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GEOLOGIC FRAMEWORK OF THE ALASKAN CONTINENTAL TERRACE IN THE CHUKCHI AND BEAUFORT SEAS

By

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Geologic Framework of the Alaskan Continental Terrace in the Chukchi and Beaufort Seas

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Abstract

Seismic, magnetic and gravity data indicate that the Chukchi and Beaufort epicontinental seas off northern Alaska overlie three sedimentary basins, or provinces, separated by structural highs of regional extent. The basins trend west to northwest and their enclosed sediments become increasingly marine from south to north. The Chukchi-Beaufort continental margin is similar to those of Atlantic type.

(1) Hope basin, in the southern Chukchi Sea, overlies strongly deformed Paleozoic to mid-Cretaceous rocks of the Brooks Range orogen. The basin is inferred to contain nonmarine and marine clastic sedimentary rocks in a 1-km-thick Upper Cretaceous(?), a 1 1/2-km-thick Paleogene(?), and a 3/4-km-thick Neogene(?) sequence. A large anticline and many faults and smaller folds disrupt (mainly the older) sequences. — all but the youngest

The Hope basin sedimentary units onlap Herald arch, which trends northwest from Cape Lisburne in the central Chukchi Sea. At the Herald fault zone Brooks Range rocks in the arch are thrust east or northeast over Mississippian to Jurassic shelf carbonate and clastic rocks of the

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Arctic Alaska (Ellesmerian) basin and overlying Cretaceous flysch and molasse of the Colville geosyncline. These Mississippian to Cretaceous rocks underlie the northeast Chukchi Sea and reportedly are about 10 km thick near the Herald fault zone on the Lisburne Peninsula. The great Chukchi syntaxis in western Brooks Range rocks and structures is thought to result from intersection of the west-trending Brooks Range orogen with the northwest-trending Herald fault zone.

The Mississippian to Jurassic shelf sequence thins northward, and onlaps the Barrow arch, which trends northwest from Point Barrow to 161° W. long., thence west-southwest to the Herald fault zone. The Colville geosyncline sequence oversteps both the pre-Cretaceous rocks and the Barrow arch to form the North Chukchi basin west of 161° W. long. and the progradational Beaufort continental terrace to the east.

(2) The North Chukchi basin may contain about 6 km of probable Cretaceous and Tertiary section, which may be deltaic in origin. Diapirs (of Cretaceous shale?) pierce the gently northward-dipping strata of this basin, in places reaching the sea floor.

(3) Thick Tertiary marine and nonmarine clastic rocks of the Camden basin overlie the Cretaceous rocks of the North Slope and inner Beaufort continental terrace east of the Colville River delta. These rocks dip gently seaward west of 146° W. long. but are deformed into long, high-amplitude, east-northeast-striking folds to the east.

Introduction

The geologic structure of the Alaskan continental terrace north of

Bering Strait (Fig. 1) has been studied by the U.S. Geological Survey

Figure 1 near here.

in cooperation with the U.S. Coast Guard since 1969, utilizing the icebreaking Coast Guard cutters STORIS, GLACIER and BURTON ISLAND. Reconnaissance data have now been obtained from the Alaska and Siberian coasts north to the polar ice pack between Mackenzie Bay on the east and 176° W. long. on the west (Fig. 2). Our data consist of single-channel seismic reflection

Figure 2 near here.

profiles using 120 or 160 kilojoule sparker sources and, at times, 40, 80 or 300 cu. in. air-gun sources. Total magnetic field measurements were obtained concurrently along most of the reflection profiles, and gravity data along about a third of them. Thirty-one sonobuoy refraction lines (Fig. 2) were also obtained. The seismic reflection, magnetic, and gravity data through 1973 have been released to U.S. Geological Survey open file as Cady and others, 1973; Grantz and others, 1970a, 1971, 1972a, 1972b, 1974a, and 1974b; and Hanna and others, 1974.

This report, a preliminary and in many instances a tentative interpretation of our geophysical data, was written by the senior author. Holmes and Grantz reduced the sonobuoy refraction data, and Kososki assisted in assembling data and compiling illustrations. We are grateful to the U.S. Coast Guard for ship and helicopter support, navigation, bathymetric data, and assistance in operating geophysical equipment. W. P. Brosgé, D. M. Hopkins, H. N. Reiser, and I. L. Tailleur and other

USGS colleagues, and a number of industry scientists offered valuable suggestions and discussion. We thank William P. Brosgé for reviewing the manuscript and Olive T. Whitney for assisting us in compiling data and preparing the illustrations.

Bathymetric Setting

At Point Barrow the Chukchi-Beaufort continental terrace is divided into two physiographic provinces (Fig. 1). To the east, in the Beaufort Sea, the continental shelf is shallow and relatively narrow and shoals steadily from the shelf break to the bordering low Arctic coastal plain. The adjacent continental slope, the Beaufort scarp, is steep, linear, and strongly sculptured by slumps and leveed channels off the western and central Beaufort shelf. Eastward, the slope becomes progressively smoother and gentler, and is being prograded northward by sediment from the Mackenzie delta.

West of Point Barrow the continental terrace underlies the Chukchi Sea. Its shallow shelf is part of one of the most extensive flat places on earth, the broad Laptev-East Siberian-Chukchi continental shelf (Fig. 1). Seaward this shelf is bounded by the Beaufort scarp and by presumed continental outliers, Northwind Seahigh and Chukchi Cap (Fig. 1), which lie north of the scarp in the Canada basin of the Arctic Ocean. From Point Lay north, the Chukchi continental shelf abuts the low Arctic coastal plain, but elsewhere it generally meets land at sea cliffs.

Tectonic overview and regional stratigraphy

The Beaufort continental shelf in Alaska is underlain, at least in its higher structural levels, by generally gently northward-dipping Cretaceous and Tertiary sedimentary rocks that prograded northward from the Barrow arch (Fig. 3). The arch is a broad regional structure whose

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Figure 3 near here.

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axis lies near the Beaufort coast between Point Barrow and Camden Bay (Figs 1 and 3). Because the Beaufort continental terrace is linear, progradational in at least its higher beds, lacking strong landward-directed compressional structures, and faces a deep basin with oceanic crust (the Canada basin), it resembles continental margins of Atlantic type (Beck, 1972).

The Chukchi continental shelf is geologically more diverse and complex than the Beaufort shelf because it extends southeast across the Brooks Range and associated ranges of the Cordilleran foldbelt in northwest Alaska. This extension of the Chukchi Sea was possible because Hope basin, which contains a broad prism of soft Tertiary clastic rocks, and a low-lying late Tertiary depositional surface underlie the southern Chukchi Sea. Flooding of the low-lying surface and repeated Quaternary interglacial marine planation of the soft clastic rocks has extended the southern Chukchi Sea (average depth 50 m) over almost all of Hope basin. The shorelines of this sea were, in most places, stabilized only where marine abrasion reached the harder, pre-Tertiary rocks that surround the basin.

The pre-Tertiary rocks of the Chukchi-Beaufort continental terrace are extensively exposed in the Brooks Range and in outcrops and test wells on the North Slope. However, the Tertiary basins of the terrace are known almost entirely from marine geophysical data. The megascale structure of the pre-Tertiary rocks, which is reflected in a series of sweeping syntaxial and oroclinal flexures, is shown in Figures 1 and 3. The Porcupine and Ogilvie oroclines (Fig. 1) of the eastern Brooks Range are considered to be flexures related to east-northeast transport of northern Alaska along the Kaltag and related faults (Grantz, 1966). The Chukchi syntaxis (Tailleur, 1969) of the western Brooks Range is believed to represent the intersection of the Brooks Range orogen by a slightly later early Laramide thrust and fold system in the Chukchi Sea (Grantz and others, 1970b).

The bedded rocks of the Brooks Range and North Slope and of much of the Chukchi-Beaufort continental terrace can be grouped into five sequences that reflect major stages in the tectonic evolution of Arctic Alaska (see Alaska Geological Society, 1971, 1972; Brosgé and Dutro, 1973; Brosgé and Tailleur, 1971; Churkin, 1973; and Lerand, 1973, for recent summaries of these rocks). Four of these sequences, as developed on the North Slope, are shown in Figure 4. A fifth occupies Hope basin.

Figure 4 near here.

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(1) Cambrian to Devonian strata of both eu- and miogeosynclinal facies, in many places metamorphosed, constitute basement for petroleum exploration, and generally acoustic basement for seismic energy, on the North Slope. These beds may have been deposited in an extension of the Franklinian geosyncline of Arctic Canada. For the sake of brevity they are referred

to as Franklinian(?) sequence, rocks or basement in this paper.

(2) Above the Franklinian(?) rocks is a regional angular unconformity that marks the consolidation of the Franklinian(?) geosyncline on the North Slope into the stable Arctic Platform. Late Devonian or Early Mississippian to earliest Cretaceous clastic and carbonate sediments, derived from northern source areas, were deposited on the platform in the Arctic Alaska basin of Tailleur and Brosgé (1970). Lerand (1973) assigns these rocks to his Ellesmerian sequence, a convenient usage that we will follow in this paper. The platform rocks thin, coarsen, and onlap northward toward Barrovia (Tailleur, 1973), a provenance area lying north of the Arctic Platform and the present coast. The term "Arctic Platform" (Payne, 1955; and Miller, Payne and Gryc, 1959) originally designated the northern fringe of the platform upon which the Ellesmerian rocks of the North Slope were deposited and also the offshore provenance area for these rocks. Payne and others (1952) had earlier called this feature the Barrow Platform. In the present paper, the term Arctic Platform =? Franklinian rocks is restricted to an observable feature, the foundation upon which the Ellesmerian sequence of platform rocks of the North Slope was deposited. The provenance area, the existence, dimensions and present position of which can only be inferred, requires a separate name for which Tailleur's term Barrovia is appropriate. Near Prudhoe Bay the Ellesmerian rocks contain giant oil and gas accumulations within structures on the Mesozoic Barrow arch. In and south of the southern Brooks Range, the Ellesmerian platform and shelf rocks grade into eugeosynclinal facies. The Ellesmerian beds are readily sounded by

signals from large seismic sources. However, we penetrated them only near the Barrow arch, where they are relatively shallow.

(3) In latest Jurassic and earliest Cretaceous time major tectonism reshaped northern Alaska and Canada basin, and on the North Slope southern sources of detrital sediment replaced northern ones. The Brooks Range orogeny, resulting from intense Nevadan and Laramide compression in the southern part of the Arctic Platform, caused large nappes of Paleozoic to Cretaceous eu- and miogeosynclinal rocks and platform and foredeep rocks to be thrust relatively northward onto the central part of the platform. Aggregate shortening in the western Brooks Range exceeded 100 km (Martin, 1970) and may have exceeded 240 km (Snelson and Tailleur, 1968). Concurrent depression of the overridden southern half of the Arctic Platform created a foredeep, the Colville geosyncline, which received lower Lower Cretaceous (Neocomian) flysch and olistostromes from the developing Brooks Range orogen. In the southern part of the North Slope these rocks, the Okpikruak Formation (Fig. 4), unconformably overlie the Ellesmerian sequence. Northward, the flysch grades laterally into condensed coquinoid shale and then organic shale of partly northern provenance beneath the Arctic foothills and coastal plain. The organic shale, informally called the "pebble shale" or "Okpikruak shale", is thought to be an important source rock for petroleum at Prudhoe Bay.

