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Chapter 2

Geology of the Arctic continental margin of Alaska[1]

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INTRODUCTION

Location and physiography

Alaska faces the Canada Basin of the Arctic Ocean along an arcuate continental margin, gently concave to the north, that stretches unbroken from the Mackenzie Delta, near 137°W to Northwind Ridge of the Chukchi Borderland near 162°W. (Marine geographic features mentioned below can be found on Plates 1 and 11 of Grantz and others, 1990a.) This margin, with an arc-length of about 1,050 km, marks one side of a continental rift along which the Canada Basin opened by rotation about a pole in the Mackenzie Delta region during middle Cretaceous time. The rift-margin structures, which lie beneath the inner shelf and coastal plain in the eastern Alaskan Beaufort Shelf and beneath the outer shelf in the western Beaufort and Chukchi Shelf, are now buried by a thick middle Lower Cretaceous to Holocene progradational continental terrace sedimentary prism.

We divide the Arctic continental margin of Alaska into three sectors of strongly contrasting geologic structure and physiographic expression. In the Barter Island sector (see Figs. 3 and 4) the structure is dominated by the effects of Eocene to Holocene convergence and uplift, and the continental slope is upwardly convex; in the Barrow sector the structure is dominated by the effects of middle Early Cretaceous rifting and continental breakup, and the continental slope is upwardly concave; and in the Chukchi sector the structure is controlled by an easterly trending middle Early Cretaceous rift, and the continental slope abuts the Chukchi Borderland.

Physiographically, the Alaska continental margin is expressed by the Alaska continental rise and slope (Fig. 1), which lies between the oceanic Canada Basin to the north and the flat and shallow continental shelves of the Beaufort and Chukchi Seas to the south. Outer shelf and slope morphology along the margin is dominated by gravity-driven slope failures. These include both surficial slumps and deeply penetrating slope failures related to listric normal faults that dip toward the modern and ancient free face of the continental slope. Some of the listric faults offset Quaternary deposits or the seabed (Grantz and others, 1983a).

A major influence on the physiography of the region is the relative size and age of the sediment sources that built the progradational sedimentary prisms of the narrow Alaska slope and rise and the much more extensive continental rise and abyssal plain of the Canada Basin. The great volume of clastic sediment that poured into the Canada Basin from the Mackenzie River drainage system and from the Canadian Shield via the Amundsen Gulf, in Cretaceous and especially Cenozoic time, overwhelmed that which built the Alaska slope and rise. The extensive Canada Basin fill is banked against the Alaska slope and rise at depths of a little more than 1,000 m at the Mackenzie Delta—the major sediment source for the basin—to almost 4,000 m at the abyssal plain at the foot of the Northwind Escarpment. The disparity in sediment supply is illustrated by the fact that the deepest part of the Canada abyssal plain lies near the foot of the narrow Alaska slope and rise (Grantz and others, 1990a, Plate 1).

Previous studies

Early ideas on the geology of the northern Alaska continental margin were extrapolated from studies of the surrounding landmasses. Carey (1958) originally suggested that the Beaufort Sea margin of Alaska was created by a rift in which northern Alaska was rotated away from the Canadian Arctic Islands by oroclinal bending about a pivot in the Gulf of Alaska. Regional geologic considerations led Tailleur (1969a, b, and 1973) also to postulate that rotational rifting played a crucial role in the tectonic evolution of the region. Based on data acquired during oil exploration, Rickwood (1970) concurred with the rotational rift hypothesis and proposed that rifting was crucial to creation of the trap that holds the supergiant hydrocarbon deposit at Prudhoe Bay.

In the past decade, interpretation of the geology of the Beaufort Shelf has relied heavily on multichannel seismic reflection data, but the first geological cross sections of the region were drawn from other types of geophysical data. Wold and others

[1]In order to provide coverge of the entire state of Alaska in one volume, the editors have reprinted this chapter from Grantz and others, 1990a where it appears as Chapter 16, pp. 257–288. The only differences between this reprinted text and the original are in the references to plates and chapters in Grantz and others (1990a).

Grantz, A., May, S. D., and Hart, P. E., 1994, Geology of the Arctic continental margin of Alaska, *in* Plafker, G., and Berg, H. C., eds., The Geology of Alaska: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-1.

(1970) published an interpretation of the Beaufort Sea margin based on gravity data collected from light airplane landings on sea ice. A more detailed survey, based on shipborne gravity meter readings, was presented and interpreted by Dehlinger (1980). To date, the most detailed published gravity map of the region, compiled from shipborne data gathered by the U.S. Geological Survey between 1972 and 1982, was published by May (1985). Extensive proprietary surveys also exist.

Two early seismic refraction studies of the Alaskan continental margin produced reconnaissance profiles. One, across the lower continental slope and upper rise north of Barrow by Milne (1966), is unreversed and of limited usefulness. The other, a long reversed profile from Barrow to the northern Chukchi Shelf (Hunkins, 1966), suggests that the shelf there is underlain by continental crust and that the top of basement deepens from about 1 km near Barrow to about 6 km near the shelf edge. Two studies of the seismic velocity structure of the Beaufort Sea and Chukchi Sea margins were based on sonobuoys. Houtz and oth-

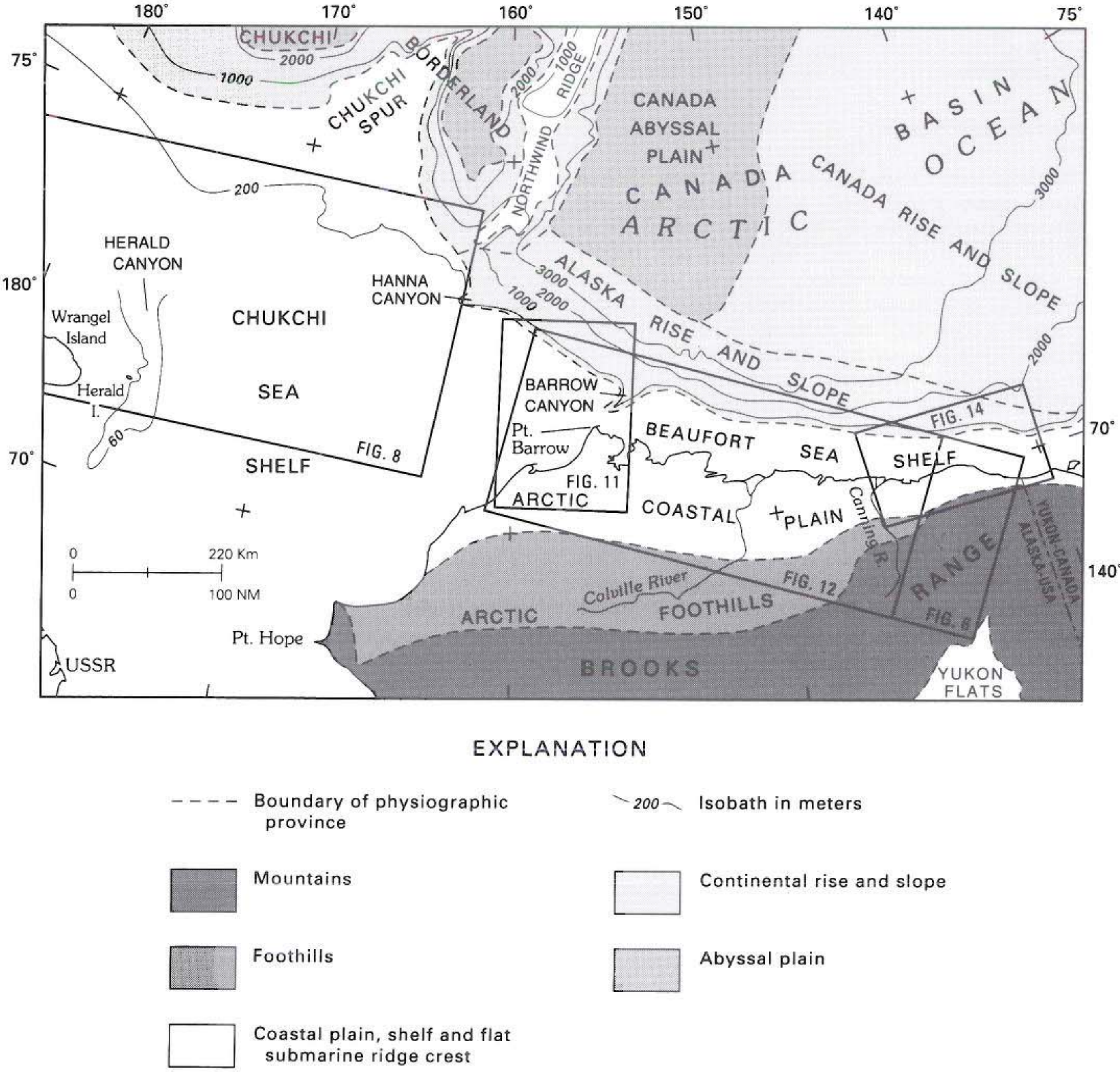


Figure 1. Map of Arctic continental margin of Alaska showing major physiographic features and location of Figures 6, 8, 11, 12, and 14.

ers (1981) used more than 100 sonobuoy records from the northern Alaskan shelves to interpret the general velocity structure of the region. A more detailed study of the velocity structure of the Beaufort Shelf between Prudhoe Bay and Cape Simpson was published by Bee and others (1984).

Published data on both present magnetic field anomalies and paleomagnetic field directions in the region are limited. Extensive proprietary aeromagnetic surveys have been conducted over the Beaufort Shelf, but published data consist primarily of a reconnaissance magnetic anomaly map (Cramer and others, 1986) of the area west of 155°W. Pioneering paleomagnetic studies of upper Paleozoic strata in the Brooks Range were interpreted to agree with the proposed counterclockwise rotation of Arctic Alaska away from the Canadian Arctic Islands (Newman and others, 1979), but Hillhouse and Grommé (1983) showed that the magnetic field direction was overprinted during the Cretaceous. More recently, Halgedahl and Jarrard (1987) have reported that oriented drill cores from the Kuparuk oil field, near the Beaufort Sea coast, apparently escaped overprinting. These cores indicate that Arctic Alaska was rotated counterclockwise with respect to North America since deposition of the cored rocks in middle Early Cretaceous time.

An early discussion of the regional geologic framework of the Beaufort and Chukchi Shelves, based primarily on analog single channel seismic reflection data, was published by Grantz and others (1975). In 1977, 1978, and 1980 the U.S. Geological Survey conducted multichannel seismic reflection surveys of the entire Alaska Beaufort Shelf and the central and eastern parts of the Chukchi Shelf. Regional geological interpretations of these data have been published in several reports (Grantz and May, 1983, 1987; Grantz and others, 1979, 1981, 1987a, b). Craig and others (1985) used proprietary subsurface and seismic reflection data, in conjunction with previously published reports, to summarize the regional geology, petroleum resources, and environmental geology of the Alaskan Beaufort Shelf. An interpretation of the stratigraphy and geologic history of the Beaufort Shelf, also based on proprietary data, was recently presented by Hubbard and others (1987). An important recent contribution is a discussion of the regional geology of the central and northern Chukchi Shelf by Thurston and Theiss (1987).

Time-to-depth conversion functions

The seismic reflection time-to-depth conversion functions used in this study were calculated from regionally averaged multichannel seismic reflection stacking velocities (Fig. 2). These functions enable the reader to determine the generalized depth of seismic horizons in Figures 7A, 7B, 8, 9, 11, 13, and 14. The curves for the Beaufort Shelf and North Chukchi Basin exhibit velocities which are common for Mesozoic and Cenozoic sedimentary strata, whereas the curve for the Chukchi Shelf shows a considerably higher velocity structure. The Chukchi Shelf velocities are higher because lower Mesozoic and Paleozoic strata lie at shallower depths beneath large areas of this shelf than they do beneath the Beaufort Shelf and North Chukchi Basin. Users of the

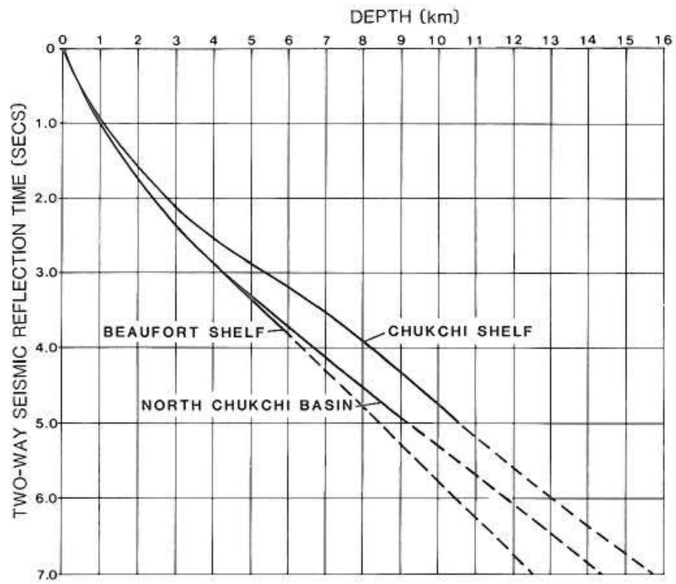


Figure 2. Depth as a function of regionally averaged seismic-reflection time for the Beaufort and Chukchi Shelves and the North Chukchi Basin, derived from seismic-stacking-velocity measurements. Dashed where inferred.

time-to-depth functions of Figure 2 should keep in mind that these are regional averages, and that they become increasingly uncertain with depth as a result of the increasing uncertainty of stacking velocities with depth.

GEOLOGIC FRAMEWORK AND REGIONAL STRATIGRAPHY

Major provinces

Three regional tectonic provinces meet at the continental margin north of Alaska: the Canada Basin of the Arctic Ocean, the Arctic Platform of the Arctic Alaska plate of northern Alaska and adjacent shelves, and the Chukchi Borderland of the Arctic Basin north of the Chukchi Shelf (Figs. 1, 3, and 4). The geologic character of the margin and the juxtaposition of these first-order features are the result of five distinct, but in part related, tectonic events. (1) Rifting beginning in Early Jurassic time separated the Arctic Platform from the North American craton and produced a series of rifts now located beneath the Alaska Beaufort Shelf and slope and Banks Island of the Canadian Beaufort margin (Fig. 12 in Grantz and others, 1990b). This extensional event was almost synchronous with the initiation of major convergence in the Brooks Range orogen in Middle Jurassic time. (2) Rotational rifting beginning in Hauterivian (middle Early Cretaceous) time led to continental breakup and drift of the Arctic Alaska plate away from the Canadian Arctic Islands about a pole of rotation near 68.5°N, 136°W (Fig. 3) and formed the Canada Basin in mid-Cretaceous time. The initiation of this event, in turn, was almost synchronous with the end of major convergence in the

Brooks Range orogen in early Albian time. (3 and 4) Poorly understood, but more localized rifting in the western Chukchi Shelf and Chukchi Borderland created the North Chukchi Basin during two events—Jurassic to Neocomian and late Early Cretaceous. An oversimplified model for these events shown in Figure 3 is speculative, but it illustrates one possible geometry for the proposed rifting after the added complication of segmentation of the borderland into north-trending ridges and basins by late Late Cretaceous and early Paleogene rifting. (For convenience, events of this general age will hereafter be called "Laramide" in this chapter.) (5) Eocene to Quaternary thrusting in the Brooks Range orogen in northeastern Alaska and the adjacent continental margin.

Arctic Platform

Regional structure. The Arctic platform slopes gently southward from the broad crest of the Barrow arch, near the sea coast, to beneath the northward-thrust nappes of the Brooks

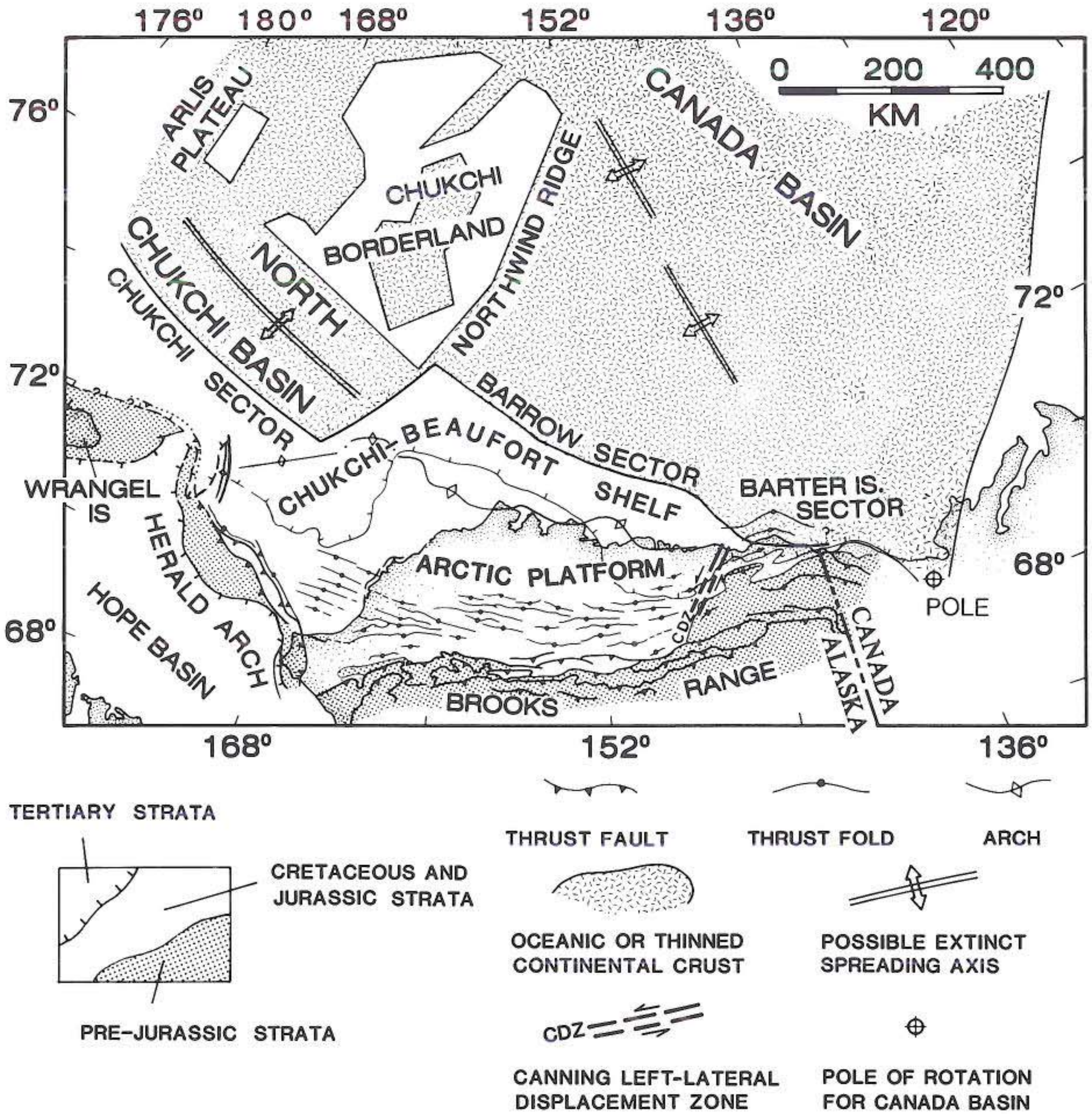


Figure 3. Tectonic model for Alaska segment of Arctic Ocean Basin showing major structural features, inferred distribution of continental versus oceanic or thinned continental crust, and the relation of the Chukchi, Barrow, and Barter Island sectors to the structural features that define them. Possible spreading axis in Canada Basin after Taylor and others (1981), in North Chukchi Basin after Grantz and others (1979).

