines normal to the slope and as much as 0.5 km in amplitude. Some appear to be elongate parallel to the slope, but for most,our lines are too widely spaced to distinguish between ridge or dome shapes. The geometry and position of the diapiric folds suggest that they rose as a consequence of the loading of large slides and thick clastic sediment onto the lower continental slope and rise. Equally large slides and thick sediment are found, however, on the slopes west of the diapirs. This distribution suggests that an easily deformed sedimentary unit susceptible to diapirism underlies the continental shelf and rise east, but not west, of 146° W. long. Seismic interval velocities in the diapiric material vary from 2.6 to 3.0 km/sec, appropriate to shale, whereas seismic velocities in the neighborhood of 4.6 km/sec, appropriate to salt, were not observed. On the basis of their apparent stratigraphic position (Fig. 13A), we tentatively suggest they may be lower Tertiary.

Because the diapiric folds buckle the seabed and pond the youngest (Holocene) sediments and slumps on the continental slope and rise, it is likely that diapirism is active now, or at least was active during the Holocene. The physiographic distinction between continental slope and rise is obscured in the area of the diapiric folds because the folds have locally transformed the Alaska Rise from a smooth sedimentary apron to a series of bathymetric steps. In places the diapiric folds have so thoroughly disrupted the Alaska Rise sedimentary prism that bedding is obscure. Beneath adjacent parts of the Mackenzie Cone, however, some diapiric folds underlie undisturbed beds more than 1,500 m thick. Low seismic velocities and estimated sedimentation rates indicate that the undisturbed beds are Neogene and Pleistocene. Thus, some of the diapirs appear to have been inactive since the Neogene.

Solid Gas Hydrate

Much of the continental slope and rise north of Alaska is underlain by an unusually strong seismic reflector (Grantz et al., 1976) that crosses bedding planes at many places. The reflector mimics, or simulates, the bathymetry of the sea floor, yet lies some 200 to 600 m beneath it (Figs. 13A, 13B, and 17). This bottom-simulating reflector (BSR) occurs only where the sea is deeper than 400 to 600 m and was recognized beneath waters as deep as 3,200 m. The BSR was identified beneath some 60 percent of our seismic lines on the Alaska Slope and Rise where the water depth exceeded 400 to 600 m. It is most strongly developed beneath bathymetric highs and weakest, and indeed commonly absent, beneath bathymetric lows. In a few places where it is particularly well developed beneath highs, the underlying reflectors are bowed downward. These observations suggest that the BSR represents the interface of a zone of free gas in the sediments and an overlying impervious cap. Because the BSR lies at the approximate pressure-temperature boundary at which solid gas hydrates of methane and some multicomponent natural hydrocarbon gases break down to a gas + water phase, we postulate that it is produced by free gas trapped beneath an impermeable cap of sediment cemented with gas hydrate.

Canada Basin

Water depths exceeding 3,500 m and dispersion patterns of Lg-phase seismic waves (Oliver et al., 1955) indicate that the Canada Basin is underlain by oceanic crust, and was therefore formed by sea-floor spreading. Some workers (e.g., Vogt and Ostenso, 1970; Hall, 1973) have postulated the spreading center to be the Alpha-Mendeleev Ridge, which crosses the basin from Greenland to eastern Siberia. Carey (1958), Tailleur (1969 and 1973), and Rickwood (1970) suggest that the Canada Basin opened by a relative rotation of northern Alaska away from the Canadian Arctic Islands about a pole near the Mackenzie Delta or in Alaska. Herron et al. (1974) postulate that the Canada Basin formed by rifting of the Kolymski massif of eastern Siberia away from the Canadian Arctic Islands along a northerly trending spreading axis, and Yorath and Norris (1975) propose a northerly trending axis of assymetric spreading beneath the head of the continental rise in the eastern Beaufort Sea.

The inferred thickness of sediment in the southern part of the Canada Basin is shown by dotted isopach formlines in Figure 5. The thicknesses are based on three sonobuoy refraction profiles and the assumption that differences in depth of the seabed reflect differences in the thickness of sediment that has accumulated on oceanic crust in the basin. As the age of the Canada Basin is inferred from stratigraphic relations to be Jurassic or Early Cretaceous, differences in age from the center to the sides are probably not significant to thickness estimates. We therefore assumed that all points in the basin are in isostatic equilibrium and generated isopach formlines from the bathymetric contours by correlating the isobaths with sediment thickness at three sonobuoy refraction stations (Fig. 5). Sediment density for our model was based on the sonobuoy-derived velocities, which suggest that the average density of the sedimentary fill beneath the Canada Rise is about 2.2 g/cm^3. We assumed a mantle density of 3.4 gm/cm^3 and that the 5.3 km/sec, 4.9 km/sec, and 4.6 km/sec refractors are from the top of oceanic layer 2 (basalt). On the basis of these assumptions, about 4.5 km of sediment underlies the Canada Abyssal Plain. Hall (1973), on the basis of seismic reflection data, reports that more than 2 km of sediment underlies the northern part of this plain.

An estimate of the age of the Canada Basin can be made from the thickness of sediment that it contains. If we assume that oceanic crust beneath the basin was isostatically depressed by the overlying sedimentary prism, we can calculate the depth of an "unloaded" crust and compare it with empirical age-depth curves for the Atlantic and Pacific sea floor. Such curves were compiled most recently by Parsons and Sclater (1977). Using mantle density 3.4 g/cm^3, sediment density 2.2 g/cm^3, and water density 1.03 g/cm^3, our data from the three sonobuoys in deep water give a "corrected" depth to basement of 6.4 km for the southern Canada Basin. This depth corresponds to a crustal age greater than 120 m.y.b.p. on the Parsons-Sclater curves. In this region, however, the curves have a low slope, and small uncertainties in the unloaded depth produce large uncertainties in age of sea floor. Thus the significance of the "unloaded" depth we obtained (6.4 km) is that it argues for a Mesozoic age for the crust of the Canada Basin.

Segmentation of the Alaskan Continental Margin

The continental margin north of Alaska consists of three sectors of contrasting geology separated by onshore extensions of possible oceanic fracture zones. The Chukchi sector is characterized by the North Chukchi basin and the Chukchi Continental Borderland; the Barrow sector is characterized by the Barrow arch, where Cenozoic sedimentary rocks are relatively thin or absent and where Mississippian to Neocomian sedimentary rocks coarsen, thin, and wedge out to the north; and the Barter Island sector is characterized by thick Cenozoic as well as Jurassic and Cretaceous clastic sedimentary rocks that appear to have been derived from the south and to become thicker and finer grained to the north. Large Neogene folds in Jurassic to Neogene strata and the northward salient of the northeastern Brooks Range also characterize this sector.

The Chukchi and Barrow sectors are postulated to be separated by a fracture zone along the northwest flank of the Barrow arch west of 160° W. long. The Chukchi Borderland may consist of fragments of continent that were transported relatively north-northeast, away from the Chukchi Shelf, along the fracture zone to create the North Chukchi basin. The Barrow and Barter Island sectors may be separated by a fracture zone near eastern Camden Bay, but its location and trend have not been recognized. The northern coastal plain and shelf east of the postulated fracture zone is apparently underlain by a thick section of Jurassic sedimentary rocks that is thin or absent to the west (Fig. 13A, 13D).

The character and distribution of the Jurassic and Neocomian bedded rocks are critical for understanding the geometry and age of the rifted Alaskan margin. On the east, in the Barter Island sector, Jurassic and Neocomian sedimentary rocks in northern Yukon Territory (Kingak Shale) appear to have southern sources and to fine northward (Young et al., 1976; Figs. 4, 5, and 7). These rocks are interpreted to be 1,800 m thick under the adjacent Beaufort Shelf

(Norris, 1977). As noted above, the Kingak Shale and the Neocomian Kongakut Formation also crop out on the Arctic Coastal Plain 30 km southeast of Barter Island. In the Barrow sector, in contrast, Jurassic and Neocomian strata have northern sources and fine southward. If projected east or east-southeast along the general trend of the depositional strike and the truncation edge of Jurassic strata on the Barrow arch, the source area would strike into the area of thick Jurassic and Neocomian marine strata inferred to underlie the coastal plain and shelf in the Barter Island sector. If projected west-northwest, the source area would strike into the deep North Chukchi basin of the Chukchi sector. These relations, and the fact that the Upper Triassic rocks of both the Barrow and Barter Island sectors were derived from northern sources (Tailleur, 1969 and 1973; Brosgé and Tailleur, 1971; Detterman et al., 1975; Norris, 1977) indicate that rifting of the Alaskan margin began in Early Jurassic time.

A northern source for the Kingak Shale and Neocomian strata of the Barrow sector is supported by subsurface stratigraphic data, but a southern source for these beds beneath the coastal plain and shelf in the Barter Island sector is less firmly based. As noted here, a southern source is inferred from a few outcrops in the Arctic Coastal Plain, preliminary interpretation of seismic records on the continental shelf, and extrapolation of facies maps of Jurassic and Cretaceous sedimentary rocks in the Mackenzie Delta region. If this distribution of source terranes is correct, it implies that in the Barter Island and Chukchi sectors Barrovia, the northern source terrane for the Ellesmerian sequence of the Arctic platform, was rifted away from the platform in Early Jurassic time. In the Barrow sector, however, the rift would have lain farther north, within Barrovia, and a large east-west-trending welt or island of the Barrovian highlands would have remained attached to the Arctic platform. The south shore of the island would have faced the epicontinental sea that covered the Arctic platform in Jurassic and Neocomian time. We propose that the postulated island was the waning northern provenance area for the Jurassic and Neocomian sedimentary rocks (Kingak Shale, Kuparuk River Sandstone, and "Pebble Shale") of the Barrow sector of northern Alaska. If additional work shows that the Jurassic and Neocomian beds beneath the coastal plain and shelf of the Barter Island sector were derived from the north, rather than from the south, then the age of rifting would have been Early Cretaceous. It would have accompanied or post-dated deposition of the Neocomian "Pebble Shale" of the Barrow sector, when sedimentation from northern sources was waning, and predated the arrival of south-sourced (Brookian) clastic sediments on the Western Beaufort Shelf in Albian time.