(4) Continued uplift in the Brooks Range orogen fed voluminous detritus northward resulting in a series of thick, northward-shingling upper Lower Cretaceous (Albian) to Tertiary molasse wedges in the Colville geosyncline (Fig. 4). These wedges grade northward into deltaic, paralic and shallow marine

clastic facies that in part onlapped and in part overstepped the Barrow arch. The depocenters of the wedges migrated progressively northward, filling the geosyncline and overspilling its northern margin, Barrow arch, to form the progradational Beaufort continental terrace and fill the North Chukchi basin. Encouraging quantities of oil and gas have been found in the Cretaceous rocks of the Colville geosyncline (Brosgé and Tailleur, 1971).

(5) Compression in the western Brooks Range orogen continued into the Late Cretaceous and perhaps the early Tertiary, and apparently into the Neogene in the northeastern Brooks Range and its foreland (Fig. 3). The Albian molasse wedges north of the Brooks Range are dominated structurally by flat thrusts and related detachment folds rooted in the northern part of the orogen. In the southern Chukchi Sea, post-orogenic crustal extension created the Hope basin, which lies athwart the structural grain of the western Brooks Range. The extension may be related to Laramide to mid-Tertiary (Patton and Hoare, 1968) east-northeastward transport of northern Alaska along the Kaltag fault.

The framework elements of the Chukchi-Beaufort continental terrace

Our seismic reflection data are best in the Cretaceous and Tertiary rocks of the Colville geosyncline, Beaufort shelf, and Hope and North Chukchi basins. Even in these relatively soft rocks, however, our maximum penetrations ranged between 1 1/2 and 3 1/2 seconds of two-way time, or about 2 to 4 km. The framework elements of the Chukchi-Beaufort continental terrace are discussed below from south to north in the Chukchi Sea, and west to east in the Beaufort Sea. The discussion is based mainly upon our seismic data and extrapolations from onshore geology, supplemented by study of four dredge hauls by the University of Washington, two long refraction lines reported by Hunkins (1966) and Milne (1966), and some magnetic and gravity measurements.

Hope basin

The southern Chukchi Sea is underlain by a sedimentary prism, deposited in Hope basin, that rests unconformably upon upper Lower Cretaceous (Albian) and older deformed rocks of the Brooks Range orogen (Fig. 3). The gentle structure and low seismic velocities that characterize this prism, together with the age of the underlying rocks, suggest that it is probably Tertiary, and possibly in part Upper Cretaceous in age. The basin has been extrapolated onshore to the Kobuk River delta and the Selawik Lowland (Figure 3) on the basis of gravity data reported by Barnes (1971).

Acoustic basement, which consists of deformed rocks of the Brooks Range orogen, can be followed from coastal outcrops in Alaska and Chukotka to beneath the deepest parts of Hope basin. In most of the basin reflection time to acoustic basement exceeds 1.0 second. In an area some 8,000 sq km in extent south of Point Hope it exceeds 2.0 seconds and in small areas 2.5 seconds. On the basis of the velocity structure derived from sonobuoy refraction profiles in Hope basin (Figs. 5 and 6), 1.0 second of two-way reflection time represents a

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Figures 5 and 6 near here.

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depth of about 3,000 feet (915 m); 2.0 seconds about 7,500 feet (2,300 m); and 2.5 seconds about 10,000 feet (3,050 m), and it is these values that are contoured in Figs. 3 and 17. The deepest refraction we obtained from acoustic basement (Vp = 4.5) is at 2,600 m, in good agreement with reflection data there.

Eastern Hope basin contains three main acoustic reflection units as shown in Figure 6 and in Figure 7, a northeast-southwest section somewhat east

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Figure 7 near here

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of the deepest part of the basin. The lowest unit, Vp = 3.1-3.3 km/sec., is as much as 0.5-0.6 seconds, or about 800-900 m thick. It occurs in the southern half of the basin and abuts against acoustic basement on the south, near Seward Peninsula and on the north, in the major synclinal downwarp of Hope basin. The top of the unit is the strongest supra-basement reflector in the basin. The middle unit, Vp = 1.9-2.9 km/sec., is as much as 1.2 seconds or about 1,500 m thick. It oversteps the basal unconformity of the lower unit and extends across the entire basin, within which it is the principal unit. Densities of this unit are evidently very sensitive to thickness of overburden, for there is a good correlation between seismic velocity and depth of burial within it. The assignment of rocks ranging in velocity from 1.9 to 2.9 km/sec. to the middle unit is supported by our seismic reflection records. Most faulting and folding in Hope basin is in the lower and middle units (Fig. 7). The upper unit, Vp = 1.7-1.9 km/sec., is as much as 0.8-0.9 seconds or about 750 m thick. It forms a slightly deformed lens of sediment in the central and northern parts of Hope basin. In the north this unit oversteps faulted and folded beds of the middle unit to rest on acoustic basement underlying Herald arch, which forms the north margin of the basin.

The axes of subsidence and sedimentation in eastern Hope basin shifted progressively northward with time. The depocenter of the middle unit overlies the northern wedge edge of the lower unit. The upper unit, in turn, oversteps the northern limit of the middle unit and occurs mainly in the northern half of the basin. Part of the structural relief of Kotzebue anticline (Figs. 3 and 7), the large, broad east-west-striking anticline in southeastern Hope basin, is due to its location between the separate axes of greatest thickness (subsidence) of the lower and middle units. Downbowing of the base of the middle and upper units south of the anticline, and local northward onlap of the base of the middle unit toward the anticline, indicates that there was growth on this structure or subsidence south of it, during middle unit and later time.

The age and lithology of Hope basin strata are unknown but some inferences can be drawn from the seismic velocities of its rocks and from the character of the few outcrops of young sedimentary rocks in the surrounding onshore.

The presumed onshore correlatives of Hope basin fill are slightly to moderately consolidated Upper Cretaceous and Tertiary sedimentary rocks. The surrounding mid-Cretaceous and older rocks are too high in seismic velocity or are too strongly deformed to correlate with the low velocity (Vp = 1.7-3.3 km/sec.) and generally gently deformed Hope basin fill. The slightly to moderately consolidated rocks are mainly nonmarine, commonly coal-bearing, and occur in small basins or basin remnants on Seward Peninsula, Chukotka and around Kotzebue Sound. The nonmarine rocks include: (1) Upper Cretaceous or Lower Tertiary coal-bearing rocks in the Kugruk River valley, Seward Peninsula (Sainsbury, 1974); (2) lower Tertiary lignite-bearing beds on Eschscholtz Bay, Kotzebue Sound (Quackenbush, 1909; D. M. Hopkins, pers. comm., 1974), (3) mid-Tertiary lignite-bearing rocks occurring as exotic blocks in maar/crater ring deposits near Devil Mountain, northern Seward Peninsula (D. M. Hopkins, pers. comm., 1974); and in outcrop in Selawik Lowland (Patton and Miller, 1968), and (4) upper Tertiary nonmarine rocks near Vankarem River, northern Chukotka (Petrov, 1967) and near Noxpaga (Sainsbury, 1974) and Deering on the Seward Peninsula. Nearshore marine deposits of Neogene age are reported from Cape Enmakai, northern Chukotka (Belevich, 1969) and near Kivalina in northwest Alaska (Hopkins and MacNeil, 1960). In addition, marine sediments were probably deposited in Hope basin during the interchanges of Pacific and Arctic marine faunas through Bering Strait which occurred from 10 to 6 and 3 1/3 to 1 million years ago, as well as intermittently during the last million years (Hopkins, 1967, and personal commun., 1974).

The character of the marginal outcrops suggests that Hope basin was filled mainly by nonmarine rocks. However, the presence of some marginal Neogene marine outcrops and the periodic exchanges of Neogene marine faunas across Bering Strait indicate that at least part of the Neogene section in the basin is marine. Indeed, given a marine connection and suitable interplay between subsidence and sedimentation, Hope basin could contain a significant section of Neogene shallow water marine sediments.

Compressional velocities in the upper part of acoustic basement beneath eastern Hope basin increase progressively from 3.5 to 3.9 km/sec. at Herald arch to 5.2 km/sec. near Seward Peninsula. These velocities, together with the character of the surrounding bedrock, suggest that deformed Mississippian to Early Cretaceous shale, sandstone, carbonate and chert underlie northern Hope Basin, and that Paleozoic carbonate and clastic rocks and probably Paleozoic and Precambrian metamorphic rocks underlie the southern part. This progression matches the north to south increase in age, induration, and metamorphism of pre-Upper Cretaceous rocks across the western Brooks Range.

The lowest reflecting unit in eastern Hope basin has seismic velocities (Vp) of 3.1-3.3 km/sec. that are common in Cretaceous rocks on the North Slope. Thus, the unit may correspond to the Upper Cretaceous or Lower Tertiary nonmarine rocks along Kugruk River. In addition, the lowest unit may contain nonmarine Paleogene rocks such as those which crop out on Eschscholtz Bay. The middle reflection unit, with seismic velocities of 1.9-2.9 km/sec., may correspond to the lower and middle Tertiary nonmarine beds near Kotzebue Sound and on northern Seward Peninsula. The upper reflection unit, with seismic velocities of 1.7-1.9 km/sec. may represent the nonmarine and shallow marine Neogene outcrops of Cape Enmakai, Kivalina and other onshore localities. Thus, eastern Hope basin comprises three successively northward migrated overlapping clastic sub basins or depocenters of possible (and approximate) Late Cretaceous, Paleogene, and Neogene age.

Herald Arch

Herald shoal and Herald Island cap a broad, low bathymetric swell that trends northwest from Cape Lisburne to beyond Wrangel Island, north of Chukotka (Figs. 1 and 3). Scattered outcrops of hard rock, generally incoherent reflections, and strongly reflective shallow bedrock characterize the swell and constitute a belt of shallow acoustic basement, termed Herald arch, that separates the sedimentary terranes of Hope basin and Colville geosyncline. The arch connects Paleozoic and early Mesozoic sedimentary rocks in nappes in Lisburne Hills on Lisburne Peninsula (Fig. 1) to rocks of similar age and character on Wrangel Island (see Bogdanov and Tilman, 1964, for a comparison of these rocks). In addition, plutonic rocks occur on Herald Island (N. A. Bogdanov, personal commun., 1970). Four dredge hauls taken from the arch by the University of Washington (see Fig. 3 for locations) contain strongly indurated graywacke and argillite, lithologically similar to Lower Cretaceous beds in the core of the Chukchi syntaxis near Cape Thompson (Platt, 1975). The acoustic character of Herald arch, extrapolated from onshore areas, geology, and the contents of the dredge hauls suggest that pre-Mississippian (Franklinian?) argillite and graywacke and Mississippian to Triassic clastics, carbonate and chert of the Ellesmerian sequence are close to the sea floor beneath the southwest half of the arch (Fig. 3). These data also suggest that deformed and strongly indurated Lower Cretaceous sandstone and shale are close to the sea floor in the northeast half of the arch. The Lower Cretaceous beds are part of the Colville Geosyncline sequence, which is normally acoustically coherent, that has been so severely deformed by thrusting and refolding in the Herald fault zone and Chukchi syntaxis that the coherence of the seismic reflectors has largely been destroyed.

