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Chapter 3

Geology of northern Alaska

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INTRODUCTION

This chapter describes the geology of northern Alaska, the largest geologic region of the state of Alaska. Lying entirely north of the Arctic Circle, this region covers an area of almost 400,000 km^2 and includes all or part of 36 1:250,000 scale quadrangles (Fig. 1). Northern Alaska is bordered to the west and north by the Chukchi and Beaufort seas, to the east by the Canadian border, and to the south by the Yukon Flats and Koyukuk basin. Geologically, it is notable because it encompasses the most extensive area of coherent stratigraphy in the state, and it contains the Brooks Range, the structural continuation in Alaska of the Rocky Mountain system. Northern Alaska also contains the largest oil field in North America at Prudhoe Bay, the world's second-largest zinc-lead-silver deposit (Red Dog), important copper-zinc resources, and about one-third of the potential coal resources of the United States (Kirschner, this volume; Magoon, this volume; Nokleberg and others, this volume, Chapter 10; Wahrhaftig and others, this volume).

Although geologic research in northern Alaska has resulted in many publications, including two symposium volumes (Adkison and Brosgé, 1970; Tailleur and Weimer, 1987), there exists no comprehensive geologic summary of the region. In this chapter we attempt to provide a summary by reviewing the essential stratigraphic and structural elements of the region, outlining the current hypotheses for the evolution of northern Alaska, and reporting problems that are currently the subject of controversy. Our objectives here are to provide a basic framework for the geology of the region and to establish a milepost from which the courses of future research can be planned. We have approached this complex topic by describing systematically the stratigraphy and structure in separate sections. These are then followed by an interpretive section that chronologically summarizes the geologic history of northern Alaska. We present the stratigraphy according to the existing tectonostratigraphic nomenclature; however, deformational features are discussed by structural province to highlight the orogenic features that developed after the formation of the major tectonostratigraphic boundaries. The data summarized here have been taken from published and unpublished geologic maps, open-file reports, circulars, abstracts, and field notes, as well as the more accessible geologic literature. Throughout the text we have related paleogeographic reconstructions to present geographic coordinates; however, many workers believe that the rocks of northern Alaska have been rotated and/or displaced significant distances from their sites of origin. An expanded version of this chapter is presented in Moore and others (1992).

Geographic and geologic framework

Northern Alaska is divided into three major, parallel physiographic provinces: from south to north, these are the Arctic Mountains (Brooks Range), the Arctic Foothills, and the Arctic Coastal Plain (Wahrhaftig, 1965, and this volume). The Brooks Range consists of rugged, east-trending, linear mountain ranges, ridges, and hills that rise to more than 3000 m in the east but progressively decrease in elevation and relief toward the west. The Arctic Foothills consists of a series of rolling hills, mesas, and east-trending ridges that descend northward from more than 500 m to less than 300 m in elevation. From the Arctic Foothills,

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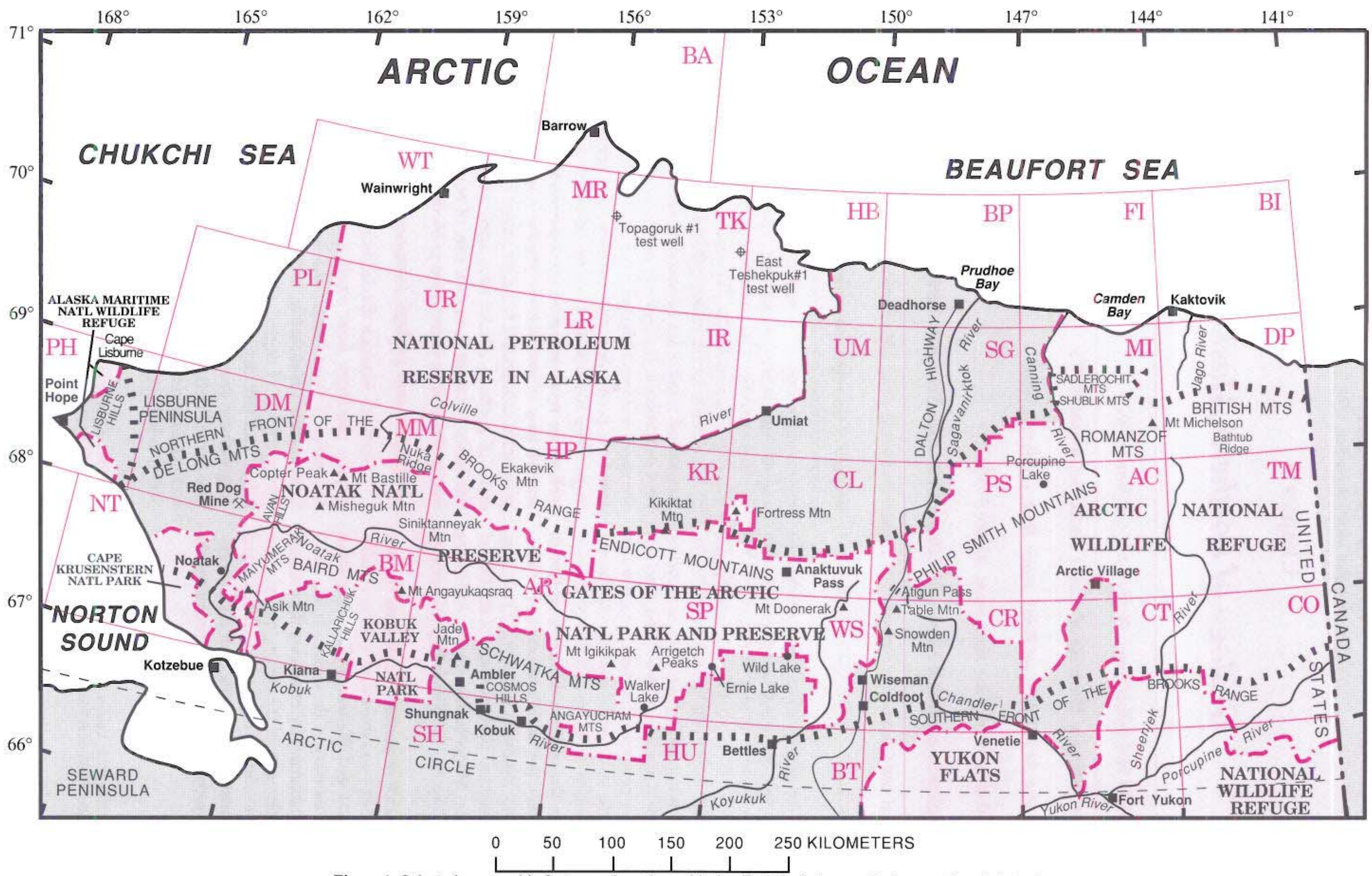

Figure 1. Selected geographic features of northern Alaska. Red shaded areas designate selected federal lands. Quadrangles (1:250,000 scale): AC, Arctic; AR, Ambler River; BA, Barrow; BI, Barter Island; BP, Beechy Point; BM, Baird Mountains; BT, Bettles; CL, Chandler Lake; CO, Coleen; CR, Chandalar; CT, Christian; DM, De Long Mountains; DP, Demarcation Point; FI, Flaxman Island; HB, Harrison Bay; HP, Howard Pass; HU, Hughes; IR, Ikpikpuk River; KR, Killik River; LR, Lookout Ridge; MI, Mount Michelson; MM, Misheguk Mountain; MR, Meade River; NT, Noatak; PH, Point Hope; PL, Point Lay; PS, Philip Smith Mountains; SG, Sagavanirktok; SH, Shungnak; SP, Survey Pass; TK, Teshekpuk; TM, Table Mountain; UM, Umiat; UR, Utukok River; WS, Wiseman; WT, Wainwright.

the marshy Arctic Coastal Plain slopes gradually northward to the Arctic Ocean. The latter two provinces, together composing the North Slope, narrow toward the east and are truncated on the west by the Chukchi seacoast (Wahrhaftig, this volume). The low, north-trending Lisburne Hills are situated along this coast.

Early investigations of the geology of northern Alaska showed that the North Slope is underlain by the large, west-trending Colville basin, a foreland basin of Cretaceous and Tertiary age (Fig. 2). The northern margin of the basin is delineated by the west-trending Barrow arch, a subsurface structural high composed of pre-Mississippian to Lower Cretaceous rocks. The northern limb of the Barrow arch lies beneath the Beaufort Sea, where it is overlain by Cenozoic rocks of the Beaufort Sea shelf. The southern part of the Colville basin is gently folded at the surface and is bordered by the west-trending disturbed belt (Brosgé and Tailleur, 1971), which is composed of mostly incompetent and structurally imbricated rocks along the northern front of the central and western Brooks Range. This belt marks the location of important north to south changes in the Paleozoic and lower Mesozoic stratigraphy. The Tigara uplift is a northwest-trending structural high that marks the southwestern limit of the Colville basin in the Lisburne Peninsula.

North of the disturbed belt in the eastern Brooks Range, the folded and faulted pre-Cretaceous rocks of the Colville basin are uplifted and exposed in the northeastern salient (Tailleur and Brosgé, 1970) of the Brooks Range. The disturbed belt is bounded on the south by the crestal belt of the Brooks Range. This belt is composed of folded and thrusted Devonian to Lower Cretaceous sedimentary rocks. South of the crest of the range, the central belt (Till and others, 1988) forms the geographic core of the Brooks Range. This belt consists of ductilely deformed Paleozoic slate, phyllite, schist, carbonate rocks, and orthogneiss that commonly retain primary textures. South of the central belt, in the southern Brooks Range, is the schist belt, which consists of

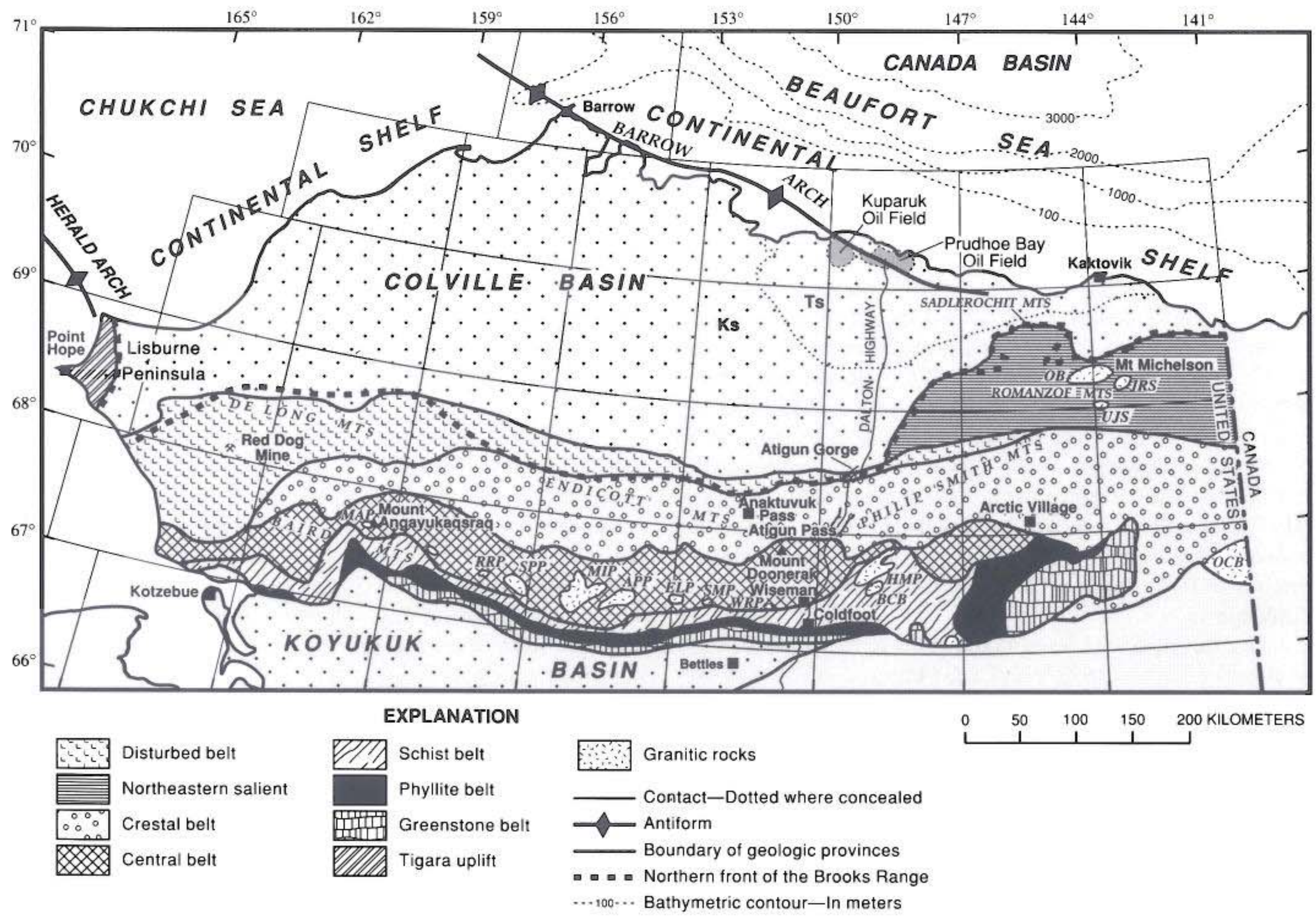

Figure 2. Geologic provinces of northern Alaska. Grid represents 1:250,000 scale quadrangle boundaries (see Fig. 1 for quadrangle names). APP, Arrigetch Peaks pluton; BCB, Baby Creek batholith; ELP, Ernie Lake pluton; HMP, Horace Mountain plutons; JRS, Jago River stock; Ks, Cretaceous sedimentary rocks; MAP, Mount Angayukaqsraq pluton; MIP, Mount Igikpak pluton; OB, Okpilak batholith; OCB, Old Crow batholith; RRP, Redstone River pluton; SMP, Sixtymile pluton; SPP, Shishakshinovik Pass pluton; Ts, Tertiary sedimentary rocks; UJS, Upper Jago River stock; WRP, Wild River pluton.

schistose metasedimentary and minor metavolcanic rocks (Brosgé, 1975; Turner and others, 1979). Two narrow belts lie south of the schist belt and underlie the southern foothills of the Brooks Range (the Ambler-Chandalar ridge and lowland section of the Arctic Mountains of Wahrhaftig, 1965, and this volume). The phyllite belt (Dillon, 1989), the more northerly of the two narrow belts, consists of recessive metasedimentary rocks, whereas the greenstone belt (Patton, 1973), the more southerly of the two, consists of resistant metabasalt and chert. The greenstone belt is commonly considered exotic with respect to most of the pre-Cretaceous rocks of northern Alaska, and its southern boundary delineates the northern margin of the Koyukuk basin (Cretaceous) to the south.

From the schist belt north to the Colville basin, exposed rocks of northern Alaska display a regional decrease in average age, grade of metamorphism, and deformational intensity. An apparent decrease in grade of metamorphism and deformation also extends southward from the schist belt into the Koyukuk basin. Although the various belts described above are commonly used to designate geologic provinces, their boundaries are not well defined, and their structural character and significance are controversial.

Lithotectonic terranes of northern Alaska

Jones and others (1987) and Silbering and others (this volume) have divided nearly all of Alaska into several tectonostratigraphic or lithotectonic terranes and subterranes. Terranes are defined as fault-bounded geologic packages of rock that display internal stratigraphic affinities and geologic histories that differ from neighboring terranes (Jones, 1983; Howell and others, 1985). We regard subterranes as fault-bounded divisions of terranes that can be geologically linked with adjacent subterranes but whose stratigraphies differ sufficiently to require significant amounts of relative displacement. We use the terrane and subterrane nomenclature herein to designate major structurally bounded stratigraphic or lithologic packages without inferring specific tectonic models of origin or distances of structural displacement.

For this report we have modified the terrane nomenclature of Jones and others (1987) and Silberling and others (this volume) for northern Alaska to incorporate new map and age data and to simplify discussion of the stratigraphy and tectonic history (Fig. 3). Principal revisions are (1) modification of the terrane-subterrane hierarchial nomenclature for northern Alaska on the basis of likely affinities among the various tectonostratigraphic units; (2) extension of the Coldfoot subterrane of the Arctic Alaska terrane into the western Brooks Range; (3) incorporation of both the southern part of the Coldfoot subterrane (that is, the phyllite belt) and the Brooks Range part of the Venetie terrane of Jones and others (1987) into the Slate Creek subterrane, a new subterrane of the Arctic Alaska terrane; (4) inclusion of the Sheenjek terrane of Jones and others (1987) into the De Long Mountains subterrane of the Arctic Alaska terrane; (5) inclusion of the Kagvik terrane of Jones and others (1987) in the Endicott Mountains subterrane of the Arctic Alaska terrane; and (6) inclusion of the Brooks Range part of the Tozitna terrane of Jones and others (1987) into the Angayucham terrane. Our revised terrane map is shown in Figure 3.

Northern Alaska consists of two lithotectonic terranes, the Arctic Alaska terrane and the Angayucham terrane (Silberling and others, this volume). The most extensive is the Arctic Alaska terrane (Newman and others, 1977; Fujita and Newberry, 1982; Mull, 1982), which underlies all of the North Slope and most of the Brooks Range. Rocks of this terrane span Proterozoic to Cenozoic time and are mostly of continental affinity. The Arctic Alaska terrane is bordered on the north by the Canada basin, which formed by sea-floor spreading in the Cretaceous (Grantz and May, 1983). The terrane extends into the Mackenzie delta region of northwest Canada, where it terminates beneath Cenozoic sedimentary cover. To the west, it may extend under the Chukchi Sea and into the Chukotsk Peninsula of the Russian Far East and terminate at the South Anyuy suture (Churkin and Trexler, 1981; Fujita and Newberry, 1982). At its southernmost exposure in Alaska, the Arctic Alaska terrane dips southward beneath the Angayucham terrane at a boundary called the Kobuk suture by Mull (1982) and Mull and others (1987c), and may continue southward beneath rocks of the Koyukuk basin. Along its southeastern margin, however, the Arctic Alaska terrane is juxtaposed against the Porcupine terrane of North American affinity along the Porcupine lineament (Grantz, 1966). Although the existence of a continuous structural break along this lineament has not been firmly established, it is commonly interpreted as a strike-slip fault of unknown age, sense of movement, and amount of displacement (Grantz, 1966; Churkin and Trexler, 1981).

The other terrane composing northern Alaska is the Angayucham terrane, which includes the greenstone belt of the southern Brooks Range and the structurally highest klippen in the crestal and disturbed belts. The Angayucham terrane is generally less than 5–10 km thick and consists largely of mafic and ultramafic rocks and siliceous pelagic rocks of Devonian through Jurassic age. Its structurally high position has led most workers to conclude that it represents the remnants of an extensive northward-transported thrust sheet of mostly oceanic rocks that overrode the Arctic Alaska terrane during Jurassic and Cretaceous time (Roeder and Mull, 1978).

On the basis of differing stratigraphy, facies, and structural position, the Arctic Alaska terrane has been divided into several subterranes and/or allochthons (Mull, 1982; Jones and others, 1987; Mayfield and others, 1988). The term "allochthon," as used by Mull and others (1987c) and Mayfield and others (1988), refers to rock packages of regional extent that are bounded by major thrust faults. These faults separate one package from adjacent ones of differing lithofacies but commonly of the same stratigraphic nomenclature. In this chapter, allochthon is used as a tectonostratigraphic subdivision of subterrane. The North Slope subterrane, the structurally lowest subterrane, consists of Cre-

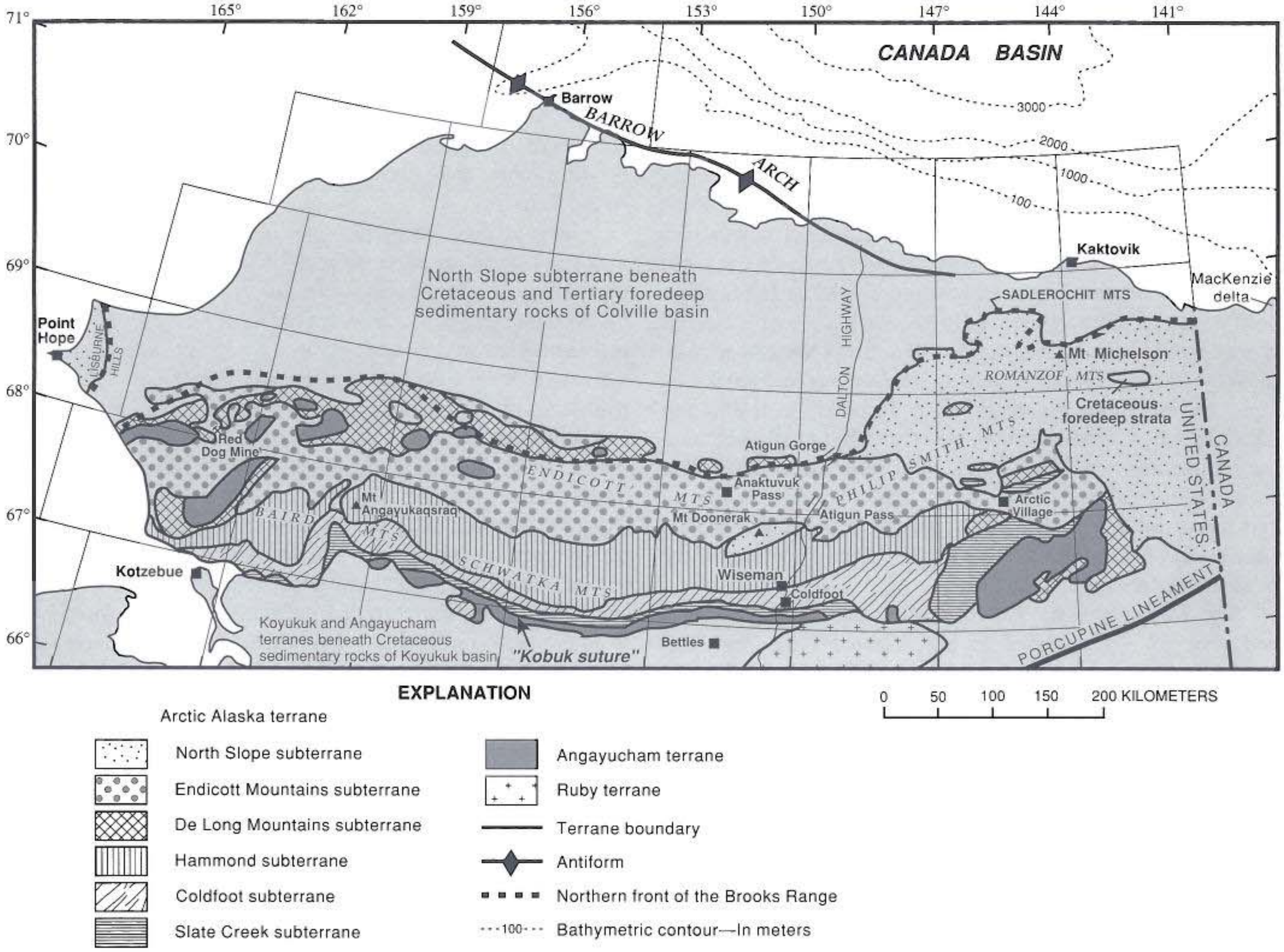

Figure 3. Terranes and subterranes of northern Alaska. Grid represents 1:250,000 scale quadrangle boundaries (see Fig. 1 for quadrangle names).

taceous and older rocks underlying the Colville basin and composing the Barrow arch, the northeastern salient of the Brooks Range, and the Lisburne Hills. These rocks were not extensively deformed by post-Mississippian orogenic activity in the subsurface of the North Slope, but they have been extensively deformed by Cretaceous and Cenozoic contractional tectonism in the northeastern salient of the Brooks Range and in the Lisburne Hills. Rocks of the North Slope subterrane are also exposed in a structural window, the Mt. Doonerak fenster, at Mt. Doonerak in the central Brooks Range (Fig. 3). This exposure is extremely significant because it indicates that the North Slope subterrane lies at depth beneath the other subterranes of the Arctic Alaska terrane. The Endicott Mountains subterrane consists of the Endicott Mountains (or Brooks Range) allochthon. This subterrane includes most of the imbricated sedimentary rocks of the crestal belt in the central Brooks Range. The presence of rocks of the North Slope subterrane both north and south (in the Mt. Doonerak fenster) of the Endicott Mountains subterrane has led most workers to conclude that the Endicott Mountains subterrane is a klippe of imbricated middle Paleozoic to Mesozoic rocks that overlie the North Slope subterrane. In various places along the length of the Brooks Range, the Endicott Mountains subterrane is structurally overlain by the De Long Mountains subterrane. Like the Endicott Mountains subterrane, the De Long Mountains subterrane consists of imbricated Paleozoic and Mesozoic sedimentary rocks but differs in important stratigraphic aspects from the North Slope and Endicott Mountains subterranes. The De Long Mountains subterrane is divided into four allochthonous successions: from base to top these are the Picnic Creek, Kelly River, Ipnavik River, and Nuka Ridge allochthons. These allochthons are the structurally highest and most displaced rocks of the Arctic Alaska terrane.

The stratigraphy of metamorphic rocks in the southern Brooks Range is not as well understood as that of the sedimentary rocks in the northern Brooks Range. For this reason, the subterranes of the southern Brooks Range consist of lithologic assemblages that are inferred, but cannot be proved, to constitute depositional successions. The Hammond subterrane includes most of the Proterozoic and lower Paleozoic mixed clastic and carbonate rocks of the central belt. These rocks display ductile deformational structures and low greenschist to local blueschist facies mineral assemblages, but relict igneous and sedimentary textures are commonly retained. The Coldfoot subterrane, which lies south of the Hammond subterrane, consists of quartz-mica schist, calc-schist, marble, and metavolcanic rocks of the schist belt. This subterrane displays Mesozoic blueschist facies metamorphic assemblages that are partly to completely overprinted by greenschist facies assemblages. The Slate Creek subterrane (also called the Slate Creek thrust panel of the Angayucham terrane by Patton and others, this volume, Chapter 7) consists of phyllite and subordinate metasandstone with rare Devonian fossils that compose the phyllite belt. The Coldfoot and Slate Creek subterranes are thought to belong to the Arctic Alaska terrane because of their quartzose composition and apparent contiguity with that terrane, but their precise relation to the other subterranes of the Arctic Alaska terrane is unknown.

The Koyukuk basin, Colville basin, and the Beaufort Sea shelf (Fig. 2) are regarded as post-tectonic basins by most workers, but they are partly overprinted by both shortening and extension that continued in the Cretaceous and Cenozoic (Tailleur and Brosgé, 1970). The Koyukuk basin is discussed by Patton and others (this volume, Chapter 7) and the Beaufort Sea continental-margin succession is discussed by Grantz and others (1990a). The Colville basin is the Early Cretaceous (Aptian[?] to Albian) and younger foredeep of the Brookian orogen (discussed in the following section). The strata of this basin rest almost entirely on the North Slope subterrane and therefore are described with that subterrane. Older Jurassic and Lower Cretaceous (Neocomian) foredeep deposits within the orogen compose the proto-Colville basin. Because the proto-Colville basin strata are preserved mainly in the allochthonous sequences of the Brooks Range, and palinspastic restoration of these rocks is uncertain, they are described below with the subterrane to which they have been assigned.

Orogenic events of northern Alaska

Geologic structures in northern Alaska are assigned to two major orogenic systems, the Ellesmerian and Brookian orogenies. The Ellesmerian orogeny affected units that lie unconformably beneath less-deformed Lower Mississippian strata in the northeastern Brooks Range and North Slope, but angular truncation by the sub-Mississippian unconformity elsewhere may indicate a greater extent for the orogen. The sub-Mississippian unconformity extends westward in the North Slope subsurface at least as far as the Lisburne Peninsula and is also exposed south of the crest of the Brooks Range at Mt. Doonerak and in the Schwatka Mountains (Fig. 1). Because Lerand (1973) inferred the sub-Mississippian structures of northern Alaska to be coeval with the Late Devonian and Early Mississippian Ellesmerian orogeny of the Canadian Arctic Islands, he extended the Ellesmerian orogen to include all early Paleozoic deformation along the Arctic Ocean margin from northern Greenland to Wrangell Island in the Russian Far East. However, recent work in the northeastern Brooks Range (Anderson and Wallace, 1990) suggests that the Ellesmerian orogen of northern Alaska is pre–Middle Devonian and is therefore older than the Ellesmerian orogen of the Canadian Arctic Islands.

The younger orogenic system is represented by the major east-trending, north-vergent fold-thrust belt that forms the Brooks Range. The orogenic event that produced these structures, the Brookian orogeny, can be divided into two major phases. The early Brookian phase is characterized by ductile deformation and metamorphism in the southern Brooks Range and by the emplacement of relatively far traveled thrust sheets in the northern Brooks Range during the Middle Jurassic and Early Cretaceous (Mull, 1982; Mayfield and others, 1988; Dillon, 1989). The thrust sheets advanced northward as far as the disturbed belt along the northern margin of the Brooks Range. The late Brookian orogenic phase deforms Albian and younger strata and is represented by structures that indicate at least three deformational episodes. The earliest episode produced gentle long-wavelength folds and north-directed thrust faults that display relatively small amounts of displacement in Albian and younger strata of the northern foothills of the Brooks Range. The Tigara uplift, exposed in the Lisburne Peninsula (Fig. 2; Payne, 1955), is an east-directed fold-thrust belt that continues northwestward under the Chukchi Sea along the Herald arch. This fold belt was regarded as Late Cretaceous or Tertiary by Grantz and others (1981), but Mull (1979, 1985) suggested that it was active in Albian (late Early Cretaceous) or older time. The youngest episode of deformation is the Romanzof uplift in the northeastern Brooks Range. This episode of deformation formed by north-directed folds and thrust faults that produced the northeastern salient of the Brooks Range and a middle Eocene unconformity that truncates deformed strata as young as early Eocene (Bird and Molenaar, 1987) in the subsurface of the Arctic Coastal Plain of Arctic National Wildlife Refuge (ANWR). Deformed Neogene and Quaternary strata also present beneath the Arctic Coastal Plain and on the adjacent Beaufort Sea continental terrace indicate that late Brookian deformation has continued into Quaternary time (Grantz and others, 1983a, 1987).

The relation between early and late Brookian structures is exposed at Ekakevik Mountain (Howard Pass quadrangle) (Figs. 1 and 4), where allochthonous Devonian to Neocomian strata of the De Long Mountains subterrane (Ipnavik River and Nuka Ridge allochthons) are unconformably overlain by gently folded conglomerate and sandstone of the Aptian(?) and Albian (upper Lower Cretaceous) Fortress Mountain Formation (Tailleur and others, 1966; Mull, 1985; Mull and others, 1987c; Mayfield and others, 1988; Molenaar and others, 1988). Brookian deformation was accompanied by regional metamorphism, as evidenced by K-Ar ages of 170 to 54 Ma, averaging 110 Ma (Turner and others, 1979), for most metamorphic rocks in the southern Brooks Range. Although the K-Ar data indicate that metamor-

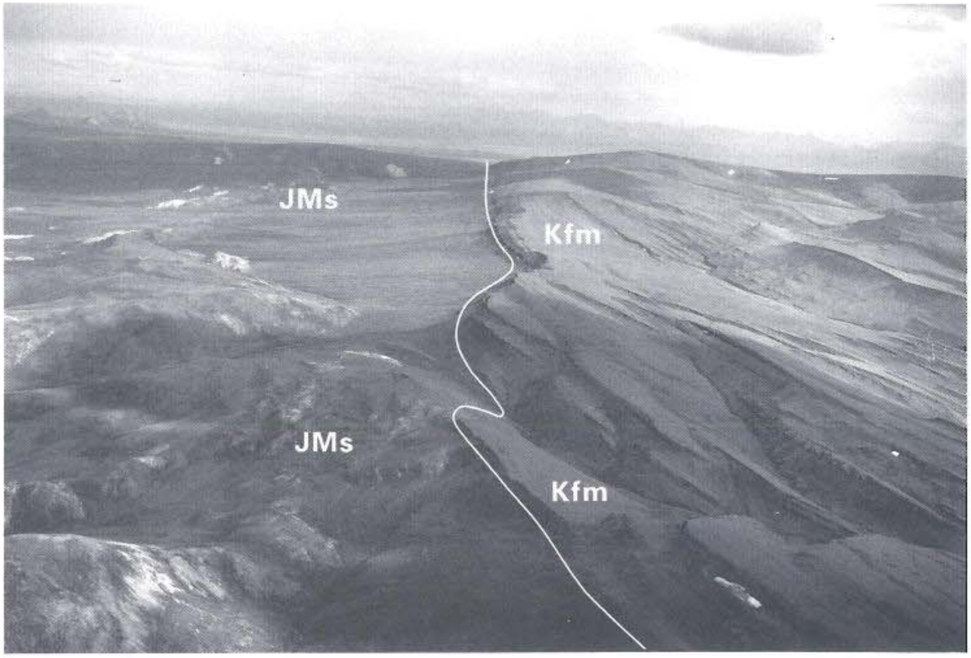

Figure 4. Eastward view of Ekakevik Mountain (Howard Pass quadrangle) depicting relation between early and late Brookian structures. Imbricate structures (early Brookian) that deform Paleozoic and Mesozoic sedimentary and diabasic rocks (JMs) of Ipnavik River and Nuka Ridge allochthons, De Long Mountains subterrane are unconformably truncated by Aptian(?) and Albian Fortress Mountain Formation (Kf), which displays gentle folds (late Brookian).

phism accompanied both Brookian orogenic phases, the data point out that regional uplift occurred mainly during the late Brookian phase.

STRATIGRAPHY OF THE ARCTIC ALASKA TERRANE

The description of the stratigraphy of the Arctic Alaska terrane is organized below by its six subterranes (North Slope, Endicott Mountains, De Long Mountains, Hammond, Coldfoot, and Slate Creek) so that the stratigraphy of these tectonic units can be compared easily. Of the six subterranes, the North Slope subterrane is the most widespread, the best studied, the least deformed, and represents the greatest amount of geologic time. For these reasons, and because of its major petroleum resources, the North Slope subterrane is the benchmark to which the others have been compared. The stratigraphic description of the Arctic Alaska terrane begins below with description of the North Slope subterrane and moves progressively southward, first to the sedimentary Endicott Mountains and De Long Mountains subterranes, which are exposed mainly in the northern Brooks Range, and finally to the metamorphic Hammond, Coldfoot, and Slate Creek subterranes, which are exposed in the southern Brooks Range.

North Slope subterrane

The North Slope subterrane, the northernmost and largest of the six subterranes that compose the Arctic Alaska terrane, is divided by structural features into four parts. The North Slope subsurface west of long 147°W consists of a relatively undisturbed post-Devonian succession with a laterally continuous, coherent stratigraphy that provides a detailed record of the depositional history of the subterrane. Information about these rocks comes primarily from wells tied to seismic-reflection records (Bird, 1982, 1988a; Bruynzeel and others, 1982; Grantz and May, 1983; Kirschner and others, 1983). To the east, the northeastern salient of the Brooks Range and adjacent North Slope expose a west-plunging cross-sectional view of the eastern Colville basin and its underlying geology that are complicated somewhat by Late Cretaceous and Cenozoic deformation. This region is important because it contains exposures of most of the units recognized in the subsurface of the North Slope. Stratigraphic information from the southern and southwestern parts of the subterrane comes from outcrop studies in the Mt. Doonerak fenster in the central Brooks Range and from the Lisburne Peninsula. The Mt. Doonerak fenster is an elongate, east-northeast–trending structural culmination, about 110 km long and 20 km wide, that lies in the central Brooks Range along the southern margin of the Endicott Mountains subterrane. The fenster is an antiform that exposes the North Slope subterrane beneath the Endicott Mountains and Hammond subterranes. The Lisburne Peninsula is a physiographic uplift and structural culmination separate from the Brooks Range, exposing a thrusted succession of strata that differs in some aspects from the North Slope subsurface. Because of these differences, Jones and others (1987) included rocks of the Lisburne Peninsula with the De Long Mountains subterrane, whereas Blome and others (1988) and Mayfield and others

(1988) have included them with the Endicott Mountains subterrane. However, an affinity of the Lisburne Peninsula succession to the North Slope subterrane is indicated by (1) the position of the region north of the northern limit of allochthonous strata in the disturbed belt of the Brooks Range, (2) the lithology of its Mississippian and older rocks, and (3) the presence of a prominent sub-Mississippian unconformity. We therefore include a description of the rocks of this region in our discussion of the North Slope subterrane.

The North Slope subterrane consists of a great thickness and variety of sedimentary rocks with a minor amount of igneous rocks (Fig. 5). Lerand (1973) grouped Phanerozoic rocks of the lands bordering the Beaufort Sea into three sequences on the basis of source area: the Franklinian sequence (northern source, Upper Cambrian through Devonian), Ellesmerian sequence (northern source, Mississippian to Lower Cretaceous), and Brookian sequence (southern source, Upper Jurassic or Lower Cretaceous to Holocene). Although drawn largely from his work in northern Canada, Lerand's scheme has provided a simplification of the complex stratigraphic nomenclature for rocks of the North Slope subterrane and is in widespread use. However, recent work has shown that the Franklinian is not a single, genetically related sequence of rocks because it includes rocks considerably older (that is, Proterozoic) and more diverse than originally defined, and the term is no longer used in Canada. Rocks assigned to the Franklinian sequence are therefore discussed under the heading pre-Mississippian rocks. This nomenclature reflects the truncation of most older rocks of the North Slope subterrane by the sub-Mississippian unconformity, which is the most distinctive feature of the subterrane. We also divide Lerand's Ellesmerian sequence into a lower carbonate and clastic succession, the lower Ellesmerian sequence, and an upper shale-rich succession, the upper Ellesmerian sequence, following the lead of other workers (Hubbard and others, 1987; Grantz and others, 1990a). The lower Ellesmerian sequence records deposition on a continental shelf that persisted from Mississippian to Triassic time. The upper Ellesmerian sequence reflects continued deposition on the continental shelf from the Jurassic through the Early Cretaceous and in addition documents the influence of rifting prior to the opening of the Canada basin.

Pre-Mississippian rocks. Pre-Mississippian rocks are known from various parts of the North Slope subterrane but for the most part have been mapped and studied only at the reconnaissance level. Some workers have inferred a regional stratigraphy for these rocks (Dutro, 1981), but existing descriptions and interpretations indicate that these rocks vary widely in age and record a number of depositional and tectonic environments. Because of the apparent absence of through-going stratigraphy and the common presence of faults bounding mapped units of pre-Mississippian rocks, we describe these rocks below by geographical area within the North Slope subterrane.

North Slope subsurface. Although pre-Mississippian rocks are buried to depths exceeding 10 km (Fig. 6), they have been penetrated by many wells along the Barrow arch. The well data show that these rocks consist mostly of steeply dipping and slightly metamorphosed, thin-bedded argillite, siltstone, and fine-grained quartzose sandstone. The argillite is locally interbedded with graywacke, limestone, dolomite, and chert, and has been dated as Early Silurian by graptolites and as Middle and Late Ordovician and Silurian by chitinozoans (Carter and Laufeld, 1975). More than 100 m of chert-pebble conglomerate and sandstone interstratified with siltstone, carbonaceous shale, and claystone was also found in the U.S. Navy Topagoruk #1 test well (Collins, 1958). Middle (or perhaps Early) Devonian plant fossils have been recovered from this nonmarine succession. Like the argillite, these rocks are truncated in angular unconformity by flat-lying Mississippian to Permian(?) strata of the lower Ellesmerian sequence, but they appear to be less metamorphosed and deformed than the argillite. This lack of significant deformation suggests that the Devonian clastic rocks in the Topagoruk well may have been deposited after the main phase of deformation of the older argillitic rocks but were tilted or folded prior to deposition of the overlying Mississippian rocks.

Northeastern salient of the Brooks Range. Pre-Mississippian rocks are widely exposed in the northeastern Brooks Range and have been divided into several assemblages or terranes (Dutro and others, 1972; Moore and others, 1985a). The best studied of these assemblages is a depositional succession of Proterozoic to Devonian carbonate strata exposed in the Shublik and Sadlerochit mountains (Fig. 1). These rocks structurally, and probably stratigraphically, overlie several hundred meters of quartzite, argillite, and tholeiitic basalt of probable continental affinity (Moore, 1987a). The Katakturuk Dolomite (Proterozoic), about 2400 m thick, forms the lowest part of the carbonate sequence and is overlain at a low-angle unconformity by the 1100-m-thick Nanook Limestone (Late Proterozoic?, Cambrian, and Ordovician) (Dutro, 1970; Blodgett and others, 1986, 1988, 1991; Robinson and others, 1989) and the 72-m-thick Mount Copleston Limestone (Lower Devonian) (Blodgett and others, 1991). Fossils in the upper 500 m of the Nanook are Cambrian and Ordovician; these ages imply that perhaps the lower part of the Nanook and presumably all of the Katakturuk are Proterozoic (R. B. Blodgett, 1991, oral commun.). A disconformity or very low angle unconformity separates Middle and/or Upper Ordovician limestone of the Nanook from Lower Devonian (Emsian) strata of the Mount Copleston Limestone.

The Katakturuk Dolomite grades upward from rocks of basin-plain to those of carbonate-platform depositional environments (Clough and others, 1988). The Nanook likewise grades upward from deep-marine carbonate turbidites at its base to shallow subtidal to intertidal deposits at its top. The Mount Copleston Limestone consists entirely of subtidal and intertidal carbonate rocks deposited on a partially restricted shallow-water carbonate platform (Clough and others, 1988; Blodgett and others, 1991).

In contrast to the carbonate succession of the Sadlerochit and Shublik mountains, the pre-Mississippian rocks of the nearby Romanzof Mountains are thick, lithologically diverse, and structurally complicated. The Neruokpuk Quartzite (Leffingwell,

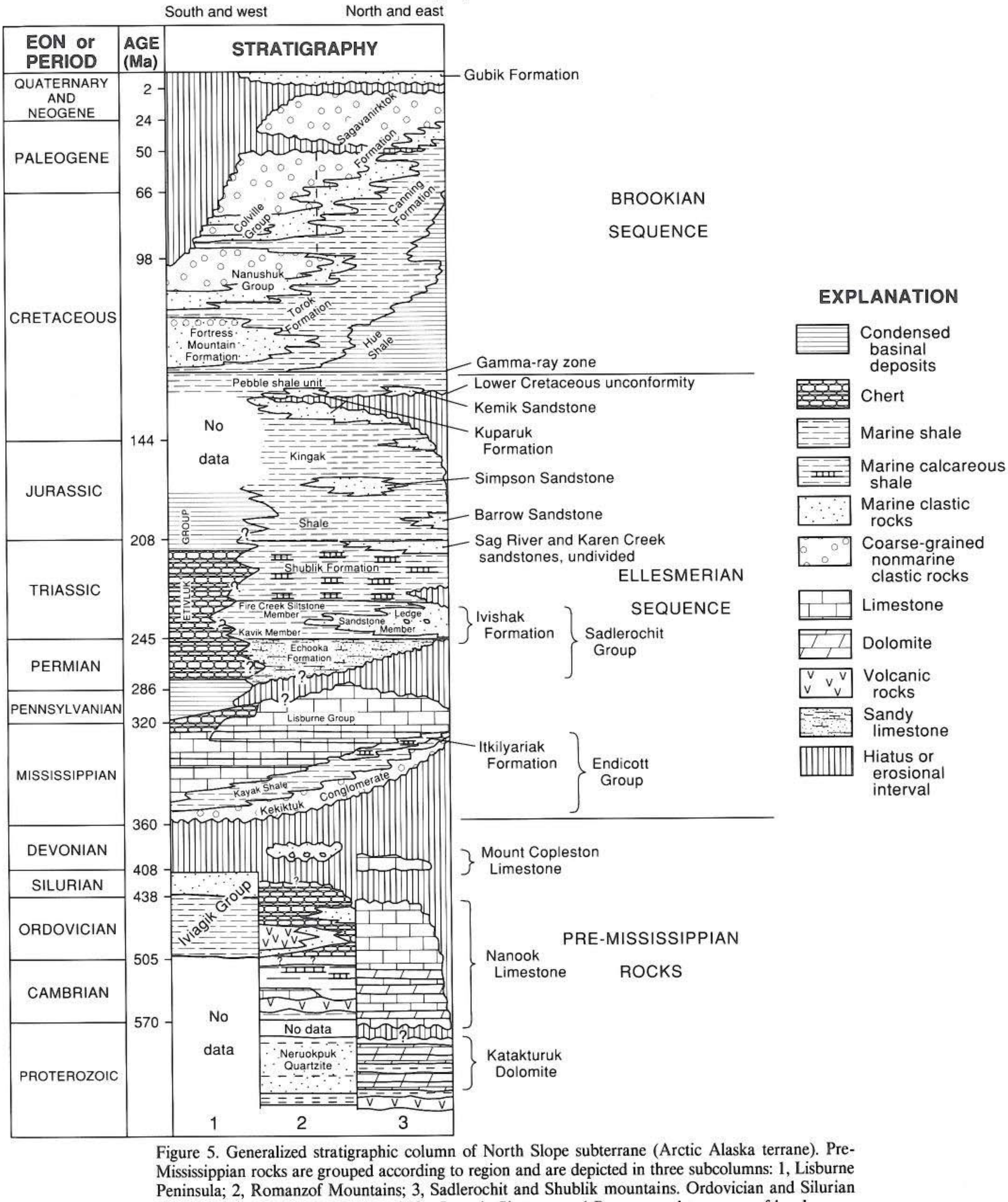

Figure 5. Generalized stratigraphic column of North Slope subterrane (Arctic Alaska terrane). Pre-Mississippian rocks are grouped according to region and are depicted in three subcolumns: 1, Lisburne Peninsula; 2, Romanzof Mountains; 3, Sadlerochit and Shublik mountains. Ordovician and Silurian Iviagik Group is that of Martin (1970). Jurassic Simpson and Barrow sandstones are of local usage. Brookian sequence depicts North Slope units only; less well known Brookian rocks in Lisburne Peninsula and northeastern Brooks Range are not shown. Absolute time scale (Palmer, 1983) is variable.

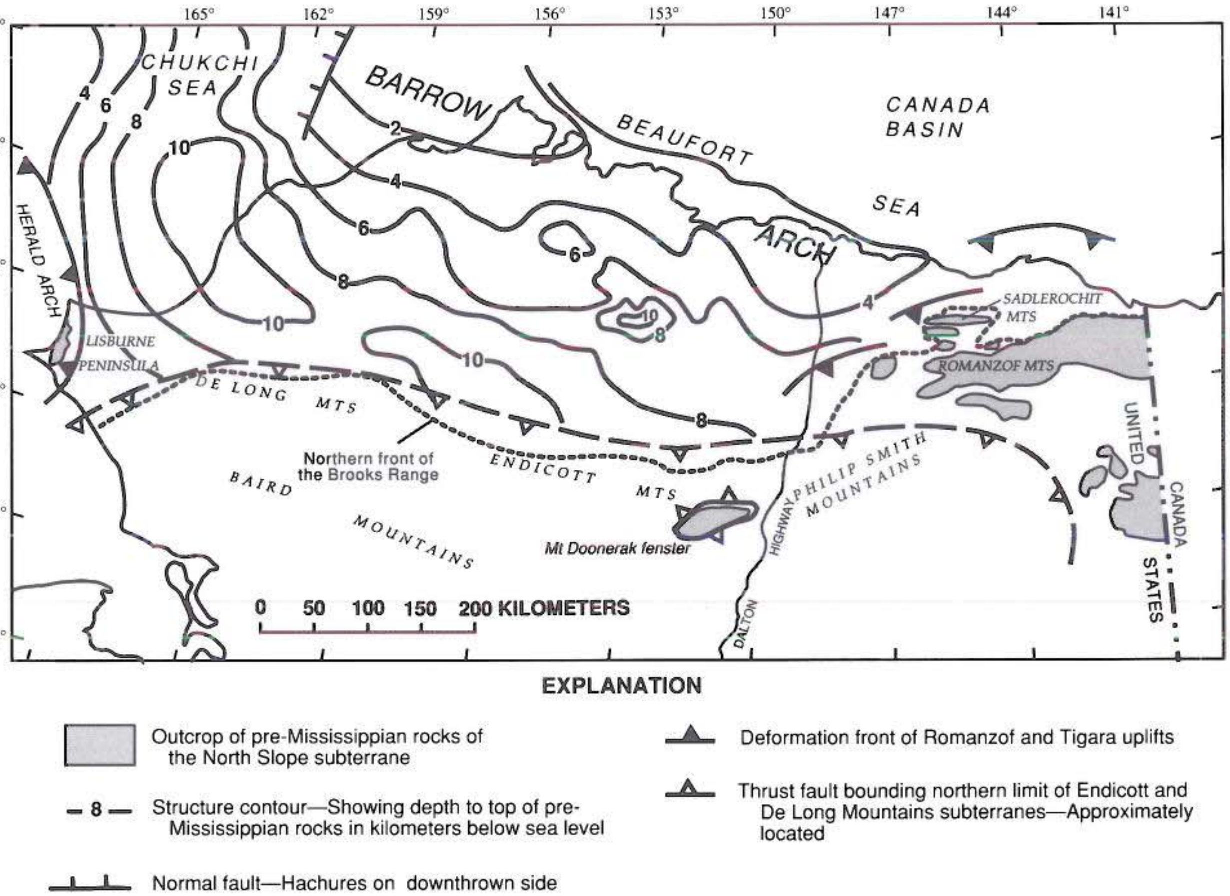

Figure 6. Distribution of pre-Mississippian rocks in outcrop and depth to pre-Mississippian rocks below sea level in North Slope subsurface and adjacent parts of Beaufort and Chukchi seas. Contours based on seismic (Gutman and others, 1982; Hubbard and others, 1987) and well data (Bird, 1982).

1919; Reiser and others, 1978, 1980) consists of metamorphosed quartzite turbidites, pebble conglomerate, phyllite, and quartzitic semischist, all of probable Proterozoic age and continental derivation. Other prominent lithologic packages of possible miogeoclinal affinity include recrystallized pelletoidal limestone and interbedded phyllite, quartzite, calcareous sandstone, and limestone of unknown age. South of these rocks lies an oceanic assemblage consisting of structurally incoherent mafic volcanic rocks, graywacke, radiolarian chert, and argillite that may structurally overlie the miogeoclinal strata. Trilobites of Cambrian age and North American affinity (Dutro and others, 1972; A. R. Palmer, 1988, oral commun.) are associated with the volcanic rocks in the oceanic assemblage, and chert of the assemblage contains Ordovician graptolites (Moore and Churkin, 1984). The oceanic assemblage is truncated by an angular unconformity, which is overlain by Middle Devonian chert arenite. The unconformity and overlying Devonian sandstone are in turn truncated at a low angle by the regional angular unconformity beneath the Mississippian rocks of the lower Ellesmerian sequence (Reiser and others, 1980; Dutro, 1981). Anderson and Wallace (1990) suggested that most deformation in this area occurred during pre–Middle Devonian time, but minor deformation may have continued into Late Devonian time. Stratigraphic relations and composition of the Devonian rocks are analogous to Devonian rocks of the Topagoruk well; the similarity suggests that pre–Middle Devonian deformation and subsequent local deposition of chert-rich clastic strata may have taken place over a wide area.

Mt. Doonerak fenster. Pre-Mississippian rocks in the Mt. Doonerak fenster consist of a structurally higher metasedimentary assemblage and a structurally lower metavolcanic assemblage. The metasedimentary assemblage consists of structurally disrupted dark argillite, phyllite, and slate with silty quartzitic laminae, black siliceous siltstone (metachert?), and lenticular limestone bodies. Middle Cambrian trilobites of Siberian affinity have been recovered from the limestone bodies (Dutro and others, 1984), and other fine-grained strata of the metasedimentary assemblage have yielded Ordovician and Early Silurian graptolites and conodonts (Repetski and others, 1987). The metavolcanic assemblage forms a series of thrust packages more than 2 km thick, consisting of pillow basalt and fragmental volcanic rocks of island-arc affinity (Moore, 1987a; Julian, 1989). Potassium-argon dating of the metavolcanic rocks indicates ages of about 470 Ma (Ordovician), although dikes intruding the assemblage yield ages of about 380 Ma (Devonian) (Dutro and others, 1976).

Lisburne Peninsula. Moderately deformed units of pre-Mississippian argillite and overlying lithic turbidites that are exposed along the western side of the Lisburne Hills were assigned to the Iviagik Group by Martin (1970). The argillite unit consists of more than 100 m of weakly metamorphosed siliceous shale and minor chert. The turbidite unit is at least several hundred meters thick and consists largely of thick-bedded, medium-grained graywacke and pebbly sandstone. A Middle Ordovician graptolite fauna has been recovered from both the argillite and turbidite units, although intercalated shale in the turbidite sequence has also yielded late Early Silurian (late Llandoverian) conodonts (A. G. Harris, 1982, written commun. to I. L. Tailleur; Grantz and others, 1983b).

Granitic rocks. A few scattered plutons intrude the pre-Mississippian rocks of the North Slope subterrane (Figs. 2 and 3). These plutons are generally elliptical in outline, range from 1 to 80 km in diameter, and consist largely of biotite granite and quartz monzonite. Porphyritic textures are common, and microcline megacrysts are reported from some plutons (Sable, 1977; Barker, 1982). Hornblende is abundant only in the small quartz monzonite stock at the headwaters of the Hulahula River in the Demarcation Point quadrangle, but it is also present in the Okpilak batholith. Dillon and others (1987b) reported a peraluminous composition for the Okpilak batholith (Demarcation Point and Mt. Michelson quadrangles) and a metaluminous composition for the nearby Jago stock (Demarcation Point quadrangle). Uranium, tin, and associated base metals are reported from the Old Crow (Coleen quadrangle) and Okpilak batholiths (Sable, 1977; Barker, 1982).

Isotopic ages for the plutons are sparse, but the available ages generally indicate crystallization in the Devonian. Devonian K-Ar, Pb-alpha, and U-Pb ages have been determined for the Okpilak batholith and nearby Jago stock. Granite found in the U.S. Navy East Teshekpuk #1 test well (Fig. 7) and the Old Crow batholith have yielded Mississippian K-Ar ages, which have been interpreted as minimum ages by Bird and others (1978) and Barker (1982). Mississippian strata rest nonconformably on both the Okpilak and Teshekpuk bodies and on hornfels associated with the Old Crow batholith (W. P. Brosgé, 1989, oral commun.), indicating a pre-Mississippian crystallization age for these plutons. In contrast, the small pluton in the headwaters of the Jago River, 15 km south of the Okpilak batholith, has yielded a Silurian K-Ar age. The distinct mineralogy and apparent age may indicate an earlier period of granitic intrusion (Silurian) than that of the other plutons in the North Slope subterrane.

Lower Ellesmerian sequence. The lower Ellesmerian sequence consists of marine carbonate rocks and quartz- and chert-rich marine and nonmarine clastic rocks that rest unconformably on pre-Mississippian rocks throughout the North Slope subterrane. Representing about 150 m.y. (Mississippian through Triassic) of sedimentation (Fig. 5), the sequence contains the most productive reservoirs of the Prudhoe Bay oil field. The lower Ellesmerian sequence averages 1–2 km thick but in local basins may exceed 5 km in thickness. It extends along the entire east-west length of the North Slope (Figs. 7, 8, and 9) but thins and fines southward beneath the foothills of the Brooks Range (Bird, 1985; Kirschner and Rycerski, 1988). The sequence also thins northward, because of onlap onto pre-Mississippian rocks, truncation by unconformities within the succession, and erosion in the Early Cretaceous along the Barrow arch. The extent of the lower Ellesmerian sequence, coupled with northward coarsening, erosional onlap, and progression to more shallow-marine and nonmarine facies, suggests that deposition occurred in shelf and platform environments along a slowly subsiding, south-facing continental margin (Bird and Molenaar, 1987). Three transgressive-regressive cycles are represented by this sequence: Mississippian to Early Permian, Early Permian to Early Triassic, and Early to Late Triassic. The lower and middle cycles are separated by a regional unconformity, whereas the middle and upper cycles are separated by a local basin-margin unconformity.