SUMMARY OF TECTONIC IMPLICATIONS AND CONSTRAINTS

1. The continental margin north of Alaska is of Atlantic type and was formed by rifting. Our data are compatible with the proposals of Carey (1958), Tailleur (1969 and 1973), Rickwood (1970), and Newman et al. (in press) that the Canada Basin was formed by rifting involving a relative rotation of northern Alaska away from the Canadian Arctic Islands. The pole of rotation was probably in the region of the Mackenzie Delta, as suggested by Rickwood.
2. Northern sources for the Mississippian to Lower Cretaceous clastic sediments along the Barrow arch of northern Alaska diminished in importance in Jurassic and Neocomian time and were removed by the close of Neocomian time. Removal is attributed by Tailleur (1969 and 1973) to opening of the Canada Basin by rifting in post-Triassic, probably Early Jurassic time. Rickwood (1970) proposes opening in the Late Jurassic and Early Cretaceous. Our tentative interpretation of data on the character and distribution of Jurassic and Neocomian strata in the Barter Island sector in Young et al. (1976), Norris (1977); Reiser et al. (1978) and the present report suggests that rifting may have begun during the Early Jurassic. A submarine canyon cut

more than 1.4 km into seaward-prograded Albian marine clastic deposits between Barrow and Harrison Bay and filled with Turonian marine sediments (Collins and Robinson, 1967, p. 183) indicates that the Canada Basin was open by middle Cretaceous time.

3. Continental extensions of oceanic fracture zones related to the geometry of rifting are postulated to have divided the northern Alaska continental margin into three sectors of contrasting structure and stratigraphy. The northeasterly trend of the postulated fracture zone between the Chukchi and Barrow sectors is compatible with proposals that rifting occurred about a pole of rotation near the Mackenzie Delta. Stratigraphic contrasts in the three sectors suggest that the postulated rift lay farther south in the Chukchi and Barter Island sectors than in the Barrow sector. These relations also imply that in early post-rift (Jurassic and Neocomian) time Barrovia was reduced to an easterly-trending island beneath the present outer continental shelf and slope in the Barrow sector. East and west of the island lay deep marine embayments of the Chukchi and Barter Island sectors.

4. The Western Beaufort Shelf is underlain by a sedimentary prism of Albian (late Early Cretaceous) to Quaternary age that was prograded across a subsiding shelf underlain mainly by bedded rocks of the Franklinian sequence.

5. The great thickness of seaward-prograded sediment in the North Chukchi basin and its position between the Chukchi Borderland and the Barrow and Wrangel arches suggest that the basin is floored by oceanic crust or thinned continental crust.

6. If continental outliers of the Chukchi Borderland originally occupied what is now the North Chukchi basin, it would remove a major obstacle to a simple geometric fit of opposite margins of the Canada Basin. Such a fit would be required if the basin formed by rotation in the manner proposed by Carey

(1958), Tailleur (1969 and 1973) and Rickwood (1970).

7. The shale(?) diapirs that underlie the North Chukchi basin and the continental slope and rise off the Barter Island sector occur in the deepest basins along the present northern Alaskan continental margin.

8. Pre-Mississippian basement (the Franklinian sequence) underlies the Barrow sector of the Western Beaufort Shelf and extends seaward to the upper continental slope (Fig. 13B). This distribution suggests that the slope may approximate the position of the initial rift that is postulated to have formed the Canada Basin. A zone of subsided continental crust seaward of the boundary is not precluded.

9. Barrow arch may be thought of as a hingeline created by Jurassic to Neocomian rifting of the Arctic platform. The north flank of the arch was created by subsidence, normal faulting, and erosional truncation near the rifted margin. The south flank is a compound of paleoslope and of tilting of the southern part of the Arctic platform in response to sediment loading. The sediments consisted of Jurassic(?) and Early Cretaceous nappes of the Brooks Range foreland thrust belt and the thick Brookian prism of Jurassic, Cretaceous and Tertiary clastic sediment deposited in the Colville foredeep and on the adjacent Arctic platform.

10. The progressive increase in depth of the shelf break eastward from 150° W. long toward the Mackenzie Delta may be related to formation of the seaward-tilted Beaufort Ramp. These features suggest that the outer part of the Western Beaufort Shelf east of 150° W. long subsided in response to loading of the adjacent Canada Basin by sediments of the Mackenzie Cone.

11. Thickness of sediment and depth to basement imply a Mesozoic or older age for the Canada Basin, assuming it is underlain by oceanic crust and that the age versus depth relations of Parsons and Sclater (1977) for the

North Atlantic and Pacific Oceans are applicable.

12. The broad region of Hope basin, Kotzebue Sound, lower Kobuk Valley, and Seward Peninsula appears to have constituted a Tertiary province of regional north-south crustal extension characterized by basin subsidence and block faulting. Late Cretaceous(?) and Paleogene (Laramide) extension created Hope basin athwart the western Brooks Range, a compressional orogenic belt formed principally during Jurassic, Cretaceous, and early Tertiary(?) time. Probably in part because of this extension the belt of Brooks Range rocks is much wider across Hope basin (400 km) than across the central Brooks Range (200 km). The paleoslope and normal faults that form the east edge of Hope basin terminated the physiographic Brooks Range at Kotzebue Sound by mid-Tertiary time. Neogene-Quaternary extension created normal faults, sub-basins, and ridges within Hope basin, and small sedimentary basins and block faults elsewhere in the province.

13. Chukchi syntaxis, the sharp swing in trend of typical Brooks Range rocks and structures at the Lisburne Peninsula, is thought to be the result of the superposition of thrust plates of the Herald fault zone across western Brooks Range structures during Late Cretaceous or early Tertiary time.

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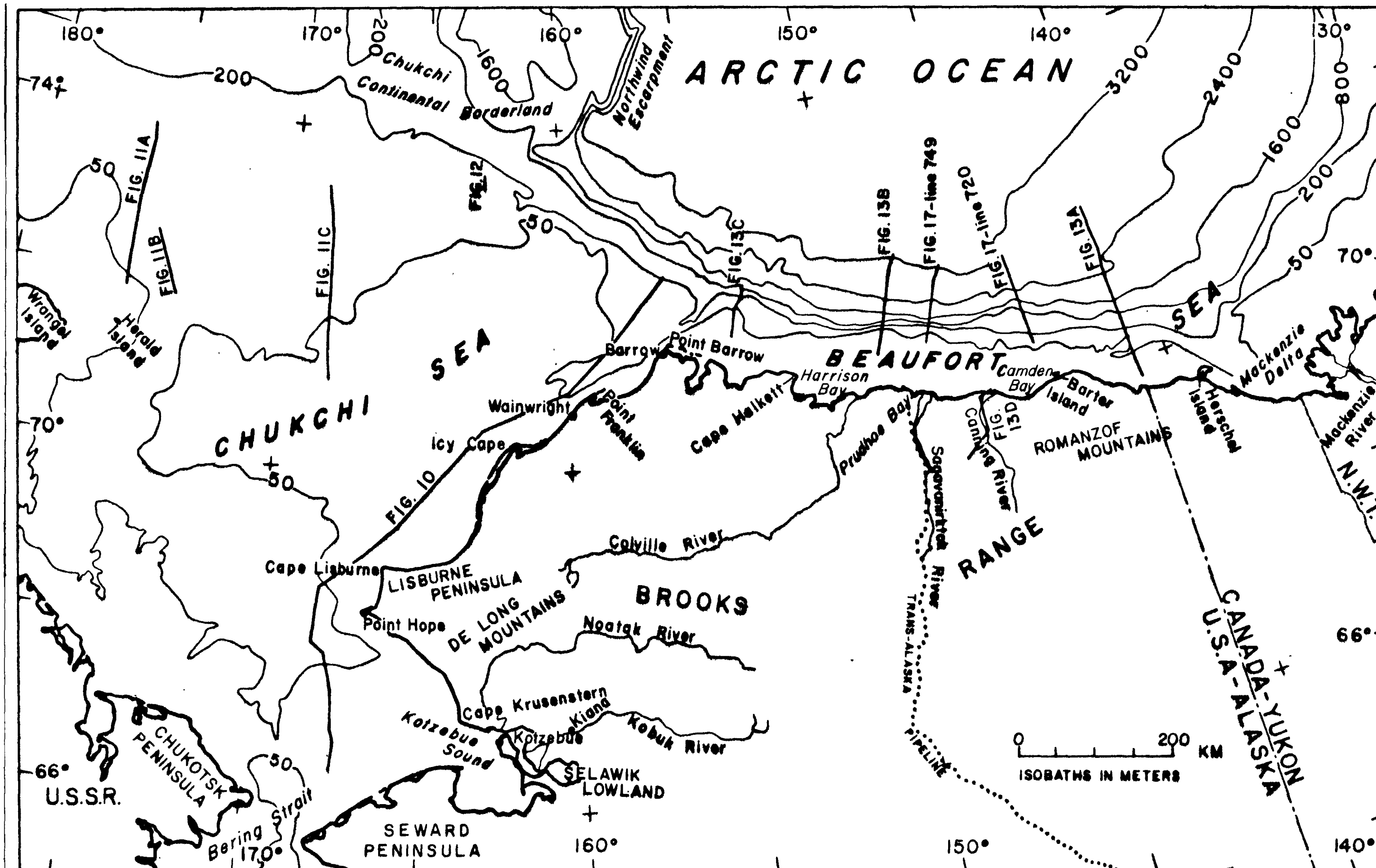


Figure 1. Bathymetry and place names in the Beaufort and Chukchi Seas and vicinity and location of seismic profiles in Figures 10, 11, 13, and 17.