Herald arch is developed on the upper plate of Herald fault zone (Figs. 1 and 3), which thrusts mainly Paleozoic and Triassic rocks of the Lisburne Hills and central Chukchi Sea relatively east and northeast over Lower Cretaceous molasse and flysch of the Colville geosyncline. Martin (1970) discussed these structural relationships in the Lisburne Hills. Herald arch owes its topographic relief to its relatively resistant rocks, and its structural relief to a combination of movement on the Herald fault zone and subsidence of the Hope basin, which began in Late Cretaceous or Paleogene time. In part, the subsidence was accomplished by normal faulting of the middle (Paleogene?) unit of Hope basin against older rocks in the arch prior to deposition of the upper (Neogene?) unit. Onlapping of the upper unit against the arch indicates that the arch essentially obtained its present geometry by Neogene(?) time. Because of the shallow depth of relatively resistant rocks in the arch, it was probably marked by a trend of hills, and later islands, that were leveled by marine planation long after the surrounding terrains of softer Cretaceous and Tertiary rocks were reduced to low plains.

Herald Fault Zone and Chukchi Syntaxis

Herald fault zone (Figs. 1 and 3) trends northwest from Cape Lisburne to about 172° W. long., where it is intersected by large north-south-trending faulted anticlines. Its continuation, or perhaps only an analogous structure, trends east-west north of Wrangel arch (Figs. 3, 11 and 17), a block of acoustic basement that lies between the Hope and North Chukchi basins west of 172° W. long. Wrangel arch is interpreted to be a structural and stratigraphic continuation of Herald Arch, Lisburne Hills and the Brooks Range.

Herald fault zone thrusts Franklinian(?) and Ellesmerian rocks over Lower Cretaceous rocks of the Colville geosyncline. It is an imbricated fault zone within which folded Cretaceous beds northeast of the fault became increasingly tilted and broken southwestward, until acoustically discernible structural coherence is lost and the broken beds merge with pre-Cretaceous acoustic basement in Herald arch. The contrast in Vp across the fault zone shown in Figure 8, 3.5 and 3.9 km/sec. south of the fault

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Figure 8 near here.

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zone vs. 2.8 and 3.4 km/sec. north of it, is interpreted to represent a change from older and more strongly deformed Cretaceous sedimentary rocks south of the fault zone to younger and less deformed Cretaceous rocks north of it. A more extended discussion and illustrations of Herald fault zone and Chukchi syntaxis are given in Grantz and others (1970b).

Off Cape Lisburne, the zone of imbrication and related detachment folds along Herald fault zone is more than 30 km wide and the folds have amplitudes of 1,000 to 1,500 m. Further to the northwest the fault-fold zone is equally wide, but amplitudes of the related folds do not much exceed 300 m. These folds are also narrower and attenuate rapidly to low amplitudes away from Herald arch. This change in the character of the fault zone may be due to a westerly increase in the age of the Cretaceous rocks on the north side of the fault. This is discussed in the next section.

It is inferred that Herald fault zone is an extension of the thrust belt that forms the eastern boundary of exposed Ellesmerian rocks in the Lisburne

Hills. North of Cape Lisburne the Herald fault zone crosscuts the east-west-striking detachment or thrust folds that trend offshore from the Arctic foothills of the Brooks Range and which are related to the uplift and thrusting of the Brooks Range orogen. The Herald fault zone thus appears to postdate the thrust faults and detachment folds of the northern Brooks Range and Arctic foothills. Similar conclusions were drawn from fieldwork onshore in the Utukok-Corwin area (Chapman and Sable, 1960, p. 144) and in the Lisburne Hills and western Brooks Range (Martin, 1970, p. 3619-3620). Both the Herald and Brooks Range fault zones are pre-Hope basin and probably late Early (late Albian) or Late Cretaceous in age. If these conclusions are substantiated by more detailed studies they would indicate that the Chukchi syntaxis (Figs. 1 and 3) represents the near normal transection of the Brooks Range orogen by the Herald fault zone rather than the oroclinal bending of a single orogen as has been proposed, for example, by Tailleur (1969).

Colville Geosyncline

Cretaceous sedimentary rocks of the Colville geosyncline underlie the western North Slope from Cape Lisburne to Point Barrow and probably underlie most of the Chukchi Sea between the Herald and Barrow arches (Fig. 3). These rocks are of southern provenance. They thin northward and in part onlap, and in part overstep the Barrow arch. Their base can be interpreted on single-channel reflection and sonobuoy refraction records only in the northern, shallow part of the geosyncline (see Figs. 8, 9 and 10).

Figures 9 and 10 near here.

Onshore the Cretaceous rocks exceed 20,000 feet in thickness in the foothills north of the western Brooks Range (Brosgé and Tailleur, 1971). The Colvillian rocks rest on the Ellesmerian sequence except locally on the Barrow arch, where they overlie mildly metamorphosed Franklinian(?) rocks. They are overlain by Tertiary sediments of the North Chukchi basin and Beaufort continental terrace.

The detachment, or thrust folds of the western North Slope occur mainly in thick, well-bedded marine and nonmarine Albian deltaic beds (Nanushuk Group) which include many good seismic reflectors. Good acoustic penetration was achieved in these rocks. Both the folds, which are mainly of the Brooks Range orogen, and the well-bedded rocks were traced (followed continuously ??) about 130 km offshore between Cape Lisburne and Point Lay. The folds have flank dips of 1-15°, amplitudes of up to 1,200 m, wavelengths of 20-25 km, and strike lengths of 50-100 km and are comparable in these characteristics to their onshore counterparts. The fact that these folds die out about 130 km offshore is of both stratigraphic and structural interest. The well-bedded Nanushuk rocks of the folded belt are replaced to the west by poorly bedded rocks with only small, irregular folds. Little acoustic penetration was obtained in the poorly bedded rocks. It is suggested that they represent the Torok Formation (lower Albian) or perhaps older Cretaceous and Jurassic shales beneath both the well-bedded Nanushuk Group and the detachment faults in which the thrust folds are believed to be rooted. Additional support for this suggestion is provided by the gravity field, which increases by about 20 mgals in passing from the folded Nanushuk terrane to the postulated older terrane west of the folds (B. R. Ruppel, personal commun., 1975).

Northerly dipping clinoform, or foreset beds occur extensively north of the folded zone. They may represent deltaic deposits in the upper Torok Formation and Nanushuk Group (Albian) and are probably similar to east-dipping foreset beds found seismically in the upper part of the Torok Formation on the central North Slope (Brosgé and Tailleur, 1971, p. 83-87). The clinoform beds can be seen to overstep the Barrow arch at the north end of reflection profile W-W' (Figs. 5 and 10) and to overlie gently south dipping Ellesmerian and perhaps earliest Cretaceous beds on the south flank of Barrow arch.

The general character of the Colville geosyncline along 168° W. long., west of the folded belt, is shown in sonobuoy refraction-based cross section B-B' (Fig. 8). Unit C (Vp = 3.0-3.4 km/sec.) appears to thin and overstep Barrow arch on the north and to come to the surface at Herald fault zone on the south. It is about 1 km thick on the south flank of Barrow arch and probably thickens considerably toward Herald fault zone. This unit is tentatively identified as the Torok Formation. The overlying unit B (Vp = 2.3-2.8 km/sec.), which also thins over Barrow arch, might then represent beds of the overlying Nanushuk and possibly Colville Groups. Note that both units A and B appear to overstep Barrow arch. It is not certain, however, that velocity correlations across the arch indicate stratigraphic correlations. Thus, comparison of section B-B' with C-C' (Fig. 9) and D-D' (Fig. 16) suggests that north of the arch in section B-B', unit B (Vp = 2.7-2.8 km/sec.) is likely to be early Tertiary, rather than Cretaceous in age. The group of refractors with Vp = 1.7-2.2 km/sec. are interpreted to be upper Tertiary beds in an embayment of the North Chukchi basin which crosses the west end of Barrow arch. Unit D (Vp = 3.7 km/sec.) is tentatively correlated with the earliest Cretaceous or the uppermost Ellesmerian sequence. Unit F (Vp = 4.9-5.9 km/sec.) is acoustic basement and likely represents the Franklinian(?) sequence. The 4.0 km/sec. refractor beneath the north flank of Barrow arch possibly represents a patch of Ellesmerian rocks within acoustic basement, and the 4.3(?) km/sec. refractor in unit C may in fact represent a patch of Ellesmerian rocks resting upon acoustic basement.

Colville geosyncline rocks also are shown in refraction profile C-C' (Fig. 9). There, near the coast, acoustic basement in the Barrow arch is closer to the sea floor and the presumed Cretaceous units B_1 (Vp = 2.3-2.4 km/sec., Nanushuk and Colville groups?), C_1 (Vp = 2.7-3.1 km/sec., Torok Formation?) and D (Vp = 3.4-3.8 km/sec., earliest Cretaceous and, perhaps, uppermost Ellesmerian sequence?) onlap and thin towards the Barrow arch. Note that seismic velocities in units B and C south of the Barrow arch tend to be a little higher in section B-B' than they are in C-C'. The differences may be attributable to the somewhat greater depths at which these units lie in section B-B'. Unit E (Vp = 4.3 km/sec.) may represent the northern wedge edge of the Ellesmerian sequence on the Arctic Platform. Unit F (Vp = 5.2(?)) probably represents Franklinian(?) rocks and is acoustic basement. Reflection profile W-W' (Fig. 10) shows these rocks on the crest and uppermost south flank of the Barrow arch.

Barrow Arch

Barrow arch is a broad regional structure of compound origin that has strongly influenced sedimentation on the northern North Slope since it came into existence in latest Jurassic or earliest Cretaceous time (Figs. 3 and 4). The Prudhoe Bay and related oil and gas fields and the South Barrow gas field are structural-stratigraphic traps at structurally high positions on the arch.

The axis of the eastern segment of Barrow arch follows the Beaufort coast from the foothills of the Brooks Range near Camden Bay to Point Barrow, where it is about 300 km north of the range. From Point Barrow the arch follows the same west-northwest trend offshore some 200 km to 72 1/4° N. lat., 161° W. long. in the northern Chukchi Sea. The eastern segment is a broad gentle arch with second-order folds and faults. It is bounded on the north by a Cretaceous and Tertiary progradational sedimentary prism beneath the Beaufort shelf. West of 161° W. long. the arch trends west-southwest to 71° N. lat., 171° W. long., where it approaches the Herald fault zone and is truncated by north-south-trending cross structures (Fig. 3). The axial region of this, the western segment of the arch, is structurally more complex than the eastern segment and is corrugated by several folds and fault blocks. It is bounded on the north by the extensive Cretaceous and Tertiary North Chukchi basin, and is in consequence much further from the continental slope than the eastern segment.

Franklinian(?) rocks beneath the petroliferous Ellesmerian and Colvillian sequences along the axis of the Barrow arch are 0.8 km deep near Point Barrow, and about 0.5 km deep at the northernmost extension of the arch in the northern Chukchi Sea. From these areas acoustic basement deepens eastward to about 3.5 km at Prudhoe Bay and perhaps 5 km where it loses identity amid foreland folds of the Brooks Range near Camden Bay. Westward, acoustic basement is projected to a depth of about 2 km near 167° W. long.

Franklinian(?) rocks in test wells on Barrow arch consist of early Paleozoic argillite and phyllite with thin beds of siliceous dolomite. Their presumed correlatives offshore have seismic velocities of 4.9-5.9 km/sec. in our sonobuoy refraction records, and 4.9 km/sec. in a long reversed refraction line trending northwest from Point Barrow (Hunkins, 1966). In the reflection and refraction profiles across the arch west of Point Barrow (Figs. 8, 9, and 10) it can be seen that refraction units thought to represent pre-Tertiary rocks wedge out against or thin over the arch, whereas units thought to be Tertiary (V_p = 1.6-2.2 km/sec.) seem little affected in overstepping it. Thus, the Barrow arch was apparently a positive feature and acted as a barrier to sedimentation during latest Ellesmerian and Cretaceous time on the Chukchi shelf.

