DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

STRATIGRAPHY, STRUCTURE, AND GEOLOGIC SYNTHESIS OF NORTHERN ALASKA

by

T.E. Moore[a], W.K. Wallace[b], K.J. Bird[a], S.M. Karl[c], C.G. Mull[d], and J.T. Dillon[d,e,f]

Open-File Report 92-330

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards (or with the North American Stratigraphic Code). Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

---

[a] U.S. Geological Survey, 345 Middlefield Road, Menlo Park, CA, 94025

[b] Department of Geology and Geophysics, University of Alaska, Fairbanks, Ak 99775

[c] U.S. Geological Survey, 4200 University Drive, Anchorage, Ak 99508

[d] Alaska Division of Geological and Geophysical Surveys, 3700 Airport Way, Fairbanks, Alaska, 99709

[e] Our colleague, John Dillon, perished in a light plane accident while returning from fieldwork in the Brooks Range during the summer 1987. His data and ideas have contributed greatly to this manuscript and to our understanding of the geology of the Brooks Range.

[f] Lead authors for the various parts of the manuscript are as follows: T. E. Moore: "Introduction", "Endicott Mountains", "De Long Mountains", "Sheenjek", "Hammond", "Coldfoot", "Venetie", and "Slate Creek subterranes" of the Arctic Alaska terrane, "Angayucham terrane", "Paleogeography and tectonics", and "Conclusion"; W.K. Wallace: "Structural geology"; K.J. Bird: "North Slope subterrane"; S.M. Karl: "Hammond", "Coldfoot", and "Slate Creek subterranes"; C.G. Mull: "Endicott" and "De Long Mountains subterranes".

CONTENTS

ILLUSTRATIONS

TABLES

PLATES

ABSTRACT

Northern Alaska consists of the extensive Arctic Alaska terrane and the structurally overlying Angayucham terrane. The Angayucham terrane, partly exposed in thin klippen, consists of a lower assemblage of Devonian to Jurassic ocean-island basalts and pelagic sedimentary rocks structurally overlain by Middle Jurassic ophiolite of probable island-arc affinity. These lower unit is thought to have been assembled as a subduction complex associated with the overlying ophiolitic rocks in Jurassic time.

Rocks of the Arctic Alaska terrane are divided into a structurally and stratigraphically complex Proterozoic to middle Paleozoic assemblage overlain by a laterally extensive succession of uppermost Devonian and Lower Mississippian to Lower Cretaceous nonmarine to marine continental margin deposits (e.g., Ellesmerian sequence), overlain, in turn, by upper Mesozoic and Cenozoic siliciclastic foredeep deposits (Brookian sequence). The Devonian and older rocks record early to middle Paleozoic convergent deformation and arc plutonism along the edge of North America, followed by rifting in Devonian time. The Devonian rifting event culminated in formation of an ocean basin and the development of a paleogeographically complex south-facing passive margin by Late Devonian time. Subsidence along the passive margin resulted in (1) progressive northward onlap of nonmarine and carbonate platform deposits in Late Devonian and Mississippian time and (2) neritic to bathyal deposits characterized by condensed basinal deposits in Mississippian to Jurassic time. A second rifting event culminated in opening of the Canada basin in Early Cretaceous time and produced the modern northern continental margin of Alaska. The Brookian orogeny began in the Middle and Late Jurassic with southward subduction of the ocean basin that lay outboard of the south-facing passive margin of the Arctic Alaska terrane. Fragments of the late Paleozoic and early Mesozoic oceanic crustal rocks were underplated by subduction beneath an intraoceanic arc + underlying ophiolite, thus forming the Angayucham and associated arc terranes. In Late Jurassic and Early Cretaceous time, the outer (distal) passive continental margin succession was partially subducted and underplated beneath the Angayucham terrane. Northward thrust imbrication placed more distal parts of the continental margin over its more proximal parts. The axis of associated Brookian foredeep sedimentation migrated northward with the thrust front, with older deposits involved in later thrusting. The continental substructure of the Arctic Alaska terrane was subducted to deeper levels, resulting in tectonic thickening and high-pressure metamorphism. By Albian time, the rate of underthrusting diminished and the Arctic Alaska terrane was rapidly uplifted and unroofed, resulting in setting of isotopic cooling ages and deposition of huge volumes of Brookian clastic detritus. Subsequent Late Cretaceous and Tertiary Brookian orogenesis is limited to the eastern Brooks Range, where thrusting and foredeep deposition have migrated northward into the offshore region, and the Lisburne Peninsula,.where east-vergent thrusting reflects local convergence between Asia and North America.

INTRODUCTION

This paper 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 thirty-six 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.

Geologic investigation of northern Alaska has been underway for more than eighty years. Spurred by the petroleum and mineral potential of the region, early efforts, mostly by government scientists, focused on understanding the stratigraphy, age, and geographic distribution of the

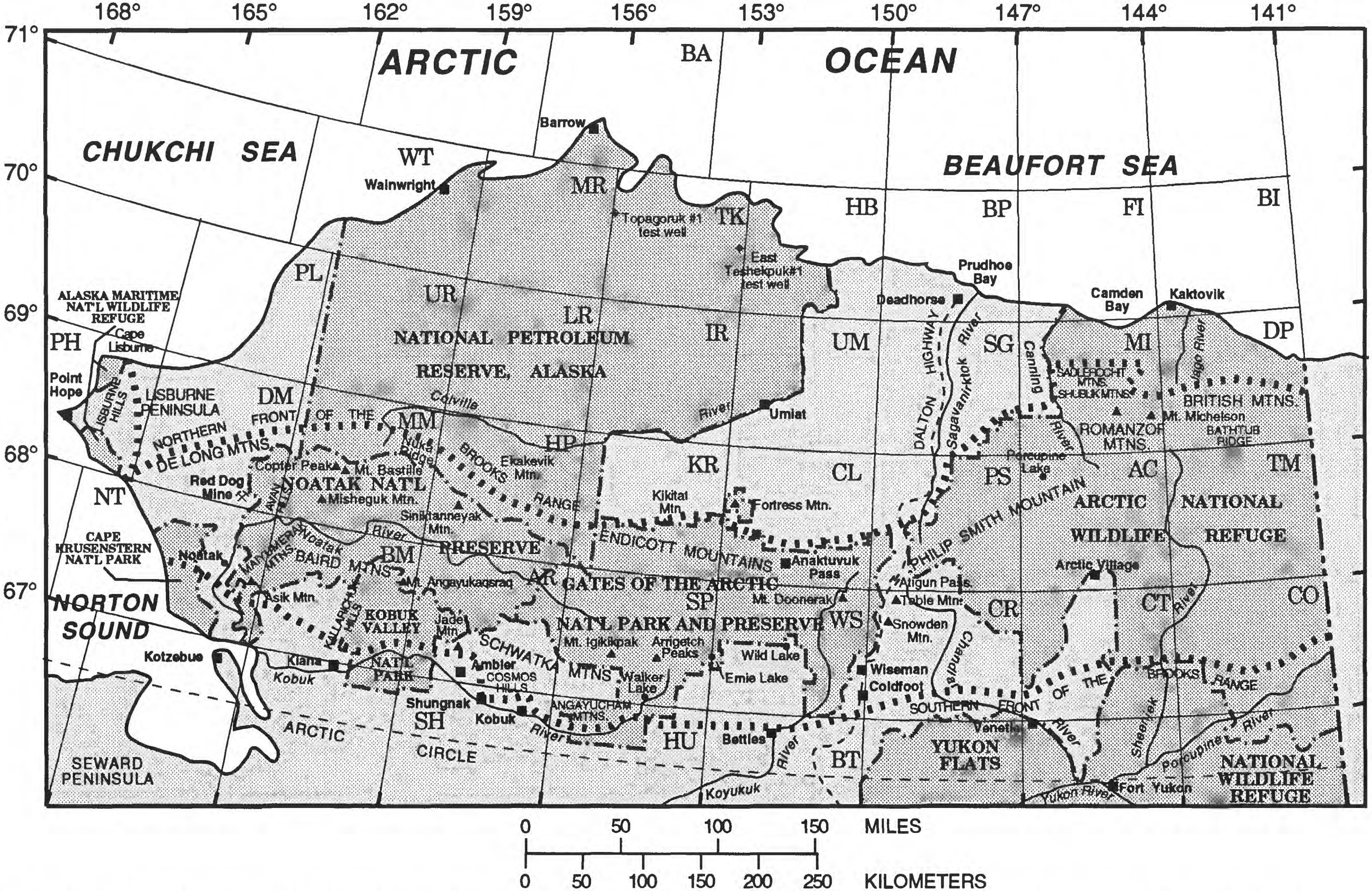


Figure 1. Selected geographic features of northern Alaska. Dark shaded areas designate federal parks, preserves, wildlife refuges, and reserves. Quadrangle abbreviations: AC-- Arctic; AR-- Ambler River; BA-- Barrow; BI-- Barter Island; BP-- Beechy Point; BM-- Baird Mountains; BT-- Bettles; CL-- Chandler 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.

geologic units of the area. These efforts were accelerated after World War II by surface and subsurface petroleum exploration by the U.S. Navy and the U.S. Geological Survey. Subsequently, the petroleum industry began the exploration program that led to the discovery of the Prudhoe Bay oil field, and the mineral industry initiated exploration for base metals in the Brooks Range. Meanwhile, governmental investigations evolved into systematic mapping and mineral-resource appraisal in the Brooks Range. Following the discovery of the Prudhoe Bay oil field, investigation of oil-bearing units in the subsurface of the North Slope was renewed by industry and the state and federal governments. Recently, geologic research in the region, which increasingly emphasized topical problems, has included greater participation by academic scientists.

Although geologic research in northern Alaska has resulted in many publications, including two symposium volumes (Adkison and Brosgé, 1970; Tailleur and Weimer, 1987a), there exists no comprehensive geologic summary of the region. In this paper, we attempt to provide one 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 systematically describing 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.

In writing this paper, we have focused particularly on the stratigraphy of northern Alaska, while the structure, metamorphism, and other aspects of the geology of the region are covered in a somewhat more general fashion. This emphasis results from: (1) much of the available data and publications are products of petroleum-related investigations of the Colville basin region; (2) faunal dates provide most temporal control bearing on the geologic history, whereas isotopic dating is in its infancy in northern Alaska; (3) metamorphic paragenesis and their relation to associated stuctural features in northern Alaska are complex and incompletely understood; and (4) the stratigraphy of the region, while subtle in detail and described with a complex nomenclature, provides a rich record of the tectonic history of northern Alaska. Moreover, the Arctic Alaska terrane, which contains most of the rocks of northern Alaska, is unique compared to the large crystalline terranes of Alaska (e.g., Yukon-Tanana, Ruby) in that the Arctic Alaska terrane contains an extensive stratigraphic record of its geologic history. If these continental terranes are fragments of the Paleozoic and early Mesozoic margin of North America as suggested by some workers (e.g., Grantz and others, 1991), then the Arctic Alaska terrane is the only one which can provide a history of that margin in its sedimentary record. Hence, much of what is known about the geology of northern Alaska has been derived from its stratigraphy and that stratigraphy has significance beyond the boundaries of area discussed here.

Our task in writing this paper is to unify the confusing stratigraphic and tectonic nomenclature of northern Alaska and to, as simply as possible, guide the reader to the essential relationships that bear on its geologic history. A fundamental hindrance in this pursuit is the usage of the same stratigraphic nomenclature in a number of tectonostratigraphic domains. This problem is a result of three factors: (1) many of the tectonostratigraphic units appear to represent parts of the same continental margin, such that the mix of interfingering stratigraphic units are used to identify specific (now displaced) tectonostratigraphic units; (2) a number of stratigraphic units were identified and mapped throughout much of northern Alaska prior to the recognition that large-displacement faults have juxtaposed similar, but significantly different facies within these units; and (3) some units have been mapped by age rather than lithology. While some workers may prefer a simple chronological approach for the presentation of all of the stratigraphic information this paper, we believe that an organization that presents stratigraphic information by tectonostratigraphic unit provides a more descriptive organization, especially given the combination of diachronous stratigraphy and presence of large-displacement structures in northern Alaska. We also believe that this approach is better suited for explanation of the structural relationships and paleogeographic reconstructions later in the paper. Thus, discussion of a specific stratigraphic unit (e.g., Lisburne Group) will be found under each of the tectonostratigraphic units in which it occurs with an emphasis on its distinctive characteristics in each. Headings within tectonostratigraphic unit are primarily at the group rank in order to help the reader access information at each stratigraphic interval.

The data summarized here has been taken from published and unpublished geologic maps, open-file reports, circulars, abstracts, and field notes as well as the more accessible geological literature. Condensed versions of this paper are presented in Moore and Mull (1989) and Moore and others (in press). This paper provides a more thorough description of the geology of the region, documentation of important relationships, and citation of the sources utilized. Throughout the text we have related paleogeographic reconstructions to present geographic coordinates. However, the reader should be aware that many workers believe that the rocks of northern Alaska have been rotated and (or) displaced significant distances from their sites of origin.

Geographic and geologic framework

Northern Alaska is divided into three major, parallel physiographic provinces, which are, from south to north, the Arctic Mountains (Brooks Range), the Arctic Foothills (northern Brooks Range), and the Arctic Coastal Plain (Wahrhaftig, 1965). The Brooks Range consists of rugged, east-trending, linear mountain ranges, ridges, and hills that rise to more than 3,000 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, the marshy Arctic Coastal Plain slopes gradually northward to the Arctic Ocean. The latter two provinces narrow toward the east and are truncated on the west by the Chukchi seacoast. The low, north-trending Lisburne Hills are situated along this coast. Although the Wahrhaftig defined the Arctic Slope or North Slope to consist of the Arctic Foothills and Arctic Coastal Plain provinces, Orth (1970) defined the southern boundary of the North Slope to be the drainage divide of the Brooks Range.

Vegetation in all three provinces consists almost exclusively of treeless tundra, although spruce and broadleaf forests are common in river valleys in the southern Brooks Range. Bedrock exposures are excellent in the higher parts of the Brooks Range, but are commonly patchy in the foothills and are limited to scattered cutbanks along streams on the Arctic Coastal Plain. Information about the subsurface geology of the Coastal Plain is greatly expanded by well and seismic reflection data gained from governmental and industrial petroleum exploration in the region.

In 1980, much of the land in northern Alaska was assigned by the Alaska National Interest Lands Conservation Act (ANILCA) to the Arctic National Wildlife Refuge (ANWR) in the eastern Brooks Range and North Slope, the Gates of the Arctic National Park and Preserve in the central Brooks Range, and the Noatak National Preserve and Kobuk Valley National Park in the western Brooks Range (fig. 1). The National Petroleum Reserve in Alaska (NPRA), covering much of the western part of the North Slope, was established in 1923 as Naval Petroleum Reserve No. 4 (NPR-4) in recognition of the possible petroleum resources suggested by oil seeps near Cape Simpson. The only road providing access to northern Alaska is the Dalton Highway. This gravel road, which follows the Trans-Alaska Pipeline northward across the Brooks Range via Atigun Pass to Deadhorse, is used to service the Prudhoe Bay and adjoining oil fields. The population of northern Alaska is sparse, and most of its people live in the native towns and villages along the coast or along the southern margin of the Brooks Range. Vegetation in all three provinces consists almost exclusively of tundra, although spruce and broadleaf forests are common in river valleys in the southern Brooks Range.

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

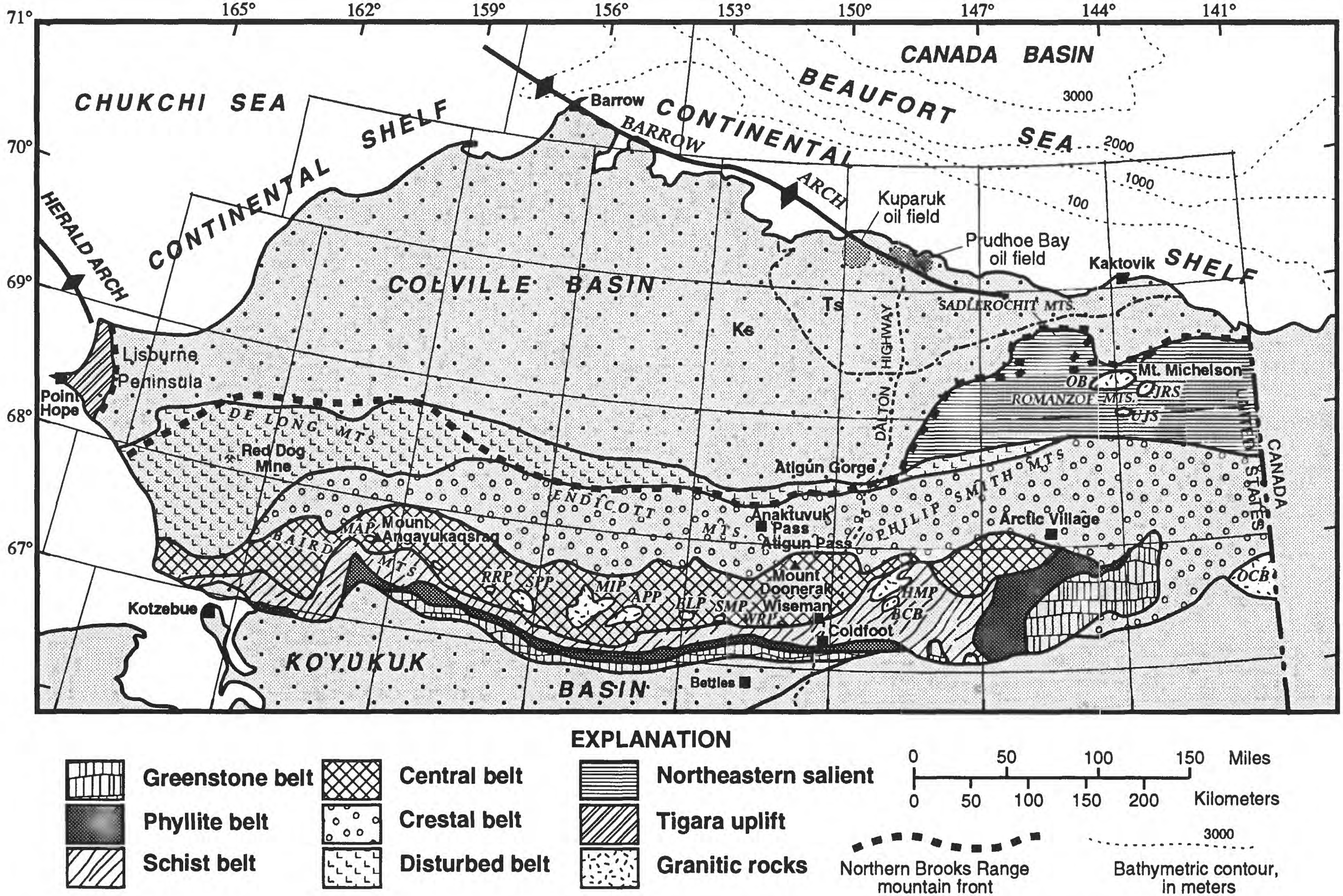


Figure 2. Geologic provinces of northern Alaska. Grid shows quadrangle boundaries (see figure 1). Lithologic abbreviations: Ts-- Tertiary sedimentary rocks; Ks-- Cretaceous sedimentary rocks. Abbreviations of granitic rock bodies: APP-- Arrigetch Peaks pluton; BCB-- Baby Creek batholith; ELP- Ernie Lake pluton; HMP-- Horace Mountain plutons; JRS-- Jago River stock; MAP-- Mount Angayukaqsraq pluton; MIP-- Mount Igikikpak pluton; OB-- Okpilak batholith; OCB-- Old Crow batholith; RRP-- Redstone River pluton; SMP-- Sixtymile pluton; SPP-- Shishakshinovik Pass pluton; UJS-- Upper Jago River stock; WRP-- Wild River pluton.

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 schistose metasedimentary and minor metavolcanic rocks (Brosge, 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). 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.

Previous work

Exploration and the initiation of geological investigation in northern Alaska began with the Klondike gold rush of 1897-98 which provoked interest in the mineral potential of all of Alaska. The first systematic geological studies in northern Alaska were by Schrader (1900, 1902, 1904) who explored the metamorphic rocks of the Brooks Range in the vicinity of the Dalton Highway and made a remarkable traverse by foot and canoe from what is now Bettles across the Brooks Range through Anaktuvuk Pass to Barrow. Schrader named the Skajit and Lisburne Limestones, recognized the presence of the latter on the Lisburne Peninsula far to the west, and described north-vergent thrusting in the Brooks Range. Following Schrader's expeditions, the geology along the rivers of the western Brooks Range was mapped and described by Mendenhall (1902) and Smith (1912, 1913) and along the seacliffs of the Lisburne Peninsula by Collier (1906) and Kindle (1909). Maddren (1912, 1913) and Mertie (1925, 1930) were the first to map and describe the geology along the rivers of the eastern Brooks Range south of the Continental Divide. Over a period of nine summers and six winters, Ernest de K. Leffingwell almost single-handedly mapped and described the entire stratigraphic succession of the northeastern Brooks Range. In his classic report, Leffingwell (1919) described and named the Neruokpuk Schist, Sadlerochit Sandstone (now Sadlerochit Group), Shublik Formation and Kingak Shale and reported extensive investigations of the geomorphology and permafrost of the region. Geologic investigation of NPR-4 was initiated in the mid-1920's. The results of this work are reported by Paige and others (1925), who were the first to publish petroleum analyses of the North Slope oil seeps, and Smith and Mertie (1930), who compiled and summarized much of the previous work. The stratigraphic section of northern Alaska was reviewed by Martin (1926) and Smith (1939).

As a result of the nation's need to expand its oil resources during World War II, a major effort to explore the petroleum resources of NPR-4 was undertaken by the U.S. Navy and the U.S. Geological Survey during the period of 1944 to 1953. This program, documented by Reed (1958) and summarized by Gryc (1970) and Dutro (1987a), produced reconnaissance geological maps of extensive areas of the northern foothills of the Brooks Range, established the modern stratigraphic nomenclature for the Brooks Range and North Slope, and documented the presence of significant petroleum resources in the region. The stratigraphic data and geologic maps resulting from this program, contained in Payne and others (1951), Bowsher and Dutro (1957), Patton (1957), Chapman and Sable (1960), Keller and others (1961), Detterman and others (1963), Chapman and others (1964), Patton and Tailleur (1964), Brosgé and others (1966), and Bergquist (1966), documented the essential geologic framework of the region.

Following the conclusion of the Naval Petroleum Reserve exploration program, geological research in northern Alaska branched into new lines of investigation. The petroleum industry, encouraged by the evidence of petroleum on the North Slope, began active exploration in northern Alaska. This effort, which ultimately led to the discovery of the Prudhoe Bay oilfield, is recounted in detail by Morgridge and Smith (1972), Jamison and others (1980) and Specht and others (1987). The U.S. Geological Survey, on the other hand, embarked on a geologic mapping program, still continuing, to understand the regional geology of the area and evaluate the mineral potential of the Brooks Range. This program has resulted in publication of reconnaissance geologic maps at a scale of 1:250,000 or larger for most of the Brooks Range (pl. 1) and compilation maps of the geology and geophysics of the region (Lathram, 1965; Beikman and Lathram, 1976; Grybeck and others, 1977; Barnes, 1977; Decker and Karl, 1977). The state of knowledge of the geology of both the North Slope and the Brooks Range shortly after the discovery of the Prudhoe Bay oilfield is contained in Adkison and Brosgé (1970). Stratigraphic summaries and interpretations resulting from the regional mapping programs are offered by Brosgé and others (1962), Tailleur and others (1967), Brosgé and Tailleur (1971), Brosgé and Dutro (1973), Detterman (1973), and Detterman and others (1975).

The discovery of a giant oilfield in northern Alaska gave birth to the present phase of detailed investigation of its geology. Major lines of investigation over the past few years have generally focused on the stratigraphy, sedimentology, and paleontology of the principal stratigraphic units of the region. Other important contributions have resulted from geologic mapping, which has revealed the existence of extensive, far-traveled allochthonous units in the Brooks Range and defined a tectonic stratigraphy that may extend the length of the range. Detailed geologic mapping by mineral exploration companies and the State of Alaska have outlined the stratigraphy, structure, and metamorphism of the southern Brooks Range. The Beaufort and Chukchi Sea continental margins have been mapped and described in reconnaissance. Regional interpretations showing the structural geology of the region, currently a topic of active investigation, are contained in the cross sections of Mull and others (1987), Oldow and others (1987), and Grantz and others (1991). The stratigraphy, structure, diagenesis, and chemistry of the North Slope oilfields form another major line of investigation. A third petroleum exploration program conducted by the U.S. Navy and the U.S. Geological Survey in NPRA (Bruynzeel and others, 1982; Gryc, 1988) has resulted in the release of many miles of seismic lines and other data from the subsurface of the western North Slope and tested most of its exploration plays. In recent years, petroleum exploration has begun to focus on the Arctic Coastal Plain within the boundaries of the Arctic National Wildlife Refuge (ANWR) and has given rise to a new generation of geological and geophysical investigation of that region (e.g., Bird and Magoon, 1987). The results of many recent topical studies in northern Alaska are published in a recent symposium volume by Tailleur and Weimer (1987).

Lithotectonic terranes of northern Alaska

Jones and others (1987) 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 some parts of northern Alaska, Mayfield and others (1988) and Mull and others (1987c) have distinguished a series of allochthons which are recognized primarily on the basis of their stratigraphy. As used by Mull and others (1987c) and Mayfield and others (1988), the term "allochthon," 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. Since the allochthons of Mayfield and others (1988) and Mull and others (1987c) correspond to two of the tectonostratigraphic units of Jones and others (1987), they are utilized as a tectonostratigraphic subdivision of lower rank than subterrane in this paper.