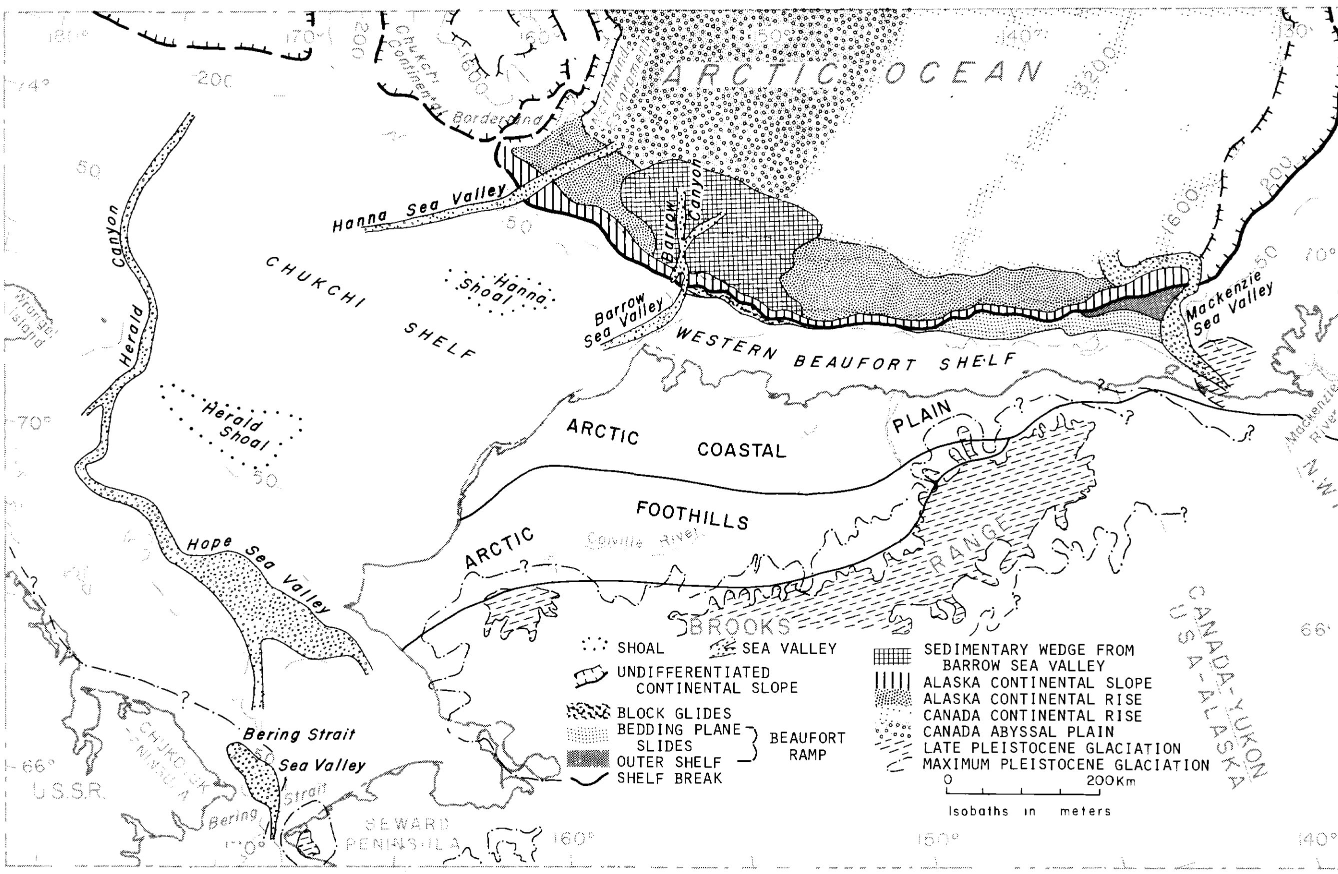


Figure 2. Physiographic features of the Beaufort and Chukchi Seas. Extent of glaciation from Alaska Glacial Map Committee, 1965; Geological Survey of Canada, 1968; Nelson and Hopkins, 1972; and D. M. Hopkins, personal communication, 1978.

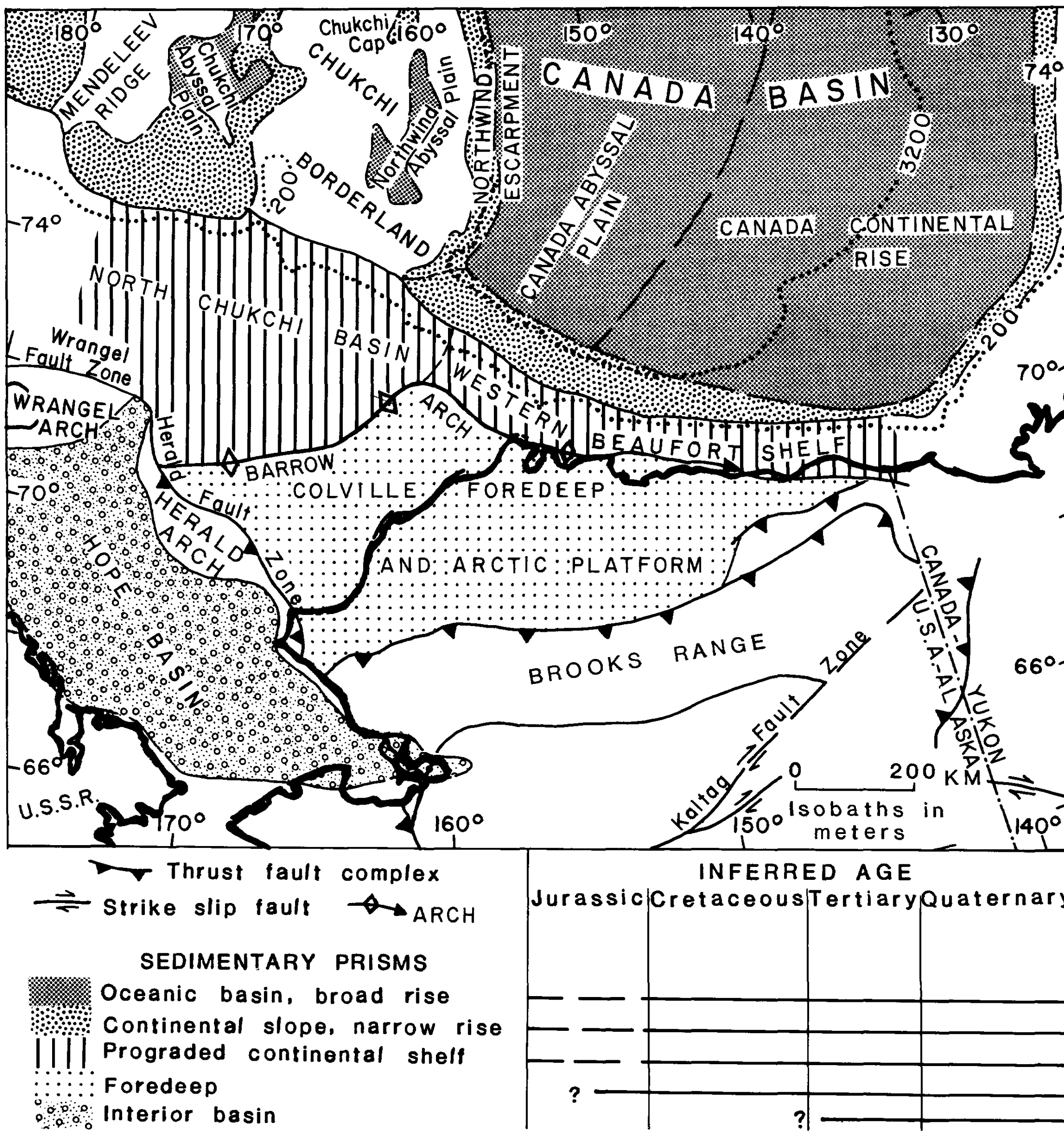


Figure 3. Post-Triassic tectonic provinces and sedimentary prisms of the Beaufort and Chukchi Seas and vicinity.

Geologic Age			Provincial Sequences	Western North Slope: Stratigraphic Units (South) — (North)	Lithology	Thickness (Meters)
Cenozoic	Quaternary		Brookian	Gubik Formation	Marine sand, gravel, silt, clay.	<100-200
Cenozoic	Tertiary	Neogene	Brookian			
Cenozoic	Tertiary	Paleo-gene	Brookian			
Mesozoic	Cretaceous	Upper	Brookian	Colville Gr.	Nonmarine sandstone, conglomerate, shale, bentonite, coal	0-~350
Mesozoic	Cretaceous	Upper / Lower	Brookian	Nanushuk Gr.	Marine and nonmarine shale, siltstone, sandstone, coal, conglomerate, and bentonite.	0-3300+
Mesozoic	Cretaceous	Lower	Brookian	Fortress Mtn. Fm. — Torok Fm. ?	Marine shale, sandstone, conglomerate. — Marine shale and siltstone with foreset beds, sandstone.	1000-3000 — 400-3000+
Mesozoic	Cretaceous	Lower	Brookian / Ellesmerian	Okpikruak Fm. ? — "Pebble Shale" ?	Marine flyschoid mudstone, shale, and graywacke sandstone. — Marine shale with rounded quartz grains, chert pebbles. Coquinoid to south.	~500 to ~4500 — 100-400+
Mesozoic	Jurassic		Ellesmerian	Telavirak(?) Fm. ? Ogotoruk(?) Fm. ? — Kingak Shale ?	? — To north - Marine shale with a glauconitic sandstone facies. To south - Marine shale, chert, oil shale, limestone, and diabase.	? — <100-~1200
Mesozoic	Triassic		Ellesmerian	Shublik Fm.	To north - shale, limestone, and glauconitic siltstone and sandstone. (Includes Sag River Ss.) To south - shale, chert, oil shale, limestone.	0-225
Paleozoic	Permian		Ellesmerian	Sadlerochit Gr and Siksikpuk Fm.	To north - Sandstone, conglomerate, shale, and mudstone. To south - Argillite, chert, and shale.	0-~600
Paleozoic	Pennsyl-vanian		Ellesmerian	Lisburne Gr.	Limestone, dolomite, and chert with minor sandstone and shale.	0->2000
Paleozoic	Mississ-ippian		Ellesmerian	Lisburne Gr. / Endicott Gr.	Sandstone, mudstone, and shale with interbeds of limestone, conglomerate, and coal.	0->1000
Paleozoic	Pre-Miss-issippian		Frank-linian	Iviagik Group of Martin, 1970	Argillite and graywacke.	Thousands of meters.