The eastern segment of the Barrow arch formed when Barrovia, the provenance area of the Arctic Platform collapsed or was displaced by rifting or transform faulting during latest Jurassic or earliest Cretaceous time. This left a south-sloping platform south of the arch and a new north-facing continental margin to the north. The southerly tilt of the Arctic Platform was augmented by thrusting of Brooks Range rocks onto the platform from the south relatively ??? and by deposition of the Cretaceous Colvillian rocks on the platform. The isostatic consequences of the removal of Barrovia also may have added structural relief to the Arch (Rickwood, 1970). Cretaceous and Tertiary sedimentation filled the newly created foredeep, the Colville geosyncline, south of the arch and prograded the Beaufort continental terrace north from the arch across the newly created continental margin. The north flank of the eastern segment of the arch thus represents a Cretaceous boundary between epicontinental foredeep and continental shelf, and slope sedimentation.

The western segment of the arch lies between the tilted Arctic Platform and the North Chukchi basin. The data upon which this report is based do not indicate whether the North Chukchi basin was built across a latest Jurassic and earliest Cretaceous continental margin, or whether it is epicontinental. In either case, the west-southwest trend of Barrow arch west of 161° W. long. is thought to be a consequence of the subsidence or collapse that created the North Chukchi basin, rather than bending or major uplift of the arch itself.

The Barrow arch is thus regarded as the structural culmination of a tilted platform, rather than a true arch. Its crest was originally positioned near the faults along which the platform north of the arch was removed by collapse or lateral displacement. Subsequently the crest was shifted southward to its present position by Early Cretaceous erosion and probably by some secondary structural collapse of the terrain adjacent to the fault zone which detached Barrovia from the Arctic Platform.

North Chukchi Basin

The Chukchi continental terrace north of the Barrow and Wrangel arches (Figs. 3 and 17) is underlain by an extensive basin filled with strata inferred to be clastic and of Cretaceous and Tertiary age. This, the North Chukchi basin, contains more than 4 seconds (5 or more km) of section. A notable feature is the occurrence of shale(?) diapirs in the basin.

Strata in the North Chukchi basin in part onlap Barrow arch, and in part thin toward, but overstep it. They meet Wrangel arch at the apparently high-angle Wrangel fault zone, which is inferred to be a thrust fault system (Figs. 3, 11, 12 and 17). Near the Wrangel arch and fault zone the

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Figure 11 near here.

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basin fill dips as much as 5-15° northerly, but away from the margins dips are 0-1° northerly. There are some folds and faults in the North Chukchi basin near the Wrangel fault zone, but the overall structure is a gently northward-dipping and deepening basin with few structural complications. Away from the basin margins the strongest and most striking deformation is adjacent to shale(?) diapirs that in places reach the sea floor. In the eastern part of the basin profiles that reach the shelf break reveal a very low amplitude anticline lying from 0 to 10 km landward from the continental shelf break, and a similarly shallow complementary syncline about 10 km south of the anticline.

Two major stratigraphic sequences, separated by a strong angular unconformity, can be recognized in the southern part of the North Chukchi basin (see Figs. 11 and 12). The unconformity increases in discordance and hiatal

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Figure 12 near here.

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value toward the south, as it approaches the Wrangel and Barrow arches, supporting the inference that these structures form the south boundary of the basin.

Near Wrangel arch (Fig. 11) the unconformity is folded above a possibly partly diapiric anticline of pre-unconformity age, and the anticline thus appears to have undergone renewed growth in post-unconformity time. Nearby (Fig. 12), the same unconformity truncates a fault block and a diapiric fault zone. The beds above the unconformity (unit 1) are little deformed and are presumed to be Tertiary, perhaps Neogene in age. The beds below (unit 2) are perhaps Cretaceous or early Tertiary in age. The post-unconformity unit is at least 3 seconds (about 3 to 4 km) thick. The pre-unconformity unit is at least

1.7 seconds (about 2 km) thick. Beneath the pre-unconformity unit lies a strongly reflective rock interface that produces an exceptionally long train of water-bottom multiples. It is uncertain whether the rocks beneath the interface are acoustic basement, or whether the train of multiples masks a possibly thick sequence of bedded rocks beneath the pre-unconformity unit.

Refraction data (Figs. 8 and 9) indicate that the North Chukchi basin contains more than 1.2 km of presumed Tertiary (perhaps Neogene) beds (unit A, Vp = 1.8–2.1 km/sec.) and more than 0.8 km of presumed Paleogene beds (units B and B_2, Vp = 2.4–2.8 km/sec) overlying assumed Cretaceous strata (unit C, Vp = 3.0–3.5 km/sec.). The 2.3–2.8 km/sec. refraction unit (B, B_2) may be mainly Paleogene in the North Chukchi basin, and mainly Upper Cretaceous in age over and south of the Barrow arch.

direct evidence of Ellesmerian rocks in the North Chukchi basin. Hunkins (1966) shows some 6 km of material with a Vp of 3.0 km/sec., interpreted to be Cretaceous and Tertiary sedimentary rocks, overlying 6 km of material with a Vp of 4.9 km/sec., interpreted to be Franklinian(?) rocks, near 74° N. lat., 165° W. long. in the northeastern part of the basin. However, Hunkins' profile was along the outer shelf and upper slope, and at least partly in the zone of the outer shelf anticline and along a trend of positive gravity anomalies. It is possible that these features reflect a structural high from which Ellesmerian rocks have been stripped by erosion. In that case, the presence of Ellesmerian rocks would not be precluded farther south, beneath the deepest reflections recorded in the central part of the North Chukchi basin. It is possible that the 4.0 km/sec. refractor in unit F (acoustic basement) on the north flank of the Barrow arch in profile B-B' (Fig. 8) represents Ellesmerian rocks. Alternatively, Hunkins' 4.9 km/sec. layer may include

Ellesmerian rocks. If the rifting or faulting that removed Barrovia and created Barrow arch at the close of the Jurassic followed the continental slope rather than the north side of Barrow arch west of 161° W. long. the North Chukchi basin may contain Ellesmerian rocks beneath its thick fill of Cretaceous and Tertiary clastics.

Diapirs in North Chukchi Basin

Diapirs were found at a few widely scattered points in the North Chukchi basin (Fig. 3) but nowhere else on the Chukchi-Beaufort continental terrace. The main, and positively identified group of diapirs intrudes the presumed Tertiary fill of the basin and reaches to the seafloor. The other group consists of diapiric fault zones and anticlines that intrude presumed Cretaceous or Paleogene rocks near the margin of the basin just north of the Wrangel arch. The latter features are overlain unconformably by the presumed Tertiary beds (Figs. 11 and 12) that host the main group diapirs.

A star pattern of reflection profiles over one of the two diapirs that were traversed of the main group demonstrated that it, at least, is circular or subcircular in plan and not elongate or ridgelike. These diapirs are about 2 km in diameter and extend 3 or more km beneath the seafloor. The parent bed, however, was not identified.

The diapirs are clearly intrusive for they have dragged the host beds upward and broken them by swarms of small faults (Fig. 13). A partial rim syncline

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Figure 13 near here.

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can be recognized near one of them.

The three interpreted diapirs of the main group (those shown by hollow triangles on Fig. 3) represent localized bending and small-scale faulting in otherwise flat beds. These disturbances are similar to those found in host beds peripheral to the traversed diapirs, and they are tentatively interpreted as "near misses".

The lithology of the main group diapirs can be inferred, although not conclusively, from magnetic profiles and gravity data over one of them (Fig. 13), a sonobuoy refraction profile (Fig. 14) and regional

Figure 14 near here.

stratigraphy. The magnetic field is not perturbed over the diapirs and the gravity field, if it is affected at all, shows a 4 mgal positive anomaly over one margin of the shallowest crossing of the diapir at 73° N., 163° W. A negative anomaly of 8 mgals over the diapir at 74° N., 166° W. (Cady and others, 1973) was recorded while the ship was changing course and thus is unreliable. The magnetic and gravity data suggest that the diapirs are not igneous, and probably not salt. They might, however, be shale, although the gravity data do not unequivocally distinguish between salt and over-pressured shale for all reasonable density contrasts between the diapirs and the host beds.

The refraction profile was recorded from a sonobuoy deployed at the edge of the diapir at 73° N., 163° W. The width of the diapir along the profile is 1 1/2 km, its top is 25-50 m below the seafloor, and the water depth is about 90 m. With this geometry the slope of the early refractors should reflect the seismic velocity of the diapir. These refractors have a slope of Vp = 2.0 km/sec., within the range of overpressured shale on the Gulf Coast (Musgrove and Hicks, 1968) and much below that of salt

($V_p \cong 4.5$ km/sec.). The absence of a gravity low over the diapirs would be accounted for if the diapirs rose to their present position as low-density, overpressured, gassy shale, but densified by degassing and dewatering enroute. The small positive anomaly over one margin of the diapir at 73° N. lat., 163° W. long. might be explained by a slab of dense rock dragged from depths to a position near the surface in the sheath of the diapir.

Regional stratigraphy supports the geophysical evidence that the diapirs are composed of shale and further suggests that such shale would most likely be Cretaceous. Evaporites have not been reported from the unmetamorphosed pre-Cretaceous (Ellesmerian) sedimentary rocks of the Arctic Platform, as penetrated in exploratory wells along Barrow arch, and as exposed on Wrangel Island. On the other hand, the diapirs cut beds of presumed Tertiary age north of Barrow arch. We postulate that the diapirs originated in prodelta shale that was overpressured and mobilized by loading beneath a northward-thickening delta complex that prograded north from Barrow arch into North Chukchi basin. The most probable age for such shale would be Cretaceous, which would, moreover, allow for the deep burial of the parent beds by Tertiary strata. We considered a Paleogene age for the parent shale, with burial by upper Paleogene and Neogene beds, to be a plausible, but less likely alternative.

We crossed or closely approached five diapirs of the main group along 2,500 km of profiles in the North Chukchi basin. The diapir targets, that is, the zones of peripheral structural disturbance surrounding the diapirs, are typically about 5-6 km in diameter, and the portion of the basin surveyed is about 120,000 sq km. Therefore, some 30 or 40 diapirs of the main group may be present in the surveyed area of the North Chukchi basin.

The diapirlike structures occupy an east-west-trending belt in the North Chukchi basin just north of the Wrangel fault zone (Figs. 11 and 12). The host rocks are gently tilted and folded beds that are presumed to be Cretaceous or Paleogene. Both the diapirlike structures and the host beds are overlain with angular unconformity by gently basinward-dipping strata of presumed Tertiary age.

These diapirlike structures are intruded masses or piercements that are commonly 1 to 4 km in apparent width. Some have as much as 2 or more km of vertical extent. Three (possibly four) of the larger diapirlike features are alined and show similar cross sections, and therefore probably represent a single elongate structure. This elongate structure is subparallel to the nearby Wrangel fault zone, suggesting that it is a related fault zone with a diapiric core. The other diapirlike structures near the Wrangel fault zone appear on our reflection profiles as isolated piercements or positive structures of small vertical displacement in flat or gently tilted or folded host beds. None of the diapirlike structures have directly associated magnetic anomalies. Taken together, these characteristics suggest that the structures in question are a feature of the faults and folds that were generated along the south margin of the North Chukchi basin by compression at the Wrangel fault zone.