Endicott and Lisburne groups (Mississippian to Early Permian cycle). The first transgressive-regressive cycle is composed of nonmarine and shallow-marine clastic rocks of the Endicott Group (Upper Devonian to Permian?) (principally the Kekiktuk Conglomerate and Kayak Shale) and the overlying marine carbonate rocks of the Lisburne Group (Mississippian to Permian) (Figs. 5 and 9). These units generally become progressively younger to the north and northwest, and undivided rocks of the Lisburne Group and possibly Endicott Group are as young as Early Permian in the northern National Petroleum Reserve in Alaska (NPRA) (Bird, 1988a, 1988b). Together the Endicott and Lisburne groups compose a genetically related sequence that is bounded at the top and base by regional unconformities. A depositional model proposed by Armstrong and Bird (1976) suggests that nonmarine and nearshore-marine clastic sediments (Endicott Group) were deposited adjacent to, and north of, carbonate sediments (Lisburne Group) on a broad shallow-marine platform.

The Kekiktuk Conglomerate (Lower Mississippian) is a discontinuous, largely nonmarine unit that characteristically rests in angular unconformity on older rocks (Mull, 1982, p. 27). It is typically less than 500 m thick in the Prudhoe Bay area, less than 100 m thick in the northeastern Brooks Range, and only about 40 m thick in the Mt. Doonerak fenster. The Kekiktuk Conglomerate was defined by Brosgé and others (1962) in the Mt. Michelson quadrangle and consists of well-sorted, cross-bedded sandstone with lenses of conglomerate and interbeds of carbonaceous shale and coal. Conglomerate in the unit consists of various proportions of subangular to subrounded chert and quartz clasts and a small to locally large percentage of quartzite and argillite clasts (Brosgé and others, 1962; Nilsen and others, 1981). Maximum clast size, which is greater than 22 cm in the northeastern Brooks Range, decreases toward the west and south (Nilsen and others, 1981). In the Mt. Doonerak fenster, the unit is no younger than late Early Mississippian (Osagean) (Armstrong and others, 1976), whereas in the subsurface of the North Slope along the

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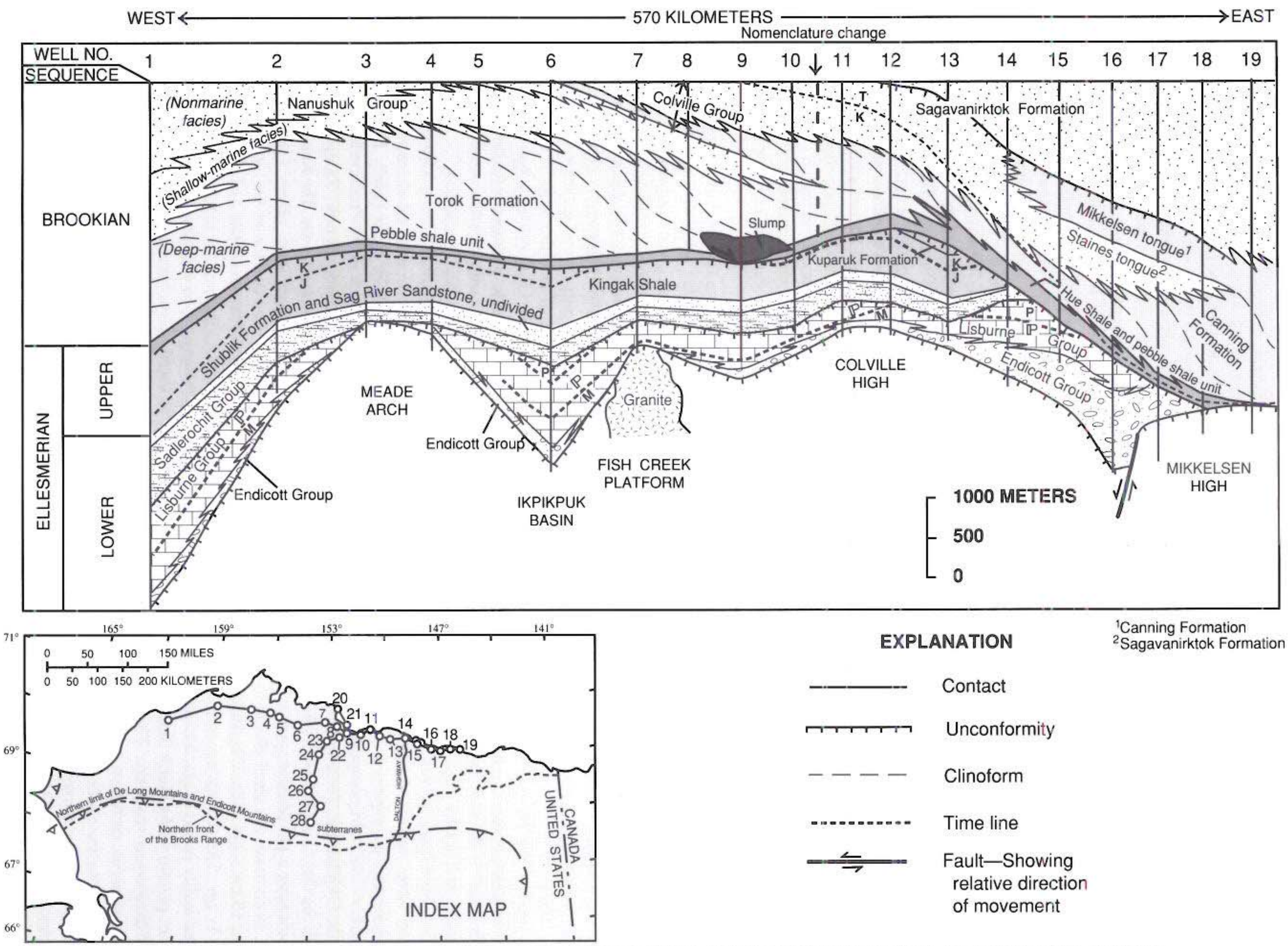


Figure 7. East-west stratigraphic cross section of North Slope subterrane (Arctic Alaska terrane) beneath northern Arctic Coastal Plain, illustrating major subsurface post-Devonian rock units of region and selected period boundaries (modified from Molenaar and others, 1986). Datum is mean sea level. Index map shows location of wells used to construct section: 1, Tunalik-1; 2, Kugrua-1; 3, South Meade-1; 4, Topagoruk-1; 5, East Topagoruk-1; 6, Ikpikpuk-1; 7, East Teshekpuk-1; 8, North Kalikpik-1; 9, South Harrison Bay-1; 10, Nechelik-1; 11, Colville Delta-1; 12, Kalubik Creek-1; 13, West Sak River-1; 14, Prudhoe Bay State-1; 15, Foggy Island Bay-1; 16, West Mikkelsen Bay State-1; 17, East Mikkelsen Bay State-1; 18, Point Thomson Unit-2; 19, Alaska State A-1.

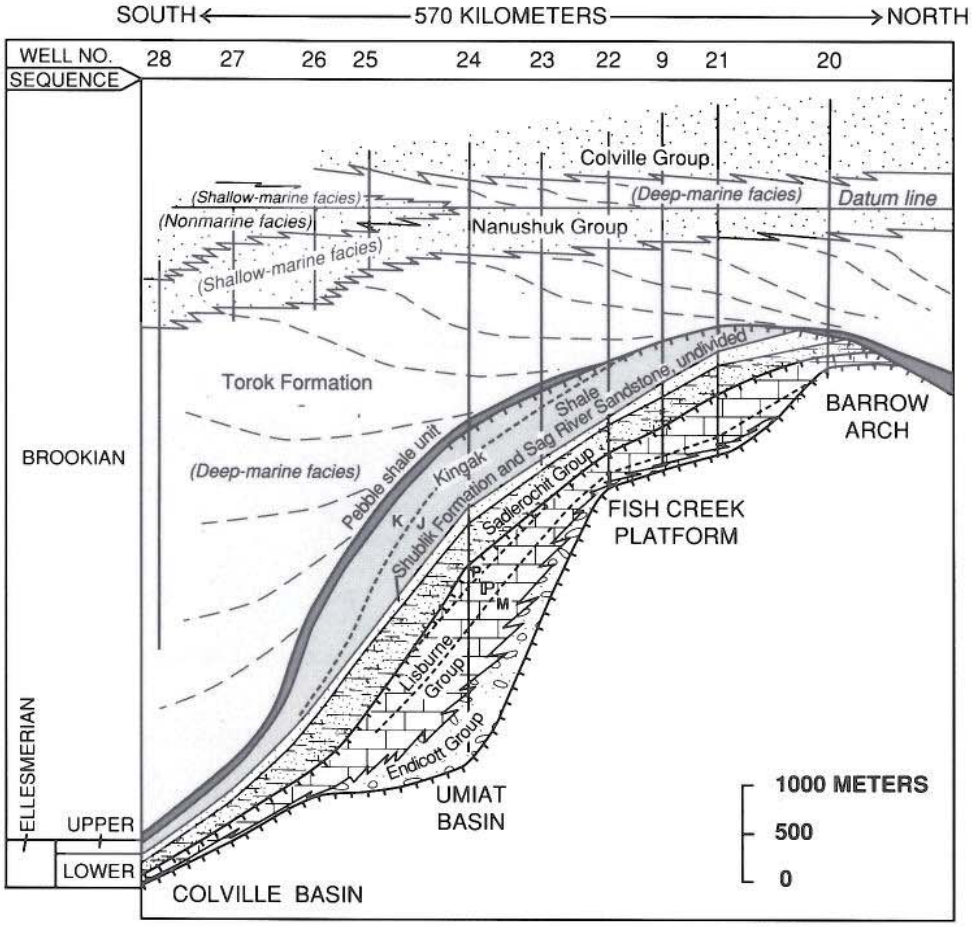


Figure 8. North-south stratigraphic cross section of North Slope subterrane (Arctic Alaska terrane) from Colville basin to Barrow arch, illustrating major subsurface post-Devonian rock units of region and selected period boundaries (modified from Molenaar and others, 1986). Datum is transgressive surface near or at top of Nanushuk Group. Numbers indicate wells used to construct diagram: 20, W.T. Foran-1; 21, Atigaru Point-1; 9, South Harrison Bay-1; 22, West Fish Creek-1; 23, North Inigok-1; 24, Inigok-1; 25, Square Lake-1; 26, Wolf Creek-3; 27, Little Twist-1; 28, East Kurupa-1. For location of wells and explanation of symbols, see Figure 7.

Barrow arch, the Kekiktuk may be as young as Late Mississippian (Meramecian), according to Woidneck and others (1987).

Seismic reflection lines show several basin-fill successions in the subsurface of the North Slope that lie conformably beneath Carboniferous strata of the Endicott Group (for example, the Umiat and Meade basins) (Fig. 9). These basins are as much as 4 km thick and postdate development of the regional middle Paleozoic unconformity. Although the basin-fill successions are not exposed and only their upper parts have been penetrated by deep wells, the basins are inferred to contain Lower Mississippian sedimentary rocks that are commonly assigned to the Kekiktuk Conglomerate and/or undivided Endicott Group (for example, Bird, 1985; Kirschner and Rycerski, 1988). Oldow and others (1987d) and Grantz and others (1990a), however, related the sedimentary fill of these basins to Devonian clastic rocks in the Topagoruk well and distinguished these two basin-fill successions from those of the thinner and more widespread strata of the Kekiktuk Conglomerate. The morphology of the basin-fill successions suggests deposition within a system of half grabens that developed during a period of regional extension (Oldow and others, 1987d; Kirschner and Rycerski, 1988; Grantz and others, 1990a).

The Kekiktuk Conglomerate and related coarse-grained clastic rocks are overlain gradationally by less than 400 m of gray to black, carbonaceous marine shale of the Kayak Shale (Mississippian), which was defined in the Endicott Mountains subterrane by Bowsher and Dutro (1957). The Kayak commonly contains various amounts of interbedded sandstone near its base and increasing amounts of fossiliferous, argillaceous limestone toward its top. Fossils from the unit indicate deposition in the Mississippian (Osagean and Meramecian?) in the Mt. Doonerak fenster (Armstrong and Mamet, 1978) and suggest deposition in the Late Mississippian (Meramecian) in the northeastern Brooks Range and North Slope subsurface (Armstrong and Bird, 1976). The Kayak interfingers laterally (northward) and vertically in the

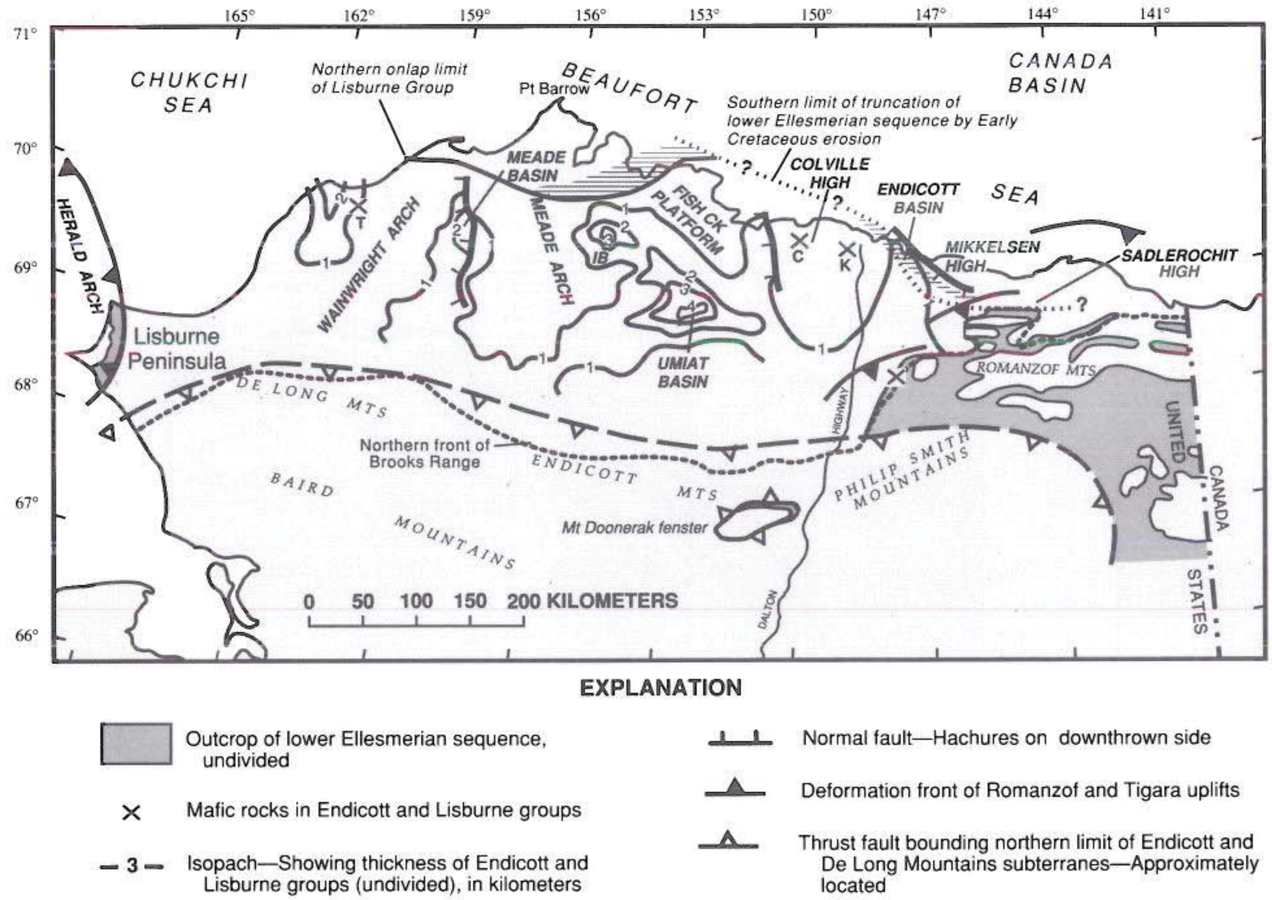


Figure 9. Summary of important structural and stratigraphic features of lower Ellesmerian sequence, North Slope subterrane (Arctic Alaska terrane), including isopachs of undivided Endicott and Lisburne groups (Gutman and others, 1982). Unusual thicknesses of clastic and carbonate rocks assigned to Endicott and Lisburne groups filled basins that developed as sags and half grabens in Mississippian or possibly Devonian time (see Figs. 7 and 8). Basin-bounding normal faults shown are generally overlapped by Lisburne Group or younger strata. Unconformity at top of Lisburne Group cut down into Endicott Group in a narrow band southeast of Point Barrow and between Mikkelsen and Colville highs (horizontal-line pattern). C, Colville State-1 well; IB, Ikpikpuk basin; K, Kuparuk State-1 well; T, Tunalik-1 well.

North Slope subsurface with the Itkilyariak Formation, a distinctive sequence of Upper Mississippian red, gray, and green shale, limestone, and sandstone (Mull and Mangus, 1972). The Kayak is a northward-transgressive unit and was deposited in brackish-water and shallow-marine environments, whereas the Itkilyariak Formation was deposited on an arid coastal plain that was flooded peridically by the sea (Bird and Jordan, 1977).

The Lisburne Group is present throughout most of the North Slope subterrane, where it consists of limestone and dolomite and various amounts of shale, sandstone, and nodular replacement chert. Its thickness is variable, averaging about 600 m and locally exceeding 1200 m, and it is thickest in basins established during deposition of the Endicott Group (Fig. 9). In most of the North Slope subterrane, the Lisburne Group consists of the Alapah Limestone (Upper Mississippian) and the Wahoo Limestone (Upper Mississippian to Middle Pennsylvanian), which was defined by Brosgé and others (1962) in the Mount Michelson quadrangle and is present only in the North Slope subterrane. The underlying Wachsmuth Limestone (Lower and Upper Mississippian) is present locally in the northeastern Brooks Range (Armstrong and Mamet, 1978). The Lisburne Group is young as Early Permian in the subsurface of the NPRA, but the Permian rocks have not yet been assigned to formations (Bird, 1988a). On the Lisburne Peninsula, for which Schrader (1902, 1904) named the group, the Lisburne consists, in ascending order, of the Nasorak Formation (Upper Mississippian), Kogruk Formation (Upper Mississippian and Lower Pennsylvanian), and Tupik Formation (Upper Mississippian and Lower Pennsylvanian?) (Campbell, 1967; Armstrong and others, 1971; Dutro, 1987; Bird, 1988a). Units of the Lisburne Group are lithologically similar, commonly having been distinguished only by age, and are difficult to map; therefore, most workers have treated the

Lisburne Group as an undifferentiated unit. Three environmental assemblages, however, are recognized within the Lisburne Group: a transgressive assemblage, a platform assemblage, and a deeper water assemblage (Armstrong, 1974; Armstrong and Bird, 1976) (Fig. 10).

The transgressive assemblage, represented primarily by the Nasorak Formation, the Wachsmuth Limestone, and the lower part of the Alapah Limestone in the North Slope subterrane, rests conformably on the Kayak Shale. This assemblage consists of spiculitic, argillaceous lime mudstone and overlying spiculitic, pelletoid crinoid-bryozoan wackestone and packstone. Dolomite, replacement chert, and shale are locally interbedded with the limestone. Upward in the assemblage, the carbonate rocks become slightly coarser grained, and the argillite content decreases, although grainstone is relatively uncommon, and well-developed oolite has not been observed. The presence of bryozoans, echinoderms, corals, brachiopods, foraminifers, and algae indicates open-marine conditions. Although this assemblage records many oscillations and, undoubtedly, hiatuses, it represents mainly open-marine carbonate environments and upward in the assemblage, the development of a carbonate platform.

The platform assemblage, which comprises the Kogruk Formation, the Wahoo Limestone, and the upper part of the Alapah Limestone in the North Slope subterrane, covers a full spectrum of carbonate lithologies from lime mudstone to grainstone. Color of the assemblage changes from gray and green in the south to red and gray in the north, near the paleoshoreline. Clastic content is also variable and increases north of the Brooks Range. The depositional model for the platform assemblage (Armstrong, 1974) is similar to those for most Phanerozoic carbonate platforms, except for a lack of reef-building organisms. Outcrop studies by Armstrong (1972) and Wood and Armstrong (1975) in the northeastern Brooks Range show that the platform assemblage is composed of many incomplete depositional cycles that indicate relatively rapid sea-level rises, protracted periods of stability, and prograding carbonate offlap. A complete cycle of carbonate deposition in the platform assemblage consists of crinoid-bryozoan packstone and wackestone overlain gradationally by ooid or crinoid packstone and grainstone that, in turn, is capped by packstone, wackestone, mudstone, and microdolomite. This succession represents progressive shallowing from open-marine through carbonate shoal, restricted platform, intertidal, and supratidal environments. Presence of algal mats, mud chips and cracks, and gypsum and anhydrite cements and replacements in beds deposited in the intertidal and supratidal environments suggests an arid climate.

In the North Slope subterrane, the deeper water assemblage is restricted to the Lisburne Peninsula, where it forms the uppermost part of the Lisburne Group (Tupik Formation). This third environmental assemblage consists of subequal amounts of dark, thin-bedded limestone, dolomite, chert, and siliceous shale, and contains relatively abundant sponge spicules, radiolarians, cephalopods, and phosphatic intervals. Limestone beds, commonly graded and laminated, consist of lime mudstone and carbonate turbidite. Chert in the assemblage is typically stratified, lenticular, and nodular, but locally crosscuts bedding, which indicates a replacement origin. The deeper water assemblage is typically thin compared to the other two environmental assemblages and represents deposition in deeper shelf, slope, and basinal environments at or near starved-basin conditions (Armstrong and Mamet, 1978).

The foraminiferal zonation of B. L. Mamet (Armstrong and others, 1970) has facilitated correlations among outcrop sections and well penetrations of the Lisburne Group (Armstrong, 1974; Armstrong and Mamet, 1977; Bird and Jordan, 1977; Bird, 1978; Witmer and others, 1981). These paleontologic correlations,

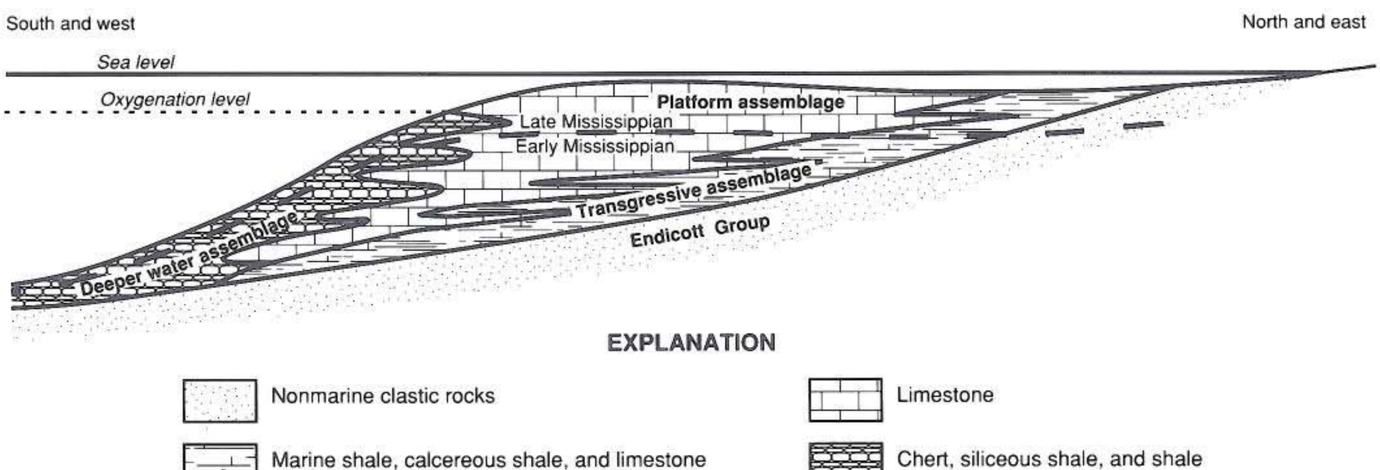


Figure 10. Depositional model for transgressive, platform, and deeper water carbonate deposits of Lisburne Group (modified from Armstrong and Bird, 1976). Distribution of facies was probably partly controlled by interplay of regional subsidence and oxygenation level in basin. Maximum thickness of carbonate strata of Lisburne Group is about 1000 m.

coupled with seismic data from the NPRA (Bruynzeel and others, 1982), show that east of the Meade arch (Fig. 9) the Lisburne Group transgressed about 100 km northward during the early Late Mississippian (Meramecian), whereas in the area of the Meade arch and the western NPRA, the Lisburne transgressed toward the northwest during Late Mississippian to Early Permian time. Gradual facies changes and wide areal distribution suggest that the sea floor upon which the Lisburne of the North Slope subterrane was deposited was a very low gradient ramp as much as 300 km wide. The areal extent of, and amount of erosion on, the regional unconformity at the top of the Lisburne are not well established and represent important unanswered questions.

Echooka Formation and lower and middle Ivishak Formation, Sadlerochit Group (Early Permian to Early Triassic cycle). Originally designated as the Sadlerochit Sandstone by Leffingwell (1919) for outcrops in the northeastern Brooks Range, the Sadlerochit is a widespread rock unit divided into two formations, the Echooka and Ivishak, and elevated to group rank by Detterman and others (1975). It is primarily a clastic, nonmarine to marine-shelf deposit of northern derivation that gradually thickens southward in the subsurface to more than 600 m (Fig. 11). The Sadlerochit overlies a regional unconformity above the Lisburne Group, which is marked by significant erosional relief but little discordance. West of long 154°W, the northern limit of the Sadlerochit is an onlap-pinchout against pre-Mississippian rocks, whereas to the east it is truncated by an Early Cretaceous unconformity.

The Echooka Formation (Permian) consists of about 100 m of calcareous mudstone, radiolarian chert, and bioclastic, glauconitic limestone of the Joe Creek Member and an overlying 100 m of quartzose sandstone and siltstone of the Ikiakpaurak Member (Detterman and others, 1975). A crudely channelized chert-pebble and chert-cobble conglomerate is present locally at the base of the formation in the Sadlerochit and Shublik mountains (Crowder, 1990). Deposits of the Echooka document the northward advance of the Sadlerochit sea across the eroded platform of

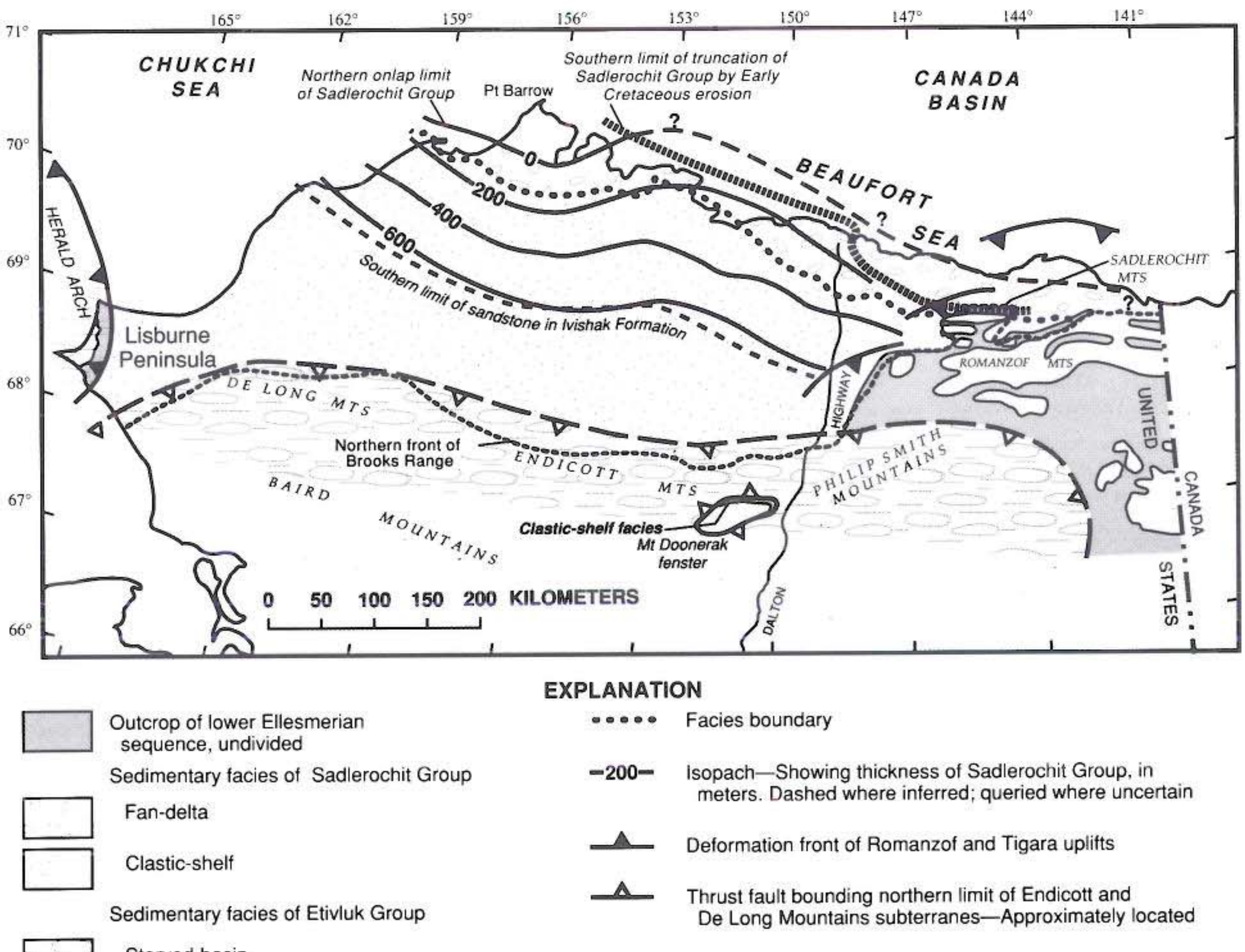


Figure 11. Isopach and facies map for Sadlerochit Group (Early Permian to Early Triassic and part of Early to Late Triassic cycles of lower Ellesmerian sequence) and facies map for part of Etivluk Group. Facies distribution is that at time of maximum regression (Early Triassic) of Ledge Sandstone Member of Ivishak Formation.

Lisburne carbonate rocks. Brachiopods indicate that the Joe Creek Member is Early and Late Permian (Sakmarian to Kazanian), and the Ikiakpaurak Member is Late Permian (Kazanian; late Guadalupian) (Detterman and others, 1975). The Echooka Formation is characterized by the trace fossil *Zoophycos.*

The Ivishak Formation (Triassic) (Keller and others, 1961; Detterman and others, 1975) consists of fine- to coarse-grained clastic rocks deposited in marine and nonmarine environments. Detterman and others (1975) divided the Ivishak into three members: in ascending order, these are the Kavik Member, the Ledge Sandstone Member, and the Fire Creek Siltstone Member. We assign the Kavik Member and Ledge Sandstone Member to the upper part of the Early Permian to Early Triassic depositional cycle, whereas the Fire Creek Member represents a younger transgressive episode and is assigned to the overlying Early to Late Triassic depositional cycle.

The Kavik Member of the Ivishak Formation (Triassic) abruptly overlies the Echooka Formation. This abrupt contact, thought to be a disconformity by Detterman and others (1975), is probably a surface of downlap by the southward-prograding Kavik Member. The Kavik consists of up to 213 m of dark-colored, laminated to thin-bedded silty shale and siltstone that thicken southward from the Barrow arch. These rocks represent prodelta deposits that grade upward into massive deltaic sandstones and conglomerates of the Ledge Sandstone Member. In outcrop, the Kavik is dated as Early Triassic (late Griesbachian, in part) by ammonites and pelecypods (Detterman and others, 1975), but the Kavik is Late Permian in the subsurface of the Prudhoe Bay area (Jones and Speers, 1976).

The Ledge Sandstone Member of the Ivishak Formation is as much as 200 m thick and consists of sandstone beds that thicken and coarsen northward, and contains thin siltstone and shale interbeds. Chert-pebble to chert-cobble conglomerate is present in its northernmost facies. Because the Ledge is the primary reservoir for the Prudhoe Bay oil field, it has been studied in considerable detail (Detterman, 1970; Eckelmann and others, 1976; Jones and Speers, 1976; Wadman and others, 1979; Jamison and others, 1980; Melvin and Knight, 1984; Lawton and others, 1987; Marinai, 1987; Payne, 1987; Atkinson and others, 1988). At Prudhoe Bay, the Ledge is a fluvial-deltaic complex, which can be divided into a lower progradational, upward-coarsening megacycle, ranging from prodelta siltstone to an alluvial-fan clast-supported conglomerate, and an upper upward-fining sandstone megacycle. Lawton and others (1987) suggested that the fluvial-deltaic facies of the Ledge was deposited on an elongate, relatively narrow coastal plain that was traversed by both braided and meandering streams. Marine sandstone of the Ledge extends southward for as far as 100 km in the subsurface (Fig. 11). A greater percentage of sandstone and conglomerate east of long 154°W suggests greater uplift in the nearby source highlands in this area than to the west.

Southward from the Barrow arch, the Sadlerochit Group becomes finer grained, more marine, and more difficult to subdivide. In the Romanzof Mountains, the Sadlerochit consists largely of a thick sequence of siliceous mudstone and locally thin bedded limestone and is overlain by dark shale and thin-bedded, ripple-marked, fine-grained sandstone that was deposited in a marine-shelf environment. In the Mt. Doonerak fenster, the Sadlerochit consists of a 55-m-thick lower unit of calcareous, very fine grained sandstone and siltstone and a 70-m-thick upper unit of black, phyllitic shale (Mull and others, 1987a). The lower unit contains the trace fossil *Zoophycos* and Early Permian (Wolfcampian) brachiopods. The sedimentary structures and fauna suggest that the Sadlerochit shelf extended southward at least as far as the Mt. Doonerak fenster.

Upper Ivishak Formation, Shublik Formation, Sag River Sandstone, and Karen Creek Sandstone (Early to Late Triassic cycle). The third transgressive-regressive cycle in the lower Ellesmerian sequence consists of the Fire Creek Siltstone Member of the upper Ivishak Formation (Sadlerochit Group), the Shublik Formation, and the Sag River and Karen Creek sandstones. The Fire Creek Siltstone Member of the Ivishak Formation is an upward-fining and northward-thinning unit composed of as much as 135 m of thin-bedded to massive, commonly laminated siltstone and argillaceous sandstone. The unit gradationally overlies the Ledge Sandstone Member and in its northernmost extent may either pinch out or be erosionally truncated by an unconformity at the base of the overlying Shublik Formation. Burrows and sparse ammonites and pelecypods indicate that the Fire Creek Siltstone Member is marine and represents a deepening of the sea and the initiation of the next transgressive-regressive cycle. Ammonites date the Fire Creek as Early Triassic (Smithian) (Detterman and others, 1975).

The Shublik Formation (Triassic) (Leffingwell, 1919; Mull and others, 1982) is a relatively thin, dark-colored, poorly exposed, heterogeneous assemblage of richly fossiliferous shale, mudstone, carbonate rocks (bioclastic limestone, dolomite, siderite), siltstone, and sandstone of Middle and Late Triassic age (Detterman and others, 1975). This unit onlaps pre-Mississippian rocks in the subsurface near Point Barrow and in outcrop just east of the international boundary bordering the northeastern Brooks Range. It rests disconformably on the Sadlerochit Group where the Fire Creek Siltstone Member of the Ivishak Formation is thin or absent, as at Prudhoe Bay and in the Sadlerochit Mountains. Along the axis of the Barrow arch and northward, the Shublik Formation is truncated by the extensive Lower Cretaceous unconformity (Fig. 12). The Shublik Formation is a blanket-like deposit that averages about 100 m thick in most areas but is nearly 200 m thick in the northeastern NPRA and in the northeastern Brooks Range, where it may have been deposited close to points of clastic-sediment influx (Bird, 1987).

The Shublik was deposited on a low-gradient, southward-sloping shelf that was inherited from the underlying Sadlerochit Group; it represents an important regional marine transgression that overstepped the northern depositional limit of the Sadlerochit Group. Parrish (1987) identified a north to south succession of facies within the Shublik that may represent regional upwelling of oceanic water from the south. The northernmost facies consists

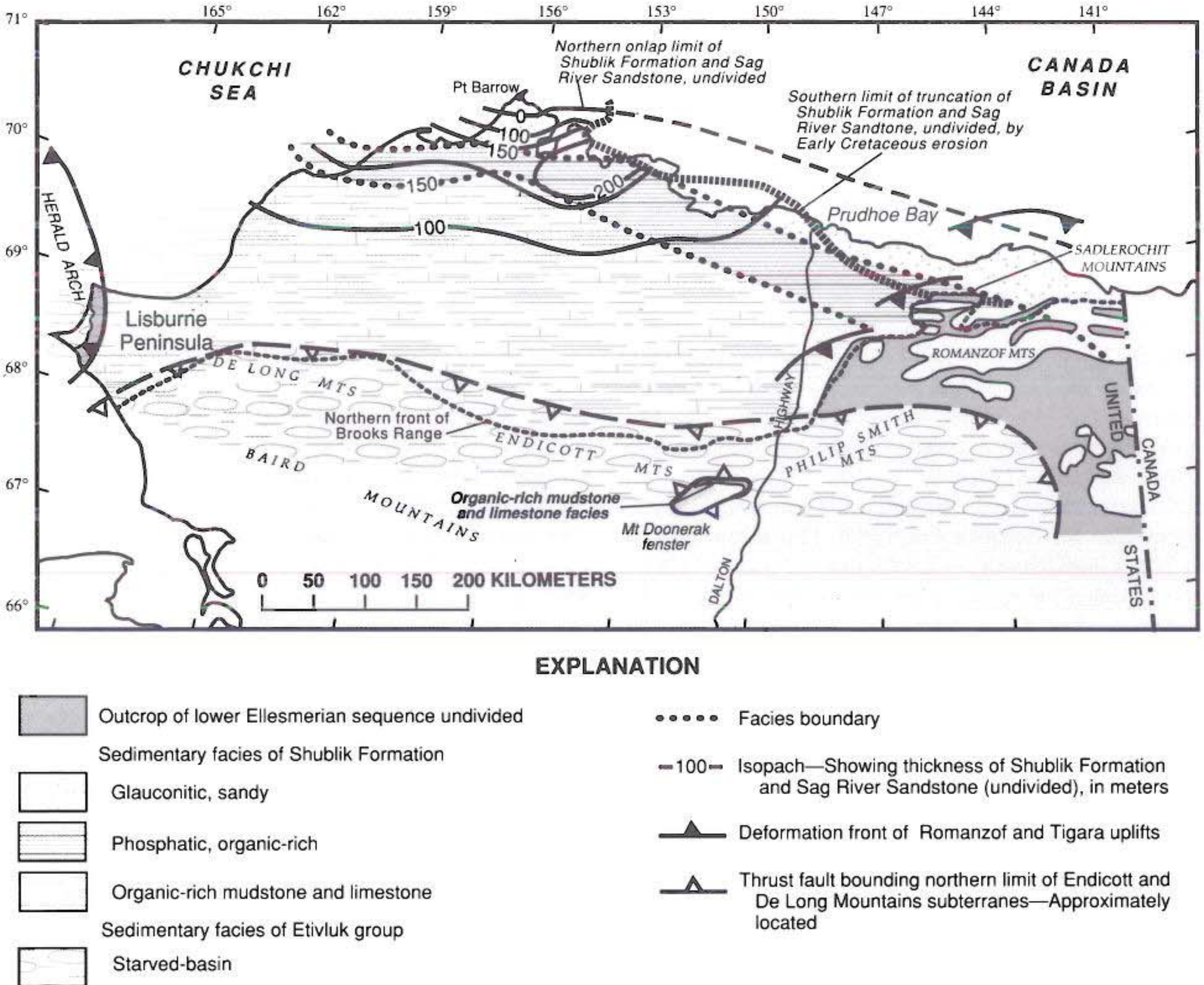


Figure 12. Isopach map for Shublik Formation and Sag River Sandstone, undivided (parts of Early to Late Triassic cycle of lower Ellesmerian sequence) and facies map for Shublik Formation (facies from Hubbard and others, 1987; Parrish, 1987), and coeval part of Etivluk Group.

of nearshore, fossiliferous sandstone and siltstone with variable amounts of glauconite. This facies grades southward into siltstone, calcareous mudstone, and limestone that contain phosphate nodules. The phosphate-bearing facies grades southward into the southernmost facies of black, organic-rich calcareous mudstone and fossiliferous limestone deposits, both of which contain abundant *Halobia* and *Monotis* bivalves. Shublik deposition was terminated by a minor regression, which deposited the overlying widespread, thin, shallow-marine sandstone sequence (Sag River and Karen Creek sandstones).

The Sag River Sandstone (Triassic) in the subsurface of the North Slope (North Slope Stratigraphic Committee, 1970) and its lithologic correlative in outcrop, the Karen Creek Sandstone (Detterman and others, 1975), are discontinuous, southward-thinning units. The maximum thickness of the Sag River Sandstone is about 100 m in the northeastern NPRA, and it thins rapidly southward (Fig. 12). The Sag River and Karen Creek sandstones comprise an intensely bioturbated succession of fine-grained to very fine grained, argillaceous, glauconitic sandstone and interbedded siltstone, and shale (Detterman and others, 1975; Barnes, 1987). Sedimentologic and stratigraphic relations of the Sag River are comparable to modern low-energy offshore-marine environments (Barnes, 1987). Late Norian bivalves from the base of the Karen Creek date the formation as Late Triassic (Detterman and others, 1975), whereas spores and pollen date the Sag River as Late Triassic to earliest Jurassic (Rhaetian to Hettangian) (Barnes, 1987). In the Prudhoe Bay area, the Sag River may become slightly older to the north, which suggests that the formation is time transgressive. Barnes (1987) interpreted this trend as evidence for Sag River deposition during culmination of a regionally significant marine regression in the North Slope that began in middle Shublik time.

Etivluk Group. Upper Paleozoic and lower Mesozoic rocks of the Lisburne Peninsula consist of 200 m of fine-grained clastic deposits and chert assigned to the Etivluk Group (Mull and others, 1982). The Etivluk of the Lisburne Peninsula is partly coeval with more proximal units of the Early Permian to Early Triassic and Early to Late Triassic cycles described above and is lithologically correlative with similar strata of the Etivluk Group in the Endicott Mountains and De Long Mountains subterranes described below. The lower part of the Etivluk succession on the Lisburne Peninsula is about 125 m thick and consists, in ascending order, of thoroughly bioturbated, gray, maroon, and green siliceous argillite, gray-green bedded chert, and argillaceous chert. The upper part is about 75 m thick and consists, in ascending order, of black siliceous shale, dark gray to black chert, thin-bedded, fossiliferous limestone, and gray chert and shale. Blome and others (1988) and Murchey and others (1988) reported that radiolarians collected from the middle part of the lower unit are Late Pennsylvanian or Early Permian, and those near the top of the lower unit are Permian; radiolarians and megafossils from the upper unit range from Middle (Ladinian) to Late (Norian) Triassic (Blome and others, 1988). The fine-grained, siliceous character of these strata, the type of faunal assemblages, and intense bioturbation indicate that the Etivluk Group rocks of the Lisburne Peninsula were deposited under starved-basin conditions in inner to outer shelf environments (Figs. 11 and 12).

Upper Ellesmerian sequence. Seismic stratigraphy shows that northern Alaska underwent a 100 m.y. interval (Jurassic to Early Cretaceous–Aptian) of extension, during which a failed rift episode in the Jurassic was followed by a successful rift episode in the Early Cretaceous (Hauterivian) (Grantz and May, 1983; Hubbard and others, 1987). This extension led to opening of the Canada basin and ultimate displacement of the Arctic Alaska terrane from the northern land mass that supplied quartz- and chert-rich sediments to the Ellesmerian sequence. The record of extension prior to opening of the Canada basin is contained in two rock sequences in northern Alaska, the Dinkum graben sequence on the Beaufort Sea shelf and the upper Ellesmerian sequence onshore.

Seismic stratigraphy of the Beaufort Sea shelf (Hubbard and others, 1987) reveals areally restricted clastic sedimentary units more than 3 km thick in the Dinkum graben and related half grabens (Fig. 13; Plate 13). These units, assumed to be coarse grained, represent rift-basin deposits (Grantz and May, 1983; Hubbard and others, 1987). Because they have been described by Grantz and others (1990a, and this volume), they are not discussed further here.

The upper Ellesmerian sequence, discussed in detail below, consists of areally extensive, fine-grained clastic strata deposited on a south-dipping shelf and slope beneath the present-day North Slope (Fig. 13) and south of the main axis of Jurassic and Early Cretaceous extension. The upper Ellesmerian sequence consists principally of the marine Kingak Shale, lower Kongakut Formation, and pebble shale unit, plus other sandstone units of local extent (Figs. 5, 7, and 8). The Kingak Shale was deposited over most of the North Slope subterrane in Jurassic and Early Cretaceous time but was uplifted along the incipient Arctic Ocean margin in the Early Cretaceous (Valanginian and Hauterivian) as part of a northwesterly elongate landmass about 250 km wide (Fig. 14). Later, the landmass was eroded to a surface of low relief and transgressed by the sea, resulting in deposition across a regional unconformity in later Neocomian time of a thin sequence of scattered sand bodies (upper part of Kuparuk Formation and Kemik Sandstone) and the blanket-like pebble shale unit. The regional unconformity, commonly referred to as the Lower Cretaceous unconformity, is restricted to the Barrow arch region, where it played an important role in the development of porosity and sealing of the North Slope petroleum reservoirs (Bird, 1987). To the south, the pebble shale and local sandstone units lie conformably on basinal, slope, and shelf deposits of the Kingak Shale. The upper Ellesmerian sequence totals more than 1.2 km thick in the NPRA but depositionally thins southward to less than half that thickness and thins northward because of erosional truncation in the Early Cretaceous (Fig. 13).

Kingak Shale. The Kingak Shale (Jurassic and Lower Cretaceous) consists predominantly of dark gray to black, micromicaceous, noncalcareous, pyritic shale and siltstone as thick as 1200 m (Detterman and others, 1975; Molenaar, 1983, 1988; Bird, 1987). The Kingak was considered Jurassic by Detterman and others (1975), but new information from the subsurface of the NPRA and reevaluation of outcrop data extended the Kingak to include Lower Cretaceous (Neocomian) black shale (Molenaar, 1983, 1988).

Seismic and outcrop data show that the Kingak Shale is composed of at least four southward-prograding, offlapping, and downlapping wedges of sedimentary rock (Bruynzeel and others, 1982; Kirschner and others, 1983; Bird, 1987; Hubbard and others, 1987; Molenaar, 1988). The clastic wedges consist of shelf and slope sequences that grade into basinal facies to the south (Molenaar, 1988). Molenaar (1988) calculated foreset angles of 1°–2° from clinoform reflectors and interpreted water depths of more than 400 to 1000 m for basinal Kingak strata. These cycles may represent local tectonism from the interplay between active rifting to the north and eustatic changes.

In vertical profiles from wells and outcrops, the sedimentary prisms are represented by gradual upward-coarsening cycles of shale and siltstone that are abruptly overlain by shale of the next cycle. The base of each cycle usually represents a downlap surface, characterized by very low rates of sedimentation (or nondeposition) and missing biozones. Fine-grained sandstone is present locally at the tops of the coarsening-upward cycles, particularly in the northern parts of the NPRA. Some of the sandstone units, such as the Lower Jurassic Simpson and Middle or Upper Jurassic Barrow sandstones (Bird, 1988a), are glauconitic and heavily bioturbated, suggesting offshore-bar deposition. The Simpson, and probably the Barrow, grade both northward and southward into finer grained marine facies of the Kingak Shale.

Kuparuk Formation. The Kuparuk Formation (Lower Cretaceous), a major oil-producing reservoir about 50 km west of Prudhoe Bay, consists of about 120 m of glauconitic sandstone

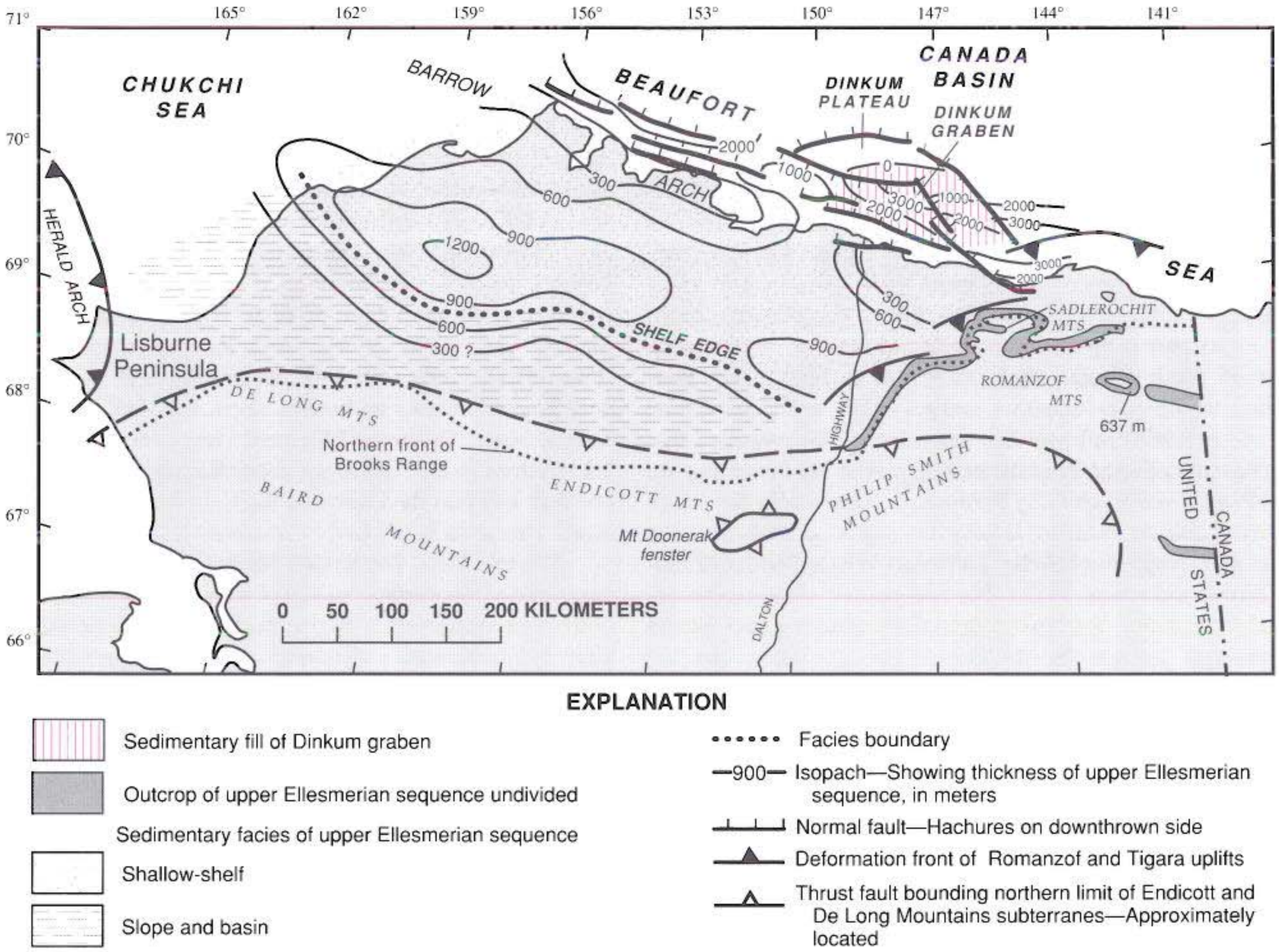


Figure 13. Isopach map for upper Ellesmerian and Dinkum graben sequences (Jurassic and Lower Cretaceous) and facies map for upper Ellesmerian sequence. Isopachs and rift-margin normal faults from Hubbard and others (1987). Abundance of normal faults on Beaufort Sea shelf suggests that main axis of Jurassic and Early Cretaceous extension was north of present coastline.

with interbedded siltstone and shale that gradationally overlies Lower Cretaceous marine shale of the Kingak (Carman and Hardwick, 1983; Molenaar and others, 1986; Masterson and Paris, 1987; Bird, 1988a; Gaynor and Scheihing, 1988). Masterson and Paris (1987) divided the Kuparuk (their Kuparuk River Formation) into two members. These are separated by the regional Lower Cretaceous unconformity. The lower member consists of six southeasterly prograding sandstone intervals, interpreted as storm deposits derived from a northern source and deposited on a marine shelf. Individual sand bodies in this member are as much as 24 m thick, 64 km long, and 24 km wide. Sandstone intervals in the upper member, as much as 15 m thick, were deposited on a marine shelf during an episode of extensional tectonism that produced local northwest-striking faults. Faulting influenced the thickness of the sandstone intervals and contributed to development of an intraformational unconformity that is probably related to the regional Lower Cretaceous unconformity. Stratigraphic thickening and rock-fragment composition suggest that an uplift near Prudhoe Bay was a source area for some of these sandstones. Dinoflagellates, palynomorphs, and pelecypods indicate that the lower part of the formation was deposited in the Berriasian(?) and Valanginian and that the upper part was deposited from the Hauterivian to the Barremian; therefore, erosional truncation occurred in late Valanginian and/or early Hauterivian time (Carman and Hardwick, 1983; Masterson and Paris, 1987).

Lower part of the Kongakut Formation. The Kongakut Formation (Lower Cretaceous) was defined by Detterman and others (1975) for a 637-m-thick sequence of shale and siltstone exposed at Bathtub Ridge in the eastern Brooks Range. They divided the Kongakut into four members: in ascending order, the clay shale, Kemik Sandstone, pebble shale, and siltstone members. In contrast to the two upper members of the Kongakut, which contain beds of feldspathic lithic sandstone and hence compose the lower part of the Brookian sequence (see below), the lower two members contain laminae and beds of quartzose sandstone and are therefore here assigned to the Upper Ellesmerian sequence.

The clay shale member consists of about 150 m of fissile,

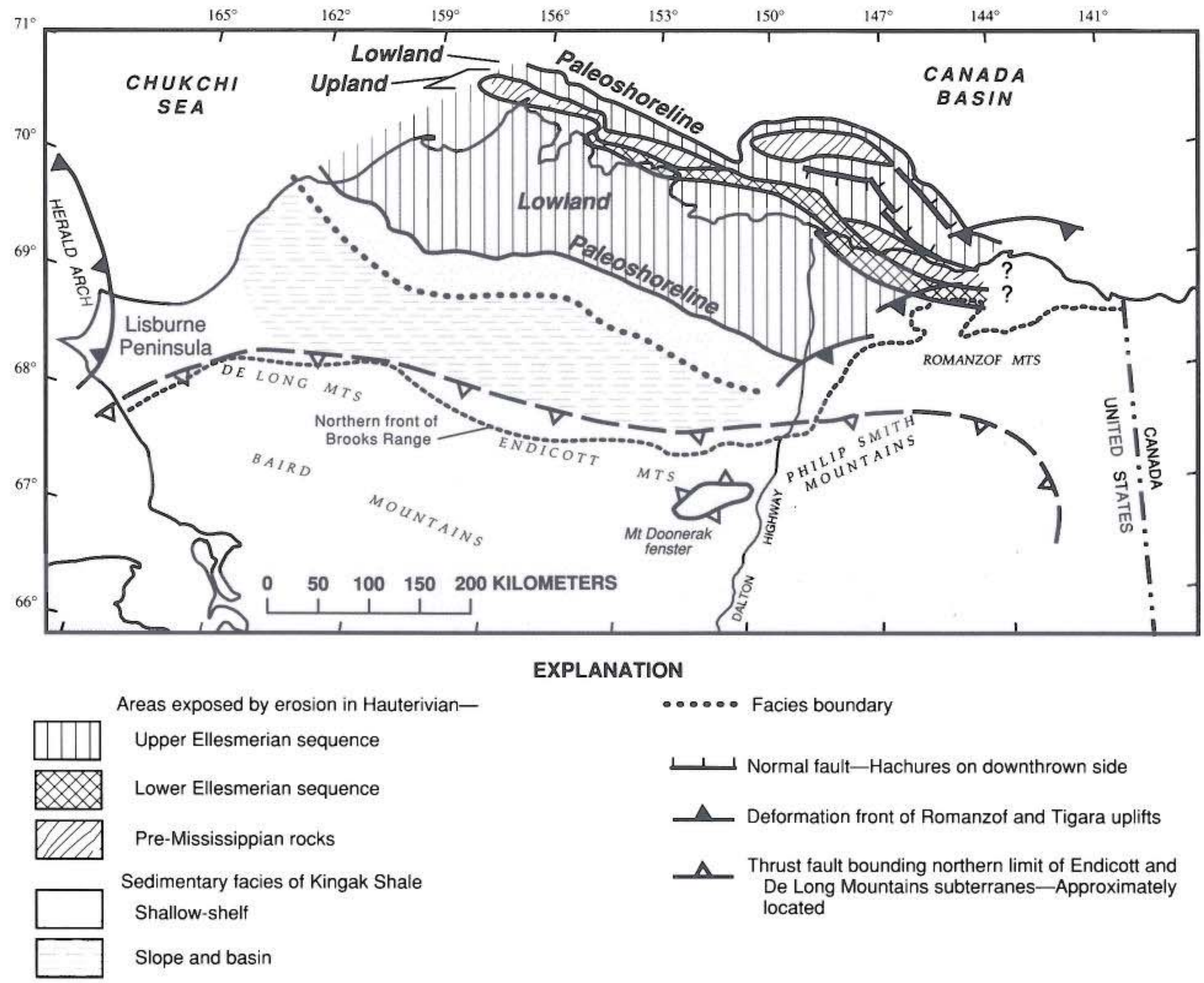


Figure 14. Paleogeography and paleogeology of North Slope subterrane (Arctic Alaska terrane) at time of maximum regression in Early Cretaceous (Hauterivian). Exposed area shows extent of Lower Cretaceous unconformity and underlying truncated rock units; shelf, slope, and basin facies of offshore areas are represented by Kingak Shale.

dark gray, marine shale that contains sparse beds of bioclastic limestone and coquinite. The overlying Kemik Sandstone Member consists of fine-grained to very fine grained sandstone turbidites and is less than 2 m thick (C. G. Mull, 1992, unpublished data), although Detterman and others (1975) reported a thickness of 80 m for this unit. *Buchia* fossils in the limestone of the clay shale member are Valanginian; the age and lithology of this member are correlative with at least part of the Kingak Shale. The Kemik Sandstone Member of the Kongakut has not been dated but is inferred to be a deep-marine equivalent of the Hauterivian, shallow-marine Kemik Sandstone, which is exposed farther north in the northeastern Brooks Range (see below).