For this report, we have modified the terrane nomenclature of Jones and others (1987) 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. 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 some distance 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 **North Slope subterrane,** the structually lowest

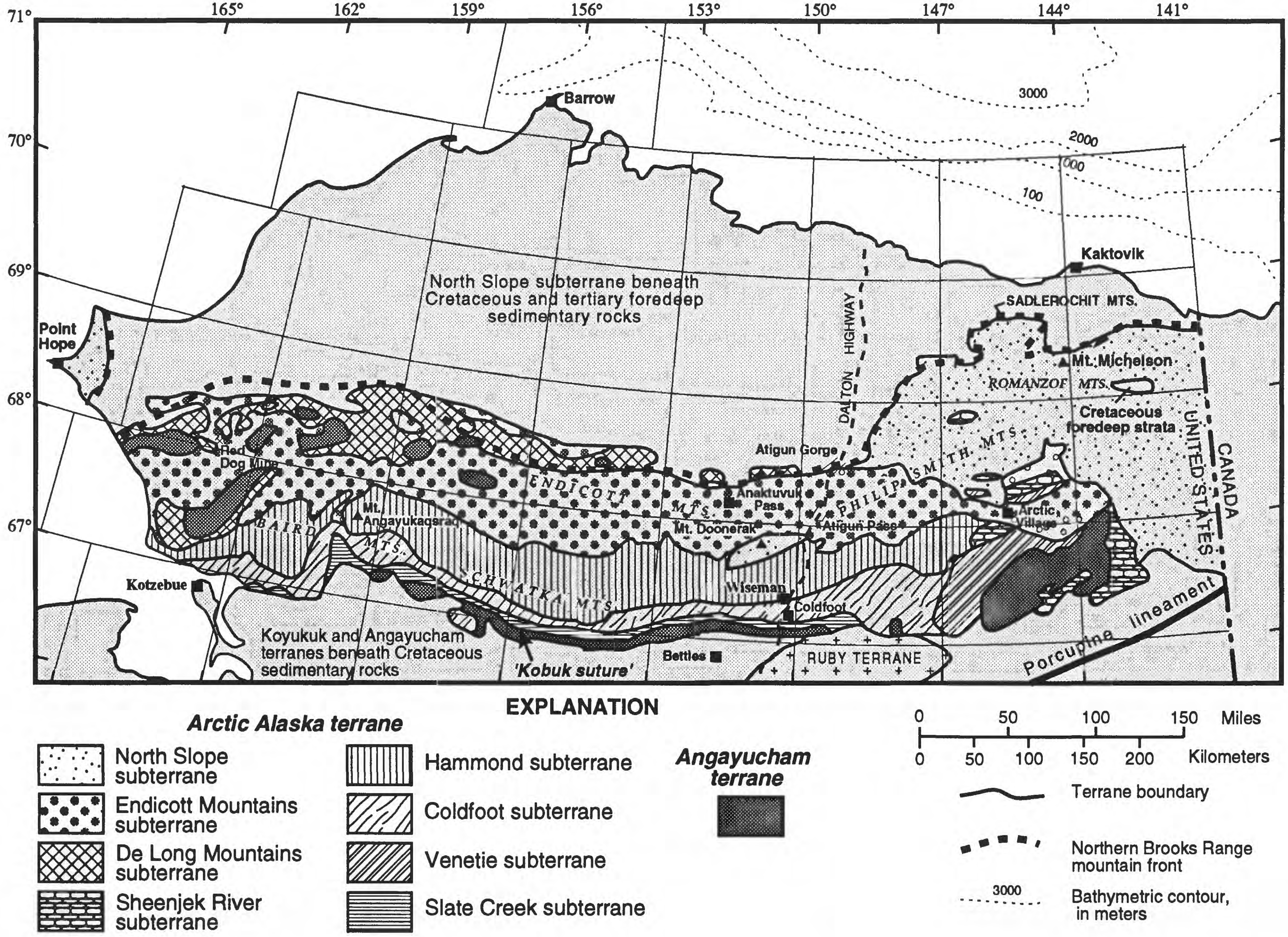


Figure 3. Terranes and subterranes of northern Alaska. Grid shows quadrangle boundaries (see figure 1).

subterrane, consists of Cretaceous 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. The Kagvik terrane of Jones and others (1987) is thought by most workers (e.g., Mull and others, 1982) to represent a siliceous facies of the Endicott Mountains subterrane and is therefore included here in that 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, which, from base to top, 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 **Sheenjek subterrane** in the southeastern Brooks Range is probably correlative with Ipnavik allochthon of the De Long Mountains subterrane based on its similarity in stratigraphy and structural position (I.L. Tailleur, oral comm., 1987, 1992; D.L. Jones, oral comm., 1987; W.P. Brosgé, oral comm., 1992). The Sheenjek is therefore regarded here as a subterrane of the Arctic-Alaska terrane, rather than as a separate terrane as shown by Jones and others (1987), but is described separately because of its distance from exposures of the De Long Mountains subterrane. However, on plate 1 the Sheenjek subterrane is included in the De Long Mountains subterrane.

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 can not 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 complex deformational patterns and poorly understood stratigraphy of the Hammond allow the possibility that it may consist of two or more distinct tectonostratigraphic units.

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 display Mesozoic blueschist-facies metamorphic assemblages that are partly to completely overprinted by greenschist-facies assemblages. Jones and others (1987) originally defined this subterrane as consisting quartz-mica schist that grades southward into Devonian(?) phyllite with metagraywacke. However, we accept the observations of Dillon (1989) and Gottschalk and Oldow (1988) that place a cryptic, but important structural boundary between the polydeformed quartz-mica schist of the schist belt and the lesser deformed phyllite of the phyllite belt.and therefore restrict the Coldfoot subterrane to the quartz-mica schists and related rocks of the schist belt. Jones and others (1987) also mapped the Coldfoot subterrane mainly in the region largely east of the Dalton Highway and included schist belt rocks to the west in the Hammond subterrane. Most workers consider schist belt rocks east of the Dalton Highway to be lithologically correlative with those to the west and would therefore extend this terrane westward to the western Brooks Range (e.g., Dillon, 1989).

We therefore restrict the Coldfoot subterrane to the quartz-mica schist, calc-schist, marble, and metavolcanic rocks of the schist belt, but extend it to include the quartz-mica schists and related rocks of the schist belt it the western Brooks Range. Rocks of the Coldfoot subterrane are distinguished from those of the Hammond subterrane by the higher textural grade of the former and the presence of carbonate massifs in the latter.

The **Slate Creek subterrane** (also called the Slate Creek thrust panel of the Angayucham terrane by Patton and Box, 1989) consists of phyllite, phyllonite, and subordinate metasandstone with rare Devonian fossils that compose the phyllite belt. As discussed above, Jones and others (1987) included some of these rocks in the Coldfoot subterrane, but we here distinguish them as a separate subterrane because of their lower textural grade and different deformational history. Lithologically similar, but geographically separate, rocks in the southeast Brooks Range were assigned by Jones and others (1987) to the **Venetie terrane**. Although the it is not included with the Arctic-Alaska subterranes by Jones and others (1987), the Brooks Range part of the Venetie terrane and the Slate Creek subterrane are considered to be distal facies of the Arctic-Alaska terrane (Mull and others, 1987c; Grantz and others, 1991; Murphy and Patton, 1988; D.L. Jones, oral comm., 1987) and both are therefore described below as distinct subterranes of the Arctic-Alaska terrane. On plate 1 the Venetie subterrane is included in the Slate Creek subterrane because of their general lithologic similarity. The Coldfoot, Venetie, 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.

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. 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 lower 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 or older time (late Early Cretaceous). 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 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) (fig. 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 metamorphism accompanied both Brookian orogenic phases, the data point out that regional uplift occurred mainly during the late Brookian phase.

Successor basins

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 consists largely of flysch shed in part from the Brooks Range in mid-Cretaceous time and deposited on Jurassic and Upper Cretaceous island-arc rocks south of the Brooks Range (Patton and Box, 1989). However, the tectonic environment of deposition of these deposits is controversial and include foredeep (Grantz and others (1991), extensional basin (Miller and Hudson, 1991) and strike-slip basin (Dillon, 1989) interpretations for the origin of the basin. 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 foredeep deposits, Jurassic and Lower Cretaceous (Neocomian), 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. Deposits of the Beaufort Sea sea shelf are Albian to Recent in age and compose a passive-margin succession along the western part of the continental margin of the Beaufort Sea (Grantz and May, 1983; Grantz and others, 1990a). North of ANWR, however, these deposits were shed principally from the younger northeastern salient of the Brooks Range and are deformed; hence they comprise foredeep deposits.

STRATIGRAPHY OF THE ARCTIC ALASKA TERRANE

The description of the stratigraphy of the Arctic Alaska terrane is organized below by its eight subterranes (North Slope, Endicott Mountains, De Long Mountains, Sheenjek, Hammond, Coldfoot, Slate Creek, and Venetie) so that the stratigraphy of these tectonic units can be easily compared. 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.

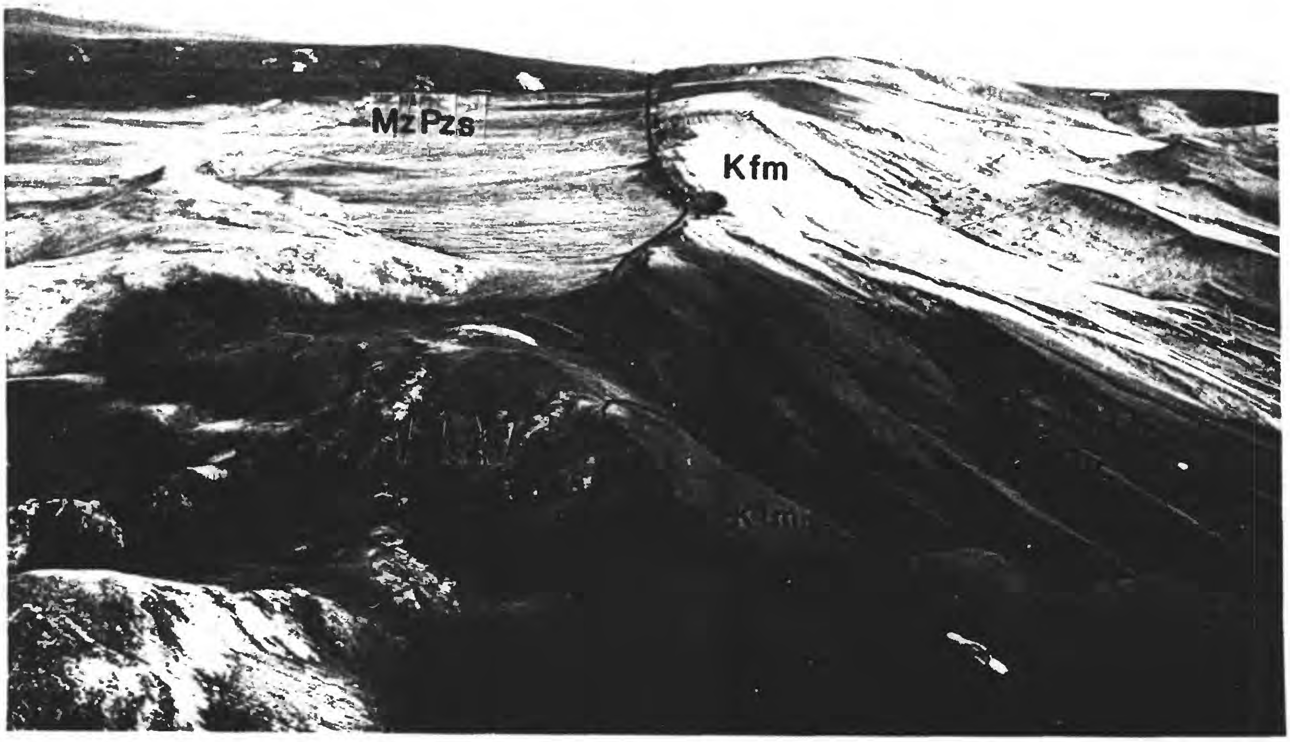


Figure 4. Eastward view of Ekakevik Mountain (Howard Pass quadrangle) showing Albian Fortress Mountain Formation (Kfm) lying unconformably on deformed allochthonous Paleozoic and Mesozoic sedimentary and diabasic rocks of De Long Mountains (Ipnavik River and Nuka Ridge allochthons) subterrane (MzPzs). In this report, pre-Albian deformational structures are considered as early Brookian, whereas the gentle 25^{o} south dip (fold) of Fortress Mountain Formation is interpreted as late Brookian.

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 come 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 (Mull and others, 1987a). 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 (figs. 5, 6, 7). 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). Lerand (1973) assumed that a single miogeoclinal belt fringed the northern margin of North America from Ellesmere Island in northern Canada to northwestern Alaska in Phanerozoic time and hence applied the same nomenclature throughout the region. More recent evidence for an oceanic origin for the Canada basin, plate tectonics in the Arctic region, and a displaced origin for northern Alaska makes Lerand's correlations equivocal and his nomenclature possibly inappropriate. Paradoxically, the term "Ellesmerian sequence" is not used to designate the Mississippian to Jurassic strata of northern Canada (for example, the Sverdrup basin).

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. 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 herein divide Lerand's Ellesmerian sequence into a lower carbonate and clastic succession, the **lower**

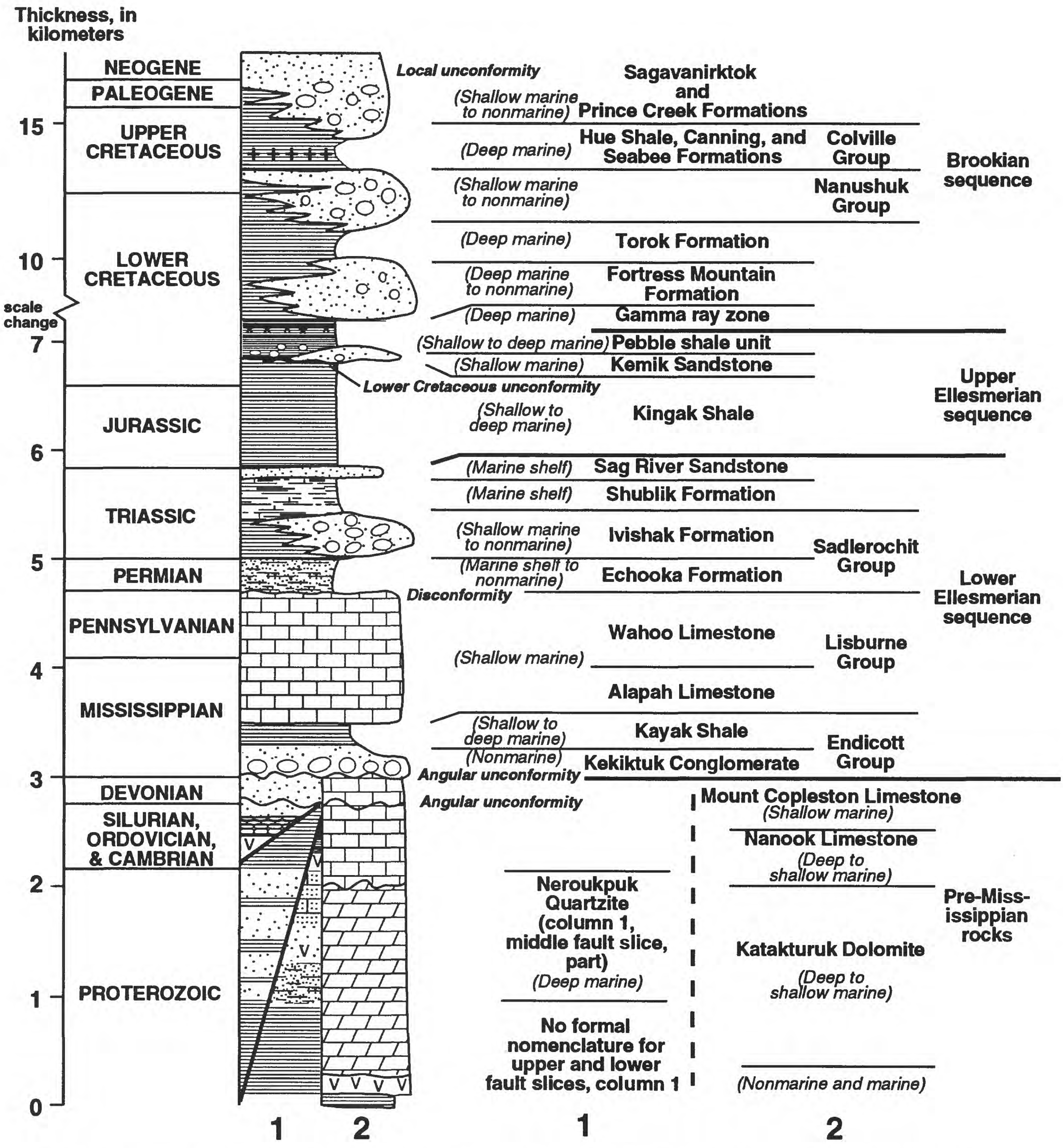


Figure 5. Generalized stratigraphy of the North Slope subterrane (of Arctic Alaska terrane) in the North Slope subsurface and northeastern Brooks Range and overlying foredeep deposits (Brookian sequence). Thicknesses are approximate. Pre-Mississippian stratigraphic subcolumns are (1), Romanzof Mountains: fault slices, from bottom to top, are northern, central, and southern belts as discussed in text; (2), Sadlerochit and Shublik Mountains; nomenclature in use for pre-Mississippian subcolumns shown to right as indicated, separated by dashed vertical line. The Brookian sequence depicts North Slope units only. Explanation of lithologic symbols in figure 6.

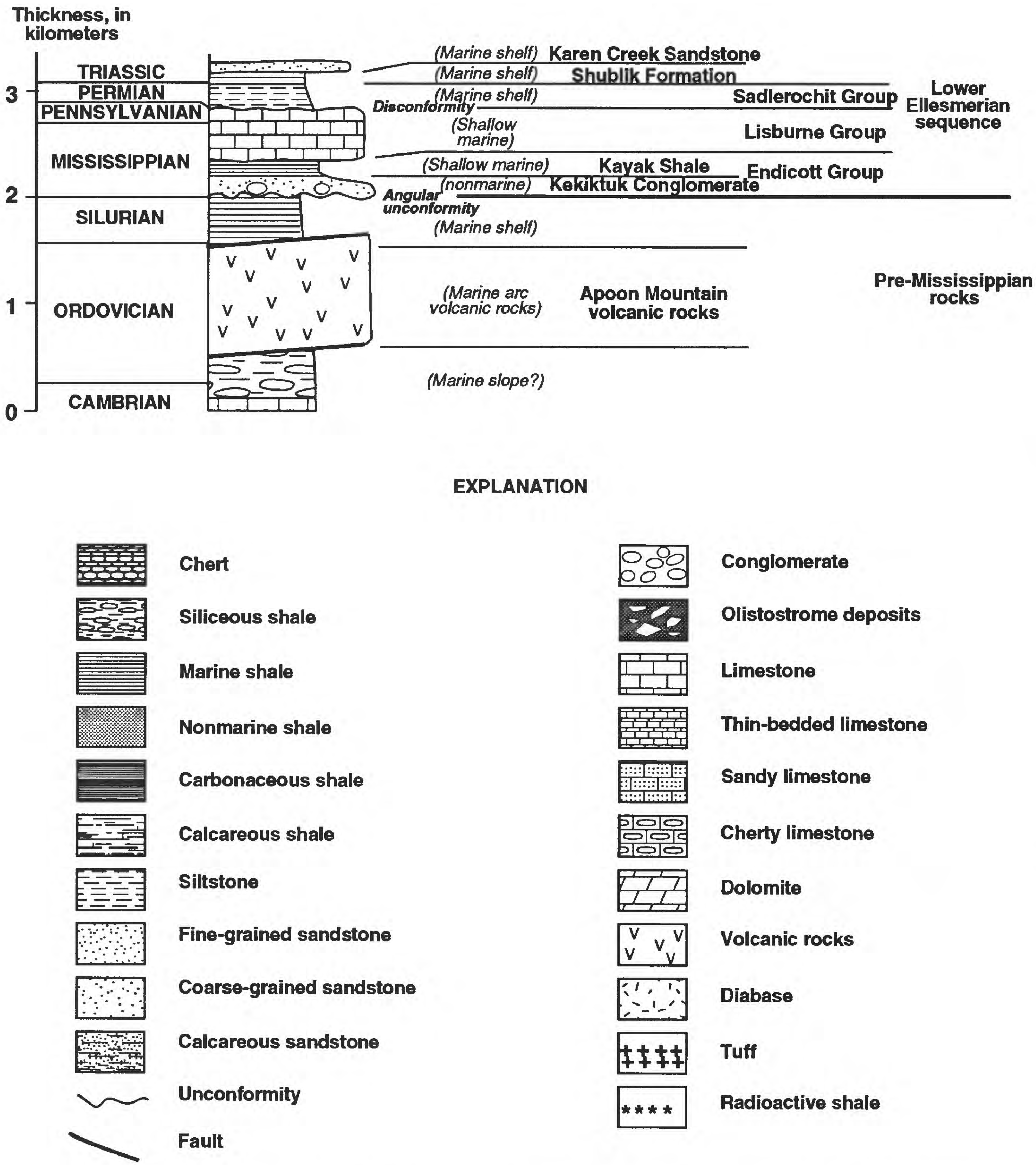


Figure 6. Generalized stratigraphy of the North Slope subterrane (of Arctic Alaska terrane) in the Mount Doonerak fenster. Thicknesses are approximate.

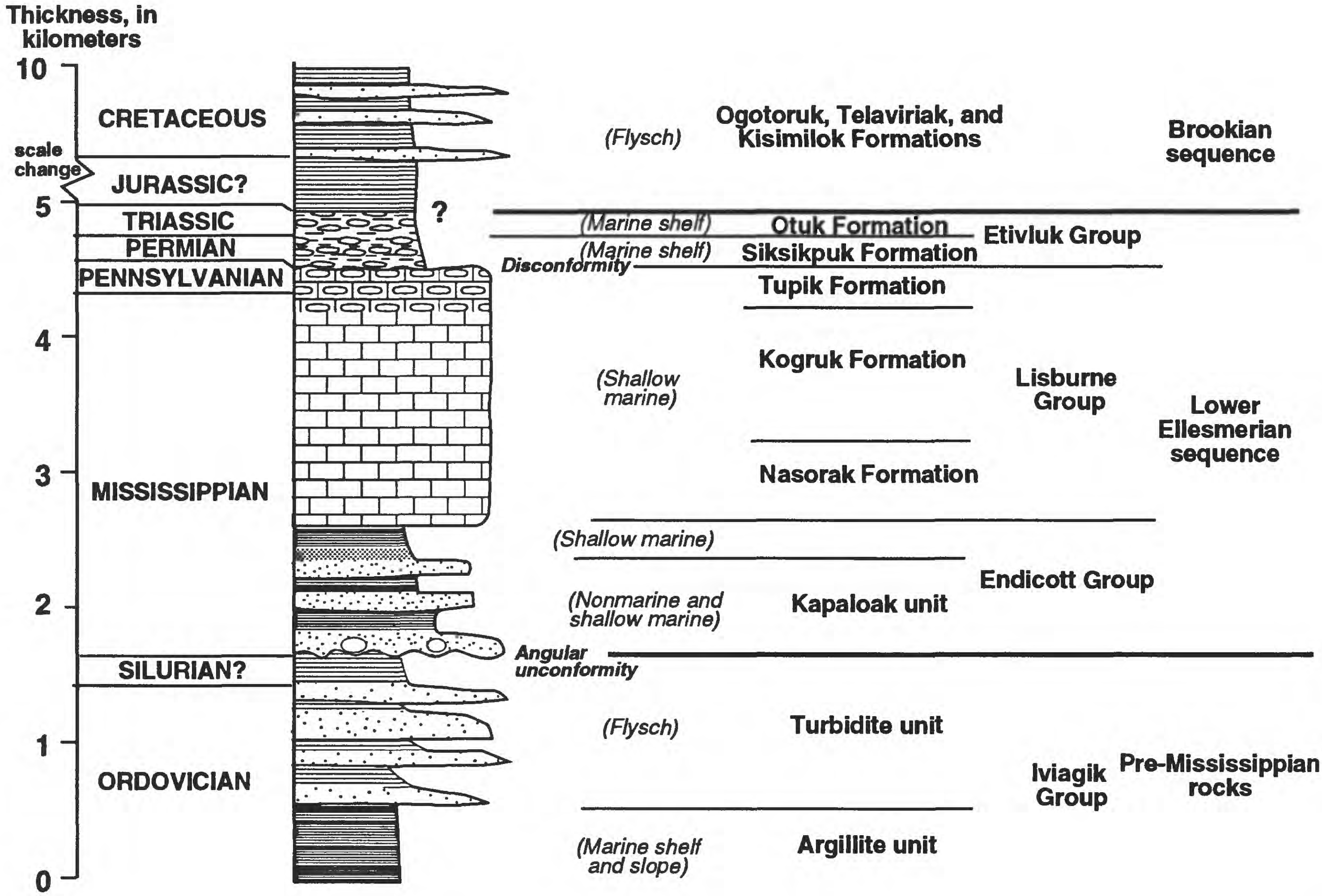


Figure 7. Generalized stratigraphy of the North Slope subterrane (of Arctic Alaska terrane) and overlying foredeep deposits (Brookian sequence) in the Lisburne Peninsula. Iviagik Group is that of Martin (1970). Thicknesses are approximate. Explanation of lithologic symbols in figure 6.