4A. Phanerozoic stratigraphy of the western North Slope of Alaska.

Geologic Age			Provincial Sequences	Eastern North Slope: Stratigraphic Units (South) (North)	Lithology	Thickness (Meters)
Cenozoic	Quaternary		Brookian	Gubik Formation	Marine sand, silt, gravel and clay.	10-200
Cenozoic	Tertiary	Neogene	Brookian	Sagavanirktok Formation	Poorly consolidated nonmarine and shallow marine shale, sandstone, and conglomerate with some carbonaceous shale, lignite, and bentonite.	0-2500
Cenozoic	Tertiary	Paleogene	Brookian	Sagavanirktok Formation		
Mesozoic	Cretaceous	Upper	Brookian	Colville Group	Upper beds - Marine and nonmarine sandstone, siltstone, shale, conglomerate, coal, and tuff. Lower beds - Marine sandstone, siltstone, organic shale, and tuff.	900-3600
Mesozoic	Cretaceous	Lower	Brookian	Nanushuk GP. (east of Canning River)	Marine graywacke, siltstone, shale (Bathtub Graywacke, Tuktu Fm.).	>200-1200
Mesozoic	Cretaceous	Lower	Ellesmerian	"Pebble Shale" - Kongakut Fm.	Marine organic siltstone and shale with rounded quartz grains and chert pebbles. Quartzose sandstone (Kemik member) near base locally.	40-700
Mesozoic	Jurassic		Ellesmerian	Kingak Shale (Includes Kuparuk River Sandstone at top locally) ?	Marine shale, siltstone, and organic paper shale.	0-1200
Mesozoic	Triassic		Ellesmerian	Shublik Formation	Fossiliferous marine argillaceous limestone and dolomite, shale, and sandstone. Upper beds locally quartzose sandstone (Sag River and Karen Creek sandstones).	0-140
Mesozoic / Paleozoic	Triassic / Permian		Ellesmerian	Sadlerochit Group	Upper beds - Marine and nonmarine quartz and chert-rich sandstone, conglomerate, mudstone, and shale. Lower beds - Marine sandstone and siltstone with interbeds of shale; local conglomerate and chert.	0->700
Paleozoic	Pennsylvanian		Ellesmerian			
Paleozoic	Pennsylvanian / Mississippian		Ellesmerian	Lisburne Group	Marine limestone and dolomite with chert, sandstone, and siltstone.	0-1200
Paleozoic	Mississippian		Ellesmerian	Endicott Group	Marine and nonmarine sandstone, shale, conglomerate, limestone, and coal.	0->1000
Paleozoic	Pre-Mississippian		Franklinian	(Pre-Mississipian rocks)	Argillite, graywacke, limestone, dolomite, chert, quartzose sandstone, and shale and their metamorphic equivalents.	Thousands of meters.

Figure 4B. Phanerozoic stratigraphy of the eastern North Slope of Alaska.

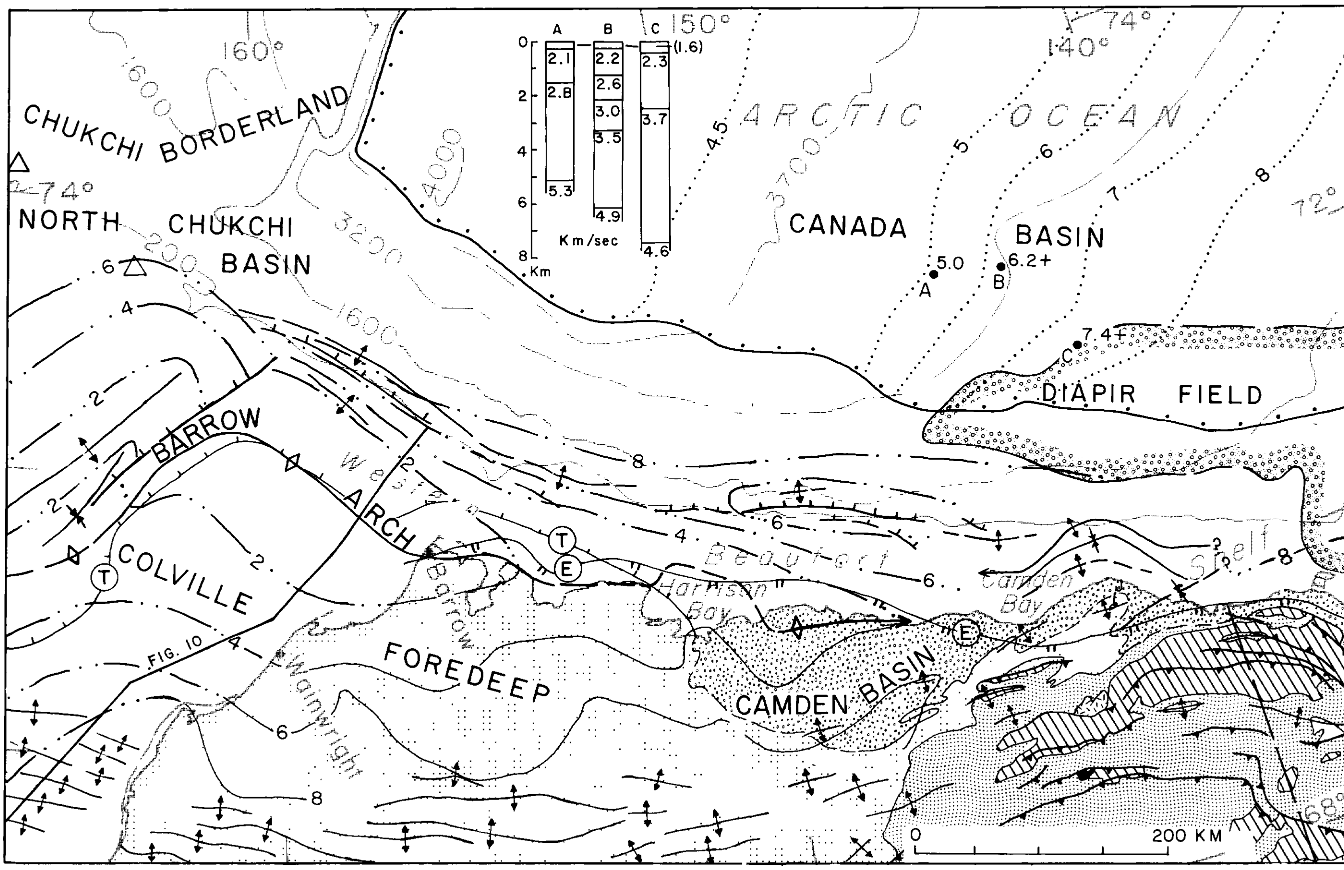


Figure 5. Geologic structure and thickness of sedimentary rock beneath the Western Beaufort Shelf and southern Canada Basin. See Figure 6 for explanation.

EXPLANATION FOR FIGURES 5, 8, AND 9

QUATERNARY AND TERTIARY CLASTIC SEDIMENTARY ROCKS, MARINE AND NONMARINE

QUATERNARY AND TERTIARY VOLCANIC ROCKS

CRETACEOUS CLASTIC SEDIMENTARY ROCKS, MARINE AND NONMARINE

dK - WHERE STRONGLY DEFORMED

CRETACEOUS VOLCANIC ROCKS - ANDESITIC IN ALASKA, ACIDIC IN CHUKOTKA, U.S.S.R.

JURASSIC TO MISSISSIPPIAN SHELF CARBONATE AND CLASTIC SEDIMENTARY ROCKS (ELLESMERIAN SEQUENCE)

J - Kingak Shale outcrop southeast of Barter Island

PRE-MISSISSIPPIAN SEDIMENTARY AND VOLCANIC ROCKS, GENERALLY STRONGLY DEFORMED OR METAMORPHOSED

CRETACEOUS TO UPPER PALEOZOIC PLUTONIC ROCKS

JURASSIC TO PERMIAN OPHIOLITES AND ULTRAMAFICS

ACOUSTIC BASEMENT. STRONGLY DEFORMED OR METAMORPHOSED CRETACEOUS TO PRECAMBRIAN ROCKS

dK? - STRONGLY DEFORMED CRETACEOUS(?) BEDDED ROCKS

pK - PRE-CRETACEOUS(?) ROCKS

2

STRUCTURE CONTOUR, STRUCTURE FORMLINE ON FRANKLINIAN SEQUENCE NORTH OF HERALD ARCH, ON ACOUSTIC BASEMENT SOUTH OF HERALD ARCH

4

ISOPACH FORMLINE, MINIMUM THICKNESS OF SEDIMENT IN CANADA BASIN, KM

200

ISOBATH, METERS

SOUTH BOUNDARY OF CANADA BASIN

5.0

A

SONOBUOY STATION SHOWING MINIMUM THICKNESS OF SEDIMENT, KM

ANTICLINE

SYNCLINE

ARCH

THRUST FAULT, SAWTEETH IN UPPER PLATE

NORMAL FAULT, HACHURES ON DOWN-THROWN SIDE

E

NORTH LIMIT OF ELLESMERIAN ROCKS, PRE-JURASSIC EAST, AND PRE-CRETACEOUS WEST, OF CAMDEN BAY

T

SOUTH LIMIT, TERTIARY SEDIMENTARY ROCKS

SHALE(?) DIAPIR

UNIVERSITY OF WASHINGTON DREDGE SAMPLES

Figure 6. Explanation for geologic structure maps, Figures 5, 8, and 9.