Kemik Sandstone and related sandstone units. Many apparently discontinuous sandstone bodies lying above the Lower Cretaceous unconformity along the Barrow arch are stratigraphically equivalent to the upper part of the Kuparuk Formation. These sandstone bodies range in thickness from a few meters to as much as 100 m, have detrital compositions indicating nearby sources, and represent a variety of nearshore shallow-marine to offshore-bar environments. In the subsurface, most of the sandstone bodies are unnamed and generally are found in only one or two wells; a few are petroleum reservoirs. Two of the better-known sandstone bodies in the subsurface are the Put River Sandstone (Jamison and others, 1980) and the Thomson sand of local usage (Bird and others, 1987; Gautier, 1987). The Kemik Sandstone (Keller and others, 1961; Detterman and others, 1975; Molenaar, 1983; Molenaar and others, 1987; Mull, 1987), a lithologically similar unit exposed in the foothills of the northeastern Brooks Range, consists of as much as 40 m of sandstone and local pebble and cobble conglomerate that unconformably overlie Triassic, Jurassic, and lowermost Cretaceous rocks. The Kemik Sandstone locally contains abundant thick-shelled megafossils, grades laterally and interfingers with bioturbated pebbly siltstone and shale, and was deposited in lagoons, barrier islands, and offshore sand ridges on a shallow shelf (Knock, 1987; Mull, 1987). Ammonites indicate an Early Cretaceous (Hauterivian) age for the unit.

Pebble shale unit. The pebble shale unit (Robinson and others, 1956; Collins, 1958, 1961; Robinson, 1959) is thin (<160 m) but widespread in the subsurface and in outcrop of the North Slope subterrane. The pebble shale rests conformably on the discontinuous Kemik Sandstone beneath the coastal plain province and in outcrop along the mountain front, but where the Kemik is absent, the pebble shale lies unconformably on older strata. The pebble shale unit is characterized by black, organic-rich, fairly fissile marine shale of Hauterivian and Barremian age that contains sparse matrix-supported, polished pebbles of chert and quartz and well-rounded, frosted sand grains (Witmer and others, 1981; Mull, 1987).

The pebble shale unit is locally pyritiferous and glauconitic and contains minor sandstone and thin beds of greenish, possibly tuffaceous shale (Molenaar, 1983, 1988; Bird, 1987; Molenaar and others, 1987). The matrix-supported pebbles are generally less than a few centimeters in diameter, but cobbles and boulders as large as 25 cm are known (Molenaar and others, 1984); sand grains are fine to coarse grained. These clasts are thought to have been derived from the uplifted Early Cretaceous rift margin to the north, but the mechanism by which they were transported and deposited in the pebble shale unit is controversial (Mull, 1987; Molenaar, 1988).

Isopachs of the pebble shale unit (Bird, 1987) are irregular, ranging from 60 to 160 m. The area of greatest thickness of the pebble shale unit (>150 m) is near Barrow, where the shale contains interbedded sandstone and is closest to its clastic source that lay to the north (Blanchard and Tailleur, 1983). South of the coastal plain and in the northeastern Brooks Range, the pebble shale passes into shelf and slope settings, where no erosion took place during the Early Cretaceous.

Brookian sequence. The Brookian sequence consists of enormous quantities of sediment that were shed northward into the adjacent foredeep from the developing Brooks Range orogenic belt. Sandstones of the Brookian sequence reflect their orogenic provenance in that they contain significantly less quartz and more feldspar and labile rock fragments than sandstones of the Ellesmerian sequence. The Brookian sequence was deposited over at least 150 m.y. (Late Jurassic to the present), but deposition may have begun as much as 30 m.y. earlier, in the Middle Jurassic. The oldest and southernmost Brookian strata were probably deposited several hundred kilometers south of the present Brooks Range in the proto-Colville basin during the Jurassic and Early Cretaceous (Neocomian). These strata were transported northward with the allochthonous sequences of the Brooks Range and are now partially preserved as the Okpikruak Formation in the Endicott Mountains and De Long Mountains subterranes (Martin, 1970; Mull, 1982, 1985; Mayfield and others, 1988). Deposition of the allochthonous older rocks of the Brookian sequence was therefore coeval with deposition of the upper Ellesmerian sequence to the north. The younger rocks of the Brookian sequence, in contrast, were deposited after most of the northward migration of the Brooks Range thrust front. These strata rest mostly on older rocks of the North Slope subterrane, form the modern Colville basin, and are less deformed and more completely preserved than the older rocks of the Brookian sequence (Fig. 5).

The Brookian sequence can be subdivided into sedimentary packages or megacycles that grade from deep-marine deposits upward into nonmarine deposits (Mull, 1985). The oldest megacycles (Jurassic and Early Cretaceous—Berriasian and Valanginian) are represented by the Okpikruak Formation in the De Long Mountains and Endicott Mountains subterranes and by lithologically similar strata along the eastern and southern parts of the Lisburne Peninsula (the Ogotoruk, Telavirak, and Kisimilok formations; see Campbell, 1967). The older Brookian strata on the Lisburne Peninsula, like the Okpikruak Formation, may have been transported northward with the allochthonous sequences of the Brooks Range but were later faulted beneath rocks of the North Slope subterrane during the east-vergent thrusting event that produced the Tigara uplift in the Late Cretaceous or Tertiary.

Within the Colville basin, at least four sedimentary megacycles can be distinguished in rocks of the Brookian sequence: (1) the Aptian(?) to Albian megacycle, consisting of the Fortress Mountain Formation, upper part of the Kongakut Formation, and Bathtub Graywacke; (2) the Albian to Cenomanian megacycle, consisting of the Torok Formation and Nanushuk Group; (3) the Cenomanian to Eocene megacycle, consisting of the Colville Group and parts of the Hue Shale, Canning Formation, and Sagavanirktok Formation; and (4) the Eocene to Holocene megacycle, consisting of the upper parts of the Hue Shale, Canning Formation, and Sagavanirktok Formation, and the entire Gubik Formation. Rocks of the Aptian(?) to Albian megacycle are exposed in the north-central foothills of the Brooks Range, but the deposits of the younger three megasequences are shingled from west to east along the length of the Colville basin.

Seismic-reflection profiles of the Colville basin delineate a series of well-developed topset, foreset, and bottomset reflectors within each megacycle that mark, respectively, (1) fluvial, deltaic, and shelf deposits, (2) slope shale and turbidite deposits, and (3) basin-plain and turbidite deposits. The age and distribution of these megacycles, coupled with relevant paleocurrent and seismic data, show that the Colville basin was filled longitudinally as sediments prograded from the west toward the northeast in the late Early Cretaceous and onward into the eastern North Slope in the Late Cretaceous and Cenozoic (Chapman and Sable, 1960; Ahlbrandt and others, 1979; Molenaar, 1983, 1985, 1988; Huffman and others, 1985; Molenaar and others, 1986, 1987, 1988). The progressive northward and eastward infill of the basin may have resulted from the migration of the Brookian thrust front from the southwest to the northeast (Hubbard and others, 1987). Composition of Brookian sandstone ranges upsection from lithic and volcanic rich to chert and quartz rich. Mull (1985) has related this compositional change to progressive unroofing of the allochthonous sequences of the Brookian orogen.

Base of the Brookian sequence. Throughout the northern Colville basin and underlying parts of all the megacycles, the base of the Brookian sequence is marked by a widespread, 8–45-m-thick interval of laminated black shale and interbedded bentonite. Like the pebble shale, this unit contains isolated well-rounded, frosted sand grains and chert pebbles and has an average carbon content of greater than 3%. In contrast, however, the basal part of the Brookian sequence in the Colville basin is characterized by relatively high gamma radiation, which can be detected on gamma-ray well logs or by scintillometer in outcrop, and is therefore variously known as the gamma-ray zone (GRZ) or the highly radioactive zone (HRZ) (Carman and Hardwick, 1983; Bird, 1987; Molenaar and others, 1987) (Fig. 5). Dinoflagellates and radiolarians from the radioactive zone indicate that it was deposited during the Aptian and Albian (Carman and Hardwick, 1983; Molenaar and others, 1987) and perhaps in the Barremian (Mickey and Haga, 1983).

The GRZ may be the distal, condensed shale facies of the Brookian sequence, deposited on the north flank of the Colville basin, on the Barrow arch, and probably north of the arch. Its high carbon content and laminated character suggest an anoxic condition of deposition. The shale probably pinches out southward, where higher rates of Brookian sedimentation prevailed, but thickens in the northeastern Colville basin, where, in sections of the Hue Shale, condensed sedimentation spanned most of Late Cretaceous time (Molenaar and others, 1987).

Fortress Mountain Formation, upper part of the Kongakut Formation, and Bathtub Graywacke (Aptian? to Albian megacycle). Rocks of the Aptian(?) to Albian megacycle consist of shale, sandstone, and conglomerate exposed along the southern margin of the Colville basin. In the central and western Brooks Range, this megacycle is represented by the Fortress Mountain Formation (Aptian? and Albian) (Patton, 1956; Patton and Tailleur, 1964). This unit is as much as 3000 m thick and consists largely of coarse-grained graywacke turbidites (Fig. 5), although some of its southernmost and stratigraphically highest units may be nonmarine (Hunter and Fox, 1976; Crowder, 1987, 1989; Molenaar and others, 1988). In some places, the Fortress Mountain Formation conformably overlies fine-grained rocks of the Torok Formation, but elsewhere it rests unconformably on deformed rocks of the De Long Mountains subterrane (Tailleur and others, 1966; Mull, 1985) (Fig. 4). The unconformity represents either subaerial or submarine erosion (Molenaar and others, 1988). Facies change abruptly in the Fortress Mountain Formation, reflecting alluvial, fluvial, submarine-canyon, inner fan channel, outer fan, and basin-plain deposits (Crowder, 1987, 1989; Molenaar and others, 1988). The Fortress Mountain Formation may represent local coastal deltas or fan deltas that were shed toward the north from the ancestral Brooks Range. Regionally, the Fortress Mountain becomes thinner bedded and finer grained to the north and grades laterally into, and intertongues with, shale and siltstone turbidites of the lower Torok Formation (Mull, 1985; Molenaar and others, 1988). A Brooks Range provenance for the Fortress Mountain is supported by abundant clasts of chert and mafic igneous rocks that were derived from the De Long Mountains subterrane and Angayucham terrane. Abundant muscovite and carbonate detritus in the compositionally distinct Mount Kelly Graywacke Tongue of the Fortress Mountain Formation of the western Brooks Range suggests that the provenance in this area included rocks of the Hammond or Coldfoot subterranes (Mull, 1985). Ammonites and pelecypods, rare in the Fortress Mountain Formation, indicate that the unit is largely early Albian, but the undated lower part of the Fortress Mountain may be as old as Aptian (Molenaar and others, 1988).

In the eastern Brooks Range, the Aptian(?) to Albian megacycle consists of the upper part of the Kongakut Formation and the conformably overlying Bathtub Graywacke. The upper part of the Kongakut Formation (the pebble shale and siltstone members of Detterman and others, 1975) (Lower Cretaceous) consists of about 800 m of very thin bedded and fine-grained phosphatic, feldspathic lithic turbidites (C. G. Mull, 1992, unpublished data). The Bathtub Graywacke (Albian?) (Detterman and others, 1975) (Fig. 15) consists of 750 m of sandstone and shale turbidites that compose a submarine-fan sequence (Mull, 1985). The upper part of the Kongakut contains poorly preserved Aptian pelecypods, whereas the Bathtub Graywacke is inferred to be Albian and is at least partly equivalent to the Fortress Mountain Formation (Detterman and others, 1975). Because the upper part of the Kongakut Formation rests conformably on the upper Ellesmerian sequence (that is, the lower part of the Kongakut Formation), the Kongakut records continuous deposition from the upper Ellesmerian sequence into the Brookian sequence, and, with the Bathtub Graywacke, probably represents an uplifted remnant of the axial part of the eastern Colville basin.

Torok Formation and Nanushuk Group (Albian to Cenomanian megacycle). The Albian to Cenomanian megacycle consists primarily of the Nanushuk Group and laterally equivalent parts of the finer grained Torok Formation, which together compose the bulk of the Brookian sequence in the central and western Colville basin. The Torok Formation (Albian) (Gryc and others, 1951) consists of dark marine shale and sandstone that ranges in thickness from 6000 m near the Colville River to less than 100 m in its distal parts east of Prudhoe Bay. In the latter area, seismic-reflection data show the Torok Formation as a clastic wedge that onlaps northward onto the Barrow arch (Fig. 8). The upper part of the Torok grades into, and intertongues with, shallow-marine sandstone of the Nanushuk Group.

On seismic sections, the Torok Formation corresponds to bottomset (basinal) and foreset (slope and shelf) units (Molenaar, 1988). The bottomset units, each 150 to more than 700 m thick, consist of black, pyritic shale and siltstone with thin beds of basin-plain, fine-grained to very fine grained sandstone turbidites. These strata were deposited in water depths of 450 to 1000 m and were deposited on, and probably pass northward into, condensed radioactive shale (GRZ) at the base of the Brookian sequence. The foreset units of the Torok consist of slope and gradationally overlying shelf deposits of shale, siltstone, and minor thin-bedded sandstone. The slope deposits of the Torok are

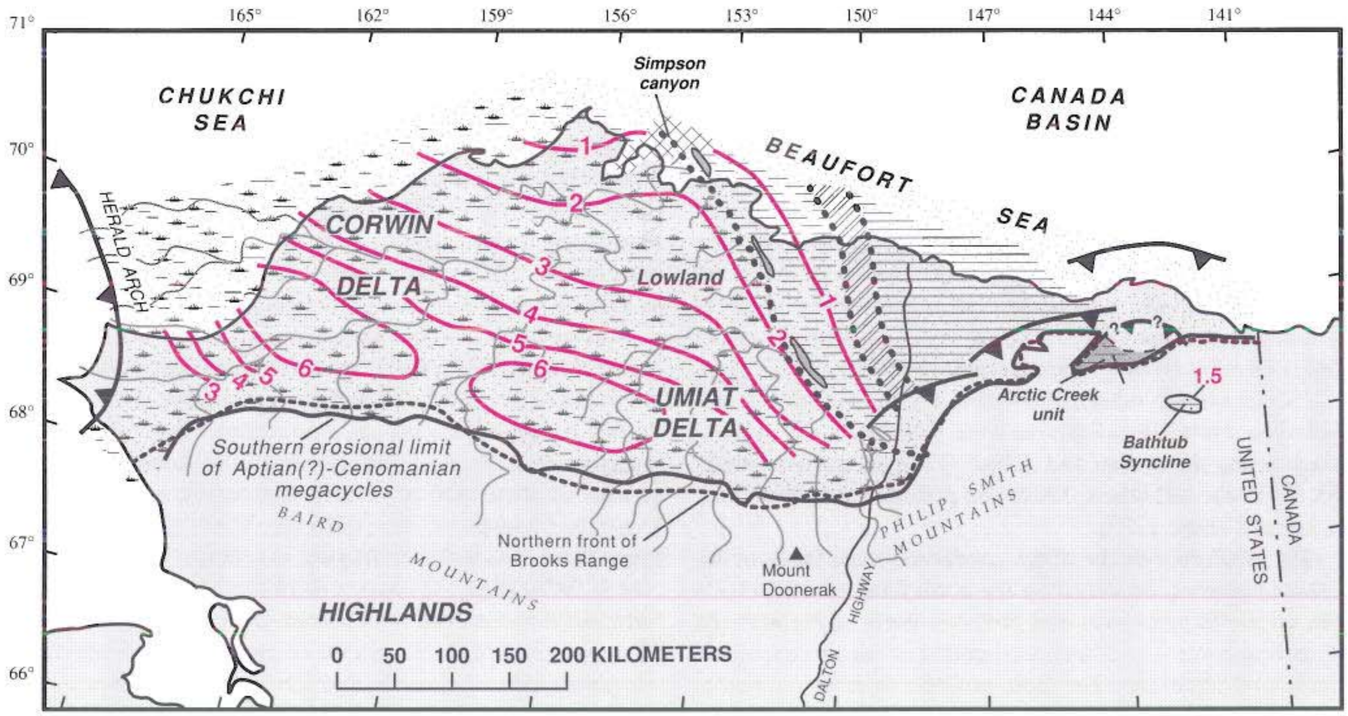


Figure 15. Isopach map (red) of Fortress Mountain Formation, upper part of Kongakut formation, Bathtub Graywacke, Torok Formation, and Nanushuk Group, undivided (Aptian[?] to Albian and Albian to Cenomanian megacycles of Brookian sequence), and paleogeographic map of Albian to Cenomanian megacycle at time of maximum regression. General position of Umiat and Corwin deltas are as described in Ahlbrandt and others (1979), Huffman and others (1985), and Molenaar (1985) and illustrate longitudinal filling of Colville basin. Note that depositional trends project into northeastern Brooks Range, evidence that this part of range postdates formation of Aptian(?) to Albian and Albian to Cenomanian megacycles. Bathtub syncline and Arctic Creek unit of Molenaar and others (1987) include deep-marine strata of Aptian(?) to Albian and Albian to Cenomanian megacycles, but these strata were transported structurally an undetermined distance northward during late Brookian tectonism. By Cenomanian time, Simpson canyon (cross-hatched pattern), a submarine feature, had been downcut and was later filled during the Cenomanian to Eocene megacycle.

450 to 1000 m thick, whereas the shelf deposits are a few meters to 335 m thick. The foreset reflectors are less distinct and less steep (<2°) in the western part of the NPRA than in the eastern part of the NPRA, where the foreset geometry is more distinct and dip angles are in the 4°–6° range. The steeper slope angle is equated with higher rates of progradation (Molenaar, 1988). The direction of progradation was northeastward, as determined from foreset directions in the Torok and paleocurrent directions and facies trends in the Nanushuk Group (Bird and Andrews, 1979).

The Nanushuk Group (Albian to Cenomanian) (Schrader, 1904; Gryc and others, 1951; Detterman and others, 1975) is a thick deltaic unit represented on seismic sections by topset reflectors that can be traced into the foreset and bottomset reflectors of the Torok Formation (Molenaar, 1985, 1988). The Fortress Mountain Formation may be a proximal equivalent of part of the Nanushuk Group (Kelley, 1988), but compositional differences and older, relatively rare megafossils (early and middle Albian) from the Fortress Mountain Formation suggest that it is in part older than the Nanushuk Group (middle Albian to Cenomanian) (Mull, 1985; Molenaar and others, 1988). The Nanushuk achieves a maximum thickness of more than 3000 m in the western North Slope. The lower part of the Nanushuk consists of a thick sequence of intertonguing shallow-marine sandstone and neritic shale and siltstone, whereas the upper part consists of dominantly nonmarine facies, including paludal shale and fluvial sandstone. The deltaic deposits contain huge, undeveloped resources of low-sulfur, low-ash bituminous to subbituminous coal in beds as thick as 6 m (Sable and Stricker, 1987; Wahrhaftig and others, this volume).

Two river-dominated delta systems, the Corwin and Umiat deltas, have been identified in strata of the Nanushuk Group (Ahlbrandt and others, 1979; Huffman and others, 1985) (Fig. 15). The Corwin delta was the larger of the two and prograded toward the northeast from a highland in the area of the Lisburne Peninsula, the present Chukchi Sea, or beyond. The width of the Corwin prodelta shelf ranged between 75 and 150 km. To the east, the smaller Umiat delta prograded northward from a source to the south and may represent a number of small deltas of rivers that once drained the ancestral central Brooks Range. By Cenomanian time, the Nanushuk deltas (principally the Corwin) had completely filled the western part of the Colville basin, prograded across the Barrow arch, and deposited sediment along the margin of the rapidly subsiding Canada basin. The Simpson canyon (Fig. 15), later filled with shale of the Upper Cretaceous Colville Group, is believed to have been cut at this time (Payne and others, 1951).

Colville Group and parts of the Hue Shale, Canning Formation, and Sagavanirktok Formation (Cenomanian to Eocene megacycle). A relative rise in sea level beginning in the Cenomanian ended the Nanushuk regression and initiated the third regressive megacycle of deposition in the Colville basin. Rocks of this megacycle include the Colville Group and parts of the Hue Shale, Canning Formation, and Sagavanirktok Formation (Fig. 5). These strata are lithologically similar to those of the Albian to Cenomanian megacycle, but rocks of the Cenomanian to Eocene megacycle characteristically contain thin beds of bentonite and tuff of mainly Late Cretaceous age. Deposition of the Cenomanian to Eocene megacycle began in the central North Slope and prograded northeastward into the eastern North Slope in the Late Cretaceous and Tertiary (Fig. 16). This progradation continued the regional northeastward shift of the main depocenter of the Brookian sequence (Molenaar, 1983; Bird and Molenaar, 1987; Molenaar and others, 1987).

In the foothills of the central North Slope, rocks of the Cenomanian to Eocene megacycle consist of the Colville Group (Schrader, 1902; Gryc and others, 1951; Brosgé and others, 1966; Detterman and others, 1975), which rests on shallow-marine to nonmarine rocks of the Nanushuk Group. The lower part of the Colville Group consists of about 500 m of marine shelf to marine basin shale, sandstone, bentonite, and tuff of the Seabee Formation (Cenomanian to Turonian). The Schrader Bluff Formation (Cenomanian to Campanian), which overlies these rocks, consists of about 800 m of shallow-marine sandstone and shale. These shallow-marine rocks intertongue with a 600-m-thick interval of nonmarine sandstone, conglomerate, shale, and coal of the uppermost Colville Group, the Prince Creek Formation (Santonian to Maastrichtian).

In the eastern Colville basin, beneath the foothills and coastal plain of the northeastern Brooks Range, the facies of the Colville basin are younger than those to the west and are represented primarily by the Hue Shale and Canning Formation (Molenaar and others, 1987). Because of deformation, poor exposure, and diachronous character of the Upper Cretaceous and Tertiary rocks of the Colville basin, Molenaar and others (1987) defined this change of nomenclature east of the eastern limit of the Nanushuk Group, about long 151°W (Fig. 7). The 300-m-thick Hue Shale (Aptian? to Campanian and probably Tertiary under the Beaufort Sea) is a condensed, basinal sequence consisting of shale, bentonite, and tuff. The basal 45 m of this unit contains the GRZ; the upper part of the unit consists of similar, but less radioactive, black shale. Because the Hue Shale forms the basal part of the Brookian sequence in the eastern Colville basin, this region must have been distal to the primary area of deposition of the earlier megacycles.

The first appearance in the eastern Colville basin of northeastward-prograding slope and shelf facies of the Cenomanian to Eocene megacycle is represented by the 1200-m-thick Canning Formation (Lower Cretaceous—Aptian to Tertiary). Although dominantly shale, the lower part of the Canning contains thin basin-plain sandstone turbidites; these pass upward into slope and shelf facies. South of Prudhoe Bay, the Canning Formation is largely Aptian to Cenomanian, whereas near the Canning River it is largely Campanian to Eocene; thus, the Canning is markedly diachronous (Molenaar and others, 1987).

The Sagavanirktok Formation (Campanian to Pliocene) (Gryc and others, 1951; Detterman and others, 1975; Molenaar and others, 1987) is a thick shallow-marine and nonmarine unit which overlies and intertongues with slope and shelf facies of the Canning Formation. It is as much as 2600 m thick and consists of sandstone, bentonitic shale, conglomerate, and coal, composing the regressive part of the megacycle. In northeastern Alaska, the Sagavanirktok Formation is primarily Paleocene and younger, but because of its diachronous nature, it may be as old as Campanian to the west, where it is stratigraphically equivalent to the Schrader Bluff and Prince Creek formations (Molenaar and others, 1987).

Gubik Formation and upper parts of the Hue Shale, Canning Formation, and Sagavanirktok Formation (Eocene to Holocene megacycle). The Eocene to Holocene megacycle consists of the Gubik Formation and the upper part of the Sagavanirktok Formation onshore, but it also includes parts of the Canning Formation and the Hue Shale offshore of the eastern North Slope (Fig. 5). Deposits of this megacycle reach a thickness of about 2 km under the coastal plain east of Prudhoe Bay (Fig. 16), but they are much thicker offshore (Grantz and others, 1990a). Wells west of the ANWR (Molenaar and others, 1986) penetrate deposits of the Sagavanirktok Formation that consist mostly of sandstone and conglomerate with about 30% interbedded siltstone and shale. These strata, representing a fluvial-deltaic environment, grade eastward and northward into finer grained shelf and slope deposits of the Canning Formation (Bird and Molenaar, 1987). The Gubik Formation (Pliocene and Pleistocene) (Schrader, 1902; Gryc and others, 1951; Detterman and others, 1975; Nelson and Carter, 1985) consists of unconsolidated, marine and nonmarine, poorly stratified to well-stratified gravel, sand, silt, and clay.

The base of the Eocene to Holocene megacycle is defined by a poorly dated erosional unconformity. This unconformity has been traced in wells along the coastline between the Colville River and the ANWR and may correlate with a late Eocene unconformity in the Mackenzie delta area (Bird and Molenaar, 1987; Molenaar and others, 1987). West of the ANWR, strata above and below the unconformity are disconformable, but in the ANWR, the unconformity separates more highly deformed rocks below from less-deformed rocks above (Bruns and others, 1987; Kelley and Foland, 1987). Development of the unconformity may be related to Tertiary thrusting and uplift in the northeastern Brooks Range, as indicated by apatite fission-track ages of 45 to 25 Ma (O'Sullivan, 1988; O'Sullivan and others, 1989).

Endicott Mountains subterrane

The Endicott Mountains subterrane is one of the three largest subterranes of the Arctic Alaska terrane, extending for about 900 km from the Chukchi Sea on the west to near the Canadian

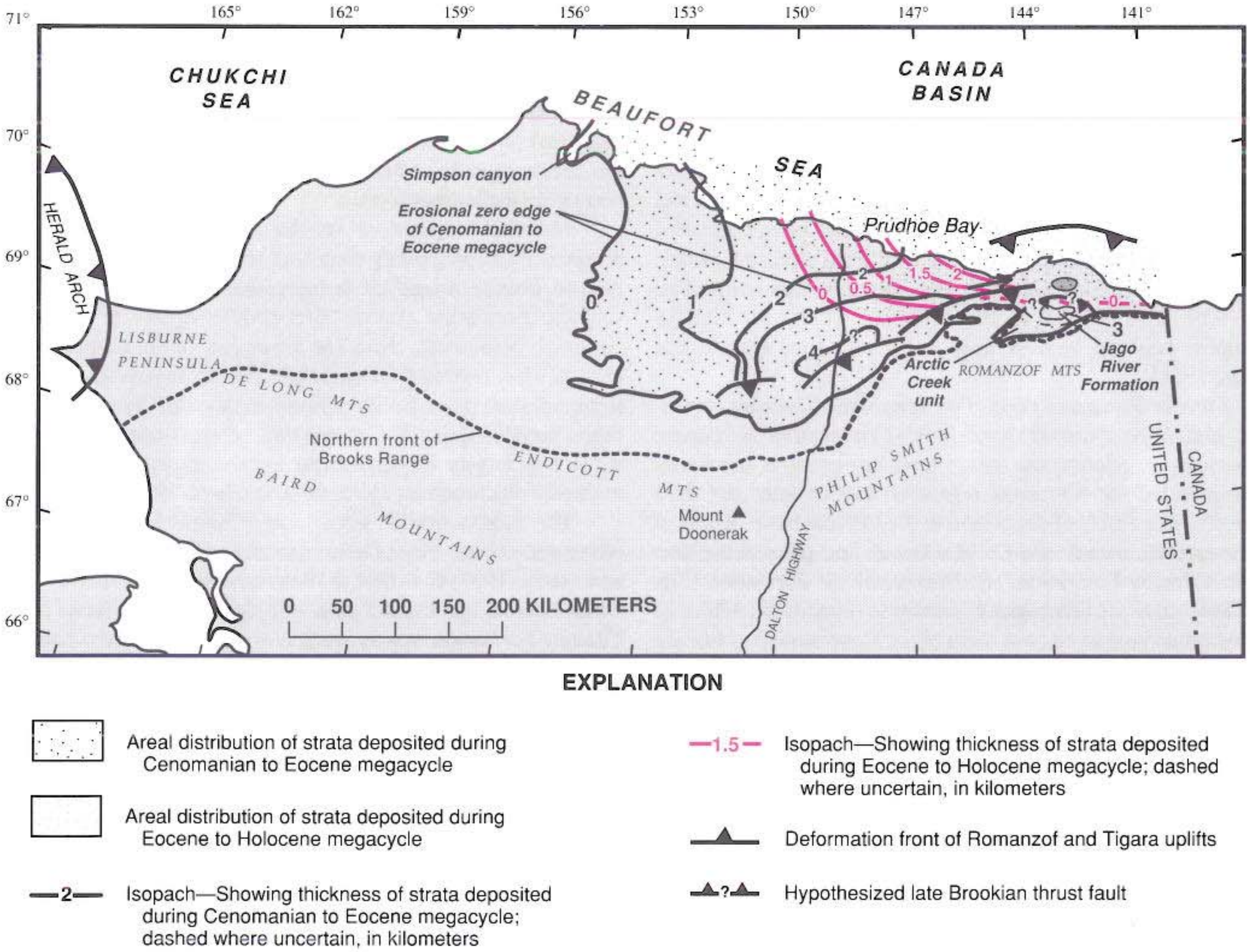


Figure 16. Isopach map of Colville Group, Hue Shale, and Canning, Sagavanirktok, and Gubik formations (Cenomanian to Eocene [black] and Eocene to Holocene [red] megacycles of Brookian sequence). Note that depocenter of Eocene to Holocene megacycle lies mostly offshore in contrast to that of earlier megacycles, which trend northeasterly, parallel to northern front of adjacent Brooks Range. Upper Cretaceous deep-water deposits of Arctic Creek unit (Molenaar and others, 1987) and Upper Cretaceous and Tertiary nonmarine deposits of Jago River Formation (Buckingham, 1987) are part of Cenomanian to Eocene megacycle, but these strata were transported structurally an undetermined distance northward during late Brookian tectonism.

border on the east (Fig. 3). The Endicott Mountains subterrane consists solely of the Endicott Mountains allochthon (Mull, 1982, 1985), which is the lowest of a stack of seven major allochthons in the Brooks Range that have been distinguished by Martin (1970) and Mayfield and others (1988).

Endicott Mountains allochthon. Although the stratigraphically lower part of the Endicott Mountains subterrane (allochthon) (Fig. 17) includes a transgressive succession analogous to that of the Endicott and Lisburne groups of the North Slope subterrane, it differs in that it has a faulted base, contains a regressive Upper Devonian sequence, lacks a sub-Mississippian unconformity, and has a much greater thickness of clastic rocks. The Permian to Lower Cretaceous part of the stratigraphic succession of the Endicott Mountains subterrane consists entirely of fine-grained rocks that represent shelf to basinal deposition in contrast to coeval shallower water deposits of much of the North Slope subterrane. Stratigraphic thickness of pre-Cretaceous rocks in this subterrane is 1500 m in the western Brooks Range and more than 6000 m in the central Brooks Range. The subterrane comprises the Beaucoup Formation, the Endicott Group, the Lisburne Group, the Etivluk Group, Ipewik unit, and the Okpikruak Formation.

Beaucoup Formation. The oldest rocks of the Endicott Mountains subterrane are those of the Beaucoup Formation (Upper Devonian) (Dutro and others, 1979) in the central Brooks Range and the correlative Nakolik River unit of Karl and others (1989) in the western Brooks Range. These units consist of a heterogeneous marine assemblage of phyllitic, calcareous siltstone and shale with lenticular limestone bodies. In its type area east of the Dalton Highway, the Beaucoup Formation forms a 545-m-thick depositional succession at the base of the Endicott Mountains subterrane conformably beneath the Hunt Fork Shale (Dutro and others, 1979). Elsewhere, however, the unit is extensively faulted and detached from the Endicott Mountains allochthon (Moore and others, 1991). Limestone bodies in the Beaucoup Formation and Nakolik River unit, although com-

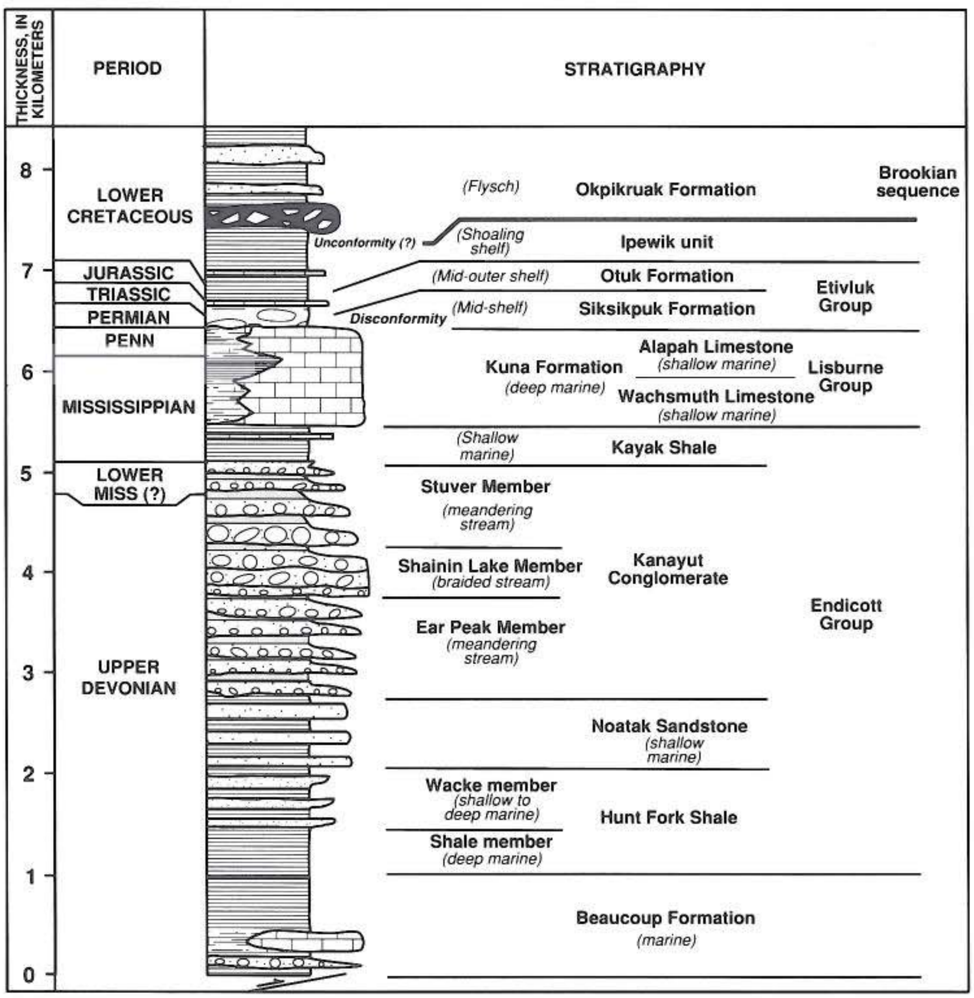


Figure 17. Generalized stratigraphic column of Endicott Mountains subterrane (allochthon), Arctic Alaska terrane. Thicknesses are maximum except that of Kuna Formation (<100 m), which could not be drawn to scale. Half arrow indicates relative northward thrust movement. For explanation of lithologic symbols, see Figure 21.

monly recrystallized, consist of bioclastic packstone and wackestone that contain early Late Devonian (Frasnian) megafossils. Dutro and others (1979) interpreted the bodies as stromatoporoid patch reefs.

Rock types not present in the type section of the Beaucoup Formation but associated with it in its type area include limestone-phyllite-pebble conglomerate, quartz-pebble conglomerate, maroon and green phyllite and argillite, mafic volcanic rocks, and silicic volcaniclastic rocks (Dutro and others, 1979). These rock types also have been mapped in the northern part of the Hammond subterrane along most of its length, leading some workers (Dillon and others, 1986; Dillon, 1989) to include many of the rocks of that subterrane in the Beaucoup Formation. However, this correlation may not be justified because the age and stratigraphic relations between Beaucoup rocks of the Hammond subterrane and those of the Endicott Mountains subterrane have not been established and because the Beaucoup would be an integral part of two discrete thrust-bounded packages of rock. Dutro and others (1979) originally envisioned the Beaucoup Formation as a link between the carbonate rocks of the Skajit Limestone (Hammond subterrane) and the clastic rocks of the Endicott Group (Endicott Mountains subterrane). At present, the Beaucoup Formation may be interpreted as (1) a tectonically disrupted stratigraphic interval that links the Endicott Mountains and Hammond subterranes; (2) two or more undifferentiated, but stratigraphically distinct, units; or (3) a detachment zone that separates the Endicott Mountains and Hammond subterranes and consists of rocks derived from both subterranes.

Endicott Group. In the Endicott Mountains subterrane, the Endicott Group, which is as much as 4500 m thick, consists in ascending order of the Hunt Fork Shale (marine), Noatak Sandstone (marine), Kanayut Conglomerate (nonmarine), and Kayak Shale (marine). This sequence represents a major fluvial-dominated deltaic clastic wedge shed southwestward during the Late Devonian and Early Mississippian from at least two major sources, one in the eastern Brooks Range and the other north of Anaktuvuk Pass in the central Brooks Range (Tailleur and others, 1967; Nilsen, 1981; Moore and Nilsen, 1984) (Fig. 18). Clasts in conglomerate of the sequence are largely chert, some containing radiolarian ghosts, and minor vein quartz, chert arenite, and chert-pebble conglomerate.

The Hunt Fork Shale (Upper Devonian) (Chapman and others, 1964) is a widespread sequence of thin-bedded, dark-gray shale, micaceous siltstone, and fine-grained quartzose sandstone more than 1000 m thick. Sedimentary structures preserved within the Hunt Fork indicate that the formation consists of thin-bedded turbidites and marginal-marine deposits that represent slope and prodelta depositional environments. Megafossils and conodonts from sparse, thin-bedded, bioclastic turbidites in the lower part of the unit are Frasnian (early Late Devonian), whereas fossils found higher in the unit, typically in shallow-marine sandstone, are Famennian (late Late Devonian) (Brosgé and others, 1979).

The Hunt Fork Shale grades upward into the Noatak Sandstone (Upper Devonian) (Dutro, 1952). The Noatak is 200 to

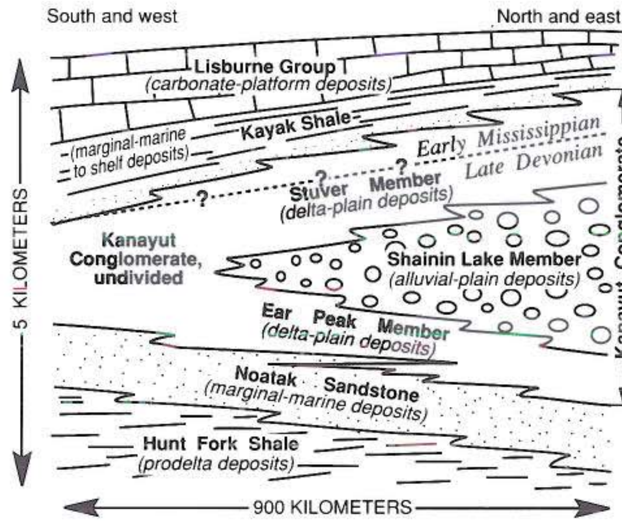


Figure 18. Diagrammatic cross section showing stratigraphic relations of Endicott Group, Endicott Mountains subterrane (allochthon) (modified from Nilsen and Moore, 1984).

300 m thick and consists of coarsening-upward packages of fine- to medium-grained calcareous sandstone that are separated by units of dark siltstone and shale (Nilsen and Moore, 1984). Abundant trough cross-stratification, megafossils, and other features indicate that the Noatak was deposited in a marginal-marine environment in the Famennian (late Late Devonian).

The overlying Kanayut Conglomerate (Upper Devonian and Lower Mississippian?) consists of as much as 2600 m of interbedded sandstone, conglomerate, and shale, subdivided, in ascending order, into the Ear Peak, Shainin Lake, and Stuver members (Bowsher and Dutro, 1957; Nilsen and Moore, 1984). The Ear Peak and Stuver members are shale-bearing successions that were deposited by meandering streams on a delta plain. The Shainin Lake Member, in contrast, consists almost entirely of sandstone and conglomerate with clasts as large as 23 cm that were deposited by braided streams on an alluvial plain (Moore and Nilsen, 1984). The Kanayut thins and fines southward and westward from near Anaktuvuk Pass, and its three members cannot be distinguished west of the Killik River quadrangle. The Kanayut is dated by Late Devonian and Early Mississippian(?) plant fossils, sparse Famennian brachiopods, and its stratigraphic position (Nilsen and Moore, 1984).

A marine transgression following deposition of the Kanayut is recorded in rippled, thin-bedded, very fine grained quartzose sandstone in the basal part of the overlying Kayak Shale (Lower Mississippian). Above this sandstone unit (basal sandstone member of Bowsher and Dutro, 1957), the Kayak Shale consists of about 250 m of black shale and minor fossiliferous limestone-debris beds, especially in its upper part (Bowsher and Dutro, 1957). Abundant megafossils and microfossils in the intercalated limestone indicate that the basal Kayak in the Endicott Mountains subterrane is at least as old as late Kinderhookian (early Early Mississippian), and the uppermost part may be as young as

Osagean (late Early Mississippian) (Armstrong and Mamet, 1978). The Kayak records submergence of the Kanayut clastic wedge and offshore deposition of fine-grained sediment prior to northward progradation of the Lisburne carbonate platform.

Lisburne Group. Carbonate rocks of the Lisburne Group in the Endicott Mountains subterrane typically consist of about 700 m of cliff-forming Mississippian and Pennsylvanian echinoderm-bryozoan wackestone and packstone that commonly contain articulated crinoid stems and bryozoan fronds. Dolomitization, and chert nodules, veins, and layers with replacement textures, are common. As in the North Slope subterrane, transgressive, platform, and deeper water assemblages are recognized in the Lisburne Group, but in the Endicott Mountains subterrane, these assemblages are somewhat older, and the deeper water assemblage is more extensive. Bowsher and Dutro (1957) divided the Lisburne Group in the Endicott Mountains subterrane into the Wachsmuth Limestone and overlying Alapah Limestone, but regional mapping has shown that these units do not coincide with the upward change from transgressive to platform-carbonate facies and are otherwise difficult to distinguish.

In the north-central Brooks Range, the basal, transgressive part of the Lisburne Group consists of massive argillaceous limestone that grades upward into cherty, less argillaceous deposits of the platform facies (Armstrong and Mamet, 1978). To the south, the platform facies interfingers with unnamed black chert, radiolarian and spiculitic lime mudstone, and black shale that represent slope and starved-basin deposits. This deeper water assemblage increases in thickness and composes a greater proportion of the Lisburne Group in the southern and western parts of the subterrane. These facies relations suggest that deposition occurred on a slowly subsiding open-marine shelf that interfingered with an euxinic basin south or southwest of the main carbonate platform (Armstrong and Mamet, 1978).

Abundant foraminifers and conodonts indicate that deposition of the Lisburne Group limestones along the southern margin of the Endicott Mountains allochthon in the central Brooks Range began in the early Osagean (late Early Mississippian) (Armstrong and Mamet, 1978). Carbonate deposition spread northward during later Osagean time and continued throughout most of the Late Mississippian. Recently, Morrowan and Atokan fossils have been recovered from carbonate rocks near the top of the Lisburne Group, showing that carbonate deposition continued into Early Pennsylvanian time in the Endicott Mountains subterrane (Siok, 1985).

In the Killik River quadrangle, carbonate rocks of the Lisburne Group become thinner, more thinly bedded, and have a higher percentage of secondary chert, possibly as a result of a westward increase in the abundance of sponge spicules. These rocks are thought to grade laterally into the Kuna Formation (Mississippian and Pennsylvanian) (Mull and others, 1982), which is exposed in nearby thrust imbricates and in structural windows in the western Brooks Range. The Kuna Formation, a deep-water assemblage, consists of less than 100 m of sooty, phosphatic black shale and dolomite interbedded with lesser amounts of black, radiolarian- and spiculite-bearing chert. Interstratified platy micritic limestone, thin-bedded quartzose turbidites, and basaltic to rhyodacitic volcanic rocks are reported from a few places in the western Brooks Range (Nokleberg and Winkler, 1982; Moore and others, 1986). The Kuna Formation hosts the strata-bound zinc-lead-silver deposit of the Red Dog Mine in the De Long Mountains quadrangle (Moore and others, 1986).

Megafossil and microfossil data indicate that the Kuna Formation ranges from late Early Mississippian (Osagean) to Early or Middle Pennsylvanian (Mull and others, 1982) and occupies the same stratigraphic position as carbonate rocks of the Wachsmuth and Alapah limestones farther east. The Kuna Formation may represent sponge-rich mud deposited in a partly oxygenated starved-basin environment (Murchey and others, 1988) that lay southwest of the platform-carbonate facies of the Lisburne Group. This environment may have been in the same euxinic basin that Armstrong and Mamet (1978) inferred to exist south and west of the platform-carbonate facies (see above).

Etivluk Group. The Etivluk Group (Mull and others, 1982, 1987b) consists of the Permian Siksikpuk Formation (115 m) and the Triassic and Jurassic Otuk Formation (100 m). The Siksikpuk Formation was named by Patton (1957) for exposures mainly of shale and siltstone in the Chandler Lake quadrangle and was subsequently extended by Mull and others (1982) to include chert-rich sequences in the central and western Brooks Range. Mull and others (1987b) restricted the Siksikpuk to the shale- and siltstone-rich facies described by Patton (1957) and reassigned the chert-rich facies to the Imnaitchiak Chert (see Picnic Creek allochthon below). We herein agree with the restriction of the Siksikpuk Formation as proposed by Mull and others (1987b).

Four lithostratigraphic units have been recognized in the Siksikpuk Formation in the central Brooks Range by Siok (1985), Adams and Siok (1989), and Adams (1991). In ascending order, these are (1) yellow-orange–weathering, pyritic siltstone (2–17 m); (2) gray to greenish-gray and maroon mudstone and siltstone, containing nodules of barite and siderite (20–100 m); (3) wispy-laminated, greenish-gray silicified mudstone (frequently referred to as chert) (1–24 m); and (4) wispy-laminated, dark gray fissile shale and minor siltstone (1–40 m). Northeastward, the Siksikpuk Formation becomes progressively darker, thicker, coarser grained, and less siliceous, but more carbonate rich, features characteristic of the coeval Echooka Formation of the North Slope subterrane (Adams, 1991). The basal contact of the Siksikpuk Formation on the Lisburne Group may be a disconformity, because Upper Pennsylvanian strata have not been recognized in the Endicott Mountains subterrane (Patton, 1957). The Siksikpuk is a transgressive unit, representing mostly suspension sedimentation in an inner to middle neritic environment (Siok, 1985; Murchey and others, 1988; Adams, 1991).

Patton (1957) initially reported the age of the Siksikpuk Formation as Permian. Mull and others (1982) regarded their extended Siksikpuk as Pennsylvanian, Permian, and Early Triassic. Later, however, Mull and others (1987b) restated the age of their restricted Siksikpuk as Permian. Siok (1985) and Adams (1991) concluded from megafossil and microfossil evidence that the Siksikpuk Formation is largely Early Permian (Wolfcampian and Leonardian), except for its uppermost part, which extends into the early Late Permian (Guadalupian). We herein agree with an age assignment of Permian for the Siksikpuk Formation.

The overlying Otuk Formation (Mull and others, 1982) consists of four members. From base to top, these are (1) the shale member, consisting of dark gray to black, organic-rich shale with thin limestone beds (6–14 m); (2) the chert member, consisting mainly of green and black silicified mudstone and rhythmically interbedded black, calcareous shale (17–53 m); (3) the limestone member, consisting of yellow-brown–weathering limestone with minor shale (7–19 m); and (4) the Blankenship Member, consisting of black, fissile, bituminous shale with minor dark gray chert and dolomitic limestone (7 m). The chert and limestone members typically contain abundant pectinid pelecypods (commonly *Monotis* and *Halobia*). The lower part of the Otuk Formation is correlative with the Shublik Formation of the North Slope subterrane. This part of the Otuk is well dated on the basis of its abundant pectinid pelecypod fauna, conodonts, and radiolarians and ranges from Early Triassic (Scythian) in the shale member to as young as Late Triassic (late Norian) in the limestone member (Mull and others, 1982; Blome and others, 1988; Murchey and others, 1988). The Blankenship Member contains pelecypods and ammonites that indicate a middle Early Jurassic (Sinemurian) to early Middle Jurassic (Bajocian) age and is correlative with the lower part of the Kingak Shale of the North Slope subterrane (Mull and others, 1982; Bodnar, 1989). The Otuk represents condensed sedimentation in an open-marine, middle neritic to inner bathyal environment distant from a source of clastic detritus (Murchey and others, 1988; Bodnar, 1989).

Ipewik unit. In the western Brooks Range, the Ipewik unit (Jurassic and Lower Cretaceous) of Crane and Wiggins (1976) and Mayfield and others (1988) consists of about 100 m of poorly exposed soft, dark, maroon and gray clay shale, concretionary mudstone, fissile oil shale, and reddish coquinoid limestone containing highly compressed *Buchia sublaevis* fossils. Local intervals of resistant, fine- to medium-grained quartzose sandstone (the Tingmerkpuk subunit of Crane and Wiggins, 1976) are also present within the Ipewik of this area. Crane and Wiggins (1976) reported that the lower part of the unit contains Early and Late Jurassic megafossils and Middle Jurassic to Early Cretaceous dinoflagellate faunas, whereas the coquinoid limestone and Tingmerkpuk subunits of the upper part of the Ipewik contain abundant megafossils of Valanginian (Early Cretaceous) age. In the foothills of the central Brooks Range, the Ipewik (clay shale unit of Molenaar, 1988) is much thinner and consists of dark gray and black shale characterized by a distinctive interval, as much as 2 m thick, of reddish-weathering Valanginian coquinoid limestone beds and interbedded maroon shale. In this area, the Ipewik may rest unconformably on Middle Jurassic beds at the top of the Otuk Formation (Mull, 1989).

The Ipewik unit is a condensed section deposited in a quiescent marine basin. The widespread coquinoid limestone is commonly interpreted as a relatively shallow water unit deposited on an intrabasin medial sill or ridge (Jones and Grantz, 1964; Tailleur and Brosgé, 1970; Molenaar, 1988), although the limestone has also been thought of as deep-marine turbidites that consist of intrabasinal shallow-marine fossil debris (Molenaar, 1988). If the limestone were deposited on an intrabasin ridge, it is thought to have separated coeval early Brookian foredeep deposits to the south, represented by the Okpikruak Formation of the De Long Mountains subterrane, from the tectonically stable upper Ellesmerian shale basin to the north, represented by the upper part of the Kingak Shale of the North Slope subterrane.

Deposits of the Brookian sequence (Okpikruak Formation) in the Endicott Mountains subterrane. The youngest rocks of the Endicott Mountains subterrane, exposed mainly in the northern foothills of the Brooks Range, consist of gray, deep-marine mudstone and minor thin-bedded sandstone and conglomerate of the Okpikruak Formation (Upper Jurassic and Lower Cretaceous). At its type locality (herein assigned to the Endicott Mountains subterrane) in the Killik River quadrangle, the Okpikruak is at least 600 m thick (Gryc and others, 1951), and in the western Brooks Range, it is estimated to be more than 1000 m thick. Conglomerate is locally prominent and contains rounded cobbles and boulders of chert, limestone, granitic rocks, dacite, diabase, and gabbro. These rock types are like those of structurally higher allochthons (Mull and others, 1976; Crane, 1987), with the exception of the granitic clasts dated by K-Ar methods at 186–153 Ma (Jurassic), which are unlike any rock type mapped in the Brooks Range (Mayfield and others, 1978). *Buchia* pelecypods in the Okpikruak indicate a Valanginian age for the formation in the Endicott Mountains subterrane; however, Curtis and others (1990) reported Berriasian fossils from one exposure of the Okpikruak in the De Long Mountains quadrangle.

The Okpikruak largely represents turbidites and local olistostromes deposited either in a foredeep that migrated northward with the advancing Brooks Range thrust front (Mull, 1985; Crane, 1987; Mayfield and others, 1988) or possibly in a piggyback basin. Commonly, however, the Okpikruak is deformed, comprising broken formation or melange, the structural position of which is difficult to ascertain. The Okpikruak Formation rests conformably to unconformably on older rocks of the Endicott Mountains subterrane in a few places in the Killik River, Misheguk Mountain, and De Long Mountains quadrangles (Curtis and others, 1984, 1990; C. G. Mull, 1987, unpublished data).

De Long Mountains subterrane

The De Long Mountains subterrane, the structurally highest subterrane of the Arctic Alaska terrane, consists of four of the seven allochthons recognized by Tailleur and others (1966), Martin (1970), Mull (1985), and Mayfield and others (1988). In ascending order, these are the Picnic Creek, Kelly River, Ipnavik

River, and Nuka Ridge allochthons. Although these allochthons display overall stratigraphic similarity to the North Slope and Endicott Mountains subterranes, they differ primarily in aspects of their constituent Mississippian to Lower Cretaceous rocks (Fig. 19). The De Long Mountains subterrane is best exposed in the De Long Mountains of the western Brooks Range (Fig. 20). It also underlies much of the disturbed belt in the central Brooks Range and occurs as thrust imbricates in the eastern Brooks Range, where it has been called the Sheenjek terrane by Jones and others (1987). Not all of the four allochthons are present everywhere in the subterrane, but all of the allochthons present in any one area occur in the same vertical succession. The youngest strata present in all four allochthons are locally derived flysch of the Okpikruak Formation that is assumed to record northward progradation of the Brookian thrust front in the Late Jurassic and Early Cretaceous (Mull and others, 1976; Crane, 1987; Mayfield and others, 1988). Because the structural position of strata of the Okpikruak Formation has not been determined in many places, the Okpikruak strata of all four allochthons of the De Long Mountains subterrane are described together at the end of this section under the heading "Deposits of the Brookian sequence (Okpikruak Formation) in the De Long Mountains subterrane."