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 the Mississippian to the Triassic. 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, they have been penetrated by many wells along the Barrow arch (fig. 5). 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. The clastic rocks typically are very thinly bedded and contain both graded and ungraded beds, locally with ripple cross-lamination. Based on their composition, low sandstone-to-shale ratios, sedimentary structures, and apparent great thickness and extent, a continental slope environment of deposition is likely. The argillite has been dated as Early Silurian by graptolites and as Middle and Late Ordovician and Silurian by chitinozoans (Carter and Laufeld, 1975) (fig. 8). These fossils are from wells as much as 300 km apart which suggests that most of the argillite on the Barrow arch may be of similar age. However, red and green phyllite from the Simpson well yielded a K-Ar whole-rock date of 592 Ma (Brosgé and Tailleur, 1970), and a suite of K-Ar dates ranging from 547-584 Ma were obtained from dark gray argillite in the West Staines State 18-9-23 well (Drummond, 1974) (fig. 8). It has not been established whether that these ages spanning the Proterozoic-Cambrian boundary date the time of metamorphism of these rocks, the age of their detrital components, or incomplete isotopic resetting of the detrital ages by metamorphism.

More than 100 m of nonmarine 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). Lithologically similar carbonaceous shale and chert-pebble conglomerate were also encountered in the lowermost 156 m of the South Meade well, located 37 km west of the Topagoruk well (fig. 8). Middle (or perhaps Early) Devonian plant fossils have been recovered from the nonmarine succession of the Topagoruk well. These strata dip 35-60 degrees and, 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. However, seismic reflection data in these areas has failed to reveal the depositional geometry of the conglomeratic units and their relationship with the argillite.

Large, northwesterly-elongated magnetic and gravity anomalies flanked by smaller, northeast-trending anomalies (Woolson and others, 1962; Gutman and others, 1982) are present beneath the Colville basin in a band about 160 km-wide, south and east of Point Barrow (fig 8). Calculated anomaly depths compared to depths to pre-Mississippian rocks from seismic reflection and well data indicate that these anomalies lie within the pre-Mississippian section. These anomalies may indicate a northwest-trending structural grain and the presence of igneous rocks in this part of the North Slope subterrane (Grantz and others, 1991). The source of these magnetic anomalies,

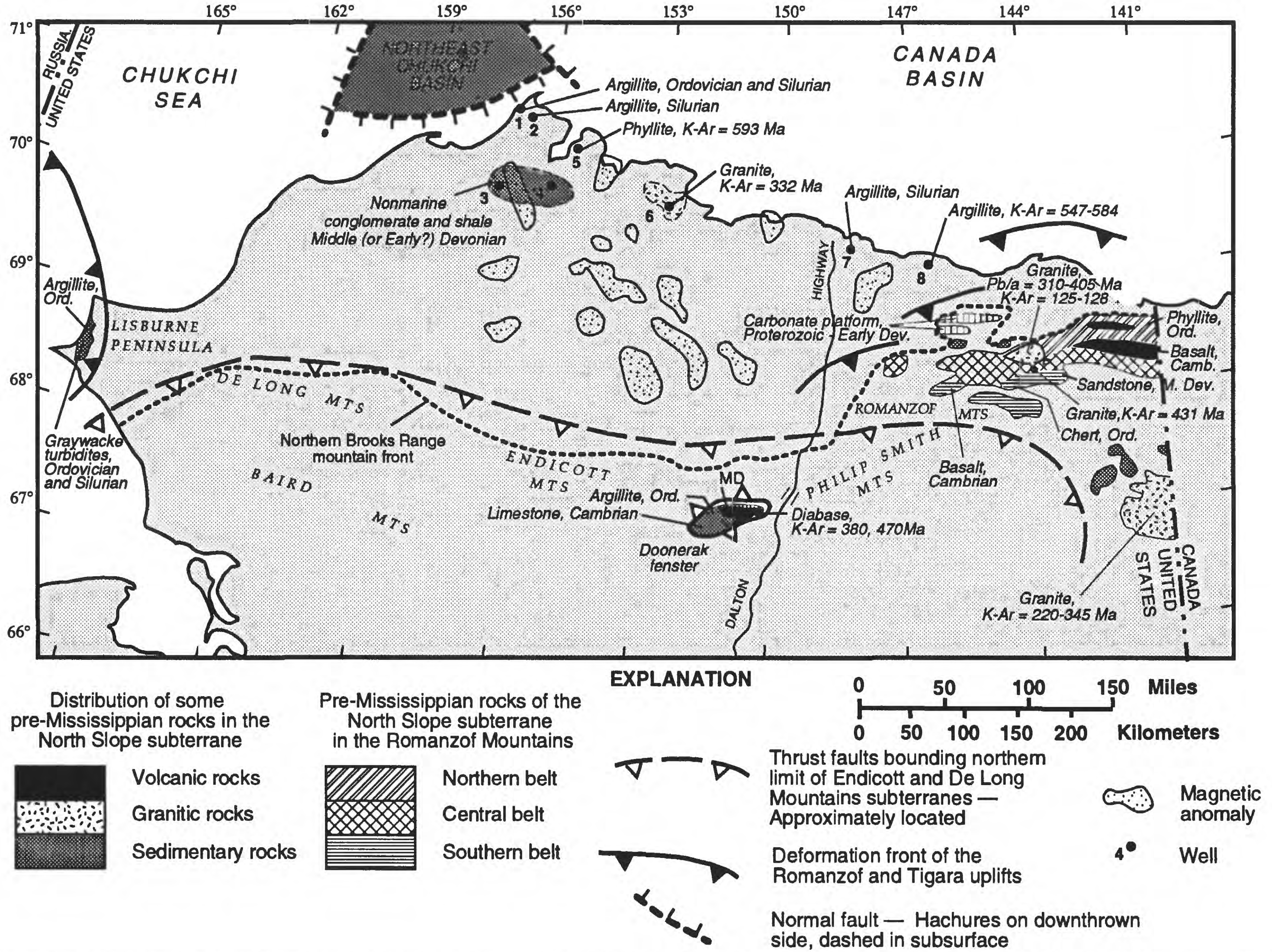


Figure 8. Ages and major structural and stratigraphic features of pre-Mississippian rocks of the North Slope subterrane. See text for sources of ages. Large positive magnetic anomalies from Woolson and others (1962) and Gutman and others (1982). Size and shape of granite pluton at well number 6 ibased on negative gravity anomaly (Gutman and others, 1982, map 1). Well identifications: 1, South Barrow-1; 2, South Barrow-3; 3, South Meade-1; 4, Topagoruk-1; 5, Simpson-1; 6, East Teshekpuk-1; 7, Sag River State-1; 8, West Staines State 18-9-23. Abbreviations: MD, Mount Doonerak

however, is uncertain because magnetic profiles across exposed igneous rocks in the northeast Brooks Range (Brosgé and others, 1970) show only small anomalies.

In the Chukchi Sea just west of Point Barrow, lies the enigmatic Northeast Chukchi basin (fig. 8), revealed on seismic records to be a half-graben filled with as much as 6 km of slightly deformed pre-Permian strata (Craig and others, 1985). Basin fill consists of two distinct seismic units: a lower unit of relatively uniform thickness characterized by parallel, high-amplitude, laterally-continuous reflections interpreted to be carbonate rocks, and an upper unit characterized by sigmoidal clinoform reflections interpreted to be an eastward-prograding clastic wedge.

Northeastern salient of the Brooks Range. Pre-Mississippian rocks are widely exposed in the cores of a number of large antiforms in the northeastern Brooks Range. In the Sadlerochit and Shublik Mountains (Mt Michelson quadrangle), pre-Mississippian rocks consist largely of a succession of carbonate rocks spanning Proterozoic to Devonian time, whereas those exposed to the south in the Romanzof Mountains (Demarcation Point, Table Mountain, Mt Michelson, Arctic, and Sagavanirktok quadrangles) are of similar age, but consist largely of metaclastic and metavolcanic lithologies. The pre-Mississippian rocks of both regions have been interpreted as a conformable stratigraphic succession (Dutro and others, 1972; Brosgé and Dutro, 1973; Churkin, 1975; Reiser and others, 1980), but Moore and others (1985a) have suggested the possibility that they may comprise two or more tectonostratigraphic terranes amalgamated in pre-Mississippian time.

Carbonate sequence of the Sadlerochit and Shublik Mountains The carbonate sequence of the Sadlerochit and Shublik Mountains, first described by Dutro (1970) and Dutro and others (1972) and more recently studied by Blodgett and others (1986, 1988, 1991), Robinson and others (1989) and Clough and others (1988, 1990) is important because of its thickness, as much as 3 km, and the great span of geologic time represented. It is exposed in relatively small area, but may has an undetermined extent in the subsurface. If depositional, the known areal distribution and facies suggest that they represent a carbonate bank with dimensions of at least 80 by 25 km.

The carbonate sequence rests conformably on more than 100 m of tholeiitic basalts that display both pillow and pahoehoe structures and red-weathering zones. The basalts are amygdaloidal to scoriaceous and consist of fine-grained, aphanitic to very sparsely porphyritic to ophitic, olivine-clinopyroxene-plagioclase metabasalt. Metamorphic minerals in the metabasalt are indicative of low greenschist facies metamorphism. The metavolcanic rocks appear to interfinger with and overlie local exposures of thin-bedded quartzite and argillite suggesting a continental origin, although geochemical data also allow an oceanic origin (Moore, 1987a). A diabase sill or dike intruding the metasedimentary rocks yields a Rb-Sr isochron age of 801±20 Ma and Nd-Sm isochron age of 704±38 Ma (Clough and others, 1990).

Conformably overlying these basalts is the 2,400-m -thick **Katakturuk Dolomite** (Proterozoic), (Dutro, 1970) which grades upward from basin-plain to carbonate platform depositional environments (Clough and others, 1988). Clough and others (1988) reported that the lower part of Katakturuk consists of debris-flow breccia, turbidites, and hemipelagic shale deposited in deep water slope-apron to basin plain settings. The upper part consists if three upward-shoaling cycles dominated by subtidal cross-bedded oolitic grainstone, intertidal stromatolitic wackestone and grainstone, and supratidal dolomitic mudstone. Paleocurrent and facies thickness trends suggest that the basin deepened toward the south and southeast. The Katakturuk Dolomite and underlying rocks are considered to be Proterozoic because they lie stratigraphically beneath Cambrian strata of the Nanook Limestone.

The **Nanook Limestone** (Late Proterozoic?, Cambrian, and Ordovician) (Dutro, 1970; Blodgett and others, 1986, 1988, 1991; Robinson and others, 1989) is 1,100 m thick and rests unconformably on the Katakturuk Dolomite. The basal part of the Nanook consists of burrowed dolomite interbedded with calcareous siltstone turbidites deposited in a slope environment. The middle and upper parts of the Nanook consist of limestone and vuggy dolomite deposited in shallow marine, subtidal to intertidal environments. More than 700 m of unfossiliferous limestone underlies the lowest occurrence of Late Cambrian fossils. This interval may be Cambrian or Precambrian in age. The upper 500 m of the Nanook includes fossiliferous beds dated as Cambrian and Ordovician. Fossils present include trilobites, cephalopods, gastropods, bivalve molluscs, corals, crinoids, brachiopods, ostracodes, conodonts, tentaculitids, and stromatoporoids of North American affinity (Blodgett and others, 1986). The Ordovician fauna suggests the area was situated near the paleoequator during that time (Clough and others, 1988).

A disconformity or low-angle unconformity marks the top of the Nanook, placing Early Devonian (Emsian) depositionally on Late Ordovician (Ashgillian) limestones such that Silurian strata are absent (Blodgett and others, 1988; Clough and others, 1990). The strata above the unconformity, 72 m thick, compose the **Mount Copleston Limestone** (Lower Devonian) (Blodgett and others, 1991). The Mount Copleston Limestone consists entirely of subtidal and intertidal carbonate rocks deposited on a partially restricted shallow-water carbonate platform (Clough and ohters, 1988; Blodgett and others, 1991). The Mount Copleston Limestone, Nanook Limestone, and Katakturuk Dolomite are unconformably overlain by Mississippian rocks and generally dip southward at an angle of about 15 degrees relative to the sub-Mississippian unconformity.

Pre-Mississippian rocks of the Romanzof Mountains Incontrast to the Sadlerochit and Shublik Mountains, the pre-Mississippian rocks in the Romanzof Mountains are composed of a thick, diverse, structurally complicated assemblage of metamorphosed clastic rocks interbedded with chert, carbonate, and volcanic rocks (Dutro and others, 1972). In the northeast Brooks Range, Reiser and others (1980) estimated an aggregated total thickness of about 6.5 km and in northwestern Canada, Norris (1985) reported that Precambrian rocks in the assemblage may be more than 13 km thick, but these thicknesses must regarded as structural thicknesses. Fossils in these rocks are rare and widely scattered, but show that all periods of the early Paleozoic are represented although their stratigraphic relationships are often unclear. Individual rock units in this region are mostly unnamed. Lithologic units in the Romanzof Mountains are generally east-trending and, for the purpose of this discussion, are grouped into three belts of contrasting lithology (fig. 8).

The **northern belt of pre-Mississippian rocks in the Romanzof Mountains** is exposed principally in the Demarcation quadrangle and consists chiefly of rocks considered by Reiser and others (1980) to be of Precambrian age. These rocks comprise three rock units, the lower two of which are Precambrian and are thought by Reiser and others (1980) to include the oldest rocks of the northeastern Brooks Range. The structurally lowest unit is several hundred meters thick and includes at its base gray phyllite interbedded with thin-bedded quartzite. The phyllite unit is overlain by crossbedded calcareous sandstones that may grade laterally into a unit of brown-weathering limestone and shale. The uppermost part of this unit consists of dark-green basaltic graywacke and volcaniclastic rocks (> 200 m) .

The middle unit of the northern belt is several hundred meters thick and consists largely of carbonate rocks which may rest unconformably on the volcanogenic rocks (Reiser and others, 1980). The rocks of this unit consists of limestone that typically is recrystallized, but locally is pelloidal and pisolitic and contains sparse quartz sand grains. Some parts of the carbonate assemblage consists of dark gray, thin- to thick bedded and locally crossbedded limestones that weather orange, red, or gray. Calcareous sandstone, phyllite, and slaty shale are locally intercalated with the carbonate assemblage.

The uppermost unit of the northern belt are less than 200 m thick and consists of black slate, gray phyllite and chert, and basaltic breccia, volcanic graywacke and conglomerate, tuffaceous sandstone, and tuff. A hornblende lamprophyre dike intruding underlying Precambrian rocks has yielded a K-Ar date of 484 Ma (Ordovician). In the easternmost Demarcation Point quadrangle, a single, unconfirmed, Late Ordovician graptolite specimen dates black phyllitic slate that intertongues with volcanic and volcaniclastic rocks (Reiser and others, 1980). These data and map relationships, coupled with these data, suggest that the Precambrian rocks of the northern belt may be overlain unconformably by volcanogenic strata of Ordovician age.

The **central belt of pre-Mississippian rocks in the Romanzof Mountains** is the most extensive belt of pre-Mississippian rocks in the Romanzof Mountains, extending for more than 250 km eastward from the Sagavanirktok quadrangle through the Mount Michelson and Demarcation point quadrangles and into Canada. Its distinctive lower part is more than 2,000 m thick and consists primarily of a resistant, thin- to thick-bedded turbidites composed of quartzose sandstone and granule conglomerate with subordinate phyllite and argillite. This unit originally was designated the Neruokpuk Schist by Leffingwell (1919) and was stratigraphically extended as the Neruokpuk Formation to include most of the pre-Mississippian rocks of the Romanzof Mountains by many workers (e.g., Brosgé and others, 1962; Reed, 1968, Dutro and others, 1972; Sable, 1977). Reiser and others (1978, 1980) later recognized the wide range in age and lithology of these rocks and therefore stratigraphically restricted the formation to the rocks originally described by Leffingwell and renamed the unit the **Neruokpuk Quartzite** (Proterozoic).

Stratigraphically beneath the Neruokpuk are several hundred meters or more of gray, green, and red argillite and phyllite interbedded with limestone, chert, and quartzite. Reiser and others (1980) inferred a Precambrian age for Neruokpuk Quartzite and underlying lithologies and suggested that they rest unconformably above the Precambrian assemblages of the northern belt of pre-Mississippian rocks. The combination of sedimentary structures, composition, presence of blue quartz grains, and other features suggest that the Neruokpuk Quartzite and related rocks may be representatives in northern Alaska of the strata of the Windemere Supergroup of the Canadian Cordillera.

Resting on the Neruokpuk Quartzite in the Demarcation Point quadrangle on a conformable or thrust-faulted contact are 100 m of maroon, red, green, and black phyllite with local manganiferous zones of siltstone and slate. These rocks interfinger with and are overlain by up to 1300 m of gray to brown-weathering calcareous siltstone and sandstone. The sandstone beds are very thinly bedded, ripple cross-laminated, and contain abundant grains of quartz and mica. Rare echinoderm columnals indicate a Paleozoic age for this unit.

The structurally highest unit of the central belt consist of as much as 1300 m of volcanic and volcaniclastic rocks that form a unit 6 km wide, and extends for more than 75 km eastward into Canada. These rocks consist of interbedded amygdaloidal pyroxene-phyric basalt flows, breccia, tuff, and pebble and cobble volcanic conglomerate of mildly alkalic composition. Moore (1987a) reports that geochemical analyses from these rocks (his Whale Mountain volcanic rocks) are very high in titanium and have an affinity with basalts from ocean-island or continental environments. Intercalated with the volcanic rocks are discontinuous units of dark gray medium- to thick-bedded limestone, shaly and sandy limestone and chert. The limestone contains Late Cambrian brachiopods and trilobites (Dutro and others, 1972; Reiser and others, 1980) and basaltic grains and pebbles, indicating a Cambrian age for the volcanic unit. The trilobites are of probably North American affinity (A.R. Palmer, personal communication, 1988).

The **southern belt of pre-Mississippian rocks in the Romanzof Mountains** are exposed in the southern Mount Michelson and Demarcation Point quadrangles and the northern Arctic quadrangle and may overlie the central belt (Dutro and others, 1972). This belt is characterized by its structural complexity, Paleozoic age, and presence of apparent oceanic lithologies and consists of two important units. The lowermost unit is structurally incoherent and consists chiefly of chert, phyllite, mafic volcanic rocks, graywacke, and sparse limestone bodies. These rocks are estimated to be as much as 1000 m in thickness by Reiser and others (1980), but tectonic repetition of units indicate that at least part of these rocks may have a much thinner stratigraphic thickness. The most widespread rocks of the lower unit consist of map-scale lenses of chert, mafic volcanic rocks, and limestone contained in phyllitic argillite and siltstone that locally is melange (Moore,1987a). Chert in the unit is thin-bedded and contains graded beds of radiolarians. Phyllitic partings in the chert in the Arctic quadrangle have yield graptolites of approximate Middle Ordovician age (Moore and Churkin, 1984). Other lithologic packages in the lowermost unit consist of thin- to thick-bedded graywacke turbidites and radiolarian-bearing siliceous argillite. These clastic rocks are locally conglomeratic and consist largely of mafic volcanic and epizonal granitic rock fragments with only minor amounts of quartz ($Q_{15}F_{10}L_{75}$). Associated with the graywacke is a 5-m-thick resedimented limestone bed that contains an abundant trilobite fauna of Early Cambrian age (Dutro and others, 1972) and North American affinity (A.R. Palmer, personal communication, 1985, 1988).

Volcanic rocks are mapped throughout the lowermost unit of the southern belt of pre-Mississippian rocks and typically occur as discontinuous bodies. Moore (1987a) reported that one volcanic body is at least 30 m thick, displays amygdaloidal pillowed and pillow-breccia textures, and is overlain by bedded chert. Regionally, the volcanic rocks are mostly fine-grained aphanitic to sparsely porphyritic metabasalt that contain plagioclase and, locally pyroxene and olivine, phenocrysts. Metamorphic assemblages are typically low greenschist facies, although schistose varieties with epidote-bearing greenschist facies assemblages are locally present. Geochemical analyses indicate tholeiitic to mildly alkalic compositions and deposition in either a continental or, more likely, an oceanic setting (Moore, 1987a).

The uppermost unit of the southern belt consists of 100 m or more of gray, fine-grained, thin-bedded quartzose sandstone that also includes interbeds of shale, pebble to boulder conglomerate, and limestone which contain brachiopods of Middle Devonian age (Reiser and others, 1980; Anderson and Wallace, 1990). In the Demarcation quadrangle, these rocks overlie in angular unconformity more deformed rocks of the oceanic lower unit; both units are in turn unconformably truncated by the Mississippian Kekiktuk Conglomerate. Based on these observations, Anderson and Wallace (1990) concluded that most deformation in this area occurred during pre-Middle Devonian time, although minor deformation may have continued into Late Devonian time. The stratigraphic relationships and composition of the Devonian rocks are analogous to the Devonian rocks of the Topagoruk well, suggesting that pre-Middle Devonian deformation followed by deposition of chert-rich clastic strata may have taken place over a wide area.

Mt. Doonerak fenster. The pre-Mississippian stratigraphy in the Doonerak fenster is structurally complex and poorly understood but is generally divided into metasedimentary and metavolcanic assemblages (fig. 6). The metasedimentary assemblage is the structurally higher and more extensive and consists of units composed of thinly bedded fine-grained siliceous black quartzitic siltstone (metachert?) with local thin limestone lenses, quartz-bearing semischist, dark gray argillite with intercalated fine-grained quartzose beds and laminae, black, gray, and green phyllite, and siliceous argillite. Trilobite and brachiopod fauna of Middle Cambrian age have been recovered from a limestone lens within the widespread black quartzitic siltstone package (Dutro and others, 1984). The trilobite fauna from this locality is notable in that it exhibits affinities to Siberian, rather than North American, fauna (Palmer and others, 1984). Other fine-grained strata within the metasedimentary unit have yielded Ordovician conodonts and Early Silurian graptolites (Repetski and others, 1987).

The 20-km-long metavolcanic unit, informally designated as the **Mount Doonerak volcanic rocks** by Dutro and others (1976), consists of a succession of thrust packages more than 2 km thick that may comprise a rootless mass emplaced onto the underlying metasedimentary assemblage (Dillon and others, 1986; Dillon, 1989). The metavolcanic assemblage consists of structurally complex fragmental and extrusive rocks of mostly basaltic composition that are cut by diabase dikes. Some chloritic phyllite and metagraywacke may be interstratified with, or overlie the metavolcanic rocks, but depositional relationships have not been documented. Julian (1986, 1989) describes the assemblage as consisting of four major volcanic facies that are structurally stacked one on top of another. These consist, from north to south and structural base to top, of pyroclastic breccia and related rocks, coarse-grained volcaniclastic rocks, mostly fine-grained volcaniclastic rocks, and volcanogenic slate and phyllite. The volcanic rocks generally consist of aphanitic to porphyritic rocks that contain abundant large, euhedral plagioclase and locally clinopyroxene phenocrysts. Pillowed and amygdaloidal basalts are locally present. Hornblende-clinopyroxene gabbro and diorite are also common and probably form dikes and/or stocks. The volcanic rocks commonly contain metamorphic assemblages indicative of prehnite-pumpellyite and greenschist facies and static to cataclastic textures.

Dutro and others (1976) reported K-Ar ages of about 470 ma (Ordovician) and 380 Ma (Devonian) for diabase intruding the metavolcanic rocks. Stepwise degassing experiments on these rocks suggest that these dates represent two different mafic intrusive events rather than one event which has been complicated locally by argon loss or gain (Dutro and others, 1976). Moore (1987a) and Julian (1989), based on trace element geochemical data and abundance of volcaniclastic lithologies, inferred an island-arc origin for the metavolcanic assemblage. These data suggest a deposition of the assemblage in a convergent tectonic setting during Ordovician or earlier time.

Lisburne Peninsula. Moderately deformed pre-Mississippian rocks along the western side of the Lisburne Hills, named the **Iviagik Group** (Ordovician and Silurian)by Martin (1970), isdivided into units consisting of (1) Ordovician argillite and (2) Silurian lithic turbidites (fig. 7). Both units are unconformably overlain by nonmarine Mississippian deposits. The argillite unit consists of thin-bedded black graptolite-bearing siliceous shale with local siltstone beds and minor chert. The maximum thickness of the argillite unit where exposed is about 100 m, but its total thickness is probably much greater. The turbidite unit is at least several hundred meters thick and consists largely of thick-bedded medium-grained graywacke and pebbly sandstone with several 30-m-thick thinner bedded intervals. Sandstones from the turbidite unit have the approximate composition $Q_{50}F_{20}L_{30}$ with most lithic grains consisting of sedimentary (siltstone, argillite, chert and limestone) and metamorphic (quartzite and schist) detritus. Potassium feldspar grains are abundant and coarse and grains of muscovite, chlorite, hornblende, and epidote are common. The source region of this detritus is unknown. 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, written commun. to I. L. Tailleur, 1982).