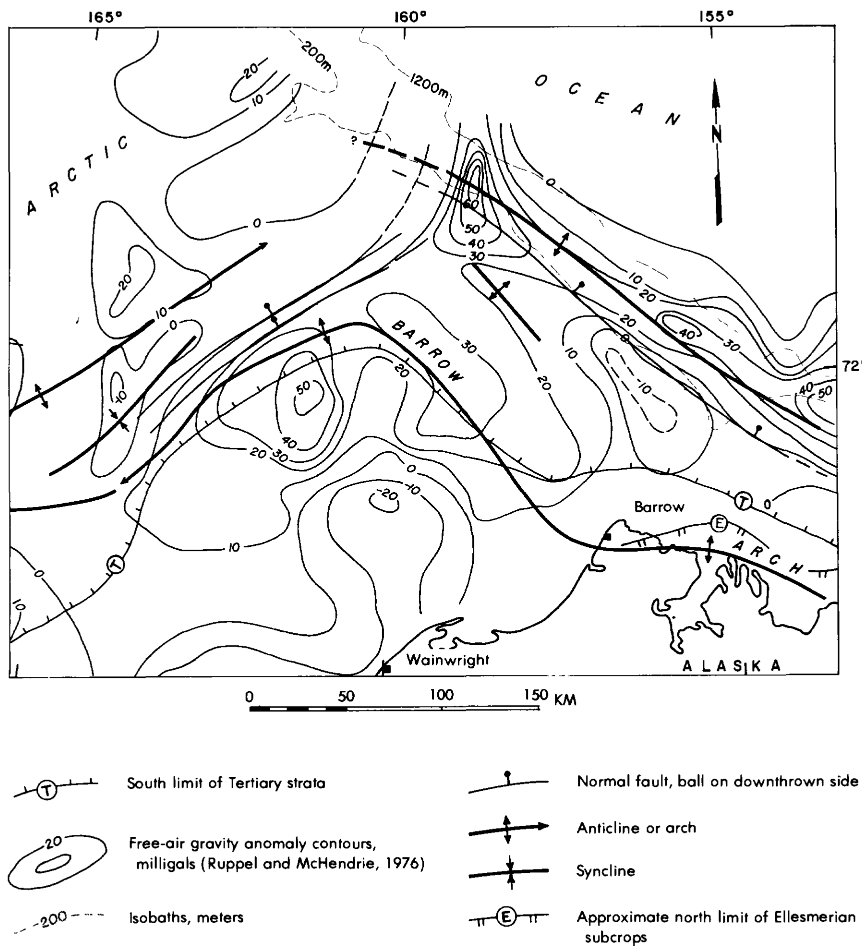


Figure 7. Seismic reflection structure and free air gravity anomalies near the change in trend of the Barrow Arch at 72° N, 160° W.

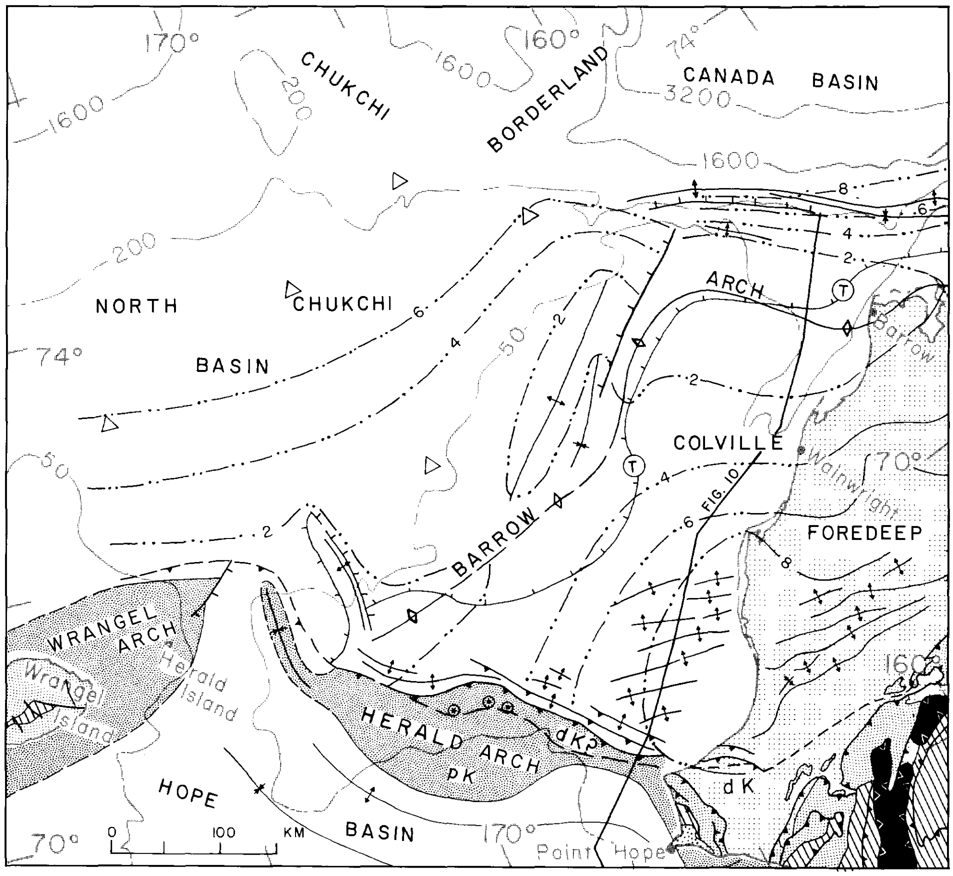


Figure 8. Geologic structure and thickness of sedimentary rock beneath the northern Chukchi Sea. See Figure 6 for explanation.

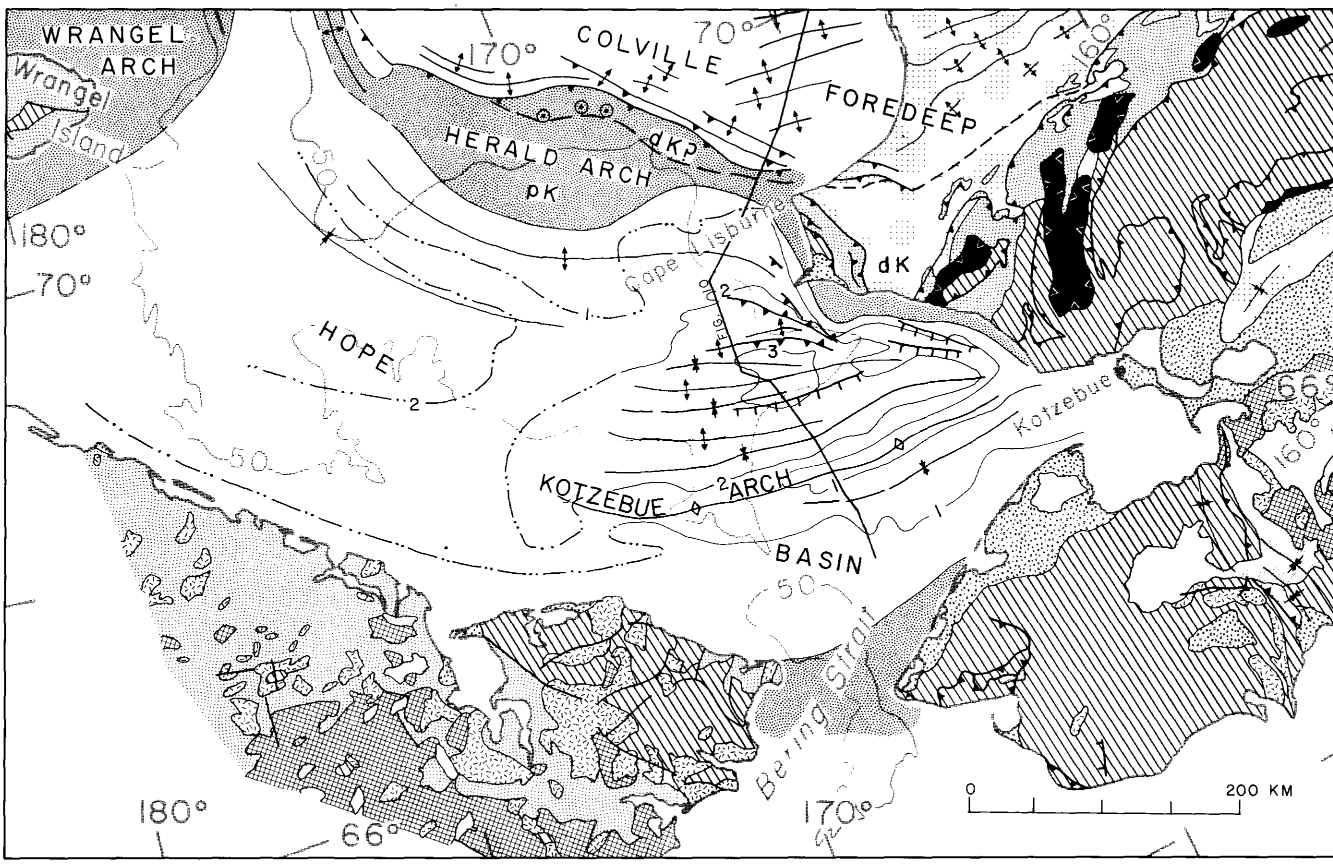


Figure 9. Geologic structure and thickness of sedimentary rock beneath the southern Chukchi Sea. See Figure 6 for explanation.