Picnic Creek allochthon. The Picnic Creek allochthon is named for exposures in the Picnic Creek fenster in the Misheguk Mountain quadrangle (Mayfield and others, 1984). However, the most detailed examination of the stratigraphy of the allochthon has been in the disturbed belt in the Killik River quadrangle in the central Brooks Range, where a stratigraphic nomenclature has been established by Mull and others (1987b; Fig. 19). The thickness of pre-Cretaceous strata of the Picnic Creek allochthon is less than 1000 m (Mayfield and others, 1988), but these rocks are imbricated so that the true thickness is uncertain. The allochthon comprises the Endicott Group, the Lisburne Group, the Etivluk Group, and the Okpikruak Formation.

Endicott Group. In the Killik River quadrangle, the base of the Picnic Creek allochthon consists of about 100 m of dark greenish-gray shale that grades upward into interbedded dark gray to black shale and thin sandstone beds. This unit, exposed in only a few places, is unfossiliferous, but Mull and others (1987b) correlated it with the Hunt Fork Shale (Upper Devonian) because of its fine-grained character and stratigraphic position below the Lower Mississippian Kurupa Sandstone. The disrupted and incompetent nature of this unit suggests that it has acted as a detachment surface along which the Picnic Creek allochthon was emplaced. In the western Brooks Range, the basal unit of the allochthon consists of about 50 m of calcareous, fine- to medium-grained sandstone with intercalated siltstone. These rocks contain brachiopods of Fammenian (late Late Devonian) age, which implies that the unit is at least partly correlative with the coeval marine Noatak Sandstone (Curtis and others, 1984; Ellersieck and others, 1990).

In the Killik River quadrangle, the Hunt Fork Shale grades up to about 40 m of quartzose sandstone, named the "Kurupa Sandstone" (Lower Mississippian) by Mull and others (1987b); we herein adopt this nomenclature. This relatively competent unit becomes more shale rich to the west and is not recognized in the western Brooks Range. The Kurupa Sandstone consists of thin- to medium-bedded, medium- to coarse-grained sandstone with siltstone and minor granule and pebble conglomerate. Mull and others (1987b) interpreted the Kurupa as turbidites that were deposited toward the southeast on a prodelta ramp. Abundant plant fossils near the top of the formation and a sparse brachiopod fauna suggest an Early Mississippian age and a Siberian affinity for the unit (Mull and others, 1987b).

The Kayak Shale (Lower Mississippian) is 15 to 40 m thick and, in the Killik River quadrangle, conformably overlies the Kurupa Sandstone. The Kayak consists of recessive siltstone and black clay shale with red-brown–weathering ironstone concretions and contains Mississippian megafossils (Mull and others, 1987b). In the western Brooks Range, the formation also contains local, thin, rusty- to buff-weathering bioclastic limestone beds. In a few places, the Kayak also contains as much as 30 m of fossiliferous, quartzose, fine- to medium-grained sandstone and sandy limestone. Megafossils and microfossils in the sandstone are Early Mississippian (Osagean) (Curtis and others, 1984; Ellersieck and others, 1984).

Lisburne Group. A distinctive unit in the Picnic Creek allochthon is the 87-m-thick sequence of thin-bedded, black, spicule- and radiolarian-bearing chert that rests conformably on the Kayak Shale. In the Killik River quadrangle, Mull and others (1987b) named this unit the "Akmalik Chert" (Upper Mississippian and Lower Pennsylvanian); we herein adopt this nomenclature. The Akmalik contains black shale partings and minor siliceous black mudstone and rare dolomitic limestone beds. Radiolarian and conodont assemblages and a plant fossil indicate a Late Mississippian (Meramecian and Chesterian) and Early Pennsylvanian (Morrowan) age for the unit. Mull and others (1987b) considered these rocks to be at least partly correlative with the Kuna Formation of the Endicott Mountains subterrane and to represent a deep-water, basinal equivalent of the platform carbonate sequence elsewhere in the Lisburne Group.

Etivluk Group. In the Picnic Creek allochthon, the Etivluk Group consists of gray, radiolarian chert with lesser amounts of brown, green, and maroon siliceous shale. These strata were assigned to the Siksikpuk Formation by Chapman and others (1964) and Mull and others (1982), but Mull and others (1987b) later restricted the Siksikpuk Formation to the dominantly shaly and silty beds typical of the stratotype and reassigned the more siliceous rocks of the Picnic Creek allochthon to the Imnaitchiak Chert (Lower Pennsylvanian to Jurassic?); we herein agree with this reassignment. In its type locality in the Killik River quadrangle, the Imnaitchiak Chert is 75 m thick and can be divided into six subunits (Siok, 1985). From base to top, these subunits are (1) greenish-gray glauconitic and phosphatic siltstone and sandstone and a local conglomerate bed that consists mostly of spherical oncoids, replaced by barite, and chert clasts (Siok and Mull, 1987) (<2 m); (2) bedded gray chert that contains an increasing amount of shale upsection (14–17 m); (3) green chert,

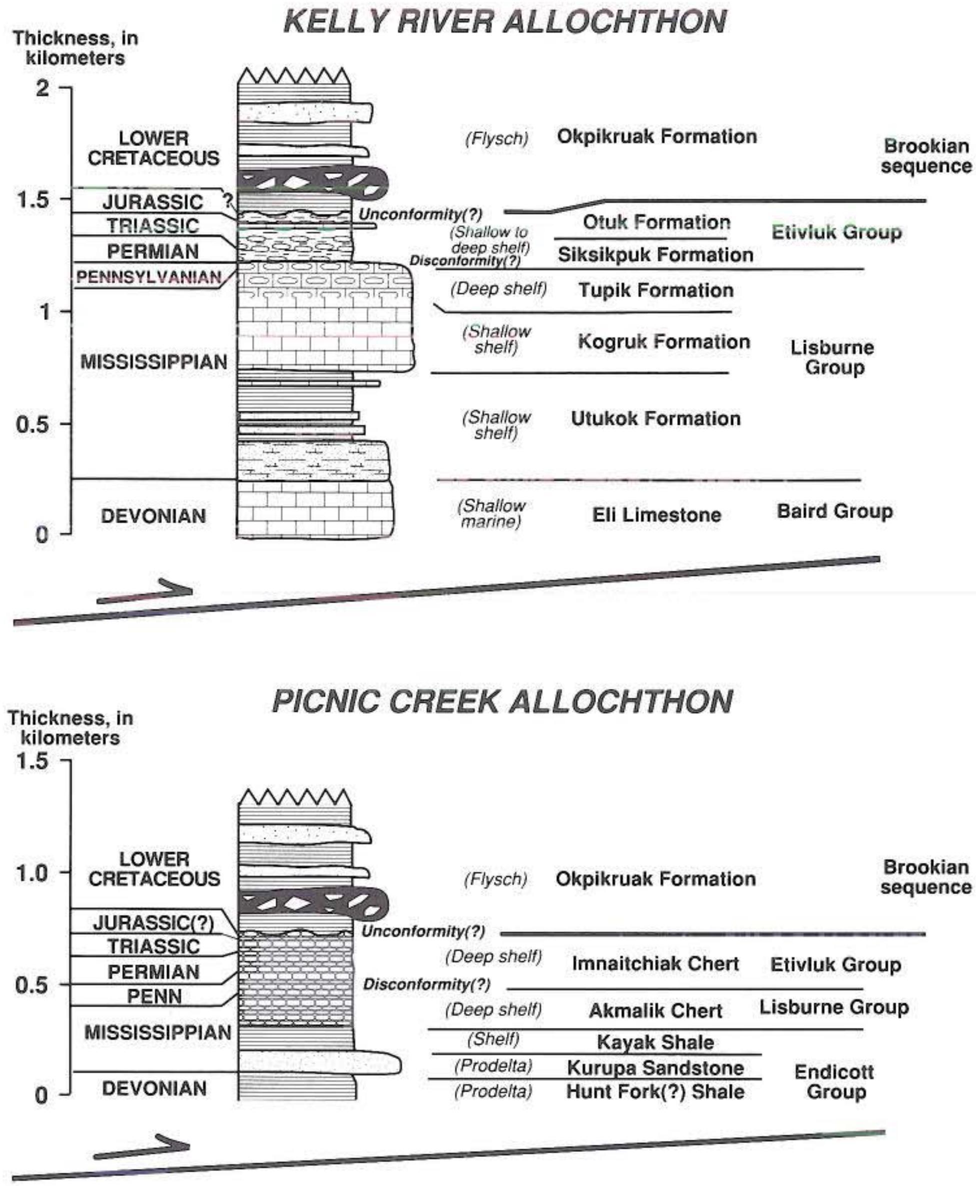
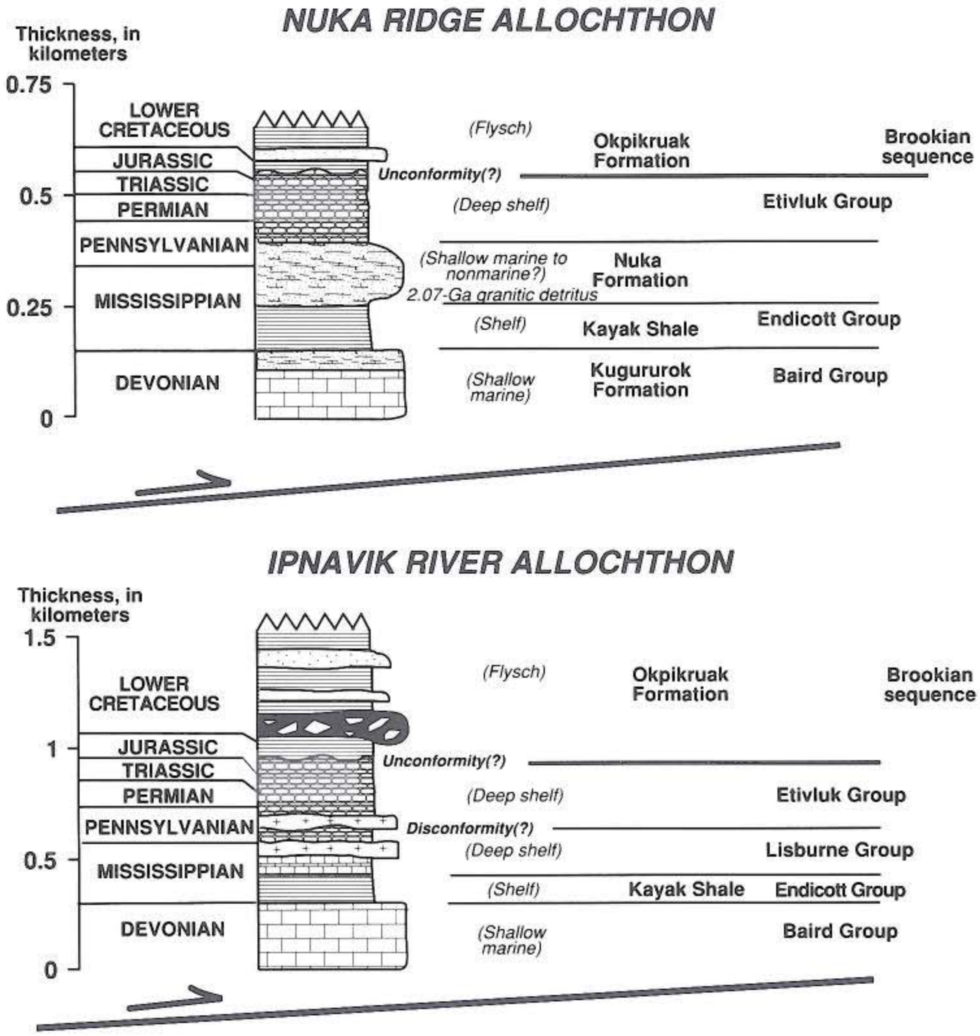


Figure 19. Generalized stratigraphic columns of allochthons of De Long Mountains subterrane, Arctic Alaska terrane. Thicknesses (approximate) from Mayfield and others (1988). Half arrows indicate relative northward thrust movement between allochthons. For explanation of lithologic symbols, see Figure 21.

siltstone, and yellow-orange claystone (8–10 m); (4) interbedded greenish-gray or red siltstone and shale (10–25 m); (5) rhythmically interbedded green and red chert that contains a decreasing amount of shale upsection (10–12 m); and (6) violet-gray chert and cherty siltstone that contain laminae of volcanogenic sandstone and grade upsection into silty shale (>8 m). The Imnaitchiak Chert contains conodonts and abundant radiolarians that indicate a Pennsylvanian and Permian(?) age for most of the unit (Mull and others, 1987b); however, the faunal assemblages may be as old as Late Mississippian (Meramecian to Chesterian) (Siok, 1985; Holdsworth and Murchey, 1988). Radiolarian assemblages at the top of the Imnaitchiak Chert indicate that the unit is as young as "Middle/Late" Triassic (Mull and others, 1987b, p. 650); an unconformity beneath Lower Cretaceous flysch at the top of the unit at the type locality hints at the possibility that elsewhere the Imnaitchiak may include Jurassic strata. The increased proportion and diversity of radiolarians relative to the underlying sponge-spicule–rich Akmalik Chert suggest deposition in relatively deep water in a subsiding, distal-platform environment (Murchey and others, 1988).



Kelly River allochthon. The Kelly River allochthon (Fig. 19), which is prominently exposed in the western Brooks Range, has not been identified east of the Misheguk Mountain quadrangle (Mayfield and others, 1988). The thickness of pre-Cretaceous strata of this allochthon prior to Brookian deformation is estimated to be less than 1500 m (Mayfield and others, 1988). The allochthon consists of strata assigned to the Baird Group, the Lisburne Group, the Etivluk Group, and the Okpikruak Formation.

Baird Group and related units. The term "Baird Group" includes a variety of Devonian and older carbonate units that are presumed to lie stratigraphically below the Lisburne Group (Tailleur and others, 1967). Recent workers, however, have questioned the usefulness of the Baird Group nomenclature and are currently reassessing the classification (see Hammond subterrane).

Thick, northeasterly-striking belts of rock assigned to the Baird Group compose the base of the Kelly River allochthon in the Baird Mountains and Misheguk Mountain quadrangles. In other areas of the Kelly River allochthon, carbonate rocks of the Baird Group are preserved as isolated fault-bounded slivers at the base of the allochthon. The carbonate rocks typically consist of massive to thick-bedded, light gray–weathering limestone and lesser amounts of dark gray–weathering limestone and dolomite; locally the unit contains thin yellowish-brown–weathering silty limestone. Foraminifers, conodonts, and brachiopods indicate Early, Middle, and late Late Devonian (Famennian) ages, but the fossil data may allow ages as old as Silurian and as young as Early Mississippian (Osagean) for various parts of the Baird Group of the Kelly River allochthon (Curtis and others, 1984, 1990; Ellersieck and others, 1984; Mayfield and others, 1984, 1987, 1988).

Recent work on the Baird Group of the Kelly River allochthon in the northwestern Baird Mountains quadrangle has shown that it consists of about 200 m of pelletoidal dolostone and rare metalimestone that contain Early and Middle Devonian (Emsian and Eifelian) conodonts (Karl and others, 1989). These strata are similar in lithofacies and biofacies to carbonate rocks of similar age in the Hammond subterrane (west-central Baird Mountains sequence), exposed immediately to the east, except that they lack

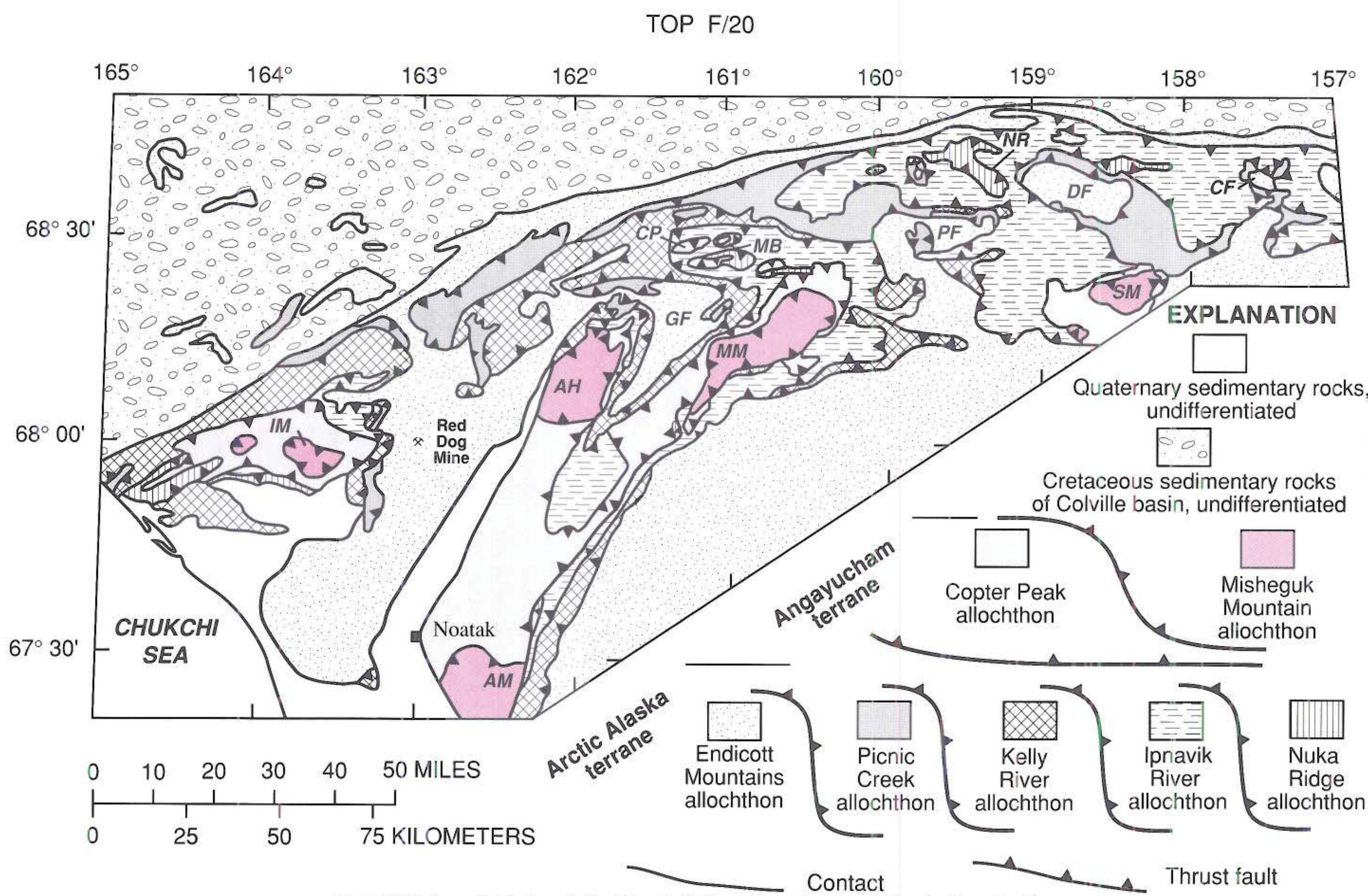


Figure 20. Outcrop distribution of allochthons in De Long Mountains, western Brooks Range (modified from Mayfield and others, 1988). AH, Avan Hills klippe; AM, Asik Mountain klippe; CF, Cutaway fenster; CP, Copter Peak klippe; DF, Drinkwater fenster; GF, Ginny fenster; IM, Iyikrok Mountain klippe; MB, Mount Bastille klippe; MM, Misheguk Mountain klippe; NR, Nuka Ridge klippe; PF, Picnic Creek fenster; SM, Siniktanneyak Mountain klippe.

evidence for blueschist facies metamorphism. These Early and Middle Devonian carbonate rocks of the Kelly River allochthon grade upward into 165 m of bioturbated, laminated, locally argillaceous shallow-marine carbonate rocks assigned to the Eli Limestone of the Baird Group by Tailleur and others (1967). Conodonts from the basal Eli Limestone are Middle Devonian (Givetian), whereas those from near its top are latest Devonian (Famennian) (Karl and Long, 1990).

Lisburne Group. The Lisburne Group in the Kelly River allochthon consists of three formations composed chiefly of carbonate rocks. In ascending order, these are the Utukok Formation, Kogruk Formation, and the Tupik Formation (Sable and Dutro, 1961). In contrast to exposures of the Lisburne Group in other allochthons, the Lisburne Group in the Kelly River allochthon rests conformably on carbonate strata of the Eli Formation rather than on terrigenous clastic rocks of the Endicott Group, which are not present in the Kelly River allochthon. However, the calcareous clastic rocks of the Utukok Formation may be correlative with the Endicott Group of other allochthons (Sable and Dutro, 1961). The Lisburne in the Kelly River allochthon represents progressive onlap onto a shallow platform that slowly subsided through Mississippian time (Armstrong, 1970).

The Utukok Formation (Mississippian), defined by Sable and Dutro (1961) in the Misheguk Mountain quadrangle, consists of interbedded and reddish-brown–weathering, fine-grained, quartzose sandstone, calcareous sandstone, sandy limestone, and gray, calcareous shale. The Utukok Formation is nearly 1000 m thick at its type locality, but it thins to as little as 10 m to the south in the Baird Mountains quadrangle (Sable and Dutro, 1961; J. A. Dumoulin, 1988, written commun.; Karl and others, 1989; Mayfield and others, 1990). At the type locality, sandstone is most abundant in the basal part of the unit, whereas limestone, sandy limestone, and shale are more abundant in the upper part of the unit. The sandstone is thin to medium bedded, consists almost entirely of well-sorted grains of quartz with minor chert and opaque-rich argillite, and is characterized by bioturbation, current-worked megafossils, abundant ripple marks, and small-scale cross-stratification. Megafossils and conodonts from the Utukok indicate an Early Mississippian (Kinderhookian and Osagean) age for the formation, whereas foraminifers indicate an Early and Late Mississippian (Osagean and Meramecian) age (Sable and Dutro, 1961; Curtis and others, 1984, 1990; Ellersieck and others, 1984, 1990; Mayfield and others, 1984, 1987, 1990; Karl and Long, 1990).

The Kogruk Formation (Mississippian and Pennsylvanian), also defined by Sable and Dutro (1961) in the Misheguk Mountain quadrangle, conformably overlies the Utukok Formation and consists of 650 m of light gray weathering, cliff-forming limestone with abundant nodular black chert and silicified zones. The limestone comprises medium-bedded to massive bryozoan-echinoderm packstone and wackestone and lesser amounts of peloidal lime mudstone and ooid grainstone and packstone (Armstrong, 1970). The lower 300 m of the unit is an oolite-bearing transgressive assemblage deposited in shoaling-water and tidal-channel environments. The upper 350 m is a carbonate-platform assemblage deposited in an open-marine to shoaling-water environment on a subsiding shelf on which subsidence and carbonate deposition were in near equilibrium (Armstrong, 1970). Corals, brachiopods, foraminifers, and conodonts indicate Early to Late Mississippian (late Osagean to early Chesterian) ages for the Kogruk in the Kelly River allochthon (Sable and Dutro, 1961; Armstrong, 1970; Curtis and others, 1984, 1990; Ellersieck and others, 1984, 1990; Mayfield and others, 1984, 1987, 1990; Dutro, 1987; J. A. Dumoulin, 1988, written communication), although the Kogruk Formation of the North Slope subterrane on the Lisburne Peninsula is as young as Pennsylvanian (Dutro, 1987).

The uppermost unit of the Lisburne Group in the Kelly River allochthon, the Tupik Formation (Upper Mississippian), consists of subequal amounts of thinly bedded, dark gray limestone and nodular and bedded, spiculitic, black chert that conformably overlie the Kogruk Formation. The Tupik is less than 30 m thick at its type section in the Misheguk Mountain quadrangle, but locally it may be as thick as 230 m (Sable and Dutro, 1961). The formation represents the deep-water assemblage of Armstrong and Bird (1976). Recovered foraminifers and a sparse megafauna indicate a Late Mississippian (Meramecian) age for the unit, but its undated upper part may include Pennsylvanian strata (Sable and Dutro, 1961; Curtis and others, 1984).

Etivluk Group. The Etivluk Group of the Kelly River allochthon consists of relatively nonresistant and poorly exposed, thinly interbedded silicified limestone and mudstone, chert, and shale of the Siksikpuk (20–40 m) and Otuk (20–40 m) formations. These units contain more shale than those of the Etivluk Group of the underlying Picnic Creek and overlying Ipnavik River allochthons, but they are similar to Etivluk Group units of the Endicott Mountains subterrane.

The Siksikpuk Formation (Pennsylvanian, Permian, and Triassic) of the Kelly River allochthon has not been studied in detail; therefore, its stratigraphy is not well known. The lower part of the formation, which may disconformably overlie the Tupik Formation, consists dominantly of chert, locally containing radiolarians, and silicified limestone and mudstone. Higher in the section, the Siksikpuk Formation consists of thinly interbedded, greenish-gray to gray silicified mudstone and nodular bedded chert that grade upward to maroon nodular chert and silicified mudstone with isolated barite crystals. Although the upper part of the Siksikpuk Formation is poorly exposed, it apparently consists of greenish-gray to maroon siltstone and mudstone. Few fossils have been described from Siksikpuk sections of the Kelly River allochthon, but because of the similarity of these sections with dated Siksikpuk sections in the Endicott Mountains subterrane, the Siksikpuk of the Kelly River allochthon is considered to be Pennsylvanian to Triassic (Curtis and others, 1984; Ellersieck and others, 1984; Mayfield and others, 1984).

The Otuk Formation (Triassic and Jurassic) rests conformably on the Siksikpuk Formation (Curtis and others, 1984; Ellersieck and others, 1984; Mayfield and others, 1984). Like the Otuk Formation in the Endicott Mountains subterrane, the Otuk Formation of the Kelly River allochthon can be divided into shale, chert, and limestone members; however, the uppermost member of the Otuk, the Blankenship, has not been recognized in the area of the Kelly River allochthon. The lower part of the chert member of the Otuk Formation consists dominantly of green to greenish-gray or maroon chert beds. Higher up, bedding is thinner and more regular, and yellowish-gray–weathering beds are more common. The lower part of the limestone member consists chiefly of banded, black- and yellowish-gray–weathering silicified limestone beds with abundant *Monotis* fauna. Maroon chert, similar to that in the Siksikpuk Formation, has been observed in the Otuk Formation at several localities in the Kelly River allochthon. Recovered radiolarians and the abundant pelecypod fauna are Late Triassic.

Ipnavik River allochthon. The Ipnavik River allochthon (Fig. 19) comprises the Baird Group, the Endicott Group, the Lisburne Group, the Etivluk Group, and the Okpikruak Formation. In addition, the allochthon is distinguished by many reddish-brown–weathering diabase sills that intrude black chert and limestone of the Lisburne and lower Etivluk groups. Reconstructed pre-Cretaceous strata of this allochthon total less than 900 m thick (Mayfield and others, 1988).

Baird Group. White- to light gray–weathering limestone assigned to the Baird Group is well exposed at the base of the Ipnavik River allochthon in the Picnic Creek fenster in the Misheguk Mountain quadrangle. At this locality, the Baird Group can be divided into a lower unit of limestone and interbedded gray shale (200 m) and an upper unit of massive to thin-bedded, coarse- to fine-grained limestone (500 m) (Mayfield and others, 1988). Sparse fossils, including stromatoporoids, corals, conodonts, brachiopods, and foraminifers, indicate an Early and Middle Devonian and early Late Devonian (Frasnian) age for the lower unit and a late Late Devonian (Famennian) age for the upper unit (Ellersieck and others, 1984; Mayfield and others, 1987, 1990).

Endicott Group. In the Ipnavik River allochthon, the Endicott Group consists only of the Kayak Shale (Mississippian). Here, the Kayak comprises 40 to 70 m of poorly exposed and sparsely fossiliferous, fissile black shale with interbedded orange-weathering limestone, siltstone, and ironstone concretions. Although the Kayak commonly crops out along faults at the base of the allochthon, the shale was originally deposited on carbonate rocks of the Baird Group (Ellersieck and others, 1984; Mayfield and others, 1990). Conodonts from the Kayak of the Ipnavik River allochthon are generally Early Mississippian (Kinderhookian) (Mayfield and others, 1990), but Late Mississippian conodonts were reported by Ellersieck and others (1984). Locally, the unit interfingers with as much as 200 m of buff limestone, sandstone, and gray shale that has been mapped as the Utukok Formation (Lisburne Group) by Mayfield and others (1990).

Lisburne Group. The Lisburne Group of the Ipnavik River allochthon is undivided and consists of as much as 250 m of interbedded black chert, black siliceous shale, and dark gray, laminated micritic limestone and fine-grained dolomite. These rocks overlie the Kayak Shale at a sharp, but conformable, contact (Ellersieck and others, 1984; Mayfield and others, 1984). Black chert, the dominant lithology of the Lisburne Group in this allochthon, is thin bedded and spiculitic and interfingers laterally with the carbonate rocks and siliceous shale of the Lisburne. The carbonate rocks locally compose more than 50% of the unit, are thin bedded, and typically display bioclastic textures. Foraminifers from the Lisburne Group of the Ipnavik River allochthon are Late Mississippian, whereas radiolarians from the unit are Mississippian to Early Pennsylvanian. The abundance of chert interstratified with thin-bedded, fine-grained limestone suggests that the Lisburne Group of the Ipnavik River allochthon is a deep-water assemblage deposited near the edge of a carbonate platform.

Etivluk Group. Although Mayfield and others (1984, 1990) suggested that rocks of the Etivluk Group of the Ipnavik River allochthon be assigned to the Siksikpuk and Otuk formations, the Etivluk Group of the Ipnavik River allochthon is more like the Imnaitchiak Chert of the Picnic Creek allochthon. The Etivluk of the Ipnavik River allochthon consists of a lower unit of gray to maroon chert with minor siliceous argillite and an upper unit of gray to greenish-gray chert with rare, *Monotis*-bearing siliceous limestone that together are 100 m thick (Blome and others, 1988). The base of the Etivluk Group is conformable with the underlying Lisburne Group. Radiolarians, foraminifers, and conodonts indicate a Pennsylvanian and Permian age for the lower part of the Etivluk Group and a Triassic to Early Jurassic (late Pliensbachian to Toarcian) age for the upper part (Mayfield and others, 1984, 1988, 1990; Blome and others, 1988).

Igneous rocks. Diabase sills that intrude the Lisburne Group and lower Etivluk Group of the Ipnavik River allochthon are up to 100 m thick and consist of microgabbro of tholeiitic or mildly alkaline composition (Ellersieck and others, 1984; Mayfield and others, 1984, 1988; Karl and Long, 1990). Several geochemical analyses from sills in the Misheguk Mountain quadrangle display nearly flat rare earth element patterns, suggesting that the sills were extruded at a mid-ocean ridge, continental margin, or ocean island (Moore, 1987b). No definitive radiometric dates have been obtained from these igneous rocks; therefore, their age, post–Early Mississippian, can be delimited only by stratigraphic relations.

Nuka Ridge allochthon. The Nuka Ridge allochthon, the highest of the allochthons of the De Long Mountains subterrane, is distinguished by an unusual, widespread arkosic limestone of Carboniferous age (Fig. 19). Although extensive exposures of the allochthon are limited to the Nuka Ridge and Mount Bastille klippen (Fig. 20) in the Misheguk Mountain quadrangle, the arkosic rocks are imbricated with Cretaceous strata in a number of widely scattered localities from the Chukchi Sea coast to the Chandler Lake quadrangle. Some of these exposures are clearly fault-bounded slivers, but many others are isolated blocks as much as a few tens of meters in maximum dimension; some of these may be olistoliths in the Upper Jurassic and Lower Cretaceous Okpikruak Formation. The maximum thickness of reconstructed pre-Cretaceous strata of the allochthon is probably less than 600 m thick, although the allochthon is as thick as 1.5 km due to structural repetition (Mayfield and others, 1988). The allochthon consists of strata assigned to the Baird Group, Endicott Group, Nuka Formation, Etivluk Group, and Okpikruak Formation.

Baird Group. In the Nuka Ridge allochthon, the Baird Group consists of the Kugururok Formation (Devonian) (Sable and Dutro, 1961). The lower part of the Kugururok as mapped by Ellersieck and others (1984) is about 300 m thick and consists of calcareous shale and minor hematite-bearing conglomeratic limestone overlain by massive to thin-bedded limestone and dolomite with sparse chert lenses. The upper part of the formation consists of 125 m of light colored, locally glauconitic, laminated to cross-bedded limestone, and toward the top of the formation, the limestone contains as much as 15% potassium feldspar grains (Sable and Dutro, 1961; Ellersieck and others, 1984). Megafossils and conodonts from the lower Kugururok indicate a Middle and Late Devonian (Givetian and Frasnian) age (Sable and Dutro, 1961; Ellersieck and others, 1984), but Ellersieck and others (1984) and Mayfield and others (1990) suggested that the feldspar-bearing uppermost part of the unit may be equivalent to the Upper Mississippian and Lower Pennsylvanian(?) Nuka Formation.

Endicott Group. The Endicott Group in the Nuka Ridge allochthon is represented only by the Kayak Shale (Mississippian). Here, the Kayak consists of as much as 350 m of poorly exposed, fissile black shale with minor interbedded reddish-brown–weathering bioclastic limestone and fine-grained sandstone that is locally feldspathic. Where exposed, the Kayak Shale is bounded at the base by a thrust fault, but it may stratigraphically pinch out within the allochthon. Mayfield and others (1984, 1987) reported that the Kayak Shale contains Mississippian foraminifers and brachiopods.

Nuka Formation. The Nuka Formation (Mississippian and Pennsylvanian?) consists of as much as 300 m of interbedded, light gray–weathering limestone to arkosic limestone, arkose, and quartzose sandstone that rest conformably on the Kayak Shale. In the area of Nuka Ridge in the Misheguk Mountain quadrangle (Tailleur and Sable, 1963; Tailleur and others, 1973), the Nuka Formation consists of massive to medium-bedded, fine-grained to very coarse grained sandstone and minor granule conglomerate that display parallel stratification and abundant tabular and trough cross-stratification. Strata of this area also exhibit many diagnostic features of a shallow-marine environment, including herringbone cross-stratification, inclined lamination, calcareous and bright green glauconitic zones, and beds rich in marine fossils. Elsewhere, however, Nuka sections display a prominent red coloration and sedimentary structures suggestive of nonmarine deposition or other sedimentary structures indicative of turbidite deposition. Sandstone and limestone of the Nuka Formation contain abundant, unweathered, coarse-grained, subangular potassium feldspar grains indicative of a nearby granitic source area. Uranium-lead isotopic ages of detrital zircons in the sandstone indicate that the granitic rocks from which the arkose was derived had an age of about 2.07 Ga (Hemming and others, 1989). This age is older than any known granitic source in northern Alaska. Although the abundant megafauna in the Nuka Formation was originally interpreted to range from Mississippian to Permian (Tailleur and Sable, 1963), foraminifers and conodonts indicate that the Nuka ranges only from Late Mississippian (late Meramecian) to Early Pennsylvanian(?) (early Morrowan?) (Mayfield and others, 1984, 1987, 1990).

Etivluk Group. The Etivluk Group of the Nuka Ridge allochthon consists of less than 150 m of gray and greenish-gray to maroon chert and minor shale to siliceous shale. The chert is typically well bedded and contains abundant Late Triassic radiolarians; the upper part of the sequence also contains rare *Monotis* fossils (Mayfield and others, 1984; T. E. Moore, 1985, unpublished data). Mayfield and others (1984) reported that the Etivluk Group rests conformably on the Nuka Formation and that, locally, chert at the base of the Etivluk Group contains feldspar grains, which supports their interpretation. Although this cherty succession of the Etivluk Group has been assigned to the Siksikpuk and Otuk formations (Mayfield and others, 1987), it is lithologically similar in most respects to the Imnaitchiak Chert of the Picnic Creek allochthon. On the basis of megafossils and the stratigraphic position, Mayfield and others (1984) considered the Etivluk of the Nuka Ridge allochthon to be Pennsylvanian to Jurassic.

Deposits of the Brookian sequence (Okpikruak Formation) in the De Long Mountains subterrane. The Upper Jurassic and Lower Cretaceous Okpikruak Formation (Gryc and others, 1951; Mayfield and others, 1988) consists of flysch that is widely exposed in the northern foothills of the central and western Brooks Range. The Okpikruak rests unconformably on the Etivluk Group of the Picnic Creek, Kelly River, Ipnavik River, and Nuka Ridge allochthons of the De Long Mountains subterrane, but the structural position of many other outcrops of the Okpikruak is difficult to determine because of poor exposure and structural complexity. Although detailed petrographic descriptions of the Okpikruak Formation of the Picnic Creek allochthon were provided by Wilbur and others (1987) and Siok (1989) for a few localities in the central Brooks Range, only generalized descriptions are available for the unit in most areas (for example, Patton and Tailleur, 1964).

In the De Long Mountains subterrane, the Okpikruak Formation consists of thin- to thick-bedded, fine- to coarse-grained lithic sandstone and gray, brown, or black shale and mudstone. Lenticular units of polymict pebble to boulder conglomerate and pebbly mudstone are locally present in beds as thick as 50 m. Clasts in the conglomerate are rounded to angular and consist of chert, limestone, granitic rocks, and felsic and mafic volcanic rocks. Thick intervals of fine-grained strata are common in the unit, although sandstone-to-shale ratios are as high as 5:1 for some intervals. Sedimentary structures in sandstone beds include flute casts, tool marks, ripple cross-lamination, graded bedding, shale rip-up clasts, starved ripples, and Bouma sequences. In the Okpikruak Formation of the Nuka Ridge allochthon, conglomerate and coarse-grained sandstone appear to be absent, but calcareous concretions are common. A maximum thickness of more than 1000 m is estimated for the Okpikruak in the Picnic Creek, Kelly River, and Ipnavik River allochthons, but a thickness of only 200 m has been reported for the unit in the Nuka Ridge allochthon (Curtis and others, 1984).

Sandstone of the Okpikruak Formation in the Picnic Creek allochthon in the Killik River and Chandler Lake quadrangles contains moderate to high proportions of lithic grains, including chert, volcanic, and clastic-sedimentary rocks. Although the lithic proportions of these rocks vary widely with location, the proportions indicate derivation from mixed magmatic-arc and recycled-orogen provenances (Wilbur and others, 1987; Siok, 1989). Siok (1989) concluded from sedimentologic evidence that these strata were deposited at bathyal to abyssal depths in the inner to middle, and possibly outer, regions of a submarine fan.

Olistostromes, locally present in the Okpikruak Formation in all except the Nuka Ridge allochthon, are the most widespread and have the most diverse olistolith compositions in the Ipnavik River allochthon. The olistoliths, some more than 10 m in diameter, consist of chert, mafic rocks, limestone, and arkosic limestone (Mull, 1979) that were derived from the Angayucham terrane and the Baird Group, Kogruk Formation, Nuka Formation, and Etivluk Group of the De Long Mountains subterrane (Mull, 1979; Crane, 1987; Curtis and others, 1990). Mull and others (1976) and Crane (1987) suggested that the olistostromes were deposited by debris flow and submarine gravity sliding adjacent to a tectonically active area.

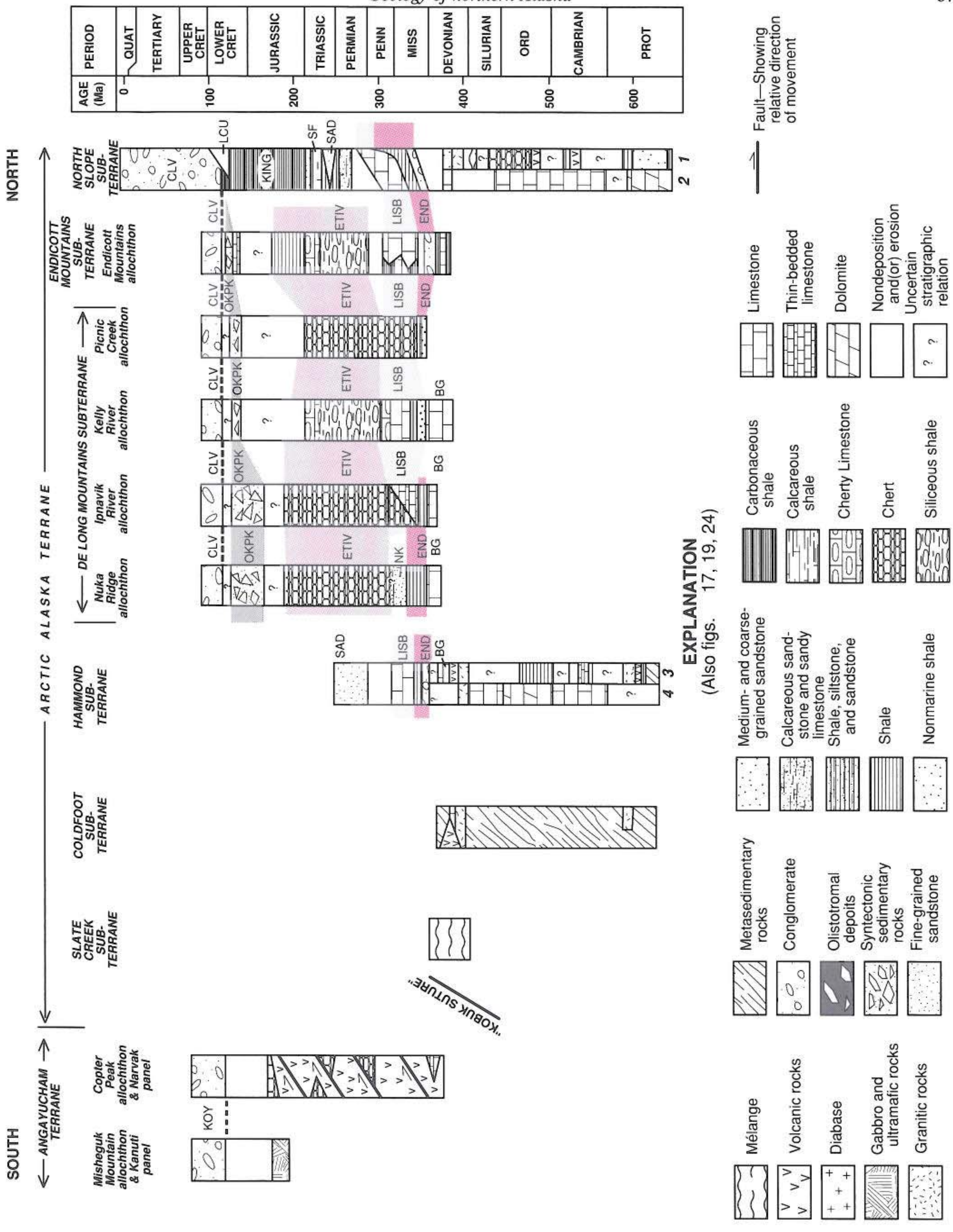
Fossils are rare in the Okpikruak and consist of various species of *Buchia* pelecypods that indicate a mainly Neocomian age for the formation (Jones and Grantz, 1964; Patton and Tailleur, 1964). Where assigned to the Picnic Creek allochthon in the Chandler Lake, Killik River, and De Long Mountains quadrangles, and the Kelly River allochthon in the Misheguk Mountain quadrangle, the *Buchia* fossils indicate a Valanginian (Early Cretaceous) age for at least part of the unit (Curtis and others, 1984; Wilbur and others, 1987; Mayfield and others, 1988; Ellersieck and others, 1990). Both Berriasian and Valanginian species of *Buchia* have been recovered in Okpikruak strata of the Ipnavik River allochthon in the Misheguk Mountain quadrangle (Curtis and others, 1984); no fossils have been reported from Okpikruak strata of the Nuka Ridge allochthon. Okpikruak strata in the De Long Mountains quadrangle have yielded a *Buchia* of Late Jurassic age, but the outcrop from which the fossil was recovered may be assigned to either the Kelly River, Ipnavik River, or Nuka Ridge allochthons (Curtis and others, 1990). These data suggest that the Okpikruak Formation of structurally higher allochthons of the De Long Mountains subterrane was deposited earlier than the remainder of the formation of underlying allochtons (Mayfield and others, 1988).

Hammond subterrane

The Hammond subterrane extends for nearly 800 km along most of the length of the southern Brooks Range and includes most of the rocks of the central belt (Figs. 2 and 3). The Hammond subterrane consists of a structurally imbricated assemblage of thick carbonate and clastic units with phyllitic and schistose textures and greenschist and locally blueschist and amphibolite facies metamorphic mineral assemblages (Jones and others, 1987). Deformational fabrics, typically inhomogeneous, vary from penetrative to nonpenetrative; however, relict sedimentary and igneous textures are commonly preserved. Some local allochthonous sequences have been identified within the Hammond subterrane, but their regional extent is not fully known (for example, Kugrak River allochthon of Mull and others, 1987c; Skajit allochthon of Oldow and others, 1987d). Fossils, found primarily in carbonate rocks, are rare, but they indicate that much of the subterrane consists of lower Paleozoic rocks. Isotopic ages from sparse granitic rocks intruding the terrane yield Late Proterozoic and Devonian ages and indicate the presence of Precambrian basement rocks in the subterrane (Fig. 21).

Because of limited age control, metamorphism, and structural complications, the stratigraphy of the Hammond subterrane is poorly known; stratigraphic studies of the subterrane have been concentrated mainly in the Baird Mountains quadrangle and along the Dalton Highway. For the purpose of this discussion, we divide the rocks of the subterrane into several general lithologic assemblages: (1) Proterozoic and Proterozoic(?) metasedimentary and metavolcanic rocks; (2) thick units of pre-Mississippian carbonate rocks assigned to the Baird Group; (3) lower Paleozoic metasedimentary rocks; (4) metasedimentary rocks assigned to the Devonian Beaucoup Formation and the Hunt Fork Shale; (5) upper Paleozoic carbonate and metaclastic rocks assigned to the Endicott, Lisburne, and Sadlerochit(?) groups; and (6) metagranitic rocks. Stratigraphic relations within and between the various assemblages are controversial, and future work may indicate that the assemblage comprises two or more tectonostratigraphic units.

Figure 21. Generalized stratigraphic columns for Arctic Alaska and Angayucham terranes. Subterranes and terranes are shown in present relative positions; allochthons of De Long Mountains subterrane are shown in restored positions relative to one another (Mayfield and others, 1988). Shaded regions highlight selected rock units; dashed line indicates base of overlapping sedimentary rocks of Colville and Koyukuk basins. Subcolumn 1, undivided pre-Mississippian rocks of North Slope subterrane in northeastern salient of Brooks Range, except Sadlerochit and Shublik mountains; subcolumn 2, pre-Mississippian carbonate succession in Sadlerochit and Shublik mountains; subcolumn 3, undivided pre-Mississippian rocks of Hammond subterrane; subcolumn 4, pre-Mississippian rocks of Baird Group in Baird Mountains quadrangle. Abbreviations: BG, Baird Group; CLV, Brookian sequence in Colville basin; END, Endicott Group; ETIV, Etivluk Group; KING, Kingak Shale; KOY, sedimentary rocks of Koyukuk basin; LCU, Lower Cretaceous unconformity; LISB, Lisburne Group; NK, Nuka Formation; OKPK, Okpikruak Formation; SAD, Sadlerochit Group; SF, Shublik Formation. Absolute time scale from Palmer (1983).


SOUTH
NORTH
ANGAYUCHAM TERRANE
ARCTIC ALASKA TERRANE
Misheguk Mountain allochthon & Kanuti panel
Copter Peak allochthon & Narvak panel
SLATE CREEK SUBTERRANE
COLDFOOT SUBTERRANE
HAMMOND SUBTERRANE
DE LONG MOUNTAINS SUBTERRANE
Nuka Ridge allochthon
Ipnavik River allochthon
Kelly River allochthon
Picnic Creek allochthon
ENDICOTT MOUNTAINS SUBTERRANE
Endicott Mountains allochthon
NORTH SLOPE SUBTERRANE
"KOBUK SUTURE"
KOY
CLV
OKPK
ETIV
LISB
END
BG
NK
KING
LCU
SF
SAD
AGE (Ma)
PERIOD
QUAT
TERTIARY
UPPER CRET
LOWER CRET
JURASSIC
TRIASSIC
PERMIAN
PENN
MISS
DEVONIAN
SILURIAN
ORD
CAMBRIAN
PROT
0
100
200
300
400
500
600
EXPLANATION
(Also figs. 17, 19, 24)
Mélange
Volcanic rocks
Diabase
Gabbro and ultramafic rocks
Granitic rocks
Metasedimentary rocks
Conglomerate
Olistotromal depoits
Syntectonic sedimentary rocks
Fine-grained sandstone
Medium- and coarse-grained sandstone
Calcareous sandstone and sandy limestone
Shale, siltstone, and sandstone
Shale
Nonmarine shale
Carbonaceous shale
Calcareous shale
Cherty Limestone
Chert
Siliceous shale
Limestone
Thin-bedded limestone
Dolomite
Nondeposition and(or) erosion
Uncertain stratigraphic relation
Fault—Showing relative direction of movement

Proterozoic and Proterozoic(?) metasedimentary and metavolcanic rocks. Although Proterozoic rocks of the Hammond subterrane have been recognized only in structural culminations at Mount Angayukaqsraq in the northeastern Baird Mountains quadrangle and near Ernie Lake in the Wiseman and Survey Pass quadrangle, Proterozoic rocks may be more widespread throughout the subterrane (Dillon and others, 1986; Karl and others, 1989; Till, 1989). At Mount Angayukaqsraq, Proterozoic rocks consist of two imbricated lithologic assemblages. The structurally lower assemblage consists mainly of undated dolostone, metalimestone, and marble with subordinate intercalated phyllite, quartzite, carbonate-cobble metaconglomerate, and metabasite. The dolostone contains well-preserved stromatolitic mounds, fenestral fabrics, oolitic intraclasts, and grainstone that contains ooids, composite grains, and pisoids. Together these features suggest an intertidal to shallow subtidal depositional environment (Dumoulin, 1988). The intercalated metabasite displays massive, layered, pillowed, and pillow-breccia structures. The structurally higher assemblage contains interleaved metavolcanic and metasedimentary units with well-developed metamorphic fabrics and no relict sedimentary or volcanic structures. The metasedimentary unit consists of interlayered quartzite, micaceous quartzite, calc-schist, pelitic schist, and garnet amphibolite that are intruded by granitic rocks. The granitic rocks yielded a U-Pb zircon age of 750 ± 6 Ma (Karl and others, 1989). Hornblende and white mica K-Ar and Rb-Sr ages on rocks of the metasedimentary unit suggest that amphibolite facies metamorphism occurred at about 655 to 594 Ma (Turner and others, 1979; Mayfield and others, 1982; Armstrong and others, 1986). The metavolcanic unit, also intruded by Proterozoic granitic rocks, contains thick bodies of massive to crudely layered metabasite that are interlayered with thinner lenses of carbonate rock. Relict green hornblende found in the cores of blue amphibole of the metabasite (A. B. Till, oral commun., cited *in* Karl and others, 1989) indicate that these rocks were also affected by the Proterozoic amphibolite facies metamorphic event and were overprinted by blueschist facies assemblages in Mesozoic time (Karl and others, 1989; Till, 1989). The metavolcanic unit has yielded K-Ar hornblende ages of 729 ± 22 and 595 ± 30 Ma (Turner and others, 1979; Mayfield and others, 1982).

In the Ernie Lake area, Proterozoic(?) granitic gneiss intrudes interlayered quartz-mica schist, quartzite, metaconglomerate, marble, graphitic phyllite, calcareous schist, and metabasite (banded schist unit of Dillon and others, 1986). These rocks have not been investigated in detail; they are the structurally lowest rocks in the area and may extend eastward along the southern margin of the Hammond subterrane into the vicinity of the Proterozoic rocks at Mount Angayukaqsraq (W. P. Brosgé, 1988, oral commun.; Till, 1989).

Massive carbonate units of the Baird Group. The Hammond subterrane is characterized by widespread, prominent units of thick-bedded to massive, light gray limestone, dolostone, and marble as much as 1 km thick. These thick carbonate bodies extend over distances of 50 km or more and wedge out laterally into thinner carbonate units that are interlayered with metaclastic rocks. Mapping suggests that the lateral changes in thickness of these carbonate units may result from facies changes, as well as structural truncation along low-angle faults. Schrader (1902) gave the name Skajit Formation to one of these carbonate massifs, a 400-m-thick sequence of unfossiliferous marble (Henning, 1982) along the John River in the southern Wiseman quadrangle. Smith and Mertie (1930) later extended the formation to include most of the thick, massive carbonate units throughout the southern Brooks Range and renamed the formation the Skajit Limestone. Rare megafossils of Silurian and Devonian age were recovered from some of these limestone bodies in both the eastern and western Brooks Range, leading most workers to conclude that the Skajit Limestone is a regional stratigraphic marker unit of middle Paleozoic age (Brosgé and others, 1962, 1979; Tailleur and others, 1967; Oliver and others, 1975; Mayfield and Tailleur, 1978; Nelson and Grybeck, 1980; Dillon and others, 1986; Dillon, 1989).

To distinguish the Skajit Limestone and other older carbonate units in the southern Brooks Range from the upper Paleozoic Lisburne Group, Tailleur and others (1967) defined the Baird Group to consist of the Skajit Limestone, Kugururok Formation, and Eli Limestone (the latter two herein included in the De Long Mountains subterrane), and other unnamed carbonate units. They also suggested that the Baird Group represents remnants of a once-widespread carbonate-platform succession of largely Devonian age. However, subsequent recovery of Ordovician graptolites from the Baird Group (Carter and Tailleur, 1984) and the detailed micropaleontologic investigations of Dillon and others (1987a), Dumoulin and Harris (1987), and Dumoulin (1988) have revealed that the Baird Group consists of two or more successions of carbonate strata of mainly early Paleozoic age. These data have raised questions about the correlation and the stratigraphic usefulness of the various carbonate bodies assigned to the Skajit Limestone and the Baird Group as a whole.

The most detailed work on the carbonate rocks of the Baird Group is the conodont biostratigraphy and associated sedimentary facies studies of Dumoulin and Harris (1987), who have recognized two distinctive metacarbonate sequences, the northeastern carbonate sequence and the west-central carbonate sequence, in the Baird Mountains quadrangle in the western Brooks Range. Both sequences are tectonically disrupted, so they were reconstructed from incomplete, but overlapping, sections in different thrust sheets.

The northeastern carbonate sequence in the Baird Mountains quadrangle consists of at least 360 m of Middle Cambrian to Upper Silurian and Devonian(?) metalimestone and dolostone. The Middle and Upper Cambrian rocks grade upward from massive marble to thin-bedded metalimestone-dolostone couplets that contain mollusks, acrotretid brachiopods, and agnostid trilobites. These rocks were deposited under shallow-marine conditions (Dumoulin and Harris, 1987). The Cambrian rocks are overlain by Lower and Middle Ordovician metalimestone and graptolitic phyllite. Graptolites and conodonts indicate that the

Ordovician rocks were deposited in cool-water, mid-shelf to basinal conditions (Carter and Tailleur, 1984; Dumoulin and Harris, 1987). Upper Ordovician rocks of the sequence consist of bioturbated to laminated dolostone containing warm, shallow-marine conodonts, whereas Upper Silurian rocks consist of thinly laminated dolomitic mudstones that were deposited in a restricted shallow-marine environment. A few conodont species from the succession range into the Devonian, but no uniquely Devonian conodonts have been recovered. Although the geographic extent of this sequence is unknown, lithofacies similar to those of this sequence are found as far east as the Dalton Highway.

The 1200-m-thick west-central carbonate sequence of the Baird Mountains quadrangle consists largely of Ordovician metalimestone with Silurian dolostone and Devonian metalimestone (Dumoulin and Harris, 1987). The Lower Ordovician rocks consist of argillaceous metalimestone deposited in a normal-marine environment and fenestral dolostone deposited in a shallow-water, locally restricted platform environment. Middle Ordovician rocks consist partly of dolostone that was deposited in a warm, very restricted, shallow-water, innermost platform environment, whereas sparse Upper Ordovician rocks are metalimestone that was deposited in a cool and deep-water environment. Middle and Upper Silurian rocks consist of at least 100 m of shallow-water dolostone that may unconformably overlie the older rocks. Devonian rocks, widely exposed in the west-central sequence, conformably overlie the Silurian dolostone and consist of fossiliferous metalimestone deposited in a range of normal-marine to slightly restricted shelf environments. This sequence, which appears to be restricted to the southwestern Brooks Range, is found in a structurally higher position than the northeastern carbonate sequence. Lower and Middle Ordovician strata of the west-central carbonate sequences are not recognized outside the Baird Mountains quadrangle in the southern Brooks Range, but these strata show many similarities in biofacies and lithofacies to age-equivalent rocks of the York Mountains terrane on the Seward Peninsula. Harris and others (1988) reported that these Lower and Middle Ordovician strata contain a significant proportion of conodont species that are of Siberian provincial affinity.