Beaufort Shelf West of Camden Bay

The geologic structure beneath the Beaufort continental shelf changes character at western Camden Bay (Figs. 1, 2 and 3). To the west, the strata underlying the shelf are but slightly deformed and in general dip gently seaward. To the east, they have been dislocated into long, large amplitude, east-northeast-striking folds. The change occurs where the east-southeast-plunging Barrow arch approaches the northeast Brook Range and loses its identity in the foreland folds, which are as young as Neogene, and which flank that part of the range.

Bedded rocks in the western Beaufort shelf dip about 1° northerly, but north of Barrow a local monocline has dips of 5° or more (Fig. 15).

Figure 15 near here.

Between Camden Bay and Cape Halkett the outer part of the western Beaufort shelf is characterized by a structural terrace, or flattening, in the gentle north dip, and west of Cape Halkett by a broad shallow anticline (max. amplitude ~200 m) as in the northern Chukchi Sea (Figs. 3 and 15). The shallow anticline and a parallel syncline about 10 km (range 5 to 20 km) to the south trend west-northwest along the outer shelf at least to 160° W. long. For most of their length the axis of the anticline and structural terrace lies 0 to 10 km, but in one area, 20 km landward of the continental shelf break.

The continental slope in the western Beaufort Sea is steep (5–10° with local steeper slopes) and broken by many large slumps. In places the slumps have stepped the flat outer continental shelf down as much as 200 m. The upper part of the sedimentary section beneath the shelf crops out in the upper part of the steep slope wherever it is not jumbled in slumps. Landward from the shelf break, bedded rocks in the western Beaufort continental terrace are, in places, broken by faults of small displacement that are predominantly down to the north on profiles run normal to the coast. There appear to be changes in the thickness of some sedimentary units across some of the faults (Fig. 15), which thus may be growth faults.

The post-Franklinian(?) section beneath the western Beaufort shelf thickens northward from about 0.8 km near Barrow Village and from about 3.5 km near Prudhoe Bay, both near the crest of the Barrow arch. At Barrow Village thin Neocomian shale and thick Albian marine shale and paralic sandstone rest unconformably on Franklinian(?) rocks and thicken northward at about 35 m/km. Near Prudhoe Bay some 50-60 m of Neocomian shale on the north side of the Barrow arch locally, and perhaps regionally, oversteps the Ellesmerian sequence to rest unconformably on Franklinian(?) rocks. At the Prudhoe Bay field the thin Neocomian beds are overlain by about 1.2 km of Upper Cretaceous marine and nonmarine sandstone, shale and conglomerate and 1 to 1 1/2 km of Tertiary nonmarine sand, gravel, and silt. The nonmarine units are thought to become increasingly marine, and many of the sandstones appear to pinch out in that direction. Disconformities underlie the Upper Cretaceous and possibly the Tertiary units at Prudhoe Bay.

Sonobuoy refraction profile D-D' (Fig. 16), trends parallel to the

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Figure 16 near here.

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western Beaufort coast about 30 miles offshore, and reveals an upper unit 0.5 to 1.2 km thick with a Vp of 1.8-2.2 km/sec. and a lower unit 0.8 to one km thick with a Vp of 2.4-2.9 km/sec. Both units are correlated with the Tertiary section in the Prudhoe Bay wells. The underlying beds have seismic velocities of 3.1-3.2 km/sec. on the west, and 3.8 km/sec. on the east. The former would be appropriate for the Albian shales and sands that trend northward beneath the Beaufort shelf from the Barrow area. The

3.8 km/sec. refractor presumably represents the Upper Cretaceous rocks of the Prudhoe Bay area, although its seismic velocity matches unit D of section C-C' (Fig. 9), which is thought most likely to be earliest Cretaceous.

The Tertiary-Cretaceous contact as projected from onshore and from refraction profile D-D', and, as tentatively identified on reflection profiles, lies well offshore west of Harrison Bay. Thus a relatively narrow band of Tertiary strata beneath the western Beaufort shelf connects the North Chukchi and Camden Tertiary basins. Local stratigraphic irregularities interpreted as buried slumps and channels (Fig. 15), the apparent growth faults noted above, and local clinoform units in the Tertiary section beneath the shelf elsewhere support the conclusion that these beds constitute a progradational shelf and slope sequence. A tendency for the stronger reflectors to weaken or fade out toward the outer shelf break in at least the Tertiary units suggests that these reflectors are sandstone beds that pinch out seaward. Possibly this pinching out occurred in part against a syndepositional bathymetric swell over the shelf edge anticline discussed above. Locally, seismic reflectors beneath the outer shelf have been disrupted by incipient slumping related to the present slope, and by slump deposits within the sedimentary section itself.

Eastern Beaufort Shelf

East-northeast-striking folds, one with strike length exceeding 100 km and amplitude exceeding 1 km, dominate the structure of the Beaufort continental terrace from Camden Bay to the Canadian border. Some of the folds extend at least to the upper continental slope. Three large anticlines were mapped, one a possible offshore extension of the Marsh Creek anticline (Figure 3). However, wide spacing and disruption of track lines by pack ice created uncertainties in the delineation of the folds, and in particular in the identification of the offshore extension of Marsh Creek anticline. In and north of Camden Bay these folds have flank dips of as much as 11°. The folds resemble those in the Cretaceous rocks in the northern Arctic foothills of the Brooks Range and, like them, may be thrust folds. However, they are developed in rocks as young as Neogene. The folds may be related to young uplift and thrusting which created the Romanzof Mountains salient of the northeastern Brooks Range (Figs. 1 and 3). It is of interest that where the folds of the eastern Beaufort Sea reach the continental slope, the latter slopes more gently than to the west and is dominated by sedimentation, rather than by erosion. On the continental slope the folded beds are being covered by sediment from the Mackenzie delta.

South of Camden basin and Marsh Creek anticline (Fig. 3) lies a prism of Cretaceous marine and nonmarine sandstone and shale at least 3,700 m thick (Reiser and others, 1974). The prism overlies Ellesmerian rocks and appears to extend into the offshore east of Humphrey Point (142°30' W. long.).

Outer Shelf Gravity High

A series of positive free-air gravity anomalies with peak amplitudes exceeding 100 mgals occur along the outer shelf and upper slope of the Beaufort Sea from north of Banks Island on the east to 161° W. long. on the west (Wold and others, 1970). According to Chiburis and Dehlinger (1974) the belt of positive anomalies coincides with the upper continental slope in the eastern Beaufort Sea and the outer shelf in the central and western

Beaufort Sea. Our data verify the presence of the positive outer shelf anomaly as far as 159° W. long. and possibly as far as 168° W. long. and suggest that peak anomaly amplitudes become lower to the west.

Wold and others (1970) ascribe the anomaly to thinning of the crust at the edge of the continent plus a ridge in the basement near the 200-m isobath. Weber (1963), Barnes (1969), and Sobczak (1974) ascribe it to an uncompensated wedge of young sedimentary rocks beneath the outer shelf and slope. The discontinuous character of the gravity anomaly and the fact that it corresponds closely in position to the outer shelf structural terrace and anticline shown by our seismic reflection profiles in the central and western Beaufort Sea lends support to the origin suggested by Wold and others (ibid.).

Configuration of Prospective (Acoustic) Basement

Form lines on basement for oil and gas exploration (prospective basement) on the North Slope and Chukchi-Beaufort continental terrace are presented in Figure 17. Franklinian(?) rocks are thought to constitute

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Figure 17 near here.

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both prospective basement and acoustic basement beneath the North Slope. The form-line map and a generalized structure section along 168° W. long. in the Chukchi Sea (Fig. 18) summarize our present, tentative views of the

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Figure 18 near here.

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geologic framework of the Alaskan continental terrace in the Chukchi and Beaufort Seas. Onshore, the form lines are after Figure 1 in Morgridge and Smith (1972); offshore they are based on U.S.G.S. single channel seismic reflection and refraction data, refraction lines reported by Hunkins (1966) and Milne (1966) and projections from North Slope exploratory wells. Our reflection data include basement returns only in the Hope basin and along Barrow arch. Elsewhere the form lines were inferred from higher reflectors, to which acoustic basement was arbitrarily assumed to be parallel. Although this assumption is not likely to be correct in detail, we believe that the resulting form lines nevertheless provide a first approximation of the distribution, thickness, and megastructure of prospective rocks on the North Slope and in the Chukchi-Beaufort continental terrace.

Hope basin, western Colville geosyncline, North Chukchi basin and the Beaufort shelf are shown in Figure 17 to be major offshore sedimentary provinces with sufficient thicknesses of sedimentary rocks to be prospective for oil or gas. The Barrow arch appears as a doubly plunging regional feature that terminates east and west against thrust-fault belts. The doubly plunging arch, the two thrust belts, and the embayments of Tertiary sedimentary rock that cross the arch near both plunging terminations constitute a striking, albeit lopsided symmetry that dominates the megastructure of northern Alaska and the Chukchi-Beaufort continental terrace.

The two stratigraphic sequences known to be petroliferous on the North Slope, the Ellesmerian and overlying Colvillian rocks, lie between the thrust fault zones and the Barrow arch, the structural culmination of the southward tilted Arctic Platform. The presence of oil and gas in the Hope and North Chukchi basins and on the Beaufort shelf remains to be established. The likelihood that Hope basin is filled mainly by nonmarine rocks suggests that it has better prospects for dry gas than for oil.

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List of Illustrations

Figure 5. Map showing location of seismic refraction profiles A-A' (Fig. 6), B-B' (Fig. 8), C-C' (Fig. 9), D-D' (Fig. 16) and seismic reflection profiles V-V' (Fig. 7), W-W' (Fig. 10), X-X' (Fig. 11), Y-Y' (Fig. 12) and Z-Z' (Fig. 15). H designates the long reversed refraction profile reported by Hunkins (1966); M designates the unreversed refraction profile reported by Milne (1966).

6. North-south sonobuoy refraction profile A-A' across the Hope basin near 168° W. long. (see Fig. 5 for location). Compare with the northeast-southwest seismic reflection profile V-V' across the Hope basin shown in Figure 7. The dashed line in unit C shows an alternative position for the wedge-out of that unit between units B and D. Unit A is tentatively inferred to consist of Neogene marine and nonmarine clastic rocks; unit B of Paleogene nonmarine clastic rocks, and unit C of Upper Cretaceous and/or Paleogene nonmarine clastic rocks. Unit D, acoustic basement, consists of Lower Cretaceous and older rocks of the Brooks Range orogen.

7. Northeast-southwest continuous seismic reflection profile V-V' across eastern Hope basin (see Fig. 5 for location). Units 1, 2, 3 and 4 correspond approximately to units A, B, C and D of sonobuoy profile A-A' (Fig. 6).

8. North-south sonobuoy refraction profile B-B' from Herald arch to North Chukchi basin near 168° W. long. (see Fig. 5 for location). Unit A is tentatively inferred to consist of Tertiary clastic rocks; unit B of mid-Cretaceous clastic

rocks of the Nanushuk and Colville groups south of Barrow arch and Paleogene clastic rocks north of the arch; and unit C of Lower Cretaceous Torok Formation south of Barrow arch and Cretaceous clastic rocks of unknown age north of the arch. Unit D may consist of earliest Cretaceous or upper Ellesmerian sequence rocks. Unit F, acoustic basement, is inferred to consist of rocks of the Franklinian(?) sequence.