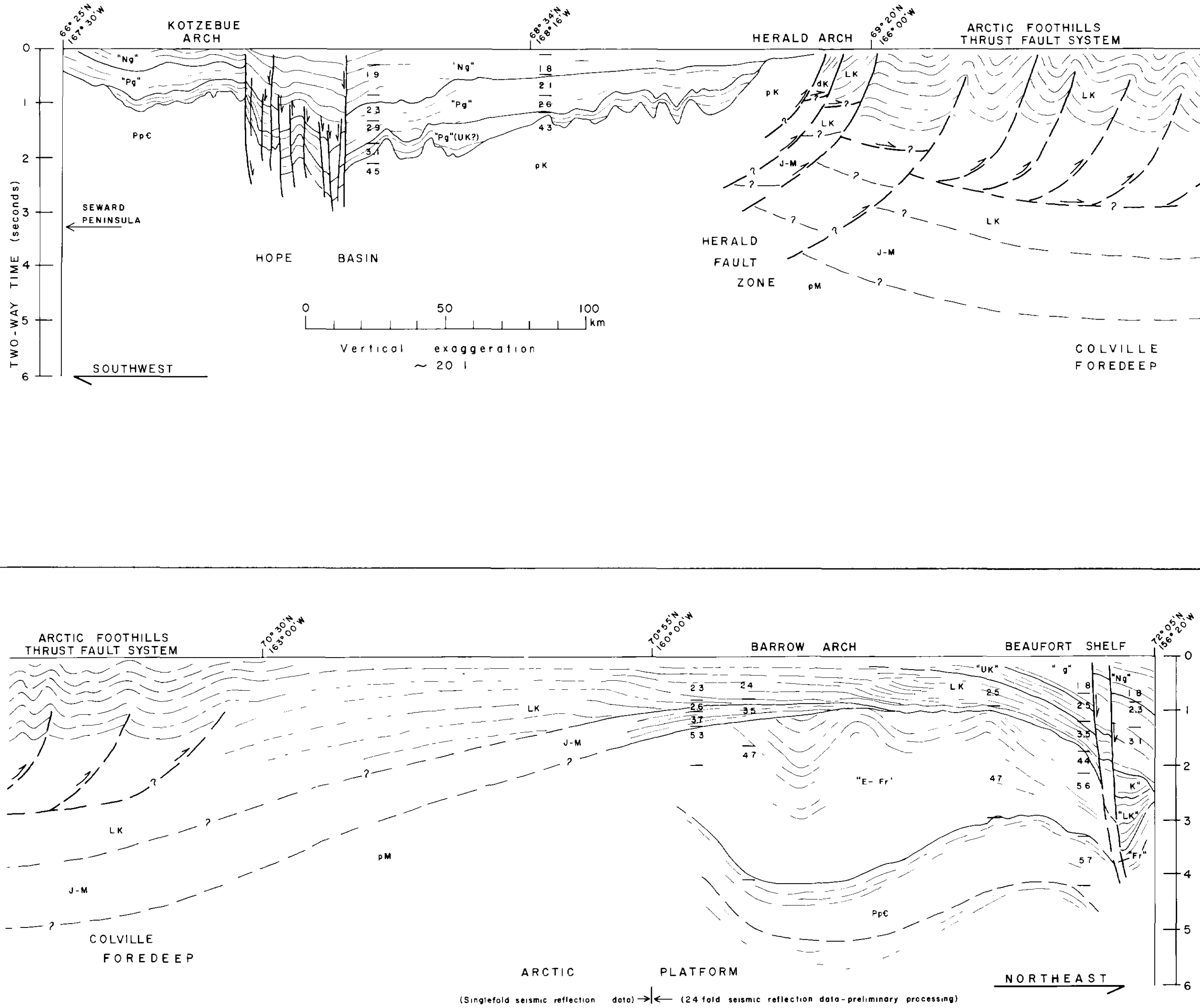
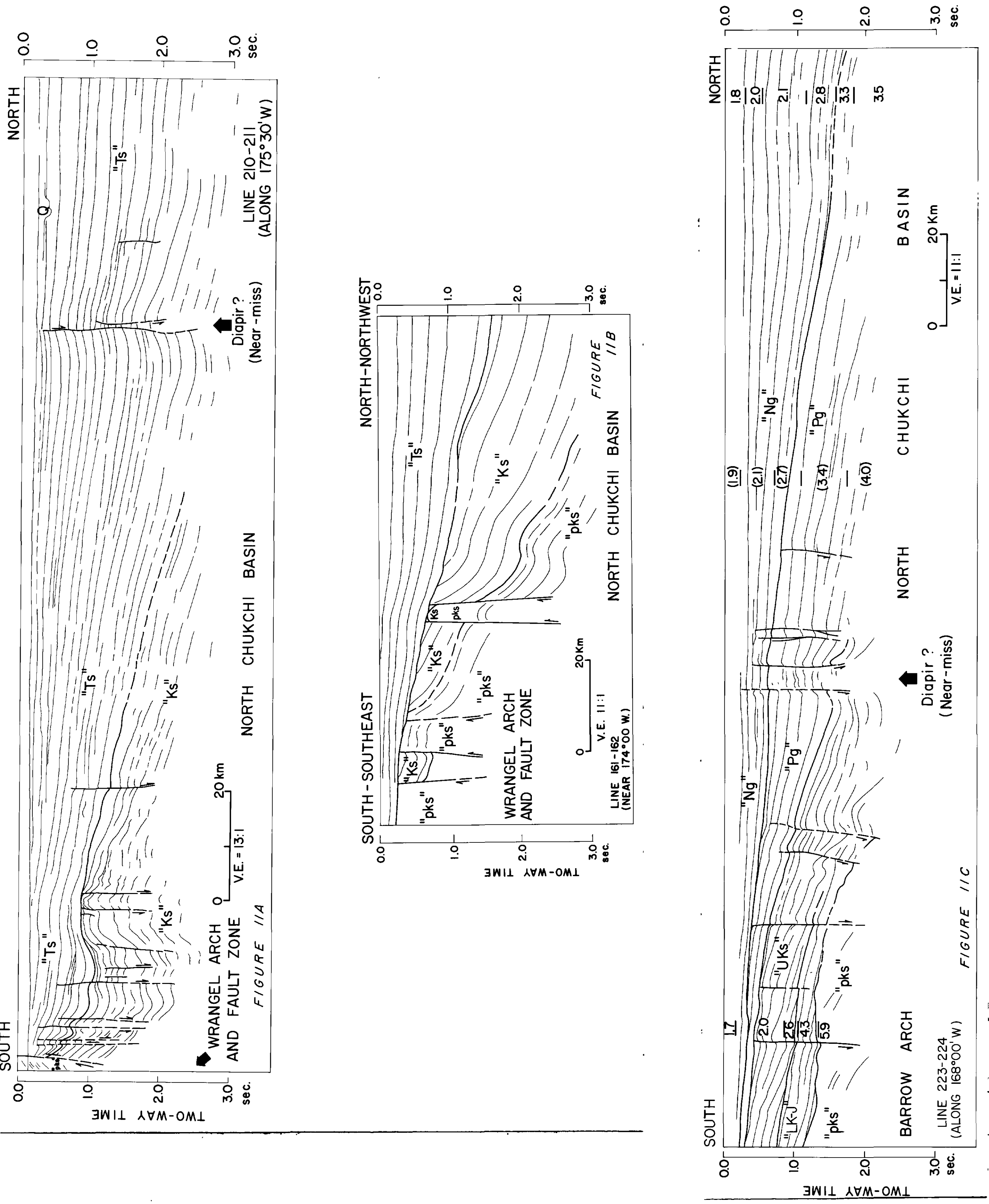


Figure 10. Geologic cross section interpreted from seismic reflection data in the eastern Chukchi Sea between the continental shelf break and southern Hope Basin. See Figure 1, 8, and 9 for location. Sedimentary strata shown are "Ng"-Neogene(?) clastics, "Pg"-Paleogene(?) clastics, "UK"-Upper Cretaceous(?) marine clastics, "LK"-Lower Cretaceous marine and nonmarine clastics, "J-M"-Mississippian to Jurassic (Ellesmerian) marine and nonmarine clastics and carbonates, "E-Fr"-Lower Ellesmerian or Franklinian clastics, and "dK"-strongly deformed Cretaceous clastics. Undifferentiated rock units are pK-pre-Cretaceous, pM-pre-Mississippian, PpC-Paleozoic and(or) Precambrian. Seismic CDP interval velocities in km/sec.



igure 11A,B,C Geologic interpretations of seismic sections across the North Chukchi Basin. See Figure 1 for location. Inferred clastic sedimentary rock units are Q-Quaternary, "Ts"-Tertiary, "Ng"-Neogene, "Pg"-Paleogene, "Ks"-Cretaceous, "UKs"-Upper Cretaceous, "LK-J"-Jurassic-Early Cretaceous, "pKs"-pre-Cretaceous(?). Seismic sonobuoy interval velocities (Fig. 13C) in km/sec.

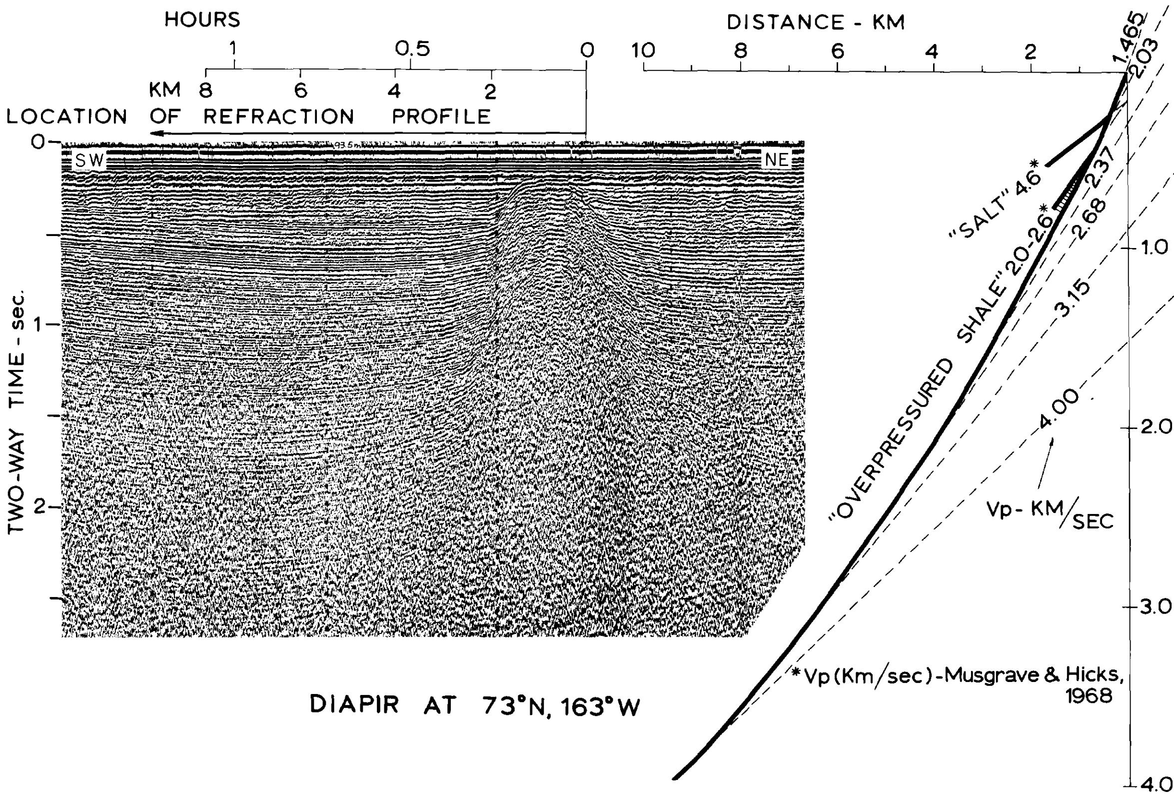


Figure 12. Seismic reflection and refraction profiles across shale(?) diapir at 73° N, 163° W, North Chukchi Basin.