Lower Paleozoic metasedimentary rocks. In the Baird Mountains quadrangle, lower Paleozoic metaclastic and metavolcanic rocks of the Tukpahlearik Creek unit of Karl and others (1989) are situated between thrust sheets containing the contrasting sequences of carbonate rocks of the Baird Group as described by Dumoulin and Harris (1987). The Tukpahlearik Creek unit consists of black carbonaceous quartzite and siliceous argillite with lenses of dolostone and marble, pelitic schist, chert-pebble metaconglomerate, calc-schist, thin-bedded micaceous marble, and metabasite. Karl and others (1989), who recovered Ordovician conodonts from a dolostone lens in the black quartzite, inferred a basinal depositional environment for these rocks.

Cambrian and Ordovician metaclastic rocks have been reported from near the Dalton Highway in the Hammond subterrane by Dillon and others (1987a). The Cambrian rocks are at least 100 m thick and consist of thin-bedded, red-weathering, phyllitic, calcareous siltstone and sandstone with intercalated black, carbonaceous phyllite. A thin but massive limestone unit, which forms the uppermost part of the sequence, contains Middle Cambrian phosphatic brachiopods and trilobites that Palmer and others (1984) considered similar to those in open-shelf facies of the Siberian platform. However, recent mapping shows that the trilobite-bearing limestone has ambiguous relations with both the metaclastic rocks and marble of the Skajit Limestone and may well be a fault slice of the Skajit Limestone (T. E. Moore, 1990, unpublished data). Dillon and others (1987a) inferred that the Cambrian rocks are overlain by at least 50 m of imbricated thin-bedded, black, carbonaceous phyllite and crinoidal limestone that are interstratified with thick-bedded marble and sparse thin-bedded, black quartzite and calcareous sandstone. Conodonts from the basal part of the black phyllite and crinoidal limestone unit are late Early Ordovician (middle Arenigian) and those in the uppermost part are Late Ordovician (Caradocian or younger) (Dillon and others, 1987a). These carbonaceous Ordovician rocks represent a basinal or off-platform depositional environment, but their relation to the assumed underlying rocks is uncertain because of extensive faulting.

Devonian metasedimentary rocks. Rocks exposed extensively in the Hammond subterrane, especially its northern part, compose a foliated, imbricated assemblage of black calcareous phyllite, calcareous chlorite phyllite, black siliceous phyllite, maroon and green phyllite, argillite- and limestone-pebble conglomerate, metagraywacke, mafic pillowed flows and volcaniclastic rocks, quartz- and chert-pebble conglomerate, quartzose sandstone, and lenticular limestone bodies. Stratigraphy of the assemblage is ambiguous due to variations in thickness, in proportion of rock types, and in stacking order. In the Wiseman quadrangle, Dillon and others (1986) divided the assemblage into three primary units: (1) a lower, unnamed unit of coarse-grained, siliceous, clastic metasedimentary rocks; (2) a middle, heterogenous unit locally assigned to the Beaucoup Formation; and (3) an upper unit of phyllite and slate assigned to the Hunt Fork Shale. Metamorphosed volcanic rocks and diabase are present locally in all three units.

The lowest unit consists of complexly interlayered and metamorphosed calcareous, chloritic siltstone, sandstone, and quartz conglomerate. Dillon (1989) reported that these rocks rest unconformably on Cambrian and Ordovician metasedimentary rocks and grade laterally and upward into the Skajit Limestone and associated metamorphosed silicic volcanic rocks and volcanogenic graywacke informally named the "Whiteface Mountain volcanics" (Dillon, 1989). Although no fossils have been recovered from the lowest unit, Dillon (1989) inferred a Middle Devonian age.

Where mapped as part of the Hammond subterrane in the Wiseman quadrangle, the Beaucoup Formation (Devonian) (Dutro and others,1979) consists of, from base to top, (1) black calcareous phyllite, siltstone, and other fine-grained rocks; (2) lenticular bodies of fossiliferous limestone or marble containing Middle and Late Devonian (Givetian and Frasnian) brachiopods and conodonts; and (3) calcareous, chloritic phyllite, metasandstone, and metaconglomerate (Dillon and others, 1986). These rocks have been correlated with the Beaucoup Formation of the Endicott Mountains subterrane because of their similarity in overall lithology and in age of enclosed carbonate strata and because of their structural proximity to the Endicott Mountains subterrane.

Dillon (1989) hypothesized that the Beaucoup Formation in the Hammond subterrane is characterized by complex facies changes. He suggested that the lenticular bodies of Devonian limestone of the middle Beaucoup grade laterally and downward into the carbonate massifs of the Skajit Limestone. To the west, where the Skajit is absent, the upper Beaucoup Formation grades laterally and downward into thick units of the Devonian metagraywacke and felsic metavolcanic rocks of Dillon's Whiteface Mountain volcanics. Dillon (1989) interpreted the metavolcanic rocks as the volcanic equivalents of Devonian plutonic rocks exposed elsewhere in the subterrane and correlative with the Ambler sequence of the Coldfoot subterrane. Associated rock units representing local facies of the clastic upper part of the Beaucoup Formation include quartzitic schist and metaconglomerate, calcareous schist and phyllite, chlorite-rich metasiltstone and phyllite, and quartz conglomerate (Dillon and others, 1987a). Units of black metachert and argillaceous, thin-bedded carbonate rocks were interpreted as facies of the lower black phyllite unit of the Beaucoup. All these associated units are unfossiliferous, and many are exposed over wide areas of the Hammond subterrane. Recent conodont biostratigraphic studies and new structural data (Moore and others, 1991), however, suggest that many of the rocks currently assigned to the Beaucoup Formation in the Hammond subterrane may be parts of allochthonous sequences that are unrelated, or only partly related, to each other and to the type section of the Beaucoup Formation in the Endicott Mountains subterrane.

Where mapped in the Hammond subterrane, rocks assigned to the Hunt Fork Shale consist of an undetermined thickness of noncalcareous, black and dark gray slate and phyllite that weather dark brown. Interstratified metasandstone beds are sparse but are locally concentrated at the base of the unit, along with stretched quartz- and chert-pebble conglomerate (Brosgé and Reiser, 1964; Dillon and others, 1986). Relict siltstone and very fine sandstone laminae indicate that the protolith of the slate and phyllite was mud-rich turbidites. Fossils are absent in these rocks; therefore, a Late Devonian age for the Hunt Fork of the Hammond subterrane is inferred on the basis of lithologic correlation to the fossiliferous Upper Devonian Hunt Fork Shale of the Endicott Mountains subterrane. Dillon (1989) concluded that in the Hammond subterrane the Hunt Fork Shale rests on a regional unconformity marked by local conglomeratic beds but locally grades downward into clastic rocks of the Beaucoup Formation.

Mississippian to Permian(?) rocks. Restricted exposures of the Endicott, Lisburne, and Sadlerochit(?) groups in the Schwatka Mountains (Fig. 1) (Ambler River and Survey Pass quadrangles) are the youngest strata included in the Hammond subterrane (Fig. 21). Mull and Tailleur (1977), Tailleur and others (1977), and Mull (1982) compared the Schwatka Mountains succession to the lower Ellesmerian sequence at the Mt. Doonerak fenster in the North Slope subterrane. However, the upper Paleozoic rocks of the Hammond subterrane differ from those in the Mt. Doonerak fenster in that (1) the former rest on granitic rocks and on carbonate rocks of the Baird Group instead of on clastic and mafic volcanic rocks as in the Mt. Doonerak fenster and (2) existing mapping indicates that the Schwatka Mountains succession does not occur in a structural window like that at Mt. Doonerak.

Endicott Group. The structurally lowest unit in the upper Paleozoic Schwatka Mountains succession is the Kekiktuk Conglomerate; it consists of 100 to 200 m of cross-stratified quartzite and stretched pebble to cobble conglomerate with intercalated red, green, and gray phyllite. These rocks unconformably overlie Devonian granitic rocks (Mull and Tailleur, 1977; Mull, 1982; Mull and others, 1987c) and older carbonate rocks of the Baird Group (Tailleur and others, 1977; Mayfield and Tailleur, 1978; Nelson and Grybeck, 1980), although Till and others (1988) interpreted the basal contact as a fault. The Kekiktuk Conglomerate grades upward into less than 300 m of Kayak Shale, including black carbonaceous phyllite, slate, and argillite with thin, red-weathering, fossiliferous limestone interbeds. These rocks are commonly tectonically thickened but may lie unconformably on older rocks in the Survey Pass and the Baird Mountains quadrangles (Nelson and Grybeck, 1980; Karl and others, 1989). Conodonts from the Kayak in the Ambler River quadrangle indicate an Early Mississippian (Osagean) age (Tailleur and others, 1977), whereas megafossil and microfossil assemblages from the Kayak in the Survey Pass quadrangle are Late Devonian (late Famennian) to Early Mississippian (Kinderhookian) and Late Mississippian (Nelson and Grybeck, 1980).

Lisburne Group. The Lisburne Group in the Schwatka Mountains consists of about 100 m of medium- to thick-bedded, gray to black limestone and white dolomite that are commonly replaced with nodular chert; thin, irregular chert beds are also present near the base of the unit. The Lisburne is deformed and locally metamorphosed to marble. Microfossils from the basal part of the group in this area are Early Mississippian (no younger than Osagean), whereas microfossils from the uppermost part of the group are Late Mississippian (late Meramecian to Chesterian) (I. L. Tailleur, 1988, oral commun.). Megafossils from the Lisburne in this area are also Early and Late Mississippian (Mayfield and others, 1978).

Sadlerochit(?) Group. Rocks mapped by Mayfield and Tailleur (1978) as the Sadlerochit(?) Group at Shishakshinovik Pass in the Schwatka Mountains consist of a schistose and reddish-brown–weathering succession of calcareous, fine-grained quartzose sandstone and interbedded siltstone that grades upward into black phyllitic shale. These rocks, less than 100 m thick, are well bedded and overlie the Lisburne Group on a probable disconformity. No fossils have been recovered from these rocks, but their lithology and stratigraphic position suggest a possible correlation with the clastic rocks of the Sadlerochit Group mapped elsewhere (Mull and Tailleur, 1977; Tailleur and others, 1977; Mayfield and Tailleur, 1978).

Metagranitic rocks. Metagranitic rocks of Proterozoic and Devonian age have been recognized in the Hammond subterrane (Plate 13). The Proterozoic metagranitic rocks comprise widely scattered, typically fault-bounded stocks and small plutons along the southern margin of the subterrane. The best studied of these are the intrusive rocks at Mount Angayukaqsraq (Baird Mountains quadrangle) (Dillon and others, 1987b; Karl and others, 1989), which consist of about 70% gabbro and leucogabbro and 30% granodiorite and alkali feldspar granite. These rocks, which yielded a U-Pb crystallization age of 750 Ma, intrude well-foliated metasedimentary and mafic volcanic rocks that were metamorphosed to amphibolite facies prior to intrusion in Proterozoic time (Karl and others, 1989). Granitic rocks of this intrusive complex are highly evolved and mildly peraluminous and are interpreted as "within-plate" magmas derived from a weakly fractionated source and emplaced in a non-arc, continental setting (Karl and others, 1989). Nelson and others (1989) reported Sm-Nd model ages based on an alkali-depleted mantle source for the crust of 1.3 to 1.5 Ga and ϵ_{Nd} values of 1.2 for the Proterozoic granitic rocks at Mount Angayukaqsraq. They inferred from those data that a major source for the granitic rocks was continental crust at least as old as Early Proterozoic. Granitic gneiss of the Ernie Lake (Survey Pass quadrangle) and nearby Sixtymile (Wiseman quadrangle) plutons has yielded highly discordant Late Proterozoic U-Pb ages that are broadly similar to ages of the Mount Angayukaqsraq rocks (Dillon and others, 1980, 1987b; Karl and others, 1989); however, the Ernie Lake and Sixtymile plutons show evidence of an older crustal component (1000–800 Ma) (Karl and others, 1989).

The younger granitic rocks comprise several large, metamorphosed plutons that define a west-trending belt in the Chandalar, Survey Pass, and Ambler River quadrangles. The plutons are elliptical, range from 5 to 50 km in length, and are commonly fault bounded. The largest are the Arrigetch Peak and Mount Igikpak plutons (Fig. 2) in the Survey Pass quadrangle. They consist mostly of peraluminous muscovite-biotite granite but range from alkali-feldspar granite to tonalite (Nelson and Grybeck, 1980; Newberry and others, 1986; Hudson, this volume). However, microprobe analysis indicates that muscovite in some of the Devonian plutons in the Survey Pass quadrangle may be partly or entirely metamorphic in origin (A. B. Till, 1990, oral commun.). Commonly associated with these plutons are augen gneiss, schistose orthogneiss, and aplitic and pegmatitic gneisses that all locally display isoclinal folds (Newberry and others, 1986). In contrast, the Horace Mountains plutons (Fig. 2) in the Chandalar quadrangle are composed largely of foliated metaluminous, porphyritic biotite ± hornblende granodiorite, porphyritic hornblende-biotite granodiorite, and leucogranite; these plutons also contain diorite, quartz monzonite, and tonalite (Newberry and others, 1986; Dillon, 1989). Discordant U-Pb zircon ages indicate crystallization of the Arrigetch Peak pluton at 366 ± 10 Ma (Late Devonian) and the Horace Mountain plutons at 402 Ma (Early Devonian) (Dillon, 1989). Initial Sr ratios for the Survey Pass plutons are high (about 0.715), and their granitic composition shows affinity with S-type granitoids, which suggests that the Survey Pass plutons were formed by melting of continental crust (Nelson and Grybeck, 1980; Newberry and others, 1986). The calculated Sm-Nd model ages for the Survey Pass plutons range from 0.7 to 1.6 Ga, and initial ϵ_{Nd} values for these plutons range from –6 to +3. These figures indicate varying involvement of older crust and younger material in the genesis of the Survey Pass plutons (Nelson and others, 1989). Compositional data from the Horace Mountain plutons, in contrast, indicate affinity with I-type granitoids (Newberry and others, 1986). Metamorphic aureoles surrounding the plutons locally contain noneconomic Sn-W skarns in the Survey Pass quadrangle and Cu-Ag and Pb-Zn-Ag skarns in the Chandalar quadrangle (Newberry and others, 1986).

Coldfoot subterrane

The Coldfoot subterrane consists largely of fine- to coarse-grained metasedimentary rocks that form the schist belt, a continuous 15–25-km-wide belt that extends for at least 600 km along the southern Brooks Range (Brosgé and Reiser, 1964; Mayfield and Tailleur, 1978; Nelson and Grybeck, 1980; Dillon and others, 1986; Dillon, 1989; Karl and others, 1989) (Figs. 2, 3, and 21). These metamorphic rocks are bounded to the south by the Slate Creek subterrane and to the north by the Hammond subterrane along boundaries that are difficult to identify in the field and are of uncertain structural significance. The Coldfoot subterrane is distinguished from the Hammond subterrane by the former's pervasive penetrative deformation, generally higher textural grade, smaller proportion and size of enclosed carbonate units, and near absence of relict sedimentary and igneous textures. The Coldfoot subterrane consists of four primary lithologic assemblages that have undetermined stratigraphic significance: (1) a lower unit of Proterozoic and lower Paleozoic metasedimentary rocks, exposed in structural windows; (2) the quartz-mica schist unit, consisting of various units of pelitic and semipelitic schist; (3) the Bornite carbonate sequence of Hitzman and others (1986), composed mainly of carbonate rocks that locally overlie the quartz-mica schist unit; and (4) the Ambler sequence of Hitzman and others (1982), composed of mixed metaclastic rocks, metavolcanic rocks, and marble that are enclosed by the quartz-mica schist unit. Like the Hammond subterrane, the Coldfoot subterrane contains granitic rocks of Late Proterozoic and Devonian age.

Lower unit of Proterozoic and lower Paleozoic metasedimentary rocks. The structurally lowest rocks in the Coldfoot subterrane are exposed along the northern margin of the subterrane and in structural windows through the quartz-mica schist unit. These rocks, mostly pelitic and calcareous schists, vary in lithology from place to place; this variability suggests that the protoliths represent either diverse sedimentary facies or different tectonostratigraphic units. Some of the schists are compositionally and temporally similar to rocks of the Hammond subterrane but differ in having structural features characteristic of the Coldfoot subterrane. The unit includes mixed schists in the Kallarichuk Hills (Baird Mountains quadrangle), the Kogoluktuk schist of Hitzman and others (1982), and unnamed units of calcareous schist and marble in the Chandalar and Wiseman quadrangles (Brosgé and Reiser, 1964; Dillon and others, 1986).

The undivided mixed schists of the Kallarichuk Hills unit (Karl and others, 1989) consist of silvery green quartz-mica schist with intercalated black quartzite and brown calcareous schist. Sparse lenses of gray marble, blue amphibole-bearing metabasite, felsic metavolcanic rocks, and rare metaconglomerate are also present in the unit. Conodonts indicate a Silurian to Mississippian age for one carbonate lens, whereas two-hole crinoids recovered in another area indicate a Devonian age. However, a Proterozoic age for part of the unit is suggested by a Proterozoic granodiorite body that intrudes marble of the unit.

The Kogoluktuk schist of Hitzman and others (1982) consists of schists that underlie the quartz-mica schist unit in a structural window in the Cosmos Hills. In the window, the Kogoluktuk consists of about 2500 m of interlayered pelitic schist, micaceous quartzite, feldspathic schist, metabasite, chlorite schist, chloritic dolomite, and marble that are distinguished from overlying units by coarser texture, relict epidote-amphibolite metamorphic assemblages, and more complex structural fabric. Hitzman and others (1982) correlated the Kogoluktuk with thinly layered micaceous quartzite and minor dolostone, marble, metaconglomerate, calc-schist, semipelitic schist, and metabasite along the northern margin of the subterrane in the Ambler River quadrangle. This northern assemblage can be traced westward into a structural window at the border of the Ambler River and Baird Mountains quadrangles. Marble in this structural window locally contains stromatolites, which suggest that it is correlative with the stromatolite-bearing Proterozoic rocks of the Hammond subterrane to the north (Karl and others, 1989). Hitzman and others (1982) inferred a Devonian or older age for the Kogoluktuk because it is intruded by granitic gneiss of probable Devonian age in the Cosmos Hills.

In a structural window west of the Dalton Highway in the Wiseman quadrangle, interlayered calcareous schist, pelitic schist, and marble underlie the quartz-mica schist unit along a tectonic contact. These rocks, at least 1000 m thick, contain prominent, 5–10-m-thick, laterally discontinuous, highly strained marble units that are structurally thickened by isoclinal folding or imbrication. Conodonts recovered from a dark argillaceous carbonate lens indicate an early Early Devonian (Lochkovian) age for at least some of these rocks (A. G. Harris, 1989, written commun.). Near the town of Wiseman, these rocks can be traced northward into a narrow belt of highly strained calcareous and pelitic schist that extends along strike for more than 150 km across much of the Wiseman and Chandalar quadrangles (Dillon and others, 1986).

Quartz-mica schist unit. The quartz-mica schist unit, exposed throughout the Coldfoot subterrane, consists generally of uniform pelitic and semipelitic quartz-mica schist and minor metabasite and metacarbonate rocks. This unit has an estimated structural thickness of 3–12 km (Hitzman and others, 1982; Dillon and others, 1986; Gottschalk, 1987) and is characterized by quartz stringers, boudins, and segregations that commonly define isoclinal folds. These rocks (Anirak and Maunelek schist units of Hitzman and others, 1982; knotty-mica schist unit of Dillon and others, 1986; Koyukuk schist unit of Gottschalk, 1987) typically consist of green-, gray-, or brown-weathering quartz + white mica + chlorite + albite ± chloritoid schist with graphitic and quartz-rich compositional layers generally less than a few meters thick. East of the Dalton Highway, the unit consists of about 95% interlayered pelitic schist, quartz-rich schist, and paragneiss, and about 5% metabasite, metagabbro, and albite-schist lenses (Gottschalk, 1987). The metabasite lenses contain greenschist facies assemblages (chlorite + albite + epidote + actinolite + sphene) but retain relict blueschist facies assemblages and pseudomorphs. Notably, one metabasite body near the Dalton Highway retains an eclogite (garnet + sodic clinopyroxene + rutile) assemblage (Gottschalk, 1990). The quartz-mica schist unit represents a thick, deformed, and metamorphosed succession of organic-rich shale and siliciclastic sedimentary rocks (Hitzman and others, 1982, 1986; Gottschalk, 1990); however, no relict primary structures have been preserved and possible earlier structural fabrics have been mostly transposed into a position parallel with the regional south-dipping foliation. The age of the protolith of the quartz-mica schist unit is unknown, but Hitzman and others (1986) considered it Devonian and older. Dillon and others (1986) and Dillon (1989) correlated the apparently less deformed parts of this unit with the Devonian Beaucoup Formation and Hunt Fork Shale of the Endicott Mountains subterrane, largely because of structural position and assumed comagmatic character of the interstratified metavolcanic rocks.

Bornite carbonate sequence. The Bornite carbonate sequence of Hitzman and others (1986) consists of about 1000 m of carbonate rocks in the Cosmos Hills that may conformably overlie rocks of the quartz-mica schist unit. The carbonate rocks grade upward from phyllitic marble to carbonate breccia, marble, massive fossiliferous dolostone, and massive encrinitic dolostone, and represent a carbonate mudbank complex or bioherm (Hitzman and others, 1986). Nearby lateral equivalents include marble, graphitic marble, carbonaceous phyllite, and fossiliferous, laminated dolostone, and represent back-reef lagoonal limestone and intratidal to supratidal deposits. A variety of Middle to Late Devonian or earliest Mississippian megafossils are preserved within the Bornite carbonate sequence (Patton and others, 1968), including well-preserved brachiopods of Middle Devonian age (R. B. Blodgett, 1990, oral commun.). Conodonts from one locality in the unit indicate a Silurian age (A. G. Harris and J. A. Dumoulin, 1987, unpublished data); thus, the Bornite carbonate sequence spans a large part of middle Paleozoic time. A 1-km-wide body of hydrothermal dolostone in the biohermal facies hosts the Ruby Creek copper deposit, which contains more than 100 million tons graded at 1.2% copper (Hitzman and others, 1986).

Ambler sequence. A well-known lithologic assemblage of the Coldfoot subterrane is the Ambler sequence of Hitzman and others (1982), named for the volcanogenic massive sulfide mineral district in the southern Ambler River and Survey Pass quadrangles. In this area, the sequence consists of a complexly interfingering and deformed, 700–1850-m-thick succession of foliated to massive metarhyolite, felsic schist, metabasite, marble, chloritic schist, calcschist, and graphitic schist that is inferred to wedge out to the south within the quartz-mica schist unit (Hitzman and others, 1982). Dillon and others (1986) extended the sequence eastward into the Wiseman quadrangle, where it forms thinner and laterally less extensive units and lenses.

Hitzman and others (1986) estimated the composition of the sequence in the Ambler River quadrangle to be 60% metavolcanic and volcaniclastic rocks, 25% marble, and 15% metasedimentary rocks. The metavolcanic rocks of the Ambler sequence, which include both felsic and basaltic lithologies, have been metamorphosed to blueschist and greenschist facies assemblages. The felsic rocks consist in part of porphyritic metarhyolite with relict potassium feldspar and resorbed bipyramidal quartz phenocrysts (the so-called button schist). The metabasalt is tholeiitic in composition and is massive and concordant, except locally where it contains pillow and breccia structures (Hitzman and others, 1986). Hitzman and others (1982) interpreted the metavolcanic rocks of the Ambler sequence as a compositionally bimodal succession of submarine mafic flows and felsic domes, ignimbrites, ash flows, pyroturbidites, and reworked clastic aprons of volcanic debris. Major copper, zinc, lead, and silver sulfide resources in the Ambler mineral district are distributed among many deposits associated with the felsic metavolvanic rocks of the Ambler sequence (Hitzman and others, 1986; Nokleberg and others, this volume, Chapter 29 and Plate 11).

Corals recovered from dolomitic lenses within the Ambler sequence are Late Devonian to Mississippian (Hitzman and others, 1986; Smith and others, 1978), but poor preservation casts doubt on their identification (R. B. Blodgett, 1990, oral commun.). Discordant zircon U-Pb and Pb-Pb ages of 373 to 327 Ma have been derived from felsic metavolcanic rocks in the sequence (Dillon and others, 1980); the ages indicate extrusion at 396 ± 20 Ma (Early Devonian) (Dillon and others, 1987b). On the basis of these ages, along with the reconstructed stratigraphy of the sequence and the bimodal composition of metavolcanic rocks, Hitzman and others (1982, 1986) proposed that the Ambler sequence was deposited in a continental-rift setting during Devonian time.

Metagranitic rocks. The oldest known intrusive rocks in the Coldfoot subterrane are small bodies of metamorphosed plutonic rocks of granitic to dioritic composition exposed in the Kallarichuk Hills (Baird Mountains quadrangle) (Fig. 1). Karl and others (1989) reported that the metagranitic rocks intrude marble of the Proterozoic and lower Paleozoic metasedimentary unit of the Coldfoot subterrane and yielded a Proterozoic U-Pb age of 705 ± 35 Ma.

A younger generation of metaplutonic rocks is represented by granitic gneiss in the Cosmos Hills (Ambler River quadrangle), by the Baby Creek batholith in the Chandalar quadrangle, and by several other small metagranitic bodies near Wild Lake and the village of Wiseman in the Wiseman quadrangle. The Baby Creek batholith is a metamorphosed S-type, peraluminous biotite-muscovite granite with a tentative initial Sr ratio of 0.707 (Newberry and others, 1986; Dillon, 1989). This batholith, which intrudes the quartz-mica schist unit, has yielded discordant U-Pb ages indicative of crystallization in the Early Devonian. The Baby Creek batholith is similar in most respects to most other porphyritic orthogneiss bodies of Devonian age in the Hammond and North Slope subterranes (Newberry and others, 1986) and is cogenetic with the felsic metavolcanic rocks of the Ambler sequence (Dillon and others, 1980; Dillon, 1989).

Slate Creek subterrane

Various parts of the 5–10-km-wide, topographically recessive phyllite belt along most of the southern Brooks Range have been included in the Venetie and Coldfoot terranes of Jones and others (1987), the Rosie Creek allochthon of Oldow and others (1987c, 1987d), and the Slate Creek thrust panel of the Angayucham terrane by Dillon (1989) and Patton and others (this volume, Chapter 7). Because of their quartzose character, chert-rich composition, and middle Paleozoic age, we combine these metaclastic rocks and discuss them here as the Slate Creek subterrane of the Arctic Alaska terrane (Fig. 3). Herein we limit the Slate Creek subterrane to rocks in the southern Brooks Range because these rocks are bounded to the south by prominent structures (South Fork–Malamute fault, Porcupine lineament). Rocks of similar lithologic character south of this area rest on rocks of the Ruby terrane (Patton and others, this volume, Chapter 7).

The Slate Creek subterrane consists of metamorphosed, thin-bedded, dark-colored shale, siltstone, and fine- to medium-grained sandstone, and local units of phyllonite and chloritic schist (Fig. 21). In a few areas, metagabbro and diabase dikes intrude the rocks (Nelson and Grybeck, 1980; Dillon and others, 1986; Dillon, 1989; Karl and others, 1989), and near Coldfoot, mafic intrusive rocks form lenses in phyllonite and argillite-matrix melange (Moore and others, 1991). Radiolarian chert of late Paleozoic age is associated with the metaclastic rocks along the southern margin of the subterrane, but a conformable relation between the chert and the metaclastic rocks has not been confirmed. No mappable internal stratigraphy has been recognized, and zones of tectonic melange and broken formation are prominent in the subterrane, especially along its southern margin. Zones of phyllonite and mylonite, pervasive along the northern margin of the subterrane, may represent an important zone of dislocation (Dillon, 1989). Elsewhere, Hitzman and others (1982) reported that the phyllitic rocks (their Beaver Creek phyllite unit) conformably grade downward into the quartz-mica schist unit of the Coldfoot subterrane (Dillon, 1989). Hitzman and others (1986) and Howell and others (1986, Fig. 2) estimated structural thicknesses of about 3 km for the Slate Creek subterrane in the western and eastern Brooks Range; Gottschalk (1987) estimated a thickness of about 1000 m for rocks of the subterrane near the Dalton Highway.

Where sedimentary structures are preserved, sandstone to shale ratios are typically less than 1:10 but in the eastern Brooks Range may be as high as 1:3. Sedimentary structures characteristically formed by turbidity currents (for example, graded beds, flute casts) have been reported by most workers (Hitzman and others, 1986; Murphy and Patton, 1988). Gottschalk (1987) also described shallow-marine sedimentary structures, including hummocky cross-stratification, in a local fault-bounded unit of the subterrane east of the Dalton Highway. The sandstone of the Slate Creek subterrane is largely composed of chert and quartz grains, but minor granitic, quartzose metamorphic, unfoliated sedimentary, and volcanic rock fragments are locally present. The quartzose composition of these strata suggests a continental provenance (Murphy and Patton, 1988).

Palynomorphs in the fault-bounded unit east of the Dalton Highway indicate an Early Devonian (Siegenian to Emsian) age (Gottschalk, 1987). In the eastern Brooks Range, palynomorphs indicate Early(?) Devonian and Middle or Late Devonian ages, and plant fossils indicate a Late(?) Devonian age (W. P. Brosgé, 1988, oral commun.). Murphy and Patton (1988) suggested that sedimentary rocks of the Slate Creek subterrane are the deep-marine equivalents of Upper Devonian rocks of the Endicott Group in the Endicott Mountains subterrane; Oldow and others (1987d), however, correlated the Slate Creek rocks with Devonian rocks of the Hammond subterrane.

DESCRIPTION OF THE ANGAYUCHAM TERRANE

The structurally highest units of the Brooks Range are allochthonous mafic and ultramafic rocks exposed in the greenstone belt in the southern foothills of the Brooks Range and to the north in a series of synclinal remnants of large thrust sheets in the crestal and disturbed belts of the western and eastern Brooks Range (Mull, 1982, p. 30; Figs. 2, 3, and 20). In both areas, the mafic rocks of the Angayucham terrane have been divided into two structural packages (Fig. 21). The structurally lower package consists principally of fault imbricates of metamorphosed mafic volcanic rocks. In the greenstone belt, this package has been called the Narvak thrust panel by Patton and Box (1989) (herein referred to as the Narvak panel), whereas in the crestal and disturbed belts it is called the Copter Peak allochthon by Mayfield and others (1988). The structurally higher package, which consists mainly of gabbroic and ultramafic rocks, is called the Kanuti thrust panel in the greenstone belt (Patton and Box, 1989) (herein referred to as the Kanuti panel) and the Misheguk Mountain allochthon in the crestal and disturbed belts (Mayfield and others, 1988). On the basis of similar lithology, age, and structural position, Roeder and Mull (1978) correlated the two packages of the greenstone belt with those of the crestal and disturbed belts and suggested that the former is the "root zone" for extensive thrust sheets now represented by the klippen in the crestal and disturbed belts. We organized rocks of the Angayucham terrane below by geographic location so that the evidence for this correlation, which is of fundamental importance to tectonic reconstructions, is apparent.

Greenstone belt

The Angayucham terrane in the greenstone belt is a narrow zone of slightly metamorphosed mafic igneous rocks, chert, and serpentinite that extends for more than 500 km along the southern margin of the Brooks Range. These rocks dip moderately to steeply southward and rest structurally on deformed and metamorphosed rocks of the Slate Creek subterrane of the Arctic Alaska terrane. Patton and Box (1989) have divided the igneous rocks into two lithotectonic units, herein referred to as the Narvak panel and Kanuti panel. These units are distinguished by the abundance of mafic volcanic rocks in the Narvak panel, in contrast with the large proportion of ultramafic rocks in the Kanuti panel.

Narvak panel. The Narvak panel consists of an imbricate stack of fault slabs composed of pillow basalt and subordinate diabase, basaltic tuff, argillite, limestone, and radiolarian chert that has a structural thickness of more than 10 km in the Angayucham Mountains and 6 km near the Dalton Highway (Dillon, 1989; Pallister and others, 1989) (Fig. 22). Bodies of amphibolite are locally present near the structural top of the unit in the Cosmos Hills and Angayucham Mountains (Hitzman and others, 1982; Pallister and others, 1989). The Narvak panel structurally overlies the Slate Creek subterrane along a zone of south-dipping faults, tectonic melange, cataclasite, and mylonite (Hitzman and others, 1986; Dillon, 1989). Fault slivers of diabase; Mississippian to Triassic chert and argillite; Devonian, Mississippian, Pennsylvanian, and Permian limestone; and calcareous arkose are locally present along this fault zone (Gottschalk, 1987; Pallister and Carlson, 1988; I. L. Tailleur, 1988, oral commun.; Dillon, 1989).

The volcanic rocks of the Narvak thrust panel consist largely of pillow basalt and pillow breccia. The basalts are very fine to fine-grained, nonvesicular to amygdaloidal, and commonly aphypric. Where porphyritic, they contain sparse microphenocrysts of plagioclase and/or clinopyroxene and, locally, titaniferous augite (Pallister and others, 1989). Microgabbro and rare cumulate layered gabbro have been reported locally from near the base of the Narvak (Barker and others, 1988). The rocks are metamorphosed to prehnite-pumpellyite or greenschist facies assemblages but have mainly static metamorphic textures (Gottschalk, 1987; Gottschalk and Oldow, 1988; Dillon, 1989; Pallister and others, 1989).

Associated sedimentary rocks consist largely of interpillow chert, thinly bedded radiolarian and tuffaceous chert, siliceous tuff breccia, argillite, and minor lenses of limestone and marble. The chert is gray, black, and red, and as much as 60 m thick (Gottschalk, 1987; Jones and others, 1988; Dillon, 1989; Pallister and others, 1989). Depositional contacts between the chert and basalt are present, but the bedded-chert sequences commonly

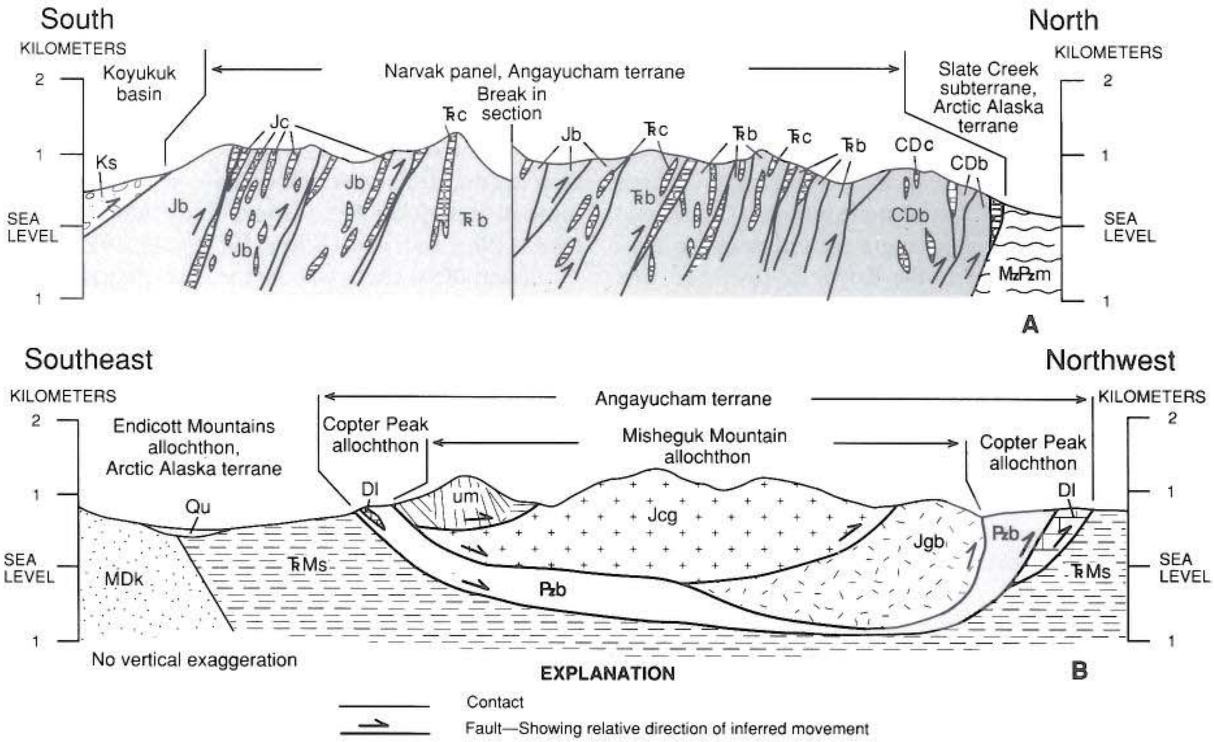


Figure 22. Diagrammatic cross sections showing stratigraphic relations of Angayucham terrane. A, Greenstone belt in Angayucham Mountains, Hughes quadrangle (modified from Pallister and others, 1989). Note imbricate structure and progressively younger age of rocks in thrust imbricates from structural base to top of Narvak panel. B, Crestal belt at Siniktanneyak Mountain, Howard Pass quadrangle (modified from Nelson and Nelson, 1982). Geologic units: Greenstone belt—Ks, Cretaceous sedimentary rocks; Jb, Jurassic pillow basalt, diabase, and microgabbro; Jc, Jurassic chert; Ŧb, Triassic pillow basalt, diabase, and microgabbro; Ŧc, Triassic chert; CDb, Devonian and Carboniferous pillow basalt, diabase, and microgabbro; CDc, Devonian and Carboniferous chert; MzPzm, Paleozoic and Mesozoic melange. Crestal belt—Qu, Quaternary deposits; Jcg, Jurassic(?) cumulate gabbro; Jgb, Jurassic(?) isotropic gabbro with plagiogranite dikes and stocks; ŦMs, Mississippian to Triassic fine-grained sedimentary rocks of undivided Kayak Shale and Lisburne and Etivluk groups; MDk, Devonian and Mississippian(?) terrigenous clastic rocks of Kanayut Conglomerate; DI, Devonian fossiliferous carbonate rocks; Pzb, Paleozoic diabase and pillowed volcanic rocks; um, dunite, harzburgite, and pyroxenite.

mark the position of faults bounding the imbricates that compose the Narvak panel.

Map relations and radiolarians from interpillow chert show that in the Angayucham Mountains, the Narvak panel consists of four to eight map-scale fault imbricates of restricted age (Pallister and Carlson, 1988). Radiolarian assemblages define an age progression, from structural base to top of the imbricate sequence, of (1) Late Devonian (Famennian), (2) Mississippian, (3) Pennsylvanian or Early Permian, (4) Triassic, and (5) Early Jurassic(?) (Murchey and Harris, 1985; B. L. Murchey, 1987, written commun.). In the vicinity of the Dalton Highway, various units of chert, including those of Late Devonian, Late Devonian to Early Mississippian(?), Mississippian, Late Mississippian(?) to Early Pennsylvanian, Early Permian, and Triassic to Early Jurassic indicate a similar spread of ages (Jones and others, 1988), although a consistent pattern is not apparent. Shallow-water fossils, abundant sponge spicules, and the finely laminated character of some of the chert units suggest deposition in intermediate (500 to 1500 m) water depths (Murchey and Harris, 1985), but chert containing abundant radiolarians is common and indicates deposition under deeper marine conditions (Karl, 1989).

Geochemical data from the volcanic rocks show that many are hypersthene-normative tholeiitic basalts (Barker and others, 1988; Pallister and others, 1989) and are transitional between normal and enriched mid-ocean ridge basalts (MORB). Rare earth element (REE) patterns vary from relatively flat to slightly depleted or moderately enriched in light REE (LREE). Considering the fine-grained, siliceous character of the associated sedimentary rocks and their wide range of ages, Barker and others (1988) and Pallister and others (1989) interpreted the geochemical data as evidence for extrusion of the igneous rocks on oceanic plateaus such as seamounts and ocean islands.

Kanuti panel. Ultramafic rocks in the southern Brooks Range foothills are exposed in the Jade Moutains and in the nearby Cosmos Hills (both in the Ambler River quadrangle) and as scattered fault slivers along the greenstone belt. In the Jade Mountains, serpentinite lies structurally on pillow basalt of the Narvak panel along a south-dipping fault contact and contains relict minerals and textures of a harzburgite protolith (Loney and Himmelberg, 1985). Prominent linear gravity and magnetic highs trend along the northern edge of the Koyukuk basin and pass through these exposures (Barnes, 1970; Cady, 1989), which suggests that the ultramafic rocks compose a regionally extensive sheet mostly buried beneath Cretaceous sedimentary rocks of the Koyukuk basin (Loney and Himmelberg, 1985; Dillon, 1989). Cady (1989), however, concluded that ultramafic rocks were rare and attributed the potential-field anomalies to mafic rocks of the Narvak panel.

Crestal and disturbed belts

The Angayucham terrane in the crestal and disturbed belts consists of klippen of slightly metamorphosed mafic volcanic rocks, diabase, gabbro, and ultramafic rocks that are exposed discontinuously along the length of the Brooks Range (Figs. 2 and 3). The klippen rest on unmetamorphosed sedimentary rocks of the De Long Mountains and Endicott Mountains subterranes of the Arctic Alaska terrane and consist of two lithotectonic units, the Misheguk Mountain allochthon and the subjacent Copter Peak allochthon (Mayfield and others, 1988). These units are distinguished by the abundance of mafic volcanic rocks and diabase in the Copter Peak allochthon in contrast with the largely ultramafic rocks and gabbro of the Misheguk Mountain allochthon.

Copter Peak allochthon. The structurally lower Copter Peak allochthon consists of imbricated units of basalt and diabase with subordinate basaltic tuff and breccia, microgabbro, siliceous tuff, radiolarian chert, and gray argillite. Although generally massive and highly fractured, pillow structures and lava flows are commonly reported, and columnar basalt is present locally (Moore, 1987b). The basalt is mostly very fine to fine grained, sparsely amygdaloidal and typically aphyric, although sparse plagioclase and/or clinopyroxene microphenocrysts are present in some rocks. These basalts have been partly to completely altered to assemblages of albite, green amphibole, chlorite, sphene, and calcite. Diabase dikes and sills intrude the lava flows and intercalated sedimentary rocks; they may compose a large part of some fault imbricates within the Copter Peak allochthon (Bird and others, 1985). In the klippen of the western Brooks Range, the Copter Peak allochthon is less than 3 km thick (Nelson and Nelson, 1982; Curtis and others, 1984; Ellersieck and others, 1984; Karl and Dickey, 1989) (Fig. 22). Geochemical data from the Kikiktak Mountain (Killik River quadrangle), Siniktanneyak Mountain (Howard Pass quadrangle), Copter Peak (Misheguk Mountain quadrangle), Asik Mountain (Noatak quadrangle), and Avan Hills (De Long Mountains and Misheguk Mountain quadrangles) klippen indicate that the mafic igneous rocks are tholeiites. REE patterns for most of the mafic rocks show moderate enrichment in LREEs, whereas others are flat. These data suggest that the mafic igneous rocks were extruded at a mid-ocean ridge or seamount (Moore, 1987b; Wirth and others, 1987). Data from the Maiyumerak Mountains klippen (Noatak and Baird Mountains quadrangles), however, indicate an oceanic-arc affinity for some of the rocks of the Copter Peak allochthon (Wirth and others, 1987; Karl and Dickey, 1989; Karl, 1991).

Interpillow chert is a minor, but ubiquitous, component throughout the Copter Peak allochthon; bedded chert is present locally. The chert is typically red or light colored, contains abundant radiolarians and little argillite, and represents slow sedimentation in an oxygenated, deep-water environment (Murchey and others, 1988). Limestone and marble, in places containing Devonian fossils, are present in the lower part of the Copter Peak allochthon. The carbonates are commonly interpreted as tectonic blocks or slivers that were incorporated along the basal thrust of the allochthon during its emplacement (Roeder and Mull, 1978; Mayfield and others, 1988). Nelson and Nelson (1982), however, reported that some fossiliferous carbonate units are interbedded with pillow lava and breccia of the Copter Peak allochthon; this evidence suggests extrusion of some of the basalts at relatively shallow depths.

Age and structural relations of the rocks of the Copter Peak allochthon are delimited mostly by fossils collected from intercalated chert and limestone. Interpillow chert in the Copter Peak allochthon in the western Brooks Range has yielded radiolarians that are largely Triassic (Ellersieck and others, 1984), but Mississippian and Pennsylvanian radiolarians have also been recovered from the Christian and Kikiktat mountain massifs (D. L. Jones, 1987, oral commun; B. L. Murchey, 1987, written commun.; C.G. Mull, 1987, unpublished data). Limestone interstratified with volcanic rocks near the base of the Siniktanneyak massif has yielded megafossils and conodonts of Late Devonian age (Nelson and Nelson, 1982).

Misheguk Mountain allochthon. The Misheguk Mountain allochthon consists of ultramafic tectonite and cumulate rocks, cumulate and isotropic gabbro, and diabase that have a reconstructed thickness of at least 6 km at Siniktanneyak Mountain (Fig. 22). The ultramafic rocks consists largely of dunite with chromitite layers and subordinate harzburgite, wehrlite, and pyroxenite (Zimmerman and Soustek, 1979; Bird and others, 1985). These are interlayered with, and pass upward into, layered cumulate gabbroic rocks, including troctolite, melagabbro, leucogabbro, and anorthosite; olivine, clinopyroxene, and plagioclase are the cumulate phases in these rocks (Zimmerman and Soustek, 1979; Nelson and Nelson, 1982; Bird and others, 1985). Noncumulate gabbro, locally intruded by small plagiogranite dikes and stocks, composes a large part of the Misheguk Mountain klippen and forms irregular intrusions in most other klippen in the western Brooks Range. This gabbro is ophitic, consisting of plagioclase, green hornblende, and uratilized clinopyroxene, and commonly displays miarolytic cavities. Diabase dikes locally intrude both the ultramafic and gabbroic rocks. In some of the klippen, dikes and stocks of potassium feldspar–bearing granitic rocks intrude the ultramafic rocks and gabbro and may represent a later plutonic episode (Zimmerman and others, 1981; Nelson and Nelson, 1982; Boak and others, 1987). Crystallization sequences and mineral chemistries of rocks in the Misheguk Mountain allochthon at Misheguk Mountain indicate crystallization in an arc, rather than a mid-ocean ridge setting (Harris, 1988).

Hornblende and biotite K-Ar ages from gabbro in the Siniktanneyak, Misheguk Mountain, and Christian klippen range from 172 to 147 Ma (Patton and others, 1977; Boak and others, 1987). Wirth and Bird (1992) reported ^{40}Ar-^{39}Ar incremental-heating ages of 187–184 Ma on hornblende from gabbro of the Asik Mountain klippe. These dates indicate that crystallization of the Misheguk Mountain allochthon occurred during the Middle Jurassic.

Metamorphic rocks. In klippen of the western Brooks Range, the contact between the Misheguk Mountain allochthon and the underlying Copter Peak allochthon is marked by pods and zones as much as a few tens of meters thick of low- to medium-grade, and locally high-grade, amphibolite. These rocks are schistose to gneissic and display cataclastic texture (Boak and others, 1987). Boak and others (1987) determined that the protolith for the amphibolite is volcanic and siliceous sedimentary rocks of the underlying Copter Peak allochthon. The metamorphic rocks have yielded K-Ar ages of 154 and 153 Ma and ^{40}Ar-^{39}Ar plateau ages of 171 to 163 Ma (Boak and others, 1987; Wirth and Bird, 1992) and are thought to have been metamorphosed at relatively low pressures (Zimmerman and Frank, 1982) and at metamorphic temperatures up to 560 °C (Boak and others, 1987).

Tectonic affinity of the Angayucham terrane

Rocks of the Angayucham terrane were originally thought to compose a dismembered ophiolite (Talleur, 1973b; Patton and others, 1977), but Roeder and Mull (1978) and Mayfield and others (1988) have shown that the structurally higher gabbroic and ultramafic assemblage is distinct from the underlying volcanic and diabase assemblage. Evidence indicating that these units are not cogenetic include the following. (1) The volcanic and diabase assemblage ranges from Late Devonian to Early Jurassic, whereas the gabbroic and ultramafic assemblage yields isotopic ages suggesting crystallization during the Middle Jurassic. (2) Trace element geochemistry of the volcanic and diabase assemblage indicates that it is composed largely of oceanic-plateau and seamount basalts (Moore, 1987b; Wirth and others, 1987; Barker and others, 1988; Pallister and others, 1989), whereas petrochemical data from the Misheguk Mountain allochthon suggest that it has an island-arc affinity (Harris, 1988). Most workers agree that the gabbroic and ultramafic rocks of the Kanuti panel and Misheguk Mountain allochthon may represent an incomplete ophiolite, but the age span of volcanic rocks and diabase in the Narvak panel and Copter Peak allochthon is much longer than that of known ophiolites; therefore, the volcanic rocks and diabase more likely represent an accreted assemblage of basaltic seamounts (Barker and others, 1988; Pallister and others, 1989). The dynamothermally metamorphosed rocks along the contact between the upper and lower assemblages were interpreted by Zimmerman and Frank (1982) and Boak and others (1987) as metamorphic aureoles that developed under the ultramafic rocks of the higher gabbroic and ultramafic assemblage during thrust emplacement. Metamorphism of the aureole rocks at relatively high temperatures (T) and low pressures (P) suggests that the ophiolite was obducted as a young, hot body in Middle Jurassic time, within 20 m.y. of crystallization (Zimmerman and Frank, 1982; Harris, 1988; Wirth and Bird, 1992).

The Copter Peak allochthon rests structurally on Valanginian (Lower Cretaceous) and older sedimentary rocks of the De Long Mountains and Endicott Mountains subterranes (Curtis and others, 1984; Ellersieck and others, 1984; C. G. Mull, 1987, unpublished data). Sedimentary debris derived from the Copter Peak and Misheguk Mountain allochthons is present in Jurassic and Neocomian (Lower Cretaceous) foredeep deposits of the Okpikruak Formation (Mull, 1985; Crane, 1987). These data indicate that the upper ophiolitic assemblage was emplaced onto the lower volcanic and diabase assemblage during the Jurassic, but emplacement of both assemblages onto the Arctic Alaska terrane was not completed until after Valanginian time (Boak and others, 1987; Mayfield and others, 1988). Final emplacement of some or all of the Angayucham terrane may have involved normal faulting along south-dipping detachment faults in the southern Brooks Range and along north-dipping faults in the northern Brooks Range (Miller, 1987; Gottschalk and Oldow, 1988; Harris, 1988).

STRUCTURAL GEOLOGY OF NORTHERN ALASKA

The northern and southern regions of northern Alaska have distinct structural characteristics. The northern region, encompassing most of the North Slope and continental shelf, is dominated by structures related to the Jurassic and Early Cretaceous rifting that formed the northern continental margin of Alaska. This rifting separated northern Alaska from a continent to the north, producing a structural high, the Barrow arch, that has played a continuing role in the structural and depositional history of the region. The northern flank of the Barrow arch has been dominated by passive-margin subsidence and sedimentation since formation of the continental margin in the Early Cretaceous (Grantz and May, 1983). The southern limb of the Barrow arch served as the continental foreland and the northern flank of the foredeep for the Brooks Range orogen to the south.

The southern region encompasses the Brooks Range, a major orogenic belt of more than 1000 km long and as much as 300 km wide. Like most orogens, the Brooks Range is an elongate belt that displays asymmetry both in the distribution and character of its major structural elements and in the dominant direction of tectonic transport. Throughout most of its extent, the Brooks Range displays east-striking, north-transported structures.

The deepest structural levels are exposed mainly to the south, in the internal part of the orogen, and are characterized by older rocks overprinted by metamorphism and ductile deformation. A fold and thrust belt has developed to the north in the external part of the orogen in mostly younger and unmetamorphosed, dominantly sedimentary rocks. The southern part of this fold and thrust belt consists of shortened preorogenic rocks, whereas its northern part includes deformed synorogenic foredeep strata. In the youngest part of the orogen to the east, the deformational front of the Brooks Range has migrated northward to the modern continental margin.

Although it displays many characteristics common to mountain belts throughout the world, the Brooks Range is unusual in a number of respects. Extensive preservation of the highest structural levels of the orogen (that is, the Angayucham terrane) and early synorogenic deep-marine sedimentation (Okpikruak Formation) indicate that structural relief was relatively low during the period of greatest contraction in the orogen. Unlike most other parts of the circum-Pacific region, Tethyan-type ophiolites (Coleman, 1984) are present in the Brooks Range (Kanuti panel and Misheguk Mountain allochthon of the Angayucham terrane), forming its structurally highest preserved elements. Furthermore, relatively high *P*/low *T* metamorphic rocks are exposed over large areas in the internal parts of the orogen, and relatively lower *P*/higher *T* metamorphism that overprinted these rocks did not reach particularly high temperatures, nor is there evidence for synorogenic to postorogenic magmatism. In most continental orogens, deformation proceeds over time toward the interior of the continent, whereas in the Brooks Range, deformation has migrated toward what is now the northern continental margin of Alaska. Major low-angle normal faulting along the south flank and elsewhere in the Brooks Range suggests that tectonic extension has played a major role in the unroofing and uplift of the internal part of the orogen.

For purposes of description, northern Alaska is here divided into six major structural provinces: the southern Brooks Range, the northern Brooks Range, the foothills, the Lisburne Peninsula, the northeastern Brooks Range, and the North Slope (Fig. 23). These provinces are defined by their structural characteristics (Table 1), but they coincide approximately with the physiographic (Plate 2) and geologic provinces of northern Alaska (Fig. 2) and with many, but not all, of its tectonostratigraphic subdivisions (Fig. 3).

Southern Brooks Range structural province

The southern Brooks Range structural province is the core or infrastructure of the Brooks Range orogenic belt, where relatively deep structural levels are exposed. Rocks in the northern part of the province dip to the north beneath the northern Brooks Range structural province and also plunge beneath it to the east and west (Fig. 23). To the south, rocks of the province dip to the south beneath the Kouykuk basin. The northern part of the province consists of the Hammond and Coldfoot subterranes, which display polymetamorphism and complex, largely penetrative polydeformation. Rocks of the North Slope subterrane in the Mt. Doonerak fenster also display some of these characteristics (Oldow and others, 1987d; Dillon, 1989) and so are included in this province. The effects of Brookian orogenesis are much less intense in the southern part of the province (Slate Creek subterrane and Angayucham terrane) than in the northern part of the province, although penetrative structures are locally present.

The structure of the southern Brooks Range province is dominated by a series of large, generally south-dipping, thrust-bounded packages (Plate 13, sections B-B′, C-C′). The structures within and bounding these packages are mostly north directed and east striking and include major and minor folds and thrust faults and associated penetrative fabrics. Rocks of the Coldfoot subterrane are thought to have been emplaced as a coherent package, whereas rocks of the Hammond subterrane may consist of a greater than 10-km-thick, imbricate stack of 1–3-km-thick thrust sheets (Oldow and others, 1987; Till and others, 1988; Karl and others, 1989). South-vergent folds and faults overprint north-vergent structures in many parts of the Hammond and Coldfoot subterranes, and east-vergent, north-trending structures are present in the western part of the province. In addition, south-dipping normal faults and east-striking right-lateral strike-slip faults are found throughout the province, especially along the southern flank of the range; displacements on the latter faults may have been quite large.

Dynamothermally metamorphosed rocks characterize most of the province. These comprise mainly greenschist facies mineral assemblages but locally retain blueschist, epidote-amphibolite, amphibolite, and eclogite facies assemblages. Prehnite-pumpellyite facies assemblages with static textures are also present, most notably in the Angayucham terrane along the southern edge of the province. Textural grade decreases gradually to the north across the Hammond subterrane and abruptly to the south across the Slate Creek subterrane; the texturally highest grade rocks are found in the quartz-mica schist unit of the Coldfoot subterrane.

Pre-Brookian structures and metamorphism. Although most structures in this province are assumed to be related to Jurassic and younger Brookian deformation, Proterozoic and Devonian and/or Mississippian deformational and metamorphic events can be inferred. These events may have been tectonically significant, but their record has been largely obscured or transposed by Brookian penetrative fabrics and metamorphism.