Figure 9. North-south sonobuoy refraction profile C-C' from the Colville geosyncline to the junction of the Beaufort shelf and North Chukchi basins near 160° W. long. (see Fig. 5 for location). Unit A is tentatively inferred to consist of Tertiary clastic rocks; unit B of mid-Cretaceous clastic rocks of the Nanushuk and Colville groups; unit B_2 of Paleogene clastic rocks; unit C_1 of Lower Cretaceous Torok Formation; unit C_2 of Cretaceous clastic rocks of unknown age; and unit D of earliest Cretaceous and/or upper Ellesmerian sequence rocks. Unit E may represent the main Ellesmerian sequence, and unit F, Franklinian(?) rocks in acoustic basement.

10. Northeast-southwest continuous seismic reflection profile W-W' across Barrow arch and the northern part of the Colville geosyncline near Barrow (see Fig. 5 for location). Unit 1 is inferred to consist of clinoform (foreset) beds of the Lower Cretaceous Torok Formation and Nanushuk group; unit 2 Ellesmerian rocks; and unit 3 Franklinian(?) rocks in acoustic basement

the resemblance of minor structural features in its seismic profile to those in the oblique profiles across the diapir at 73° N. lat., 163° W. long. Note the sag in the beds to the south of the diapir in the upper left profile, which may indicate that a rim syncline may border the south side of the diapir at 73° N. lat., 163° W. long.

Figure 14. Sonobuoy refraction profile across the diapir at 73° N. lat., 163° W. long. Hypothetical refraction arrivals for salt and overpressured shale from the shallow diapir have been added to the actual field-recorded profile. The early refractors of the actual profile lie at the lower end of the velocity range of overpressured shale on the Gulf Coast, and are much lower than seismic velocities in salt domes.

15. North-south continuous seismic reflection profile Z-Z' from the Barrow arch near Point Barrow to the continental slope in the Beaufort Sea (see Fig. 5 for location). Unit 1 is inferred to consist of Tertiary clastic rocks; unit 2 of Cretaceous marine clastic rocks that are at least largely of Albian age; and unit 3 of Franklinian(?) rocks in acoustic basement. Note the very low amplitude outer shelf anticline-structural terrace, possible growth faults on the outer shelf, channeling and slumping within unit 1, and slumping on the steep upper continental slope.

16. East-west sonobuoy refraction profile D-D' on the western Beaufort continental shelf (see Fig. 5 for location). Units

A and B are correlated with the Sagavanirktok Formation (Tertiary) of the Camden basin and units C and D with Cretaceous rocks of the Colville geosyncline. The apparent sag in the refractors near the west end of the profile is an artifact resulting from the position of the sonobuoy in the sag farther down dip than its neighbors.

Figure 17. Major tectonic features and sedimentary basins of the North Slope and the Alaskan continental terrace in the Chukchi and Beaufort Seas. The gross structure is outlined by form lines on acoustic basement, which in general is also basement for petroleum exploration. Line A-A' locates the diagrammatic cross section presented in Figure 18.

18. Diagrammatic north-south cross section of the continental terrace in the Chukchi Sea along 168° W. long. (see Fig. 17 for location). The intrusive feature in Tertiary rocks north of the Barrow arch represents a shale(?) diapir.

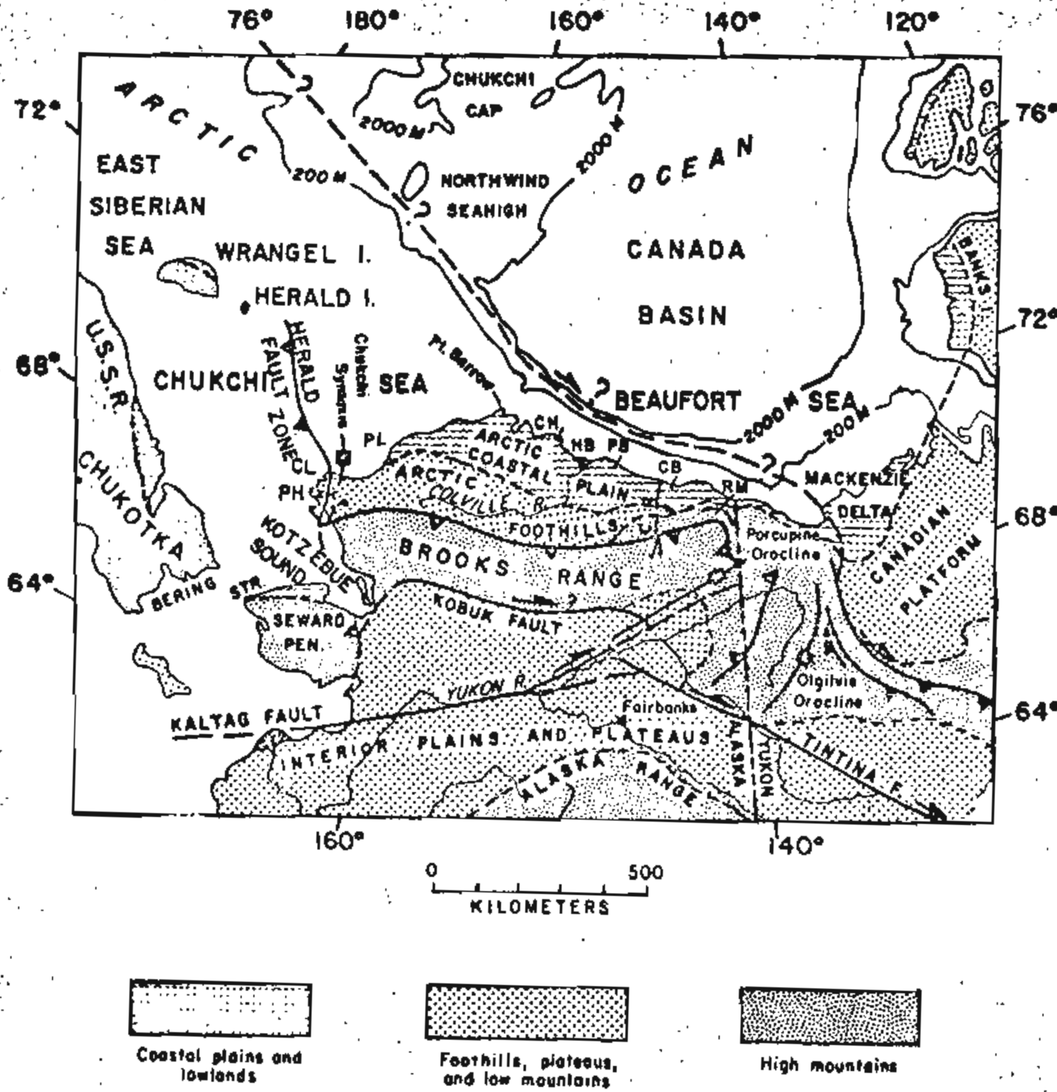

ARCTIC OCEAN
EAST SIBERIAN SEA
WRANGEL I.
HERALD I.
CHUKCHI CAP
NORTHWIND SEAHIGH
CANADA BASIN
BEAUFORT SEA
CHUKCHI SEA
HERALD FAULT ZONE
Chukchi Syncline
Pt. Barrow
U.S.S.R.
CHUKOTKA
BERING STR.
KOTZEBUE SOUND
SEWARD PEN.
ARCTIC COASTAL PLAIN
ARCTIC FOOTHILLS
COLVILLE R.
BROOKS RANGE
KOBUK FAULT
MACKENZIE DELTA
CANADIAN PLATFORM
Porcupine Orocline
Olgilvie Orocline
YUKON R.
KALTAG FAULT
Fairbanks
INTERIOR PLAINS AND PLATEAUS
ALASKA RANGE
ALASKA
YUKON
TINTINA F.
BANKS I.
PL
CL
PH
CH
HB
PB
CB
RM
200 M
2000 M
76°
180°
160°
140°
120°
72°
68°
64°
KILOMETERS
0
500
Coastal plains and lowlands
Foothills, plateaus, and low mountains
High mountains