Figure 13A,B,C Geologic interpretations of seismic sections across the Western Beaufort Shelf (Figs. 13A-C) and a cross section near the Canning River based on correlated test wells (Fig. 13D). See Figure 1 for location. Seismic CDP interval velocities (Figs. 13A,B, and C) in km/sec.

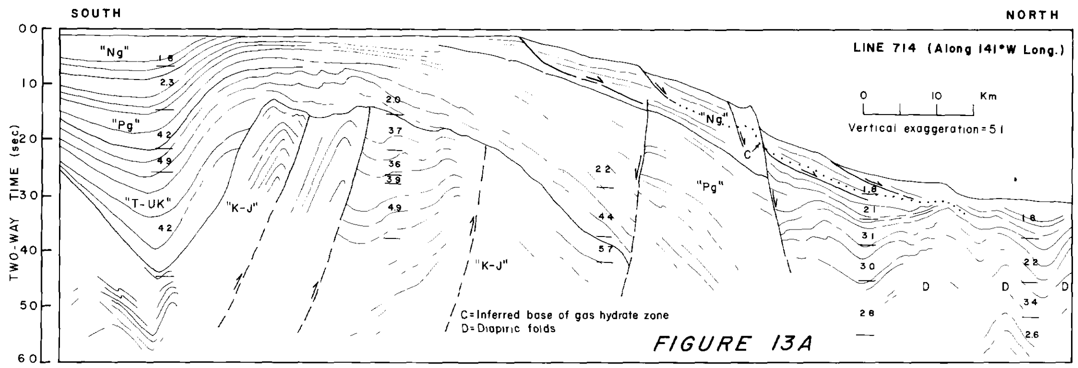


Figure 13A. Inferred clastic sedimentary rock units are "Ng"-Neogene, "Pg"-Paleogene, "T-UK"-Tertiary and(or) Upper Cretaceous, "K-J"-Cretaceous and Jurassic(?), possibly only Lower Cretaceous and Jurassic(?).

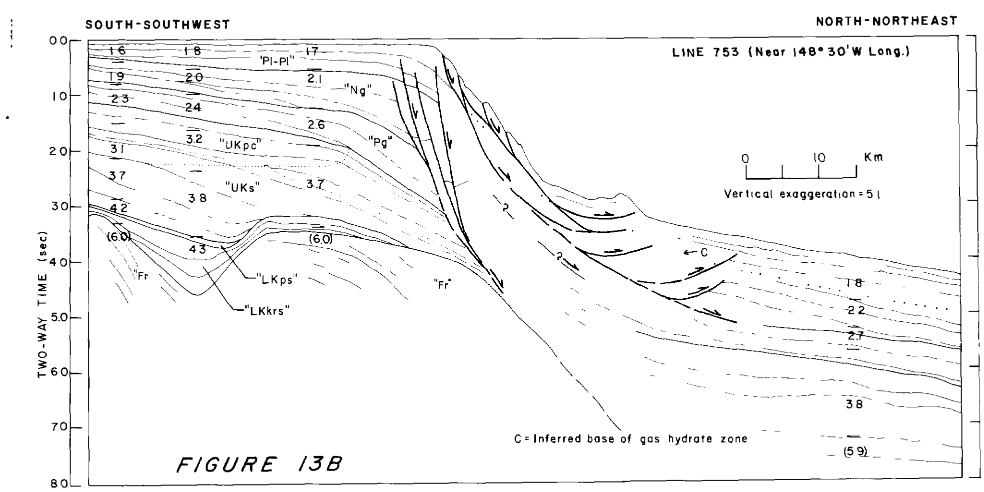


Figure 13B. Inferred clastic sedimentary rock units are "Pl-Pl" Plio-Pleistocene, "Ng"-Neogene, "Pg"-Paleogene, "UKpc"-Upper Cretaceous, Prince Creek Formation, "UKs"-Upper Cretaceous, Schrader Bluff Formation, "LKps"-Lower Cretaceous "Pebble Shale", LKkrs"-Lower Cretaceous, Kuparuk River Sandstone, "Fr"-Franklinian sequence.

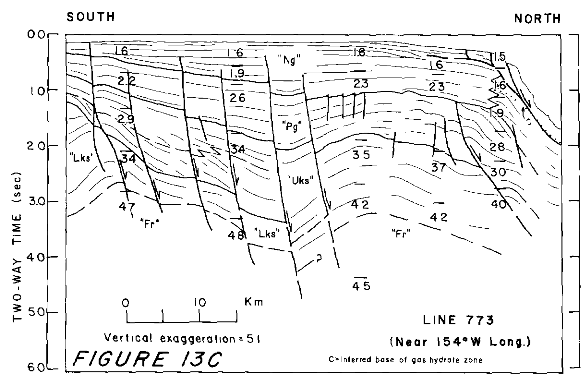


Figure 13C. Inferred clastic sedimentary rock units are "Ng"-Neogene, "Pg"-Paleogene, "UKs"-Upper Cretaceous, "LKs"-Lower Cretaceous, "Fr"-Franklinian sequence.

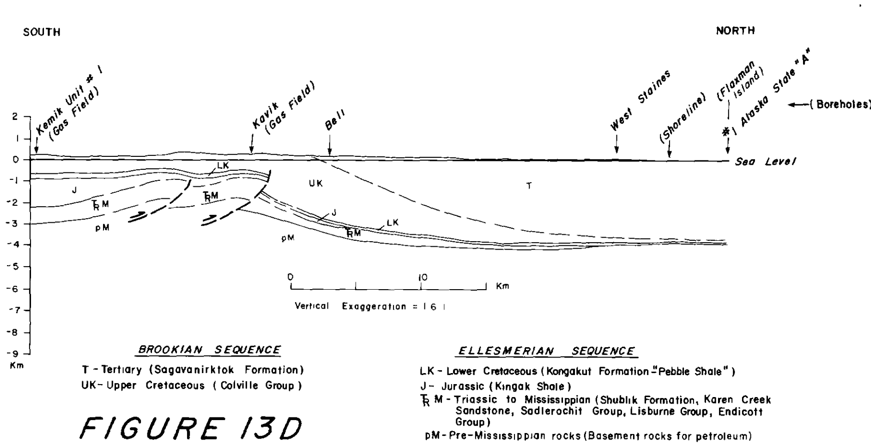


Figure 13D. Generalized structural cross section from Kemik gas field to Flaxman Island. Data interpreted from a compilation of geologic formations encountered in boreholes between the Canning and Colville Rivers by Tailleur et al. (1978). The control points for the cross section (boreholes) would not suffice to delineate any small-scale geologic structures that might be present.

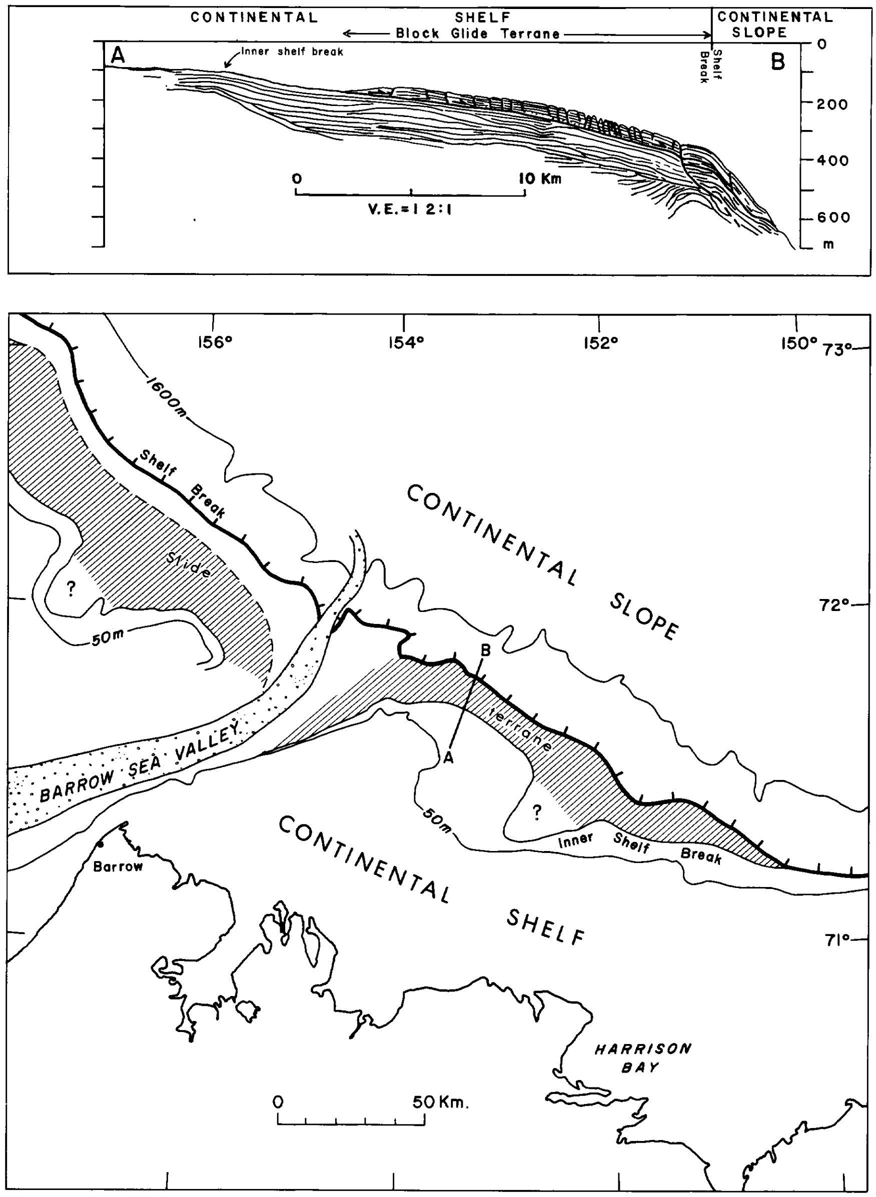


Figure 14. Block glide terrane on the outer Beaufort Shelf east of Barrow Sea Valley, mapped from 3.5 KHz seismic profiles.