In the Hammond subterrane, Proterozoic metamorphism and deformation are indicated by Late Proterozoic amphibolite and metapelite in the Baird Mountains quadrangle and by Late Proterozoic plutons scattered throughout the subterrane. The metapelite and amphibolite have yielded minimum K-Ar ages of 729 ± 22 Ma (muscovite) and 594 ± 18 Ma (hornblende) (Mayfield and others, 1982). Isoclinal folds and lineations in the amphibolite facies rocks predate intrusion of the plutons, which have been dated at 750 ± 6 Ma (Karl and others, 1989). This relation indicates that the amphibolite facies rocks represent a regional metamorphic event (Karl and others, 1989; Till, 1989). Likewise,

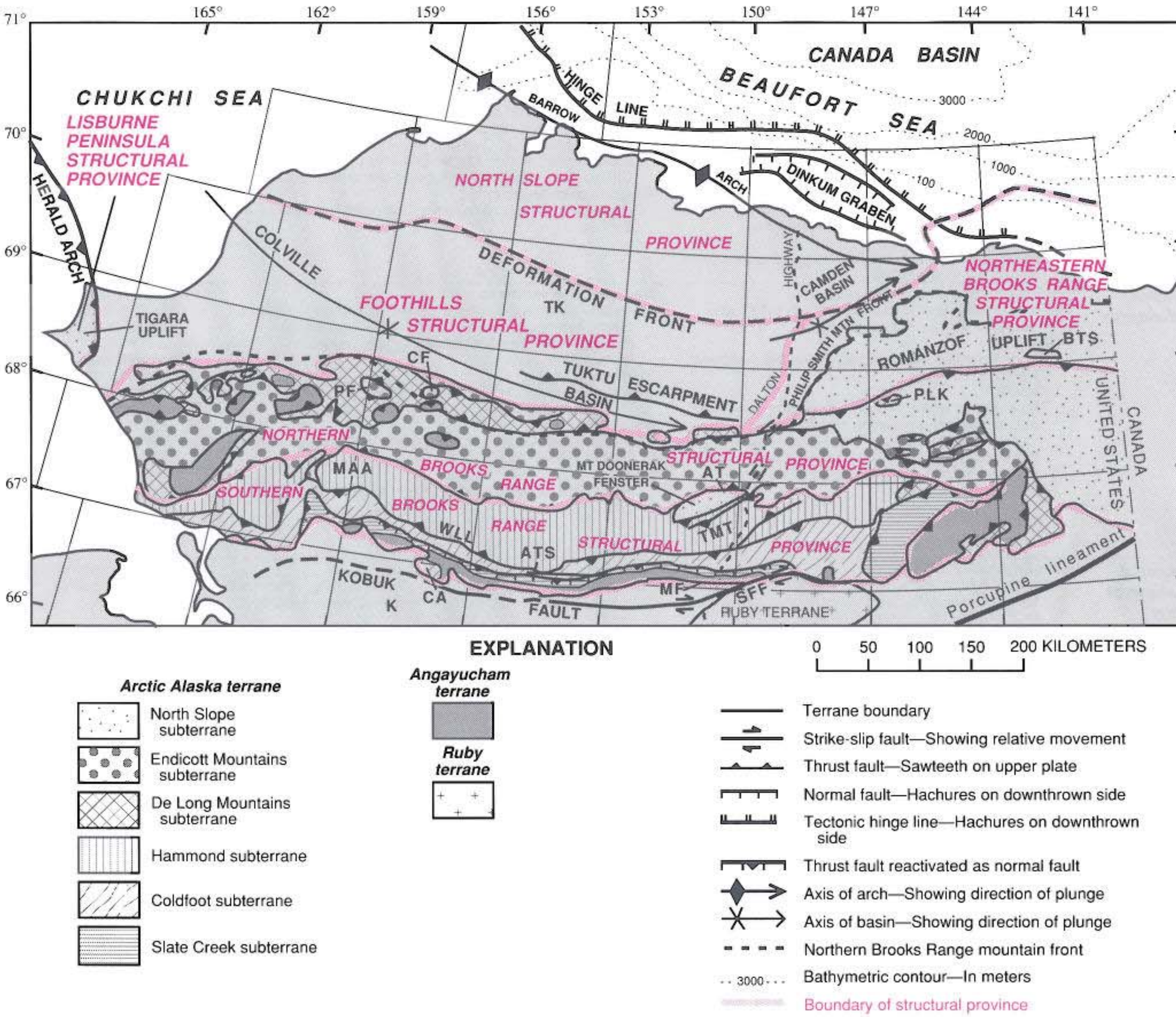


Figure 23. Structural provinces (red) and major tectonic elements of northern Alaska. AT, Amawk thrust; ATS, Angayucham "thrust" system; BTS, Bathtub syncline; CA, Cosmos arch; CF, Cutaway fenster; K, Cretaceous rocks of Koyukuk basin; MAA, Mount Angayukaqsraq antiform; MF, Malamute fault; PF, Picnic Creek fenster; PLK, Porcupine Lake klippe; SFF, South Fork fault; TK, Cretaceous and Tertiary rocks of Brookian sequence; TMT, Table Mountain thrust; WLL, Walker Lake lineament.

kyanite-bearing schist associated with Late Proterozoic gneiss of the Ernie Lake pluton (Survey Pass quadrangle) may represent remnants of a regional high-grade metamorphic belt (Nelson and Grybeck, 1980; Till, 1989).

In the Coldfoot subterrane, the earliest, coarse-grained fabric in the Proterozoic(?) Kogoluktuk Schist of Hitzman and others (1982) predates known Brookian structures and is associated with relict epidote-amphibolite facies assemblages (Hitzman and others, 1986). Also providing evidence for pre-Devonian orogenesis in this subterrane are fabrics in part of the quartz-mica schist unit that are not present in Devonian plutons (Dillon, 1989). Turner and others (1979) originally suggested that K-Ar data from the Coldfoot subterrane indicated a Precambrian episode of blueschist facies metamorphism, but Till and others (1988) considered the disparity of K-Ar ages to be the result of Late Proterozoic amphibolite facies assemblages overprinted by Mesozoic blueschist facies assemblages.

An Early or Middle Devonian intrusive event is indicated by the belt of orthogneiss bodies that intrudes rocks of both the Hammond and Coldfoot subterranes. Newberry and others (1988) suggested that narrow metamorphic aureoles around these plutons indicate emplacement at a high structural level. Late

TABLE 1. GEOLOGIC CHARACTERISTICS OF NORTHERN ALASKA STRUCTURAL PROVINCES
(Structural provinces shown in Fig. 23)

Geologic characteristics	Southern Brooks Range	Northern Brooks Range	Lisburne Peninsula
Stratigraphy	**Arctic Alaska terrane:** *North Slope subterrane:* In Mt. Doonerak fenster, lower Paleozoic argillite, volcanic rocks, and limestone unconformably overlain by Mississippian through Triassic, stratified clastic and carbonate rocks. *Hammond, Coldfoot, and Slate Creek subterranes:* Mainly Proterozoic to Upper Devonian and locally upper Paleozoic, metamorphosed clastic, carbonate, volcanic, and plutonic rocks. **Angayucham terrane:** Devonian to Jurassic basalt and subordinate chert, limestone, and argillite.	**Arctic Alaska terrane:** *North Slope subterrane:* Mainly Mississippian through Triassic, stratified clastic and carbonate rocks; pre-Mississippian rocks present locally. *Endicott Mountains, De Long Mountains, and Slate Creek subterranes:* Mainly Upper Devonian through Lower Cretaceous, stratified clastic and carbonate rocks. **Angayucham terrane:** Devonian to Triassic basalt and Jurassic(?) peridotite and gabbro.	**Arctic Alaska terrane:** *North Slope subterrane:* Pre-Mississippian clastic rocks unconformably overlain by Mississippian to Lower Cretaceous clastic and carbonate succession.
Province boundaries	**Northern, eastern, and western:** Thrust faults dipping beneath structurally higher northern Brooks Range province. **Southern:** Depositionally overlapped by Cretaceous rocks of Koyukuk basin. **Internal:** Thrust faults between North Slope and Hammond subterranes and between Hammond and Coldfoot subterranes. Thrust and/or normal faults between Coldfoot and Slate Creek subterranes and between Slate Creek subterrane and Angayucham terrane.	**Northern and western:** Depositionally overlapped by mid-Cretaceous terrigenous clastic foredeep deposits of the foothills province. Boundary commonly modified by late Brookian deformation. **Northeastern:** Zone of transition in structural style to northeastern Brooks Range province. **Southern:** North-dipping thrust fault structurally overlying southern Brooks Range province. **Internal:** Thrust faults underlying constituent allochthons.	**Northern and eastern:** Thrust over foredeep deposits of the foothills province. **Southern and western:** Depositionally over-lapped offshore by deposits of younger Hope basin. **Northwestern:** Offshore continuation (Herald arch) thrust over foredeep deposits of Colville basin.
Structural features of early Brookian deformation	**Arctic Alaska terrane:** *North Slope, Hammond, and Coldfoot subterranes:* Large, dominantly north vergent, thrust-bounded fault slices and associated major and minor, tight to isoclinal folds. Penetratively polydeformed with at least two generations of minor folds and associated foliation. Thrusting outlasted ductile deformation. *Slate Creek subterrane:* Penetratively polydeformed but monometamorphic. Contains major, south-dipping normal faults. **Angayucham terrane:** Brittle major and minor imbricate thrust faults.	**All units:** Dominantly north vergent folding and thrusting. Penetrative structures and metamorphic overprint present locally, mainly in association with major thrust faults. **Arctic Alaska terrane:** *North Slope subterrane:* Closely spaced north-vergent folds and imbricate thrust faults. *Endicott and De Long Mountains subterranes:* Five(?) regionally extensive, but commonly laterally discontinous, predictably stacked thrust packages or "allochthons." Allochthons contain folds and duplexes, but character and intensity of deformation varies according to lithology. **Angayucham terrane:** Comprises the two structurally highest allochthons of the province. These allochthons behaved as coherent thrust sheets with little internal deformation.	Not significantly affected by early Brookian deformation.
Structural features of late Brookian deformation	Broad, doubly plunging, ENE- to WSW-trending open folds and, mainly in Slate Creek subterrane and Angayucham terrane, south-dipping low-angle normal faults and east-trending high-angle faults, south side down, with probable major right-lateral strike-slip displacement. Local south-vergent folding and faulting in North Slope, Hammond, and Coldfoot subterranes.	**All units:** Regional west plunge exposes progressively deeper structural levels eastward. **Arctic Alaska terrane:** *North Slope subterrane:* Early and late Brookian structures indistinguishable. *Endicott and De Long Mountains subterranes:* Broad anticlines and synclines superimposed on early Brookian allochthons. Smaller late Brookian folds and faults probably present but difficult to distinguish from earlier deformational features. Range-front deformation, defined by abrupt northward decrease in structural relief, postdates emplacement of allochthons and mid-Cretaceous foredeep deposition. **Angayucham terrane:** Same as for Endicott and DeLong Mountains subterranes of Arctic Alaska terrane.	East-vergent thrust faults and associated folds. Related east-vergent structures probably superimposed on adjacent parts of foothills and northern Brooks Range provinces.
Structural features related to rifting of Canada basin	Not significantly affected by rifting in Canada basin.	Not significantly affected by rifting in Canada basin.	Not significantly affected by rifting in Canada basin.
Metamorphism	**Arctic Alaska terrane** *North Slope subterrane:* Prehnite-pumpellyite to lower greenschist facies. *Hammond and Coldfoot subterranes:* Greenschist and blueschist facies, mostly overprinted by lower greenschist facies. Grade increases southward. *Slate Creek subterrane:* Lower greenschist facies. **Angayucham terrane:** Prehnite-pumpellyite to lower greenschist facies.	Incipient metamorphism to lower greenschist facies. Conodont color alteration index values indicate metamorphism at <300 °C.	Little or no Brookian metamorphism.

TABLE 1 (continued)

Northeastern Brooks Range	Foothills	North Slope
Arctic Alaska terrane: *North Slope subterrane:* Upper Proterozoic and lower Paleozoic sedimentary and igneous rocks deformed in pre-Mississippian time unconformably overlain by Mississippian to Lower Cretaceous carbonate and clastic continental-margin succession. In Arctic Foothills and Coastal Plain, unconformably overlain by Albian and younger terrigenous clastic deposits.	**Arctic Alaska terrane:** Albian and younger terrigenous clastic rocks shed northward and eastward from Brooks Range into Colville basin foredeep. Deposited on gently south dipping, Mississippian to Lower Cretaceous clastic and carbonate continental-margin succession of North Slope subterrane.	**Arctic Alaska terrane:** *North Slope subterrane:* Mainly pre-Mississippian argillite unconformably overlain by south-facing, Mississippian to Lower Cretaceous, clastic and carbonate continental-margin succession. Albian and younger terrigenous clastic rocks shed from Brooks Range rest conformably to unconformably on these rocks and form a constructional continental-margin sequence along margin of Canada basin.
Northern and northeastern: Separated from Canada basin by northern front of compressional deformation. **Eastern:** Zone of transition to north-trending structural low in Canada. **Southern:** Zone of transition in structural style to northern Brooks Range province. **Western:** Zone of transition to similar, but probably older, structures of foothills province. **Northwestern:** Separated from North Slope province by northern front of compressional deformation.	**Northern:** Separated from North Slope province by northern front of compressional deformation. **Eastern:** Zone of transition to similar, but probably younger, structures of the northeastern Brooks Range province. **Southern:** Mid-Cretaceous foredeep deposits of foothills province depositionally overlap northern Brooks Range province. Boundary modified by late Brookian deformation. **Western:** Overthrust by Lisburne Peninsula province.	**Northern:** Separated from Canada basin by tectonic hinge line marked by downbowing of pre-Albian rocks. **Southern and southeastern:** Separated from northeastern Brooks Range and foothills provinces by northern front of compressional deformation. **Western:** Separated from rocks of North Chukchi basin by tectonic hinge line marked by zone of significant downbowing of pre-Albian rocks.
Not significantly affected by early Brookian deformation.	Not affected by early Brookian deformation.	Not affected by early Brookian deformation.
Regionwide: Northward-convex, north-vergent fold belt. **Mountains:** Broad, east-trending anticlinoria cored by pre-Mississippian rocks; overlying Mississippian to Lower Cretaceous rocks shortened by detachment folds or widely spaced thrust faults. **Arctic Foothills and Coastal Plain:** Sharp northward decrease in structural relief at mountain front, although similar structures present in mountains probably present in subsurface. To north, foredeep deposits display broad synclines and narrow anticlines; these structures probably underlain by complex north-vergent imbricate thrust faults at depth. Structural relief and intensity of deformation gradually decreases northward.	North-vergent thrusting and associated broad synclines and narrow anticlines mainly above detachment in Torok Formation; stratigraphically lower units locally involved in deformation to south. Structural relief and intensity of deformation decreases gradually northward.	Not affected by late Brookian deformation.
Jurassic to Cretaceous extensional faulting (Dinkum graben); post-Jurassic northward downbowing of pre-Cretaceous, south-dipping continental-margin deposits (Barrow arch); and local late Neocomian uplift and erosion along Barrow arch. All overprinted by late Brookian contractional structures.	Not significantly affected by rifting in Canada basin.	Jurassic to Cretaceous extensional faulting (Dinkum graben); post-Jurassic northward downbowing of pre-Cretaceous, south-dipping continental-margin deposits (Barrow arch); middle and Late Cretaceous listric faulting offshore and minor Jurassic and Cretaceous extensional faulting in subsurface; local late Neocomian uplift and erosion along Barrow arch.
Little or no Brookian metamorphism.	Not affected by Brookian metamorphism.	Not affected by Brookian metamorphism.

Devonian and Mississippian deformation in the province was interpreted by Hitzman and others (1986) as extensional on the basis of inferred down-to-basin (predominately southward) faulting in the Survey Pass quadrangle. Subsequent uplift and erosion during the Devonian and Early Mississippian may be indicated by the sub-Mississippian unconformity in the Schwatka Mountains (Hammond subterrane) and in the Mt. Doonerak fenster (North Slope subterrane). However, Oldow and others (1987d) argued that penetrative fabrics in the pre-Mississippian rocks in the Mt. Doonerak fenster were not formed by deformation in early Paleozoic time; rather, they are related to later Brookian orogenesis.

Early Brookian structures. The semipenetrative and penetrative fabrics that characterize most of the southern Brooks Range structural province are generally interpreted as contractional structures that were developed during early Brookian deformation. This interpretation is supported by the apparent stability of high-P/low-T mineral phases along foliation surfaces and ^{40}Ar-^{39}Ar loss spectra for white mica in glaucophane schist (A. B. Till, 1992, oral commun.). Although there is currently considerable discussion about the timing and significance of some of these fabrics, particularly in the Coldfoot and Slate Creek subterranes (for example, Miller and Hudson, 1991), we group them here as early Brookian structures and note points of controversy.

Hammond and Coldfoot subterranes. The Hammond and Coldfoot subterranes and the North Slope subterrane in the Mt. Doonerak fenster are characterized by pervasive polyphase deformation and metamorphism resulting from the Brookian orogeny. Two or more generations of Brookian fabrics are generally present, although assignment of specific structures to a particular deformational event is commonly difficult (Grybeck and Nelson, 1981; Hitzman and others, 1986; Oldow and others, 1987d; Dillon, 1989). Tight to isoclinal folds occur from thin-section to regional scale. Axes of the folds, most commonly subhorizontal, trend approximately eastward, though some earlier structures are more north trending. Fold axial surfaces, most axial-planar fabrics, foliations, and associated thrust faults are moderately to gently dipping, and they commonly have been folded during later deformational events.

Near the Dalton Highway, the area for which the most information is available, Dillon (1989) and Gottschalk (1990) recognized three major fabric elements. The earliest fabric element, locally preserved in rocks of the Coldfoot subterrane, is a penetrative schistosity associated with isoclinal folds and sheath folds that are mostly to completely transposed by the second schistosity. The second fabric element, the most prominent foliation in the Coldfoot and Hammond subterranes, is also present in the North Slope subterrane in the Mt. Doonerak fenster. It generally parallels lithologic layering and is associated with megascopic to mesoscopic, tight to isoclinal folds. These folds are commonly intrafolial and have fold axes that parallel mineral lineations. The third fabric element is a semipenetrative, axial-planar schistosity or cleavage that increases in intensity to the south. In the northern part of the Hammond subterrane and in the Mt. Doonerak fenster, this fabric element is a centimeter-spaced phyllitic cleavage that is locally intense near major faults, but in the southern part of the Hammond subterrane, it is a millimeter-spaced axial planar schistosity. The geometry of folds associated with the latest fabric is variable and includes asymmetric, upright, and kink folds that display both northward and southward vergence. The earliest, mostly transposed, structural fabric was attributed by Dillon (1989) to pre-Devonian deformation; however, Gottschalk (1990) attributed the earliest two sets of structures to progressive deformation and metamorphism of the Brookian orogeny under conditions of top-to-the-north ductile shear. The latest fabric element is interpreted as the result of top-to-the-south extensional deformation that was related to uplift in the orogenic belt (Dillon, 1989; Gottschalk, 1990).

It is currently unclear if structures of the Dalton Highway area are representative of structures along strike. A. B. Till (1990, written commun.) reported that Brookian deformation is more complex and associated metamorphic events less distinct in the Hammond subterrane in the Dalton Highway area than in rocks of the subterrane in the western Brooks Range. Zayatz (1987), however, reported that rocks in the western part of the Coldfoot subterrane (Kallarichuk Hills) had a structural history comparable to that of rocks of the Coldfoot subterrane in the Dalton Highway area.

The nature of the northern limit of the southern Brooks Range structural province (that is, the southern limit of the Endicott Mountains subterrane) is poorly understood. This contact has been mapped both as a conformable surface and a thrust fault, probably folded, above rocks here assigned to the Hammond subterrane, and the North Slope subterrane in the Mt. Doonerak fenster (Coney and Jones, 1985; Mull and others, 1987c; Karl and others, 1989) (Fig. 23). In the Ambler River and Survey Pass quadrangles (Fig. 1), the contact is a regional north-dipping thrust fault that places Devonian rocks of the Endicott Mountains subterrane on Mississippian and older rocks of the Hammond subterrane (Kugrak River allochthon of Mull and others, 1987c). In the Baird Mountains, Chandalar, and Philip Smith Mountains quadrangles, however, a north-dipping thrust requires younger rocks—Upper Devonian strata of the Endicott Mountains subterrane—to be thrust onto older rocks—Devonian and older units of the Hammond subterrane (Brosgé and Reiser, 1964; Dillon and others, 1986; Karl and others, 1989). Jones and Coney (1989), however, reported detailed biostratigraphic data in the Philip Smith Mountains quadrangle that show that this contact places older Upper Devonian strata on younger Upper Devonian rocks. Along the northern margin of the Mt. Doonerak fenster, the northern boundary of the southern Brooks Range structural province is the north-dipping Amawk thrust (Mull, 1982, p. 21; Plate 6, section B-B′), which places the Devonian Beaucoup Formation of the Endicott Mountains subterrane over the Triassic Shublik Formation and Karen Creek Sandstone of the North Slope subterrane (Mull, 1982; Mull and others, 1987a) (Fig. 23). South of the Mt. Doonerak fenster, however, the southern limit of the Endicott Mountains subterrane is the south-dipping Table Mountain thrust of Dillon (1987, 1989), which, at least locally, places older rocks of the Hammond subterrane over younger rocks of the Endicott Mountains subterrane (Plate 13, section B-B′). Oldow and others (1987d) interpreted the Table Mountain thrust as the primary contact between the Endicott Mountains subterrane and the Hammond subterrane (their Skajit allochthon) and, on the basis of existing mapping, extended it along much of the central Brooks Range. Grantz and others (1991), however, interpreted the Table Mountain thrust as a local out of sequence thrust fault that developed across an earlier, north-dipping thrust fault between the two subterranes.

The contact between the Hammond and Coldfoot subterranes is an important structural lineament (for example, in the Schwatka Mountains, the "Walker Lake lineament" of Fritts and others, 1971) that has been variously interpreted as a change in depositional facies, an unconformity, a metamorphic boundary, and a folded thrust fault. Oldow and others (1987d) and Till and others (1988) considered this boundary a thrust fault, although the nature of this contact is commonly ambiguous in the field. Oldow and others (1987d) suggested that the Coldfoot subterrane was deformed by ductile shear during high-pressure (>8 kbar) metamorphism in a crustal-scale, north-vergent duplex that was bounded above by a decollement. Above the decollement, which acted as the roof thrust of the duplex, rocks of the Hammond subterrane were imbricated under lower pressure (<5–6 kbar) conditions. The decollement was later breached by younger thrust faults, and Coldfoot subterrane rocks were thrust northward to a higher structural level onto rocks of the Hammond subterrane. Thus, the present contact between the Hammond and Coldfoot subterranes may be a compound structure that includes both north- and south-dipping thrust faults. Till (1988), in contrast, noted differences in K-Ar cooling ages and metamorphic assemblages between the Hammond and Coldfoot subterranes and, as a result, suggested that the contact is a major thrust system along which earlier metamorphosed rocks of the Coldfoot subterrane were uplifted and emplaced northward onto the Hammond subterrane while the latter rocks were still undergoing metamorphism.

Slate Creek subterrane and Angayucham terrane. Although rocks of the south-dipping Slate Creek subterrane are polydeformed, they display only a single lower greenschist facies metamorphic overprint, in contrast with the higher grade, polymetamorphosed rocks of the Coldfoot subterrane to the north (Hitzman and others, 1986; Dillon, 1989; Karl and others, 1989). Because cleavage in the Slate Creek subterrane is similar in appearance and orientation to the latest cleavage in the underlying Coldfoot subterrane, Dillon (1989) suggested that the two cleavages formed during the same metamorphic event. Gottschalk (1987) likewise reported that the Slate Creek subterrane displays several generations of north-vergent folds that correspond to those of the Coldfoot subterrane to the north. Miller and Hudson (1991), however, reported down-to-the-south sense of shear indicators in the Slate Creek subterrane and interpreted the pervasive south-dipping fabric as ductile deformation due to regional extension in mid-Cretaceous time.

The Angayucham terrane dips gently to moderately southward, and its base is defined by a complex fault zone, commonly a unit of melange (Pallister and Carlson, 1988; Dillon, 1989). Rocks of the Angayucham terrane are metamorphosed to prehnite-pumpellyite and greenschist facies but lack the penetrative, north-vergent structures characteristic of rocks structurally beneath them to the north (Hitzman and others, 1986; Dillon, 1989). However, the Angayucham terrane displays complex internal imbrication (Jones and others, 1988; Pallister and Carlson, 1988; Dillon, 1989; Pallister and others, 1989). For example, Pallister and others (1989) described multiple 1-km-thick fault slabs mostly of basalt, as well as a complex melange zone bordering the northern margin of the terrane. In addition, detailed biostratigraphic studies have shown that chert units within the terrane are highly imbricated (Jones and others, 1988; Dillon, 1989).

Brookian metamorphism. The regional metamorphic mineral assemblages that characterize the southern Brooks Range structural province developed during the Brookian orogeny. The earliest formed are the blueschist facies assemblages, preserved locally in the Coldfoot and Hammond subterranes in the Baird Mountains, Ambler River, Survey Pass, and Wiseman quadrangles (Turner and others, 1979; Nelson and Grybeck, 1981; Armstrong and others, 1986; Hitzman and others, 1986; Dusel-Bacon and others, 1989, and this volume). Elsewhere, early blueschist facies metamorphism is shown by pseudomorphs of glaucophane and pseudomorphs after lawsonite in garnet (Gottschalk, 1987, 1990; Till and others, 1988). Till (1988) reported that high-P/low-T assemblages of the Coldfoot subterrane consist of early lawsonite-bearing and later epidote-bearing blueschist facies assemblages, whereas the Hammond subterrane preserves crossite-bearing assemblages that are associated with greenschist facies assemblages.

Throughout much of the province, the earlier high-P/low-T assemblages are overprinted by pervasive retrograde chlorite-zone greenschist facies assemblages. The retrogradation represents a nearly isothermal drop in pressure during metamorphism (Hitzman and others, 1986). In the Baird Mountains quadrangle, the chlorite-zone retrograde assemblage is modified by late development of randomly oriented biotite at the expense of chlorite, which suggests that late prograde greenschist facies metamorphism was caused by an increase in temperature (Zayatz, 1987).

Estimates of the maximum temperature and pressure attained during metamorphism in the province are in the range of 400–500 °C and 6–11 kbar (Hitzman and others, 1986; Gottschalk and Oldow, 1988). Metamorphic zones extend over a distance of about 5 km from pumpellyite-actinolite facies in the Angayucham terrane to blueschist facies in the Coldfoot subterrane. These data suggest that peak metamorphism of the Coldfoot subterrane occurred at depths of more than 25 km, whereas metamorphism of the Angayucham terrane occurred above 10 km. Dusel-Bacon and others (1989) concluded that Brookian metamorphism of the Coldfoot subterrane followed a clockwise

P-T path that evolved from low-T to high-T subfacies of the blueschist facies followed by greenschist facies.

Although isotopic dating of the prograde high-P/low-T assemblages has proved to be a formidable problem because of the polymetamorphic history of the host rocks, the age of high-P/low-T metamorphism is generally regarded as Late Jurassic to Early Cretaceous (Armstrong and others, 1986; Hitzman and others, 1986). Recently obtained ^{40}Ar-^{39}Ar loss spectra for white mica in a glaucophane schist indicate a minimum age of 149 Ma for high-P/low-T metamorphism (A. B. Till, 1992, oral commun.). The high-P/low-T metamorphism is commonly interpreted to have been caused by southward subduction of the Arctic Alaska terrane beneath the Angayucham terrane, whereas the later greenschist facies metamorphism was probably due to later thermal recovery and decreasing pressure associated with uplift and unroofing of the Brooks Range orogen later in Cretaceous time (Dusel-Bacon and others, 1989).

Late Brookian structures. The onset of late Brookian deformation in the southern Brooks Range structural province is difficult to determine because late Brookian deformation is defined on the basis of stratigraphic relations not present in metamorphic rocks of the southern province. In the northern foothills of the Brooks Range, early Brookian structures are unconformably truncated by Aptian and Albian foredeep deposits; therefore, we consider Aptian and younger structural features in the Brooks Range to be part of late Brookian deformation. This timing corresponds roughly with the change from prograde to retrograde metamorphism. Late Brookian structures include uplift and late folding of the southern Brooks Range, extension and strike-slip faulting along its southern margin, and east-vergent deformation in part of the range.

Uplift of the southern Brooks Range. Potassium-argon and ^{39}Ar-^{40}Ar cooling ages of metamorphic minerals suggest that a major uplift and unroofing event occurred in the southern Brooks Range between 130 and 90 Ma and culminated at about 120 to 100 Ma (Turner and others, 1979; Mull, 1982; Dillon, 1989; Blythe and others, 1990; Miller and Hudson, 1991). Till (1988) reported that K-Ar cooling ages are 100–86 Ma for the Hammond subterrane and 130–100 Ma for the Coldfoot subterrane and concluded that uplift may have occurred somewhat earlier in the southern part of the southern Brooks Range province. This major uplift event was probably the result of (1) isostatic rebound following crustal thickening during early Brookian large-displacement thrust faulting; (2) continued shortening during late Brookian orogenesis; and (3) tectonic denudation resulting from crustal extension. Uplift in the core of the range was previously assumed to be the result of isostatic rebound or south-vergent folding and thrusting, and denudation was thought to be caused primarily by erosion during uplift (Mull, 1982, 1985; Dillon, 1989).

Extension in the southern Brooks Range. South-dipping faults, mylonite, and phyllonite in, and at the base of, the Slate Creek subterrane and the southern foothills belt of the Angayucham terrane have been interpreted as thrust faults by most workers (for example, Angayucham thrust system of Dillon, 1989; this volume, Plate 6). However, apparent younger over older relations, the abrupt upward decrease in metamorphic grade across some of the faults, and sense of shear indicators have led many workers (Carlson, 1985; Box, 1987; Miller, 1987; Oldow and others, 1987a, 1987c, 1987d; Gottschalk and Oldow, 1988; Miller and Hudson, 1991) to propose the existence of major south-dipping, low-angle normal faults along the southern margin of the Brooks Range. Gottschalk and Oldow (1988) described structures in the Wiseman quadrangle consistent with normal faulting and documented petrologic evidence for the omission of at least 10 km of structural section. Box (1987) and Miller and Hudson (1991) reported that kinematic indicators support down-to-the-south displacement on gently south dipping faults in the Ambler and Wiseman quadrangles. Miller and Hudson (1991) interpreted the mid-Cretaceous sedimentary deposits of the Koyukuk basin as detritus derived from the footwall and deposited on the hanging wall of a regional south-dipping normal fault.

Despite the possibility that the Angayucham terrane and the Slate Creek subterrane may now be underlain by normal faults, most workers agree that the Angayucham terrane and the Slate Creek subterrane were originally emplaced on north-vergent thrust faults. Subsequent extensional deformation is related to mid-Cretaceous uplift of the southern Brooks Range and filling of the Koyukuk basin, but extensional structures involve rocks as young as Late Cretaceous (Box, 1987), which indicates that the extension may have continued into Late Cretaceous or Tertiary time (Gottschalk and Oldow, 1988). It is unclear whether normal faulting occurred along preexisting or newly formed fault surfaces, whether it was brittle or ductile, and whether it occurred as a consequence of deformation in a contractional orogen or in association with a regional episode of extension.

Folding in the southern Brooks Range. Postmetamorphic broad, upright, open folds have been superimposed over early Brookian structures in the southern Brooks Range (Hitzman and others, 1986; Dillon, 1989). These folds are typically doubly plunging, are symmetric to slightly asymmetric, and have wavelengths of tens of kilometers. They trend east-northeast in the vicinity of the Dalton Highway (Dillon, 1989) but gradually change westward to a west-northwest orientation in the Ambler River quadrangle (Hitzman and others, 1986). This generation of folds accounts for many of the most conspicuous regional-scale folds within the southern Brooks Range, including the Cosmos arch (Hitzman and others, 1986), the Mt. Doonerak anticlinorium (Dillon, 1989), and the Mt. Angayukaqsraq anticlinorium (Till and others, 1988), and may also account for regional arching of the Coldfoot subterrane (for example, the Kalurivik arch of Hitzman and others, 1982). Although these folds generally cannot be related demonstrably to faults exposed at the surface, they probably are related to shortening above faults at depth. This can be best demonstrated for the Mt. Doonerak and Mt. Angayukaqsraq anticlinoria, both of which formed above an anticlinal stack of horses in a duplex (Oldow and others, 1987d; Till and others, 1988). The time of construction of the Mt. Angayukaqsraq anticlinorium is uncertain, but the Mt. Doonerak anticlinorium may have been constructed by thrusting related to shortening in the northeastern Brooks Range in the Late Cretaceous or Tertiary (Oldow and Avé Lallemant, 1989; Grantz and others, 1991). The Cosmos arch may also be a relatively late structural feature, as evidenced by deformed Upper Cretaceous rocks and antecedent drainages that cross the arch.

Strike-slip faults along the southern flank of the Brooks Range. Some east-striking high-angle faults with down-to-the-south and probable right-lateral strike-slip displacements have been observed or inferred in the southern Brooks Range and the adjacent Koyukuk basin (Dillon, 1989) (Fig. 23). The Kobuk fault (Grantz, 1966), which lies immediately south of the Brooks Range within Cretaceous deposits of the Koyukuk basin, was inferred to underlie a topographic depression occupied for much of its length by the Kobuk River. To the east, it merges with the Malamute fault to form the Malamute–South Fork fault system (Dillon, 1989). This fault system cuts Cretaceous deposits of the Koyukuk basin and rocks of the Angayucham terrane and juxtaposes the Brooks Range and Ruby geanticline. The Malamute fault is a more northerly strand of the Kobuk fault system that cuts rocks of the Angayucham terrane and the Slate Creek subterrane. Both the Malamute and South Fork faults are locally exposed as narrow zones of unrecrystallized, brittlely deformed rocks, commonly including breccia, gouge, and slickensides, and are marked by prominent steps in magnetic and gravity intensity. Dillon (1989) interpreted a minimum of 90 km of post–Early Cretaceous right separation for the system. Although the Malamute–South Fork fault system is broadly concordant with regional trends in the Brooks Range, it sharply truncates northeast-striking lithologic and structural trends within the Ruby geanticline to the south (Decker and Dillon, 1984; Coney and Jones, 1985; Dillon, 1989), suggesting that larger amounts of separation are possible. Grantz (1966) and Dillon (1989) suggested that the Kobuk and Malamute–South Fork fault systems may represent a westward continuation of the Tintina fault system, which was offset by right-lateral displacement on an inferred extension of the northeast-trending Kaltag fault system of western Alaska.

A major northeast-striking lineament, called the Porcupine lineament by Grantz (1966), parallels the Porcupine River southeast of the Brooks Range (Fig. 23). Exposures in this area are poor, but deformed rocks at least as young as Triassic are exposed over a broad area, along with overlying undeformed Miocene basalt (Plumley and Vance, 1988; Oldow and Avé Lallemant, 1989). Although no displacement of geologic features has been demonstrated across the Porcupine lineament, it separates rocks of northern Alaska from those of east-central Alaska and is thought to represent a regionally important strike-slip fault. Most workers have inferred a Cretaceous (post-Neocomian) age for the postulated fault but differ over the amount and direction of relative movement along the structure. Some have speculated that it represents as much as 2000 km of left slip (Dutro, 1981; Nilsen, 1981), whereas others have proposed 150–200 km of right slip (Churkin and Trexler, 1980, 1981; Jones, 1980, 1982b; Norris and Yorath, 1981; McWhae, 1986; Dillon, 1989), and at least one worker (Smith, 1987) suggested movement in both directions.

East-vergent deformation in the southwestern Brooks Range. The east-striking structures that dominate most of the Brooks Range give way to northeast- to north-striking structures in the southwestern Brooks Range (Fig. 23; Plate 13). This change in structural trend has been interpreted to represent an oroclinal bend of originally east-striking structures (Patton and Tailleur, 1977). However, on the basis of work in the Baird Mountains, Karl and Long (1987, 1990) suggested that the northeast- to north-striking structures have been superimposed over older east-striking structures. The younger structures consist of east-vergent folds and thrusts that decrease in intensity eastward but may extend as far east as the Dalton Highway (Gottschalk, 1990). Although the age of overprinting is uncertain in the Baird Mountains, it seems likely that this deformation was related to east- to northeast-directed deformation along the Tigara uplift and Herald arch.

Northern Brooks Range structural province

The northern Brooks Range structural province contains much of the preserved superstructure of the main axis of the Brooks Range orogen; it is a gently north sloping structural plateau between the structurally higher southern Brooks Range province to the south and the structurally lower foothills province to the north (this volume, Plate 6). Rocks are generally younger to the north (the "regional north dip" of Mull, 1982), but dip of bedding and thrust faults varies within the province. Throughout most of the northern Brooks Range province, dominantly north-vergent fold and thrust structures are spectacularly exposed; however, the rocks are only locally metamorphosed and penetratively deformed. All recognized structures in the province can be ascribed to Brookian orogenic events, although the presence of extensional faults of Devonian to Mississippian and Cretaceous age may be inferred from regional stratigraphic patterns and local structural features.

Allochthons and significance of the Mt. Doonerak fenster. The northern Brooks Range structural province is characterized by generally coeval, but distinctive, stratigraphic sequences that are structurally stacked in predictable succession over large areas. This observation, first recognized by Tailleur and others (1966), has led to the interpretation that the various stratigraphic sequences constitute regionally extensive thrust packages, or allochthons, stacked one on top of another (Martin, 1970; Ellersieck and others, 1979; Mull, 1982; Mayfield and others, 1988). On the basis of successions exposed in structural windows in the northwestern Brooks Range (Picnic Creek, Drinkwater, Ginny, and Cutaway fensters; Figs. 20 and 23), seven allochthonous sequences have been recognized. From base to top, these are (1) the Endicott Mountains (or Brooks Range) allochthon; (2) the Picnic Creek allochthon; (3) the Kelly River allochthon; (4) the Ipnavik River allochthon; (5) the Nuka Ridge allochthon; (6) the

Copter Peak allochthon; and (7) the Misheguk Mountain allochthon (Fig. 21). As described earlier, the rocks of the structurally lowest five allochthons belong to the Arctic Alaska terrane and are assigned to the Endicott Mountains subterrane (Endicott Mountains allochthon) and the De Long Mountains subterrane (Picnic Creek, Kelly River, Ipnavik River, and Nuka Ridge allochthons). The two structurally highest allochthons, the Copter Peak and Misheguk Mountain allochthons, constitute the Angayucham terrane in the crestal and disturbed belts.

Rocks thought to be relatively in place compared to the above units are those of the North Slope and the Hammond subterranes. However, with the exception of rocks of the North Slope subsurface, rocks of the North Slope and the Hammond subterranes have been transported northward above thrust faults and hence are allochthonous in the strict sense (Oldow and others, 1987d; Till and others, 1988). Mississippian to Triassic rocks (lower Ellesmerian sequence) of the North Slope subterrane structurally underlie the Endicott Mountains allochthon in the northeastern part of the northern Brooks Range province and in the Mt. Doonerak fenster along the southern margin of the province (Fig. 23; this volume, Plate 6). A Mississippian and younger sequence similar to that of the North Slope subterrane is also exposed discontinuously to the west in the Hammond subterrane (Schwatka Mountains) (Mull and Tailleur, 1977; Tailleur and others, 1977; Mayfield and others, 1988). The lithology of these Mississippian and younger stratigraphic sequences differ markedly from the coeval sequence in the structurally overlying Endicott Mountains allochthon (Fig. 21). Thus, the Mississippian and younger rocks exposed south of the Endicott Mountains allochthon probably underlie the Endicott Mountains allochthon and connect to the north with the lower Ellesmerian sequence of the North Slope subterrane on the North Slope and in the northeastern Brooks Range (Dutro and others, 1976; Mull and others, 1987a). Consequently, most workers agree that the Endicott Mountains and overlying allochthons must be restored to a position south of these rocks and the pre-Mississippian rocks that depositionally underlie them (Mull and others, 1987a, 1987c; Oldow and others, 1987d; Mayfield and others, 1988; Grantz and others, 1991). Mull and others (1987a) suggested a minimum northward displacement of the Endicott Mountains allochthon of 88 km, the distance from the northernmost exposures of the allochthon to the southern margin of the Mt. Doonerak fenster. This figure does not account for shortening within or below the allochthon. Oldow and others (1987d) suggested that the northern edge of the allochthon has been displaced about 200 km from its original position, assuming significant shortening within the subjacent North Slope subterrane. Oldow and others (1987d) also estimated an additional 35%–45% shortening to account for thrust imbrication and macroscopic folding within the allochthon.

Early Brookian structures. Although most completely and extensively preserved in the western Brooks Range, all but one of the allochthons (Kelly River) have been recognized along the length of the Brooks Range nearly to the Canadian border (Fig. 23). The structural stacking of coeval stratigraphic sequences over such a large area shows that deformation in the northern Brooks Range structural province is characterized by major shortening and indicates that the rocks of these allochthons are underlain by thrust faults of large displacement. Direction of tectonic transport, indicated by fold asymmetry and the tendency of thrust faults to cut stratigraphically upsection, is generally to the north, except in the westernmost part of the province, where the direction of tectonic transport is less certain. Most structures related to mapped thrusts probably formed during emplacement of the allochthons before Albian time, when foreland-basin deposits of the Aptian(?) and Albian Fortress Mountain Formation to the north unconformably overlapped the allochthons and their associated structures (Mull, 1982, 1985; Mayfield and others, 1988). The origin of many thrust-related structures, however, is unclear, and some may have developed in late Brookian time. Emplacement of the structurally lowest allochthon (Endicott Mountains allochthon) could not have occurred prior to deposition of its youngest strata in Early Cretaceous (Valanginian) time, but emplacement of the structurally higher allochthons in the De Long Mountains subterrane may have begun prior to the Early Cretaceous because foredeep strata of these allochthons are as old as Late Jurassic.

Although widespread, the allochthons commonly are not structurally intact and display internal folds, thrust faults, and fault-bounded changes in stratigraphic thickness and facies. In the northwestern Brooks Range, allochthons are laterally discontinuous, and one or more consecutive allochthons may be missing from the idealized structural sequence at any given location. Complete structural sequences consisting of all seven allochthons occur in only a few places, and even in many of those places, certain allochthons disappear laterally over distances of only a few kilometers. These features can be attributed to several factors, including (1) variation in original stratigraphic thickness within individual allochthons; (2) imbrication and development of duplexes within individual allochthons during thrusting, especially where relatively thin bedding and/or alternating competent and incompetent layers characterize all or part of the stratigraphy of an allochthon; (3) local extension of individual allochthons during thrusting; (4) breaching by out of sequence thrust faults; and (5) displacement along superimposed low-angle normal faults. The latter possibility is supported by the observation that faults at the base of allochthons locally cut downward through stratigraphic section to the north, in the inferred direction of tectonic transport (Roeder and Mull, 1978; Harris, 1988).

Angayucham terrane. Remnants of the Angayucham terrane in the northern Brooks Range structural province are locally preserved as klippen comprising the Copter Peak and Misheguk Mountain allochthons. These klippen range up to 150 km along strike and 20 km across strike (Patton and others, 1977; Roeder and Mull, 1978; Mayfield and others, 1988) and total less than 3 km thick. The thin dynamothermal aureole commonly marking the contact between the Copter Peak and Misheguk Mountain allochthons (Roeder and Mull, 1978; Boak and others, 1987;

Mayfield and others, 1988), and associated structural fabrics in adjacent parts of both allochthons, are related to original thrust emplacement of the Misheguk Mountain allochthon over the Copter Peak allochthon. Discontinuity of the aureoles and faulting of the metamorphic rocks within them indicate that the contact has been reactivated since its origin, probably along thrust faults that flatten upward beneath the Misheguk Mountain allochthon and later along down-to-the-north normal faults (Harris, 1988).

De Long Mountains subterrane. The structural thickness of the De Long Mountains subterrane is about 4 km, and constituent allochthons have respective structural thicknesses of no more than 3 km. These allochthons consist largely of structurally incompetent, thin-bedded rocks that formed multiple detachment horizons and complex and closely spaced (on the order of tens to hundreds of meters) folds and thrust faults. The thicker and more competent intervals, especially carbonate rocks of the Lisburne Group in the Kelly River allochthon, typically formed more extensive thrust sheets, broader folds, and more widely spaced thrust faults. Asymmetric to overturned folds in these competent intervals are as much as 1–2 km across. The stratigraphically lowest detachment horizons within the De Long Mountains subterrane are in fine-grained clastic rocks of the Endicott Group and older carbonate, or mixed carbonate and clastic, rocks.

Endicott Mountains subterrane. The Endicott Mountains subterrane (allochthon) has a structural thickness of at least 7 km in the central Brooks Range (Oldow and others, 1987d) and more than 10 km in the western Brooks Range (Mayfield and others, 1988). It is the stratigraphically and structurally thickest, most extensive, and most continuous of the allochthons. In the eastern part of the northern Brooks Range province, the Endicott Mountains allochthon comprises thick, structurally competent units, such as the Noatak Sandstone, Kanayut Conglomerate, and carbonate rocks of the Lisburne Group. In the southern part of the province, the basal detachment of the allochthon is developed in fine-grained clastic rocks of the Beaucoup Formation and Hunt Fork Shale, which display penetrative, dominantly north-vergent structures. These rocks acted as a shear zone and display an upward decrease in strain and in number of generations of small-scale folds (Handschy and Oldow, 1989). To the north in structurally higher levels of the allochthon, deformation is characterized by imbricate thrust sheets and large single-generation folds that detached within incompetent fine-grained rocks of the Hunt Fork Shale, Kayak Shale, and Etivluk Group (Kelley and others, 1985; Handschy and others, 1987; Kelley and Bohn, 1988; Handschy and Oldow, 1989). The shorter, steep to overturned limbs of anticlines face north in this area and display a strong sense of asymmetry; locally the folds are recumbent. In the western part of the province, the Endicott Mountains allochthon is composed largely of structurally incompetent units, especially the Kuna Formation, Etivluk Group, and Ipewik unit. Deformation in these rocks is characterized by complex and closely spaced folds and thrust faults; thus, fault spacing and fold wavelength regionally decrease to the west.

North Slope subterrane. Rocks assigned to the North Slope subterrane structurally underlie the Endicott Mountains subterrane and make up the eastern part of the northern Brooks Range structural province. North-vergent, asymmetric to overturned folds, between about 100 to 1000 m across, are the dominant structural element of these rocks. Thick and competent carbonate rocks of the Lisburne Group act as the rigid structural unit controlling the geometry of the folds. The folds, which are relatively closely spaced, are underlain and commonly separated by thrust faults rooted in the Kayak Shale. These structures probably formed during or after emplacement of the Endicott Mountains allochthon, but their absolute age is not determined.

Late Brookian structures. Exposures of the allochthons, particularly in the northwestern Brooks Range, are controlled primarily by folding. Structurally higher allochthons are preserved in broad synforms, and structurally lower allochthons are exposed in broad antiforms. These structural highs and lows, 15 to 30 km across, are gentle to open folds with gently to moderately dipping limbs. Local asymmetry of folds or associated thrust faults indicate tectonic transport to the north (in the western part of the province, to the northwest). The structures generally trend to the east, although there is a gradual change to northeast in the western part of the province. Both the anticlines and synclines tend to be doubly plunging, reflecting structural culminations and depressions along strike. The same regional pattern of folding affects all the allochthons. This pattern suggests that the folding occurred mainly after emplacement of the allochthons. As in the southern Brooks Range province, this style of large-scale folding may be directly related to postemplacement structural thickening by duplexing in underlying rocks.

Major features of the northern Brooks Range structural province. The northern Brooks Range structural province displays several major features that are the result of the accumulation of early and late Brookian deformation. These features are (1) the regional westward plunge of the orogen, (2) the disturbed belt, and (3) the range front of the western and central Brooks Range.

Regional westward plunge of the orogen. In the northern Brooks Range, progressively deeper structural levels are exposed from west to east due to regional westward plunge (Fig. 23). The structurally highest rocks, including the Angayucham terrane and De Long Mountains subterrane, are most extensively preserved in the northwestern Brooks Range. The central part of the province is underlain by the Endicott Mountains subterrane, indicating a relatively constant level of structural exposure for about 900 km in an east-west direction. Deformed rocks of the North Slope subterrane, the structurally lowest subterrane of the Arctic Alaska terrane, underlie the eastern part of the province. Increasing structural relief to the east probably resulted from greater depth to detachment but may also have resulted from greater shortening in the east and/or an oblique intersection of Brookian structures with regional Paleozoic and Mesozoic sedimentary facies patterns.

Disturbed belt. The northern part of the northern Brooks

Range structural province is characterized by complex folds and imbricate thrust faults and so is referred to as the "disturbed belt" (Brosgé and Tailleur, 1970, 1971; Tailleur and Brosgé, 1970) (Fig. 2). The disturbed belt consists of the northern part of the Endicott Mountains allochthon and remnants of other higher allochthons. Most of the allochthons are relatively thin and discontinuous in this region, probably because the original northern extent of the far-displaced allochthons corresponds roughly with the present northern boundary of the northern Brooks Range structural province.

The structural style of this belt has been strongly influenced by the dominance of thin-bedded and incompetent rock types. Fold wavelengths are short (meters to hundreds of meters), and faults are closely spaced in the thin-bedded rocks. Buckle folds are common where competent and incompetent rocks are interbedded. In dominantly incompetent (typically shale-rich) intervals, deformation produced complex, commonly incoherent, small-scale structures that are penetrative in many places. Where relatively thin competent layers make up a small percentage of a dominantly incompetent interval, broken formation is common. The incompetent intervals typically include flysch of the Okpikruak Formation that is interleaved with older, more competent allochthonous rocks. Where overprinted with a strong deformational fabric, it can be difficult to distinguish tectonically imbricated sections of the Okpikruak Formation from olistostromal units of the Okpikruak.

The disturbed belt has been mapped eastward across the mountain front and far into the eastern Brooks Range (Brosgé and Tailleur, 1970, 1971) (Fig. 2), where it is a major structural low that defines the transition between the northern and northeastern Brooks Range structural provinces (Wallace and Hanks, 1990) (Fig. 23). At its easternmost end, the disturbed belt consists entirely of the Endicott Mountains and North Slope subterranes, with the exception of an isolated klippe in the Porcupine Lake area (Arctic quadrangle) (Figs. 1 and 23). The klippe, composed of De Long Mountains subterrane and Angayucham terrane rocks, overlies rocks of the North Slope subterrane, confirming that, prior to erosion, highly allochthonous rocks once extended into the eastern Brooks Range at least as far north as the disturbed belt. To the northeast at Bathtub Ridge (Demarcation Point quadrangle (Fig. 1,), no allochthons are present; rather, autochthonous Lower Cretaceous deposits of the Colville basin are preserved in a structural low (the Bathtub syncline), conformably overlying rocks of the North Slope subterrane (Detterman and others, 1975; Reiser and others, 1980) (Figs. 3 and 23).

Range front of the western and central Brooks Range. An abrupt change in structural relief and elevation at the mountain front of the Brooks Range interrupts the progressive northward increase in level of structural exposure. The mountain front is most commonly marked by a sharp, down-to-the-north step of erosion-resistant carbonate rocks of the Lisburne Group. Where the carbonate rocks are stratigraphically thin or absent, the mountain front is marked by a step of Kanayut Conglomerate. In simplest terms, the range-front structures typically are down-to-the-north monoclines, in which the steep (north dipping) to overturned (south dipping) beds define the range front. The geometry of these monoclines suggests that they are underlain by north-directed thrust faults that generally are not exposed at the mountan front (Vann and others, 1986; Jamison, 1987). The east-trending range-front monoclines intersect older, presumably early Brookian, structures at an oblique angle (Crane and Mull, 1987), transect allochthon boundaries, and locally involve Albian and younger rocks. These observations suggest that the range-front structures are of late Brookian age.

Foothills structural province

The foothills structural province (Fig. 23) consists of deposits shed northward from the Brooks Range into its foredeep, the Colville basin, and later deformed during northward migration of the Brooks Range orogenic front (Mull, 1985). Deposition of Albian and younger clastic rocks of the Colville basin postdates the Late Jurassic to Neocomian emplacement of allochthons of the northern Brooks Range structural province; however, deformation of the clastic rocks indicates that contraction continued in the western and central Brooks Range to latest Cretaceous or earliest Tertiary time (Mull, 1985). Structures in the foothills structural province record shortening at least an order of magnitude less than that in the northern Brooks Range structural province. According to Kirschner and others (1983), only about 11 km of shortening (10%) has occurred in Brookian deposits of the foothills structural province; similarly, Oldow and others (1987d) suggested a figure of 15 km on the basis of a balanced cross section through the central Brooks Range.

The southern boundary of the province is the southern limit of exposure of the stratigraphically lowest deposits of the Colville basin, the Fortress Mountain and Torok formations of Albian age. There is a significant northward decrease in structural complexity across this boundary, in part because the allochthonous rocks to the south record the effects of large-scale thrust transport that has not affected the Colville basin deposits. The northern boundary of the province is the northern limit of structural thickening by thrust faulting and folding.

In vertical section, the foothills structural province is a northward-thinning wedge composed of deformed foredeep deposits (Plate 6, cross section B-B′). The wedge configuration is in large part the product of a southward increase in structural thickening, but it also reflects the original gentle south dip of the northern flank of the Colville basin. North of the deformation front, the top of the underlying upper Ellesmerian sequence dips about 1° south, as defined on seismic-reflection profiles by the reflector of the pebble-shale unit (Kirschner and others, 1983). South of the deformation front, the dip of this reflector increases to 3°, probably because of loading by both the Brookian thrusts and foredeep deposits. Reflectors in the Ellesmerian and subjacent Franklinian sequences can be traced southward at least as far as, and perhaps south of, the Brooks Range mountain front. These reflectors show little evidence of shortening over most of their length, but at least some evidence of thrusting and folding is visible to the south near the range front, despite the poor quality of data in this area (Kirschner and others, 1983; Mull and others, 1987c; Oldow and others, 1987d).

Outcrop, seismic, and well data indicate that the Torok and Fortress Mountain formations form a thick, northward-tapering, shale-rich wedge between the underlying homoclinal, south-dipping upper Ellesmerian sequence and overlying regionally north dipping deposits of the Nanushuk Group and younger units (Kirschner and others, 1983; Mull and others, 1987c; Molenaar, 1988). The Torok Formation is little deformed where it laps northward onto the northern flank of the Colville basin, but to the south it is imbricated and tectonically thickened, as is the Fortress Mountain Formation. Thickening in the wedge suggests that detachments exist within it and between it and the underlying relatively little deformed, gently south dipping rocks. Deformation within the wedge developed mainly by a combination of duplexing and detachment folding, though its precise character is difficult to define due to poor seismic data and lack of distinctive marker horizons. The sand-rich strata of the overlying Nanushuk Group are structurally more competent than the underlying shale of the Torok and Fortress Mountain formations and therefore have deformed more competently. The Nanushuk has been folded into sharp anticlines separated by broad synclines. The amplitude of the anticlines generally decreases and wavelength increases northward toward the deformation front. The anticlines typically are asymmetric, having steep limbs to the north, and are commonly breached by north-directed thrust faults.

In much of the central part of the foothills, a contrast in deformational geometry is marked by a prominent topographic feature, the Tuktu escarpment (Fig. 23), which delineates the southern limit of the north-dipping, more erosion-resistant sandstones of the Nanushuk Group. In the lowlands south of the Tuktu escarpment, small-scale, south-vergent folds in the Torok Formation are compatible with backthrusting near the top of the Torok and at the base of the Nanushuk Group, as hypothesized by Kelley (1988) in the Chandler Lake quadrangle (his Cobblestone fault). This geometry suggests that, as is typical in a triangle zone (Jones, 1982a), a thickened wedge of Torok and Fortress Mountain formations is overlain by a north-dipping, south-directed thrust fault at the Tuktu escarpment. Structurally lower and to the south, similar backthrusts separate synclinal remnants of competent sandstones and conglomerate of the Fortress Mountain Formation from underlying incompetent Okpikruak shale of the disturbed belt (Oldow and others, 1987d; Howell and others, 1992).