Fig. 1

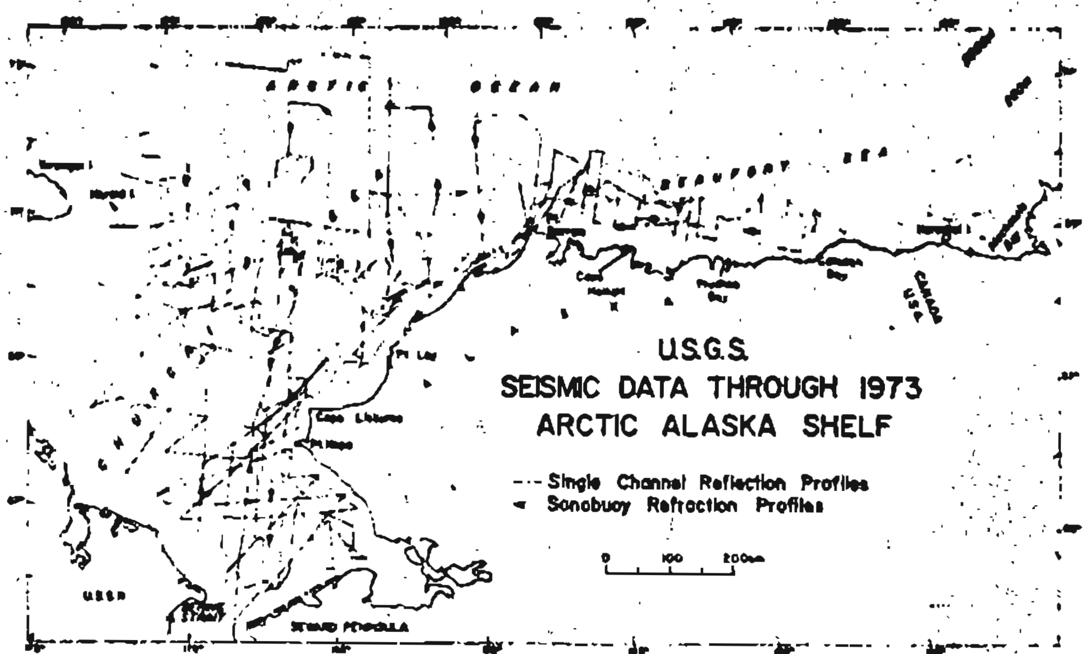
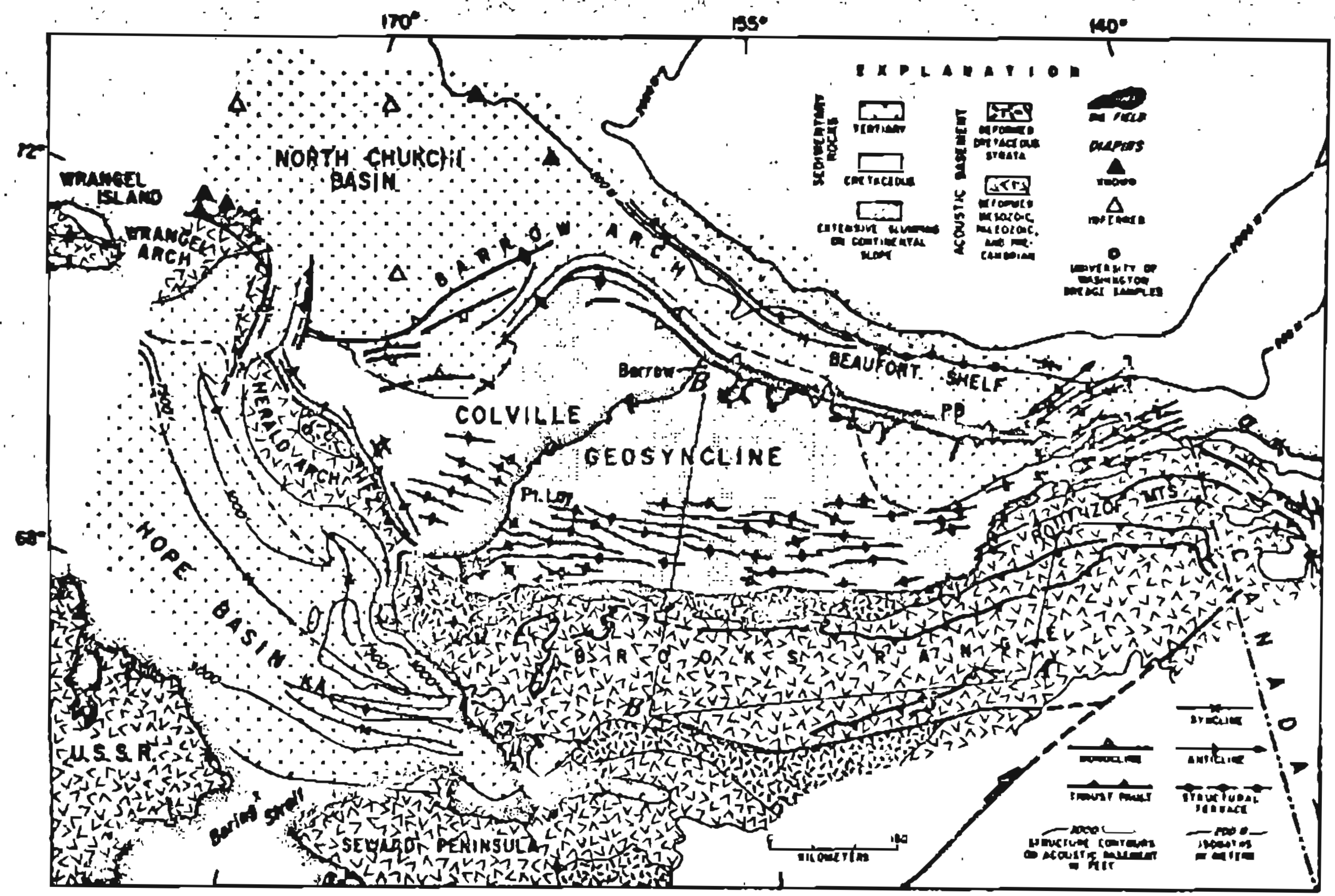
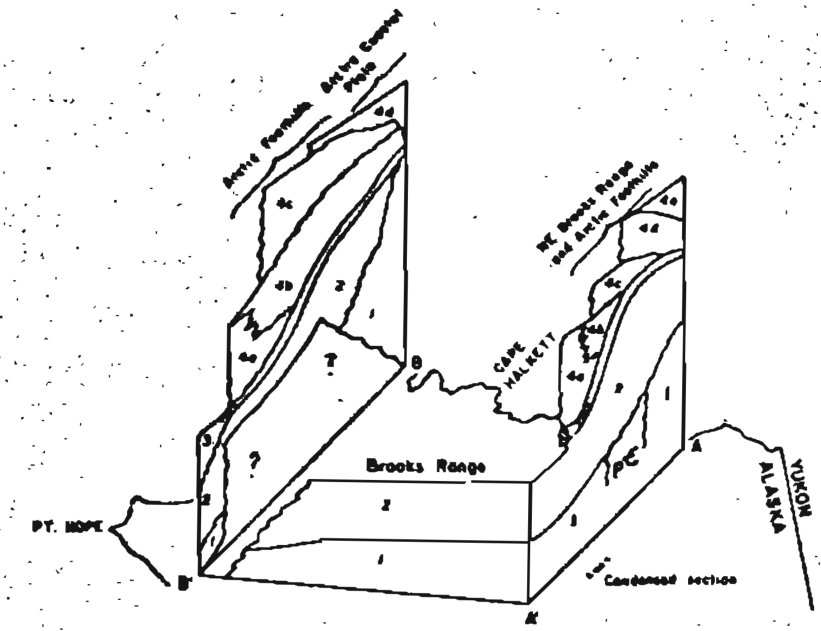

ARCTIC
OCEAN
BEAUFORT
SEA
Pt Lay
Cape Lisburne
Pt Hope
SEWARD PENINSULA
USSR
CANADA
USA
U.S.G.S.
SEISMIC DATA THROUGH 1973
ARCTIC ALASKA SHELF
Single Channel Reflection Profiles
Sonobuoy Refraction Profiles
0
100
200

Fig. 2



170°
155°
140°
72°
68°
EXPLANATION
SEDIMENTARY ROCKS
TERTIARY
CRETACEOUS
EXTENSIVE SLUMPING ON CONTINENTAL SLOPE
ACOUSTIC BASEMENT
DEFORMED CRETACEOUS STRATA
DEFORMED MESOZOIC, PALEOZOIC, AND PRE-CAMBRIAN
OIL FIELD
DIAPIRS
INFERRED
UNIVERSITY OF WASHINGTON DREDGE SAMPLES
NORTH CHUKCHI BASIN
WRANGEL ISLAND
WRANGEL ARCH
BARROW ARCH
BEAUFORT SHELF
Barrow
PB
COLVILLE
GEOSYNCLINE
HERALD ARCH
Pt. Lay
HOPE BASIN
KA
BROOKS RANGE
ROMANZOF MTS
CANADA
U.S.S.R.
Bering Strait
SEWARD PENINSULA
KILOMETERS
SYNCLINE
MONOCLINE
ANTICLINE
THRUST FAULT
STRUCTURAL TERRACE
STRUCTURE CONTOURS ON ACOUSTIC BASEMENT IN FEET
ISOBATHS IN METERS

Fig.3



4e. Sagavanirktok Fm (Tertiary)
d. Colville Gp (Turonian and Senonian)
c. Nanushuk Gp (Albian and Cenomanian)
b. Torok Fm (Albian)
a. Fortress Mtn. Fm (Albian)

} Molasse wedges in Camden basin (Tertiary) and Colville geosyncline (Cretaceous)

3. Flysch and shale in Colville geosyncline. Okpikruak Fm (flysch) on south, "Pebble shale" on north (Neocomian - Lower Cretaceous)
2. Ellesmerian sequence. Shelf clastic and carbonate rocks of the Arctic Alaska basin; Mississippian to Jurassic and locally lowest Cretaceous
1. Franklinian (?) sequence. Miogeosynclinal and eugeosynclinal rocks; Cambrian to Devonian

Fig. 4

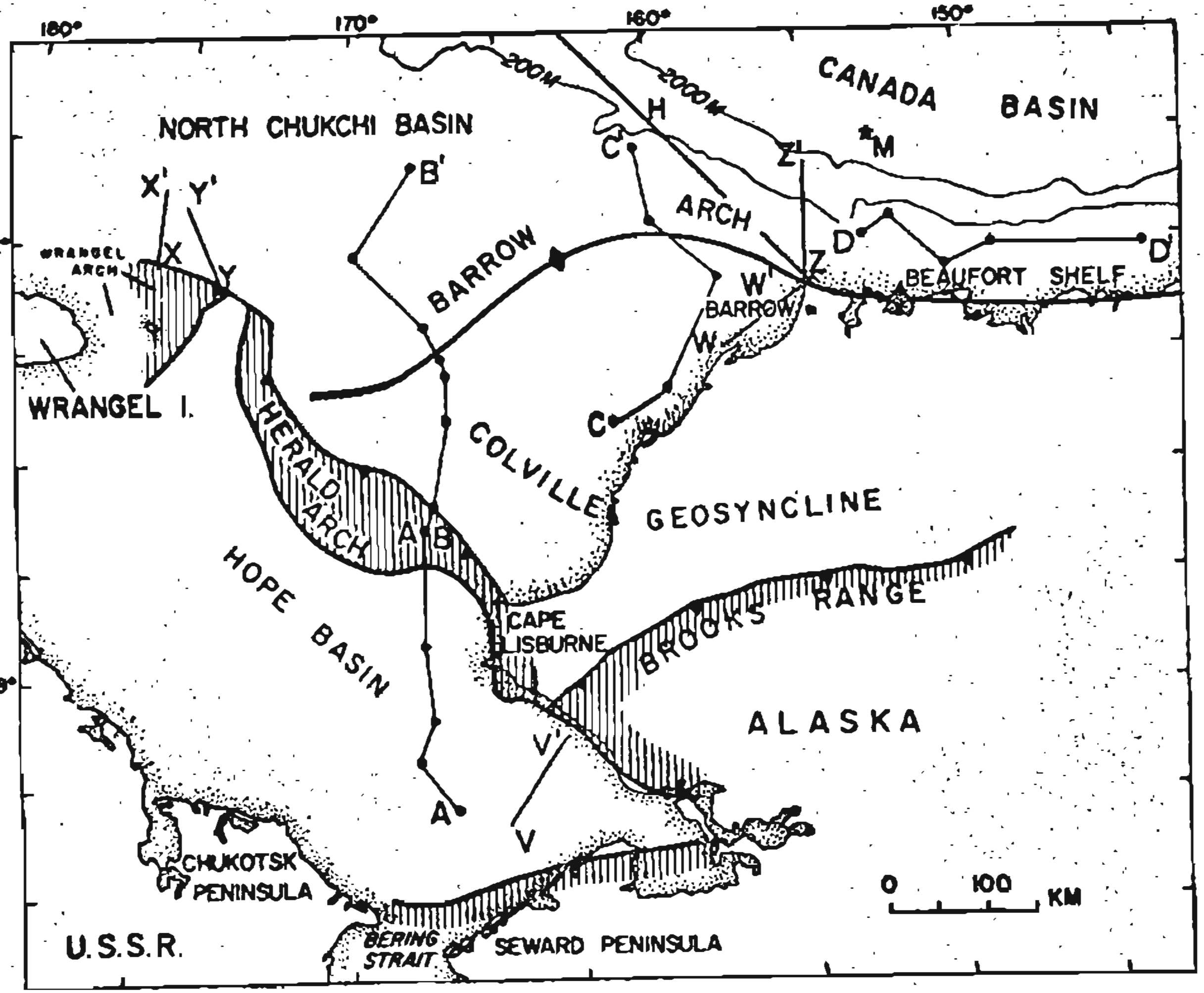

180°
170°
160°
150°
72°
68°
NORTH CHUKCHI BASIN
CANADA BASIN
200M
2000M
H
M
C'
B'
X'
Y'
X
Y
Z'
Z
D
D'
W'
W
C
ARCH
BARROW
BARROW
BEAUFORT SHELF
WRANGEL ARCH
WRANGEL I.
HERALD ARCH
A
B
A'
COLVILLE GEOSYNCLINE
HOPE BASIN
CAPE LISBURNE
BROOKS RANGE
ALASKA
V'
V
CHUKOTSK PENINSULA
U.S.S.R.
BERING STRAIT
SEWARD PENINSULA
0
100
KM