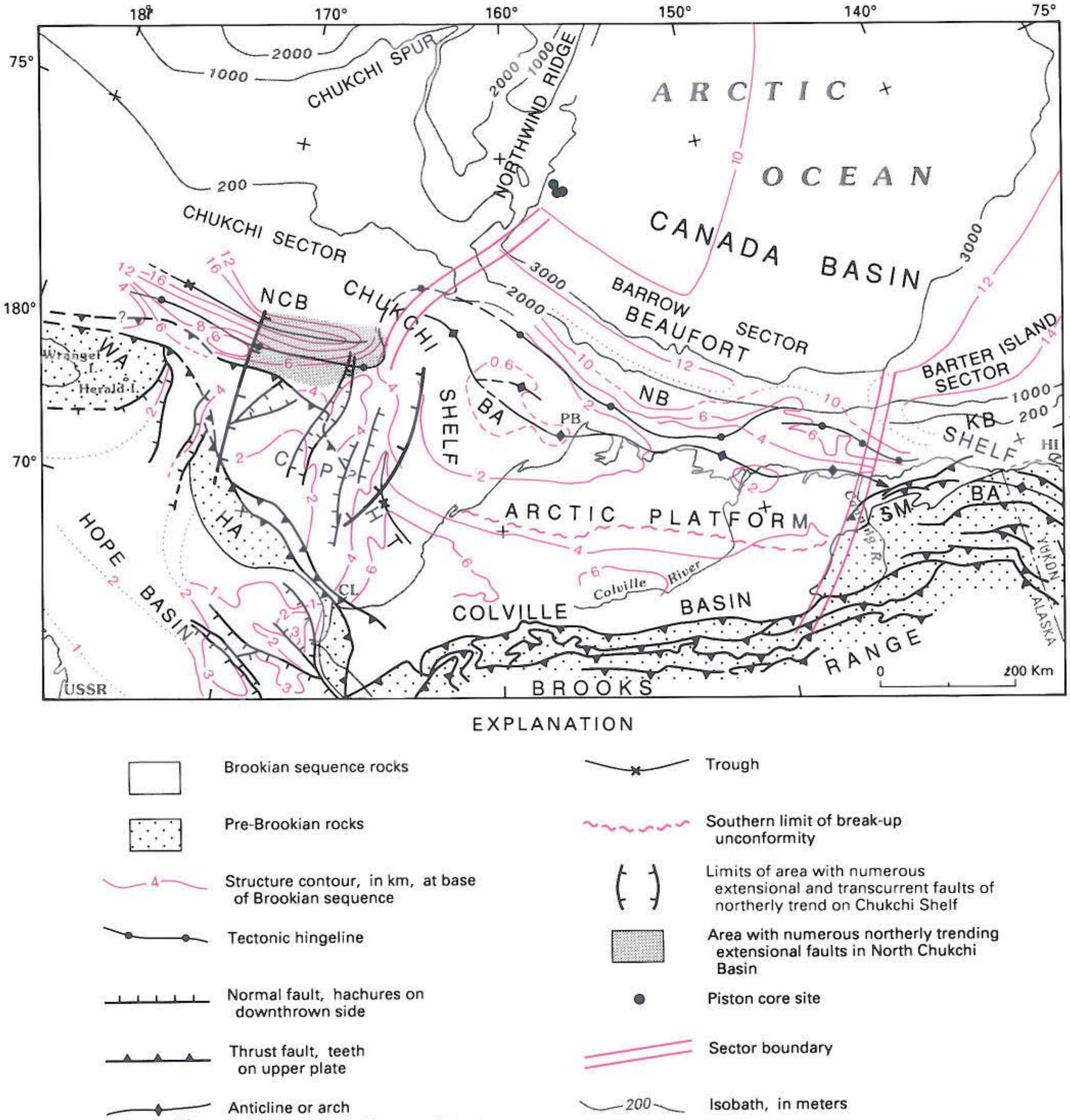


Figure 4. Major geologic features of the Alaska segment of the Arctic continental margin. BA, Barrow arch; CL, Cape Lisburne; CP, Chukchi Platform; HA, Herald arch; HI, Herschel Island; HT, Hanna trough; KB, Kaktovik Basin; NB, Nuwuk Basin; NCB, North Chukchi Basin; PB, Point Barrow; SM, Sadlerochit and Shublik Mountains; WA, Wrangel arch.

Range orogenic belt (Fig. 3). The platform gradient is about 1° beneath the Arctic Coastal Plain and about 2° to 4° beneath the Arctic (Northern) Foothills of the Brooks Range. This gradient developed in two stages. The initial gradient developed in Mississippian to Neocomian time, when the Arctic Platform was the site of clastic and carbonate deposition in a stable shelf environment. The sourceland for the clastic sediments (Barrovia of Tailleur, 1973) lay north of the present continental shelf, and the platform sloped generally southward to a rifted margin of Devonian age south of the present Brooks Range. The initial gradient was augmented in Middle or Late Jurassic and Early Cretaceous time by loading of the southern part of the Arctic Platform by multiple nappes from the Brooks Range orogen to the south and by the weight of sediment deposited in the Colville Basin, a foreland basin on the north side of the orogen.

Brooks Range orogen. Multiple, far-travelled nappes of the Brooks Range orogen override the Arctic Platform beneath the present Brooks Range across the width of Alaska, and related thrust faults and folds extend into the Cretaceous and Tertiary strata of the Colville foreland basin beneath the Arctic Foothills of the Brooks Range. (See Moore and others, this volume, Chapter 3), for a recent summary of Brooks Range tectonics.) Nappe emplacement was a response to convergence between the Paleo-Pacific Basin and the southern margin of Arctic Alaska. Convergence began in Middle Jurassic time, and the major displacements, which were northerly directed, were largely completed during Albian time. Mayfield and others (1988) estimate that crustal shortening across the western Brooks Range exceeds 700 to 800 km.

In the eastern Brooks Range, renewed thrusting in Eocene or earlier time was superimposed upon the Jurassic and Cretaceous compressional events. The Cenozoic thrusting is strongest east of a narrow, northeasterly striking zone of earthquake epicenters designated the Canning displacement (fault) zone (Fig. 4) by Grantz and others (1983a). This zone is a northern extension of Aleutian arc Benioff zone earthquakes from central Alaska to the Beaufort Sea. Some Tertiary thrust displacement also occurred in the foreland west of this zone. Counterclockwise rotation of fold axes, faults, and geologic contacts indicate that the Canning displacement zone was, and continues to be, the site of significant left-lateral deformation. Earthquake epicenters suggest that the zone has a counterpart to the east, along the north-trending Cordilleran front at the east face of the Richardson Mountains, which lie west of the lower Mackenzie River valley north of 66°N. The intervening region, which corresponds to the Barter Island sector of the continental margin, has been uplifted 300 to 500 m above the surrounding plains and plateaus to form the northeastern Brooks Range.

Elevation of the northeastern Brooks Range is related to thickening of the crust by thrusting. Depression of the crust to form the deep Kaktovik Basin (Fig. 4), which lies north of the northeast Brooks Range, resulted from loading by the northward-thrust nappes and by thick accumulations of Upper Cretaceous and Cenozoic detritus derived from accelerated erosion of the new topography generated by nappe emplacement. The amount of Cenozoic displacement of the nappes is uncertain, but total tectonic transport, including that which occurred in late Mesozoic time, is estimated by Rattey (1985) to exceed 400 km. On the basis of rotated fold axes and faults in Upper Cretaceous and lower(?) Tertiary rocks in and adjacent to the Canning displacement zone, Grantz and others (1983a) estimated that Cenozoic tectonic transport in the northeast Brooks Range was at least 25 to 50 km northward with respect to the Arctic Coastal Plain and Foothills to the west.

Barrow arch. A broad structural high known as the Barrow arch (Fig. 4) trends along the Arctic coast of Alaska from the northeastern Chukchi Shelf to Yukon Territory. This feature is the product of multiple Jurassic and Cretaceous events of regional influence rather than the product of a single episode of folding or upwarping. The south flank of the arch is the south-sloping Arctic Platform. The north flank is a collapsed continental margin formed by thermal subsidence and subsequent sedimentary loading adjacent to the rifts that separated northern Alaska from the Canadian Arctic Islands in Jurassic and Early Cretaceous time. The overall slope of the top of Paleozoic basement toward the Canada Basin, including the effects of faulting, is as steep as 12° and locally may exceed 16°.

The western part of the Barrow arch appears to have been uplifted in Tertiary time. Shale compaction studies by Ervin (1981) suggest that west of the Colville River the crest of the arch has been differentially uplifted with respect to areas south and east. The uplift increases westward from about 100 to 200 m near the Colville River to a maximum of 600 to 900 m near Barrow. The uplifted area presumably extends westward beneath the northeastern Chukchi Shelf, where the western limit of uplift is not defined by compaction data. Regional stratigraphy suggests that the uplift was post-Cretaceous in age. Structural relief on the Barrow arch at the meridian of Prudhoe Bay, east of the area of presumed Tertiary uplift, is about 5 km on the south flank and about 10 km on the north flank.

Characteristic stratigraphy permits the Barrow arch to be recognized even where the position of its crestline is obscured by structural complexity. The most distinctive stratigraphic feature is a Hauterivian breakup unconformity that overlies the crest and upper flanks of the arch. A second characteristic is the absence or patchy occurrence of the otherwise widespread stable shelf clastic and carbonate strata of the Mississippian to Neocomian Ellesmerian sequence from the crestal region and north flank of the arch. A third is the presence of failed rift deposits of probable Jurassic to Neocomian age seaward of the Barrow arch crestline. By these criteria, the Barrow arch can be traced from the northeast Chukchi Sea to Flaxman Island and projected southeast from Flaxman Island beneath the Arctic Coastal Plain to the front of the Brooks Range some 40 or 50 km west southwest of Demarcation Bay. An analogous feature can be traced across the north slope of the British Mountains in northern Yukon Territory. If the position of the arch is correctly projected beneath the Arctic Coastal Plain in northeastern Alaska, its counterpart in coastal Yukon has been offset some 20 or 30 km northward with respect to its position beneath the coastal plain on the frontal thrust faults of the Brooks Range (Fig. 4).

Stratigraphy. Stable shelf deposits of northern provenance and Early Mississippian to Neocomian age that lie beneath and north of the far-travelled nappes of the Brooks Range orogen define the Arctic Platform of northern Alaska. The rocks upon which the platform was developed, and those that were deposited upon it, have been divided into four distinct stratigraphic sequences whose lithologic character reflects their tectonic environment (Fig. 5). The pre-platform rocks, of Ordovician or older through Devonian age, are correlated with the lithologically similar main part of the Franklinian sequence of Lerand (1973). This sequence was named for the Upper Cambrian through Devonian eugeoclinal and miogeoclinal strata of the areally extensive Franklinian geosyncline and adjacent cratonic shelf of the Canadian Arctic Islands.

In Late Silurian to Early Devonian time the Franklinian rocks of northern Alaska were strongly deformed, mildly metamorphosed, and structurally consolidated (cratonized) by an early stage of the Ellesmerian orogeny. Large grabens and half grabens developed in the tectonized Franklinian rocks during probably two cycles of late- and early post–Ellesmerian orogeny extension. Basins of the older cycle were filled by Lower(?) or Middle Devonian nonmarine sediments, now strongly folded but unmetamorphosed, that are assigned to the upper part of the Franklinian sequence. Basins of the younger cycle, well observed on seismic reflection profiles (Plate 9.2 in Kirschner and Rycerski, 1988), were filled by Upper Devonian(?) and Lower Mississippian nonmarine clastic rocks of local derivation, which are here designated the Eo-Ellesmerian sequence. Deep erosion and extensional faulting associated with the formation of these basins constituted the final stage in the development of the Arctic Platform. A measure of the tectonic stability achieved by these Devonian events is the virtual lack of deformation of the 340-Ma Arctic Platform beneath the North Slope in spite of middle Early Cretaceous rifting, which severed the platform from the Canadian Arctic Islands, and Middle Jurassic to Quaternary convergence, which buried its southern part beneath the large nappes of the Brooks Range orogen. Gravity modelling along the Trans-Alaska Pipeline route south of Prudhoe Bay tied to refraction measurements in the Canada Basin suggests (Grantz and others, 1990) that the crust in the area of the Arctic platform is about 34 km thick, and thus of normal continental thickness.

On the Arctic Platform the Eo-Ellesmerian sequence is succeeded by the gently dipping stable-shelf clastic and platform carbonate rocks of the Early Mississippian to Neocomian Ellesmerian sequence, which is of northern provenance (Fig. 5). The term Ellesmerian sequence was proposed by Lerand (1973) for the carbonate and overlying clastic rocks of Mississippian through Jurassic age in the Sverdrup Basin of the Canadian Arctic Islands. In northern Alaska, platformal Neocomian beds of northern provenance have been added to the Ellesmerian sequence as defined by Lerand (1973). Failed rift deposits of inferred Jurassic and Neocomian age beneath the central and eastern Alaskan Beaufort Shelf, the Dinkum succession, are correlative with the upper part of the Ellesmerian sequence of the North Slope. The Ellesmerian and Dinkum beds are overlain by the Brookian sequence. This sequence consists of thick continental-deltaic and shelf clastic deposits of southern (Brooks Range) provenance that prograded across the Arctic Platform and the newly established continental margin in Aptian or Albian to Quaternary time. The Ellesmerian rocks wedge out toward an ancient sourceland (Barrovia) near the present Beaufort Sea coast, but the underlying Franklinian and overlying Brookian sequences extend to the outer shelf and slope. Principal sources for the discussion of the stratigraphy of the Arctic Platform that follows include Moore and Mull (1989), Moore and others (this volume, Chapter 3), Kirschner and Rycerski (1988), and Molenaar and others (1986).

Franklinian sequence. Outcrops in the northeast Brooks Range and test wells on the North Slope show that the Arctic Platform, and probably the adjacent continental shelf, is underlain by lithologically varied sedimentary and volcanic rocks of Proterozoic and early Paleozoic age. West of the Canning River, deep test wells encounter strongly deformed, mildly metamorphosed argillite, arenite, carbonate rocks, and chert containing graptolites and chitinozoans of Ordovician and Silurian age (Carter and Laufeld, 1975). Lithologically and faunally these beds resemble the Ordovician and Silurian flysch of the Franklinian geosyncline in the Canadian Arctic Islands (Trettin, 1972; Trettin and Balkwill, 1979), Ordovician and Silurian graptolite-bearing argillite in northern Yukon Territory about 50 km south of Herschel Island (Lane and Cecile, 1989), and graptolitic flysch and shale of Ordovician and Silurian age on the Lisburne Peninsula of the westernmost Brooks Range (Grantz and others, 1983b).

In test wells on Flaxman Island, near the mouth of the Canning River, and in outcrops in the Sadlerochit and Shublik Mountains east of the river (Fig. 4) are found Proterozoic to Devonian carbonate rocks with minor amounts of quartzite, argillite, and mafic volcanic rocks (Blodgett and others, 1986; Clough and others, 1988). Only the Cambrian to Devonian beds of this basin plain to carbonate platform assemblage correlate with the Franklinian sequence. Farther east, beneath the narrow Arctic Coastal Plain of northeastern Alaska, seismic reflection data suggest to Fisher and Bruns (1987) the presence of pre-Mississippian rocks there are more than 5 to 7 km thick and possess a simple structure.

Upper part of Franklinian sequence: More than 100 m of strongly folded, but unmetamorphosed nonmarine beds at the bottom of the Topagoruk test well, in the western part of the North Slope, are here placed in the upper part of the Franklinian sequence. These beds are chert-pebble conglomerate and dark gray shale with carbonaceous partings and plant fragments of Middle (possibly Early) Devonian age. As described by Collins (1958), these beds dip 35° to 60° and are overlain unconformably by gently inclined beds that we correlate with the Ellesmerian sequence. Lack of metamorphism in the Middle Devonian rocks indicates that they postdate the main orogeny, which regionally deformed and mildly metamorphosed the un-

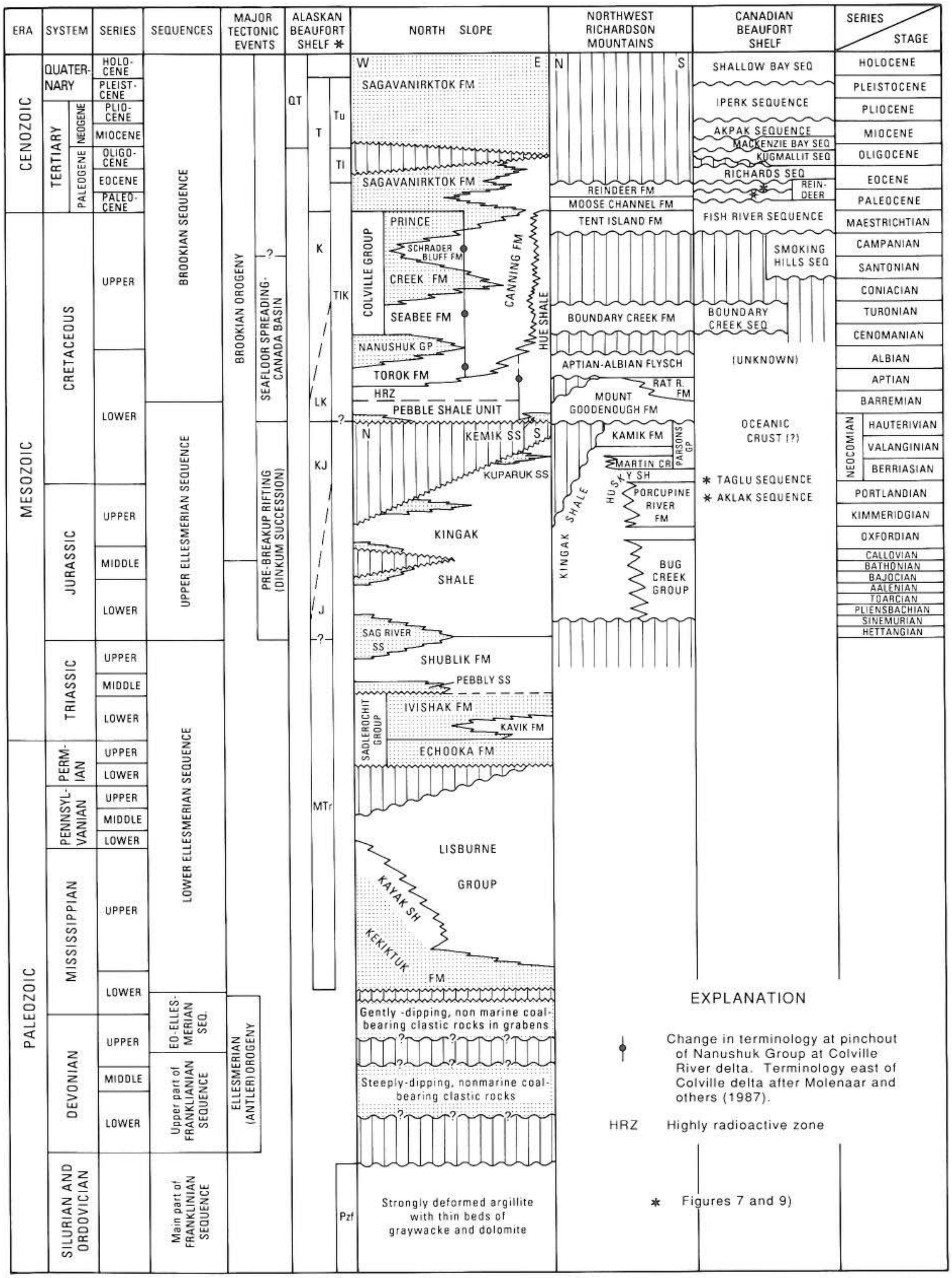


Figure 5. Stratigraphy of Arctic Alaska and adjacent continental shelves after Mickey and Haga (1987), Molenaar and others (1987), Dietrich and others (1989), J. Dixon (personal communication, 1989), and this chapter.

derlying Ordovician and Silurian argillite and graywacke. The moderately steep dip of the Lower(?) or Middle Devonian beds indicates that they were, in turn, folded and truncated by erosion before the low-dipping beds of the overlying Ellesmerian sequence were deposited. The Late Devonian structural event that tilted the Lower(?) or Middle Devonian beds correlates with the Late Devonian and Early Mississippian Ellesmerian orogeny of Lerand (1973). Together the stronger Early Devonian event and the weaker Late Devonian or Early Mississippian event constitute the main phases of the Ellesmerian orogeny on the North Slope.