Granitic rocks. A few scattered plutons intrude the pre-Mississippian rocks of the North Slope subterrane (fig. 2). 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 (table 1). 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. 8) 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, oral commun., 1989), 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 (the Beaufortian sequence of Hubbard and others, 1987, see also Moore and Mull, 1989) 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, 6, 7), 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. 9,

Table 1. Summary of isotopic ages for granitic rocks of the Arctic Alaska terrane [see summaries of subterranes in figure 27, granitic rocks in figure 2. All ages as Ma]

Sample	K-Ar				Pb-alpha	U-Pb	Rb-Sr
	feldspar	muscovite	biotite	hornblende	zircon	zircon	isochron
North Slope subterrane							
Teshekpuk well	332±10[a]		243±7[a]				
Okpilak batholith			125[b] 128[b]	*348±10[d]	310±35[b] 405±45[b]	380±10[c]	
Jago stock			59±2[c]			380±10[c]	
Upper Jago River stock				431±1[e]			
Old Crow batholith		335±10[f]	220 to 345±10[f]				
Hammond subterrane							
Intrusive rocks at Mount Angayukaqsraq				557±17[h] 539±16[h]		750±6[g]	
Gneiss of the Ernie Lake pluton						1000?[i]	
Shishshakshinovik pluton		98.8±2.2[k,p]					
Arrigetch pluton		92±5[o]	86±4[o] 88±4[o] 90±2.7[k]			363[j]	373±25[m]
Wild River pluton						357[j]	
Horace Mountain. plutons						402±8[j]	
Coldfoot subterrane							
Mixed schists of the Kallarichuk Hills		104±3.1[k]	93.6±2.8[k] 96±1.2[n]			705±35[n]	
Baby Creek batholith			125±13[l]		380±40[l]	382±20[l]	380±12[j]

Sources of data: [a] Bird and others (1978); [b] Sable (1977); [c] Dillon and others (1987b); [d] unpublished data of W. P. Brosgé referred to by Bird and others (1978); [e] Reiser and others (1980); [f] ages summarized by Barker (1982); [g] Karl and others (1989) (previously reported as 820±30 Ma by Dillon and others, 1987b); [h] Mayfield and others (1982); [i] Dillon and others (1980); [j] Dillon (1989); [k] Turner and others (1979); [l] Brosgé and Reiser (1964); [m] Silberman and others (1979); [n] Karl and others (1989); [o] Brosgé and Reiser, (1971); [p] Pessel and others (1973).
*Incorrectly reported as 384±10 Ma by Bird and others (1978) (W.P. Brosgé, oral communication, 1985, 1989).

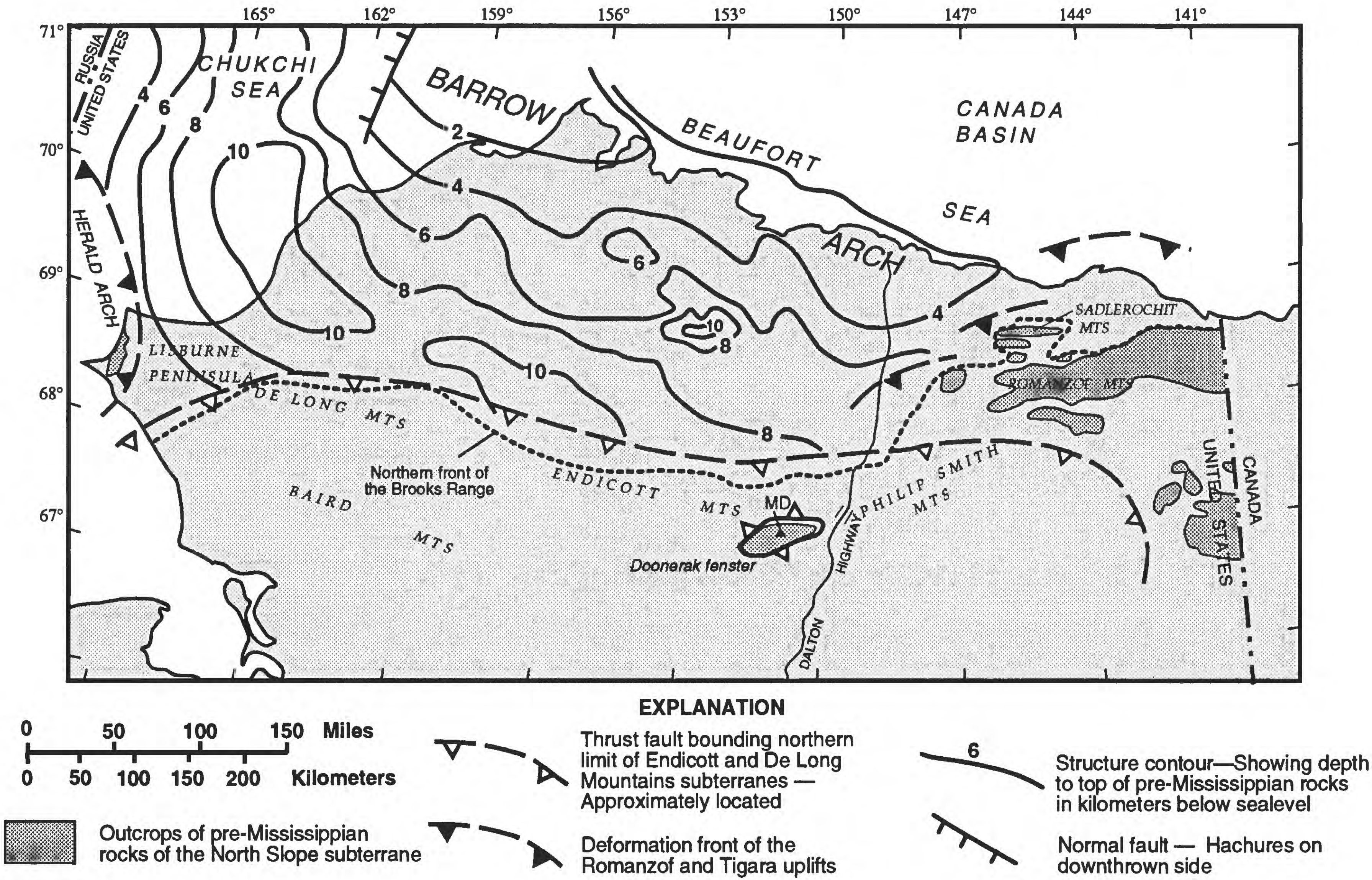


Figure 9. Depth to pre-Mississippian rocks in subsurface and distribution of pre-Mississippian rocks in outcrop. Contour values also indicate total thickness of Mississippian and younger rocks, including tectonically thickened rocks along north edge of Brooks Range. Contours based on seismic data (Gutman and others, 1982; Hubbard and others, 1987) and well data (Bird, 1982). Abbreviations: MD, Mount Doonerak.

10, and 11) 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, 10, 11, 12). These units generally become progressively younger to the north and northwest and are as young as Early Permian in northern NPRA (Bird, 1988). They 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 (figs. 5, 6, 10, 11). In the northeastern Brooks Range and subsurface of the North Slope, the sub-Kekiktuk unconformity has substantial angular discordance with underlying rocks and rests on a number or units, suggesting a large amount of structural relief existed prior to its deposition. In the Doonerak fenster where the basal contact is commonly tectonized and preserved at only a few locations, the unconformity is thought to be angular by many workers (e.g., Dutro and others, 1976; Mull and others, 1987a, c), although Oldow and others (1987c), based on structural studies, have argued that the contact is a disconformity in that area.

The Kekiktuk is 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. Defined by Brosgé and others (1962) in the Mt. Michelson quadrangle, the Kekiktuk Conglomerate 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 Doonerak fenster, the maximum clast size is about 3 cm. Sandstone in the unit is medium grained, moderate to well-sorted, and consists of monocrystalline quartz and chert grains with quartz overgrowth cement and a kaolinite matrix (Woidneck and others, 1987). Proportions of quartz and chert are variable, ranging from as little as about 10 percent chert in the Prudhoe Bay area to as high as about 50 percent chert in the Doonerak fenster where a minor amount of feldspar is also present. Coal beds with an aggregate thickness of 15 m are reported from the subsurface and are locally present in outcrop (Bird and Jordan, 1977). 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 Barrow arch, the Kekiktuk may be as young as Late Mississippian (Meramecian), according to Woidneck and others (1987).

Sedimentologic studies of the Kekiktuk in the northeast Brooks Range (Nilsen, 1981; LePain and Crowder, 1990) and the subsurface (Woidneck and others, 1987) show generally similar nonmarine fining-upward vertical successions. Except for the subsurface east of Prudhoe Bay where the sequence begins with fine-grained swamp deposits, the vertical sequence consists of braided-stream deposits grading upward into meandering-stream and floodplain deposits gradually

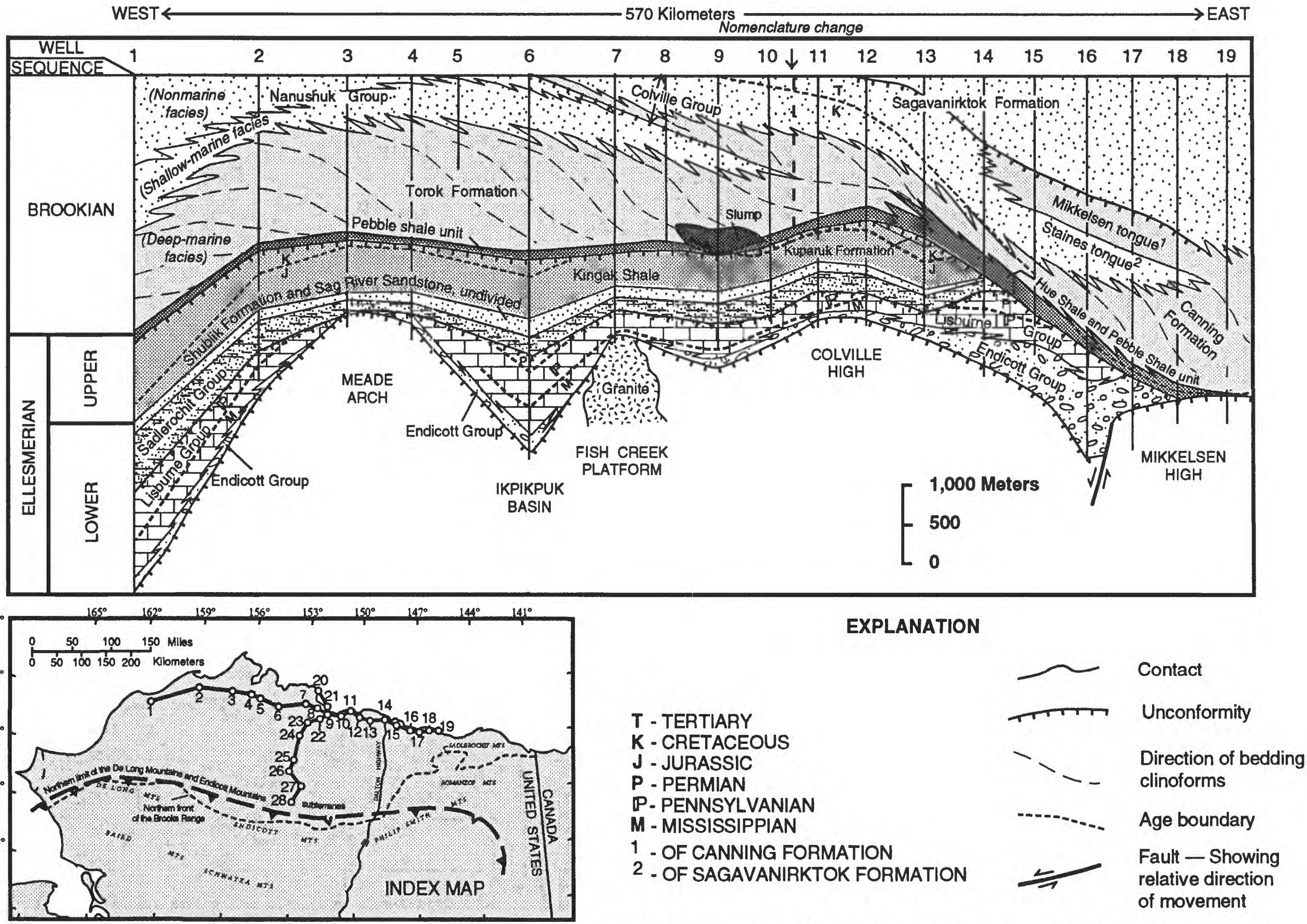


Figure 10. West to east well-correlation section for coastal plain province of North Slope subterrane (of Arctic Alaska terrane) showing post-Devonian subsurface stratigraphy, sequences, and selected ages (modified from Molenaar and others, 1986). Datum is sea level. Index map shows location of section. Numbers indicate wells used to construct diagram: (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.

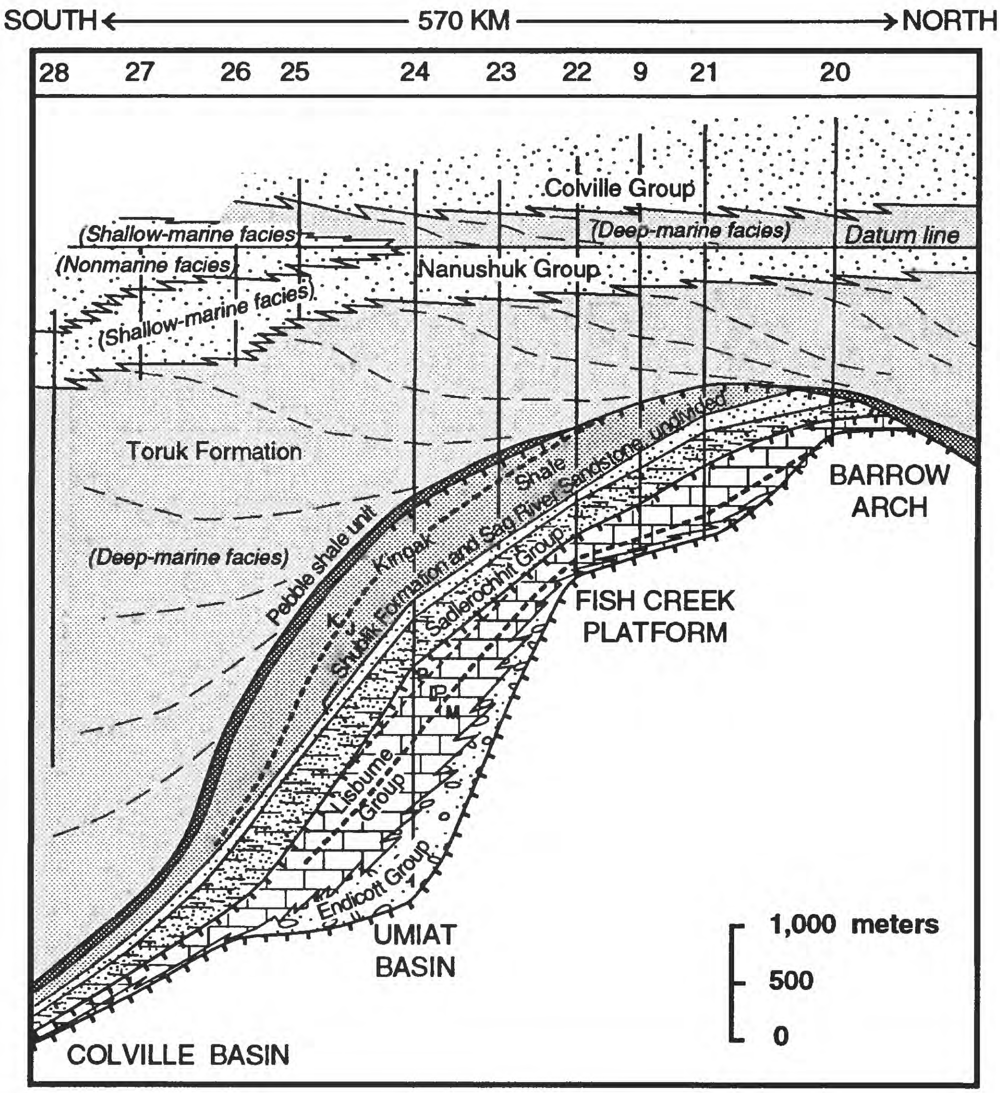


Figure 11. North to south well-correlation section for North Slope subterrane (of Arctic Alaska terrane) from Barrow arch to Colville basin showing post-Devonian subsurface stratigraphy and selected ages (modified from Molenaar and others, 1986). Datum is marine transgression near or at top of the Nanushuk 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. See Figure 10 for location of section and wells and explanation of symbols.

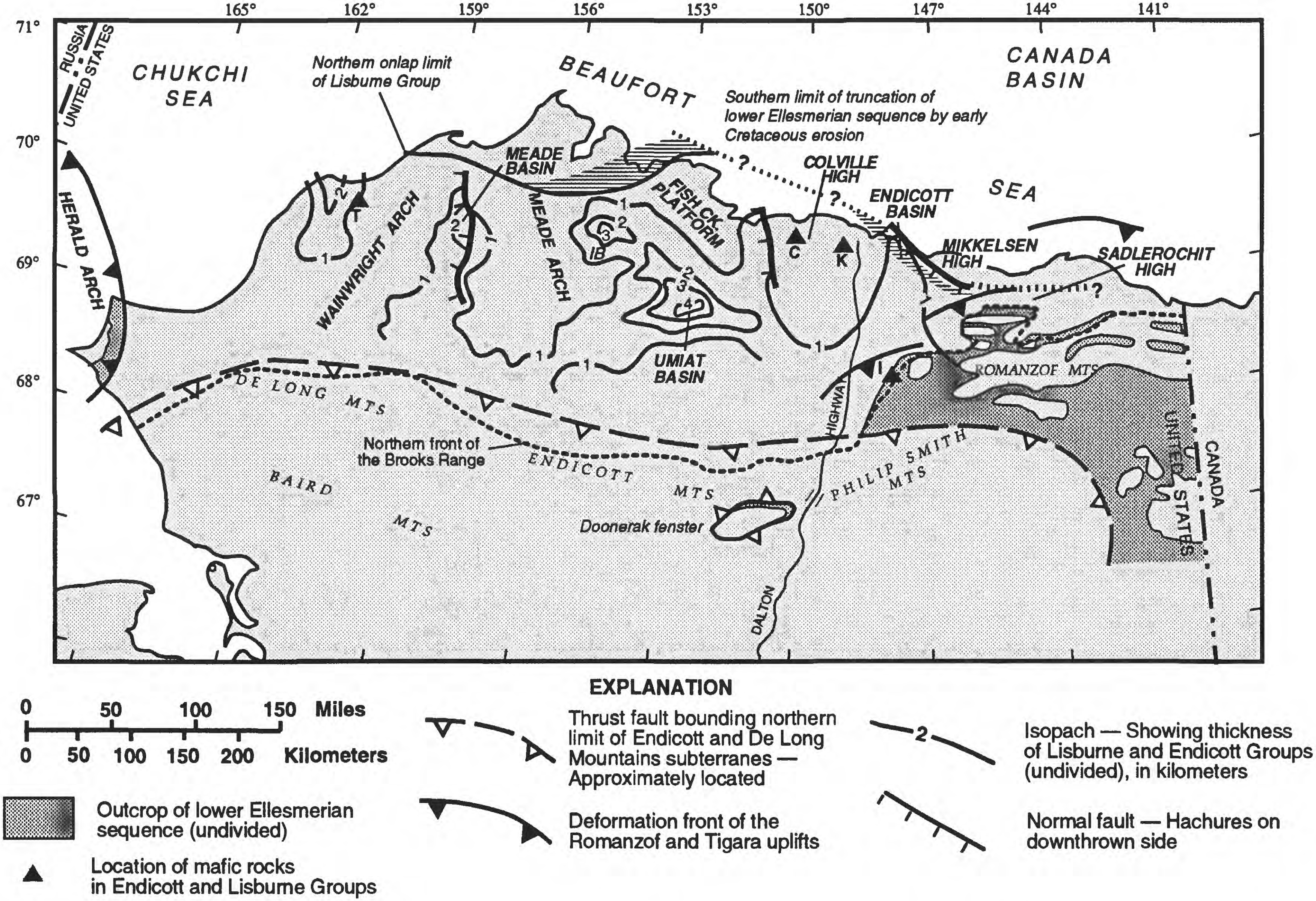


Figure 12. Summary of important structural and stratigraphic features of lower Ellesmerian sequence and isopachs of undivided Lisburne and Endicott Groups, North Slope subterrane (of Arctic Alaska terrane) (Gutman and others, 1982). Basins, which developed as sags and half-grabens in Mississippian or possibly as early as Devonian time, filled with unusual thicknesses of clastic and carbonate rocks assigned to the Endicott and Lisburne Groups (see figs. 7 and 8). Basin-bounding normal faults shown are generally overlapped by the Lisburne Group or younger strata. Contours and northern onlap and truncation limits are based on well penetrations and seismic records. Unconformity at top of Lisburne cut down into Endicott Group in a narrow band southeast of Point Barrow and between Mikkelsen and Colville highs (horizontal-line pattern). Abbreviations: T - Tunalik-1 well; C - Colville State-1 well; K - Kuparuk State-1 well; I - Ivishak River. IB = Ikpikpuk basin.

passing into marine and tidal deposits of the Kayak Shale. Paleocurrent data indicate south and west transport directions. Based on the facies, lateral variations in thickness, and compositional evidence of local source areas, the Kekiktuk is thought to have been shed from local topographic highs into possibly fault-bounded basins on a regional unconformity surface (Grantz and others, 1991; LePain and Crowder, 1990).

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 (e.g., Umiat and Meade basins) (fig. 12). 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), on the other hand, related the sedimentary fill of these basins to Devonian clastic rocks in the Topagoruk well, distinguishing these basin-fill strata 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 gradationally overlain by less than 400 m of gray to black, carbonaceous marine shale of the **Kayak Shale** (Mississippian). 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. The limestone, in many places cherty and dolomitic, is generally spiculitic lime mudstone with ostracodes. Other fossils, found only rarely, include brachiopods, corals, bryozoa, crinoid debris, foraminifers, and algae. The Kayak Shale may gradationally or abruptly overlie the Kekiktuk Conglomerate or, where the Kekiktuk is missing, unconformably overlie pre-Mississippian rocks. It is gradationally overlain by the Lisburne Group or the Itkilyariak Formation (Bird and Jordan, 1977; Woidneck and others, 1987). The thickness of the Kayak varies considerably and, like the Kekiktuk Conglomerate, it is thickest in local basins (>400 m) and thin or absent in extrabasinal areas. It is generally found throughout the northeast Brooks Range (Brosgé and others, 1962; Armstrong and Mamet, 1975) and is postulated to be present throughout most of the subsurface (Bird and Jordan, 1977; Bruynzeel and others, 1982). Fossils from the unit indicate deposition in Early Mississippian (Osagean and Meramecian?) time in the Doonerak fenster (Armstrong and Mamet, 1978) and suggest deposition in Late Mississippian (Meramecian) time in the northeastern Brooks Range and subsurface (Armstrong and Bird, 1976). The Kayak Shale is interpreted as having been deposited in a broad variety of tidally influenced shallow-marine environments, including brackish-water, barrier bar, and offshore environments. Overall, the unit grades upward from terrigenous clastic coastal plain and shallow-marine to carbonate shelf depositional environments (LePain and Crowder, 1990).

The Kayak interfingers laterally (northward) and vertically in the North Slope subsurface with the **Itkilyariak Formation** (Late Mississippian), a distinctive sequence of Upper Mississippian red, gray, and green shale, limestone, and sandstone (Mull and Mangus, 1972). The Itkilyariak Formation was defined by Mull and Mangus (1972) in the Sadlerochit Mountains (Mount Michelson quadrangle), but is known primarily in the subsurface along the Barrow arch (Bird and Jordan, 1977). Shale comprises more than half and sandstone less than ten percent of the unit, but. limestone is more abundant and accounts for as much as a third of the upper part of the unit. Nodules of anhydrite are common in the shale and limestone. The Itkilyariak Formation may be as thick as 260 m and rests conformably on gray shale and limestone of the Kayak Shale. In some areas such as the Colville high (Fig. 12), the section consists predominantly of sandstone, conglomerate, and shale which may be a red, oxidized facies of the Kekiktuk Conglomerate or an unusually coarse-grained facies of the Itkilyariak Formation. The age of the Itkilyariak, determined from foraminifer-bearing limestone interbeds, is Late Mississippian (Visean). Because of its northward time-transgressive nature, it is possible that the Itkilyariak may range in age to as young as Pennsylvanian or even to Early Permian. A northward-transgressive unit, the Itkilyariak Formation was deposited under arid subaerial conditions on a coastal plain that periodically was flooded by the sea, whereas the Kayak Shale was deposited in a northward-transgressive, brackish-water, coastal-plain environment grading upward to a shallow-marine environment (Bird and Jordan, 1977).

On the Lisburne Peninsula, the **Kapaloak sequence** (Early Mississippian) unconformably overlies pre-Mississippian rocks and probably is equivalent to the Kekiktuk Conglomerate and Kayak Shale. The Kapaloak is an informal name for a 600-m-thick sequence of interbedded quartzose sandstone, silty shale, mudstone, minor conglomerate, and a number of interbedded coal seams up to 1 m thick (Collier, 1906; Tailleur, 1965; Moore and others, 1984). The base of the formation consists of four meters of nonmarine granule to pebble conglomerate and coarse-grained sandstone. These rocks are overlain by intercalated nonmarine (about 60 percent) and marine (about 40 percent) strata with the marine and nonmarine intervals commonly separated by coal and carbonaceous shale. Nonmarine intervals contains abundant plant fossils, in situ trees, root casts and display channelized fining-upward sequences of trough crossbedded sandstone, current ripple marks. Sandstone in the marine intervals contain abundant oscillation ripple markings, shale drapes, rip-up clasts, and abundant and diverse ichnofossils. The upper part of the formation is richer in black marine shale and contains interbedded thin, fossiliferous limestone beds that appears to be gradational upward into the overlying marine carbonate rocks of the Nasorak Formation (Lisburne Group).Clasts in the conglomerate at the base of the Kapaloak formation have a maximum size 7 cm and consist dominantly of chert with minor quartz and quartzite. Sandstone from the sequence contains an average of 75 percent quartz, 15 percent chert, and 5 percent argillite and siltstone grains. Tailleur (1965) reported an Early Mississippian age for plant fossils from the unit.