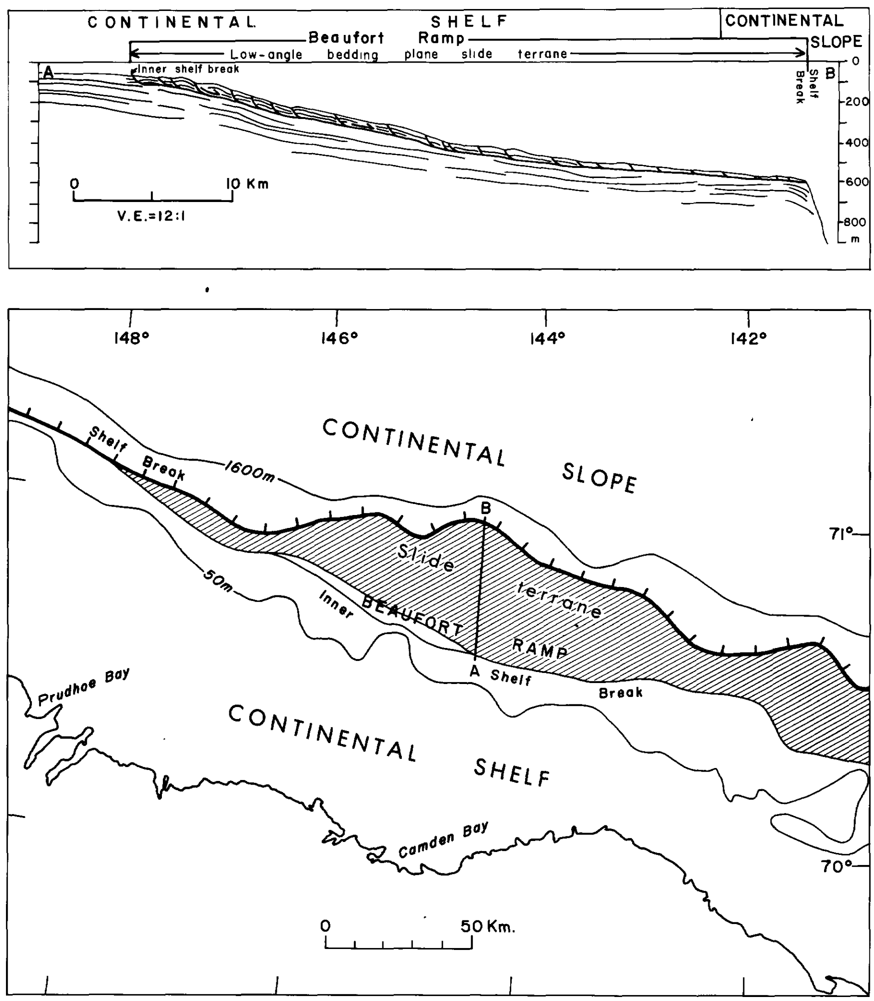


Figure 15. Bedding plane slides on the Western Beaufort Shelf east of 147° W long., mapped from 3.5 KHz seismic profiles.

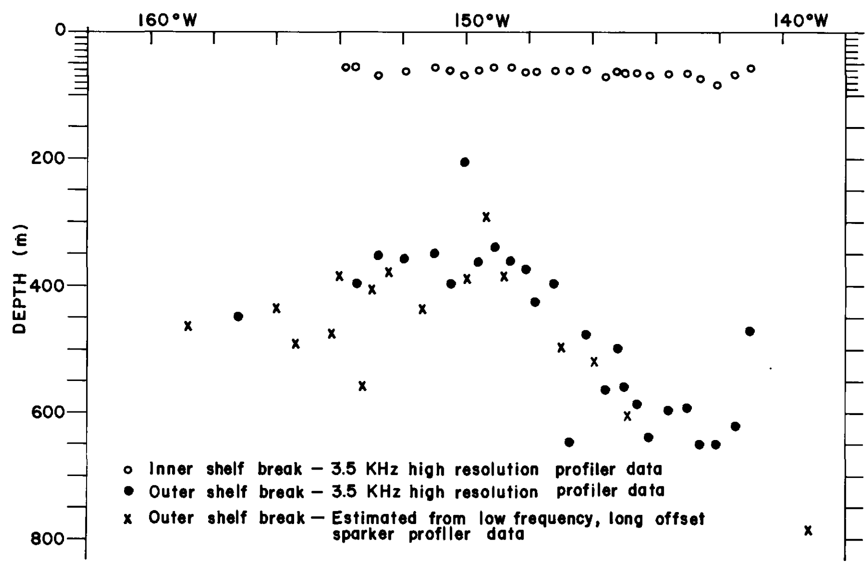


Figure 16. Depth of inner and outer continental shelf breaks on the Western Beaufort Shelf between 139° W and 160° W long.

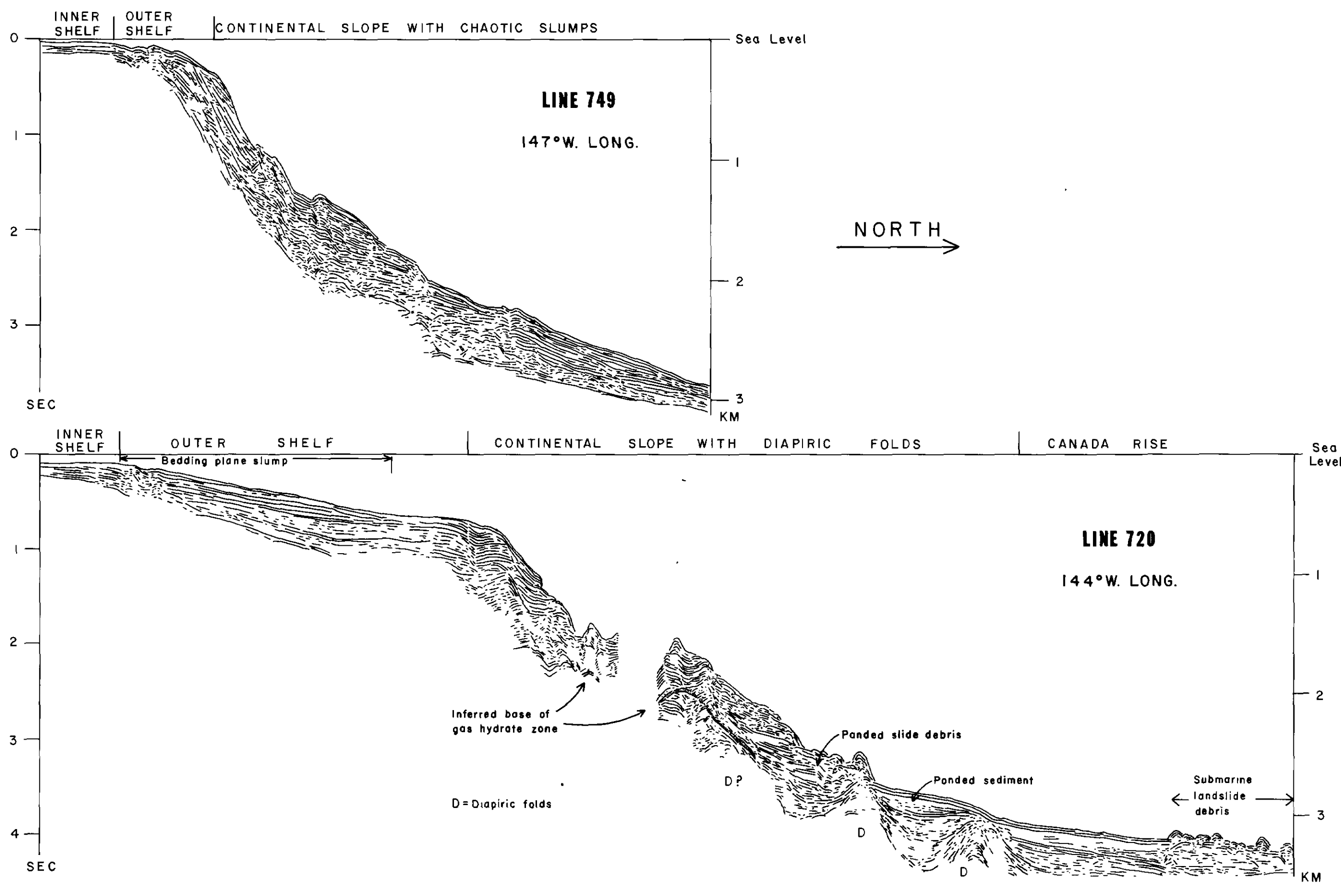


Figure 17. Shallow structure interpreted from seismic profiles across the continental slope in the Western Beaufort Sea where diapiric folds are present (Line 720) and absent (Line 749).