Ellesmerian sequence. Eo-Ellesmerian sequence: Unmetamorphosed Upper Devonian(?) and Lower Mississippian coal-bearing nonmarine strata, the oldest beds of the Ellesmerian sequence on the Arctic Platform, rest nonconformably on Franklinian beds. Seismic reflection records (Kirschner and Rycerski, 1988, Plate 9.2) show that these strata occupy fault-bounded basins (grabens and half grabens) and range in thickness from a knife edge to more than 3,000 m. Kirschner and Rycerski (1988) place these strata in the Endicott Group, but their confinement to grabens isolates them from the Upper Devonian and Lower Mississippian type-Endicott strata of the Brooks Range allochthons, from which the coastal plain rocks also differ greatly in character of substrate, lithology, and depositional environment. In this chapter we refer to these beds as Eo-Ellesmerian in the sense that they are atypical beds in the earliest part of the Ellesmerian sequence that are transitional between the nonmarine beds of the upper Franklinian sequence below and the typical Ellesmerian marine shelfal strata above. The seismic reflection records of Kirschner and Rycerski (1988) show that an erosional unconformity with mild angular discordance overlies the Eo-Ellesmerian strata and that the main body of Ellesmerian rocks oversteps the areally more restricted graben deposits. This Lower Mississippian unconformity represents the waning, final phase of the Ellesmerian orogeny on the North Slope.

Lower part of the Ellesmerian sequence: Ellesmerian strata above the Eo-Ellesmerian graben deposits consist of four transgressive-regressive cycles whose clastic components were derived from the northern sourceland of Barrovia. The sequence as a whole, and many of its constituent units, thins northward to pinch-outs, mainly erosional truncations in paralic facies, near the Beaufort coast and beneath the northern Chukchi Shelf.

Well-bedded sedimentary rocks of shelf facies that in general produce strong seismic reflections characterize the lower part of the Ellesmerian sequence on the North Slope, where they have been divided into three major, partly unconformity-bounded transgressive-regressive sedimentary cycles (Moore and Mull, 1989). The lowest cycle consists of platform carbonate rocks of the Lower Mississippian to Lower Permian Lisburne Group and the partly underlying, partly time-equivalent Kayak Shale and subjacent basal Kekiktuk Conglomerate. The cycle ranges in thickness from a wedge edge near the coast to more than 1,700 m beneath the central part of the coastal plain. The middle cycle is a dominantly clastic deposit, the Lower Permian to Lower Triassic Sadlerochit Group, which overlies the Lisburne Group on a regional unconformity. The Sadlerochit grades from commonly coarse nonmarine facies near the coast to marine lutite and fine-grained sandstone in North Slope wells. Its thickness ranges from a wedge edge near the coast to more than 800 m beneath the central coastal plain. The highest cycle consists of Middle and Upper Triassic marine shelf deposits of the Shublik Formation and its proximal facies, the partly overlying Sag River Sandstone and the coeval Karen Creek Sandstone of the eastern North Slope. The Shublik is as much as 200 m thick and consists of phosphatic shale, siltstone, and coquinoid limestone.

Upper part of the Ellesmerian sequence and the Hauterivian breakup unconformity: Basinal marine lutite with a few thin sandstone bodies of the Jurassic and early Neocomian (Berriasian and Valanginian) Kingak Shale constitutes the lower stratigraphic unit of the upper part of the Ellesmerian sequence beneath the North Slope and the central Chukchi Shelf. Hauterivian and Barremian (Mickey and Haga, 1987) organic-rich marine shale of the informally named pebble shale unit (PSU in this chapter) constitutes the upper stratigraphic unit. An angular unconformity lies between these units on Barrow arch, but south of a middle Neocomian shelf break beneath the northern part of the Arctic Foothills the PSU rests conformably on lower Neocomian clinoforms at the top of the Kingak Shale (Molenaar, 1988).

Foreset beds interpreted from seismic reflection records show that the Kingak prograded south- or southeastward from the Barrow arch onto a subsiding shelf that was about 1 km deep beneath the Arctic Foothills. Neocomian erosion at the base of the PSU has in many places stripped the Kingak from the north flank and crest of the Barrow arch. Total thickness of the Kingak ranges from a knife edge along the crest of the arch to a maximum of 1,200 m in the northern part of the Arctic Foothills (Bird, 1988a).

The PSU consists mainly of highly organic marine shale characterized by floating grains and pebbles of frosted quartz and chert, elevated levels of gamma ray activity, and low seismic velocity. The unit is 60 to 150 m thick on the Barrow arch and 60 to 75 m thick beneath the Arctic Foothills (Bird, 1988a). At several places on the arch, as much as 15 m of locally and northerly sourced sandstone and pebble conglomerate occur at the base of the PSU. According to Witmer and others (1981) and Mickey and Haga (1987) foraminifer and palynomorphs indicate that below a highly radioactive zone (HRZ) in its uppermost 6 to 12 m, the PSU is Hauterivian and Barremian in age. The floating quartz and chert grains that characterize the PSU below the HRZ are thought to have a local source on Barrow arch or its northern flank, as did the more voluminous Kingak Shale.

The HRZ is a condensed organic shale that contains Barremian to possibly lower or middle Albian radiolarians and palynomorphs (Mickey and Haga, 1987), and it lacks the floating quartz and chert grains that characterize the PSU. Its scant thickness (6 to 12 m), modest time span, fine-grained texture, high organic content, and high gamma ray activity demonstrate that the HRZ is a pelagic or hemipelagic deposit largely isolated from sources of terrigenous clastic sediment. If the HRZ were a bottomset basinal deposit at the base of the prograding Brookian sequence, as suggested by Mickey and Haga (1987), it should contain distal turbidites from the adjacent continental terrace, and be thicker. Because the HRZ is a pelagic or hemipelagic deposit with neither Ellesmerian nor Brookian sedimentary contributions, it should be regarded as an independent transitional unit. Because of its thinness, however, and because it cannot ordinarily be separated from the PSU on seismic reflection records, the HRZ is in practice lumped with the PSU and the Ellesmerian sequence (Fig. 5).

The erosional unconformity at the base of the PSU is thought to be the breakup unconformity associated with initiation of continental drift in the Canada Basin. The thin, strongly reflective, highly organic PSU is considered to be the product of feeble, locally sourced, synbreakup or earliest post-breakup sedimentation on the rift-margin high. Like the HRZ, the PSU is a transitional, synrift unit between the Ellesmerian and Brookian sequences. The change from the feeble clastic sedimentation of the PSU to the condensed, pelagic or hemipelagic sedimentation of the HRZ records the early post-breakup subsidence of the rift-margin high below wave base. This subsidence ended the era of rift-margin sedimentation from local (Barrow arch) sources that had nourished the PSU and began the era of condensed sedimentation in a deeper environment, which was isolated from terrigenous sourcelands that produced the HRZ. Overtopping of the Barrow arch by detritus from the Brooks Range orogen terminated HRZ deposition, and initiated south-sourced Brookian sedimentation above the HRZ by Aptian or Albian time.

Dinkum succession (Failed rift deposits of the Beaufort Shelf and slope). On the central Beaufort Shelf north of Barrow arch, the PSU rests unconformably on strata of inferred Jurassic and early Neocomian age in and north of the Dinkum graben (Figs. 6, 7). We interpret these beds to have been deposited in a failed rift system along the continental margin. Hubbard and others (1987) have grouped the graben-filling beds of the Beaufort Shelf and the upper beds of the Ellesmerian sequence (for convenience, herein referred to as the upper Ellesmerian beds) of the North Slope in a new sequence, the Beaufortian, on the premise that both are rift related. In this chapter we place these deposits in separate sequences because, although largely coeval, they were deposited in different tectonic and sedimentary environments and have differ-

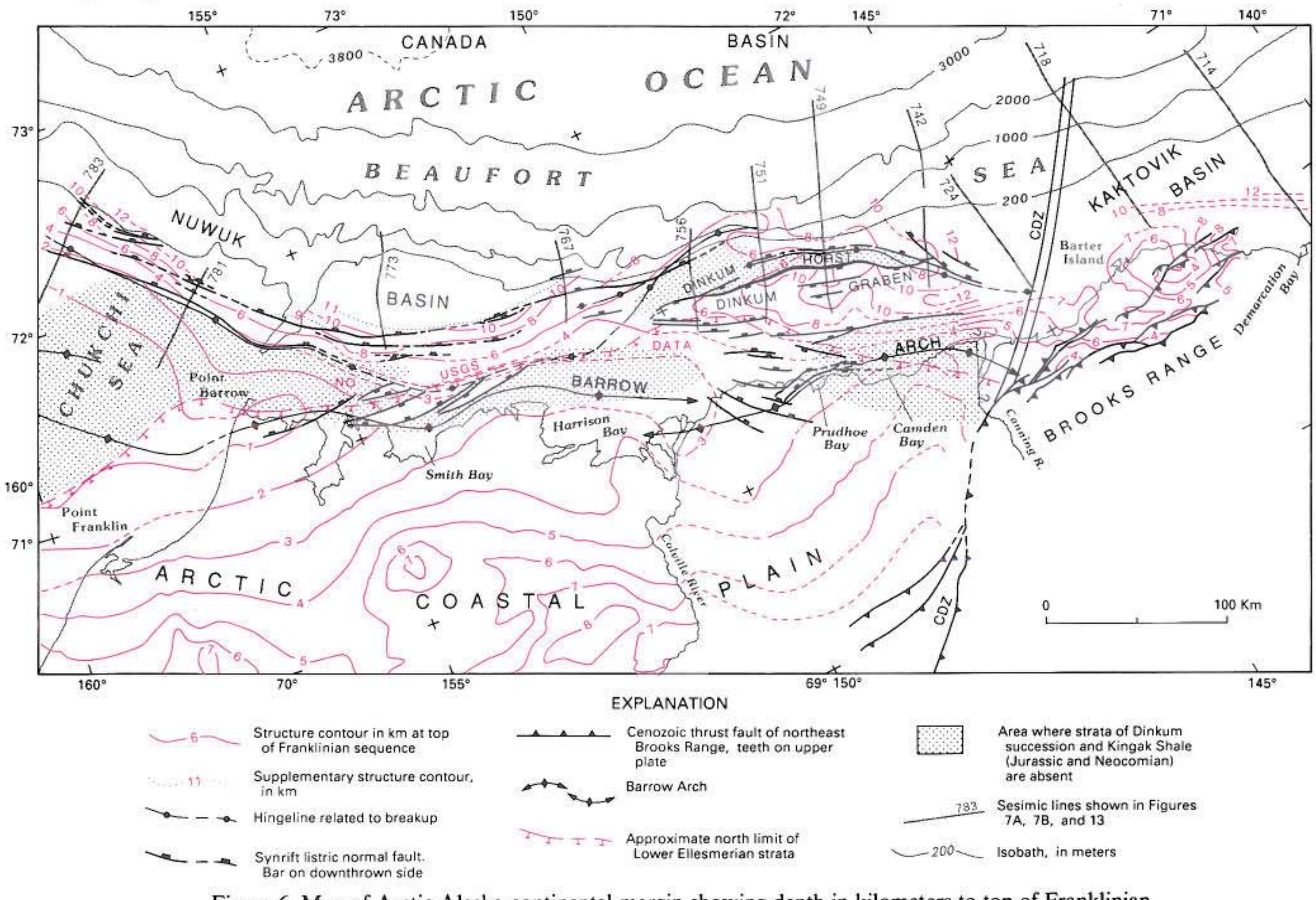


Figure 6. Map of Arctic Alaska continental margin showing depth in kilometers to top of Franklinian sequence, location of synrift structures, and area adjacent to rift stripped of Jurassic and early Neocomian strata in late Neocomian time. Onshore data from Bruynzeel and others (1982), Tailleur and others (1978), Bruns and others (1987), Bird (1988a, b), and Jamison and others (1980). Offshore data from profiles in Grantz and others (1982, 1986) and maps in Hubbard and others (1987), Craig and others (1985), and Pessel and others (1978). Lines dashed where projected or speculative.

ent stratigraphies. The upper Ellesmerian beds of the North Slope were deposited on an areally extensive stable shelf that subsided and tilted southward in response to tectonic overriding and loading by the early phases of the Brookian orogeny. In contrast the Dinkum graben fill, and the probably related deposits of the outer shelf and slope, were deposited in fault-bounded half grabens or grabens and have much higher ratios of length and thickness to width. We retain the term upper Ellesmerian for the areally extensive Jurassic and Neocomian marine deposits of the tectonically stable Arctic Platform and use Dinkum succession to designate the thick, but elongate and areally limited deposits of Dinkum graben and the tectonically related deposits of the continental margin.

Brookian sequence. The Brookian sequence of the North Slope was deposited in the Colville Basin, a foreland basin, and as a progradational continental terrace sedimentary prism along the continental margin. The stratigraphy of the sequence is complicated by east-west changes in facies and sediment thickness related to the location and timing of local domains of convergent tectonism and uplift in the Brooks Range.

South-sourced syntectonic flysch and molasse of the Aptian(?) and early Albian Fortress Mountain Formation lie at the base of the Colville Basin section in the southern North Slope. These sandstones, lutites, and conglomerates grade laterally northward into the lower part of the Torok Formation, which consists of foreset and bottomset turbidite and hemipelagic clastic deposits of Aptian(?) and Albian age that extend north to the continental shelf. The partly coeval, partly younger Torok Formation is about 6,000 m thick beneath the Arctic Foothills and less than 150 m thick on the Barrow arch. Beneath the central and western parts of the Arctic Coastal Plain the Torok downlaps onto the south-dipping upper surface of the HRZ.

The Fortress Mountain Formation is overlain by the post-tectonic (molassoid) Nanushuk Group—regressive shallow marine and deltaic sandstone, lutite, conglomerate, and coal of middle or late Albian to early Cenomanian age. The Nanushuk intertongues with foreset beds in the partly underlying, partly equivalent upper Torok Formation in the central and northern parts of the Colville Basin. By middle or late Albian time, post-rift subsidence of the rift margin permitted Torok sediments to overtop the Barrow arch in many places, and to begin the progradation of a continental terrace sedimentary prism along the then recently formed Beaufort Sea margin of the Canada Basin. The Nanushuk-Torok interval is several thousand meters thick west of the lower Colville River, but east of the river it thins drastically and is represented by condensed bottomset shale, which is no more than a few tens of meters thick on the Barrow arch east of Prudhoe Bay (Molenaar and others, 1986). The post-Nanushuk deposits of the Colville Basin rest on a middle Cenomanian unconformity that is distinct on logs and seismic sections according to Bruynzeel and others (1982), but correlated well sections by Molenaar and others (1986) suggest that at least in places this contact is a facies boundary. A widespread transgressive marine shale, the late Cenomanian and Turonian Seabee Formation of the Colville Group, rests on the unconformity and is presumably related in origin to the major long-term worldwide rise in sea level that culminated in late Cenomanian and early Turonian time (Haq and others, 1987). Molenaar and others (1986, 1987) apply the name "Hue Shale" to the highly organic and bentonitic basinal marine shale of Aptian(?) to Maastrichtian (and possibly Paleocene) age that constitutes the diachronous basal Brookian unit east of the Colville Delta. The unit is a condensed deposit, 300 m or less thick. It is overlain by prodelta or basin slope marine shale of Aptian or Albian to Eocene or Oligocene age, with turbidites in the lower beds, which Molenaar and others (1986, 1987) named the Canning Formation. The Canning is laterally equivalent to all of the shales of the Torok Formation, Colville Group, and lower Sagavanirktok Formation to the west of the Colville Delta. Between the Canning and Colville Rivers the Canning Formation is 1,500 to 3,000 m or more thick, but east of the Canning River where the formation is Campanian to Eocene or Oligocene in age, its thickness is unknown.

All of the nonmarine and marine deltaic and alluvial plain sandstones, lutites, and conglomerates above the Canning Formation east of the Colville River were placed in the Sagavanirktok Formation by Molenaar and others (1986, 1987). Near the Canning River the unit is 1,800 to 2,300 m thick and Late Eocene through Pliocene in age. The base of the unit becomes older to the west and near the Colville River the basal beds are Campanian. West of the Colville River, where the preexisting stratigraphic terminology is retained, the post-Nanushuk-Torok section is placed into two units: the Colville Group of middle Cenomanian through Maastrichtian age, and the Sagavanirktok Formation of Tertiary age. All of these units extend beneath the continental shelf. The overlying glacial and interglacial deposits, which are no more than a few tens of meters thick beneath the North Slope, thicken to 100 meters or more near the shelf break. These heterogeneous deposits are assigned to the upper Pliocene and Quaternary Gubik Formation, which is summarized in Dinter and others (1990).