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 1,200 m, and it is thickest in basins established during deposition of the Endicott Group (fig. 12). 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 locally present in the northeastern Brooks Range (Armstrong and Mamet, 1978). The Lisburne Group is young as Early Permian In the subsurface of 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, 1987b; 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. 13).

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, 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,

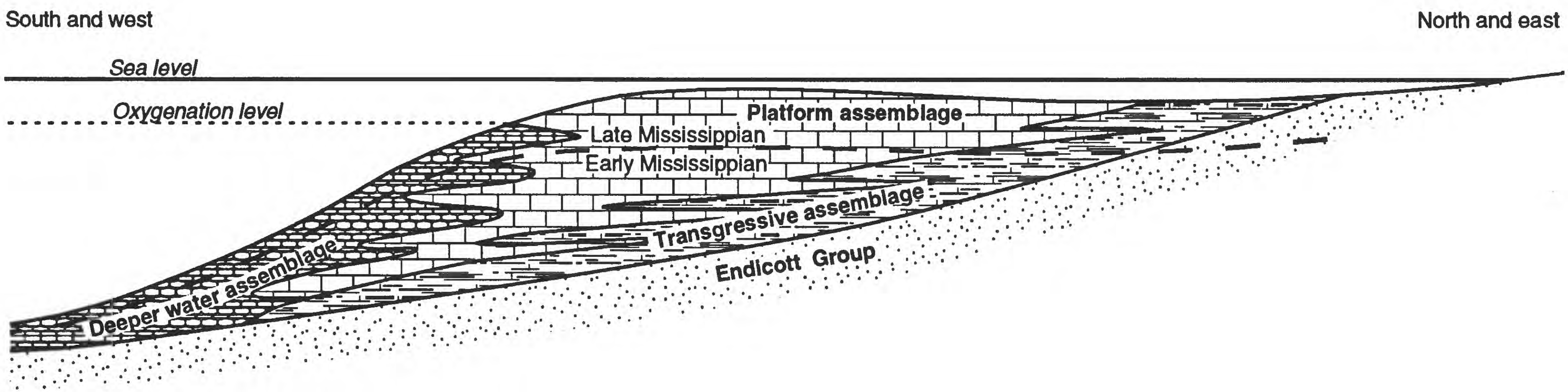


Figure 13. Depositional model for transgressive, platform, and deeper water carbonate deposits of Lisburne Group (modified from Armstrong and Bird, 1976). Distribution of facies probably was controlled partly by interplay of regional subsidence and oxygenation level in basin. Maximum thickness of carbonate strata of Lisburne Group is about 1000 m. See figure 6 for lithologic symbols.

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 gradationally overlain by ooid or crinoid packstone and grainstone that, in turn, is cappedby 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 anyhdrite 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 turbidites. 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). While most of the Lisburne Group in the Doonerak fenster consists of the transgressive and platform assemblages, the argillaceous material and darker color of some intervals in this area suggest deposition in local foreslope environments of deposition (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 (Armstong, 1974, Armstrong and Mamet, 1977; Bird and Jordan, 1977; Bird, 1978; Witmer and others, 1981). These paleontologic correlations, coupled with seismic data from NPRA (Bruynzeel and others, 1982), show that east of the Meade arch (fig. 12) the Lisburne Group transgressed about 100 km northward during the early Late Mississippian (Meramecian), whereas in the area of the Meade arch and western NPRA, the Lisburne transgressed toward the northwest during the Late Mississippian to Early Permian. Microfossils collected from the base of the Wachsmuth Limestone in the Doonerak fenster yield early Merimecian (early Late Mississippian) ages whereas the top of the Alapah Limestone is dated as early Morrowan (early Early Pennsylvanian) (Armstrong and Mamet, 1978; Mull and others, 1987a), suggesting a somewhat older age for this Lisburne Group section than that to the north in the North Slope subterrane. 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 widespread rock unit was 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. 14). 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), named by Keller and others (1961) and subsequently revised by Detterman and others (1975), consists of a sequence less than 200 m thick of calcareous siltstone, chert, limestone, and sandstone that thins northward. It represents transgressive deposits of the northward advance of the Sadlerochit sea across the eroded platform of Lisburne carbonate rocks. The lower member of the Echooka is the **Joe Creek Member.** This member, about 100 m thick, consists of a lower calcareous mudstone and siltstone unit, succeeded by a middle medium to massively bedded spiculitic, radiolarian chert unit of probable secondary origin, and capped by an upper thin-bedded, sandy, bioclastic, glauconitic limestone unit. In the northeastern Brooks Range, the Joe Creek onlaps and interfingers with the overlying Ikiakpaurak Member, the upper member of the Echooka Formation at about 69 degrees N. latitude. The **Ikiakpaurak Member**, also about 100 m thick, consists of massive quartzose sandstone and siltstone that is locally glauconitic and calcareous. Well-defined channel conglomerates, composed of pebble- to cobble-sized clasts of chert, are locally present at the base of the member in the Sadlerochit and Shublik Mountains. The zero edge of the Ikiakpaurak is irregular and generally lies along the Barrow arch. The Echooka Formation is characterized by the trace fossil *Zoophycos.* Brachiopods indicate that the Joe Creek Member is Early and Late Permian (Sakmarian to Kazanian), whereas the Ikiakpaurak Member is Late Permian (Kazanian; late Guadalupian) (Detterman and others, 1975).

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, 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 hence 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), probably is a surface of downlap by the southward-prograding Kavik Member. The Kavik, about 85 m thick, consists 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. The zero edge of the Kavik lies along the Barrow arch. The Kavik is dated in outcrop as Early Triassic (late Griesbachian, in part) by ammonites and pelecypods (Detterman and others, 1975) but 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 northward-thickening and -coarsening sandstone beds with thin siltstone and shale interbeds. Chert-pebble to -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). In that area, the detrital composition of the Ledge is 27 to 63 (average 47) percent monocrystalline quartz, 6 to 44 percent (average 19) percent dense chert, 1 to 12 (average 5) percent, and an average of 9 percent accessory constituents including polycrystalline quartz, sedimentary and metasedimentary rock fragments, and feldspar. The development of the Early Cretaceous unconformity along the uplifted rift margin of the Canada basin exposed the Ledge in the Prudhoe Bay area to the influx of acidic meteoric waters resulting in the selective dissolution of grains and cements and the development of unusually good porosity averaging in excess of more than 20 percent.

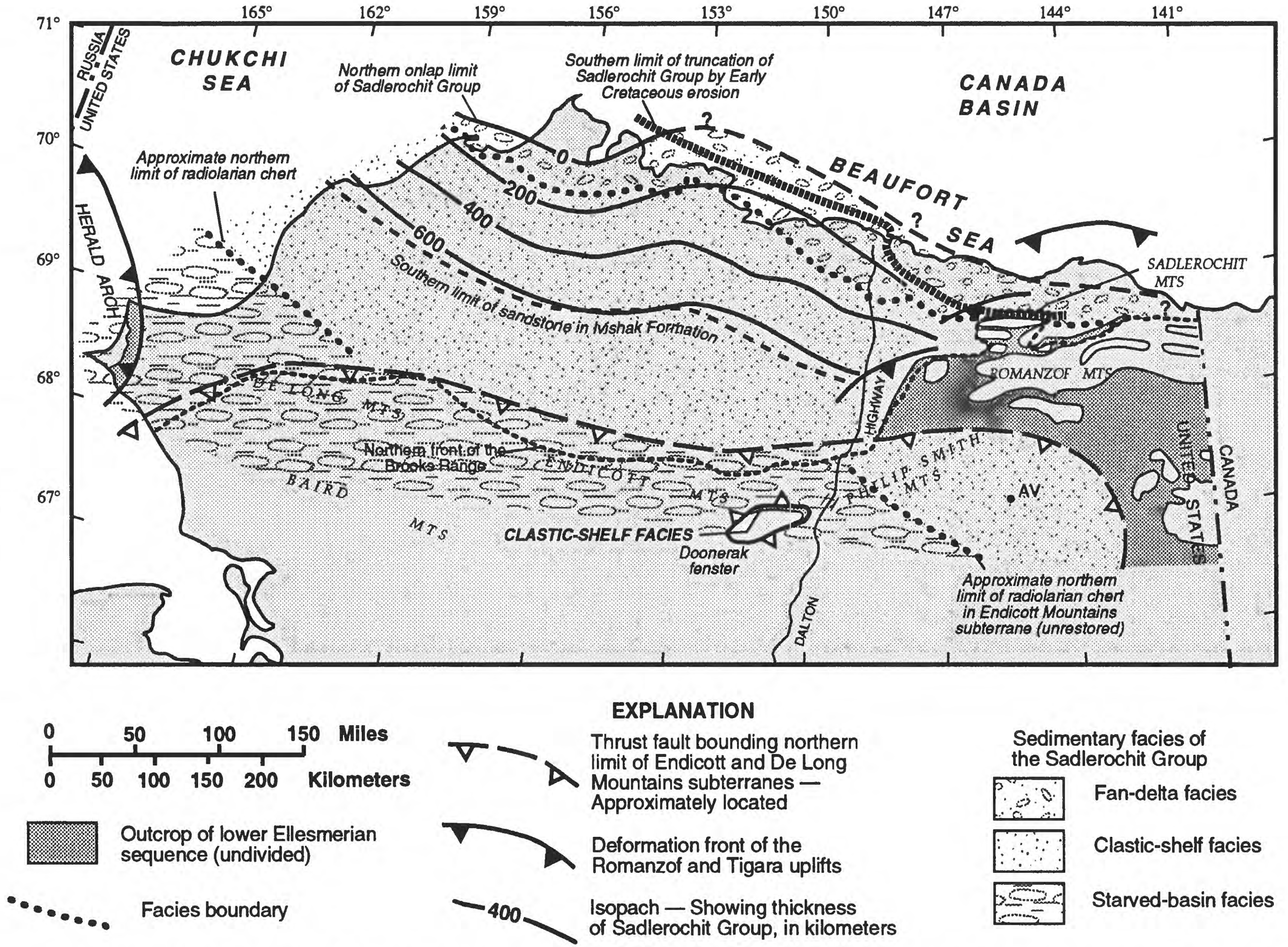


Figure 14. Isopach and facies map for Sadlerochit Group (Early Permian to Early Triassic cycle of Lower Ellesmerian sequence). Facies distribution shown is that at time of maximum regression (Early Triassic) of Ledge Sandstone Member of Ivishak Formation. Location of northern limit of radiolarian chert in subsurface of North Slope subterrane adapted from Hubbard and others (1987); approximate unrestored position of northern limit of radiolarian chert in allochthonous rocks in Brooks Range provided by C.G. Mull (unpub. data).

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 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. 14). 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, yellow-brown-weathering very fine grained sandstone and siltstone and a 70-m-thick upper unit of black, phyllitic shale (Mull and others, 1987a). The lower unit displays ripple cross-lamination and bioturbation, and it contains the trace fossil *Zoophycos* and Early Permian (Wolfcampian) brachiopods. The Early Permian age suggests a correlation with the Joe Creek Member of the Echooka Formation (Dutro and others, 1976; Mull and others, 1987a). The unfossiliferous upper part of the Sadlerochit Group in the Doonerak fenster may be correlative to the Ikiakpaurak Member of the Echooka Formation (Mull and others, 1987a) or alternatively, to the distal, prodelta (Kavik Shale Member) lithofacies of the Ivishak Formation in the northeastern Brooks Range. 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 thin-bedded to massive, commonly laminated siltstone and argillaceous sandstone that gradationally overlies the Ledge Sandstone Member. In its northernmost extent, this unit 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). The Shublik was defined by Leffingwell (1919) for outcrops in the northeast Brooks Range (Mount Michelson quadrangle) and was modified by Detterman and others (1975). It is present throughout most of the subsurface as indicated by well penetrations and its characteristic strong reflection on seismic records. 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. 15). The Shublik Formation is a blanket-like deposit that averages about 100 m thick in most areas but is nearly 200 m thick in northeastern NPRA and in the northeastern Brooks Range, where it may have been deposited close to points of clastic-sediment influx (Bird,

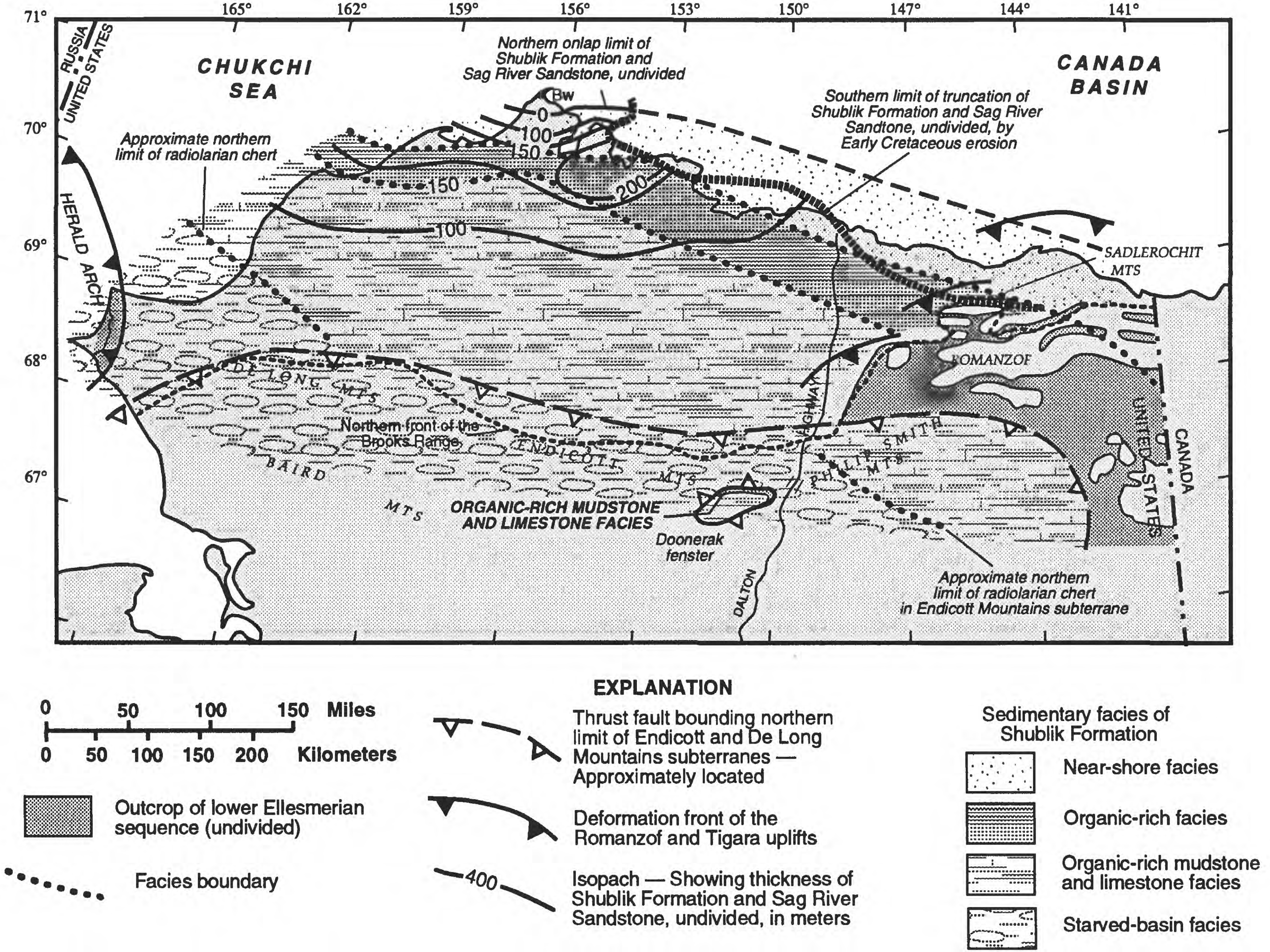


Figure 15. Isopach map for undivided Shublik Formation and Sag River Sandstone (Early to Late Triassic cycle of lower Ellesmerian sequence), and facies distribution for Shublik Formation (facies from Parrish, 1987; Hubbard and others, 1987). Sources for shelf-edge position same as for Figure 15.

1987). Ammonites and abundant *Halobia* and *Monotis* bivalves indicate that the Shublik Formation spans Middle and Late Triassic time (Anisian to Norian) (Detterman and others, 1975)

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 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. In turn, 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 units that have thicknesses and facies trends similar to those of the Shublik Formation. The maximum thickness of the Sag River Sandstone is about 100 m in northeastern NPRA, and it thins rapidly southward. It is the stratigraphically highest unit exposed in the Doonerak fenster where it consists of a few meters of black very fine-grained sandstone and siltstone.

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 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, sometimes assigned to the Siksikpuk Formation), 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, sometimes assigned to the Otuk Formation, 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 lower unit are Late Pennsylvanian or Early Permian, and those near its top are Permian; radiolarians and megafossils from the upper part of the succession 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.14 and 15).

Igneous rocks of the lower Ellesmerian sequence. Igneous rocks are rare in the Ellesmerian sequence, but four widely separated occurrences of mafic intrusive and extrusive rocks associated with the Lisburne and Endicott Groups have been recognized (fig. 12). On the Colville high, dikes or sills intruding the Endicott Group were penetrated by the Sinclair Colville State-1 well (depth interval 2848-2852 m) and by the Mobil Kuparuk State-1 well (depth interval 3374-3380 m). Drill-cuttings of the igneous rocks in both wells display a diabasic texture with prismatic feldspar altered to calcite and interstices filled with chlorite and opaque heavy minerals.

At the edge of the northeastern Brooks Range near the Ivishak River in the Mount Michelson quadrangle, the Lisburne Group is intruded by a 45 m-thick andesite porphyry sill that contains limestone xenoliths (Keller and others, 1961). This sill may be related to an eruptive sequence of volcanic rocks that crop out over a 10-km long area bisected by the Ivishak River (Reiser and others, 1979). These volcanic rocks, as much as 200 m thick, include breccia, tuff, volcanic conglomerate, tuffaceous limestone, and flows that are pillowed. Fossils from limestone, below and interbedded with the volcanic rocks indicate a Late Mississippian (latest Visean or early Namurian) age.

In the western part of the NPRA, the Tunalik well penetrates a 223 m interval of mafic igneous rock (depth interval 5356-5579 m) within a sequence of of siltstone and interbedded chert and limestone dated by microfossils as Early Permian (Witmer and others, 1981). Drill cuttings suggest these rocks consist of interbedded flows and volcaniclastic rocks. A 9-m core from the upper part of this interval, believed to represent a single flow unit, consists of fine-grained, vesicular basalt with relict porphyritic texture, now altered to chlorite, albite, epidote, sphene, iron oxides, and minor biotite. Six whole-rock K-Ar ages from the core range from 35 to 110 Ma and are interpreted to indicate thermal homogenization of argon trapped in the volcanic interval by the surrounding impermeable sedimentary rocks (M.L. Silberman, written communication, 1980).

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. 16 and pl. 1). These units, assumed to be coarse grained, represent rift-basin deposits (Grantz and May, 1983; Hubbard and others, 1987). Because they are described by Grantz and others (1990a), 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. 16) and south of the main axis of Jurassic and Early Cretaceous extension.

Hubbard and others (1987) suggested modification of the Ellesmerian sequence nomenclature by designating Ellesmerian strata deposited during rifting in Jurassic and Early Cretaceous time as the "Beaufortian Sequence". This nomenclature was later utilized by Moore and Mull (1989). However, Hubbard and others (1987) defined the Beaufortian sequence by relating the extensional structures and related strata seen in seismic profiles offshore in the Beaufort Sea with the upper part of the Ellesmerian Sequence onshore. The Barrow arch intervenes between the two areas making the precise stratigraphic relationship between the onshore and offshore sections speculative. Although largely coeval, Grantz and others (1991) pointed out that the upper part of the Ellesmerian sequence onshore was deposited on an aerially extensive stable shelf, whereas the offshore Beaufort Shelf section was deposited in fault-bounded grabens in an extensional tectonic environment. We agree with Grantz and others' (1991) conclusion that the two sections were deposited in different sedimentary and tectonic environments and therefore are likely to have different stratigraphies. Thus, we herein and in Moore and others (in press) designate the Ellesmerian strata deposited during the period of extension and successful rifting documented

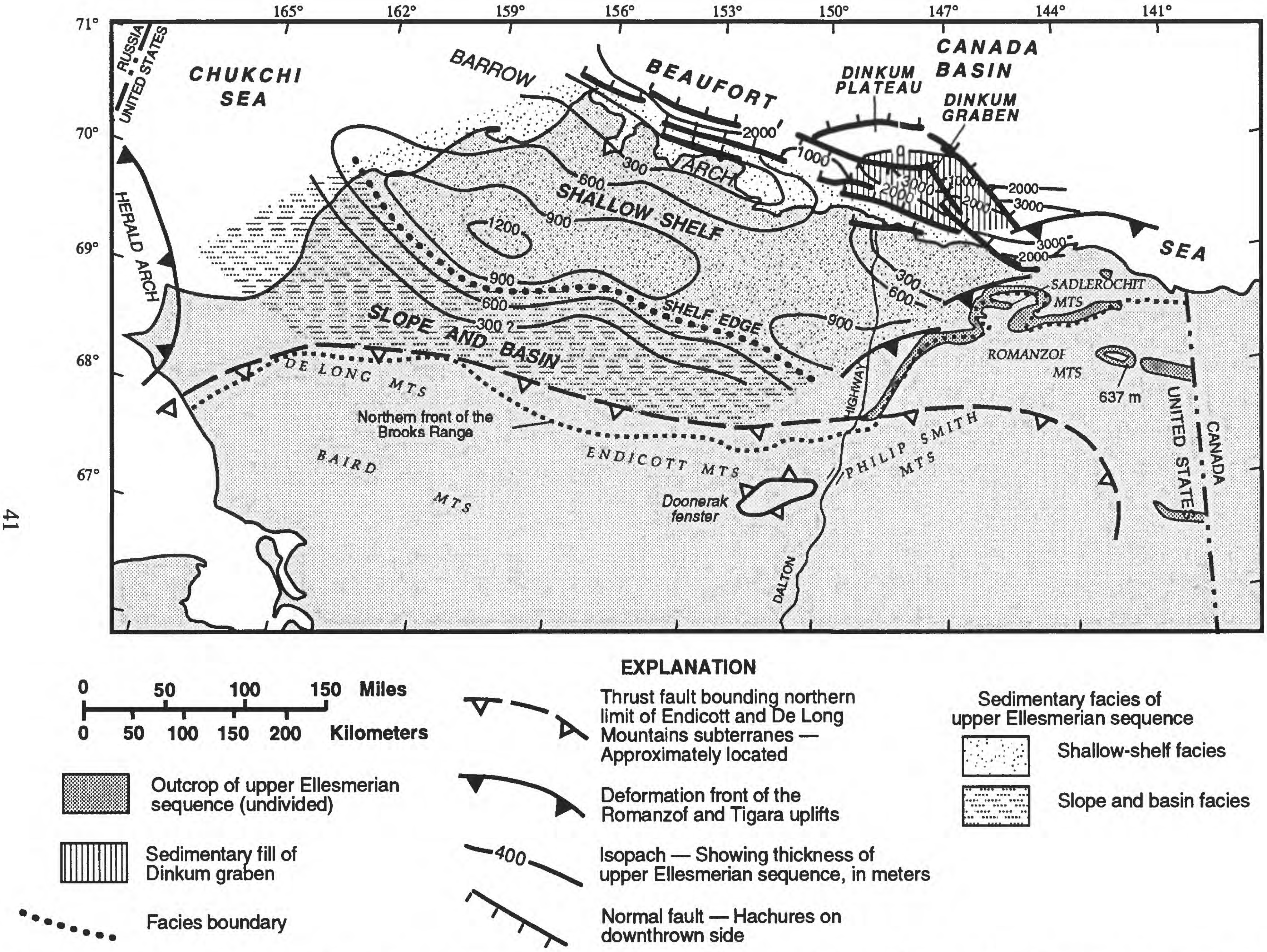


Figure 16. Isopach map for upper Ellesmerian and Dinkum graben sequences (Jurassic and Lower Cretaceous). Rift-margin normal faults and isopachs from Hubbard and others (1987). Abundance of normal faults on the Beaufort Sea shelf suggests that the main axis of Jurassic and Early Cretaceous extension was north of the present coastline.

offshore as the upper Ellesmerian sequence and restrict the Beaufortian sequence to strata in the offshore region.

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 (fig. 5). 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. 17). 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). In this area, the pebble shale rests and local sandstone units rest unconformably on the Kingak and older strata. To the south, the pebble shale and local sandstone units lie conformably on basinal, slope, and shelf deposits of the Kingak Shale (fig. 11). The upper Ellesmerian sequence totals more than 1.2 km thick in NPRA but depositionally thins southward to less than half that thickness and thins northward because of erosional truncation in the Early Cretaceous (fig. 16).

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 1,200 m (Detterman and others, 1975; Molenaar, 1983, 1988; Bird, 1987). The Kingak was named by Leffingwell (1919) for outcrops in the northeastern Brooks Range (Mount Michelson quadrangle) and was considered Jurassic by Detterman and others (1975). New information from the subsurface of the NPRA and re-evaluation of outcrop data extended the Kingak to include Lower Cretaceous (Neocomian) black shale (Molenaar, 1983, 1988).