Fig.5

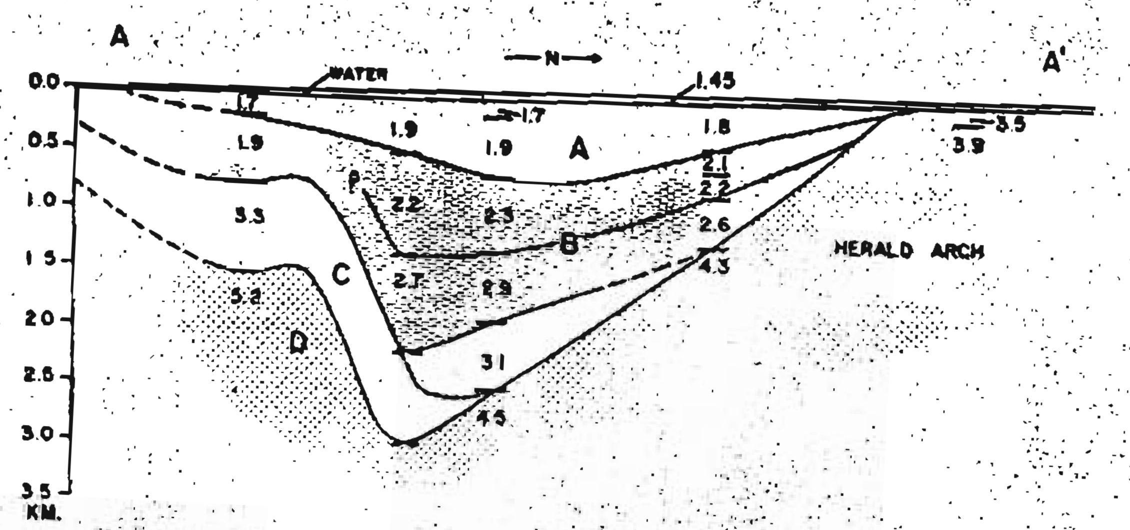
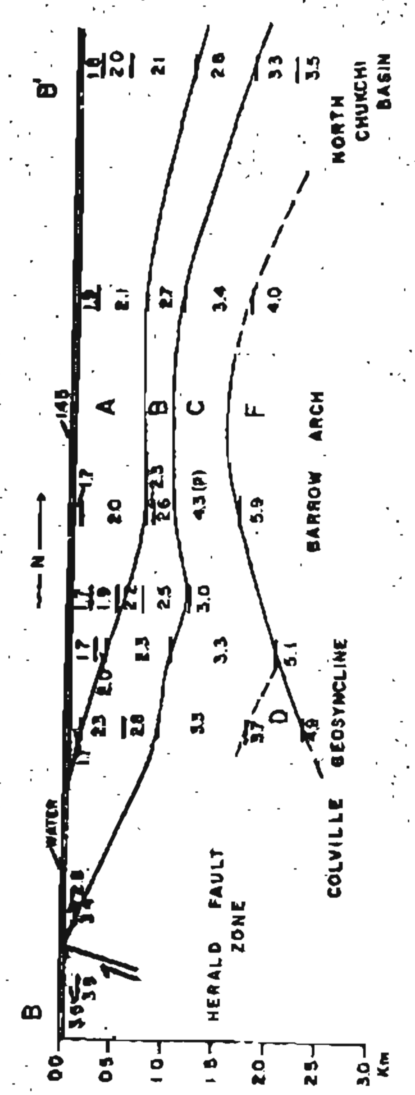

A
A'
N
WATER
1.45
1.7
1.9
1.8
2.1
2.2
2.6
4.3
3.5
3.9
3.3
3.2
2.7
2.9
31
4.5
A
B
C
D
HERALD ARCH
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
KM.

Fig. 6



F = Franklinian Basement

D = uppermost Ellesmerian Sequence.

C = Torok Fm ?

B = Nanushuk or Colville Group rocks ??

Fig. 8

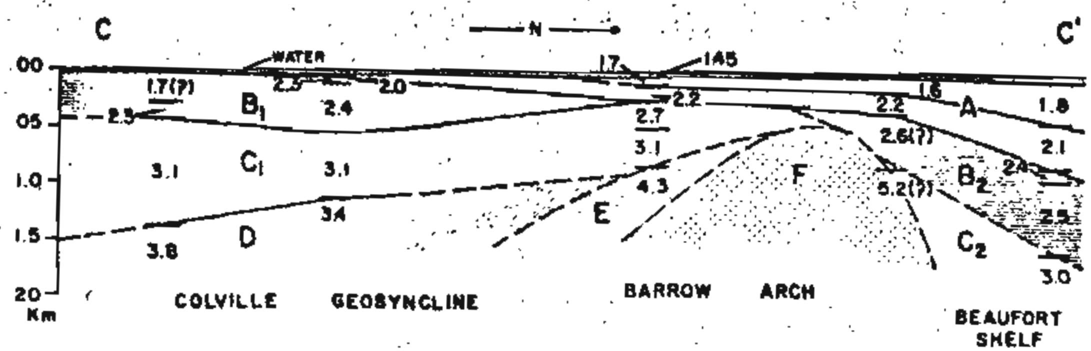

C
C'
N
WATER
1.7(?)
2.5
2.0
1.7
145
B1
2.4
2.2
2.2
1.6
A
1.8
2.5
2.7
2.6(?)
2.1
3.1
C1
3.1
3.1
F
B2
2.4
4.3
5.2(?)
E
2.5
3.4
D
C2
3.8
3.0
.00
0.5
1.0
1.5
2.0
Km
COLVILLE
GEOSYNCLINE
BARROW
ARCH
BEAUFORT
SHELF

Fig. 9

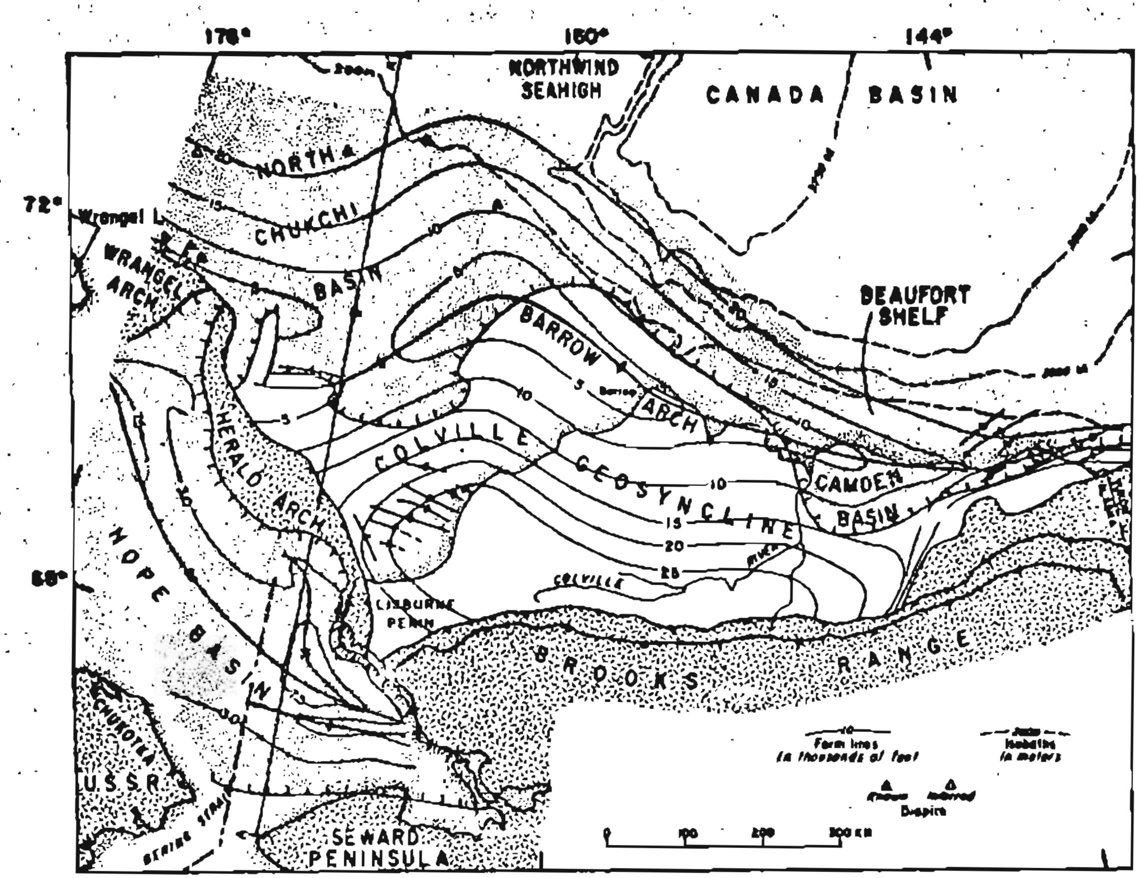

176°
160°
144°
72°
68°
NORTHWIND SEAHIGH
CANADA BASIN
BEAUFORT SHELF
NORTH
CHUKCHI
BASIN
Wrangel I.
WRANGEL ARCH
BARROW
ARCH
Barrow
COLVILLE GEOSYNCLINE
CAMDEN BASIN
HERALD ARCH
HOPE BASIN
LISBURNE PENIN
BROOKS RANGE
COLVILLE RIVER
CHUKOTKA
U.S.S.R.
SEWARD PENINSULA
BERING STRAIT
Form lines (in thousands of feet)
Isobaths in meters
Known
Inferred
Diapirs
0
100
200
300 KM

Fig. 17

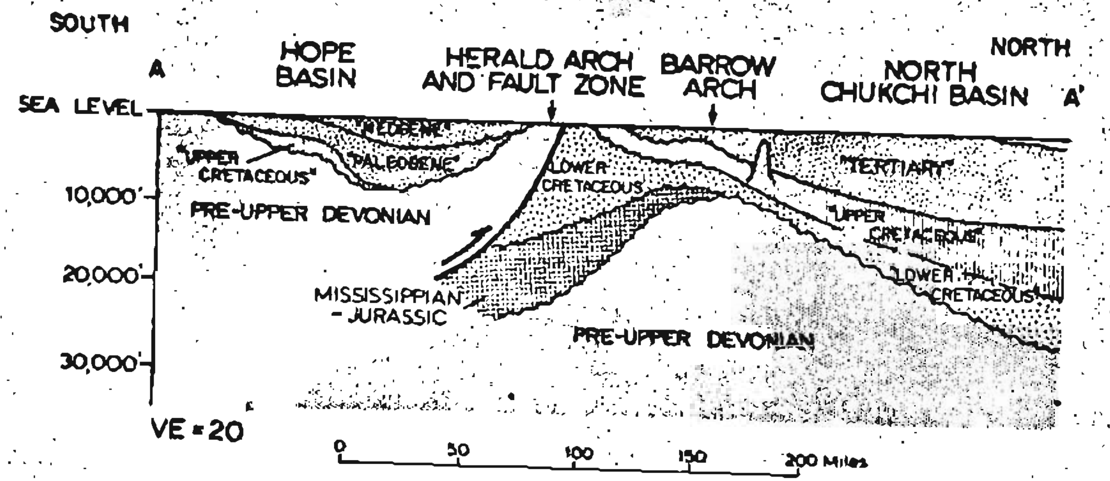

SOUTH
NORTH
A
A'
HOPE BASIN
HERALD ARCH AND FAULT ZONE
BARROW ARCH
NORTH CHUKCHI BASIN
SEA LEVEL
10,000'
20,000'
30,000'
"NEOGENE"
"PALEOGENE"
"UPPER CRETACEOUS"
PRE-UPPER DEVONIAN
LOWER CRETACEOUS
MISSISSIPPIAN - JURASSIC
"TERTIARY"
"UPPER CRETACEOUS"
"LOWER CRETACEOUS"
PRE-UPPER DEVONIAN
VE = 20
0
50
100
150
200 Miles

Fig. 18