Canada Basin

The Canada Basin is thought to have formed by rotational rifting during Hauterivian to early Late Cretaceous time. Available data (May and Grantz, 1990; Grantz and others, 1990b) suggest that oceanic crust (layers 2 and 3) beneath the southern Canada Basin is of near normal thickness (6 to 8 km) but that it is overlain by an unusually thick sedimentary layer (part 1). The layer 1 sediments are stratigraphically continuous with those of the post-rift sedimentary prism of the Barrow sector of the continental margin. An empirical relation between regional bathymetry and sediment thickness derived from seismic refraction data (Fig. 8 in Grantz and others, 1990c) suggests that oceanic crust lies less than 10 km below sea level north of the Chukchi Shelf to 12 km or more off the Mackenzie Delta, and that the overlying sedimentary layer may be a little more than 6 km thick in the former area and 12 km in the latter. The apex of the large

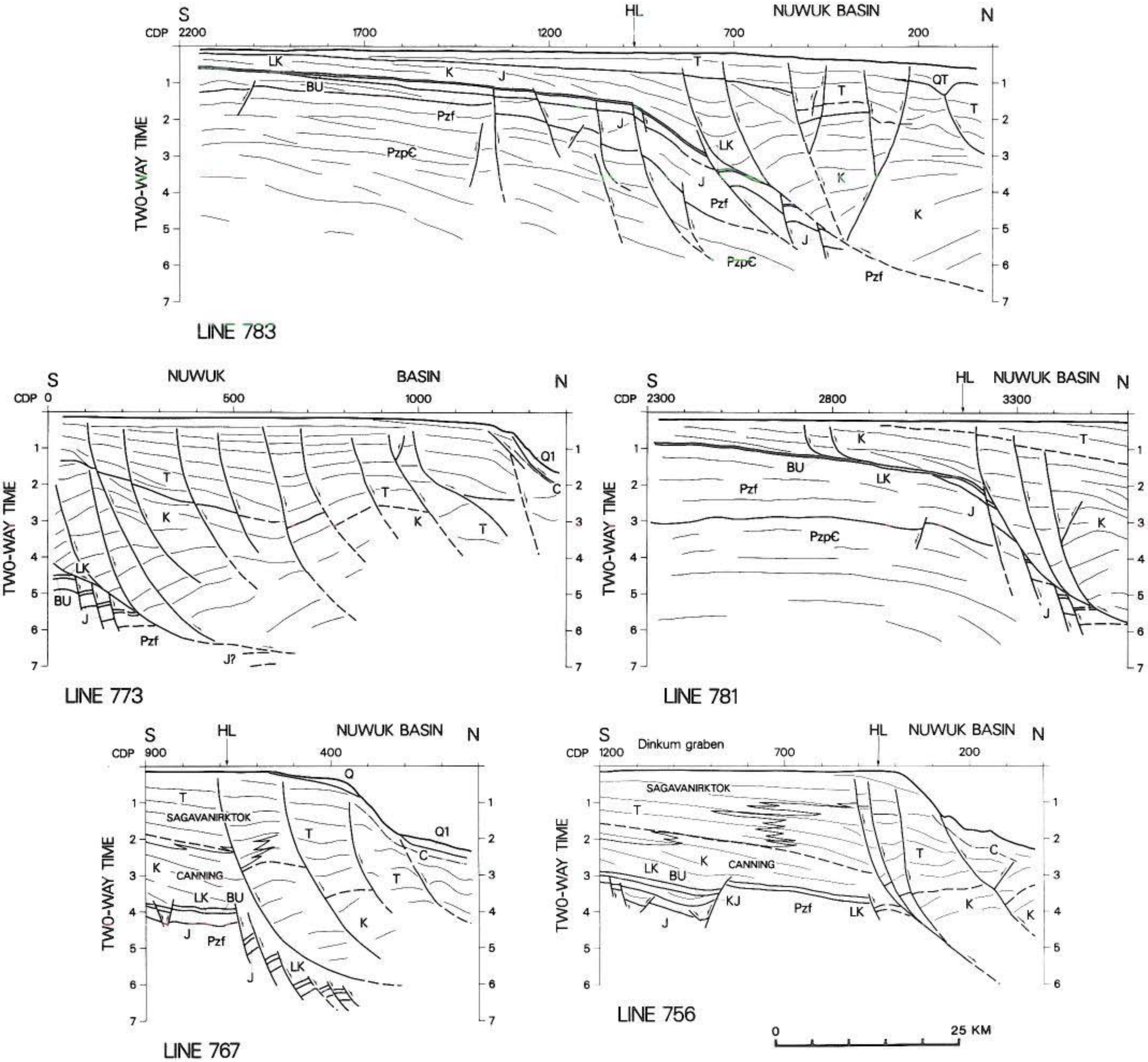
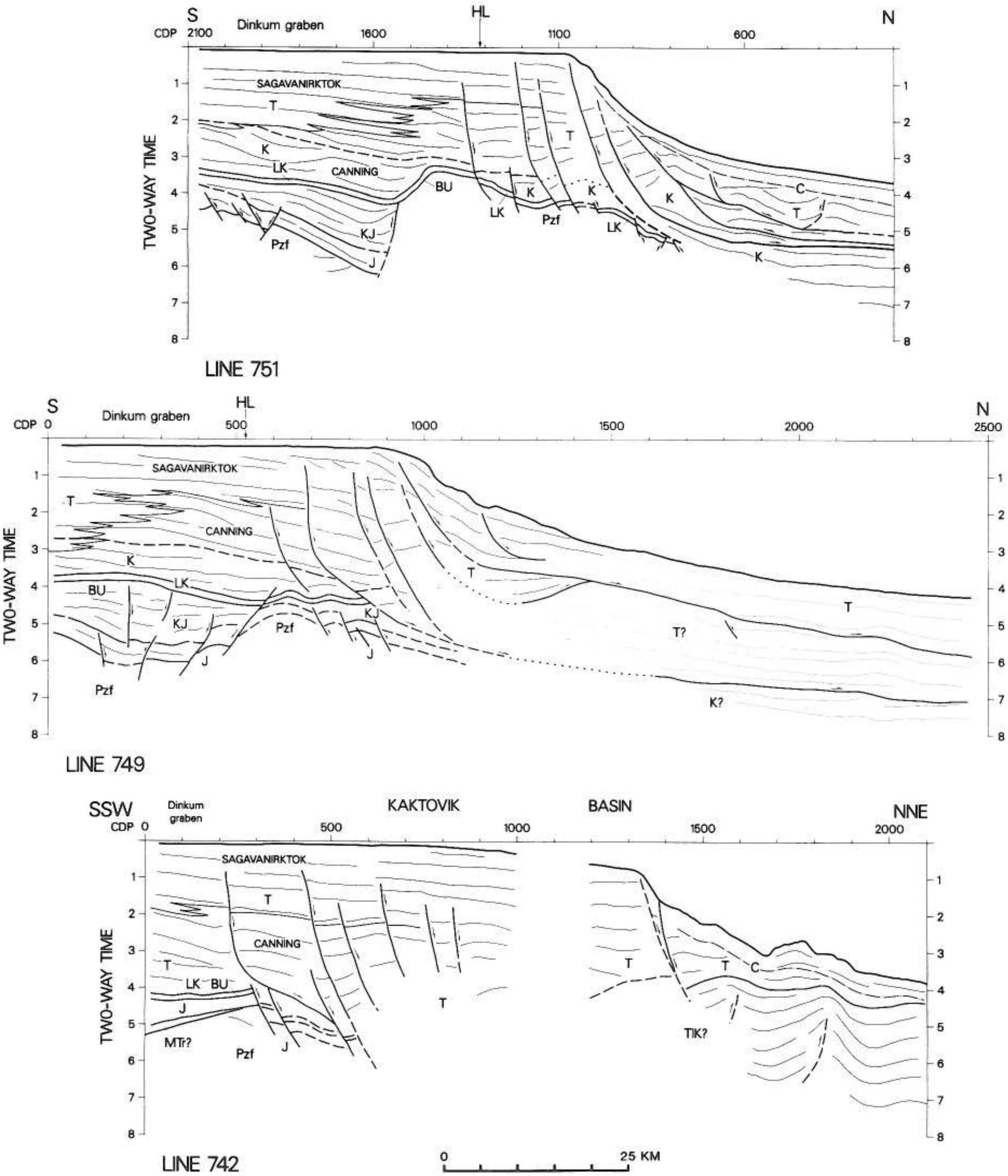


Figure 7. (This and facing page) Line drawings showing geologic structure and stratigraphy on seismic reflection profiles 756, 767, 773, 781, and 783 (shown on A) and 742, 749, and 751 (shown on B) across the Arctic Alaska continental margin. Time sections from Grantz and others (1982). Figure 2 shows approximate equivalence of seismic reflection time and depth, Figures 6 and 12 show location of profiles. Vertical exaggeration in water column is 7; in subsea sediments roughly 3.5, but highly variable. Q1, Quaternary submarine slide deposits; QT, Quaternary and late Tertiary marine sedimentary strata; T, Tertiary strata of the marine and nonmarine Gubik Formation, the dominantly nonmarine Sagavanirktok Formation, and the marine Canning Formation; Tu, upper Tertiary marine and nonmarine strata of the eastern Beaufort Shelf and slope; T1, post–middle Eocene lower Tertiary marine sedimentary strata of the eastern Beaufort Shelf and slope; T1K pre–middle Eocene to Cretaceous, and in places possibly Jurassic, marine sedimentary strata of the eastern Beaufort Shelf and slope; K, Upper to upper Lower Cretaceous strata of the marine and nonmarine Colville Group and Nanushuk Group and the marine Torok Formation and their equivalents beneath the continental slope and rise; LK, Hauterivian to early or middle Albian condensed marine shale with local lenses of sandstone and conglomerate of



the "pebble shale unit" (PSU) on the western Beaufort Shelf and the Barremian to Maastrichtian Hue Shale on the eastern Beaufort Shelf; KJ, Jurassic and Neocomian synrift marine lutite of Dinkum succession; J, inferred sandstone and possibly conglomerate equivalent to the lower part of the Kingak Shale and possibly lower Ellesmerian sequence marine and paralic stable shelf deposits; MTr, lower Ellesmerian sequence marine and paralic stable shelf deposits; Pzf, lower Paleozoic (pre-Mississippian) eugeoclinal clastic and miogeoclinal carbonate and clastic strata; PzpꞒ, lower Paleozoic and Precambrian strata, inferred to include carbonate or possibly quartzite; BU, breakup unconformity; SU, syntectonic unconformity; SU-Teu, middle Eocene syntectonic unconformity; HL, tectonic hinge line related to rifting; D, diapiric core of thrust fold; C, base of solid gas hydrate.

continental rise sedimentary prism that fills the southern Canada Basin heads against the Mackenzie Delta and Amundsen Gulf (Grantz and others, 1990a, Plate 1), which indicates that most of the fill originated in the Mackenzie River valley and the glacial drainages entering Amundsen Gulf. Most of the geologic structure in the Canada Basin was imposed by stresses that originated within or south of the Beaufort Shelf. These structures include large submarine slides and, in the Barter Island sector, large thrust faults and thrust-folds related to detachment faults that root beneath the Brooks Range. Grantz and others (1990b) discuss the structure and stratigraphy of the Canada Basin.

Chukchi Borderland

A compact group of aseismic submarine ridges and plateaus and intervening deep basins, the Chukchi Borderland, intersects the continental shelf and slope west of 162°W (Fig. 1). The ridges and plateaus are high-standing, flat-topped features with a dominant trend of about N20°E, whose geologic character and mode of origin are poorly known. Present knowledge of Chukchi Borderland geology and geophysics is summarized by Hall (1990), who concludes that the borderland consists of three or more highstanding continental blocks separated by deep, graben-like basins formed by rifting. The physiography of the borderland suggests that the bounding faults of the continental blocks and grabens have a northerly trend.

Understanding of the character and origin of the borderland is a prerequisite for a complete understanding of the Alaskan Arctic continental margin because the Northwind Escarpment, which forms the eastern boundary of the borderland, is on strike with the eastern boundary of the North Chukchi Basin of the northwestern Chukchi Shelf. This juxtaposition suggests that these features may be genetically linked. Grantz and others (1979) and Vogt and others (1982) proposed that the highstanding ridges of the Chukchi Borderland were rifted from the continental shelf in the western Chukchi and East Siberian Seas, an area now occupied by the North Chukchi Basin.

Some data bearing on the origin of the borderland were collected over the southern part of Northwind Ridge in 1988. A two-channel seismic profile across the eastern half of the ridge showed that it is underlain by 400 to 600 m of flat-lying strata characterized by strong seismic reflectors. The flat-lying strata rest unconformably on moderately dipping to probably strongly deformed beds that are at least 2 km, and possibly 4 km or more thick. Three piston cores from the lower slopes of the Northwind Escarpment near 74°35′N (Fig. 3), at water depths of 3,200 m to 3,700 m, sampled the deformed beds. The lowest unit in the cores consists of bedrock or coarse rubble composed of yellowish brown to light gray, oxidized, foraminifer-bearing marine lutite and dark brown lutite containing abundant palynomorphs. The foraminifers, dated by W. V. Sliter of the U.S. Geological Survey as Albian (personal communication, 1989), resemble forms found in parts of the thick Nanushuk Group of paralic sedimentary rocks of the North Slope. The character and age of the flat-lying upper beds are not known, but their structural position, local deep erosion, and the presence of block faulting that is on strike with that of the eastern North Chukchi Basin suggest that they are no older than latest Cretaceous or Tertiary.

STRUCTURE AND STRATIGRAPHY OF THE ALASKAN MARGIN

Chukchi sector

North Chukchi Basin. The North Chukchi Basin and the Chukchi Borderland are the characterizing features of the Chukchi sector of the continental margin. Principal sources of data on the geologic character of the North Chukchi Basin are eight multichannel and a few single-channel U.S. Geological Survey seismic reflection profiles (Grantz and others, 1972a, b, and 1986) shown in Figures 8 and 9, and Thurston and Theiss (1987), which is based on unpublished proprietary data. We rely mostly on the sparser, but published, Geological Survey data.

The full extent of the North Chukchi Basin is not known. On the east the basin's Brookian strata thin toward the western extension of the Barrow arch (the North Chukchi High of Thurston and Theiss, 1987) beneath the north-central Chukchi Shelf (Fig. 8), and on the southeast they thin toward the Chukchi Platform. To the south the basin is bounded by a south-dipping Cenozoic thrust-fault system near 72°N that extends to the base of the Quaternary cover at the sea floor (Figs. 4 and 8). South of this fault system lies the Wrangel arch, which on Herald and Wrangel Islands (Fig. 8), exposes Proterozoic(?) to Middle Cambrian(?) metavolcanic and metasedimentary rocks and folded and thrust-faulted Paleozoic to Triassic sedimentary rocks (Cecile and Harrison, 1987). Between the Chukchi Platform and Wrangel arch, the south limit of the basin is obscured by thick sequences of Tertiary strata in northerly striking horst and graben structures (Jessup, 1985). Multichannel seismic reflection data extend the known area of the basin as far north as 73°10′N and as far west as 176°15′W, and single-channel data suggest that the basin extends north of 74°N. The basin axis is incompletely mapped, but it appears to lie near 72°30′ to 73°N and to trend N65° to 85°W.

Stratigraphy and internal structure. We recognize five major seismic-stratigraphic units in the North Chukchi Basin and tentatively correlate them with units in northern Alaska and the Beaufort Shelf. Line drawings in Figure 9 show these units plus pre-Cretaceous (unit pK) strata for which no correlation is apparent. The oldest unit (LE) is interpreted to consist of strata in the lower part of the Ellesmerian sequence that are poorly bedded in the lower part and well bedded in the upper part. These beds appear to lack clinoforms and may be shelf deposits. Unit LE is interpreted to be overlain by Jurassic and Neocomian marine clastic rocks of the upper Ellesmerian sequence (unit UE), which thickens from less than 1 km at the basin edge to more than 2.5 km within the basin 15 km to the west. It may have been a precursor of the North Chukchi Basin, just as the Dinkum succession of the Barrow sector was a precursor to the Hauterivian and younger rift basins of the Beaufort margin. The lower two-thirds or more of unit UE consists of weakly reflective beds thought to

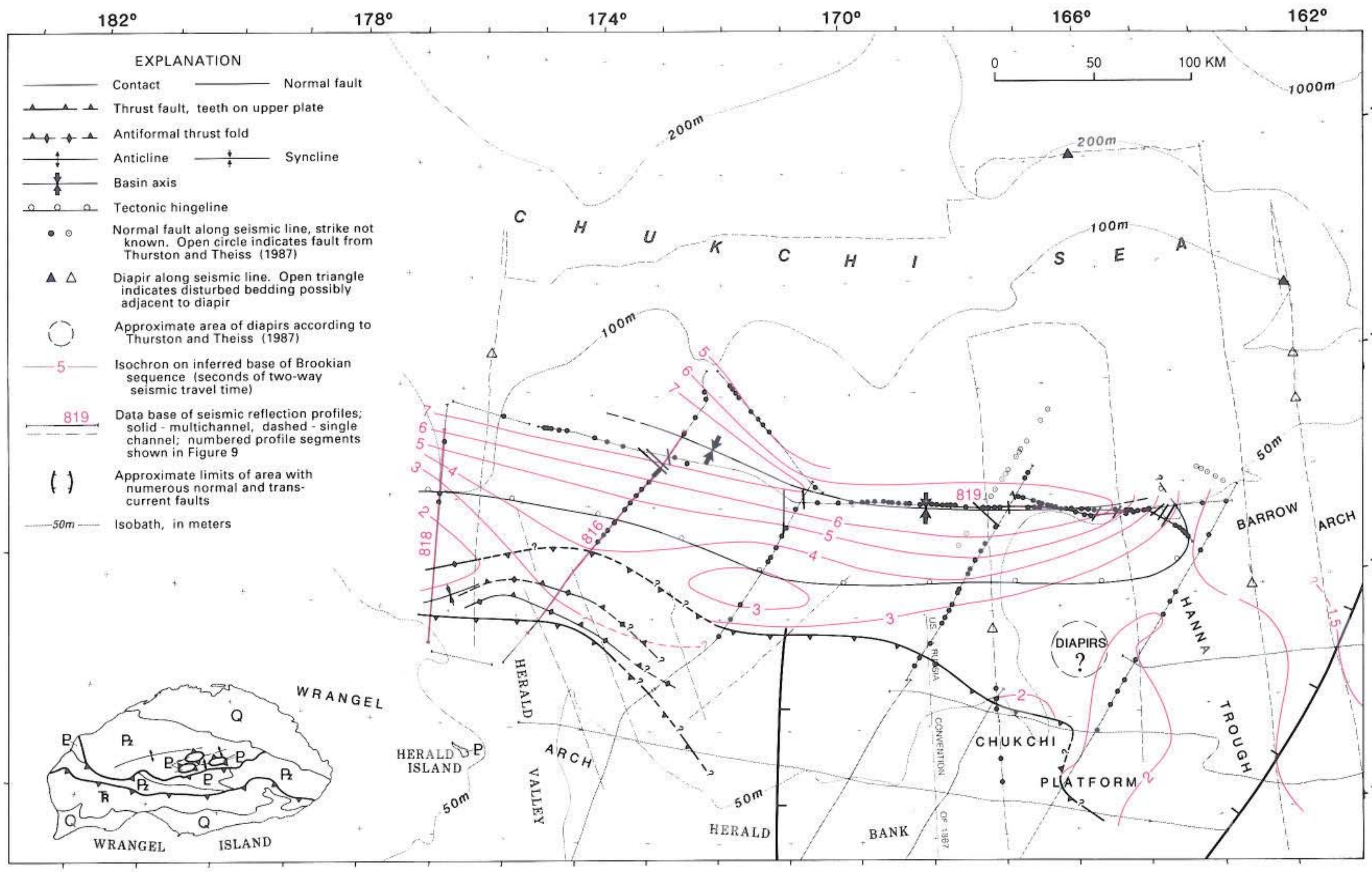


Figure 8. Map of northwestern Chukchi Shelf showing seismic-geologic features and isochrons on base of Brookian sequence in North Chukchi Basin, generalized geology of Wrangel Island after Cecile and Harrison (1987), and location of seismic reflection profiles shown in Figure 9. See Figure 2 for relationship between isochrons and depth. Q, Quaternary deposits; ₮, Triassic flyschoid strata; Pz, Paleozoic fluvial to shelfal clastic and platform to slope carbonate rocks; Ꝑ, Proterozoic(?) to Middle Cambrian(?) metavolcanic and metasedimentary rocks intruded by granitic sills and dikes (Gromov Complex). Contacts, faults, and axes are dashed where inferred, queried where speculative.