The Kingak Shale crops out discontinuously along the front of the northeastern Brooks Range and in a few structural lows within the range (fig. 16). At Point Barrow, the Kingak oversteps the onlap edge of the Sag River Sandstone and lies directly on Ordovician and Silurian argillite. Along the coast southeast of Barrow as far east as the northern Sadlerochit Mountains, the Kingak is discontinuously exposed because of erosion on the regional Lower Cretaceous unconformity. In the subsurface, the Kingak is readily identified on seismic records by prominent seismic reflector associated with the Sag River Sandstone and Shublik Formation and above by another prominent reflectors associated with the Sag River Sandstone and Shublik Formation (below) and the pebble shale unit (above).

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 1,000 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, 1988), 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.

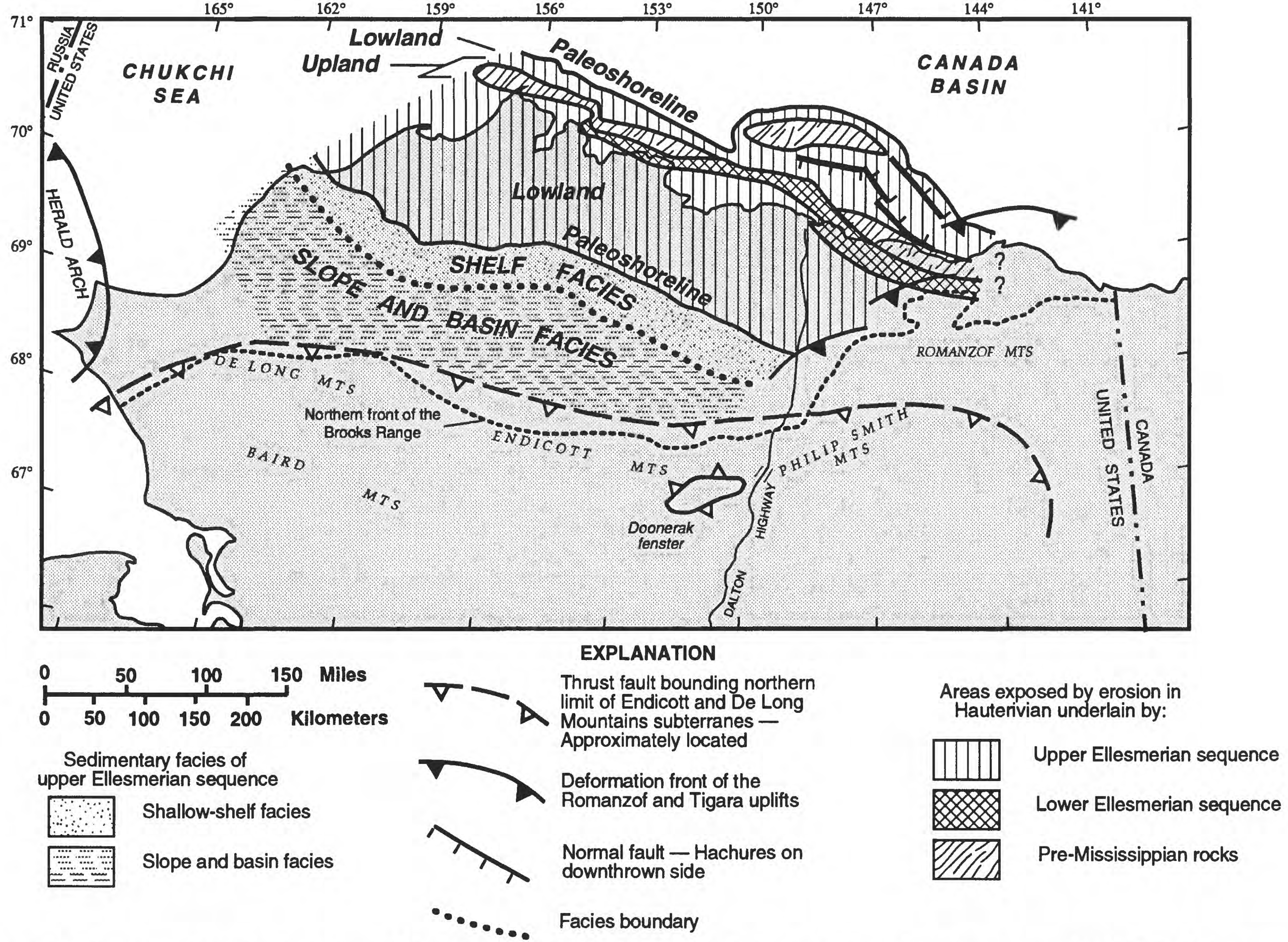


Figure 17. Paleogeography and paleogeology of North Slope subterrane of Arctic Alaska terrane at time of maximum regression in Early Cretaceous (Hauterivian) time. Exposed area shows extent of Lower Cretaceous unconformity and underlying rocks. Shelf, slope and basin facies are for Kingak Shale which was deposited in offshore areas.

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 with interbedded siltstone and shale that gradationally overlies Lower Cretaceous (Valanginian) 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 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, dark-gray, marine shale that contains sparse beds of bioclastic limestone and coquinite. The overlying Kemik Sandstone Member consists of fine- to very fine grained sandstone turbidites and is less than 2 m thick (C.G., Mull, unpub. 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 latter unit has an unusual composition of detrital dolomite grains and cleavage fragments (>50%), monocrystalline quartz (35%), and sedimentary and metasedimentary rock fragments (10%) and demonstrates extreme grain size variation ranging from fine sand to boulders greater than 1 m. in diameter.

The best known of these sandstones is 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. The Kemik was defined in the Demarcation Point quadrangle (Detterman and others, 1975), but later revised by Molenaar and others (1987) and Mull (1987) The Kemik Sandstone is everywhere of formation rank, except at Bathtub Ridge, where it is designated as a formal member, the Kemik Sandstone Member, of the Kongakuk Formation (see above). The Kemik 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 sandstone commonly is cross-bedded, glauconitic, and locally includes thin layers of pebble to cobble conglomerate containing clasts of chert and quartz. Sandstone petrography indicates the unit consists chiefly of moderately to well sorted grains of quartz (75-80%) and chert (<20%) with feldspar (5%) and minor fine-grained clastic and carbonate lithic grains (Mull, 1987). 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** is thin (<160 m) but widespread in the subsurface and in outcrop of the North Slope subterrane. It is present throughout the subsurface of the North Slope and in scattered exposures along the front of the northeastern Brooks Range and in structural lows within the range. It is thin or missing locally along the Barrow arch (fig. 11). In the area south and west of Harrison Bay, the pebble shale is thin, disrupted, or missing because of a large submarine slump (Weimer, 1987b). In the Flaxman Island area (well 19, fig. 10), the pebble shale unit and the overlying Brookian Hue Shale are thin or missing, probably by submarine slumping or scouring that occurred in latest Cretaceous or earliest Tertiary time (Molenaar and others, 1986).

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 informal name "pebble shale" was first used in the subsurface of NPR-4 (NPRA) (Robinson and others, 1956; Collins, 1958, 1961; Robinson, 1959), although the shale had been recognized much earlier near the Sadlerochit Mountains (Leffingwell, 1919).

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.

Within the NPRA, Bird (1982) included at the top of the pebble shale unit an interval with thin bentonitic beds and a zone of high gamma-ray readings that is a distinctive marker in the subsurface of the North Slope. East of the NPRA, this interval, called the gamma-ray zone (GRZ) or highly radioactive zone (HRZ), was included in the overlying Hue Shale by Molenaar and others (1986, 1987) although other workers consider it as part of the pebble shale (e.g., Mull, 1987). Grantz and others (1990) pointed out that the unit consists of pelagic and hemipelagic deposits without sedimentary detritus from either Ellesmerian or Brookian sources and hence should be regarded as a unit transitional between the upper Ellesmerian sequence and the overlying Brookian sequence. Because of its thinness, regional relations, paleontology, and the radioactive nature of this interval, we treat the unit as a condensed, distal part of the Brookian sequence, and consider it separately from the Beaufortian pebble shale unit. Accordingly, description of the GRZ is found below in the discussion of the Brookian sequence.

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. These sediments infilled the northward migrating foreland basin and eventually prograded across the Beaufortian rifted continental margin, forming a progradational continental terrace sedimentary prism along the continental margin. Sandstones of the Brookian sequence reflect their orogenic provenance by containing 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, therefore, was 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 stratigraphy of the Colville basin rocks is complicated by (1) important east-west changes in sedimentary facies and (2) shifting of depocenters related to changing domains of uplift in the Brooks Range source region through time.

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 Toruk 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 northcentral 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. The four megasequences rest partly on a thin zone of highly radioactive shale that extends throughout the basin and marks the base of the Brookian sequence.

Seismic-reflection profiles of the Colville basin delineate a series of well-developed topset, foreset, and bottomset reflectors within each megacycle. These respectively mark (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) (figs. 18, 19 20, 21). 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.

The progressive northward and eastward infill of the basin was inferred by Hubbard and others (1987) to have resulted from the general migration of active thrust fronts in the Brookian orogenic belt from the southwest to northeast. The Albian to Cenomanian megacycle deposits suggest that the mountain front was located beneath the Chukchi shelf, whereas the Cenomanian to Eocene megacycle was located east of the Albian to Cenomanian megacycle, in the central part of the North Slope. The Eocene to Holocene megacycle is located along the coast in northeastern Alaska and mostly offshore and are deformed by late Brookian tectonism. However, deposits of the earliest Colville basin cycle (Aptian? to Albian) were derived from source areas in the west-central part of the North Slope subterrane, but an erosional outlier in the eastern Brooks Range (Bathtub syncline, Demarcation Point quadrangle) indicates that the source area probable extended to near the Canadian border. Total Brookian sediment thickness is greater than 8 km in both the Colville foredeep basin and the Beaufort Sea passive margin (Hubbard and others, 1987, fig. 20) (fig. 5). Thickness trends for the Albian-Cenomanian megacycle are shown in figure 18, Cenomanian-Eocene megacycle in figure 20, and Eocene-Holocene megacycle in figure 21.

Proto-Colville basin? deposits of the North Slope subterrane. The earliest known Brookian strata in the North Slope subterrane is a thick section (as much as 1600 m) of generally poorly exposed tectonized mudstone, fissile clay shale, and interbedded sandstone and siltstone of Early Cretaceous age on the Lisburne Peninsula (fig. 7). At the southern end of the Peninsula (Point Hope quadrangle), Campbell (1967) subdivided and named these strata, in ascending order, the Ogotorok, Telavirak, and Kisimilok Formations. These three formation are all apparently gradational and consist of turbiditic strata distinguished primarily on the basis of their sandstone-to-shale ratios. Campbell (1967) shows them as resting disconformably on the Permian and Triassic strata of the Etivluk Group, but the most extensive areas of outcrop may be interpreted as lying structurally beneath older Ellesmerian rocks of the Lisburne Peninsula

The **Ogotorok Formation** contains abundant graded beds of siltstone, mudstone and shale. Micaceous fine-grained sandstone and bioturbation are locally present. The **Telairik Formation,** in contrast, contains somewhat thicker sandstone beds and more nearly equal percentages of sandstone and mudstone. The **Kisimilok Formation** contains thick zones of markedly different proportions of sandstone and mudstone. All of the units are thinly bedded and contain partial Bouma sequences. Sandstone in these units have a composition of about $Q_{50}F_{25}L_{25}$ and contain abundant sedimentary lithic fragments with less common chert and volcanic lithic grains. Feldspar is mostly plagioclase. Relatively abundant pelecypods occur at the top of the sequence and indicate an early Neocomian (Berriasian and Valanginian) age for this part of the section. Because an apparently very thick unfossiliferous section of turbidites underlies the fossiliferous horizons, Campbell (1967) inferred a Jurassic age for the lower part of the sequence. If these rocks eventually prove to be Jurassic, they would be by far the oldest Brookian rocks of the North Slope subterrane, and would be comparable in age to the oldest Brookian strata in the De Long Mountains subterrane. The relationship of the Brookian strata of the Lisburne Peninsula to coeval upper Ellesmerian strata of the North Slope subterrane is unknown, but may be tectonic (Mull, 1985).

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- to 45-m-thick interval of laminated, black shale and interbedded bentonite (fig. 5). Like the pebble shale, this unit contains isolated well-rounded, frosted sand grains and chert

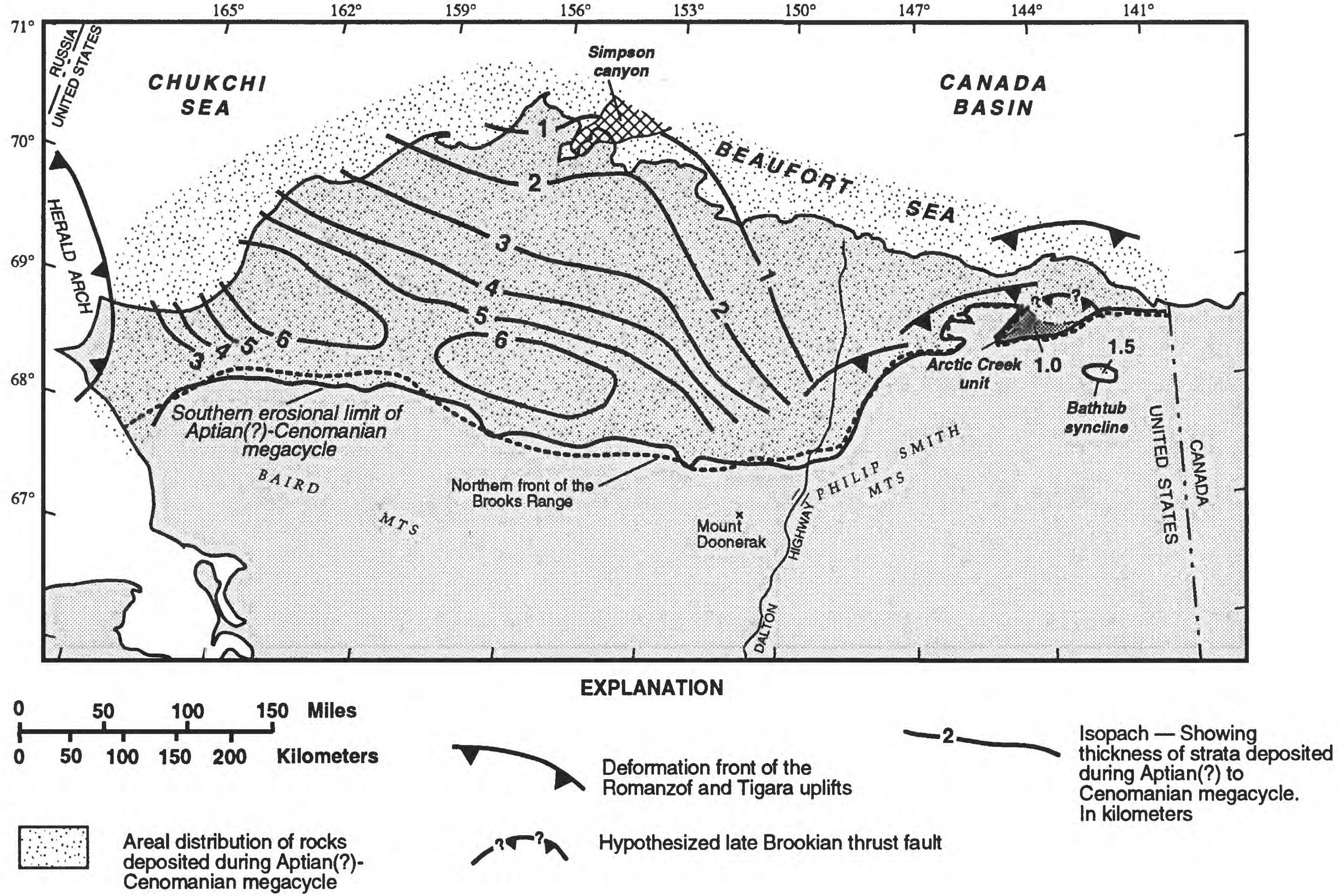


Figure 18. Thickness of strata deposited during the Aptian(?)-Albian to Cenomanian megacycle of Brookian sequence (Fortress Mountain and Torok Formations, Nanushuk Group, upper part of Kongakut Formation, and Bathtub Graywacke). Bathtub syncline and the Arctic Creek unit of Molenaar and others (1987) include deep-marine strata of the Aptian(?)-Albian to Cenomanian megacycle, but these strata are believed to have been tectonically transported northward an undetermined distance during late Brookian tectonism. Simpson canyon is a submarine canyon formed in the subsequent Cenomanian to Eocene megacycle.

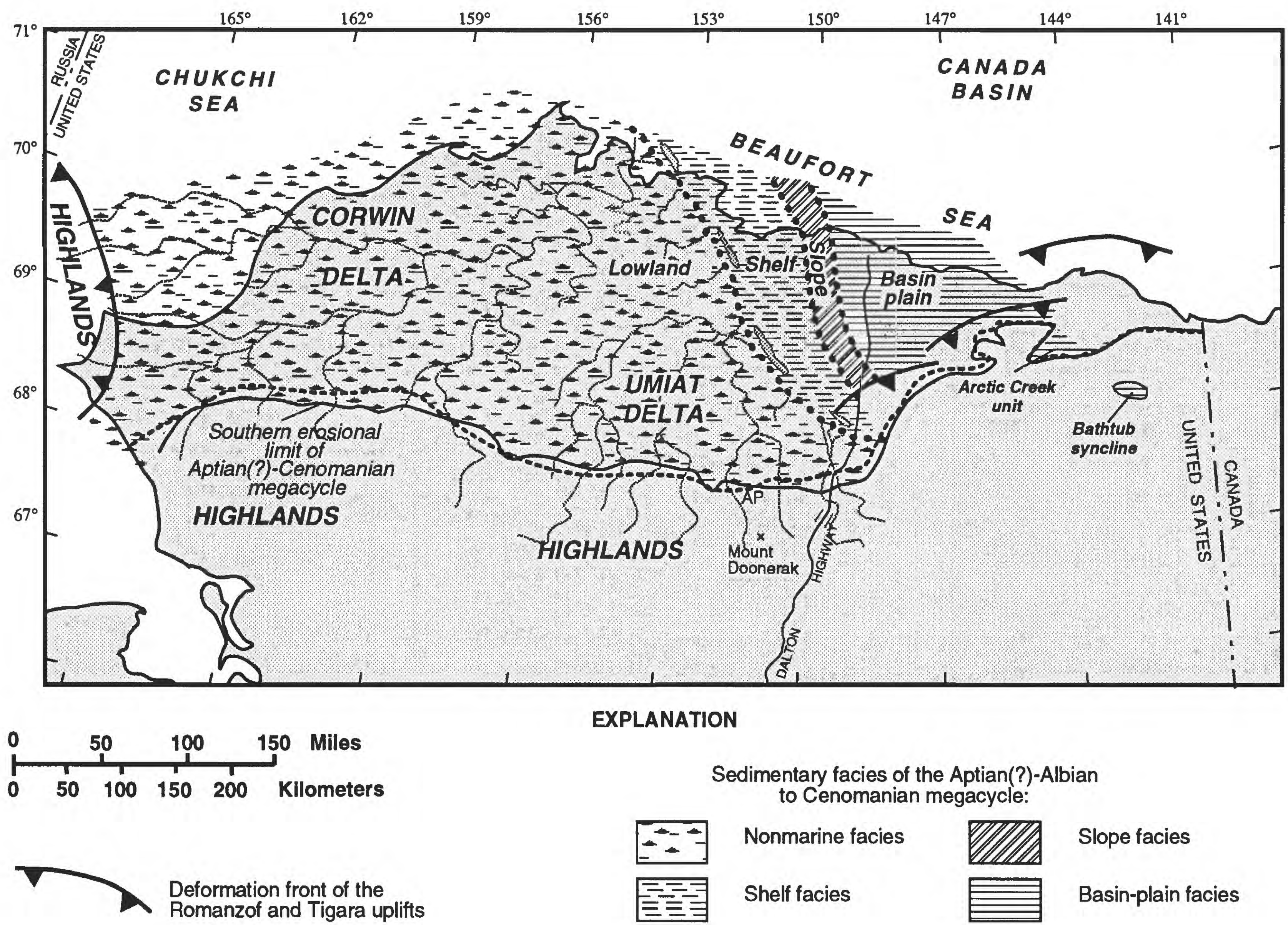


Figure 19. Paleogeography at time of maximum regression of the Aptian(?)-Albian to Cenomanian megacycle. The general position and areal distribution of the Umiat and Corwin deltas are as described in Ahlbrandt and others (1979), Molenaar (1985), and Huffman and others (1985) and illustrate longitudinal filling of the Colville basin. Note that depositional trends project into northeastern Brooks Range, evidence that this part of range postdates formation Aptian(?)-Albian to -Cenomanian megacycle. Bathtub syncline and the Arctic Creek unit of Molenaar and others (1987) include deep-marine strata of the Aptian(?)-Albian megacycle, but these strata are believed to have been tectonically transported northward an undetermined distance during late Brookian tectonism.

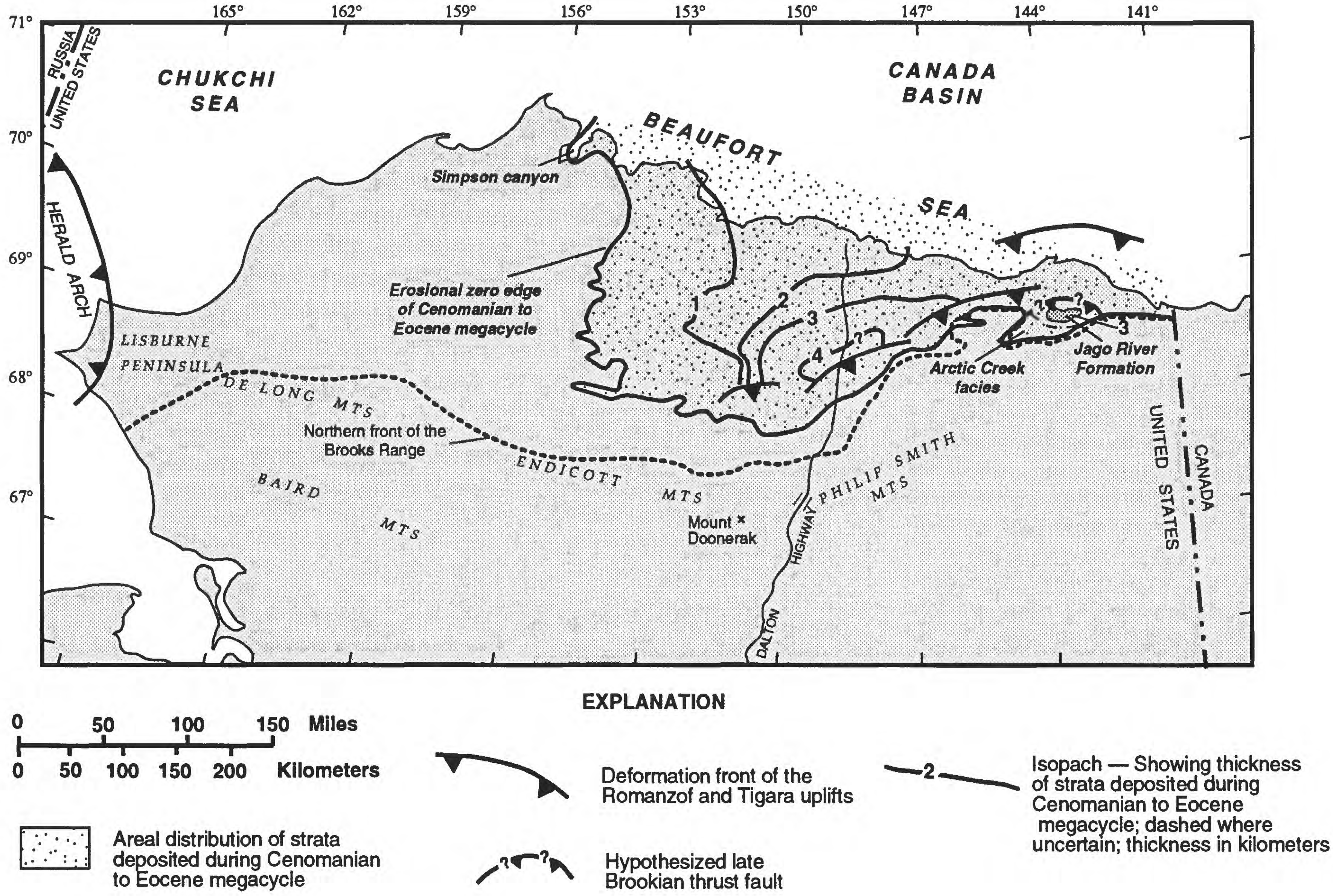


Figure 20. Thickness and distribution of strata of Cenomanian to Eocene megacycle of the Brookian sequence. Upper Cretaceous deep-water deposits of the Arctic Creek unit of Molenaar and others (1987) and the nonmarine Upper Cretaceous and Tertiary Jago River Formation of Buckingham (1987) are part of the Cenomanian to Eocene megacycle, but these strata are believed to have been tectonically transported northward an undetermined distance during late Brookian tectonism.