The Colville basin subsided by loading of the Brooks Range allochthons and sediments shed into the basin. However, analysis of gravity profiles across the Brooks Range and Colville basin suggests that an additional subsurface load is required to account for the total subsidence of the trough (Nunn and others, 1987). The nature of this load is unknown, but it may be due to (1) subduction of down-going lithosphere; (2) thinning of the dense lithospheric mantle beneath the crust prior to Brookian deformation in the lower plate of the orogen (that is, the southward continuation of the North Slope subterrane beneath the Brooks Range); and/or (3) obduction of a lithospheric block from the south (Angayucham terrane).

Lisburne Peninsula structural province

Pre-Cretaceous rocks of the Lisburne Peninsula are separated from coeval rocks of the Brooks Range proper by about 50 km of Cretaceous foredeep deposits of the Colville basin (Figs. 2 and 23) and display a northerly structural trend, in sharp contrast with the trend of the other structural provinces of northern Alaska. These pre-Cretaceous and overlying Lower Cretaceous deposits are deformed by west-dipping imbricate thrust faults and associated folds that characterize the structural style of the Lisburne Peninsula (Campbell, 1967). The southern part of the thrust front on the peninsula is marked by Mississippian and Pennsylvanian carbonate rocks of the Lisburne Group thrust over Neocomian clastic rocks of the Brookian sequence; the northern part exposes a regional-scale fold overturned to the northeast in Mississippian to Neocomian(?) rocks. These structures constitute an east-vergent fold and thrust belt that produced the Tigara uplift (Campbell, 1967), the onshore extension of the Herald arch of the Chukchi Sea (Grantz and others, 1970, 1981). Progressively older rocks are exposed to the west in the Lisburne Peninsula, probably reflecting progressively deeper basal detachment to the west.

The age of the Tigara uplift is not determined precisely. Campbell (1967) and Grantz and others (1970, 1981) reported that rocks as young as Albian are deformed, but Mull (1985) argued that the uplift already existed by Albian time. An Albian or older age for thrusting is inferred from paleocurrent data and distribution of Albian and younger sedimentary rocks in the Colville basin, which were deposited from west to east and were derived from a western source in the vicinity of the present Tigara uplift–Herald arch (Mull, 1985). The minimum age of thrusting is delimited only by undeformed Tertiary strata of the Hope basin that unconformably overlie the Tigara uplift south of Point Hope in the Chukchi Sea. This relation suggests that thrusting may be as young as early Tertiary (Grantz and others, 1981; Grantz and May, 1987). The Tigara uplift–Herald arch may represent a continuation of the Brooks Range, either formed originally along a different trend or later bent oroclinally (Patton and Tailleur, 1977). Alternatively, the Tigara uplift–Herald arch may have been formed in the Late Cretaceous or early Tertiary by tectonic processes unrelated to early Brookian orogenesis (Grantz and others, 1981).

Northeastern Brooks Range structural province

The northeastern Brooks Range structural province consists of the eastern part of the Arctic Coastal Plain and a prominent northward-convex arcuate topographic and structural salient, with respect to the northern Brooks Range structural province (Fig. 23). The topographically highest parts of the Brooks Range are found in the northeastern Brooks Range, and relatively deep structural levels of the North Slope subterrane are exposed extensively. Consequently, Proterozoic to lower Paleozoic rocks are widely exposed and display clear evidence of pre-Mississippian and younger deformational events. In structural style, the province is dominated at the surface by folding and lacks the closely spaced, large-displacement thrust faults characteristic of the northern Brooks Range structural province to the south (Mull, 1982; this volume, Plate 6; Wallace and Hanks, 1990; Howell and others, 1992). For this reason, the northern salient of the Brooks Range is thought to have escaped early Brookian deformation and was instead constructed mainly by late Brookian deformation, which extended north to the continental margin. Because the salient represents a younger deformational belt, it is known by the separate term, the Romanzof uplift (Fig. 23).

Pre-Mississippian structures. Pre-Mississippian rocks in the northeastern Brooks Range province display low metamorphic grades, and semipenetrative to penetrative structures that dip moderately to steeply with respect to the sub-Mississippian angular unconformity that characterizes the North Slope subterrane. The pre-Mississippian structures have been thought to have formed during a single Late Devonian to Early Mississippian event, the Ellesmerian orogeny. However, the presence of an angular unconformity beneath Middle Devonian strata not affected by the penetrative pre-Mississippian deformation indicates that major deformation preceded Middle Devonian deposition (Anderson and Wallace, 1990). East of the international border in the British Mountains, the youngest strongly deformed pre-Mississippian rocks are Early Silurian argillite (Lane and Cecile, 1989). This observation, coupled with the presence of undeformed Middle Devonian strata, indicates that the pre-Mississippian deformation occurred in the Silurian or Early Devonian in the North Slope subterrane. Polydeformational structures in Proterozoic to lower Paleozoic rocks of the northeastern Brooks Range suggest that an older deformation also may have affected some of these rocks (Anderson, 1991).

Geologic mapping by Reiser and others (1971, 1980) showed that faults displacing the pre-Carboniferous rocks in the northeastern Brooks Range dip mostly south. Reed (1968) and Reiser and others (1980) considered these faults evidence that structures formed during middle Paleozoic deformation were north directed and similar in orientation to younger Brookian structures. Oldow and others (1987b), however, interpreted these south-dipping faults and minor north-vergent structures as related to Brookian deformation and concluded from structural data that south-directed pre-Carboniferous penetrative deformation occurred in the northeastern Brooks Range.

Late Brookian structures. Although the northeastern Brooks Range province contains a fold and thrust belt, abundant evidence indicates that Brookian structures in the northeastern province were formed by late Brookian deformation. (1) The province lies north of the northern limit of the early Brookian allochthons. (2) The axis of the Colville basin strikes eastward into the province. (3) Albian foredeep deposits within the province have been uplifted and largely eroded, indicating significant late Brookian deformation (Mull, 1982, 1985). (4) Deformed Upper Cretaceous and Paleogene clastic rocks are locally preserved in the northern margin of the northeastern Brooks Range proper. (5) Neogene and Quaternary deposits are deformed above a middle Tertiary unconformity on the coastal plain and continental shelf (Craig and others, 1985; Bruns and others, 1987; Kelley and Foland, 1987). (6) Isotopic-cooling ages and apatite fission-track ages indicate uplift of the northeastern Brooks Range at about 60 Ma and uplift of the coastal plain to the north during later Tertiary time (Dillon and others, 1987b; O'Sullivan, 1988; O'Sullivan and others, 1989). (7) The province continues to be seismically active (Grantz and others, 1983a).

Romanzof uplift. The structure of the southern, mountainous part of the northeastern Brooks Range structural province is characterized by a series of east-trending anticlinoria, about 5–20 km wide, which expose pre-Mississippian rocks in their cores (Plate 6). These anticlinoria mark south-dipping horses in a duplex that is bounded by a floor thrust deep within the pre-Mississippian sequence and a roof thrust in the Mississippian Kayak Shale (Namson and Wallace, 1986; Wallace and Hanks, 1990). Although the overlying younger Mississippian through Triassic rocks conform to the structure of these anticlinoria, they also display shorter wavelength chevron folds above a major detachment horizon in the Kayak Shale. These detachment folds are hundreds of meters wide and do not display a strong or consistent sense of vergence. At structurally higher levels, detachment horizons occur in the Kingak Shale and in the pebble-shale unit. On the basis of a balanced cross section, Namson and Wallace (1986) estimated that about 40–45 km (27%–29%) of shortening occurred across the western part of the northeastern Brooks Range structural province, from its boundary with the northern Brooks Range province north to the range front.

North of the range front of the northeastern Brooks Range, rocks of the Arctic Coastal Plain are also deformed. Upper Cretaceous to Tertiary foredeep deposits are exposed at the surface and extend to considerable depth (Bader and Bird, 1986; Bruns and others, 1987; Kelley and Foland, 1987). These rocks define large antiforms that are currently thought to be the most prospective structures for petroleum exploration in the ANWR. Seismic reflection profiles suggest that these antiforms were probably formed by complex north-vergent imbrication beneath north-dipping roof thrusts. At deeper structural levels, large, north-tapering wedges are present above south-dipping thrust faults within pre-Mississippian rocks, similar to the horses in the pre-Mississippian rocks of the northeastern Brooks Range.

Offshore from Camden Bay eastward to Canada, Cretaceous and Tertiary clastic rocks have been deformed into an arcuate belt of folds (Grantz and May, 1983; Craig and others, 1985; Moore and others, 1985b; Grantz and others, 1987). Within this belt, structural relief and dip decrease northward toward the deformation front, which at its northernmost extent parallels the modern continental slope, about 170 km north of the landward limit of the northeastern Brooks Range structural province. On the coastal plain and offshore to the north, a major Eocene unconformity separates more highly deformed Paleogene deposits from underlying, less-deformed deposits. This unconformity suggests that a major deformational event occurred in Eocene time (Bruns and others, 1987; Kelley and Foland, 1987). Deformation has continued to the present, as indicated by exposures of steeply dipping Pliocene beds and offshore Quaternary structures, as well as active seismicity (Grantz and others, 1983a, 1987; Leiggi, 1987).

Late Cretaceous and Tertiary deformation in the northeastern Brooks Range structural province was influenced significantly by the Barrow arch and associated Lower Cretaceous unconformity and northward thinning of pre–Lower Cretaceous strata (Kelley and Foland, 1987; Wallace and Hanks, 1990). Because uplift of the Barrow arch occurred in Early Cretaceous time and prior to late Brookian deformation (see "North Slope structural province" below), the depth to Lower Cretaceous and older rocks was probably less in the northeastern Brooks Range province than anywhere else in the Brooks Range, and it decreased progressively northward toward the crest of the arch. Furthermore, the thickness of pre–Lower Cretaceous strata decreased northward because of onlap onto the northern highland that was the source of the Ellesmerian sequence and because of erosion during Early Cretaceous time. Consequently, the late Brookian deformation front prograded northward onto the northern flank of the Colville basin and southern flank of the Barrow arch and involved previously deformed upper Proterozoic(?) and Paleozoic rocks near the leading edge of the mountain belt.

Range front of the northeastern Brooks Range. The range front of the western part of the northeastern Brooks Range structural province trends northeasterly, diverging sharply from the easterly trend of the adjacent part of the front in the northern Brooks Range structural province. This northeast-trending segment is distinguished as the Philip Smith Mountains front (Fig. 23). The range front returns to a generally easterly trend to the northeast, where it is offset by a local salient defined by a series of east-trending front ranges, including the Sadlerochit and Shublik mountains (Figs. 1 and 23).

The range front of the northeastern Brooks Range province is probably defined by thrust-related folds, as in the northern Brooks Range province. However, the range front of the northeastern Brooks Range is younger than that of the northern Brooks Range province, having formed in response to the Cenozoic deformation that resulted in the Romanzof uplift. The origin of the arcuate trend of both the northeastern range front and the structures within the northeastern Brooks Range is uncertain. If tectonic transport was to the north-northwest, as structures in the central part of the arc suggest, then the northeast-trending Philip Smith Mountains front would mark an oblique ramp in a subsurface thrust fault (Rattey, 1985; Wallace and Hanks, 1990). Alternatively, the northeast-trending front may mark a zone of distributed left-lateral displacement that deformed earlier folds ("Canning displacement zone" of Grantz and May, 1983).

North Slope structural province

The North Slope structural province (Fig. 23) is characterized by nearly flat lying strata of Mississippian and younger age and by the absence of structures ascribed to the Brookian orogeny. Prominent structural features of this province, known from seismic reflection profiles and well data, are (1) pre-Mississippian structures of poorly known character truncated by a regional sub-Mississippian unconformity; (2) local basins of Devonian and/or Mississippian age; and (3) extensional structures related to formation of the northern continental margin of Alaska, the Barrow arch, and the regional Lower Cretaceous unconformity.

Pre-Mississippian structures. Structures in pre-Mississippian rocks of the North Slope province are poorly known, although existing data indicate that these rocks are penetratively deformed, weakly metamorphosed, and have a general easterly strike. Most of the pre-Mississippian rocks sampled by drill core are argillites or phyllites; they display slaty cleavage, small-scale isoclinal folds, or small-displacement faults. Drill cores and dipmeter logs indicate steep dips in the pre-Mississippian rocks, seismic data show local dipping and folded reflectors, and gravity and magnetic anomalies suggest the presence of major faults or dipping lithologic contacts. Except for the shallowest parts of the Barrow arch, there is little contrast in degree of induration between pre-Mississippian and immediately overlying Mississippian rocks. This observation suggests that the pre-Mississippian rocks were never buried to depths much greater than their present 3–5 km. However, the widespread presence of deformed Ordovician and Silurian argillitic rocks suggests that there is a great thickness of rocks of these ages, probably as a result of tectonic thickening.

Mississippian basins and faulting. By Mississippian time, following pre-Mississippian deformation, subsidence and deposition took place in several local basins (Meade, Umiat, Ikpikpuk, and Endicott) of the North Slope subterrane (Fig. 9). Seismic records indicate that these basins developed as sags or partly fault bounded basins (half grabens) and are filled with Mississippian and perhaps older strata. Well and seismic data show that bounding faults in the Endicott basin truncate Mississippian strata; in the Umiat basin, bounding faults truncate strata possibly as young as Pennsylvanian. Regionally, the bounding faults have north to northwest strikes and display as much as 700 m of throw. The origin of the basins has been attributed to extension and subsidence associated with formation of the passive continental margin of the Arctic Alaska terrane to the south during middle Paleozoic time (Kirschner and Rycerski, 1988; Grantz and others, 1991). Alternatively, Hubbard and others (1987) suggested that the basins represent local foredeeps and transtensional pull-apart basins associated with regional contraction during pre-Mississippian orogenesis.

Mesozoic rifting. A series of Jurassic and Early Cretaceous normal faults lie mostly beneath the continental shelf and strike subparallel to the northern continental margin of Alaska (Grantz and May, 1983; Craig and others, 1985; Hubbard and others, 1987). Seismic-sequence analysis indicates that faulting occurred over a span of about 60 m.y. (Bathonian to Aptian) (Hubbard and others, 1987; Grantz and others, 1990a, and this volume). An early episode of failed rifting, characterized by faults downthrown to the south, began in Middle Jurassic time and led to the development of sediment-filled grabens (for example, the Dinkum graben) (Fig. 23) under the modern Beaufort continental shelf. A later episode of successful rifting, characterized by faults downthrown to the north, resulted in continental breakup and opening of the oceanic Canada basin in Early Cretaceous (Hauterivian) time. Faulting and uplift associated with the continental breakup led to the formation of the north flank of the Barrow arch and truncation of its upper surface by the regional Lower Cretaceous unconformity, which developed in the Early Cretaceous (Valanginian to Hauterivian).

Barrow arch. The Barrow arch (also referred to as the "Barrow inflection" by Ehm and Tailleur [1985] and the "Beaufort sill" by Mull [1985] and Mull and others [1987c]) is a broad, west-northwest–trending structural high that underlies the coastal area of northern Alaska and separates the Colville basin to the south from the Canada basin to the north (Fig. 23). Flanks of the arch dip generally less than 2°, and its axis plunges eastward at about a half degree. At its crest near Barrow, pre-Mississippian rocks are at depths of only about 700 m, and structural relief across both flanks is about 10 km. Although recognized as a local structural high by Payne (1955), the full extent of the Barrow arch was first discussed by Rickwood (1970), who defined its crest by the inflection of dip in Ellesmerian strata. Recent mapping of the crest of the Barrow arch from seismic data has focused on the inflection of dip of either the Lower Cretaceous pebble-shale unit or the (erosional) structural top of the pre-Mississippian rocks that form the core of the Barrow arch. The southern flank of this structural high, with the associated Lower Cretaceous unconformity, forms the primary trap for the Prudhoe Bay oil field.

As pointed out by many workers, the Barrow arch did not form as a result of a single deformational event; instead, it is a composite structural high. Its southern flank was established by late Paleozoic time as the gently southward sloping continental margin of the Arctic Alaska terrane, and its dip was increased in the Early Cretaceous by tectonic and sedimentary loading related to emplacement of the early Brookian thrust sheets in the Brooks Range. The northern flank was initially developed as a discontinuous feature associated with failed rifting in the Middle Jurassic. It did not become a continuous structural feature, displaying a regional reversal of dip in Ellesmerian and older strata, until continental breakup and formation of the oceanic Canada basin in the Early Cretaceous (Hauterivian). Since Early Cretaceous time, the northern flank of the Barrow arch has been modified further by development of a thick prism of Cretaceous and Tertiary passive-margin deposits and continued southward instepping of normal faults in the Beaufort continental margin. The southern flank has been modified also by tectonic and sedimentary loading associated with late Brookian tectonism to the south. In the coastal plain adjacent to the northeastern Brooks Range, these modifying factors have converged, resulting in subsidence of the Barrow arch to depths exceeding 4 km and overshadowing of the structural high by late Brookian anticlinoria.

PALEOGEOGRAPHY AND TECTONIC HISTORY OF NORTHERN ALASKA

In the previous sections we have described the physical stratigraphy and structure of northern Alaska and related them to the major tectonic units in the region. In this section we discuss the depositional and tectonic implications of these data and use the tectonic units to construct speculative paleogeographic and tectonic models for northern Alaska. These models are discussed in chronological order but are considered in relation to the tectonic environment we have inferred for various intervals of time. Accordingly, the major subjects to be discussed are as follows: (1) depositional framework of a pre-Devonian continental margin, (2) early to middle Paleozoic orogenesis, (3) continental breakup along the southern margin of the Arctic Alaska terrane in Devonian time, (4) depositional framework of the latest Devonian to Jurassic passive continental margin, (5) Jurassic to Early Cretaceous (early Brookian) orogenesis, (6) origin of the present northern Alaska continental margin, (7) evolution of the Colville and Koyukuk basins, and (8) post-Neocomian (late Brookian) tectonism. We then discuss the relation of northern Alaska to the North America continent and consider the various models for its origin as part of the Arctic realm.

Pre-Devonian continental margin

Paleogeographic reconstruction of the pre-Devonian stratigraphy of the Arctic Alaska terrane is complicated not only by Brookian orogenesis during Mesozoic and Cenozoic time but also by one or more episodes of contractional and/or extensional deformation in pre-Mississippian time. The deformational style, vergence, and tectonic significance of the older orogenic episodes are poorly known, making pre-Devonian paleogeographic reconstructions speculative. For the purpose of discussion here, pre-Devonian rocks in the North Slope, Hammond, and Coldfoot subterranes are classified as carbonate-platform, continental-slope, and oceanic deposits. The carbonate-platform deposits in the North Slope and Hammond subterranes are thick; they span part of Proterozoic and much of early Paleozoic time. Continental-slope or distal continental-margin deposits in the North Slope subterrane are mostly fine-grained quartzose rocks, widespread in both the subsurface and surface; in the northeastern Brooks Range, these include quartzose turbidites (Neruokpuk Quartzite) that may be analogous to the Windemere Supergroup of the Canadian Cordillera. Other, typically fine-grained rocks that may be continental-margin or continental-slope deposits crop out in the Hammond subterrane and may make up much of the Coldfoot subterrane. Where dated, these fine-grained rocks are typically Ordovician and Silurian, but some of them were probably deposited during Proterozoic and Cambrian time. Rocks indicative of oceanic deposition include Cambrian, Ordovician, and Silurian radiolarian chert, argillite, graywacke turbidites, mafic volcanic rocks, and island-arc volcanic rocks. These rocks occur both as melange and coherent masses in the North Slope subterrane. They are abundant in the northeastern and south-central Brooks Range and Lisburne Peninsula and, on the basis of gravity and magnetic data (Grantz and others, 1991), are inferred to be in the subsurface of the North Slope. Volumetrically, however, oceanic deposits may compose only a small part of the pre-Devonian rocks of the Arctic Alaska terrane.

Norris (1985), Dillon and others (1987a), and Lane (1991) suggested that pre-Devonian rocks of the North Slope, Hammond, and Coldfoot subterranes formed a thick carbonate-shelf to deep-marine-slope succession marginal to North America in Late Proterozoic and early Paleozoic time. In such a reconstruction, the oldest of the pre-Devonian rocks represent lateral equivalents of the Tindir Group and related Proterozoic rocks, now 450 km to the south in the Canadian Cordillera and Kandik area of east-central Alaska, whereas the Cambrian, Ordovician, and Silurian oceanic rocks are interpreted as lateral equivalents of coeval fine-grained miogeoclinal rocks of the Selwyn basin in the central Yukon Territory. This reconstruction is supported by (1) the quartzose composition of most of the pre-Devonian siliciclastic rock of the Arctic Alaska terrane and their lateral equivalents, (2) the general stratigraphic similarities between the pre-Devonian rocks of the Arctic Alaska terrane and, as originally defined by Stewart (1976), the North American continental-margin succession of the Canadian Cordillera, (3) the North American affinity of most fauna in the northeastern Brooks Range, and (4) the general position of northern Alaska on depositional strike with the North American miogeocline. The continental margin represented by pre-Devonian rocks of the Arctic Alaska terrane may be the northward continuation of the Late Proterozoic and early Paleozoic passive margin of the Canadian Cordillera. Contemporaneous carbonate platforms may be represented by the Proterozoic to Devonian carbonate succession in the Sadlerochit and Shublik Mountains of the northeastern Brooks Range and the Baird Group in the southern Brooks Range, although their original positions relative to each other and the continental-margin deposits are unknown.

A passive-margin model alone does not explain the widespread evidence for pre-Mississippian deformation in the eastern part of the Arctic Alaska terrane. For this reason, and because of the presence of pre-Devonian oceanic and volcanic-arc deposits in the south-central and eastern Brooks Range, Moore and others (1985a), Moore (1986), and Grantz and others (1991) suggested that originally disparate tectonic elements (displaced terranes) may have been accreted to the pre-Devonian continental margin of North America along one or more sutures in the Brooks Range. They suggest that lower Paleozoic volcanic-arc rocks and lithic flysch in the North Slope subterrane record closure of an ocean basin outboard of the North American continent. Possible evidence of a closure event may be represented by faunas of different affinity in the Arctic Alaska terrane. In the North Slope subterrane in the northeastern Brooks Range, Cambrian trilobites are of North American affinity, whereas in the southern part of the North Slope subterrane at the Doonerak fenster and in the Hammond subterrane, Cambrian trilobites and Ordovician conodonts are of Siberian affinity (Dutro and others, 1984; Blodgett and others, 1986; Dillon and others, 1987a; Harris and others, 1988; A. R. Palmer, 1988, oral commun.). These paleontologic data suggest that the Siberian continent (or continental fragments related to it) was involved in the closure and that most or all of the lower Paleozoic rocks of the Hammond and Coldfoot subterranes are of peri-Siberian origin, whereas those of the North Slope subterrane north of the crest of the Brooks Range are of North American affinity.

Early to middle Paleozoic orogenesis

Brosgé and others (1962) were the first to suggest that the regional sub-Mississippian angular unconformity in the northeastern Brooks Range may be evidence for early to middle Paleozoic contractional or extensional deformation. They also noted the thick, widespread, coarse-grained Upper Devonian and Lower Mississippian(?) clastic rocks of the Kanayut Conglomerate (Endicott Group, Endicott Mountains subterrane) and suggested that these were derived by erosion from a mid-Paleozoic orogenic zone. Subsequent work has shown that the sub-Mississippian unconformity extends throughout the subsurface of the North Slope to the Lisburne Peninsula and also is present in the Mt. Doonerak fenster (North Slope subterrane) and in the Schwatka Mountains (Hammond subterrane) in the southern Brooks Range; the extent of this unconformity suggests that the hypothesized middle Paleozoic orogenic episode affected much of northern Alaska. Lerand (1973) inferred that this orogenic episode occurred in the Devonian, and he linked it to the Ellesmerian fold belt, which he traced from northern Greenland through the Canadian Arctic and northern Alaska to at least as far west as Wrangell Island.

In the northeastern Brooks Range, deformed rocks beneath the sub-Mississippian unconformity include highly strained rocks (Oldow and others, 1987b), the direction of structural transport of which is unknown or controversial. In the Sadlerochit and Shublik mountains, pre-Mississippian deformation is indicated by large-scale tilting. In the Hammond subterrane and in the North Slope subterrane in the Mt. Doonerak fenster, a regional pre-Mississippian orogenic episode has not been documented, even though Mississippian rocks and the sub-Mississippian unconformity are present; the significance of the unconformity is controversial. Pre-Mississippian penetrative deformation, however, has been suggested for some rocks of the Hammond subterrane in the southern Brooks Range (Dillon, 1989; Till, 1989), and uplift and tilting are likely for some of the others in the Hammond subterrane. In the Endicott Mountains and De Long Mountains subterranes, the sub-Mississippian unconformity is absent, and the Devonian to Mississippian stratigraphic section is conformable. Mississippian to Triassic strata of the North Slope subterrane onlapped northward across the sub-Mississippian unconformity onto older rocks presently in the subsurface of the North Slope. This relation indicates that a middle Paleozoic highland existed north of the Barrow arch. Southward sediment transport during deposition of the Upper Devonian to Lower Permian(?) Endicott Group also indicates a northern highland (Moore and Nilsen, 1984; Bird, 1988a; Mayfield and others, 1988). Taken together, this evidence suggests that the area of middle and late Paleozoic erosion extended south at least as far as the southern Brooks Range, but maximum uplift was located north of the present-day Barrow arch.

A minimum age for early to middle Paleozoic orogenesis is indicated by the Early Mississippian age of the Kekiktuk Conglomerate, which rests on the sub-Mississippian unconformity. Rocks as young as Middle Devonian are truncated at a low angle by the unconformity in the northeastern Brooks Range (Reiser ad others, 1971, 1980; Anderson and Wallace, 1990). A Devonian age for the orogenesis is also suggested by emplacement of large granitic plutons and batholiths yielding Devonian U-Pb crystallization ages in the North Slope, Hammond, and Coldfoot subterranes (Dillon and others, 1987b). In the northeastern Brooks Range, these plutons are truncated by the pre-Mississippian unconformity, indicating that uplift occurred between the time of crystallization in Devonian time and their erosional truncation in Early Mississippian time.

Brosgé and others (1962) reported several unconformities in pre-Mississippian strata of the northeastern Brooks Range and concluded that pre-Mississippian orogenesis in northern Alaska was diachronous or involved more than one event. In the southern Demarcation Point quadrangle, Reiser and others (1980) mapped Middle Devonian calcareous sandstone in angular unconformity with a highly deformed unit of Cambrian and Ordovician chert, argillite, mafic volcanic rocks, and lithic graywacke described by Dutro (1981) and Moore and Churkin (1984). The absence in the Middle Devonian rocks of complex structures present in the underlying, older rocks indicates that significant deformation took place in pre–Middle Devonian time (Anderson and Wallace, 1990). Lower Devonian (Emsian) limestone rests with angular unconformity on Upper Ordovician and older carbonate strata in the Sadlerochit and Shublik mountains (Blodgett and others, 1988). Dillon and others (1987a), who assumed a Devonian age for the Skajit Limestone, suggested that Devonian carbonate rests unconformably on older rocks in the central Brooks Range. On the basis of these observations and the apparent absence of Lower Devonian strata throughout most of the Hammond and North Slope subterranes, Dillon (1989) argued that a pre–Middle Devonian unconformity exists throughout the central and eastern Brooks Range and concluded that orogenesis occurred in Silurian or Early Devonian time.

The tectonic causes for early to middle Paleozoic orogenesis in northern Alaska are unclear. As discussed for the pre-Devonian continental margin, the presence of a deformed pre-Devonian oceanic assemblage in the northeastern Brooks Range, pre-Devonian volcanic-arc rocks in the Mt. Doonerak fenster, and exotic faunal affinities led Moore and others (1985a), Moore (1986), and Grantz and others (1991) to suggest convergent deformation between Ordovician and Early Devonian time. Although pre-Carboniferous ophiolitic assemblages have not been recognized in northern Alaska, a west-trending band of low-amplitude magnetic anomalies thought to originate in pre-Mississippian rocks in the southern North Slope may be interpreted as a suture marked by serpentinite or, alternatively, as a belt of intrusive or mafic extrusive rocks of oceanic or arc affinity (Grantz and others, 1991). Dillon and others (1980) suggested that Devonian granitic rocks of northern Alaska have an arc affinity and, on the basis of this interpretation, Hubbard and others (1987) concluded that convergent deformation continued into Early Devonian time. This conclusion may be supported by the predominance of radiolarian chert detritus in Upper Devonian clastic rocks of the Endicott Group in the Endicott Mountains subterrane (Moore and Nilsen, 1984), which implies uplift and exposure of pelagic deposits.

Continental breakup along the southern margin of the Arctic Alaska terrane

Following convergent deformation and tectonic juxtaposition of lower Paleozoic rocks of the Arctic Alaska terrane by Middle Devonian time, deposition of continental-shelf sediments of the Arctic Alaska terrane resumed. Depositional successions of Late Devonian to Jurassic age are characterized by overall deepening conditions that gradually evolved from nonmarine deposition in latest Devonian and earliest Mississippian time to carbonate-platform and platform-margin deposition in Carboniferous time and finally to fine-grained clastic-rock, siliceous-shale, pelagic-limestone, and chert deposition from Permian to Jurassic time. This succession suggests that the Arctic Alaska terrane was subjected to regional subsidence, particularly along its southern margin (Endicott Mountains and De Long Mountains subterranes) for more than 200 m.y. The presence of Devonian to Jurassic oceanic rocks of the Angayucham terrane resting on the southern margin of the Arctic Alaska terrane suggests that the Arctic Alaska terrane was bordered to the south by an oceanic region from which the Angayucham rocks were derived. These relations indicate that an ocean basin was opened, presumably by rifting, along the southern margin of the terrane in middle to late Paleozoic time and that all or part of the Upper Devonian to Jurassic stratigraphy of the Arctic Alaska terrane composed a south-facing passive-margin sequence.

The detailed history of rifting, continental breakup, and onset of passive-margin deposition is uncertain. Because a southern highland province (see below) is inferred from Early Proterozoic arkosic detritus in the Mississippian and Pennsylvanian(?) Nuka Formation (De Long Mountains subterrane), Mayfield and others (1988) proposed that continental breakup of the southern margin of the Arctic Alaska terrane and opening of the Angayucham ocean basin began in Early Pennsylvanian time. A rifting event of this age may be supported by the many undated mafic sills that intrude Carboniferous chert of the Ipnavik River allochthon and by rare mafic volcanic rocks within the Lisburne Group. Evidence is also provided by extensional structures of Carboniferous age (Moore and others, 1986) and the presence of Carboniferous evaporites and mineral deposits (Metz and others, 1982).

Alternatively, Einaudi and Hitzman (1986), Hitzman and others (1986), Schmidt (1987), and Dillon (1989) interpreted rhyolite-dominated bimodal volcanic rocks, associated massive sulfide deposits, and abrupt facies changes with related unconformities of Devonian age in the Hammond and Coldfoot subterranes as evidence of rift-related high-angle faulting and extensional tectonism of the southern Arctic Alaska terrane during Devonian time. Dillon and others (1987b) interpreted the more siliceous of the bimodal volcanic rocks as extrusive equivalents of Devonian plutonic rocks in the Hammond and Coldfoot subterranes and argued that isotopic data indicating a crustal source for the plutons provide evidence for their origin by partial melting of continental crust in an extensional setting. The complex facies relations of Middle and Late Devonian sedimentary rocks in the Hammond and North Slope subterranes, the multiple erosional episodes in the North Slope subterrane during Devonian and Early Mississippian time, and the regional Late Devonian to Jurassic subsidence of the Arctic Alaska terrane indicate that continental breakup took place in Middle to Late Devonian time (Grantz and others, 1991). Thick, but local, accumulations of Middle Devonian terrigenous clastic rocks in the northeastern Brooks Range (Anderson and Wallace, 1990) and in the North Slope subsurface (Collins, 1958) were tilted prior to the Early Mississippian, suggesting that extensional deformation related to rifting took place in Middle Devonian time. However, the consistent southwest-directed paleocurrent indicators and the uniform clast composition of the Upper Devonian to Lower Mississippian(?) chert-rich, fluvial-deltaic Kanayut clastic wedge of the Endicott Mountains subterrane indicate that latest Devonian sediments were deposited as a south-facing, constructional continental-margin succession rather than as a rift-basin succession. Thus, the Kanayut clastic wedge was probably shed from an uplifted area of older orogenic deposits along the northern shoulder of the rifted southern margin of the Arctic Alaska terrane and was deposited on the outboard, southern margin of the Arctic Alaska terrane after continental breakup in earlier Devonian time. Together, these relations suggest that Early Devonian or older convergent tectonism culminated in plutonism and was succeeded in Middle and Late Devonian time by a rifting event that resulted in continental breakup, formation of the Angayucham ocean basin, and establishment of a south-facing Atlantic-type continental margin by latest Devonian time. If continental drift began in Middle or Late Devonian time, as suggested here, then the inferred southern highland of the Arctic Alaska terrane of Mayfield and others (1988) may have been partly or wholly composed of a Proterozoic granitic terrane that had been accreted to the Arctic Alaska terrane in pre-Mississippian time and then subsided as a large continental block along the southern margin of the terrane during rifting and opening of the Angayucham ocean basin.

Latest Devonian to Jurassic passive continental margin

Two contrasting paleogeographic reconstructions of the Arctic Alaska terrane have been suggested for latest Devonian (Famennian) to Jurassic time. Mayfield and others (1988) hypothesized that the Brooks Range orogen consists of at least seven regional internally imbricated thrust sheets or allochthons characterized by distinct upper Paleozoic and Mesozoic stratigraphic sequences. They proposed a simple south-to-north thrust emplacement sequence for these allochthons. This model assumes that each allochthon restores to a position immediately south of the allochthon it overlies structurally, and that each allochthon was thrust into place prior to thrusting of the allochthon it overlies structurally. Thus, the structurally higher allochthons have been displaced farther than the structurally lower allochthons because the higher allochthons have been carried northward in piggyback fashion on top of the lower allochthons. Because of the presence of a lithologically equivalent upper Paleozoic to Mesozoic stratigraphic section in both the Hammond and North Slope subterranes, Mayfield and others (1988) believed the Hammond subterrane to be a deformed, southward continuation of the North Slope subterrane and that both subterranes are autochthonous or parautochthonous relative to the Endicott Mountains and De Long Mountains subterranes. This palinspastic reconstruction therefore restores the latter subterranes to positions south of the Hammond subterrane. The structural assumptions used in this reconstruction result in a relatively complex paleogeography of alternating basins and stable platforms, particularly during Mississippian time.

Churkin and others (1979), however, assumed a paleogeographic model featuring an uncomplicated south-facing passive continental margin throughout late Paleozoic and early Mesozoic time. They assumed that condensed, siliceous Mississippian to Triassic basinal sequences (their Kagvik sequence) were deposited on oceanic crust located south of the coeval thicker continental-shelf deposits of the North Slope and Endicott Mountains subterranes and the Kelly River and Nuka Ridge allochthons of the De Long Mountains subterrane. In contrast to the model of Mayfield and others (1988), this model requires a more complicated history of structural shortening during the Brookian orogeny, involving a currently undocumented interval of southward-vergent thrusting separating two intervals of northward-vergent thrusting. Mayfield (1980) and Mull (1980) pointed out several lines of evidence indicating that the deep-water siliceous successions were deposited partly in shelf and platform environments of the Endicott Mountains and De Long Mountains subterranes, and suggested a subsiding platform-margin and slope, rather than oceanic, site for deposition of the siliceous succession. The model of Mayfield and others (1988) is therefore generally preferred by most workers, although the Pennsylvanian or younger time of breakup called for in their model is not accepted by all workers (Hitzman and others, 1986; Grantz and others, 1991).

Figure 24 shows a series of block diagrams illustrating paleogeographic reconstructions for latest Devonian to Neocomian time. This model is modified from Mayfield and others (1988), who proposed a two-sided basin in northern Alaska in pre-Pennsylvanian time followed by a simple south-facing passive margin from Pennsylvanian to Jurassic time. The alternative model of Churkin and others (1979) requires restoration of the Kelly River and Nuka Ridge allochthons of the De Long Mountains subterrane to positions north of the Endicott Mountains subterrane but south of the combined Hammond and North Slope subterranes. Note that the position of the southern basin margin shown by Mayfield and others (1988) hinges on the palinspastic position of the inferred source area for clastic rocks of the Nuka Formation and has not been observed in outcrop.

The regional sub-Mississippian unconformity shows that during latest Devonian and earliest Mississippian time (Fig. 24A), much of northern Alaska (North Slope subterrane and at least part of the Hammond subterrane) was uplifted and exposed as extensive northern highlands. Quartz- and chert-rich detritus from these highlands was shed southward and westward along drainage courses through at least two major alluvial plains onto a broad delta plain, which together constituted the sites of deposition for fluvial strata of the Kanayut Conglomerate (Moore and Nilsen, 1984). These fluvial deposits (Kanayut Conglomerate) prograded southward across related shallow-marine sediments and prodelta shale (Noatak Sandstone and Hunt Fork Shale) in Famennian (late Late Devonian) time, resulting in construction of the thick, south-facing fluvial-deltaic clastic wedge (Brosgé and Tailleur, 1971; Nilsen, 1981; Moore and Nilsen, 1984) now contained in the Endicott Mountains subterrane. Distal, submarine parts of the fluvial-deltaic wedge may be represented by compositionally mature sandstone turbidites of the Slate Creek subterrane (Murphy and Patton, 1988).

By Early Mississippian time, erosion reduced the northern highlands source region (Hammond and North Slope subterranes) to a broad, southward-sloping platform. Marine transgression across the Kanayut clastic wedge and northward onto the erosional surface resulted in the unconformable infill of remaining broad drainage basins by thin sequences of fluvial strata of the Kekiktuk Conglomerate, followed by deposition of marine shale and fine-grained sandstone of the Kayak Shale. Grabenlike basins on seismic-reflection records and thick accumulations of the Kekiktuk Conglomerate (as much as 1500 m) in the subsurface of the North Slope suggest that local extensional basins modified the erosional surface and were infilled with locally derived nonmarine strata (Oldow and others, 1987d; Woidneck and others, 1987; Grantz and others, 1991) prior to the marine transgression. By the end of Visean (Late Mississippian) time, the paleostrandline had migrated northward across the eroded highlands to the vicinity of Prudhoe Bay (Melvin, 1987), resulting in deposition of the marine Kayak Shale over a large part of the Arctic Alaska terrane.

In contrast to the siliciclastic-dominated subterranes that restore to more northerly positions, the latest Devonian and earliest Mississippian parts of the more southerly Kelly River, Ipnavik River, and Nuka Ridge allochthons of the De Long Mountains subterrane consist largely of carbonate and siliceous strata with only local accumulations of siliciclastic strata. These carbonate and siliceous strata rest conformably on Devonian carbonate rocks that may represent a long-lived carbonate platform not influenced by coeval clastic sedimentation of the Kanayut Conglomerate and related formations of the Endicott Group. The accumulations of latest Mississippian and Pennsylvanian(?) arkosic sandstone in the Nuka Ridge allochthon of the De Long Mountains subterrane indicate a nearby granitic source for which there is no evidence in other parts of the Arctic Alaska terrane. Mayfield and others (1988) suggested that rocks of the De Long Mountains subterrane were deposited on a carbonate platform and slope that was marginal to a southern highland in Devonian and Mississippian time, because of the subterrane's structurally high position and inferred restoration to more southern positions. To distinguish the hypothetical southern highland from the demonstrated northern source region, Tailleur (1973a) and Mayfield and others (1988) termed the southern paleohighland "Nukaland" for the distinctive arkosic strata in the Nuka Formation, and the northern paleohighland "Barrovia" for the town of Barrow located in the northernmost part of the North Slope subterrane. The basinal area between the two highlands was named the Arctic Alaska basin and was interpreted as an epicontinental sea by Mayfield and others (1988) because of the presence of older carbonate-platform deposits beneath Upper Devonian rocks on both flanks of the basin.

Deposition of carbonate-platform rocks of the Lisburne Group began along both margins of the epicontinental basin in the Early Mississippian (Osagean) and migrated northward across the older clastic-wedge deposits (Endicott Group) of the northern margin following cessation of clastic deposition during the early Late Mississippian (Meramecian) (Fig. 24B). By middle Pennsylvanian time, carbonate-platform rocks of the Lisburne Group had been deposited as a diachronous sheet across most of the Endicott Mountains and North Slope subterranes and the intervening Hammond subterrane. Siliceous sediments deposited within the epicontinental basin in Mississippian and Early Pennsylvanian time consisted of radiolarian chert and siliceous shale (Akmalik Chert of the De Long Mountains subterrane and Kuna Formation of the Endicott Mountains subterrane). These units were deposited in basinal areas distant from the carbonate-platform deposits, but they migrated locally onto the southern and western margins of the carbonate platform (Wachsmuth and Alapah limestones, Endicott Mountains allochthon) as it gradually subsided. The Kelly River allochthon (De Long Mountains subterrane), the only allochthon of the De Long Mountains subterrane to contain a thick succession of Lisburne Group carbonate-platform rocks, is restricted to the western part of the Brooks Range. This restricted extent may indicate that the Kelly River allochthon was deposited on a local structural high, per-

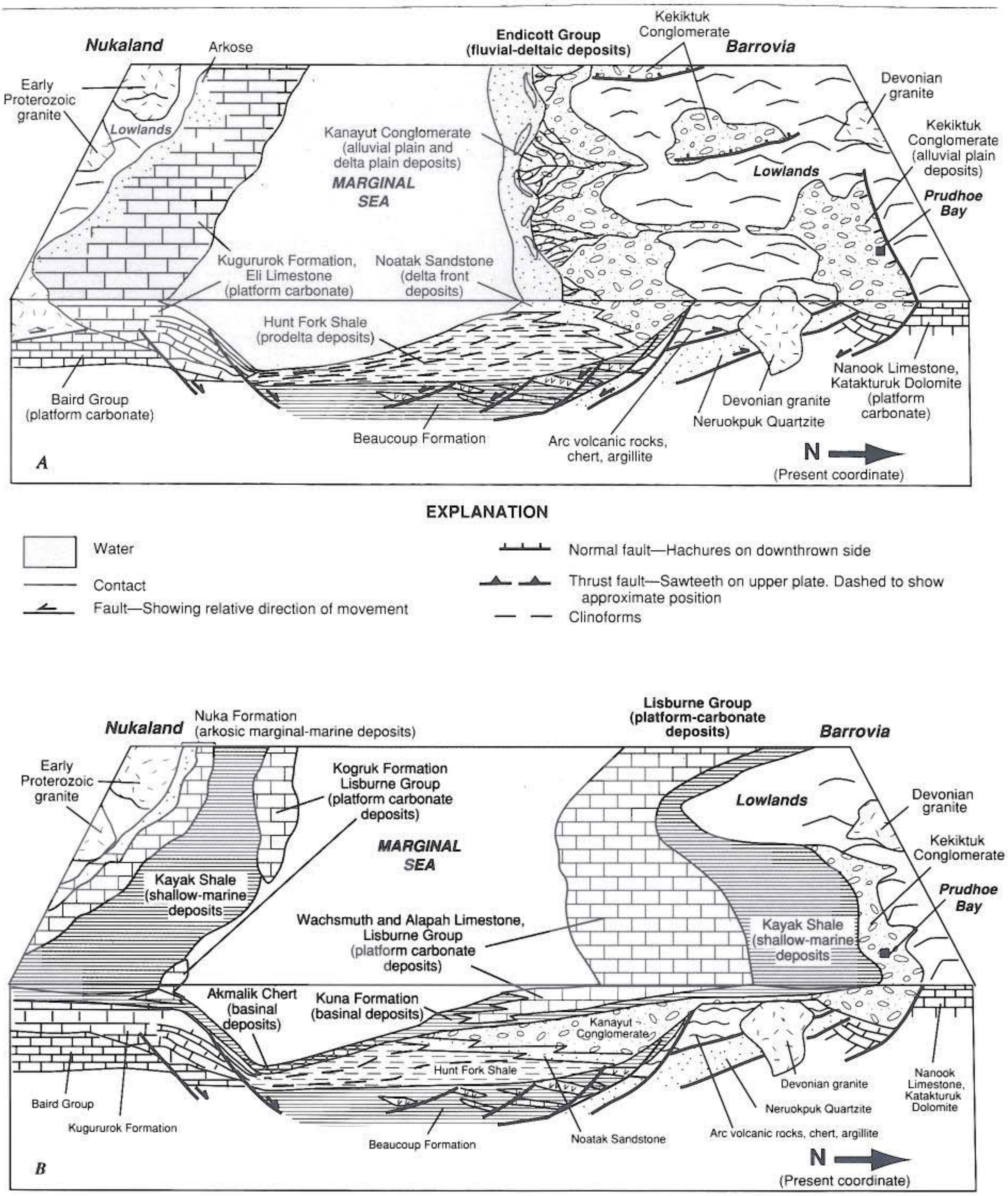
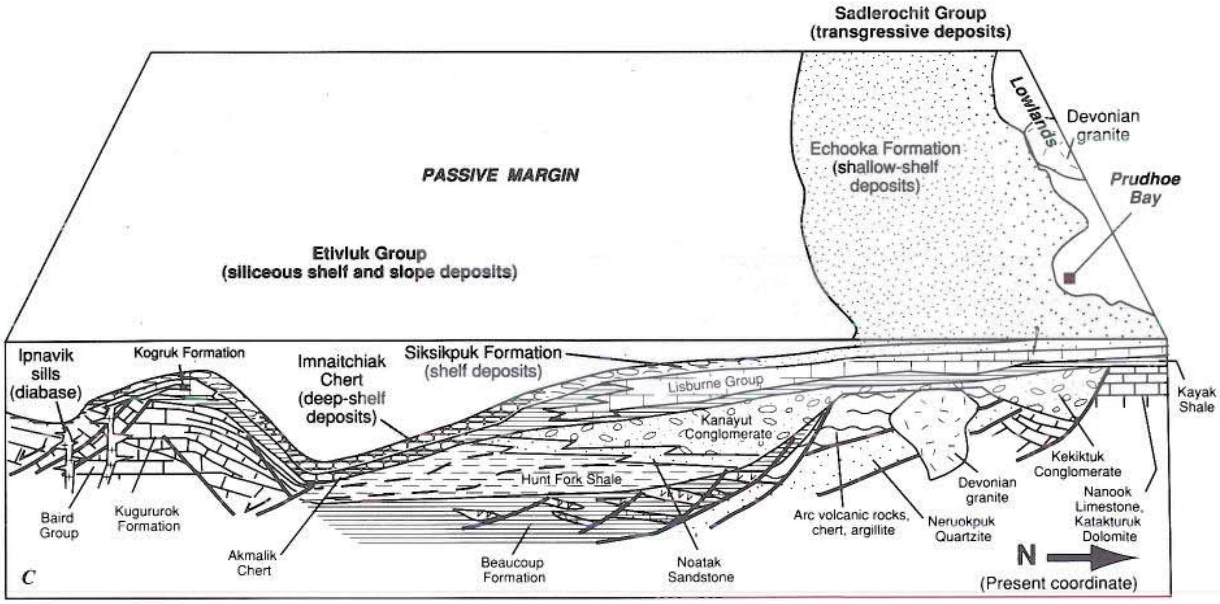
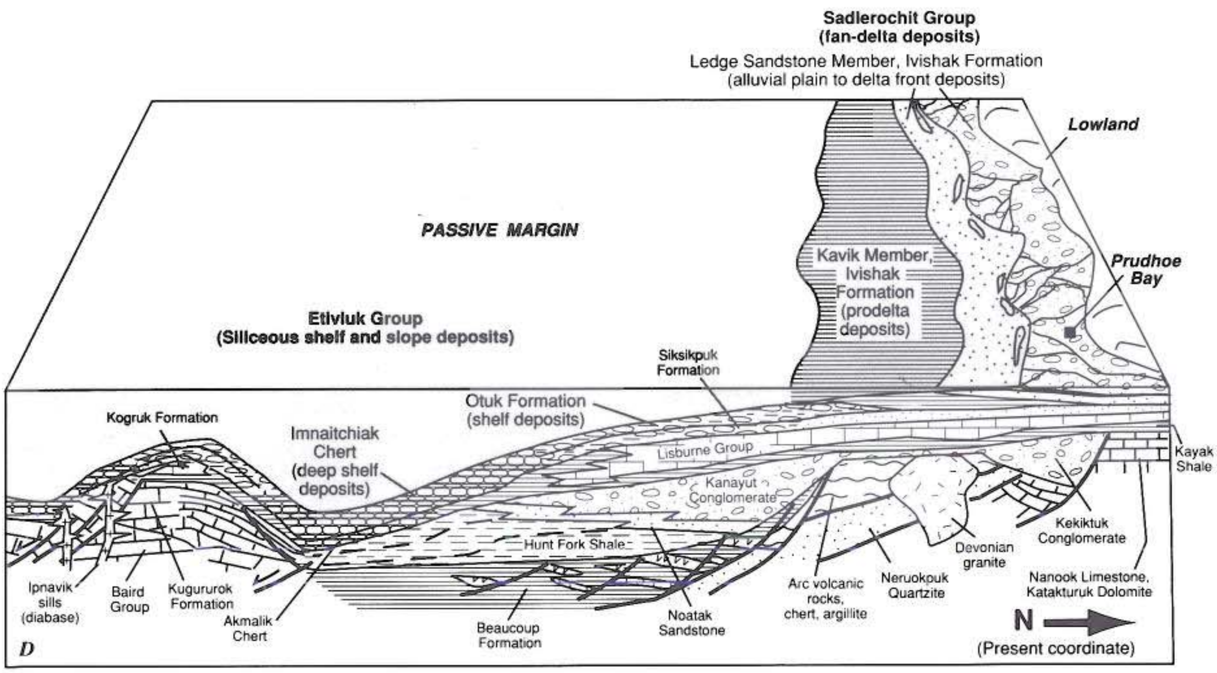


Figure 24 (on this and following two pages). Paleogeographic diagrams depicting depositional history of Arctic Alaska terrane for latest Devonian to Early Cretaceous. A, Latest Devonian (Fammenian) and earliest Mississippian. B, Early Late Mississippian (Meramecian). C, Late Permian. D, Early Triassic. E, Late Triassic. F, Early Cretaceous (Valanginian). For explanation of lithologic symbols, see Figure 21.

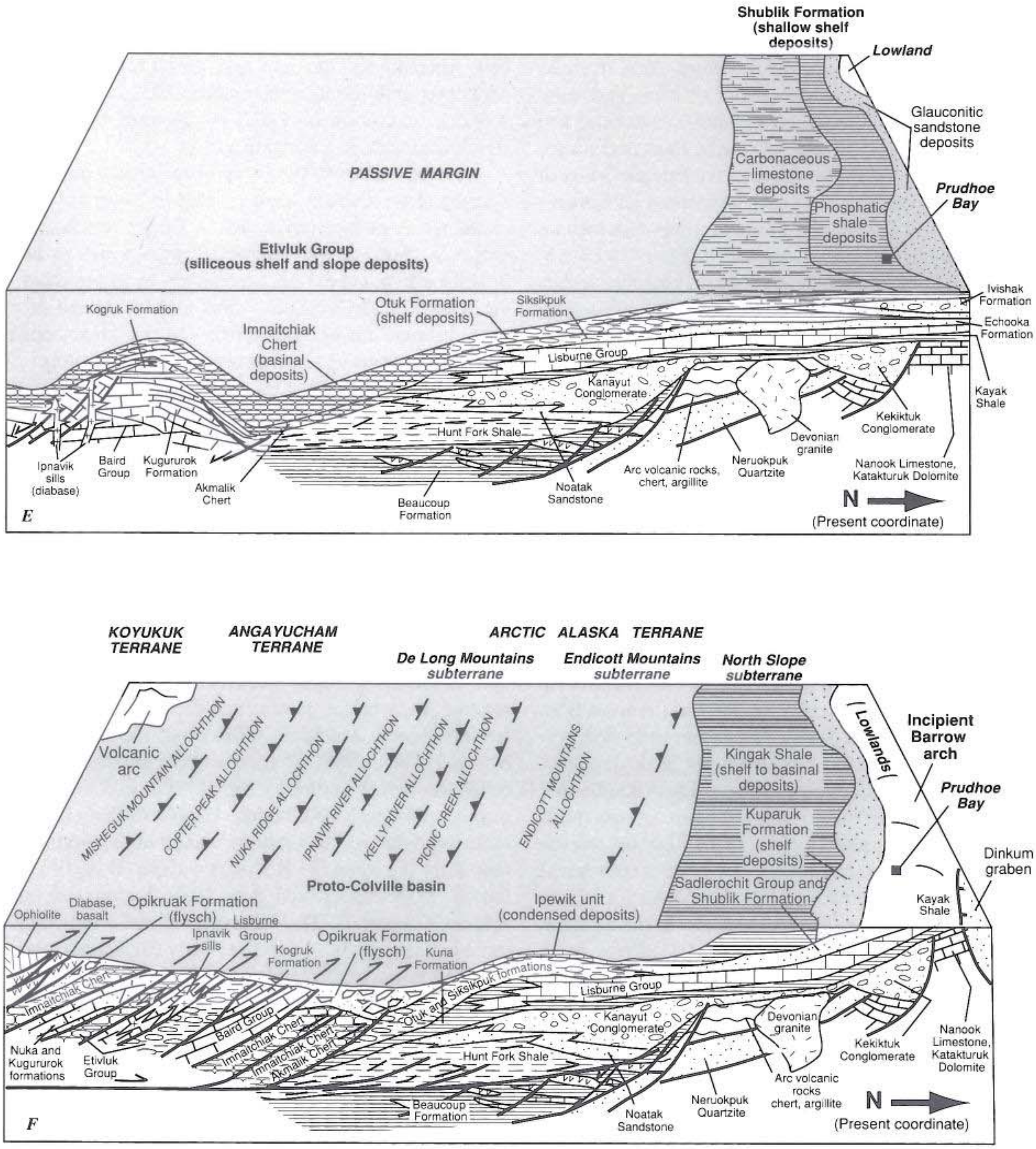




haps a fault block, within the epicontinental basin separating Barrovia and Nukaland.

By Permian time (Fig. 24C), deposition of carbonate-platform rocks in the North Slope subterrane gave way to deposition of transgressive siliciclastic rocks across a regional pre-Permian disconformity. These fine-grained siliciclastic rocks appear to fine and grade southward and westward into a shale-rich sequence in the Endicott Mountains subterrane (Siksikpuk Formation of Mull and others, 1987b), and into chert-rich sequences in most of the De Long Mountains subterrane (part of the Imnaitchiak Chert). The chert-rich sequences indicate that deposition in southern areas took place in basins remote from the influence of siliciclastic sedimentation. A regional increase with time in the ratio of radiolarians to sponge spicules in the siliceous rocks indicates gradual subsidence of the southern part of the Arctic Alaska terrane through the late Paleozoic (Murchey and others, 1988).

Uplift in the Early Triassic (Fig. 24D) in the region north of the present Beaufort Sea coastline is inferred to have caused erosion and deposition of coarse-grained marine and nonmarine



clastic detritus (Ledge Sandstone Member, Ivishak Formation, Sadlerochit Group). These deposits, inferred to represent a fan-delta (Melvin and Knight, 1984) or coastal-plain complex (Lawton and others, 1987) in the vicinity of the Prudhoe Bay oil field, were derived from a compositionally mature source area to the north and prograded southward across related prodelta deposits (Kavik Member of the Ivishak Formation) in the northern part of the North Slope subterrane. The thinness of the Sadlerochit Group (less than 700 m) indicates that the clastic wedge was constructed entirely across a shelf. Little is known about the cause of the hypothesized uplift in the northern highlands in Early Triassic time, but the alluvial-fan depositional environment favored by most workers for the northern and most proximal part of the Sadlerochit Group may suggest block faulting (I. L. Tailleur, 1988, oral commun.) that preceded Jurassic rifting of the Canada basin. Throughout the period of inferred tectonism, sedimentation in more southerly subterranes of the Arctic Alaska terrane consisted of siliceous shale and chert, indicating that Early Triassic tectonism was restricted to the northern margin of the terrane.