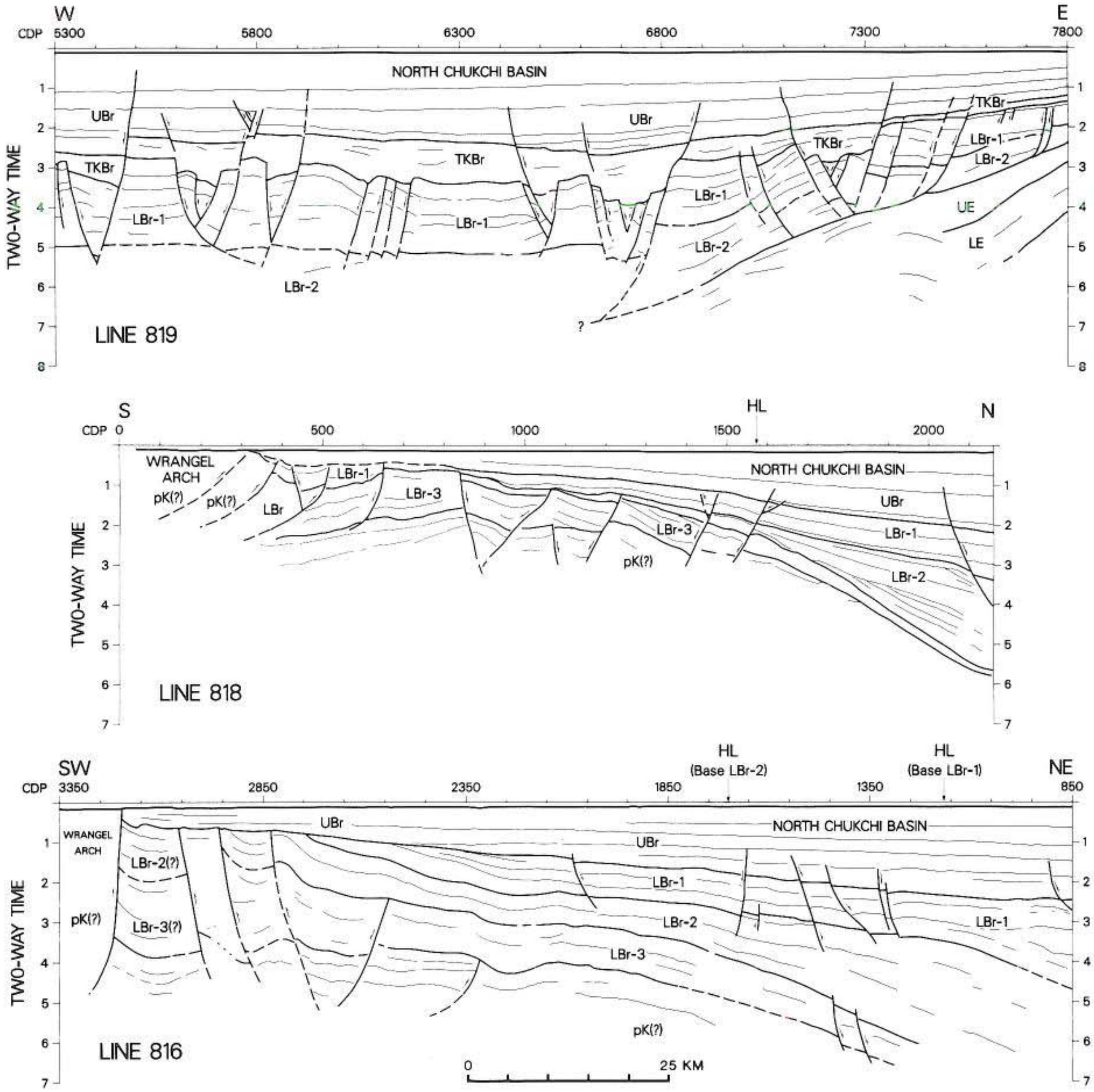


Figure 9. Line drawings showing inferred geologic structure and stratigraphy on seismic reflection profiles 816, 818, and 819 across North Chukchi Basin. Profiles from Grantz and others (1986). See Figure 2 for equivalence of reflection time and depth and Figure 8 for location of profiles. Vertical exaggeration in water column is 7; in subsea sediments roughly 3.5, but highly variable. UBr, upper Brookian (Tertiary) marine strata; TKBr, "Laramide" (uppermost Cretaceous and/or lower Paleogene) marine strata; LBr-1, LBr-2, and LBr-3, seismic-stratigraphic subdivisions of inferred lower Brookian (Cretaceous) marine strata; pK, inferred pre-Cretaceous strata; UE, inferred upper Ellesmerian (Jurassic) marine strata; LE, inferred lower Ellesmerian stable shelf marine strata; HL, tectonic hinge line.

be lutites, but the upper third or less on profile 819 (Fig. 9) also contains beds that produce stronger reflections and may include sandstone. These upper beds are gently folded and have been truncated by an angular unconformity at the base of the overlying Brookian sequence. Erosion has locally removed most of unit UE from the east flank of the basin.

A thick sequence of reflections, interpreted to represent clastic rocks in the lower (Cretaceous) part of the Brookian sequence (LBr), unconformably overlies units pK and UE. The internal stratigraphy of unit LBr is hard to define on the basis of our widely spaced profiles, but it may be divisible into three units. Unit LBr-3, the oldest, is shown on profiles 816 and 818 (Fig. 9), where it thins basinward from 1.8 to 3.2 km or more on the paleoshelf at the southern margin of the basin to less than 0.2 to

2.0 km where the unit fades out of our records in the axial deep to the north. The unit consists of weakly to moderately reflective beds, apparently topsets, that have been offset locally by mild folds and at least one thrust fault. These beds were erosionally truncated before unit LBr-2 was deposited upon them.

Units LBr-2 and -1 consist of moderately to strongly reflective, well-bedded rocks that are in topset facies south and east of the tectonic hinge line that separates the paleoshelf regions of the basin from its axial deep (Figs. 8 and 9). On the paleoshelf, unit LBr-2 ranges from 0 to at least 1.7 km, and unit LBr-1 from 0 to at least 1.4 km in thickness. North and west of the hinge line units LBr-2 and -1 increase dramatically in thickness—LBr-2 to more than 6.7 km and LBr-1 to more than 5.4 km. Reflective properties of the constituent beds also are more varied basinward of the hinge line, ranging from weak to strong, and with foreset as well as topset beds present, especially in the lower half of each unit.

The tectonic hinge line at the base of unit LBr-1 (Fig. 9) is about 20 to 30 km farther north than is the hinge line at the base of unit LBr-2, which suggests that subsidence was a multistage event that progressed basinward. On the westernmost profile (818 in Fig. 9), Unit LBr-2 was faulted, uplifted, and eroded on the paleoshelf before overstepping unit LBr-1 was deposited. On the eastern part of line 819 in Figure 9, which crosses the edge of the axial deep, unit LBr-2 can be seen to rest on a glide plane. In consequence, the relation of unit LBr-2 to older units on this profile is not known, and as drawn the unit may include part of unit LBr-3.

An extensional event block-faulted the LBr units in the eastern part of the basin (Fig. 8) and created a spectacular horst and graben paleotopography that was infilled and smoothed by unit TKBr (profile 819, Fig. 9). The extension produced fault scarps with local relief that in places exceeds 2.5 km. The extensional faulting that produced this relief was below wave base because the height of the fault scarps approximates the structural relief on the faults. The area affected is shown on Figures 4 and 8. Unit TKBr, of inferred "Laramide" age, consists of weakly to moderately reflective foreset and bottomset beds that were deposited in local sediment catchments, as well as some topset beds. The unit is as much as 3.2 km thick. A change to markedly better bedded, and more strongly reflective rocks in overlying unit UBr suggests that the deposition of unit TKBr brought the seabed close to wave base and largely filled the depression formed by the extensional faulting.

Unit TKBr thins eastward and southeastward toward a bordering paleoshelf beneath the present central Chukchi Shelf, and it thins over broad structural highs on the shelf such as the Chukchi Platform. It also infills low-lying areas such as the partly erosional, partly structural "Laramide" depression that overlies part of the Hanna trough (Figs. 4 and 8) between the Chukchi Platform and the western part of the Barrow arch. Unit TKBr is about 2 km thick in the trough, is about 2 km deep, and is connected with the main body of unit TKBr in the North Chukchi Basin by two very broad channels. These channels, like the "Laramide-age" depression in the Hanna trough, are partly structural, partly erosional. We postulate that a graded surface originally extended from the depression over the Hanna trough to the deeper North Chukchi Basin during unit TKBr deposition. This surface was uplifted after unit TKBr deposition in the area between the northern part of the Chukchi Platform and the western part of the Barrow arch, and the base of the broad channel now lies above the base of the "Laramide" depression. In the western part of the mapped area of the North Chukchi Basin, beyond the area affected by intense extensional faulting (see Figs. 4 and 8), unit TKBr assumes the geometry of the underlying and overlying formations and has been included in unit LBr-1.

Conformably above unit TKBr in the North Chukchi Basin lies a sequence of well-bedded, moderately to strongly reflective rocks, unit UBr, that is 3.7 km or more thick. The unit was deposited on a generally smooth surface with a long-wavelength structural sag in the eastern part of the basin (profile 819 in Fig. 9). Topset beds are dominant in unit UBr, although it contains some foreset and bottomset beds in the western part of the mapped area. The predominance of topset beds throughout this thick unit indicates that sedimentation generally kept pace with subsidence and that the sediment supply was abundant. Continuing or renewed activity on the larger listric faults that distended units LBr and TKBr has in places offset beds in the lower part of unit UBr (profile 819). Some of the faults that offset lower UBr beds are of moderate displacement and have similar thicknesses of TKBr in their hanging and footwalls. These appear to represent tectonic movement during the early stages of unit UBr deposition. Most of the faults that offset lower UBr beds, however, have displacements of only 100 to 200 m in the UBr, much larger displacements in underlying units, and markedly disparate thicknesses of unit TKBr in their hanging walls and footwalls. These small offsets are thought to have resulted from differential compaction.

Diapirs. Thurston and Theiss (1987) report that a north-trending graben on the northern part of the Chukchi Platform appears to be the source of diapirs, diapir mounds similar to "salt pillows," and associated collapse and withdrawal structures (Fig. 8). The diapirs originate in the upper part, and possibly in the lower part of the Ellesmerian sequence in the graben, and some of them pierce strata as young as upper Brookian (Tertiary).

Several diapirs, and structural features possibly associated with diapirs, were also observed in upper Brookian strata on Geological Survey seismic profiles in and near the North Chukchi Basin. Figure 10 shows two of these diapirs, piercement structures reaching to within 200 m of the seabed, that were identified on a single-channel seismic reflection profiles. A star pattern of seismic profiles across the diapir at 73°21′N shows that this feature is about 2 km in diameter, that its base lies more than 2.5 km below sea level, and that it may be surrounded by a withdrawal syncline. Morphologically these features resemble late-stage salt diapirs, but reconnaissance gravity and refraction measurements (Fig. 10) showed no associated negative density or velocity anomalies. Grantz and others (1975) therefore inferred that these diapirs may be shale cored.

Listric-normal fault province. The eastern part of North Chukchi Basin is underlain by a province of listric faults, horsts, and grabens illustrated in profile 819 (Fig. 9). The faults are mainly of latest Cretaceous or earliest Tertiary age because they disrupt unit LBr, inferred to be of middle Early to Late Cretaceous age, and are overlain by mainly undeformed unit TKBr, of inferred "Laramide" age. A few offset the lower beds of unit UBr of inferred Tertiary age. The extent of the fault province is shown in Figures 4 and 8. Correlation of the faults between U.S. Geological Survey seismic profiles and text figures in Thurston and Theiss (1987) indicate that the strike of the faults is variable, but mainly northerly. Maximum observed displacement on individual fault sets of the listric fault system is about 2.5 km. Extension along our seismic profiles in the listric fault area, as measured by offsets in unit LBr, ranges from 5 to 12 percent. The down-dip terminations of the listric faults in the axial deep lie below our deepest identifiable seismic reflections (6.5 seconds, about 13 km), but the faults can be seen on profile 819 to merge in a detachment, or sole, fault on the eastern slope of the basin Fig. 9). This detachment fault follows the top of unit UE, which underwent some fault truncation of its uppermost beds, from a depth of 3 km near the eastern end of profile 819 to more than 14 km at the east end of the axial deep, 55 km to the west.

The extensional fault terrane lies between a zone of north- to northeast-striking faults to the south and east, and the north-northeast–striking ridges and basins of the Chukchi Borderland to the north (Fig. 4). The faults to the south of the extensional fault terrane were mapped by Jessup (1985), who reported that they were normal faults that displace upper Brookian (Tertiary) strata. Those to the east and south were mapped by Thurston and Theiss (1987) as the Hanna wrench fault zone. Thurston and Theiss (1987) suggest that many of the faults in the Hanna wrench-fault zone formed in transtensional or transpressional stress fields, but the sense of displacement is not reported. Wrench-fault features are best developed in the eastern part of the Hanna fault zone and may give way to normal faults to the west and in the North Chukchi Basin. The wrench faults reportedly do not extend south of Herald arch and they can not be traced into the North Chukchi high at the west end of the Barrow arch.

Salient features of the listric normal fault province that bear on its origin are the north to northeast trend of its individual faults, the large structural relief on individual fault sets (2.5 km or more), its compactness (fault densities are high within the province and low beyond its boundaries), the significant extension produced by the fault system (5 to 12 percent), and the position of the province at the continental margin opposite the north- to northeast-trending aseismic ridges of the Chukchi Borderland. Restriction of the extensional fault system to only the eastern part of the North Chukchi Basin and the northerly trend of the fault is incompatible with a rift origin above the east-trending axial deep of the North Chukchi Basin or with sliding toward the west-northwesterly striking free face of the adjacent continental margin.

An origin for the listric fault province is suggested by its

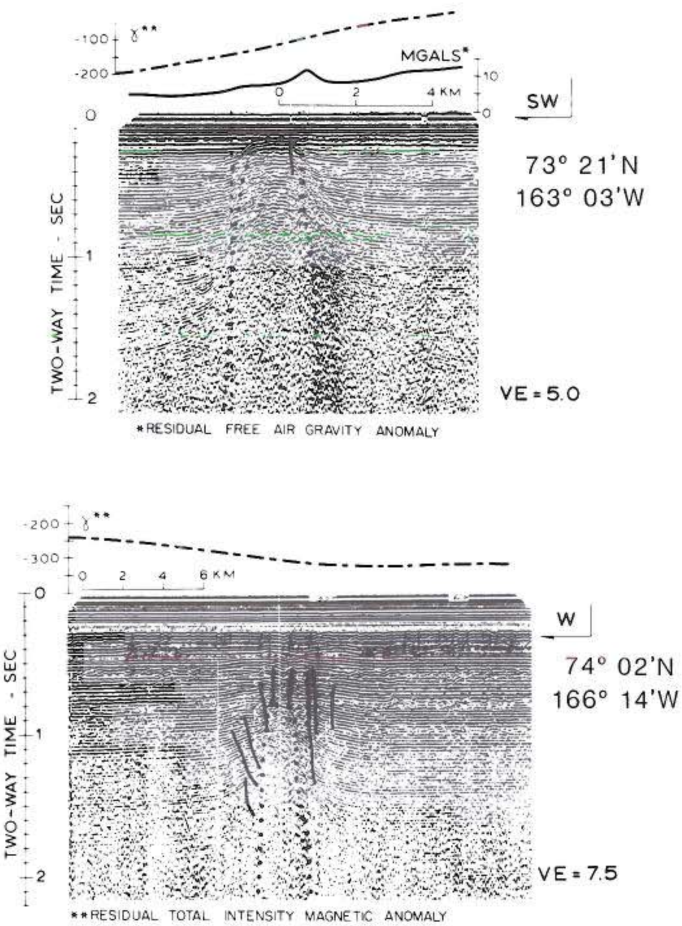


Figure 10. Single-channel air gun seismic reflection, gravity, and magnetic profiles across piercement diapirs in North Chukchi Basin. The upper profile is a central crossing of diapir at 73°21′N, 163°03′W; the lower profile is probably an oblique crossing of diapir at 74°02′N, 166°14′W. See Figure 8 for location.

resemblance to the extensional fault system, which disrupts the Eurasian continental margin where it is impinged by the Arctic Mid-Ocean Ridge of the Eurasia Basin in the Laptev Sea (see Grantz and others, 1990a, Plate 11). Similarities include structural position at the continental margin, trend and character of faulting, and dimensions. Based on this resemblance, we suggest that entry of a "Laramide" spreading center from the Arctic Basin into the continent also created the north-northeast–trending ridge and basin topography of the eastern Chukchi Borderland and the listric normal faults of the eastern North Chukchi Basin. Insufficient data are available to constrain a geometric model, but bathymetry and the regional distribution of extensional features of broadly "Laramide" age in the Arctic region suggest that the normal faults of the western Chukchi Shelf may belong to a regional spreading ridge and transform fault system of latest Cretaceous–early Tertiary age. This system might extend from the Chukchi Shelf to the Mid-Atlantic Ridge via north-south trending structures within the Chukchi Borderland, Mendeleev Ridge, Makarov Basin, and Baffin Bay, and transform faults such as Nares Strait and possibly others, as yet not identified, in the central Arctic Basin (Figs. 1, 3, 4; Grantz and others, 1990a, Plate 11).

Barrow sector

An arcuate continental margin of simple geometry faces the Canada Basin between Northwind Ridge on the west and the Canning displacement (fault) zone on the east (Figs. 4 and 6). This, the Barrow sector of the Arctic Alaska margin, is characterized by the Dinkum graben, a failed rift of Jurassic and Neocomian age, and the Hauterivian to early Late Cretaceous sea-floor spreading that created the Canada Basin. A syn- and post-rift progradational continental terrace sedimentary prism, the Nuwuk Basin, consists of post-Neocomian (Brookian) clastic sediment that buries the rifts. Cretaceous beds are the principal component of the basin on the west and Tertiary beds to the east. The principal structural features of the Barrow sector are shown in map Figures 3, 4, and 6, seismic reflection profiles 724 to 783 in Figures 7A, B, and 13, and seismic profiles 9D and E in Grantz and others, 1990a, Plate 9.

Stratigraphy. *Franklinian rocks.* Seismic reflection and refraction data indicate that in many areas the Ordovician and Silurian (Franklinian) argillite and graywacke encountered in many wells on the central and western North Slope extend offshore beneath the Beaufort and Chukchi Shelves. For example, sonobuoy refraction measurements by Bee and others (1984) from the inner Beaufort Shelf from west of Smith Bay to Prudhoe Bay found uppermost basement velocities of 4.24 to 6.08 km/s, which they interpret to represent Franklinian basement composed of argillite and phyllite. These workers, however, also found sonobuoy refraction velocities of 6.4 to 7.07 km/s from the top of basement in a smaller area of the inner shelf adjacent to 153°W, between Smith and Harrison Bays. The measurements suggest to these workers that the top of basement in this area, which is about 30 km in east-west dimension, consists of crystalline rock, probably silicic in composition. This high-velocity basement may be related to granite found immediately below the basal Ellesmerian unconformity at the nearby East Teshekput well (Bird and others, 1978), which lies near 153°W about 20 km west-southwest of Harrison Bay. The granite underlies Late Mississippian beds, and K/Ar dating and correlation with plutonic events in the northeast Brooks Range suggest that it may be Devonian. If a large negative gravity anomaly in the area of the well (Barnes, 1977) is created by the pluton, then the diameter of the pluton may be on the order of 50 km—commensurate in size with the area of the inner shelf underlain by high-velocity basement.