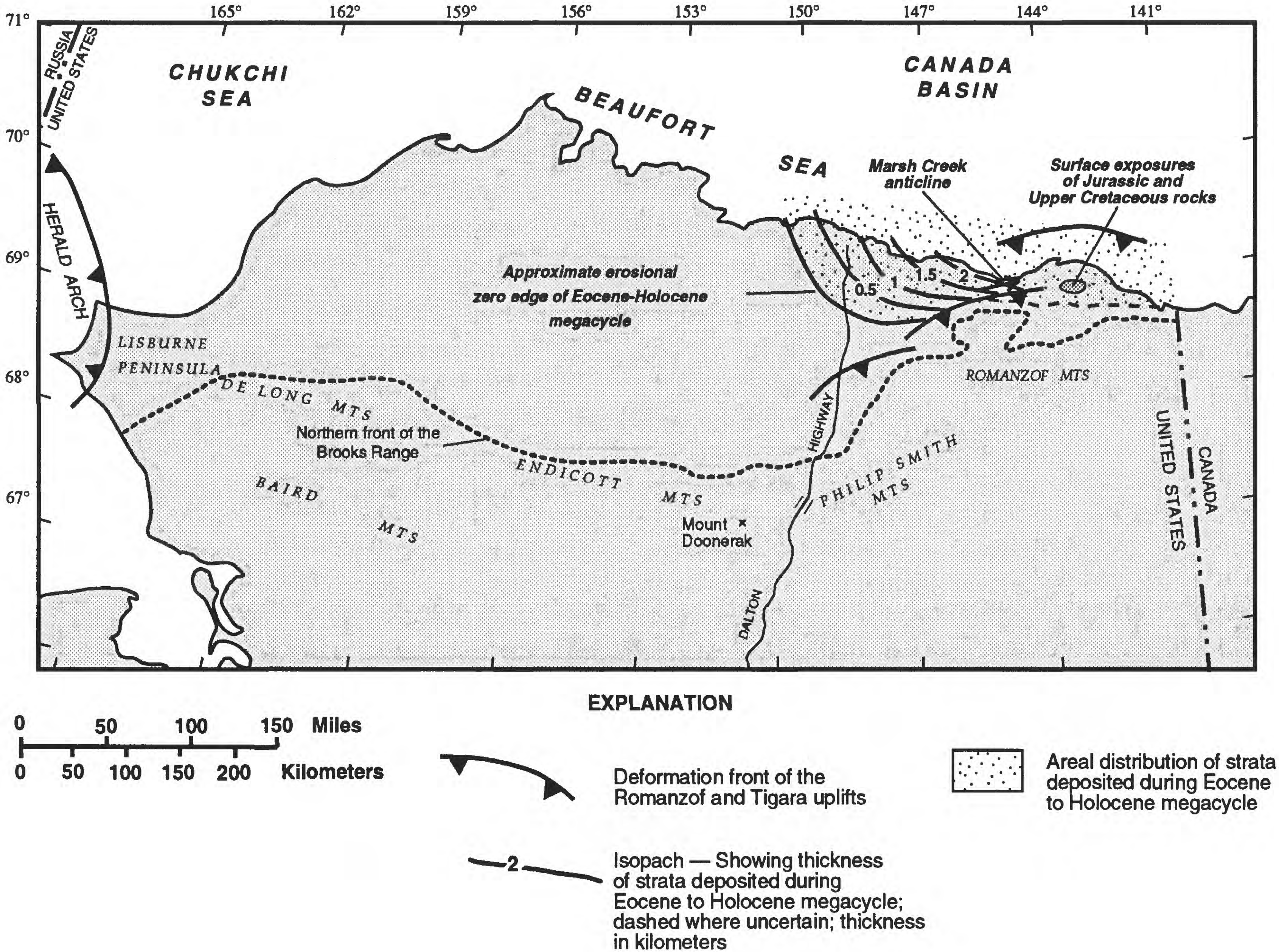


Figure 21. Thickness and distribution of strata of the Eocene to Holocene megacycle of the Brookian sequence. Note that depocenter of earlier megacycles trend northeasterly, parallel to the front of adjacent Brooks Range, whereas depocenter of this cycle lies mostly offshore. Surface exposures of Jurassic to Upper Cretaceous rocks on the coastal plain lie in the core of the Niguanak antiform; these strata are folded and tectonically transported northward an undetermined distance during late Brookian tectonism.

pebbles and has an average carbon content of greater than 3 percent. 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). 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) which was named by Patton (1956) for a thick section of lower Albian shale, sandstone, and conglomerate that crops out in the disturbed belt along the northern margin of the central Brooks Range (Patton and Tailleur, 1964). The Fortress Mountain is as much as 3,000 m thick but it is doubtful that the formation is that thick in other areas even though it is incompletely exposed. Local thickness variations can be explained by penecontemporaneous folding and local unconformities reported in the southern part of the outcrop belt (Patton and Tailleur, 1964; Tailleur and others, 1966; Chapman and others, 1964; Molenaar and others, 1988; Crowder, 1987).

The Fortress Mountain Formationconsists 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 conformable 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 distinction between Fortress Mountain and Torok Formation is arbitrary. The placement of this contact in the subsurface in the northern foothills is also complicated by the occurrence of thin-bedded turbidites in the Torok that were derived from Nanushuk deltas to the west and southwest. For this reason, Molenaar and others (1988) recommended that the Fortress Mountain name be dropped as a subsurface unit in the northern foothills and areas to the north. The deep-water sandstones are then included in the Torok Formation and referred to informally as lower Torok sandstones.

Where it rests depositionally on the De Long Mountains subterrane, the basal 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 also 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, unpub. data, 1992). The **Bathtub Graywacke** (Albian?) (Detterman and others, 1975) 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.

Toruk 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 (fig. 18). The **Torok Formation** (Albian) (Gryc and others, 1951) consists of dark marine shale and sandstone that ranges in thickness from 6,000 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 (figs. 10 and 11). The upper part of the Torok grades into, and intertongues with, shallow-marine sandstone of the Nanushuk Group. In outcrops in the foothills province, strata presently included in the Torok and Fortress Mountain Formations were originally assigned to the Torok Formation (Gryc and others, 1951). Later, these strata were separated into a northern predominantly shale facies, the Torok Formation, and a southern coarser clastic facies, the Fortress Mountain Formation. More recent studies (Bird and Andrews, 1979; Molenaar, 1988), with the advantage of modern seismic data, showed that the Torok is part of a single depositional system with the overlying Nanushuk Group consisting of distinct topset, foreset, and bottomset reflections.

The Torok is exposed in surface outcrops in the foothills province along the structurally complex southern margin of the Colville basin. In the Point Barrow area, the Torok subcrops beneath a thin veneer of Pleistocene deposits on the eroded crest of the Barrow arch (Bird, 1987). Southeast of Barrow in the Dease Inlet area, the Torok is incised by the Simpson canyon (fig. 18). In the western part of Harrison Bay, the Torok and underlying pebble shale unit are involved in a submarine slide complex (Molenaar, 1988; Kirschner and others, 1983; Weimer, 1987b). East of the NPRA, the Torok thins rapidly over a distance of several kilometers from more than 300 m to less than 100 m.

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- to very fine grained sandstone turbidites. These strata were deposited in water depths of 450 to 1,000 m and were deposited on, and probably pass northward into, condensed radioactive shale (GRZ) at the base of the Brookian sequence. Most of the sandstone beds are thought to be derived from the temporally equivalent Nanushuk delta to the west-southwest. 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 450 to 1,000 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).

Because both the Fortress Mountain Formation and the Nanushuk Group grade laterally into finer grained strata of the Torok Formation, and because of deformation, poor exposure, and imprecise age control, the relation between the Fortress Mountain Formation and the Nanushuk Group is ambiguous. The Fortress Mountain Formation may be a proximal equivalent of part of the Nanushuk Group (Kelley, 1988), but compositional differences and relatively rare early and middle Albian megafossils from the Fortress Mountain Formation suggest that it is in part older than the Nanushuk Group (Mull, 1985; Molenaar and others, 1988).

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 Nanushuk crops out in the northern foothills and is present in much of the subsurface in the western and central North Slope. The Nanushuk Group has a maximum thickness of over 3,000 m in the western North Slope. It ranges in thickness from at least 3,444 m in outcrops at Corwin Bluff (Smiley, 1969) along the Chukchi Sea on the west to a pinchout edge in the area of the present Colville delta on the east.

The lower part of the Nanushuk consists of a thick sequence of intertonguing shallow-marine sandstone and neritic shale and siltstone that grade seaward into the deeper water deposits of the Torok Formation. The upper part of the Nanushuk Group consists of predominantly nonmarine facies including paludal shale and fluvial sandstone. Conglomerate is present, primarily in the fluvial facies and in the southern part of the outcrop belt, which is more proximal to the source. Deltaic deposits contain enormous, virtually undeveloped resources of low-sulfer, low-ash bituminous to subbituminous coal in beds as thick as 6 m (Sable and Stricker, 1987).

The marine and nonmarine facies are the basis for the differentiation of most of the formations of the group. Dominantly marine formations of the Nanushuk Group include the Tuktu, Grandstand, Kukpowruk, and Ninuluk, whereas dominantly nonmarine units include the Corwin and Chandler Formations.The lower part of this unit 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-sulfer, low-ash bituminous to subbituminous coal in beds as thick as 6 m (Sable and Stricker, 1987).

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. 19). 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. This delta was a high-constructional delta that had a low-sand, high-mud content (Molenaar, 1988). Paleocurrent directions in outcrops indicate that the Corwin delta was probably derived from a source area to the southwest (Molenaar, 1988) Because the Corwin delta dominated the depositional patterns of the Nanushuk Group, a source area encompassing a large drainage area probably extended far to the west or southwest in the area of the Lisburne Peninsula (Mull, 1985), the present Chukchi Sea, or beyond (Molenaar, 1985).

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.(Molenaar, 1988). The Umiat delta was initiated as a river-dominated delta, but later evolved into a wave-dominated delta (Huffman and others, 1985) . In contrast to the Corwin delta, the Umiat delta is smaller, more lobate, coarser grained, and sandier. These characteristics resulted from progradation of the Umiat delta into the deeper water along the southern edge of the asymmetric Colville basin (Molenaar, 1988) and a source area that yielded coarser grained detritus for the Umiat delta (Huffman and others, 1985).

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, 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 Formations (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. 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) (fig. 20).

Four lithofacies are recognized in the prograding clastic wedge that makes up this megacycle. These lithofacies are (1) nonmarine deltaic sandstone facies represented by the Sagavanirktok and Prince Creek Formations; (2) shallow-marine deltaic sandstone and shale facies represented by the Sagavanirktok and Schrader Bluff Formations and the Ayiyak Member of the Seabee Formation; (3) marine shelf, slope, and basinal shale facies with sandstone turbidites represented by the Canning Formation, and (4) distal condensed shale facies with bentonitic interbeds represented by the Hue Shale and Shale Wall Member of the Seabee Formation. The northeasterly progradation of these facies during Late Cretaceous and Tertiary time produced a markedly diachronous nature for these units. Because of deformation, poor exposure, and diachronous character of the Upper Cretaceous and Tertiary rocks of the Colville basin, Molenaar and others (1987) defined a change of nomenclature for them east of the eastern limit of the Nanushuk Group, about long 151° W. (fig. 10)

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 -basin shale, sandstone, bentonite, and tuff of the **Seabee Formation** (Cenomanian to Turonian) which rests conformably to unconformably on shallow-marine to nonmarine rocks of the Nanushuk Group.. 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). The 300-m-thick **Hue Shale** (Aptian? to Campanian and probably Tertiary under the Beaufort Sea) is a condensed, basinal sequence. The basal 45 m of this unit contains the GRZ; the upper part of the unit consists of similar, but less radioactive, black shale. In some of the coastal and offshore wells, the Hue Shale is thin or missing probably by submarine scour and(or) slumping (fig. 10).

The Hue Shale consists of interbedded fissile, black, non-calcareous, clay shale, tuff, and bentonite. The basal 45 m of this unit consists of radioactive shale that is the facies equivalent of the GRZ to the west. The upper part of the unit consists of similar, but less radioactive, black shale that contains thin beds of indurated tuff in the middle part of the unit. Bentonite may account for as much as 30 percent in some parts of the formation, although the overall content is much less. The Hue Shale includes a number of distinctive marker zones or beds including: (1) the basal 30-45 m thick highly radioactive shale zone (GRZ or HRZ), a 6-8 m-thick bed rich in prismatic shell material of the bivalve *Inoceramus*, and a 23-30 m-thick interval of interbedded shale, bentonite, and hard indurated tuff that weathers bright red in outcrop.

The Hue Shale is a distal condensed shale facies deposited on the north side of the Colville basin, on the Barrow arch, and probably north of the arch. Its condensed nature is evident when its 300 m thickness, representing Aptian(?) to Campanian or Maestrichtian time, is compared to the greater than 5 km thickness of Albian to lower Campanian rocks south of Umiat (fig. 10). Lying below large-scale clinoform beds of the Canning Formation, at least the upper part of the Hue Shale is a deep-water (>200 m) deposit. When considered with the underlying pebble shale unit, which represents shoreline conditions, these units apparently represent deposition during a time when the rate of subsidence was greater than the rate of sedimentation. 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 **Canning Formation** (Lower Cretaceous—Aptian to Tertiary). The Canning Formation (Late Cretaceous and Tertiary) was defined by Molenaar and others (1987) for a thick, dominantly shale unit that conformably overlies the Hue Shale and underlies thick, deltaic deposits of the Sagavanirktok Formation (fig. 5). Total thickness, including tongues of Sagavanirktok Formation, ranges from 1,200 to about 1,900 m. Although dominantly shale, the lower part of the Canning contains thin basin-plain sandstone turbidites; these pass upward into slope and shelf facies.

The turbidite sandstone facies of the Canning Formation consists of 300-400 m of dark-gray to gray-brown bentonitic shale and siltstone, with generally thin beds of fine- with some medium- to very fine grained, well-sorted sandstone. The average composition of the sandstone is 65 percent quartz and chert, 7 percent feldspar, and 28 percent rock fragments (Bird and others, 1987; Gautier, 1987). Sandstone beds are generally less than a meter thick, although a few amalgamated beds are as thick as 21 m. Sedimentary structures and seismic stratigraphic interpretations suggest that these are turbidite sandstones deposited in 600 to 1200 m water depths.

The slope and shelf facies, about 1200 m thick, consists of medium-gray to gray-brown, silty, bentonitic shale with minor thin beds of very fine or fine-grained sandstone. The sandstone beds are turbidites in the lower part of the unit and shelf sandstones in the upper part, where they grade into the overlying Sagavanirktok Formation. Matrix-supported sand grains and pebbles in the silty shale are characteristic of the Eocene part of the sequence.

The Canning Formation is a diachronous unit that becomes younger to the northeast, the direction of progradation. South of Prudhoe Bay, the Canning Formation is largely Aptian to Cenomanian, whereas near the Canning River it is largely Campanian to Eocene (Molenaar and others, 1987). The unit is the facies equivalent of the Torok Formation in the Albian to Cenomanian megacycle. Present North Slope nomenclature east of long. 151 degrees W. refers to this facies as the Canning Formation and to the west, as the Torok Formation, Shale Wall Member of the Seabee Formation, or the Rogers Creek and Sentinel Hill Members of the Schrader Bluff Formation (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 2,600 m thick and consists of sandstone, bentonitic shale, conglomerate, and coal, composing the regressive part of the megacycle.

The Sagavanirktok is discontinuously exposed throughout the east-central part of the coastal plain province, where it is unconformably overlain by less than 60 m of Gubik Formation. 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). As originally defined by Gryc and others (1951) and modified by Detterman and others (1975), the Sagavanirktok Formation was considered no older than Tertiary, but the presence of similar strata of Upper Cretaceous age resting gradationally below the Tertiary strata led Molenaar and others (1987) to extend the age of the Sagavanirktok Formation to include Late Cretaceous rocks. An arbitrary nomenclature change was proposed at about long. 151 degrees W. West of this boundary, equivalent facies are assigned to units of the Colville Group, with nonmarine facies assigned to the Prince Creek Formation, and shallow-marine facies assigned to the Ayiyak Member of the Seabee Formation or the Barrow Trail Member of the Schrader Bluff Formation (Molenaar and others, 1987).

The **Jago River Formation** (Late Cretaceous to early Tertiary), defined by Buckingham (1987), is an anomalously thick (3,000 m) section of predominantly nonmarine clastic rocks exposed in a relatively small (10 x 15 km) area on the coastal plain of ANWR (fig. 20). This formation is interpreted as a regressive sequence of shallow-marine siltstone and distributary-channel sandstone in the lowermost part that grades upward into coal-bearing delta-plain and conglomeratic alluvial-plain facies. Tuffaceous and bentonitic beds, common in coeval strata of the Colville Group, Hue Shale, and Canning Formation, are absent in this unit. Sandstone compositions are low in quartz (average 12 %) and feldspar (3.5 %), but are high in chert, siliceous argillite, and shale (49 percent) and felsic volcanic rocks (25 %) (Buckingham, 1987). These sediments were sourced to the south in the younger Brookian fold-thrust belt in the northeastern Brooks Range (Buckingham, 1987).

The geographic position, composition, and northerly direction of sediment dispersal of the thick nonmarine rocks of the Jago River Formation is anomalous with respect to thinner coeval turbidite sandstone facies of the Canning Formation 60 to 80 km to the west. Bird and Molenaar (1987) favor the interpretation that the Jago River Formation rocks originated in a foredeep basin south of their present position and were subsequently thrust northward into juxtaposition with coeval deep-water deposits.

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. 21), but they are much thicker offshore (Grantz and others, 1990a). Wells west of ANWR (Molenaar and others, 1986) penetrate deposits of the Sagavanirktok Formation that consist mostly of sandstone and conglomerate with about 30 percent 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 youngest sedimentary deposits of the North Slope subterrane include glacial and related deposits in the Brooks Range and foothills (Hamilton, 1986) and marine and nonmarine deposits, generally limited to the coastal plain province and offshore (Dinter, 1985; Wolf and others, 1987; Dinter and others, 1990). In the latter deposits, at least six marine transgressions during Quaternary and Pliocene time are recognized. These marine strata interfinger landward with nonmarine and deltaic deposits (McCulloch, 1967). These deposits, generally referred to as the **Gubik Formation** (Pliocene and Quaternary), (Schrader, 1902; Gryc and others, 1951; Detterman and others, 1975) consists of marine and nonmarine, poorly to well-stratified gravel, sand, silt, and clay. These deposits form an unconsolidated blanket as much as tens of meters thick that covers the bedrock platform of the coastal plain (Black, 1964). These deposits range from aeolian sands and silts (Carter, 1981) to fluvial, beach, and shallow glacial marine sands and gravels to lacustrine and marine silts and muds.

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 ANWR and may correlate with a late Eocene unconformity in the Mackenzie delta area (Bird and Molenaar, 1987; Molenaar and others, 1987). West of ANWR, strata above and below the unconformity are disconformable, but in 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 border on the east (fig. 3). The subterrane is particularly well exposed in the northern Endicott Mountains in the central Brooks Range where it forms a belt as much as 100 km wide in the mountainous region south of its northern limit at the rangefront and holds up the crestal part of the range. The subterrane structurally overlies the North Slope and, to the south, the Hammond subterranes along most of its length and is structurally overlain by the allochthonous sequences of the De Long Mountains subterrane and the Angayucham terrane. The Kuna Formation (Lisburne Group) of the Endicott Mountains subterrane hosts the Red Dog mineral deposit, a major lead-zinc-silver deposit in the western Brooks Range that is currently under development (Moore and others, 1986).

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). In the De Long Mountains, the subterrane is called the Brooks Range allochthon by Mayfield and others (1988) following the usage of Martin (1970). Mull (1982, 1985, 1987a,c), however, has called the subterrane the Endicott Mountains allochthon for its best area of exposure in the central Brooks Range. The basal thrust fault or sole of the subterrane is called the Amawk thrust where it has been studied along the north side of the Doonerak fenster (Mull, 1982; Mull and others, 1987a), but in many areas (e.g., the Romanzof and eastern Endicott Mountains) the basal contact is not well located. In general, rocks of the subterrane dip regionally to the north and plunge gently to the west.

The problem of the 'Kagvik terrane'

Rocks of the Kagvik terrane are mapped over a large part of the western Brooks Range (Jones and others, 1987). These rocks were originally described as the Kagvik sequence by Churkin and others (1979), who thought them to represent an allochthonous oceanic assemblage because of their condensed siliceous and volcanic character. Other workers (e.g., Crane, 1980; Dutro, 1980; Mayfield, 1980; Metz, 1980; Mull, 1980; and Nelson, 1980), however, disputed the interpretation of the Kagvik as an oceanic assemblage because: (1) it rests on Devonian and Mississippian quartzose clastic rocks of the Endicott Group; (2) parts of the Kagvik appear locally to interfinger with platform carbonate rocks of the Lisburne Group; (3) detailed studies of related siliceous sequences indicate deposition of these rocks occurred in neritic to inner-bathyal, rather than abyssal, environments (Bodnar, 1984; Siok, 1985); and (4) structural and age relationships, especially an episode of south-vergent thrusting, required by the model of Churkin and others (1979) are inconsistent with known and inferred aspects of the Brooks Range fold-thrust belt. Mull and others (1982) later assigned the rocks of the Kagvik sequence to the Lisburne (Kuna Formation) and Etivluk (Siksikpuk and Otuk Formations) Groups, and have shown it to constitute part of the Endicott Mountains allochthon. For the above reasons, we believe that the rocks of the Kagvik terrane be reassigned to the Arctic Alaska terrane. Following Mull and others (1982), we interpret the Kagvik rocks as a finer grained part of the Endicott Mountains subterrane because of its structural position and stratigraphic characteristics and describe them below with the rocks of that subterrane of the Arctic Alaska terrane.

Endicott Mountains allochthon.

Although the stratigraphically lower part of the Endicott Mountains subterrane (allochthon) 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 (fig. 22). The Permian to Lower Cretaceous part of the stratigraphic succession of

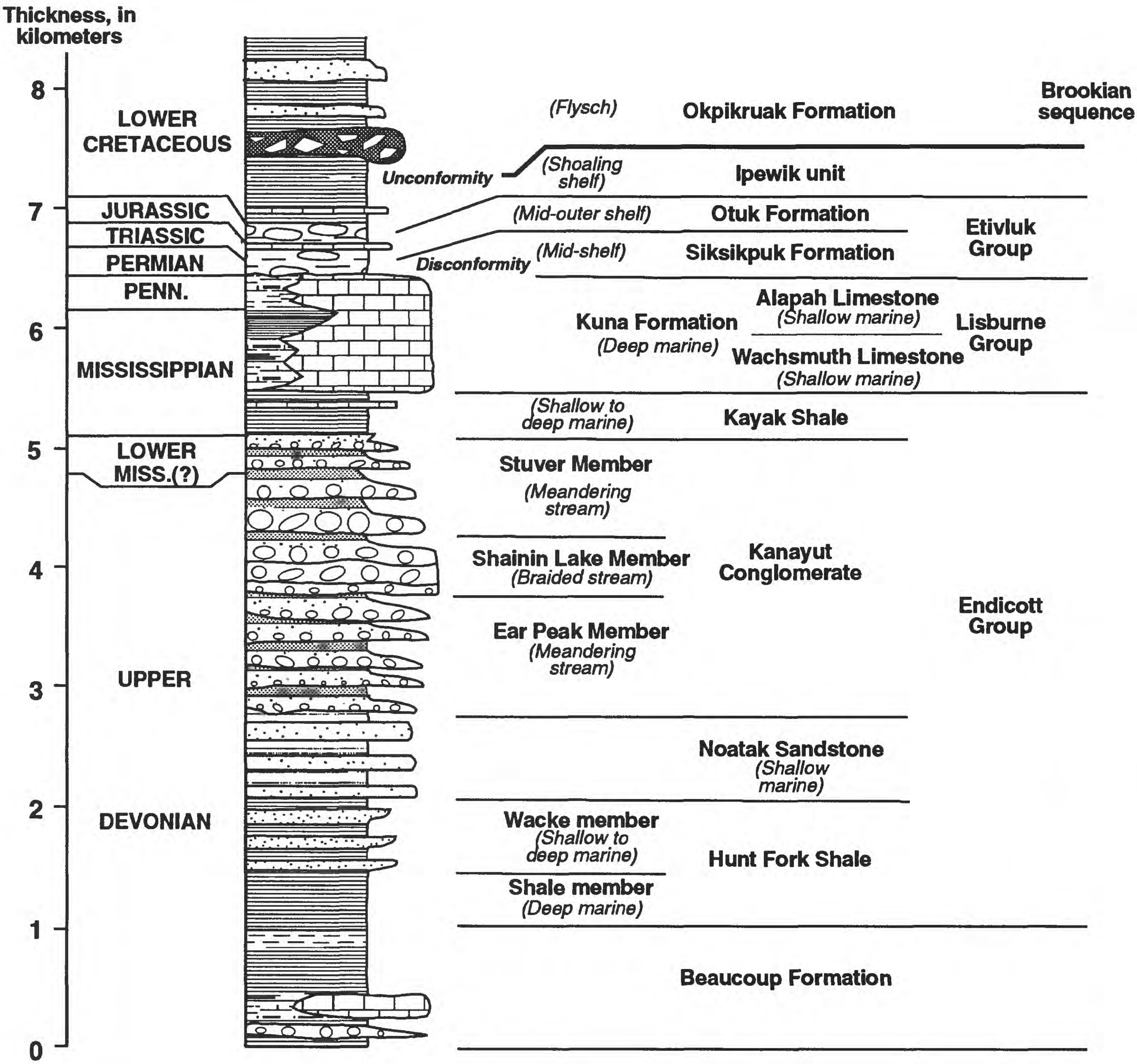


Figure 22. Generalized stratigraphy of Endicott Mountains subterrane (allochthon) of Arctic Alaska terrane. See figure 6 for lithologic symbols.

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 1,500 m in the western Brooks Range and more than 6,000 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 commonly 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.