Subsequent marine transgression later in the Early Triassic through Late Triassic covered the coarse-grained marine and nonmarine detritus of the Sadlerochit Group with shallow-marine strata, including organic-rich shale, siltstone, and limestone of the Shublik Formation. General southward thinning and fining of the Shublik (Fig. 12) to siliceous shale, chert, and pelagic limestone of part of the Otuk Formation of the Etivluk Group in the Endicott Mountains and De Long Mountains subterranes (Fig. 24E) indicate that the Shublik Formation was deposited on a broad, southward-sloping, low-gradient shelf (Fraser and Clark, 1976). Furthermore, the phosphatic, glauconitic, and organic-rich character of the Shublik, as well as the abundance of the pelecypods *Monotis* and *Halobia* thought to represent mass kills, suggests that the shelf was subjected to a rising level, or episodic upwelling, of oxygen-depleted bottom water (Parrish, 1987). Ultimately, the Early Triassic to Late Triassic transgression may have been caused by cessation of tectonism and degradation of the source region (Melvin and Knight, 1984) or by a global or regional eustatic rise (Lawton and others, 1987).

During Jurassic time, marine sedimentation continued in the areas of the Endicott Mountains and North Slope subterranes south of the present Beaufort Sea coastline and lapped across the northern limit of the Shublik Formation and onto eroded pre-Mississippian rocks of the northern highlands region. Sedimentary rocks of the North Slope subterrane deposited during this time consist largely of dark, organic-rich, locally bioturbated shale and minor siltstone and sandstone that were derived from the north (part of the Kingak Shale). On seismic-reflection profiles, the Jurassic and Lower Cretaceous Kingak Shale displays a complex pattern of southward-prograding shallow-marine and slope deposits that downlap onto condensed basin deposits (Molenaar, 1988). These fine-grained progradational deposits provide a record of early uplift associated with rifting prior to continental breakup along the northern margin of the Arctic Alaska terrane in middle Early Cretaceous time. To the south in the Endicott Mountains subterrane, Jurassic strata consist of condensed basin deposits (Blankenship Member of the Otuk Formation); these deposits have also been inferred for the De Long Mountains subterrane by Mayfield and others (1988), but Jurassic rocks have yet to be documented. Although abundant in underlying upper Paleozoic and Triassic rocks in these subterranes, bedded chert is largely absent in the Jurassic rocks, probably reflecting a slight increase in the rate of clastic sedimentation related to rifting in the north and onset of Brookian tectonism in the south. By Late Jurassic time, flysch derived from the Brookian orogen was deposited in southernmost areas of the Arctic Alaska terrane, but condensed basin sedimentation continued until at least Valanginian (Early Cretaceous) time in more northerly areas (Fig. 24F). Near the top of the condensed basin deposits of the Endicott Mountains subterrane, the Valanginian coquinoid limestone (part of the Ipewik unit of Crane and Wiggins, 1976), composed of abundant pelecypods, is thought to have been deposited in situ and in relatively shallow water (Molenaar, 1988). This unit may represent an intrabasin structural high (or sill) (Jones and Grantz, 1964; Brosgé and Tailleur, 1971) that developed as a peripheral bulge in front of the northward-prograding Brookian orogenic belt. Alternatively, this unit may reflect initial uplift associated with onset of thrusting of the Endicott Mountains allochthon that was due to a northward shift of the main thrust front of the Brookian orogen in Valanginian time.

To the north, rift-margin uplift accompanying the successful opening of the Canada basin resulted in erosion of much of the crestal region of the Barrow arch in Early Cretaceous time. This erosional platform was composed, from south to north, of a broad southern coastal plain underlain by nonresistant rocks of the Kingak Shale, a narrow (50-km-wide) upland of relatively more resistant lower Ellesmerian and pre-Mississippian rocks, and a narrow northern coastal plain underlain by upper Ellesmerian rocks that were bordered on the north by the ancestral Arctic Ocean. Marine transgression in Hauterivian (Early Cretaceous) time resulted in local deposition of fine-grained, shallow-marine sand bodies (for example, Kemik Sandstone and upper part of the Kuparuk Formation) and in widespread deposition of the pebble shale unit onto shelf areas (Fig. 14).

Jurassic to Early Cretaceous (early Brookian) orogenesis

Northward emplacement of thrust sheets during the early phase of the Brookian orogeny in Jurassic and Early Cretaceous time is related by most workers to convergence between the oceanic Angayucham terrane and the continental Arctic Alaska terrane (Roeder and Mull, 1978; Mull, 1982; Box, 1985; Mayfield and others, 1988). The contact between the two terranes was called the Kobuk suture by Mull (1982) and the Angayucham thrust by Dillon (1989). Middle Jurassic to Early Cretaceous arc rocks deposited on the southern margin of the Angayucham terrane form the extensive Koyukuk terrane (Box, 1985; Box and Patton, 1989; Patton and Box, 1989; Patton and others, this volume, Chapter 7). The Angayucham and overlying Koyukuk terranes underlie the Albian (late Early Cretaceous) and younger Koyukuk basin, which borders the southern margin of the Brooks Range (Patton and Box, 1989). The Koyukuk and Angayucham terranes may have formed part of the paleo–Pacific Ocean basin during middle Mesozoic time (Box, 1985; Grantz and others, 1991).

Plate geometry during the early Brookian convergence is delimited by several important observations. (1) Peridotite and gabbro of the Misheguk Mountain allochthon (Angayucham terrane) form the structurally highest allochthon in the Brooks Range and are underlain by the pillowed basalts and diabase of the Copter Peak allochthon (Angayucham terrane), which are underlain by the subterranes of the Arctic Alaska terrane. (2) The structurally higher subterranes of the Arctic Alaska terrane (De Long Mountains, Endicott Mountains) were folded and faulted at shallow structural levels, whereas the structurally lower Hammond and Coldfoot subterranes were deformed ductilely at greater depths (Oldow and others, 1987d; Till and others, 1988). (3) Mineral assemblages in the ductilely deformed subterranes in the southern Brooks Range indicate metamorphism at high-*P*/low-*T* conditions in Jurassic and Cretaceous time followed by higher temperature metamorphism at somewhat lower pressures, whereas metamorphism of the Angayucham terrane and the structurally higher subterranes of the Arctic Alaska terrane occurred at relatively lower temperatures and pressures (Dusel-Bacon and others, 1989). (4) Plutonic and arc volcanic rocks of Jurassic and Early Cretaceous age are not present in the Arctic Alaska terrane, although sparse Middle Jurassic tuffaceous graywacke was reported from what is now mapped as the De Long Mountains subterrane (Jones and Grantz, 1964; Patton and Tailleur, 1964). (5) Middle Jurassic to Early Cretaceous plutonic and volcanogenic rocks, composing most of the Koyukuk terrane, are probably a remnant of an intraoceanic arc accreted to Alaska in Early Cretaceous time (Box, 1985; Patton and Box, 1989; Patton and others, this volume, Chapter 7). (6) Olistostromal blocks of volcanic and granitic detritus within the Okpikruak Formation of the De Long Mountains subterrane yield Jurassic K-Ar ages and may indicate that an arc terrane once formed the cover of the Misheguk Mountain allochthon (Angayucham terrane) prior to erosion of the orogenic belt (Mayfield and others, 1978). Roeder and Mull (1978), Mull (1982), Box (1985), Mayfield and others (1988), Patton and Box (1989), and Grantz and others (1991) interpreted these observations as evidence that early Brookian convergence between the Arctic Alaska terrane and the combined Angayucham and Koyukuk terranes involved south-dipping subduction of part of the Arctic Alaska terrane beneath the Angayucham and Koyukuk terranes. Box (1985) compared subduction of the continental Arctic Alaska terrane to Cenozoic subduction of Australia beneath Timor in the eastern Indian Ocean, and China beneath Taiwan in the western Pacific Ocean.

Stratigraphic evidence and isotopic-age data indicate that the early Brookian orogeny was diachronous. Onset of Brookian deformation is represented by selvages of amphibolite at the base of the ophiolitic Misheguk Mountain allochthon (Angayucham terrane). These amphibolite bodies, isotopically dated at 169 to 163 Ma, are inferred to have been metamorphosed during obduction of young, hot ocean crust (Wirth and Bird, 1992). The protoliths of the amphibolite, mafic volcanic rocks of the Copter Peak allochthon (Angayucham terrane), suggest that the Misheguk Mountain allochthon was emplaced onto the Copter Peak allochthon in the Middle or Late Jurassic. Sedimentary rocks of this age in the Arctic Alaska terrane, mostly condensed basinal sequences, suggest that the Arctic Alaska terrane was not involved in the initial phase of Brookian convergent deformation and that the earliest deformation involved only oceanic rocks of the Angayucham terrane.

Onset of involvement of the Arctic Alaska terrane in the Brookian orogeny is marked by the change from compositionally mature, northern source areas for uppermost Devonian to Jurassic strata to compositionally immature, southern source areas for Jurassic and younger strata of the proto-Colville basin. The oldest known compositionally immature strata in the Brooks Range are Upper Jurassic lithic turbidites of the Okpikruak Formation that were probably deposited on one of the structurally higher allochthons of the De Long Mountains subterrane (Curtis and others, 1984; Mayfield and others, 1988). The Okpikruak Formation is at least as old as Berriasian (earliest Early Cretaceous) in the Ipnavik River allochthon of the De Long Mountains subterrane but is no older than Valanginian in the Endicott Mountains allochthon. The Okpikruak Formation locally contains coarse-grained detritus derived from the Misheguk Mountain, Copter Peak, Ipnavik River, and Nuka Ridge allochthons, and it was deposited in, and carried with, the various allochthons of the De Long Mountains subterrane. The locally derived composition and olistostromal character of the Okpikruak Formation suggest syntectonic deposition into the foredeep along the northern limit of the early Brookian thrust front. Moreover, the apparent decrease in age of the Okpikruak structurally downward is interpreted as evidence that the thrust front advanced northward during Late Jurassic and Early Cretaceous time (Snelson and Tailleur, 1968; Mayfield and others, 1988).

The amount of Mesozoic to Cenozoic shortening across the Brookian orogen is poorly delimited, both because of the stratigraphic and paleogeographic uncertainties reviewed above and insufficient structural data. Assuming simple restorations, Mull (1982) estimated shortening ranging from a minimum of 96 km in the eastern Brooks Range to a minimum of 580 km in the western Brooks Range. Mayfield and others (1988), using a model for simple structural unstacking and rotation about a pivot point in the Mackenzie delta, estimated shortening of the Arctic Alaska and Angayucham terranes in the western Brooks Range to be 700 to 800 km or more. However, if the direction of structural transport during shortening was constant throughout the orogen, a minimum of only about 250 km of shortening is required for Mayfield and others' (1988) paleogeographic reconstruction, neglecting shortening across most intra-allochthon regional-scale folds and faults. Oldow and others (1987d) constructed balanced cross sections through the central Brooks Range and thereby made estimates of minimum shortening for the Endicott Mountains, Hammond, and Coldfoot subterranes of about 540 km. Although these estimates vary considerably in amount, they suggest that about 250 to 500 km of north-vergent shortening occurred during the Brookian orogeny. Such a large amount of shortening offers additional evidence that the Brookian orogeny is best explained as a consequence of subduction and ultimate closure of an ocean basin.

A tectonic model for Brookian tectonism modified from Mull (1982), Box (1985), Mayfield and others (1988), and Grantz and others (1991) is shown in Figure 25. During the Middle Jurassic, the Arctic Alaska terrane formed part of a passive continental margin adjoining an ocean basin that was underlain by late Paleozoic and early Mesozoic oceanic crust. Somewhere within the ocean basin, subduction of oceanic crust began during the Jurassic, and a continentward-facing intraoceanic arc (Koyukuk and related arc terranes) was established on oceanic crust (Kanuti panel, Misheguk Mountain allochthon) (Fig. 25A). Subduction of the oceanic crust flooring the basin resulted in con-

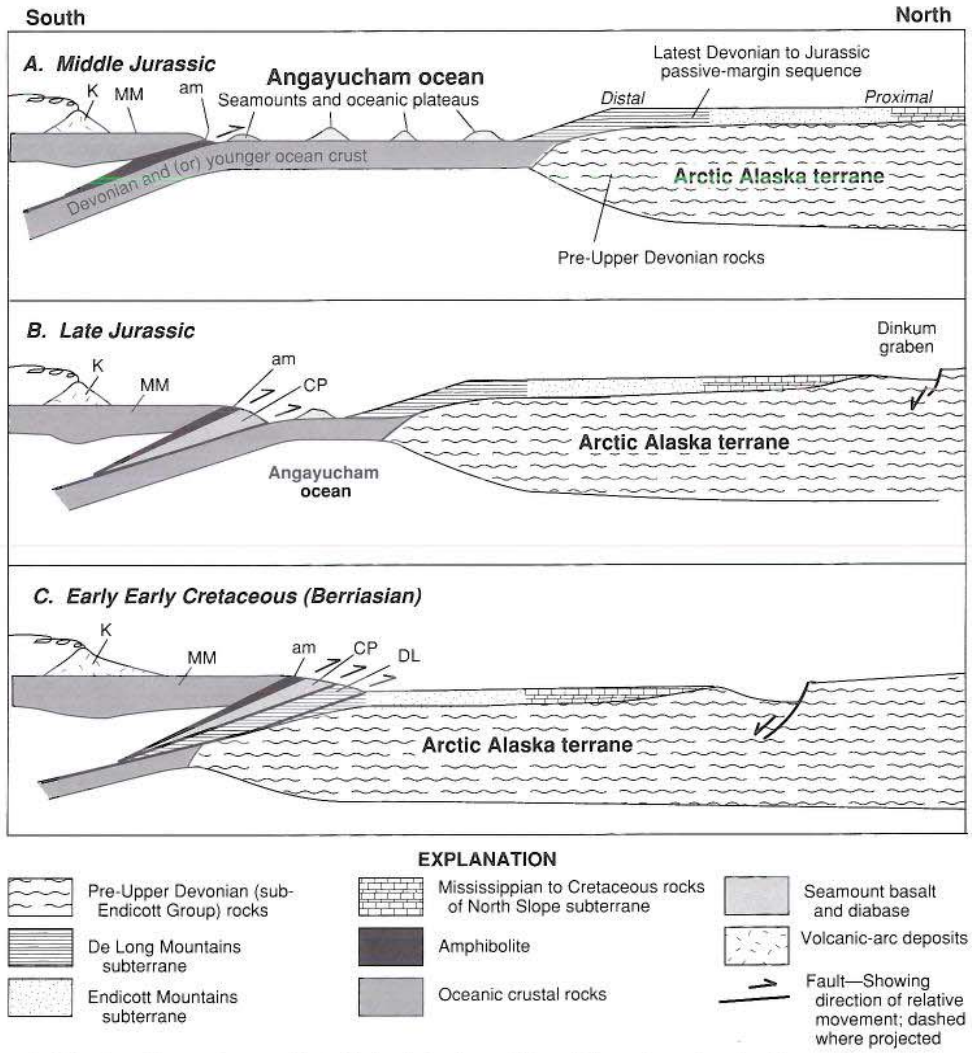
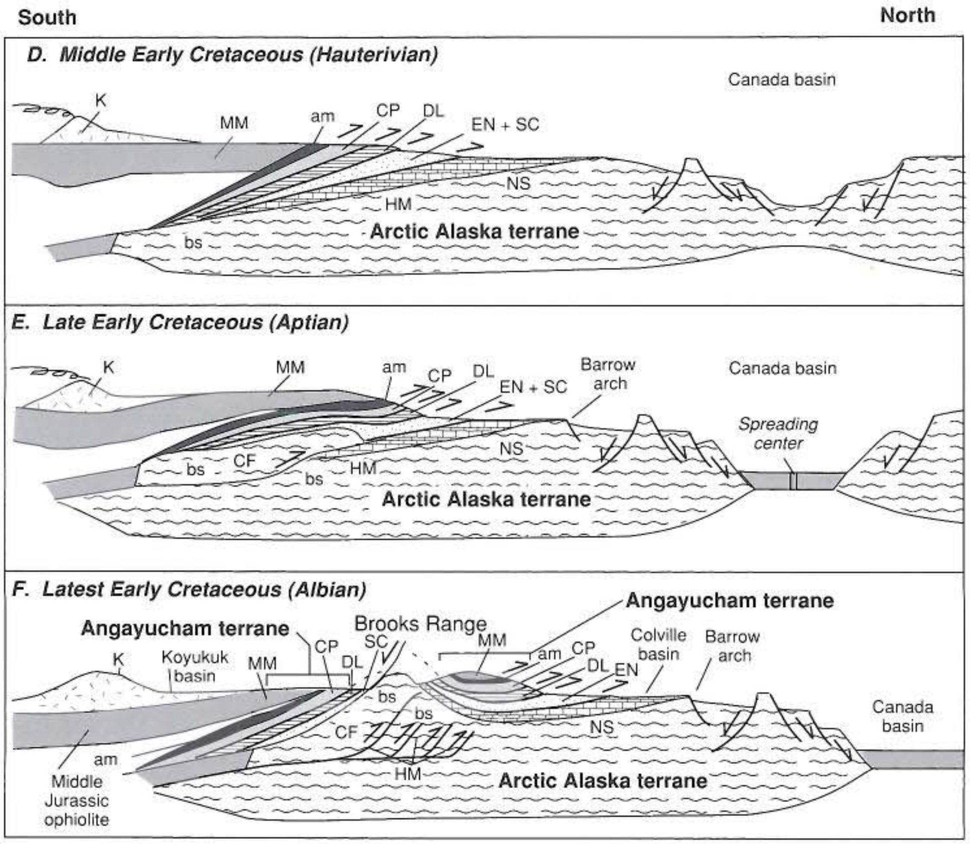


Figure 25. Tectonic model for Brookian orogeny. A, Initial subduction of late Paleozoic and early Mesozoic oceanic crust in Middle Jurassic. Underthrusting of older oceanic crust beneath young, hot oceanic crust (MM—Misheguk Mountain allochthon and Kanuti panel) and related arc terranes (K—Koyukuk terrane) produced amphibolite-grade metabasite (am). B, Subduction of oceanic crust is nearly complete; ocean basin is mostly closed by Late Jurassic. Subduction complex consists mostly of seamount and ocean-plateau fragments (CP—Copter Peak allochthon and Narvak panel) detached from subducted oceanic crust. Failed rifting associated with development of Dinkum graben in Jurassic time is shown schematically at right. C, Initial subduction of seaward part of Arctic Alaska terrane in latest Jurassic or earliest Cretaceous; outboard sedimentary cover (DL—De Long Mountains subterrane are detached from basement and imbricated. D, Subduction of continental substructure of Arctic Alaska terrane by middle Early Cretaceous to depth sufficient enough to produce blueschist facies metamorphism (bs); medial sedimentary cover of Arctic Alaska terrane (EN and SC—Endicott Mountains and Slate Creek subterranes) detached from basement, imbricated, and underthrust by inboard sedimentary cover and basement (HM and NS—Hammond and North Slope subterranes); rifting and continental breakup occurs along northern margin of Arctic Alaska terrane. E, Middle and lower crustal rocks containing blueschist facies assemblages (CF—Coldfoot subterrane) uplifted and emplaced at higher structural levels in late Early Cretaceous by large-scale out of sequence faulting, imbrication, duplexing, and thickening of lower crust; Canada basin opened and Barrow arch formed along northern margin of Arctic Alaska terrane. F, Continued contraction in latest Early Cretaceous thickened middle and lower crustal rocks; coeval crustal attenuation thinned imbricated crustal superstructure along down-to-south normal faults, particularly in southern Brooks Range. Resulting uplift and erosional unroofing shed huge volumes of clastic detritus southward into Koyukuk basin and northward into Colville basin.



struction of a subduction complex (now represented by the Narvak panel and Copter Peak allochthon) in the forearc region by the progressive accretion of oceanic plateaus and seamounts of various ages (Fig. 25B). The earliest accreted oceanic supercrustal fragments were underplated beneath hot ophiolitic rocks of the Misheguk Mountain allochthon and underwent local dynamothermal metamorphism that reached amphibolite facies in Middle Jurassic time. The structurally lowest rocks of the Angayucham terrane, and hence latest accreted rocks, consist of Devonian volcanic rocks and locally interbedded limestone that may represent carbonate-covered volcanic atolls or, alternatively, carbonate-platform deposits drowned and covered by volcanic rocks during Devonian rifting (Mayfield and others, 1988; Patton and others, this volume, Chapter 7). In the latter case, accretion of these rocks would mark the onset of subduction of the distal continental margin of the Arctic Alaska terrane.

Stratigraphic evidence, described above, indicates that subduction of the Arctic Alaska terrane began by Late Jurassic time. Partial subduction during this time resulted in detachment of the outboard upper Paleozoic and lower Mesozoic sedimentary cover from underlying Proterozoic and lower Paleozoic crustal rocks of the terrane. The generally fine grained sedimentary rocks now forming the De Long Mountains subterrane were imbricated and underplated beneath the rocks of the Copter Peak allochthon, whereas their depositional basement was detached and carried to depth (Fig. 25C). Continued subduction resulted in detachment and imbrication of more landward parts of the sedimentary cover of the Arctic Alaska terrane (Endicott Mountains and Slate Creek subterranes), leading to their underplating beneath the De Long Mountains subterrane (Fig. 25D). The latest subducted, most landward parts of the sedimentary cover of the Arctic Alaska terrane (Hammond and North Slope subterranes) were thrust beneath the earlier emplaced, more seaward parts of the passive margin. The continental basement of the southern part of the Arctic Alaska terrane was subducted to depths of more than 25 km, where it underwent blueschist facies metamorphism.

Uplift of the high-pressure metamorphic rocks from their presumed site of metamorphism at depth in the subduction zone probably caused regional setting of K-Ar cooling ages (culminating at about 120–90 Ma) and the flood of clastic detritus from metamorphic source areas into the Colville and Koyukuk basins in Albian time (Till, 1988). This uplift may have resulted from thickening of the continental lithosphere of the Arctic Alaska terrane by isostatic resistance to subduction. Crustal thickening probably occurred in part by ductile deformation, imbrication, and duplexing at lower and mid-crustal levels. Oldow and others (1987d) and Grantz and others (1991) suggested that the structural high exposing the Coldfoot subterrane and other large antiforms in the southern Brooks Range were constructed as large-scale duplexes (Fig. 25, E and F). Thickening and uplift of the subducted continental lithosphere may have been accompanied or followed by attenuation of the overlying deformed sedimentary cover of the Arctic Alaska and Angayucham terranes (Fig. 25F), as suggested by missing structural section and major low-angle normal faulting along the southern margin of the Brooks Range (Miller, 1987; Gottschalk and Oldow, 1988; Miller and Hudson, 1991).

Origin of the northern Alaska continental margin

Depositional onlap relations, clast-size data, paleocurrent data, and compositional evidence show that a large continental highland (Barrovia) bordered the northern margin of the Arctic Alaska terrane and formed the source area for strata of the Ellesmerian sequence during late Paleozoic to late Mesozoic time. The Canada basin now occupies the site of this former highland, indicating that the Arctic Alaska terrane was severed from its northern source by creation of the basin. These considerations led Tailleur (1969, 1973a) and Rickwood (1970) to suggest that the modern continental margin of northern Alaska is an Atlantic-type (passive) continental margin formed at the end of deposition of the northerly derived strata of the upper Ellesmerian sequence in Early Cretaceous time. An Atlantic-type continental margin was confirmed by Grantz and May (1983), who presented evidence that the Canada basin was formed by sea-floor spreading in the Early Cretaceous.

Grantz and May (1983) and Hubbard and others (1987) inferred from stratigraphic relations in the Dinkum graben that crustal extension and subsidence related to rifting began at about 190–185 Ma (Early Jurassic). By Early Cretaceous time, extension and associated crustal warming along the northern margin of the Arctic Alaska terrane resulted in formation of a regional uplift, the Barrow arch, and subsequent erosional truncation of the underlying Kingak Shale and older rocks. The resulting regional Lower Cretaceous unconformity cuts progressively down stratigraphic section to the north into early Paleozoic rocks beneath the Beaufort Sea shelf, and it merges southward into a conformable contact between the Kingak Shale and the overlying Hauterivian pebble-shale unit (Molenaar, 1988). Grantz and May (1983) interpreted this as a breakup unconformity, which dates the age of initiation of sea-floor spreading in the Canada basin at about 125 Ma (Hauterivian). Subsequent cooling of the thinned continental-margin lithosphere caused rapid subsidence of the northern margin of the Arctic Alaska terrane, resulting in transgressive sedimentation (that is, overlap of the Kemik Sandstone and upper part of the Kuparuk Formation by the pebble-shale unit) across the unconformity.

Evolution of the Colville and Koyukuk basins

Brookian convergent deformation resulted in uplift of the Brooks Range and consequent shedding of clastic debris into the Colville and Koyukuk basins to the north and south of the orogen, respectively. In the Koyukuk basin, flysch of Albian age is overlain by molasse of Albian and Upper Cretaceous age (Patton and Box, 1989; Patton and others, this volume, Chapter 7). The clast composition of conglomerate in the Koyukuk basin along the southern margin of the Brooks Range varies with stratigraphic position (Dillon and Smiley, 1984; Dillon, 1989; Murphy and others, 1989). The oldest conglomerate units are enriched in chert and greenstone clasts, whereas the younger conglomerate units are enriched in quartzite and quartz clasts. On this basis, Dillon (1989) suggested that the conglomerate units record sequential erosional stripping of progressively lower structural units, which, from top to bottom in the southern Brooks Range, are the Angayucham terrane, the Slate Creek subterrane, and the Coldfoot subterrane. This sequence and mid-Cretaceous metamorphic-cooling ages in the orogen suggest that infilling of the northern Koyukuk basin resulted from incremental regional erosional unroofing of the internal part of the Brooks Range orogen. Because the uplifted region exposes the deepest structural levels of the orogen and is juxtaposed against Koyukuk basin deposits along south-dipping faults, deposition in the northern Koyukuk basin was probably controlled, at least in part, by extensional faulting. On the northern side of the orogen, strata of the Colville basin, as much as 10 km thick, define an asymmetric foredeep filled with Aptian(?) to Albian and younger clastic rocks. The northern flank of the basin originated as the gently south dipping continental shelf of the Barrovian passive margin and was steepened somewhat by subsidence of the basin and rift-related uplift of the Barrow arch in Early Cretaceous time. The southern flank of the basin is defined by uplifted and imbricated older rocks south of the Brookian thrust front.

The proto-Colville basin is represented by older foredeep deposits within the Brookian orogen. These strata are the allochthonous Upper Jurassic and Lower Cretaceous flysch and olistostromal rocks of the Okpikruak Formation now preserved in the De Long Mountains and Endicott Mountains subterranes. These foredeep deposits are coeval with the upper Ellesmerian sequence to the north, and thus indicate that shelf and platform sedimentation continued in more northerly parts of the Arctic Alaska terrane while foredeep deposition associated with early Brookian tectonism occurred to the south. Deposits of the proto-Colville basin collapsed and were imbricated along the southern flank of the basin and were then transported northward with the northward-migrating Brookian thrust front. Shortening along the basin's southern margin narrowed the basin and shifted its axis northward through early Neocomian time. Because no late Neocomian (Hauterivian and Barremian) foredeep deposits have been recognized in the Brooks Range, and the oldest deposits of the successor Colville basin are Aptian or Albian, late Neocomian deposits may be buried at depth, where they were probably overridden by the advancing early Brookian thrust front. Large-scale displacement of parts of the sedimentary cover of the Arctic Alaska terrane, which characterized early Brookian tectonism, was replaced by deeper seated tectonism and a reduction in northward displacement by Albian time. As a result, northward migration of the Brookian thrust front and the axis of the proto-Colville basin slowed, and the proto-Colville basin evolved into the Aptian(?) to Albian and younger Colville basin.

The filling of the Colville basin with enormous volumes of orogenic sediment began in Aptian or Albian time. The history of infilling is recorded by thick deposits of prodelta shale and thin-bedded turbidites of the upper part of the Torok Formation and overlying deltaic deposits of the Nanushuk Group in the western part of the basin, the Fortress Mountain and Torok formations in the central part of the basin, and the upper part of the Kongakut Formation and the Bathtub Graywacke in the eastern part of the basin. Although some of the deltaic deposits (for example, the Umiat delta of the Nanushuk Group) prograded to the north from the southern margin of the basin, the main basin-filling deltaic complex was the mud-rich, river-dominated Corwin delta (Nanushuk Group), which prograded from the west toward the east-northeast, almost parallel with the Colville basin axis. A large source area, probably an orogenic highland, is therefore postulated to have existed to the west or southwest in the area of the present Chukchi Sea or beyond (Fig. 15; Molenaar, 1985). Northward progradation of the Nanushuk deltas was initially constrained by the Barrow arch, which was a passive, but subsiding, high in Albian and later time. By the end of Albian time, however, deposits of the Corwin delta spilled northward across the western part of the Barrow arch into the newly formed Canada basin (Nuwuk basin of Grantz and May, 1983). The composition of the deltaic deposits suggests that fine-grained siliceous and carbonate-rich sequences like those of the De Long Mountains subterrane and Lisburne Peninsula formed the primary source region for the Corwin delta, whereas quartzose rocks of the Endicott Mountains subterrane formed the main source region for the Umiat delta (Bartsch-Winkler, 1979; Mull, 1985). Distinctive high-pressure metamorphic detritus in the Nanushuk Group suggests that the Coldfoot subterrane also contributed sediment to both deltaic systems (Till, 1988; A. B. Till, 1990, written commun.).

Following several significant marine transgressions in Cenomanian to Santonian time, deltaic deposits continued to prograde northeastward across the central North Slope, finally filling the eastern part of the basin in latest Cretaceous and Tertiary time. Because the eastern part of the Colville basin was the last to be filled, condensed basinal deposits in this area (Hue Shale) span Albian to Maastrichtian time; the delta-plain sediments (Sagavanirktok Formation) were not deposited until as late as Eocene time (Molenaar and others, 1987). By Paleocene time, slope-deltaic deposits of the Colville basin had prograded across the eastern part of the Barrow arch and had begun to form a thick constructional continental shelf and slope in the eastern Beaufort Sea (Kaktovik basin of Grantz and May, 1963). Later in Tertiary time, deltas built by sediment both transported along the axis of the Colville basin and shed directly from the rising Romanzof uplift to the south prograded into the eastern Beaufort Sea. Northward progradation was amplified further in Late Cretaceous and Cenozoic time by northward migration of the late Brookian foredeep with the northward advance of the late Brookian thrust front of the northeastern Brooks Range.

Post-Neocomian (late Brookian) tectonism

In post-Neocomian time, following emplacement of the far-traveled allochthons that characterize early Brookian tectonism, the nature of Brookian orogenic activity changed. Late Brookian deformational phases have a relatively restricted extent compared with early Brookian deformation, and late Brookian deformation involves distinct contractional, extensional, and translational events of varying orientation and age, which cannot be easily ascribed to a single tectonic episode.

The earliest and most widespread late Brookian tectonic event is significant uplift and unroofing along the main axis of the Brooks Range. This tectonism is recorded by the preponderance of K-Ar cooling ages at about 120–90 Ma (Turner and others, 1979) and by the flood of enormous volumes of clastic detritus into the Colville and Koyukuk basins during Albian and Cenomanian time. This uplift has been assumed to be the result of isostatic uplift following early Brookian convergence (Mull, 1982; Mayfield and others, 1988), but it may also reflect shortening and imbrication at deep structural levels and/or attenuation in the internal part of the orogen. Major duplexes in the internal part of the orogen, such as the ones at Mt. Angayukaqsraq and Mt. Doonerak, may have formed during this period. Displacement related to this uplift may have continued through Late Cretaceous time and may have been transmitted northward along deep detachments into the central and western North Slope, resulting in the long-wavelength folding of Albian and Upper Cretaceous sedimentary rocks of the Colville basin.

Post-Neocomian displacement along the southern flank of the Brooks Range on the Kobuk fault system may have controlled sedimentation in the Koyukuk basin. This relation was inferred by Dillon (1989) from the narrow basinward extent of Albian and Upper Cretaceous molasse, the presence of abundant debris-flow deposits within the basin, and the apparent association of the coarse-grained rocks with the Kobuk fault system. The amount of displacement on the Kobuk system is poorly delimited, but large-scale right-slip movement is possible (Grantz, 1966; Dillon, 1989). Large-scale post-Neocomian displacement has also been proposed for the Porcupine lineament along the southeast flank of the Brooks Range, but the sense and amount of displacement are controversial and have been based on regional tectonic models rather than field observations.

The southern flank of the Brooks Range was probably also the locus of extensional tectonism in post-Neocomian time. Miller and Hudson (1991) related development of the Koyukuk basin with its coarse-grained sedimentary fill and other features to a regional extensional event that began at about 115 Ma (Aptian), whereas Gottschalk and Oldow (1988), Pavlis (1989), and Gottschalk (1990) viewed extension as a byproduct of regional convergence that continued into Albian and/or younger time. Box (1987) noted that Upper Cretaceous rocks are penetratively deformed in the Cosmos Hills, and he suggested that, at least locally, extensional deformation took place in Late Cretaceous or younger time. Plumley and Vance (1988) reported that extensional tectonism to the east along the Porcupine lineament probably took place in Paleogene time. The change from convergence to extensional and translational tectonism has been related to regional right-slip motion along the Kula–North American plate boundary and to initiation of displacement along the Tintina fault system (Grantz, 1966; Pavlis, 1989; Grantz and others, 1991).

During the Late Cretaceous and/or Paleogene, contractional deformation took place in regions north of the main axis of the Brooks Range. The east-directed fold and thrust belt of the Herald arch and the Lisburne Peninsula, which may also be related to deformation in the western Brooks Range (Karl and Long, 1987), is probably the result of convergence between North America and Eurasia prior to the Neogene (Patton and Tailleur, 1977; Grantz and others, 1981). To the east in the northeastern Brooks Range and eastern North Slope, the Romanzof uplift resulted from Cenozoic north-vergent deformation. The Romanzof uplift produced the highest peaks and greatest relief in the Brooks Range, and it resulted in deposition of as much as 12 km of sediment along the Beaufort Sea continental margin. Significant shortening of these continental-margin deposits, coupled with modern seismicity (Grantz and others, 1983a), indicates that deformation has propagated northward and has continued into the Cenozoic with a corresponding uplift of pre-Mississippian, Ellesmerian, and Brookian rocks on the south flank of the Barrow arch and development of a Neogene foreland basin along the Beaufort Sea continental margin. Moore and others (1985b) and Grantz and others (1991) related the north-vergent tectonism to compressional stress imposed by Cenozoic convergence and accretion along the North American–Pacific plate boundary in southern Alaska. This compressional stress may have been transmitted to northeastern Alaska by displacement above deep crustal detachment surfaces across all of Alaska.

Where did the Arctic Alaska terrane originate?

The Arctic Alaska terrane is considered a suspect terrane (Coney and Jones, 1985) because its relation to the North American craton and neighboring terranes is uncertain. Much of this dilemma is a consequence of unresolved questions about the history of the rifting and the opening of the adjoining Canada basin. Paleomagnetic data cannot be used to determine the basin's origin because of the absence of clearly discernible magnetic lineations and the pervasive Cretaceous to Cenozoic remagnetization of northern Alaska (Van Alstine, 1986; Hillhouse and Grommé, 1988). Other less definitive lines of evidence have led to many plate reconstructions for the origin of the Canada basin, the Arctic Ocean as a whole, and adjacent plates. Although the Arctic region has been reconstructed in many ways, the Arctic Alaska terrane is typically restored to one of the four general positions shown in Figure 26 (A–D). Reviews of the various models have been given by Nilsen (1981) and Lawver and Scotese (1990).

The most widely accepted model for the origin of the Arctic Alaska terrane is rifting and counterclockwise rotation of the Arctic Alaska terrane away from northernmost Canada about a pole of rotation near the Mackenzie delta (Fig. 26D) (Carey, 1958; Tailleur, 1969, 1973a; Rickwood, 1970; Newman and others, 1977; Mull, 1982; Sweeney, 1982; Grantz and May, 1983; McWhae, 1986; Howell and Wiley, 1987; Ziegler, 1988; Grantz and others, 1990b). In this model, the Arctic Alaska terrane originated in a position contiguous with the Canadian Arctic Island segment of the Innuitian fold belt. The opening of the Canada basin in this model would require about 66° of counterclockwise rotation in Cretaceous time. Recent paleomagnetic results by Halgedahl and Jarrard (1987) on drill core from a single well in the North Slope support this amount of rotation; Lower Cretaceous and older strata in most other wells have been remagnetized in post–Early Cretaceous time (D. R. Van Alstine, 1988, oral commun.). Variants of the rotational origin for the Arctic Alaska terrane suggest that counterclockwise movement may have been accompanied by about 270 km of right slip along the northern Canadian continental margin in middle Mesozoic time (Grantz and others, 1990b) or preceeded by more than 1500 km of left slip in Paleozoic time (Sweeney, 1982). The rotational model (1) accounts for the inferred Cretaceous age of the Canada basin, (2) explains apparent similarities between the late Paleozoic and early Mesozoic geology of the Arctic Alaska terrane and the Innuitian fold belt, (3) allows for a northern source area for the Ellesmerian sequence, and (4) provides a reasonable fit for bathymetric and gravity data across the Canada basin. The hypothesized rotation of the Arctic Alaska terrane has been linked kinematically to convergence between the Arctic Alaska and Koyukuk arc terranes and the consequent formation of the Brooks Range orogen (Mayfield and others, 1988). However, such a linkage is unlikely because the amount of crustal shortening within the orogen does not decrease toward the pole of rotation as would be expected and because Brookian plate convergence began in Jurassic time, whereas sea-floor spreading in the Canada basin did not begin until Neocomian time (Rattey, 1985; Oldow and others, 1987b). Possible Cordilleran aspects of the terrane (for example, Devonian magmatic belt, overthrusting of oceanic rocks of the Angayucham terrane, general stratigraphic similarities of parts of the Arctic Alaska terrane with North American rocks of the Canadian Cordillera) may be accounted for by restoration to a position between the Innuitian orogen and the northern limit of the Cordilleran orogen. Problems with the

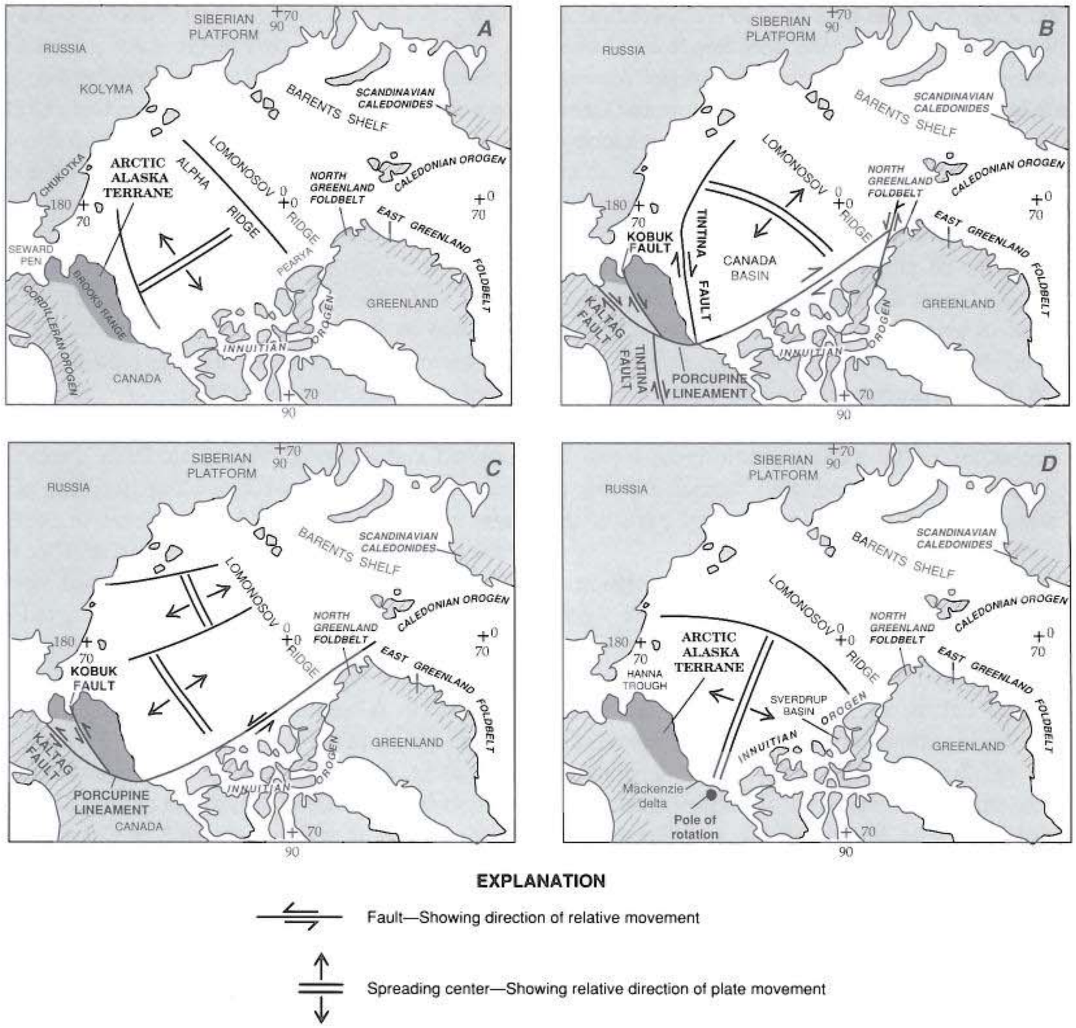


Figure 26. Paleotectonic maps showing possible restorations of Arctic Alaska terrane to positions in Cordilleran, Innuitian, and Caledonian orogens. A, In situ origin: Arctic Alaska terrane is not rotated nor translated (Bogdanov and Tilman, 1964; Herron and others, 1974; Churkin and Trexler, 1980, 1981). B, Yukon origin: Arctic Alaska terrane is translated by large-scale right slip along Tintina fault from position in northern Canadian part of Cordilleran orogen and is offset right laterally along Porcupine lineament (Jones, 1980, 1982b). C, Barents shelf origin: Arctic Alaska terrane is translated by large-scale left slip along transform fault parallel to Canadian Arctic Islands shelf edge from original position in northern Caledonian or Innuitian orogens (Dutro, 1981; Nilsen, 1981; Oldow and others, 1987b; Smith, 1987). D, Canadian Arctic Islands origin: Arctic Alaska terrane is rotated oroclinally from Innuitian orogen about a pole of rotation near present Mackenzie delta (Carey, 1958; Tailleur, 1969, 1973a; Rickwood, 1970; Newman and others, 1977; Mull, 1982; Sweeney, 1982; Grantz and May, 1983; McWhae, 1986; Howell and Wiley, 1987; Ziegler, 1988; Grantz and others, 1990b).

rotational hypothesis include structural and metamorphic differences between Devonian and older rocks across the restored boundary, opposition of middle Paleozoic sediment transport directions across this boundary, and the requirement that strike-slip displacements of several thousand kilometers must have occurred along the Lomonosov Ridge in the central Arctic Ocean as a consequence of rotation (Nilsen, 1981; Oldow and others, 1987b).

CONCLUSIONS

Northern Alaska consists of two principal tectonostratigraphic terranes: the Arctic Alaska and Angayucham terranes. The most extensive of the two is the Arctic Alaska terrane, which underlies the North Slope and most of the Brooks Range. Rocks of this terrane range from Proterozoic to Cenozoic and are divided into a structurally and stratigraphically complex pre-

Mississippian assemblage overlain by a once laterally continuous succession of Upper Devonian and Lower Mississippian to Lower Cretaceous, nonmarine to marine continental-margin deposits. These deposits are in turn overlain by upper Mesozoic and Cenozoic siliciclastic foredeep strata. The pre-Mississippian assemblage records early to middle Paleozoic convergent deformation and arc plutonism along the edge of North America and subsequent rifting in Devonian time. The Devonian rifting culminated in formation of an ocean basin and the development of a complex south-facing passive margin by Late Devonian time. Subsidence along the passive margin resulted in progressive northward onlap of fluvial-deltaic to continental-shelf and carbonate-platform deposits in the Late Devonian to Pennsylvanian and neritic, nonmarine, and bathyal deposits in the Permian to Early Cretaceous. Gradual deepening was accompanied by waning clastic input from the north, resulting in deposition of condensed basinal deposits of shale, siliceous limestone, and chert in more distal parts of the passive margin from Mississippian to Jurassic time.

The Angayucham terrane is a structurally thin succession of rocks that rests tectonically on the southern part of the Arctic Alaska terrane and consists of two assemblages, both of which originated in an ocean basin. The structurally lower assemblage comprises a structural collage of Devonian to Jurassic ocean-island basalts and pelagic sedimentary rocks that represent a subduction complex of Jurassic age. The upper assemblage comprises peridotite and gabbro that form an incomplete Middle Jurassic ophiolite of arc affinity. During Middle and Late Jurassic time, the lower assemblage was underplated by subduction to the upper ophiolitic assemblage. Sedimentary debris in Brookian foredeep deposits suggests that Jurassic granitic and volcanic rocks of magmatic-arc affinity may have once overlain the structurally higher ophiolitic assemblage, but later the volcanic rocks were eroded away.

The Brookian orogeny began in the Middle Jurassic with southward subduction of the ocean basin that lay south of the passive margin of the Arctic Alaska terrane. In Late Jurassic and early Neocomian time, progressively more inboard parts of the Arctic Alaska terrane were partially subducted beneath the oceanic forearc and earlier accreted oceanic rocks (Angayucham terrane). This convergence resulted in delamination and imbrication of the continental superstructure of the Arctic Alaska terrane, which consisted mainly of the passive-margin succession. As a consequence, more distal parts of the Arctic Alaska continental margin were progressively collapsed and thrust successively northward over more proximal parts. The axis of associated foredeep sedimentation in the proto-Colville basin migrated northward with the thrust front; later, the older foredeep deposits became involved in thrusting. The continental substructure of the Arctic Alaska terrane, meanwhile, was subducted to deeper structural levels, where it was tectonically thickened and subjected to high pressure–low temperature (blueschist facies) metamorphism.

In the northern part of the Arctic Alaska terrane, a failed episode of rifting occurred in the Early Jurassic and was followed by a successful episode of rifting in the Early Cretaceous (Hauterivian) that resulted in continental breakup and formation of the Canada basin. Northward subsidence along the newly rifted margin of the formerly south-dipping continental-margin sequence produced an inflection in dip of Lower Cretaceous and older rocks, thus forming the Barrow arch. The Barrow arch was uplifted and exposed above sea level at the time of continental breakup in the Early Cretaceous, producing a local erosional truncation of older rocks, but the arch has gradually subsided since late Early Cretaceous time.

The southern part of the Arctic Alaska terrane was rapidly uplifted and unroofed by the late Early Cretaceous (Albian) as plate convergence slowed, resulting in setting of isotopic cooling ages and in deposition of huge volumes of clastic detritus to the north in the Colville basin foredeep and to the south in the Koyukuk basin. Although sediments shed northward into the Colville basin built local northward-prograding deltas along much of the Brooks Range, the basin was filled largely by deposits of an eastward- to northeastward-prograding delta (Corwin delta) from Albian through Tertiary time. This delta eventually prograded northward across the western part of the Barrow arch, depositing an Albian and younger constructional continental-margin sequence along the margin of the Canada basin. Renewed north-vergent thrusting and uplift in Cenozoic time formed the northeastern salient of the eastern Brooks Range and caused northward migration of foredeep sedimentation across the Barrow arch and onto the adjacent part of the northern Alaska continental margin. Geologic structures and seismicity data indicate that thrusting has propagated northward across the continental margin in Neogene time and has deformed the eastern part of the Barrow arch and overlying sedimentary rocks.

Faunal affinities and broad stratigraphic similarities indicate that the Arctic Alaska terrane was part of North America by late Paleozoic time. Its exact site of origin, however, is controversial. The leading hypothesis suggests that, immediately following the culmination of early Brookian orogenesis in the Early Cretaceous, the northern margin of the Arctic Alaska terrane was rifted away from the Canadian Arctic Islands region and rotated clockwise about 67° to its present position, thus forming the Canada basin. Following rotation, east-vergent thrusting took place during the Cretaceous (post-Neocomian) along the western margin of northern Alaska (for example, the Lisburne Peninsula). This convergence probably resulted from local convergence between the Eurasian and North American plates. Likewise, convergent deformation during Cenozoic time in northeastern Alaska has been ascribed to the far-reaching effects of Pacific-North American plate interactions along the southern margin of Alaska.

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NOTES ADDED IN PROOF

Since the final draft of the chapter on the bedrock geology of northern Alaska was prepared in 1992, it has become evident that descriptions of the major regional unconformities of the North Slope subterrane were not adequately covered in the text. These unconformities are significant to the stratigraphy, structure, tectonics, and economic geology of northern Alaska so will be summarized here. We also list below some significant new age and geologic data for northern Alaska.

Unconformities of the North Slope subterrane

Sub-Middle Devonian unconformity. Weakly metamorphosed, penetratively polydeformed Ordovician metasedimentary rocks are unconformably overlain by Middle Devonian (Eifelian) and younger(?) marine to nonmarine terrigenous clastic rocks in the eastern Brooks Range (Reiser and others, 1980) (Fig. 5, column 2). Although only locally preserved beneath the sub-Mississippian unconformity, the sub-Middle Devonian unconformity postdates major contractional deformation and is interpreted to mark the onset of rifting that led to formation of the late Paleozoic to early Mesozoic south-facing passive continental margin of northern Alaska (Anderson and others, 1994).

Sub-Mississippian unconformity. The regional sub-Mississippian unconformity, a characteristic feature of the North Slope subterrane, is present beneath Lower Mississippian rocks at the base of the Ellesmerian sequence (Fig. 5). The sub-Mississippian unconformity is weakly to prominently displayed on seismic-reflection records (Kirschner and others, 1983; Kirschner and Rycerski, 1988; Molenaar, 1988) and is confirmed by well penetrations along the Barrow arch (Bird, 1982, 1988a; Molenaar and others, 1986). The unconformity crops out in the northeastern Brooks Range (Brosgé and others, 1962), Mt. Doonerak fenster (Dutro and others, 1976; Mull and others, 1987a), and Lisburne Peninsula (Moore and others, 1984). In most areas, the unconformity is angular, although it may be a disconformity at Mt. Doonerak (Oldow and others, 1987d). Seismic-reflection records indicate that regionally the unconformity has low relief, although it is flexed downward in the Meade, Umiat, and other basins in the subsurface of the North Slope (Figs. 7, 8, and 9). Structures beneath the unconformity are variable, ranging from high-strain penetrative fabrics (Oldow and others, 1987b) to gentle folding in the northeastern Brooks Range (Robinson and others, 1989). Rocks below the unconformity are as young as late Early Devonian in the northeastern Brooks Range (Dillon and others, 1987b; Blodgett and others, 1991) and early Middle Devonian in the eastern Brooks Range (Anderson and others, 1993, 1994). The amount of erosion on the unconformity is unknown because of the poorly constrained stratigraphy of underlying rocks but may be several kilometers or more where the underlying rocks are penetratively deformed. The sub-Mississippian unconformity reflects northward transgression due to Early Mississippian continental breakup and thermal subsidence of the newly formed south-facing passive continental margin of northern Alaska (Fig. 24B).

Post-Lisburne disconformity. Throughout the North Slope subterrane, the Lisburne Group and overlying Echooka Formation are separated by a regional disconformity (Fig. 5). The disconformity is exposed in the northeastern Brooks Range (Detterman and others, 1975; Crowder, 1990) and confirmed by well penetrations in the North Slope (Bird, 1982, 1988a; Molenaar and others, 1986). To the south in the Endicott Mountains subterrane, the disconformity is overlain by the Siksikpuk Formation, a distal equivalent of the Echooka Formation (Siok, 1985; Adams, 1991). Over much of its area, the age of the disconformity is constrained by Early or Middle Pennsylvanian conodonts from the underlying Lisburne Group and by Early Permian brachiopods from the overlying Echooka Formation and coeval Siksikpuk Formation. In the subsurface of the North Slope south of Barrow, however, the Lisburne Group below the disconformity is as young as Early Permian (Bird, 1988a), which suggests that the disconformity is intra-Permian. The post-Lisburne disconformity was likely caused by regional uplift of the Lisburne carbonate platform or by a eustatic change in the Early Permian (Molenaar and others, 1986).

Lower Cretaceous unconformity (LCU). The regional Lower Cretaceous unconformity (LCU), or pebble shale unconformity, is present at the top of the upper Ellesmerian sequence in the northern part of the North Slope and northeastern Brooks Range (Fig. 5). The LCU is prominently displayed on seismic-reflection records (Kirschner and others, 1983; Kirschner and Rycerski, 1988; Molenaar, 1988), confirmed by well penetrations (Bird, 1982, 1988a; Molenaar and others, 1986), and observed in outcrop (Molenaar, 1983; Bird and others, 1987; Mull, 1987). In general, the greatest amount of erosional relief on the unconformity is in the north (more than 1 km on the Barrow arch) and the least amount is in the south (Tailleur and others, 1978; Bird, 1987, Figs. 4, 6, and 13; Bird and others, 1987, Fig. 7.1). Beneath the southern part of the coastal plain and northern part of the foothills, the LCU merges with a conformable stratal succession (Fig. 8). Near its southern extent, the age of the unconformity is intra-Hauterivian, where dated in wells such as Tunalik and Seabee in the NPRA (Haga and Mickey, 1983; Mickey and Haga, 1987) and in outcrops on the Echooka River in the foothills of the northeastern Brooks Range (Molenaar, 1983, Fig. 4). On the Barrow arch, where the LCU is contained within the Kuparuk Formation, detailed well correlations constrain its age as Valanginian and/or Hauterivian (Masterson and Paris, 1987).

The paleogeography and subcrop geology at the time of maximum development of the LCU (Fig. 14) show that an elongate landmass about 250 km wide was uplifted above sea level. The Jurassic and Lower Cretaceous Kingak Shale was exposed over most of the area south of the Barrow arch, whereas older rocks were exposed closer to the axis of the arch. Normal faulting occurred along the Barrow arch prior to, and during, development of the LCU (Hubbard and others, 1987; Masterson and Paris, 1987), resulting in variable amounts of erosion on different fault blocks.

The LCU is regarded as the breakup unconformity that marked the onset of subsidence of the rifted Arctic margin and a major marine transgression (Grantz and May, 1983). The LCU and overlying shale provide part of the trapping mechanism for many Prudhoe Bay area oil fields (Bird, 1991). The weathering of rocks exposed beneath the unconformity may be responsible for the enhanced porosity in oil field reservoirs (Shanmugam and Higgins, 1988; van de Kamp, 1988).

New geologic data

(1) Jurassic fossils have recently been recovered from a condensed shale interval within the uppermost part of the Etivluk Group on the Lisburne Peninsula (North Slope subterrane) (C. G. Mull, 1993, unpublished data), as shown diagrammatically in Figure 5.

(2) Detrital zircons from the quartz-mica schist unit of the Coldfoot subterrane near Wiseman have yielded U-Pb ages as young as 360 Ma. These ages

indicate that the protolith of the unit includes elements at least as young as latest Devonian (J. N. Aleinikoff, 1993, unpublished data).

(3) Plagiogranite from the Siniktanneyak Mountain ophiolitic klippe of the Misheguk Mountain allochthon (Angayucham terrane) has yielded a U-Pb zircon age of 170 ± 3 Ma (Moore and others, 1993). A potassium feldspar-bearing granitic dike in ultramafic rocks near the base of the ophiolite has yielded a U-Pb monazite age of 163 ± 3 Ma (J. N. Aleinikoff, 1993, unpublished data).

(4) Apatite fission track analysis of rocks from the northeastern Brooks Range indicates that the age of cooling, reflecting periods of rapid uplift and unroofing, becomes progressively younger northward from 62 ± 5 Ma at Bathtub Ridge in the south to 23 ± 3 Ma in the Sadlerochit Mountains in the north (Fig. 1) (O'Sullivan and others, 1993).

(5) Integrated seismic reflection and refraction data show that the Mt. Doonerak antiform in the central Brooks Range (Fig. 23) is a crustal-scale duplex (Levander and others, 1994). Apatite and zircon fission track analysis of rocks from the antiform indicates that cooling, reflecting construction of the antiform, occurred at 70–65 Ma and again at 24 ± 3 Ma (O'Sullivan and others, 1991).

(6) Integrated seismic reflection and refraction data show that along the route of the Dalton Highway the Moho lies at a depth of 33 km beneath the North Slope, 46 km beneath the crest of the Brooks Range, and 35 km at the southern edge of the range (Levander and others, 1994).

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