West of Point Barrow, beneath the northeastern Chukchi Shelf, Mississippian strata at the base of the Ellesmerian sequence are underlain by a broadly folded unit, Pzf, that is at least 7 km thick (profiles 781 and 783 in Fig. 7A and Grantz and others, 1990a, Plate 9) and has sonobuoy seismic velocities of 4.15 to 5.35 km/s (Houtz and others, 1981). These beds, inferred to consist of clastic sedimentary rocks, overlie about 5 km of well-bedded, strongly reflective beds with sonobuoy seismic velocities of 5.7 to 7.3 km/s in the upper part of unit Pzp€ (profiles 781 and 783). The lower part of unit Pzp€ consists of conformable, but less reflective strata that may be 6 km or more thick. Some seismic reflection profiles in the eastern part of this region show that a structural detachment zone in places lie between broadly folded areas of unit Pzf and the underlying, nonfolded, unit Pzp€. This detachment zone can be seen in Figure 18A of Haimela and others (1990) and Plate 3 of Craig and others (1985).

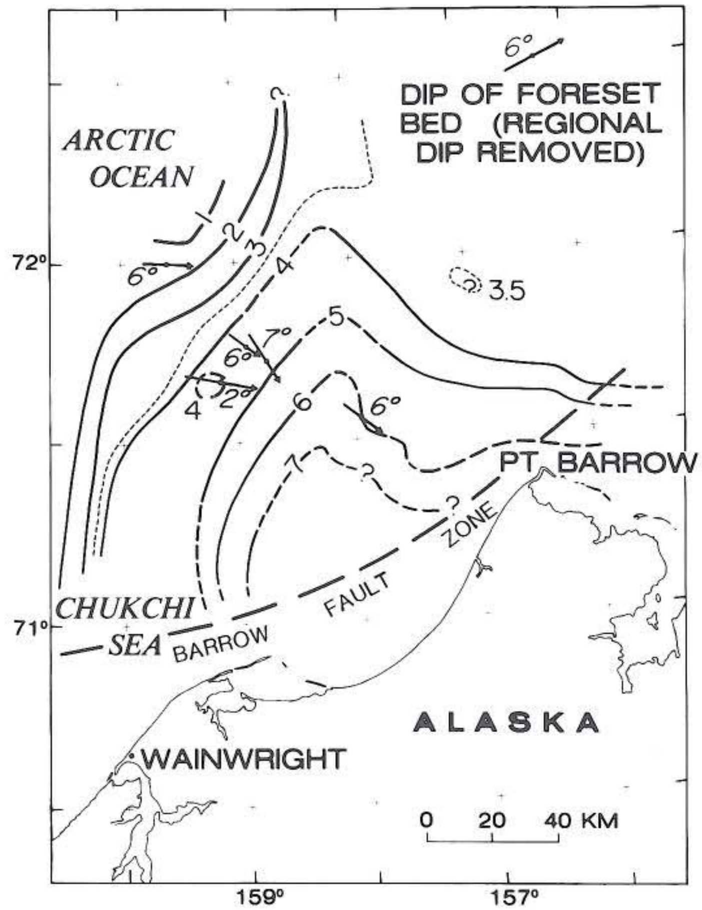


Figure 11. Isopach map (km) of unit Pzf in northeastern Chukchi Shelf showing dip of foreset beds and location of Barrow fault zone.

An isopach map of unit Pzf in the northeast Chukchi Shelf (Fig. 11) shows that the unit thins from more than 7 km near Point Barrow and Wainwright to less than 1 km about 160 km to the northwest. Seismic reflection profiles show that the unit consists of two contrasting facies and that the unit was eroded at an angular unconformity at the base of the PSU. Beyond 60 km west northwest of Point Barrow, where the base of the unit dips 6° or 7° east-southeast, the unit consists of southeasterly sloping interlayered strong to weak reflections, which we interpret to represent interbedded sandstone and lutite in foreset facies. Closer to the coast the dip flattens and the foresets grade into weak reflections, which we infer to represent basinal lutites in bottomset facies. The foreset unit thins from more than 5 km on the northwest to approximately 2.2 km where it grades into the basinal facies about 40 km offshore. This geometry indicates that the sourceland of this unit lay to the northwest, toward the sourceland of Barrovia (Tailleur, 1973).

Correlation of units Pzf and Pzp€ of the northeastern Chukchi Shelf with the North Slope section is uncertain due to the structural contrast between the mildly deformed pre-Mississippian units of the Chukchi Shelf and the strongly deformed and mildly metamorphosed pre-Mississippian strata of the western North Slope. A complicating factor is the presence of a northeast-striking structurally disturbed zone along the northwest coast of Alaska that lies between these areas of contrasting structural intensity. This feature, the Barrow fault zone, is postulated by Craig and others (1985) to be a major northeast-striking, northwest-dipping normal fault with about 10 km of stratigraphic displacement (Figs. 4 and 11).

Craig and others (1985) suggest conditionally that unit Pzf may be "age equivalent to the allochthonous Middle to Upper Devonian rocks of the Baird and Endicott Groups in the west-central Brooks Range." Underlying unit Pzp€ is thought by these workers and by Thurston and Theiss (1987, Fig. 11) to consist of Devonian carbonate and acoustic basement. Grantz and May (1983), on the other hand, suggest that unit Pzf is a mildly structured facies of the Ordovician and Silurian argillite and graywacke of the western North Slope and that the underlying, strongly reflective beds of unit Pzp€ may consist of upper Proterozoic or Cambrian carbonate or metamorphic rocks.

The stratigraphy proposed by Craig and others (1985) requires that the pre-Mississippian section of the northeast Chukchi Shelf be very different than that of the western North Slope. Thus, if offshore unit Pzf consists of Devonian clastic strata, as these authors propose, the correlative units beneath the North Slope would include the Devonian nonmarine clastic rocks encountered at the bottom of the Topagarok test well of the western North Slope (Collins, 1958). The Topogarok rocks can be inferred to rest unconformably on seismically incoherent Ordovician and Silurian argillite and graywacke, whereas unit Pzf rests on a thick section of strongly reflective beds (unit Pzp€) offshore. A contrast in stratigraphy of this magnitude across the Barrow fault zone would require large transcurrent or thrust displacement, and could not be explained by normal displacement, as proposed by Craig and others (1985).

The stratigraphy suggested by Grantz and May (1983) correlates offshore unit Pzf with the Ordovician and Silurian argillite and graywacke of the North Slope and requires that the mild metamorphism and strong deformation that characterize the North Slope rocks die out at the Barrow fault zone. This contrast in deformation could be explained if the Barrow fault zone is a major splay of a regional detachment fault that thrusts more strongly deformed argillite and graywacke of the North Slope against less strongly deformed argillite and graywacke beneath the northeast Chukchi Shelf. The detachment surface between units Pzf and Pzp€ noted above is thought to be the sole fault at which the Barrow fault zone roots. In support of this hypothesis, we note that seismic velocities of unit Pzf in the northeast Chukchi Sea (Vp = 4.15 to 6.0, average = 4.9 km/s; Houtz and others, 1981) are similar to velocities in the argillite and graywacke of the central North Slope (Vp = 4.3 to 4.9, average = 4.6 km/s; Fisher and Bruns, 1987) and the central Beaufort Shelf (Vp = 4.25 to 6.08 km/s; Bee and others, 1984), and that the argillite and graywacke unit is only mildly metamorphosed beneath the North Slope. In addition there is no subsurface or seismic reflection evidence that a well-bedded, high-velocity bedded section more than 7 km thick, such as unit Pzp€, lies between the argillite and graywacke and the unmetamorphosed Devonian and Mississippian nonmarine clastic rocks of the central and western North Slope. We consider the possibility that more than 7 km of unit Pzp€–like rocks once lay between these units on the central and western North Slope, but were subsequently completely removed by erosion, to be unlikely.

Ellesmerian and Brookian rocks. The character of Brookian offshore stratigraphic units in the Barrow sector is shown in profiles 742 to 783 (Figs. 7A, B). Ellesmerian rocks pinch out beneath the inner Beaufort Shelf and the northern Chukchi Shelf to the south of these profiles. Their maximum thickness on the Beaufort Shelf, about 1.3 km, occurs in the Colville Delta–Prudhoe Bay area.

A unit of northward-thickening, moderately strong seismic reflections that is 1.1 km or more thick lies at the base of the sedimentary fill in Dinkum graben (unit J in profiles 742 to 756; Figs. 7A, B). The tectonic setting of these beds at the base of a graben fill suggests that they consist of alternating fine- and coarse-grained clastic materials. The strength of the reflections may corroborate this inference, but other lithologies could also produce such reflections. Near Prudhoe Bay the unit appears to project into upper Ellesmerian strata of the North Slope. We infer that the basal unit of the Dinkum succession in Dinkum graben correlates with the upper Ellesmerian sequence of the North Slope, but it may include lower Ellesmerian beds in paralic facies adjacent to the northern sourceland (Grantz and May, 1983). Overlying the basal beds in Dinkum graben is a unit that produces mainly weak, but some moderate-amplitude seismic reflections. This unit, KJ in Figures 7A and B, is 3.5 km or more thick. Reflection character suggests that the unit consists of topset lutites and some sandstone. Bedding in unit KJ appears to be parallel to that in the underlying, better bedded unit J, and therefore, unit KJ may also consist of topset beds deposited in the subsiding graben. Possible south-dipping foreset beds in the unit on line 751 may indicate that some of these beds are deep-water deposits of northerly provenance. Northward thickening of the Dinkum succession and many of its subunits indicates deposition in a subsiding, north-tilting half graben.

A well-developed angular unconformity, which cuts down-section to the south, forms the upper contact of the Dinkum graben succession (profile 751, Fig. 7B). This is the breakup unconformity of Hauterivian age. The stratigraphic position of this unconformity indicates that the extension represented by the Dinkum succession and graben was an older event than the breakup unconformity and the extension that opened the Canada Basin. A Jurassic and Neocomian age is inferred for the Dinkum succession because it underlies the Hauterivian unconformity; because the succession can be projected into upper Ellesmerian rocks of the North Slope; and because Jurassic marine sedimentary rocks in an analogous stratigraphic and structural position crop out on strike in coastal northern Yukon Territory (Norris, 1984; Poulton, 1978).

A poorly observed, generally deep, northward-thickening seismic reflection unit (J) lies between unit Pzf and the breakup unconformity beneath the outer shelf and slope north of the Dinkum graben. Based on its stratigraphic position and similarities in reflection character, we correlate these beds with unit J in Dinkum graben (Figs. 7A, B). Unit J of the outer shelf produces mainly weak, but some moderately strong seismic reflections with apparent topset morphology. The unit is more uniform in thickness than unit KJ, and is more than 1.3 km thick northwest of Point Barrow and 1.9 km thick north of Prudhoe Bay. We speculate that unit J of the outer shelf was deposited on a subsiding shelf or basin floor in a graben that was tectonically related to, and coeval with, the Dinkum graben. We have, however, identified only north-dipping extensional faults, and the existence of the graben is only inferred from these faults and the position of unit J beneath the continental margin. Correlation of unit J of the outer shelf with that in the Dinkum graben is supported by the proximity of these beds across faults on the north side of the graben on profiles 742 and 749 (Fig. 7B). Unit J is an important marker for measuring the effects of down-to-the-basin rift faulting beneath the outer shelf, and it appears to be the preferred detachment surface for listric normal faults beneath the outer shelf and slope.

Units PSU and HRZ are lumped as seismic unit LK on profiles from the Beaufort and northern Chukchi Shelves (Figs. 7A and 7B). This unit thickens from an average of about 50 m (range 20 to 70 m) beneath the northern Chukchi Shelf (profile 783 in Fig. 7A) to between 400 and 500 m on profiles in the eastern part of the Barrow sector, where it consists of bottomset beds. The age of LK in the western part of the Barrow sector, where it is overlain by the Torok Formation, is Hauterivian to Aptian(?) and possibly early Albian. However, the top of the unit gets progressively younger as it thickens to the east, the direction in which the foreset facies of the Torok and younger formations also pass into bottomset facies. Near the Canning River, in the easternmost part of the Barrow sector, unit LK may include beds as young as Paleocene. Onshore, Molenaar and others (1986, 1987) assign post-PSU bottomset beds, which are equivalent to the upper part of unit LK, to the Hue Shale.

Units K and T in the seismic profiles of Figures 7A and B represent lower Brookian (Cretaceous) and upper Brookian (Tertiary) deposits of the Colville Basin on the North Slope and Chukchi Shelf and the prograding prodelta and intradelta rocks in the continental terrace sedimentary prism of the Nuwuk Basin. The boundary, which was roughly projected from the North Slope, is useful to illustrate structure but it is oblique to the lithologic and facies boundaries in these rocks. The subdivision was effected by roughly projecting the Cretaceous-Tertiary boundary offshore from the North Slope. In both units K and T, topset and foreset facies in the continental shelf pass into bottomset (basinal) facies in the Canada Basin to the north. The approximate position of the interfingering topset-foreset boundary, which is also the contact between the Canning and Sagavanirktok Formations of Molenaar and others (1986), is shown on profiles 742 to 767 (Figs. 7A, B).

On the western North Slope and central Chukchi Shelf, unit K consists of the Torok Formation and the overlying Nanushuk Group. The unit is oldest (Aptian?) in the southern part of the Colville Basin and becomes younger northward by downlap onto unit LK. It is youngest on the crest and north flank of the Barrow arch, where the basal beds are Albian. On the Beaufort Shelf and the northern Chukchi Shelf the uppermost part of unit K also includes topset and foreset beds of the Colville Group. East from Point Barrow, bottomset beds at the base of unit K increase in thickness, the foreset beds at the top of the unit decrease in thickness, and the boundary between these lithofacies becomes younger to the east. Beneath the inner shelf east of Prudhoe Bay the Cretaceous-Tertiary boundary passes from foreset to bottomset facies, and the thickness of unit K is reduced to only about 200 m. Between Prudhoe Bay and Flaxman Island the entire Canning Formation becomes Tertiary (unit T), and unit K is represented only by the condensed bottomset facies of the Hue Shale. The Canning is entirely Tertiary in age beneath the eastern Beaufort Sea.

Sedimentation in unit T of the upper Brookian sequence was a continuation of progressive progradational continental terrace sedimentation established at the beginning of Brookian time. As a result, foreset facies are predominant in unit K, and topset facies in unit T beneath the continental shelf of the Barrow sector, as suggested by bedding traces in Figures 7A and B. Unit T correlates with the Sagavanirktok Formation of the North Slope west of Prudhoe Bay, but only with its upper part to the east (Molenaar and others, 1986; Kirschner and Rycerski, 1988). The lower part of unit T east of Prudhoe Bay belongs to the Canning Formation, which encloses a thick intertongue of the Sagavanirktok Formation. The Gubik Formation, which caps the section on the Beaufort Shelf, is included in unit T.

Structure. Contours on the top of the Franklinian sequence (Fig. 6) and on the base of the Brookian sequence (Fig. 12) illustrate the regional geologic structure of the Barrow sector. The Franklinian surface slopes seaward with gradients of 30 to 100 m/km from a broad culmination at the crest of the Barrow arch to the tectonic hinge line of Early Cretaceous rifting beneath the outer shelf. At the hinge line the gradient increases abruptly to 250 to 500 m/km, which carries the surface to the lower limit of our seismic data (12 km below sea level) beneath the slope. In places, down-to-basin normal faults of modest displacement offset the Franklinian surface at the hinge line. These faults char-

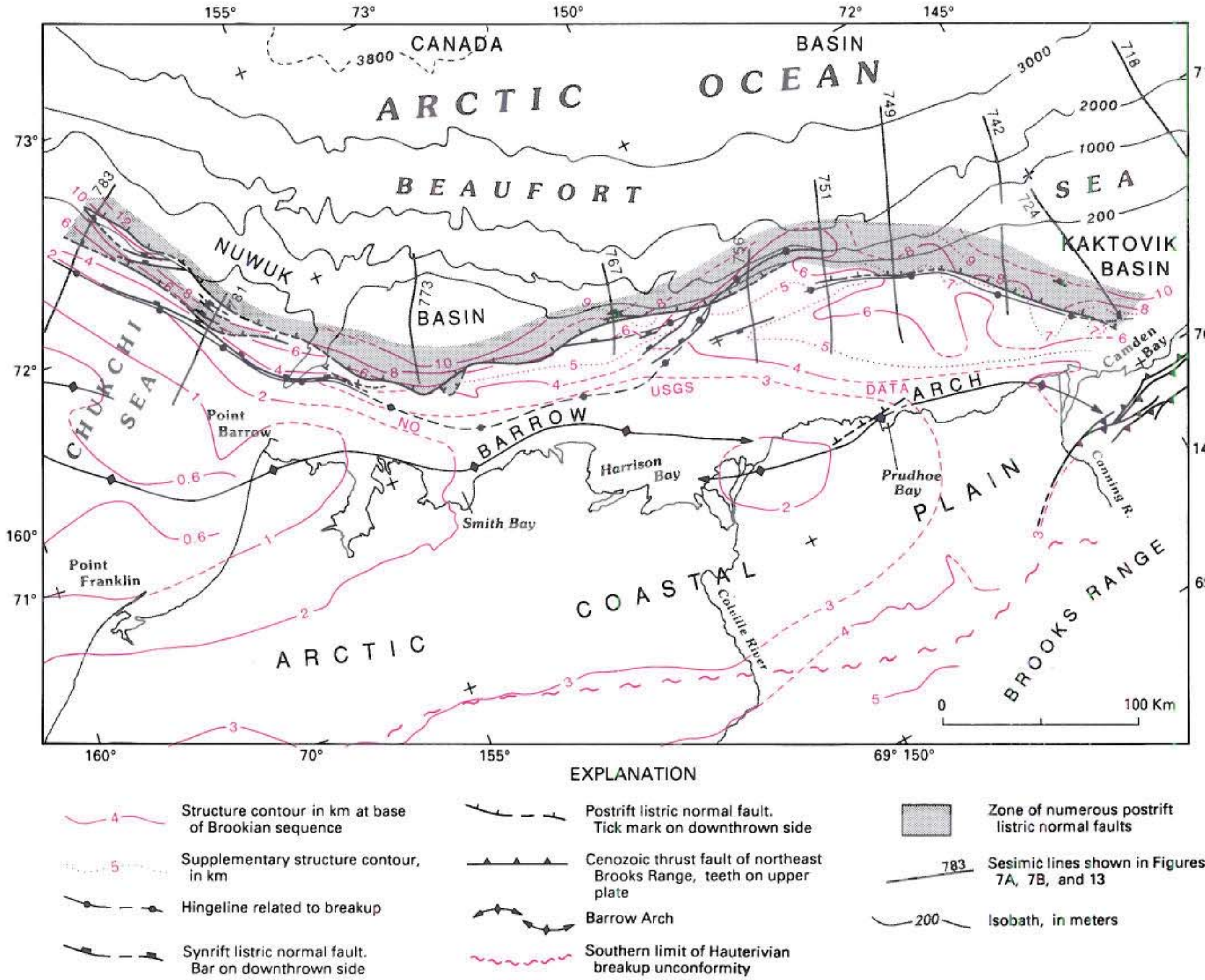


Figure 12. Map of Arctic Alaska continental margin showing depth in kilometers to base of Brookian sequence, which approximates position of Hauterivian breakup unconformity, and synrift and postrift structures. Data sources as for Figure 6. Lines dashed where projected or speculative.

acteristically are overstepped by the breakup unconformity or extend above it only a short distance into the basal Brookian strata. These faults are therefore related to the rifting events that immediately preceded and accompanied breakup. Seaward of the hinge line the Franklinian surface is offset by down-to-basin normal faults with displacements of 1.5 to 2 km. In places in the eastern part of the Barrow sector, the faults of this set have almost inverted the Dinkum graben by down-dropping rocks on the north flank of this structure below the position of their counterpart units within the graben to the south.

A 50- to 75-km northward excursion of the Early Cretaceous tectonic hinge line at the Colville River delta with respect to its position to the west (Figs. 4 and 6) reflects the influence of extension at the Dinkum graben. Extension at the graben dies out westward in the area of the excursion, suggesting that the excursion is a result of spreading at the graben. The Dinkum fault, which bounds the half graben on the north, has a vertical displacement exceeding 4 km. The principal displacement was prebreakup (pre–late Hauterivian) but the fault is also the locus of early post-breakup grabenward downflexing and minor faulting (seismic profiles 749 and 751 of Fig. 7B). Dinkum horst, which lies between the graben and the seaward-sloping Franklinian surface north of the hinge line, plunges gently east, as does the floor of the graben, at least as far east as the Canning River. East of the Canning, in the Barter Island sector, the horst and graben pass beneath the thick sedimentary section of the Kaktovik Basin and are lost on our seismic reflection records. The east-southeast trend of the graben would, if not deviated, carry its axis to the coastal plain near Barter Island. Smaller rift features of the same generation as the graben also offset the top Franklinian surface southwest and west of the Dinkum graben, in an area that is shoreward of our seismic coverage (Craig and others, 1985, Fig. 9).

The northward excursion of the hinge line trend (Fig. 4) at the west end of the Dinkum graben forms the east boundary of the middle Early Cretaceous to Tertiary Nuwuk Basin of the central and western parts of the Barrow sector. West of this excursion the width of the sedimentary prism between the hinge line and the shelf break increases from 5 km at profile 756 (Fig. 7A) near the west end of the Dinkum graben to more than 50 km at profile 783 (Fig. 7A), 80 km northwest of Point Barrow. The progradational continental terrace strata of the Nuwuk Basin are virtually undeformed and slope gently seaward south of the hinge line. North of the hinge line these strata are offset by numerous down-to-the-basin listric normal faults, and the structure is dominated by a broad hanging-wall rollover anticline with as much as 1.5 km of structural relief. The rollover formed above a system of north-dipping listric growth faults and some associated south-dipping normal faults that reach nearly to the seabed and sole out at or near the breakup unconformity (see profiles 756 to 783 in Fig. 7A). The growth faults die out within the continental rise sedimentary prism.

North of Dinkum graben, where the hinge-line/shelf-break interval is in places as narrow as 5 to 10 km, the hanging-wall rollover anticline is less well developed and is extensively dismembered by down-to-the-basin listric normal faults. Where the hinge-line/shelf-break interval widens again east of the graben, a broad, high-amplitude rollover anticline is again present beneath the outer shelf (vicinity of CDP 1,500, profile 724, Fig. 13).

Barter Island sector

Large thrust and detachment folds of Cenozoic age with northward vergence characterize the Cretaceous and Cenozoic (Colville Basin) strata of the Barter Island sector (Plates 9 and 11 and Fig. 14; Grantz and others, 1990b, Fig. 11). These structures root in thrusts superimposed on the Middle Jurassic to Albian convergent structures that regionally are the dominant features of the Brooks Range orogen. Historic earthquakes along the Camden anticline beneath the continental shelf, folding and faulting of Quaternary sediment beneath the shelf and the Arctic Coastal Plain, and warping of the seabed indicate that this compression is still active.

The thrust and detachment folds developed over a large, multistrand detachment fault system that is projected to lie between 5 and 10 km below sea level beneath the continental slope and that dies out in small folds and back thrusts beneath the continental rise about 170 km north of the coast (Fig. 3 in Grantz and others, 1990b; Reiser and others, 1980; Bruns and others, 1987). The western limit of the thrust and detachment folds and related faults, and of the Barter Island sector, is the seismically active Canning displacement zone. The eastern limit is the seismically active eastern front of the Richardson Mountains, in the lower Mackenzie River valley. Note that the Canning displacement zone is a northward extension of the Aleutian Benioff zone (Grantz and others, 1990a, Plate 11), which is of Cenozoic age. This extension and the orientation of the thrust folding and faulting suggest that Cenozoic compression in the Barter Island sector originated in convergence between the Pacific and the North American plates at the Aleutian megathrust. Cenozoic thrusting in the northeast Brooks Range is estimated to have carried older rocks now exposed in the range 25 to 50 km or more northward across the Colville Basin beds of the Barter Island sector. The basin may lie near its original position beneath the thrust sheets, but this has not been documented in seismic reflection profiles across the Arctic Coastal Plain and Foothills (see Bruns and others, 1987). Crustal loading by Cenozoic nappes in the northeast Brooks Range and accelerated erosion and clastic sedimentation from the newly uplifted nappes is also postulated to have depressed the foreland to create the Kaktovik Basin of the Barter Island sector continental margin (Fig. 4).

Stratigraphy. Platform carbonate and clastic strata more than 4.7 to 5.1 km thick, which crop out in south-dipping thrust-fault panels in the Sadlerochit and Shublik Mountains (Blodgett and others, 1986, 1988; Robinson and others, 1989), are the oldest rocks observed in the Barter Island sector. As discussed above under Stratigraphy, Arctic Platform, these beds are Late Proterozoic to Devonian in age. The platform rocks are inferred from outcrop data to rest on a large sole fault system of northern vergence that is rooted in the Brooks Range orogen.

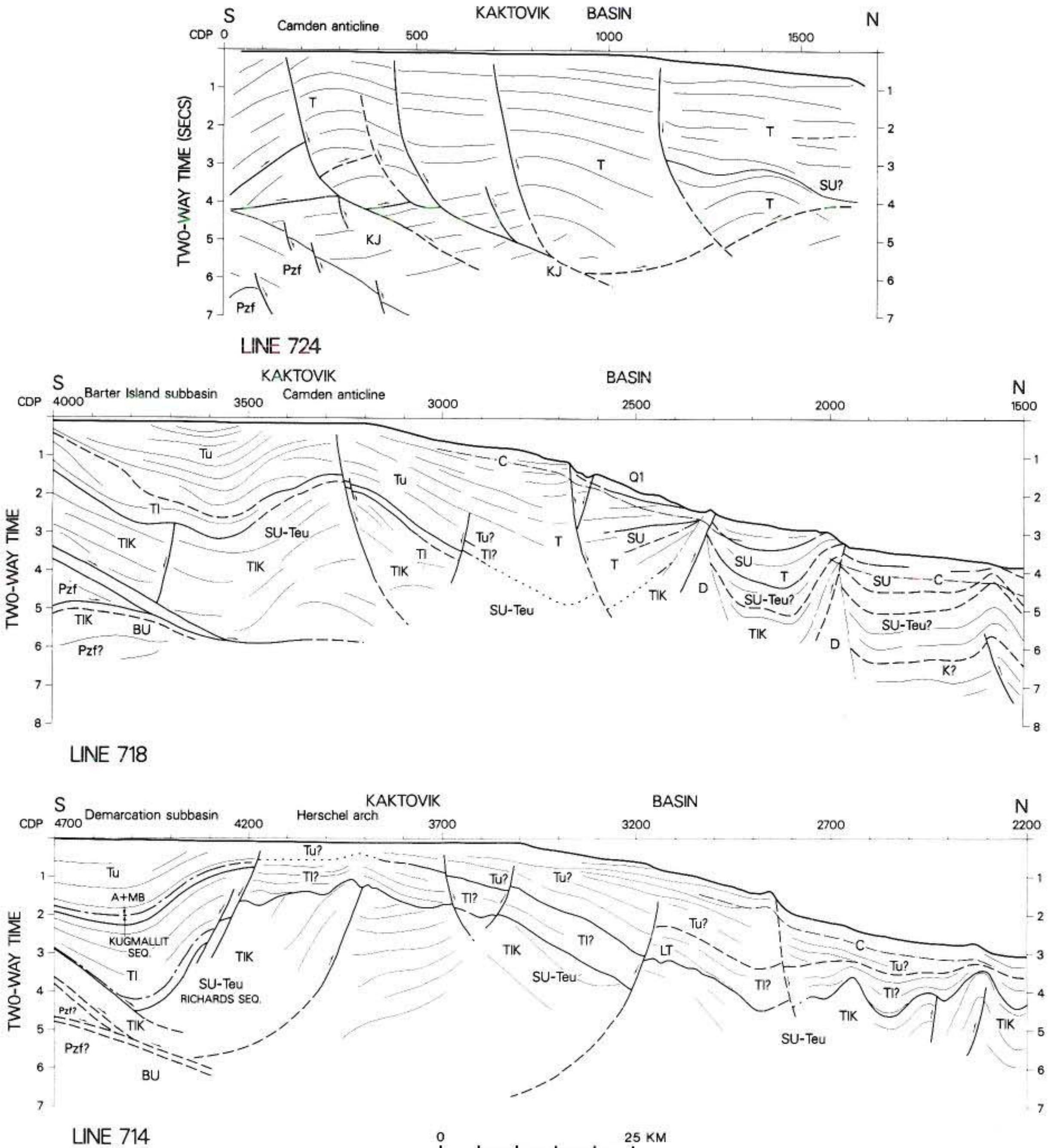


Figure 13. Line drawings showing geologic structures and stratigraphy on seismic reflection profiles 714, 718, and 724 across the Arctic Alaska continental margin. See Figure 7 for explanation and definitions. Sequence names on section 714 extrapolated from Dietrich and others (1989). Time sections from Grantz and others (1982).

East of the Sadlerochit and Shublik Mountains the oldest strata beneath the Arctic Coastal Plain are pre-Mississippian bedded rocks observed on seismic reflection records (Fisher and Bruns, 1987). These rocks have generally low dips, are 5 to 7 km thick, and are apparently disrupted by low-angle thrust faults. Offshore the pre-Mississippian bedded rocks have been tentatively identified at the south ends of profiles 714 and 718 (Fig. 13), where they have been designated unit Pzf(?). In thickness and reflection character this unit and the pre-Mississippian beds beneath the coastal plain resemble the well-bedded clastic rocks of inferred early Paleozoic age in the northeastern Chukchi Shelf (unit Pzf in profiles 781 and 783 in Fig. 7A). We suggest that all of these beds belong to the argillite and graywacke terrane of the central and western North Slope, and that they are a basinal

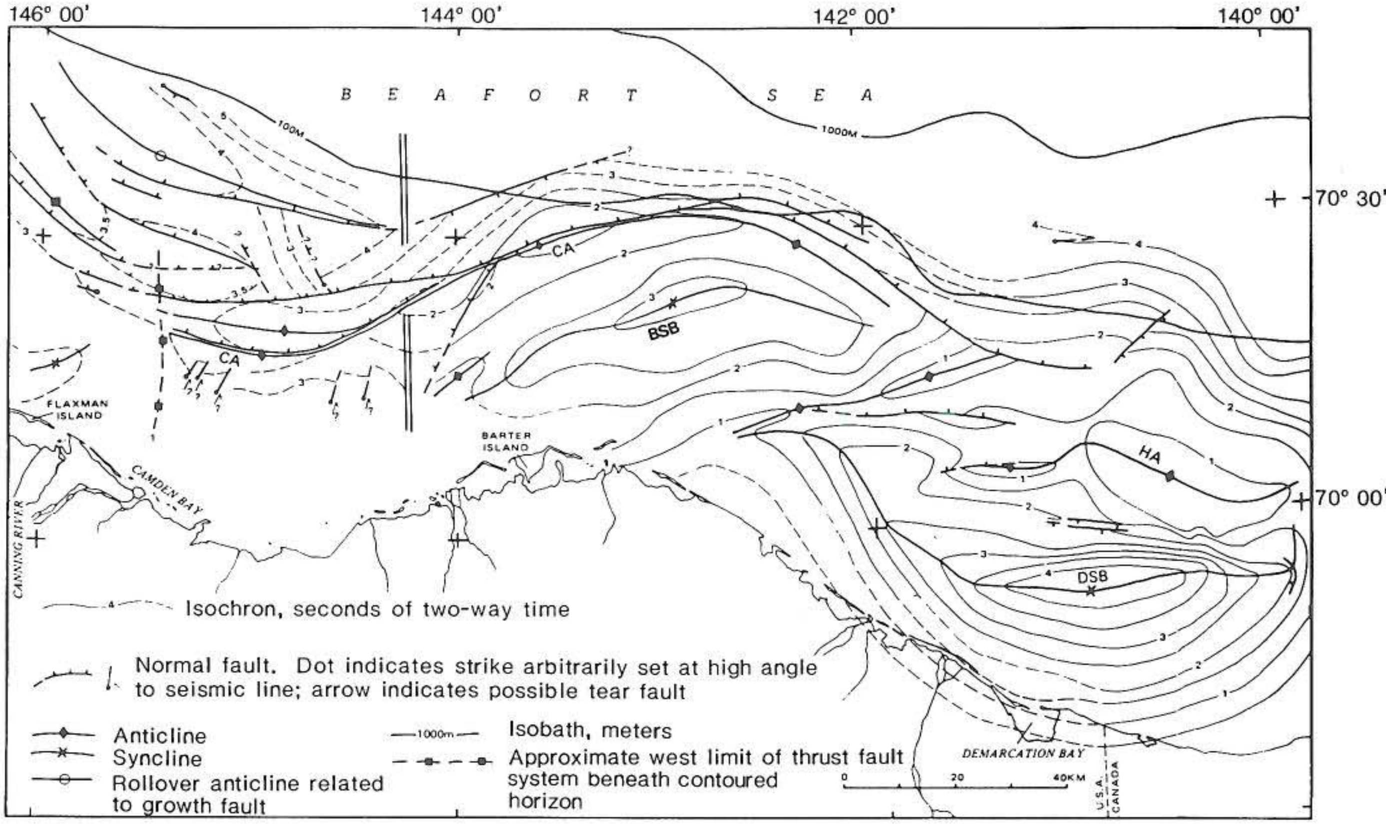


Figure 14. Isochrons (two-way reflection time) on selected surfaces beneath the eastern Alaska Beaufort Shelf; dashed where inferred. See Figure 2 for approximate equivalence of isochrons and depth. Contours are on middle Eocene unconformity east of 144°15′W and on a middle(?) Eocene horizon west of 144°15′W. Contours east of 141°W by James Dixon and James Dietrich (written communication, 1985). CA, Camden anticline; HA, Herschel arch; BSB, Barter Island subbasin; DSB, Demarcation subbasin.

facies of part of the Late Proterozoic to Devonian platformal succession of the Sadlerochit Mountains and vicinity. The north vergence of the platform rocks in the Sadlerochit and Shublik Mountains and their generally high structural position with respect to the argillite and graywacke terrane on either side suggest that the platform rocks have been thrust northward over the argillite and graywacke. The distribution of the platform rocks suggests that they, and any thrust faults that separate them from the argillite and graywacke terrane, extend beneath the continental shelf near Camden Bay and the Canning River.

The simple progradational depositional geometry of the Brookian sedimentary prism in the Barrow sector is replaced in the Barter Island sector by a complex of local Tertiary uplifts, erosional unconformities, and local sedimentary subbasins. Figure 14 shows the largest of these features. Camden anticline and Herschel arch are interpreted as large detachment folds, and the Barter Island and Demarcation subbasins as genetically related syndepositional basins. The cross-sectional geometry of these features is shown in profiles 724 to 714 in Figure 13. Growth of the detachment structures began in middle Eocene time, as dated by an erosional unconformity that formed in response to their initial growth. The unconformity, which lies between seismic-stratigraphic units TlK and Tl in profiles 714 and 718, was dated by correlation with a seismic-reflection event dated in test wells on the Canadian Beaufort Shelf (James Dixon and James Dietrich, 1990 and personal communication, 1986; Dietrich and others, 1989). It is the major stratigraphic break within the Brookian strata of the Barter Island sector. Above it lie stratigraphically simpler, but more complexly deformed units, and below it stratigraphically more complex, but less deformed units (see profiles 714 to 724 in Fig. 13, and profile 9C in Grantz and others, 1990a, Plate 9).

The character and age of the strata that lie between Franklinian basement and the middle Eocene unconformity (unit TlK in Fig. 13) are uncertain. Reflection character suggests that this unit consists of interbedded shale and sandstone or siltstone, and sonobuoy seismic refraction velocities in the range of 3.0 to 3.8 km/s suggest that the strata are Mesozoic or Paleogene, and not Paleozoic. Regional considerations and comparison with seismic profiles beneath the adjacent coastal plain (Bruns and others,

1987) suggest that near the coast the oldest strata of the unit are basal Brookian. Farther north, however, the oldest strata may, in places, belong to the Dinkum succession and contain Jurassic beds. The uppermost beds of unit TlK are middle Eocene. An unconformity is inferred to lie between unit TlK and the underlying Franklinian basement, but the unconformity is not clearly seen on the seismic profiles and its position in Figure 13 is in part speculative. The thickness of unit TlK may locally exceed 8.6 km, but its true thickness is masked by structural complexity.

Comparison with seismic-reflection profiles tied to test wells on the western Canadian Beaufort Shelf (Dixon and Dietrich, 1990; profile 8E, in Grantz and others, 1990a, Plate 8; and Dietrich and others, 1989) suggests that the upper part of unit TlK corresponds to Maastrichtian to middle Eocene strata of intertonguing intradelta and prodelta facies (Fish River and Reindeer depositional sequences on the Canadian shelf; Tent Island, Moose Channel, and Reindeer Formations of northern Yukon—see Fig. 5). The lower part of unit TlK correlates with marine shales of the Jurassic Kingak Formation (Canadian usage), a prodeltaic shale in the late Hauterivian to Aptian Mount Goodenough Formation, Albian flysch composed of detritus from the Brooks Range orogen, and organic-rich shale of the late Cenomanian to Turonian Boundary Creek Formation of northern Yukon. The Boundary Creek contains bentonite beds and ironstone concretions and correlates with lithologically similar beds in the Hue Shale and Seabee Formation of the North Slope.

Dixon and Dietrich (1990) report that upper Hauterivian strata at the base of the Mount Goodenough Formation rest on a regional unconformity that records a significant tectonic event. The character and age of the unconformity suggest to us that it correlates with the Hauterivian breakup unconformity of the Alaskan margin.

Comparison of unit TlK with the stratigraphic section in coastal wells in the eastern part of the Barrow sector indicate that it corresponds to the condensed shale of the PSU, the condensed distal shale of the Hue Shale, and the lower part of the Canning Formation. If the possible presence of Dinkum succession strata beneath the Beaufort Shelf and slope is excluded, unit TlK ranges in age from Hauterivian to middle Eocene.

Local depocenters and sedimentological complexity characterize the strata that overlie the middle Eocene unconformity in the Kaktovik Basin (units Tl and Tu in profiles 714 and 718 in Fig. 13; profile 9C in Grantz and others, 1990a, Plate 9). The largest local depocenters, the Barter Island and the Demarcation subbasins, lie on the south side of the Camden anticline and the Herschel arch detachment structures (Fig. 14). Narrower and shallower linear depocenters formed behind the ten or more long thrust folds that buckle the Cenozoic strata, and in some places the seabed, beneath the adjacent continental slope and rise. A map of these thrust folds is shown in Figure 11 of Grantz and others (1990b), and the folds are shown in cross section in profiles 714 and 718, Figure 13, and profile 9C, Grantz and others, 1990a, Plate 9.

Angular bedding discordances and thickness changes in the synclinal basins that lie upslope of Herschel arch, Camden anticline, and the thrust anticlines of the shelf and slope indicate that these basin are syntectonic with detachment and thrust folding. Total section in the Demarcation subbasin exceeds 7 km. Of this, 4 km is fill in the initial depression and 3 km is overburden. Thickening of strata into the subbasin, most strongly in the Kugmallit(?) sequence, exceeds 4 km across the south limb and 3 km across the north limb. Fill in the Barter Island subbasin is at least 1.4 km, and the overburden is more than 2.2 km thick. Fill in the basins upslope of the thrust folds of the continental slope is 0.1 to more than 1.0 km thick. The geostatic load created by the trapped sediment appears to have generated soft-sediment flow in underlying unit TlK, causing some of it to move from beneath the Demarcation subbasin, and perhaps the Barter Island subbasin, into the uplifted cores of Herschel arch and Camden anticline (profiles 714 and 718 in Fig. 13).

The basin fills in the Barter Island subbasin, and less clearly in the Demarcation subbasin, are progradational and consist of a lower unit dominated by foreset beds and an upper unit dominated by topset beds. The facies boundary between these units becomes younger to the north. We infer that this boundary, which can be observed on profile 718, Figure 13, corresponds to the similar boundary between the Canning and Sagavanirktok Formations of the Barrow sector. On our seismic records we are unsure whether the inferred Canning beds extend north of Camden anticline or Herschel arch, but locally the Sagavanirktok appears to rest directly on the middle Eocene unconformity over and north of these structures.

Correlation with data in Dixon and Dietrich (1990) and Dietrich and others (1989) indicates that the Demarcation subbasin contains the Richards and Kugmallit sequences and possibly the Mackenzie Bay, Akpak, and Iperk sequences of the Canadian western Beaufort–Mackenzie Basin (see profile 714 in Fig. 13). The Richards is middle to upper Eocene interbedded nearshore sandstone and mudstone less than 0.3 to more than 0.5 km thick; the Kugmallit about 0.8 to 1.0 km of lower and middle Oligocene mud-dominant prodelta and shelf sediment; the Mackenzie Bay as much as 2.0 km of upper Oligocene and lower Miocene prodelta sediment, and the Akpak middle and upper Miocene prodelta deposits that in places are close to 2.0 km thick. The Pliocene and Pleistocene Iperk sequence, unconsolidated gravel, sand and mud with abundant woody detritus, is about 0.2 km thick. In the Demarcation subbasin the Richards is well bedded, about 0.8 km thick, and appears to consist of topset (shelf) facies deposited on the middle Eocene unconformity. The overlying Kugmallit(?) beds consist of northward prograding topset and foreset beds that are 1.3 km thick about midslope on the south flank of the subbasin, about 2.4 km or less in thickness high on the north flank, and at least 3.8 km thick in the axial region. A correlation based on seismic reflection character suggests that an interval of strong reflections near 2.2 s in the axial region of the Demarcation subbasin (profile 714) may mark the base of the Mackenzie Bay sequence, and the base of an interval of weaker reflections near 1.05 s may mark the base of

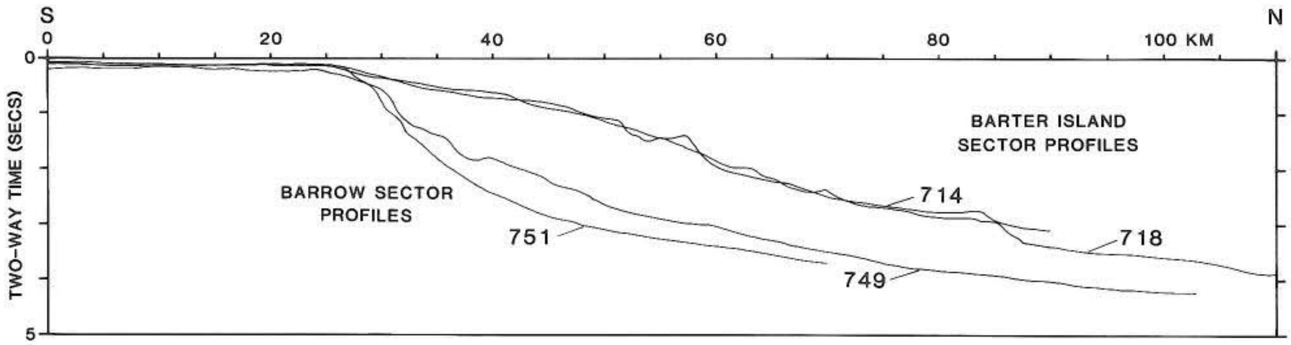


Figure 15. Comparison of seabed morphology across Arctic continental margin in Barter Island sector (profiles 714 and 718 of Fig. 13) and Barrow sector (profiles 749 and 751 of Fig. 7B). Area of prism between the two sets of profiles, equivalent to a tectonic welt almost 1 km high and 60 km wide, is a rough measure of minimum volume of Cenozoic tectonic transport across the convergent continental margin of the Barter Island sector with respect to the extensional (passive) margin of the Barrow sector.

the Akpak sequence. The Mackenzie Bay(?) interval is about 1.8 km thick and consists of mainly strongly bedded topset beds. The Akpak is about 0.7 km thick and also appears to consist of topset beds, but the reflections are obscured by multiples. If the Iperk sequence is present, it is obscured by multiples.

Structure. Convergent structures of Cenozoic age characterize the Barter Island sector and distinguish it from the Barrow sector, where convergent tectonics are absent. The convergence has also given these continental margin sectors contrasting morphologies, which are illustrated by the superimposed bathymetric profiles shown in Figure 15. The profiles across the slope of the Barrow sector are concave upward, recording the influence of extensional processes, whereas those across the Barter Island sector slope are convex upward, reflecting the influence of convergence. The cross-sectional area between the two sets of profiles extrapolated across the length of the Barter Island sector represent a bulge in the face of the continental terrace equivalent to a tectonic welt almost 1 km high, 60 km wide, and 500 km long. The average horizontal distance between the concave and convex profiles, about 30 km, is a rough measure of the minimum tectonic transport across the convergent Barter Island sector with respect to the extensional Barrow sector in Cenozoic time. An overview of the compressional structures of the Barter Island sector and their relation to regional structure is shown in Grantz and others (1990a, Plate 11.) Maps showing the character of the convergent structures are presented in Figure 14 of this chapter and Figure 11 of Grantz and others, 1990b.

Four types of Cenozoic structures, which lie in discrete, east-west–trending belts, are dominant in the upper crust of the Barter Island sector. On the south, beneath the inner and middle shelf, are the deep Barter Island and Demarcation subbasins (Fig. 14, profiles 714 to 724 in Fig. 13, and profile 9C in Plate 9). These basins are paired with broad, northward-convex, en echelon detachment folds, the Camden anticline and Herschel arch, that underlie the middle and outer shelf. North of the detachment folds, beneath the continental slope and rise, is a wide zone of slope-parallel thrust folds of large amplitude. Many of these folds buckle the sea floor and act as sediment traps. Beneath the outer shelf and upper slope are basinward-dipping listric normal faults, which are prominent only in the westernmost part of the sector (Figs. 6 and 12 and profile 724 in Fig. 13). The largest of these dip north and are related to deep slumping of Quaternary age near the present-day continental margin, but a few dip south.

Key to understanding the structure of the continental margin in the Barter Island sector is the character of Herschel arch and Camden anticline (profiles 714, 718, and 724 in Fig. 13, profile 9C in Grantz and others, 1990a, Plate 9). These folds are asymmetric, with a short south limb that dips landward at a large angle to the sea floor and a long north limb that dips seaward only a little more steeply than the sea floor. At the top of unit TlK their cross sections resemble south-facing monoclines at the short south limbs of the folds. The amplitudes of the monoclines at this horizon are 6.75 km for Herschel arch and 3.0 km or more for Camden anticline. The arch, which lies beneath the inner and central shelf, contains structural duplexes within unit TlK. Thrust-fault panels in the core of Herschel arch have a moderate south dip, which suggests that the structure was initiated in the regional, north-vergent compressional fault system of northeastern Alaska. Multiple structural culminations of the unconformity are present at the crest of the arch and must have been uplifted to wave base or the sea surface because they were the source of local sediment aprons. The culminations appear to represent small structural uplifts of the middle Eocene sea floor (see vicinity of CDP 3900, profile 714, Fig. 13). The culminations and the associated sedimentary aprons suggest that thrusting and uplift were penecontemporaneous with erosion and that the unconformity is a product of the early and middle Eocene convergence. The great disparity in thickness of unit TlK between Herschel arch and the basement for the Demarcation subbasin (Fig. 13) suggests that post-unconformity soft sediment flow in unit TlK from beneath the subbasin into the core of the arch may also have contributed to the large structural relief (6.75 km) across its south limb.

Camden anticline, in contrast to Herschel arch, appears to be a relatively simple buckle above a north-sloping detachment fault. In the central part (profile 718 in Fig. 13) the detachment fault has a relatively simple geometry and lies about 10 km below sea level at the fold axis. The amplitude of its south flank here is about 3 km. On the west (profile 724 in Fig. 13) the basal detachment fault system is a little more complex and it lies only about 6 km below sea level at the fold axis. The anticline here has an amplitude at the south flank of 4 km or more, but it is disrupted by several down-to-the-basin listric normal faults that merge with the detachment fault system at depth.

The thrust folds that lie north of Herschel arch and Camden anticline differ greatly from these structures in size and structural character. More than ten thrust folds have been identified beneath the continental slope and rise (profiles 714 and 718 in Fig. 13 and profile 9C in Grantz and others, 1990a, Plate 9; Fig. 11 in Grantz and others, 1990b). These structures are slope-parallel, range from a few tens of meters to at least 1.4 km in amplitude, and have wavelengths of 5 to 20 km. The folds are relatively narrow, elongate, and typically separated by broad, flat-bottomed synclines, in which respects they resemble detachment folds. Most are north vergent and appear to be cored by south-dipping thrusts, but a few are unfaulted or have north-dipping back thrusts in the core. Many of the folds have buckled the seabed, and some have acted as sediment traps in which hundreds of meters of sediment has accumulated. Additional discussion of these features can be found in Grantz and others (1990b).

Demarcation and Barter Island subbasins are compact, ovate extensional subbasins that lie en echelon on the landward side of Herschel arch and Camden anticline (Fig. 14). The Demarcation subbasin is 7.5 km deep, and the Barter Island subbasin a little more than 4 km deep (Fig. 13). Their north flanks, which lie against the arch and anticline, are steeper than their south flanks, and the north flank of the Demarcation subbasin is broken by south-dipping normal faults. Bedding is parallel to the subbasin floors or onlaps them in a southerly direction at low angles on the south flanks of the subbasins. In contrast, many beds onlap the floors of the north flanks of the subbasins and do so in a northerly direction and at steeper angles to the subbasin floors. In the Demarcation subbasin the lower part of the subbasin fill (upper Eocene and Oligocene beds of the Richards and Kugmallit sequences) thickens from less than 0.6 km over the south flank and less than 0.2 km over the north flank to 3.5 km at the subbasin axis. Some additional thickening occurred in higher beds, in the central part of the subbasin section, and part of the thinning on the north flank is due to normal faulting.

The regional geologic structure of northeastern Alaska, including the geologic structure of the Arctic Coastal Plain (Bruns and others, 1987), shows that the Cenozoic structures of the shelf in the Barter Island sector formed in a compressional environment. It therefore seems anomalous that the Demarcation and Barter Island subbasins are extensional features, that cross sections of Herschel arch and Camden anticline resemble south-facing monoclines, and that these large features lack the strongly compressional structural overprint of the thrust-fold belt of the adjacent continental slope and rise. Our seismic data do not penetrate deeply enough to fully resolve this anomaly, but the following hypothesis may explain our observations. We suggest that the growth of Herschel arch began in early or middle Eocene time as a compressional structure above a sole fault that extended from beneath the Brooks Range to the continental slope. As the sole fault passed from the Brooks Range to the Eocene shelf and continental margin, we propose that its dip changed from low south to low north. Compressionally thickened unit TlK was unstable where it overlay the northward-sloping portion of the sole fault beneath the continental margin, and we postulate that it began to glide slowly basinward under body forces. The rate of displacement was moderated by the resistance offered by sediment down-slope, in front of the gliding block. The space vacated by the block guide created the proto-Demarcation subbasin in late Eocene and Oligocene time. Thick and rapid Oligocene sedimentation in the subbasin may have mobilized the underlying unit TlK, facilitating the gliding and perhaps transferring some material to the glide block. An angular discordance at the base of the fill beneath the center and south flank of the basin (profile 714, Fig. 13) is interpreted as a detachment fault on which some of the gliding took place. Camden anticline and Barter Island subbasin are thought to be analogous to Herschel arch and the Demarcation subbasin; there was less thinning of unit TlK beneath the Barter Island subbasin, however, and its structure and stratigraphy indicate that this subbasin did not originate until late Cenozoic time.

Most of the thrust folds beneath the slope and rise are Neogene or Quaternary in age, but some were active during mid-Tertiary time. We suggest that these north-vergent compressional structures were formed in consequence of both middle and late Cenozoic movement on the Herschel arch block glide. Large-scale folding of the entire fill in both the Demarcation and Barter Island subbasins indicates that both subbasins were also affected by strong late Cenozoic tectonic movement. The geometry of this movement is not clear from our data. Presumably it would involve continued transmission of north-vergent compression to the rocks above the detachment faults of the Barter Island sector, moderately large displacements on the basal detachment faults where they dip north, and continued thickening and buckling of unit TlK above the detachment faults in both Herschel arch and Camden anticline. Distally, the displacement is transmitted to, and expended within the thrust folds that buckle the sea floor beneath the continental slope. The earthquake and aftershock swarm of 1968 on the Beaufort Shelf in the western part of the Barter Island sector suggest that this activity is continuing (Biswas and others, 1977).

The geometry of Herschel arch and Camden anticline suggest that these large structures formed under similar paleogeographic and structural conditions. If the Demarcation subbasin was created by block gliding, its 30 km width, is a measure of the minimum seaward displacement of the postulated Herschel arch glide block. Likewise, if the Barter Island subbasin was formed by block gliding, its width indicates that horizontal displacement of the Camden anticline glide block was also 30 km or more. The geometry and trend of the anticline indicate that its west end was fixed and that its initial position on the east was parallel to the coast about 10 or 20 km seaward of Barter Island.

TECTONIC HISTORY

The Arctic Ocean Basin is closely surrounded by the major continents of the Northern Hemisphere, which are characterized tectonically by numerous, large convergent orogens of Paleozoic, Mesozoic, and Cenozoic age. Yet, paradoxically, the Arctic Basin was formed by a series of extensional, or rifting events that began at least as early as late Paleozoic time. The best known of the extensional events that preceded formation of the Canada Basin and the Alaskan continental margin during middle Early Cretaceous time occurred in the Sverdrup basin of the western Canadian Arctic Islands. In the western part of this basin, Balkwill and Fox (1982) describe an incipient rift zone of Carboniferous to Late Cretaceous age marked by aligned normal faults, gabbro dikes, magnetic anomalies, and evaporite diapirs. The incipient rift also has stratigraphic expression in Carboniferous to Upper Cretaceous rocks. The rift strikes N40°E from Melville to northern Ellef Ringnes Island, about 25° counterclockwise from the trend of the adjacent present-day continental margin. Aligned dikes show the location of this feature on Plate 11 of Grantz and others (1990a). Balkwill and Fox (1982) state that the Sverdrup basin rift zone is likely to be the supracrustal expression of a crustal suture in Precambrian basement.

A second failed rift zone (Grantz and May, 1983) occurs along the continental margin from Banks Island to the continental slope west of Point Barrow. Stratigraphic relations in the northern slopes of the British Mountains in northern Yukon Territory indicate that this rift postdated thin, northerly sourced nearshore deposits of Late Triassic age and that the rift contains thick lutites as old as late Early Jurassic (Poulton, 1978). The presence of shale and siltstone of earliest Early to latest Middle Jurassic age in the Bonnet Lake area of the northern Richardson Mountains suggests that the oldest deposits in the rift may date back to the earliest Jurassic. Seismic stratigraphic relations along the Alaskan continental margin, detailed in previous sections of this chapter, indicate that the failed rift system contains as much as 4.7 km of Jurassic and Neocomian strata. The known and inferred distribution of the Jurassic failed rift deposits indicate that the rift was parallel to, and lay along or near the present continental margin along both the Canadian Arctic Islands and Alaskan sectors of the Canada Basin, and that the rift extended southward into the continent in the lower Mackenzie Valley. Restoring the Hauterivian to early Late Cretaceous counterclockwise rotation of Arctic Alaska away from the Canadian Arctic Islands about a pivot in the lower Mackenzie Valley (see Fig. 12 in Grantz and others, 1990b) would unite the now-separated fragments of the Jurassic failed rift deposits into a single rift system. This rift system would have lain within the peripheral platform of the Canadian Shield near, and subparallel to, the Carboniferous to Cretaceous failed rift of the Sverdrup basin.

The Jurassic rifting episode was a precursor to the late Neocomian rifting and Hauterivian breakup events that finally separated Arctic Alaska from the Canadian Arctic Islands. The newly formed Canada Basin was sufficiently well developed by Aptian time to receive more than 8.4 km of Albian progradational clastic deposits, and to serve as base level for development of submarine canyons with 1.4 km or more of erosional relief by Turonian time (Collins and Robinson, 1967). Firm evidence for the duration of rifting is not available, but the assumption of moderate rates for the spreading suggests that spreading was completed by middle Late Cretaceous time.

The geometry of the tectonic hinge line created by Hauterivian rifting and breakup (Figs. 4, 6, and 12) shows that this rifting event was the culmination of Jurassic rifting, and not a wholly independent event. Thus, the apparent position and trend of the Jurassic failed rift, as reconstructed from seismic and scattered outcrop data, is close to that of the successful Hauterivian and Barremian rift that produced the present continental margin. At a finer scale, the northward displacement of the Hauterivian hinge line at the mainly older Dinkum graben indicates that the breakup structures followed, rather than cut across, those of the precursor Jurassic rift system.

The southward excursion of the tectonic hinge line near 165°W, in the northwestern Chukchi shelf is associated with the genesis of the North Chukchi Basin. The great depth of this basin, its parallelism to the rifted margin to the east, and the apparent absence of a major transcurrent structure at its eastern margin, suggest that this offset segment of the continental margin also may have originated as a failed Jurassic rift. An intriguing unknown is whether the high-standing, northerly striking aseismic ridges of the adjacent Chukchi Borderland constitute fragments of the former northern margin of the North Chukchi Basin left behind by local complexities in the plate motions and geometry that created the Canada Basin.

A fourth episode of rifting may be represented by the wide zone of northerly trending "Laramide" extensional faults that disrupt the northwestern Chukchi Shelf and the eastern part of the adjacent North Chukchi Basin. This zone enters the continental margin from the north and apparently dies out within the Chukchi Platform of the central Chukchi Shelf. The position, trend, age, and deformational vigor of this event suggest that it may have been responsible for the dismemberment of a formerly compact Chukchi Borderland into its present array of northerly striking ridges and basins. These characteristics also suggest that the rift zone may have been connected, by a route which at present can only be conjectured, with rifting and sea-floor spreading of similar age in Baffin Bay and the Labrador Sea.

Convergent tectonics did not return to the Arctic Basin until

Cenozoic time when compression strongly deformed sediments of the continental margin in the Barter Island sector and adjacent parts of the southeastern Canada Basin. Distal effects of the deformation extend as far as 170 km north of the coast line, where water depths are in excess of 3,000 m. This episode of convergence probably began in Eocene time, and historic earthquakes and an abundance of deformed Quaternary sediments demonstrate that the convergence is still active. The tectonic position of the structures and earthquakes produced by this activity indicate that the compressional structures of the Barter Island sector in northeastern Alaska and northwestern Canada are distal effects of convergence between the Pacific Plate and North America at the Aleutian subduction zone.

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