In its type section, Dutro and others (1979) report that the Beaucoup Formation lies disconformably on the Skajit Formation and consists of fine-grained clastic rocks, argillaceous limestone, lenticular reefoidal limestone, and chert- and quartz-pebble conglomerate. The lower part of the section is composed mainly of thin-bedded ferruginous calcareous fine-grained sandstone that weathers yellowish brown. These rocks are overlain by a 15-m-thick lenticular reefoidal limestone capped by 140 m of thin-bedded black cross-laminated limestone and calcareous shale. The upper part of the section consists of four cycles, each of which displays a sandy or conglomeratic base grading upward into dark-gray to black noncalcareous shale with siliceous nodules. Two of the cycles are capped by lenticular bodies of limestone up to 30 m thick.

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 have been also 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. The Endicott Group was defined by Tailleur and others (1967) for a succession of shale, sandstone, and conglomerate that lies above the carbonate rocks of the Baird Group and below the carbonate rocks of the Lisburne Group. In the Endicott Mountains subterrane, the Endicott Group, which is as much as 4,500 m thick, consists, in ascending order, of the Hunt Fork Shale (marine), Noatak Sandstone (marine), Kanayut Conglomerate (nonmarine), and Kayak Shale (marine) (fig.23). 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

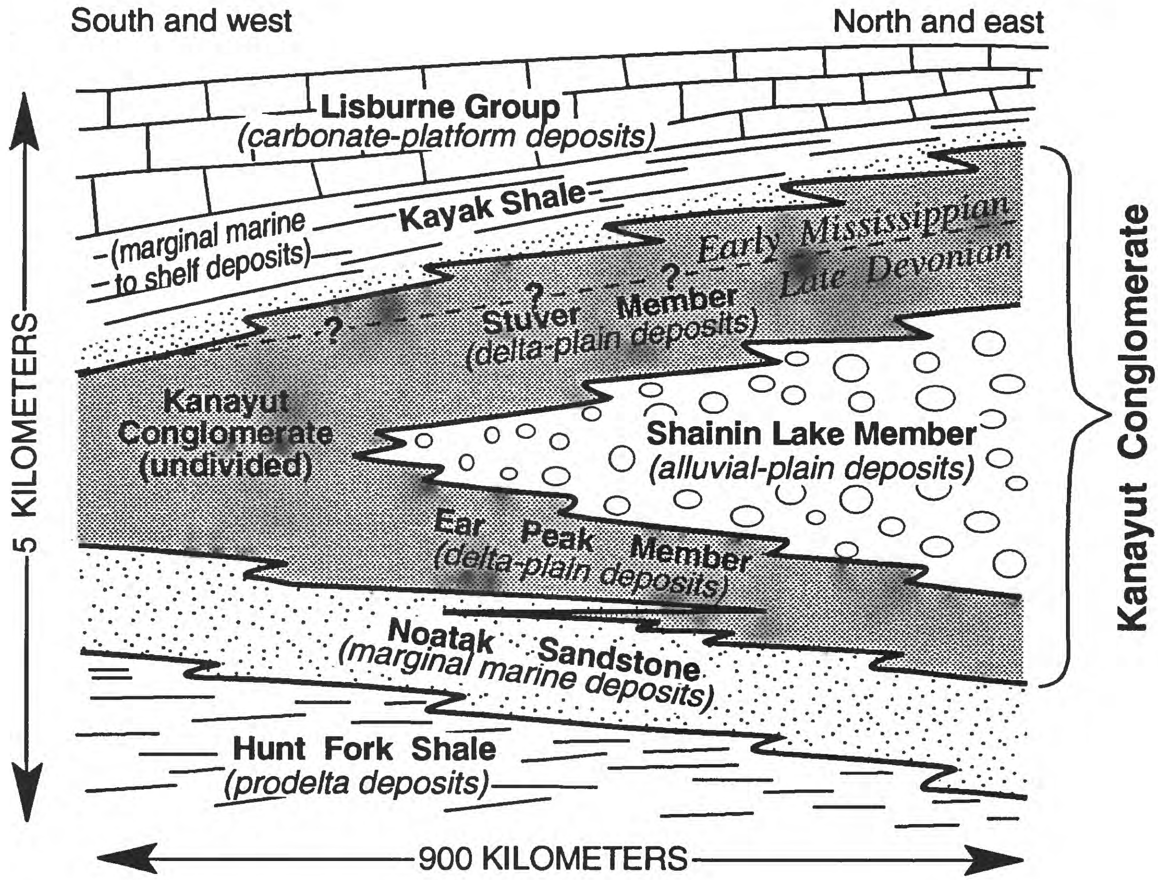


Figure 23. Stratigraphic relations and depositional model for rocks of the Endicott Group, Endicott Mountains allochthon (modified from Nilsen and Moore, 1984).

and Nilsen, 1984). 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 that weathers tan, brown, and locally, orange. In its type section in the Killik River quadrangle, the unit is over 1000 m thick and lies conformably beneath the Kanayut Conglomerate, but elsewhere, the unit is as much as 1700 m thick and lies conformably beneath the Noatak Sandstone (Chapman and others, 1964; Brosgé and others, 1979, 1988; Dillon and others, 1986). Because it is a relatively incompetent unit, the Hunt Fork Shale typically is tightly to isoclinally folded and displays a phyllitic texture, particularly along the southern margin of the subterrane. Brosgé and others (1979) have informally divided the Hunt Fork Shale into two members, both of which are 500 to 700 m thick. The **shale member** is distinguished mainly by its lower (<1:4) sandstone:shale ratio from the overlying **wacke member**, which has a sandstone:shale ratio of 1:1 to 1:5. Although the members have been differentiated only in the Philip Smith Mountains quadrangle, they illustrate the overall upward increase in the percentage of sandstone in the unit.

Strata in the Hunt Fork Shale typically form graded beds from a few centimeters to as much as one meter thick. The beds commonly display sharp bases, ripple cross-lamination, parallel lamination, and graded beds, but complete Bouma sequences are rare or absent. Burrows and mudchips are common, and plant fragments, loadcasts, mudcracks, hummocky cross-stratification, and oncolites are locally present (Nilsen, 1981; Brosgé and others, 1979; Handschy and others, 1987a; Anderson, 1987). Beds composed primarily of shallow-marine fossil debris are locally interbedded with the siliciclastic units. Pillowed volcanic rocks are reported from the unit in the Baird Mountains and Chandalar quadrangles (Brosgé and Reiser, 1964; Karl and others, 1989). Based on these observations, most workers interpret most of the Hunt Fork Shale as a succession of thin-bedded turbidites deposited in slope or prodelta settings by vertical settling from storm-generated overflow rather than from bottom-flowing turbidity currents (Nilsen, 1981; Moore and Nilsen, 1984; Handschy and others, 1987a). These rocks grade upward into shallow-marine and intertidal deposits that commonly form thickening and coarsening-upward cycles 5 to 50 m thick near the top of the unit (Nilsen, 1981; Handschy and others, 1987a).

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; Nelson and Grybeck, 1980). Sandstone from the unit typically is rich in quartz (66%), chert (25%), and mica, but contains a few percent feldspar and lithic grains including argillite and metamorphic and granitic rock fragments ($Q_{91}F_2L_7$) (Nelson and Grybeck, 1980; Anderson, 1987).

Following earlier work by Smith (1913) and Smith and Mertie (1930), Dutro (1952, 1953) designated a 215 to 305 m thick succession of sandstone with minor shale and conglomerate in the Misheguk Mountain quadrangle as the **Noatak Sandstone** (Upper Devonian). Dutro (1952, 1953) and Tailleur and others (1967) considered this unit to be a westerly, finer grained marine equivalent of the nonmarine Kanayut Conglomerate. However, Nilsen and others (1985) pointed out that the upper part of the type section of the Noatak consists largely of fluvial strata similar in most respects to the Kanayut Conglomerate. To the east in the central Brooks Range, the Noatak Sandstone has been restricted by Nilsen and Moore (1984a) to the dominantly marine sandstone interval that is transitional between the dominantly prodelta deposits of the Hunt Fork and the dominantly fluvial deposits of the Kanayut Conglomerate.

In the central Brooks Range, the Noatak Sandstone is as much as 560 m thick (Nilsen and Moore, 1984a). It characteristically consists of bundles or packages of buff-, brown-, or gray-weathering, thin- to thick-bedded, fine- to medium-grained calcareous sandstone that are intercalated with intervals of brownish-gray and black siltstone and shale. The sandstone typically displays trough cross-stratification and is locally conglomeratic, containing chert and quartz pebbles up to several centimeters in length. Other sedimentary structures found in the unit include parallel stratification, burrows, plant fossils, mud chips, shale drapes, ripple-marks, reactivation surfaces, hummocky cross-stratification, flute casts, and flaser bedding. The sandstone packages are as thick as 15 m and commonly thicken and coarsen upward, but locally are channelized and thin and fine upward. Nilsen and Moore (1984a) consider the unit to represent offshore progradation of stream-mouth bars or other shelf-to-shoreline sand accumulations, and report variable paleocurrent directions which they interpret as the product of divergence of storm, tidal, wind and wave-generated current patterns.

The Noatak Sandstone lies in conformable contact with both the underlying marine Hunt Fork Shale and the overlying nonmarine Kanayut Conglomerate. It contains late Late Devonian (middle Famennian) megafossils, including brachiopods, gastropods, pelecypods and echinoderms indicative of shelf, intertidal, lagoonal, and marginal-marine depositional environments (Nilsen and others, 1980). Anderson (1987) reported that sandstone from the Noatak Sandstone has the composition $Q_{82}F_1L_{17}$ and contains abundant chert grains (42%), some of which contain radiolarian ghosts. Other lithic grains are mostly argillite and metamorphic rock fragments. Sandstone of the unit commonly contains limonitic calcareous cement that helps to distinguish it from the silica-cemented sandstone of the overlying Kanayut Conglomerate.

The overlying **Kanayut Conglomerate** (Upper Devonian and Lower Mississippian?) was defined in the Shainin Lake area of the Chandler Lake quadrangle by Bowsher and Dutro (1957) for an approximately 1000 m-thick, largely nonmarine succession of interbedded sandstone, conglomerate, and shale. This unit is conformably overlain by the marine Kayak Shale and rests conformably on the marine Noatak Sandstone or, where it is missing, on the marine Hunt Fork Shale. Recent work has shown that the Kanayut Conglomerate is one of the major stratigraphic units of northern Alaska, extending over an east-west distance of 900 km and a north-south distance of 65 km. Near the Dalton Highway, the unit is 2600 m thick, but thins to about 240 m in the western Brooks Range (Brosgé and others, 1979b; Nilsen and others, 1980; Nilsen and Moore, 1984b, Moore and Nilsen, 1984).

In its type area, the Kanayut Conglomerate consists of three members which are, in ascending order, the Ear Peak Member, the Shainin Lake Member, and the Stuver Member (Bowsher and Dutro, 1957; Nilsen and Moore, 1984a). A fourth (basal sandstone) member was mapped by some workers (e.g., Porter, 1966; Brosgé and others, 1979), but Nilsen and Moore (1984a) assigned this fossiliferous unit to the Noatak Sandstone. 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 (Moore and Nilsen, 1984). This member, which pinches out to the south and west, consists of braid-plain deposits. The three formal members are easily recognized north of the rangecrest in the central Brooks Range, but are difficult to distinguish in the southern and westernmost areas of exposure, where the unit consists largely of interbedded sandstone and shale (Nilsen and Moore, 1984b; Moore and Nilsen, 1984).

The **Ear Peak Member** consists of subequal proportions of intercalated shale, sandstone, and conglomerate. It is 512 m thick in its type area in the Chandler Lake quadrangle, but is as thick as 1150 m to the east near the Dalton Highway (Nilsen and Moore, 1984a). These strata typically form a series of cycles 5 to 20 m thick that thin and fine upward and are laterally continuous for distances of more than 5 km (Moore and Nilsen, 1985). The cycles commence with an erosional base overlain by channelized massive and crudely parallel-stratified conglomerate, commonly with rip-up clasts of shale. The conglomerate grades upwards into trough-cross-stratified sandstone overlain by ripple cross-laminated fine-grained sandstone. The upper part of the cycles typically consists of brown, red, yellow, and black shale and siltstone, locally with thin sandstone beds. The higher parts of the cycles commonly contain fossil plant debris, ripple markings, root casts, paleosols, mudcracks and other features indicative of deposition in levee, interchannel, and floodplain environments. The conglomeratic lower parts of the cycles generally thicken and coarsen upwards in the Ear Peak Member at the expense of the finer grained strata, and grade into the overlying Shainin Lake Member.

The **Shainin Lake Member,** as thick as 526 m, consists almost entirely of interlayered pebble conglomerate and coarse-grained sandstone. These coarse-grained strata typically form normally graded conglomerate-sandstone couplets with erosional basal contacts. Crude parallel stratification, medium to large-scale cross-stratification, and pebble imbrication are locally present in the unit. Where these sedimentary structures are not obvious, the strata form massive amalgamated units of conglomerate separated by scoured horizons or thin beds of siltstone. The Shainin Lake Member contains the coarsest conglomerate in the Kanayut, with clasts as large as 23 cm near its type area in the Chandler Lake quadrangle. The maximum clast size decreases systematically toward the south and west ,where the member is inferred to pinch out (Nilsen and Moore, 1984a).

The **Stuver Member** is the uppermost member of the Kanayut Conglomerate and is as thick as 1310 m near the Dalton Highway, but only 217 m thick to the west at its type section in the Chandler Lake quadrangle. Like the Ear Peak Member, the Stuver Member consists of repetitive fining- and thinning-upward sequences of conglomerate, sandstone, and shale. Although the Stuver Member locally includes coal in its upper part, it is generally possible to distinguish it from the Ear Peak Member only by its stratigraphic position relative to the Shainin Lake Member or the overlying Kayak Shale.

The Kanayut Conglomerate is interpreted to represent the fluvial part of a coarse-grained fluvial-dominated delta (Nilsen, 1981; Moore and Nilsen, 1984). The Ear Peak and Stuver Members represent the deposits of large meandering streams on an extensive floodplain, whereas the Shainin Lake Member represents the deposits of coalescing braided streams on an extensive braidplain. The interior stratigraphic position of the Shainin Lake Member and its coarser grain size suggest that it represents proximal deposition during the culmination of tectonism in the source region of the Kanayut Conglomerate. Clast size and paleocurrent data indicate that detritus was shed to the south and west into the basin from at least two major entry points (Moore and Nilsen, 1984).

Conglomerate in the Kanayut Conglomerate consists of about 82 percent black, gray, white, and locally red and green chert, 14 percent vein quartz, and 3 percent chert arenite clasts (Nilsen and others, 1982). Sandstone in the unit is compositionally and texturally mature, consisting of about 60 percent quartz and 30 percent chert, with minor feldspar (2%) and unstable lithic grains (8%) (Anderson, 1987). Anderson (1987) reported that lithic grains include radiolarian chert, argillite, metamorphic rock fragments and rare volcanic and granitic rock fragments. Feldspar locally comprises as much as 13 percent of some sandstone beds along the Dalton Highway, but is rare in the unit to the west. The Kanayut Conglomerate is inferred to have a largely sedimentary orogenic provenance which included substantial chert of deep-marine origin (Anderson, 1987), but the present location of the source region is unknown (Smith and Mertie, 1930; Moore and Nilsen, 1984).

Shale in the Kanayut Conglomerate contains numerous plant fossils largely of Late Devonian age, but Early Mississippian plant fossils have been recovered from a few locations in the Stuver Member (Bowsher and Dutro, 1957; Porter, 1966; Nilsen and Moore, 1984a). Based on this data and its stratigraphic position between the upper Upper Devonian (Famennian) Noatak Sandstone and Early Mississippian Kayak Shale, Nilsen and Moore (1984a) considered the Kanayut Conglomerate as late Late Devonian (Famennian) to Early Mississippian (?) in age. A late Late Devonian (Famennian) brachiopod recovered from the top of the Stuver Member in one of the southernmost locations of the unit suggests that the upper contact of the formation may be time-transgressive in nature (Moore and Nilsen, 1984).

The marine **Kayak Shale** (Lower Mississippian) overlies the Kanayut Conglomerate and records a northward and eastward marine transgression that followed the submergence of the nonmarine rocks of the Kanayut Conglomerate. The type locality of the Kayak Shale is in the Shainin Lake area (Chandler Lake quadrangle) where it is 300 m thick (Bowsher and Dutro, 1957). Although the formation can be traced the entire length of the Brooks Range, it commonly is the site of structural detachment so that the unit is in most places tectonically thinned or thickened.

At its type locality, Bowsher and Dutro (1957) divided the Kayak Shale into five members. In ascending order, these are: 1) a basal sandstone member, 44 m thick; 2) a lower black shale member, 198 m thick; 3) an argillaceous limestone member, 27 m thick, 4) and upper black shale member, 47 m thick; and 5) a red limestone member, 4 m thick. The basal sandstone member consists of white to rusty-weathering, quartz-rich, thin-bedded, fine- and very fine-grained sandstone and siltstone with oscillation ripple markings, shale drapes, reactivation surfaces, channels, burrows, flaser bedding, and other features indicative of intertidal and shallow marine deposition. This unit records the drowning of the Kanayut delta and a regional marine transgression. The black shale members are the most distinctive part of the Kayak Shale and consist of laminated, fissile, graded beds of carbonaceous siltstone and shale. The limestone members typically weather orange or reddish-brown and consist of bioclastic carbonate and ungraded debris-flow deposits of fossils and calcareous debris (Porter, 1966; Nilsen, 1981). Although commonly disrupted, the lithologies comprising the various members can be identified in most of the places where the Kayak Shale is exposed.

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. The basal sandstone member is interpreted by Nilsen (1981) as a transgressive marine sequence that was deposited conformably on the Kanayut Conglomerate, although Bowsher and Dutro (1957) had previously considered this contact to be a disconformity. The overlying black shale represents lagoonal and/or deeper marine sedimentation into which some massive fossiliferous debris flows of argillaceous limestone were redeposited (Nilsen, 1981). The top of the Kayak records a transition from a terrigenous-clastic system represented by the Endicott Group to the carbonate-shelf depositional system represented by the overlying Lisburne Group.

Bowsher and Dutro (1957) and Nilsen and others (1980) reported that the limestone members of the Kayak Shale in the Endicott Mountains subterrane contain a varied marine assemblage of megafossils that indicate an early Early Mississippian (late Kinderhookian) age for the unit; microfossils indicate that the Kayak Shale may be as young as late Early Mississippian (Osagian) near the top of the unit (Armstrong and Mamet, 1978).

Lisburne Group. Widespread thick, light gray-weathering Mississippian limestone in the central Brooks Range was correlated with the Lisburne Formation of the Lisburne Peninsula by Schrader (1902, 1904). Bowsher and Dutro (1957) subdivided the Lisburne in the Shainin Lake area (Chandler Lake quadrangle) and raised the Lisburne to group rank. Although regional mapping has shown that the Wachsmuth and Alapah Limestones cannot be readily distinguished regionally on the basis of lithologic criteria, the massive cliff-forming carbonate rocks comprising these formations have been mapped largely on the basis of lighter or darker color throughout the central and eastern Brooks Range. In the western part of the Endicott subterrane, the carbonate sequence typical of the Lisburne Group is represented by a thinner sequence of black shale, limestone, and chert. This succession was given the name the Kuna Formation by Mull and others (1982) who considered these rocks to be a basinal facies of the 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.

At its type locality in the Shainin Lake area east of Anaktuvuk Pass, the **Wachsmuth Limestone** (Lower Mississippian) lies conformably on the Kayak Shale. The Wachsmuth Limestone is about 400 m thick and was divided by Bowsher and Dutro (1957) into four informal members. These units are, in ascending order, 1) a shaly limestone member; 2) a crinoidal limestone unit; 3) a dolomite unit; 4) and an upper banded chert-limestone unit. The **Alapah Limestone,** about 300 m thick, was divided into nine informal members consisting of shaly limestone at the base grading upward to variable amounts of interbedded massive limestone, black chert and shale, and limestone with abundant chert nodules. Abundant fossils and gray to black chert characterize units. The chert occurs in stratified beds, nodules, and veins and locally replaces megafossils indicating that most of the chert is secondary in origin. The source of the silica for chert replacement of carbonate rocks was probably sponge spicules which are locally abundant in the unit.

In the northcentral 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 Wachsmuth and Alapah 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. Thin lenticular beds of spiculitic chert and limestone are present near its base, but it becomes richer in black chert upwards. Phosphatic beds are locally present in the unit, especially near its eastern limit of exposure. 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 Siksikpuk Formation (115 m) of Permian age and the Otuk Formation (100 m) of Triassic and Jurassic age. In the Endicott Mountains subterrane, these formations generally consist of siltstone overlain by thinly interbedded siliceous shale, siltstone, and limestone. In the eastern part of the subterrane, these formations contain a few silicified beds, whereas cherty, silicified mudstone and limestone beds become increasingly common to the west. Because of the relatively nonresistant nature of these rocks, the formations are not well exposed and commonly crop out only in isolated stream cutbanks.

The **Siksikpuk Formation** was named by Patton (1957) for exposures of mainly shale and siltstone in the Chandler Lake quadrangle and subsequently extended by Mull and others (1982) to include chert-rich sequences in the central and western Brooks Range. More recently, 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).

Patton (1957) described the Siksikpuk as a thin, fine-grained unit consisting chiefly of variegated green, gray, black, and dark red shale and siltstone that locally are notably calcareous, cherty, or ferruginous. The Siksikpuk Formation is about 115 m thick in its type area, but commonly is thinner elsewhere. 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). Seams, veins, nodules, and finely disseminated crystal aggregates of barite are common in the maroon shale and siltstone unit. 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). To the west in the Baird Mountains quadrangle, Karl and others (1990) estimated that about 20 percent of the Siksikpuk consists of maroon, green, and black chert. These observations indicate that the Siksikpuk becomes progressively more siliceous to the west. 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).

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). In most places the contact is marked by a pronounced color change from gray platform carbonates or black shaly limestone of the Lisburne Group to yellowish-brown weathering shaly siltstone at the base of the Siksikpuk Formation. Scattered phosphate nodules are commonly found in the basal bed of the Siksikpuk (K.E. Adams, personal communication, 1987).

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 unit 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** was defined in the western Killik River quadrangle by Mull and others (1982) for an interval about 100 m thick consisting of thinly interbedded chert, shale, silicified mudstone, and silicified limestone. Most of the Otuk had previously been mapped as the Shublik Formation (e.g., Chapman and others, 1964; Patton and Tailleur, 1964; Tailleur and others, 1966), but was distinguished by Mull and others (1982) from the Shublik by its more siliceous composition. These rocks typically weather to form yellowish-gray to orangish-gray slopes covered with fine rubble of chert and siliceous limestone.

In the Endicott Mountains subterrane, Mull and others (1982) and Blome and others (1988) divided the Otuk Formation into 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 Otuk Formation is characterized by black and, in many places slightly sooty shale and by the abundant pectinacid pelecypod fauna (commonly *Monotis* and *Halobia*) that is present in the chert and limestone members. The chert member consists chiefly of thin-bedded silicified mudstone and limestone beds and commonly contains phosphatic nodules. Silicified limestone beds in the limestone member commonly have a characteristic banded appearance in which the upper and lower bedding surfaces weather light yellowish gray, whereas the interiors of the beds are dark greenish gray to black. The Karen Creek member of Bodnar (1984) is a 2-m-thick unit of massive black siltstone that intervenes between the Blankenship Member and the underlying limestone member in the eastern part of the Endicott Mountains subterrane. The Blankenship Member, defined in the Howard Pass quadrangle, is a recessive shale unit, but can be recognized by the common presence of the small *Otapiria tailleuri* pelecypod and *Inoceramus lucifer*. Although apparently conformable, paleontological data suggest that the Blankenship Member may lie disconformably on the underlying part of the Otuk Formation

The basal contact of the Otuk Formation with the underlying Siksikpuk Formation is rarely exposed, but it disconformably overlies the Siksikpuk Formation where the contact has been excavated on Tiglukpuk Creek in the Chandler Lake quadrangle. There, the contact is marked by an oxidized zone and an abrupt lithologic change from soft dark gray shale in the Siksikpuk Formation to indurated black shale at the base of the Otuk Formation.

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, outer 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) or "clay shale" unit of Molenaar (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. In its best area of exposure in the De Long Mountains quadrangle, Crane and Wiggins (1976) divided the unit into as many as ten members. The lower part of the unit consists of bentonitic shale and is characterized by calcareous concretions as large as 3 m. The bentonitic shale grades upwards into rusty weathering shale with barite and pyrite nodules and zones of carbonaceous shale, thin beds of fine-grained sandstone and siltstone, thin bentonitic seams, and rare horizons with well rounded pebbles of quartz, chert, gabbro, and granite (Crane and others, unpublished data). The upper part of the Ipewik consists of an interval of bright maroon shale overlain by dark gray to black shale with local beds of very fissile oil shale and bentonite. This part of the Ipewik is as much as 60 m thick and is characterized by the presence of beds of coquinoid limestone, termed the **coquinoid limestone** unit by Mull (1985). Although rarely over 2 m thick, the reddish-weathering coquinoid limestone beds form a distinctive unit composed almost entirely of highly compressed bivalve shells.

In a few places in the De Long Mountains quadrangle, the upper part of the Ipewik consists almost entirely of fine- and very fine-grained quartzitic sandstone which has been called the **Tingmerkpuk member** (Curtis and others, 1990; Crane and Wiggins, 1976). The sandstone of the Tingmerkpuk member is massive to thick-bedded, contains convolute lamination and sole markings, and is interpreted as turbidites by Crane and others (unpublished data). The relationship of the coquinoid limestone and the Tingmerkpuk member is not known with certainty, but is thought to be intertonguing because they contain the same fossil assemblage.

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 coquinoid limestone has also been recognized locally in the North Slope subterrane in the northeastern Brooks Range, but not in the De Long Mountains subterrane.

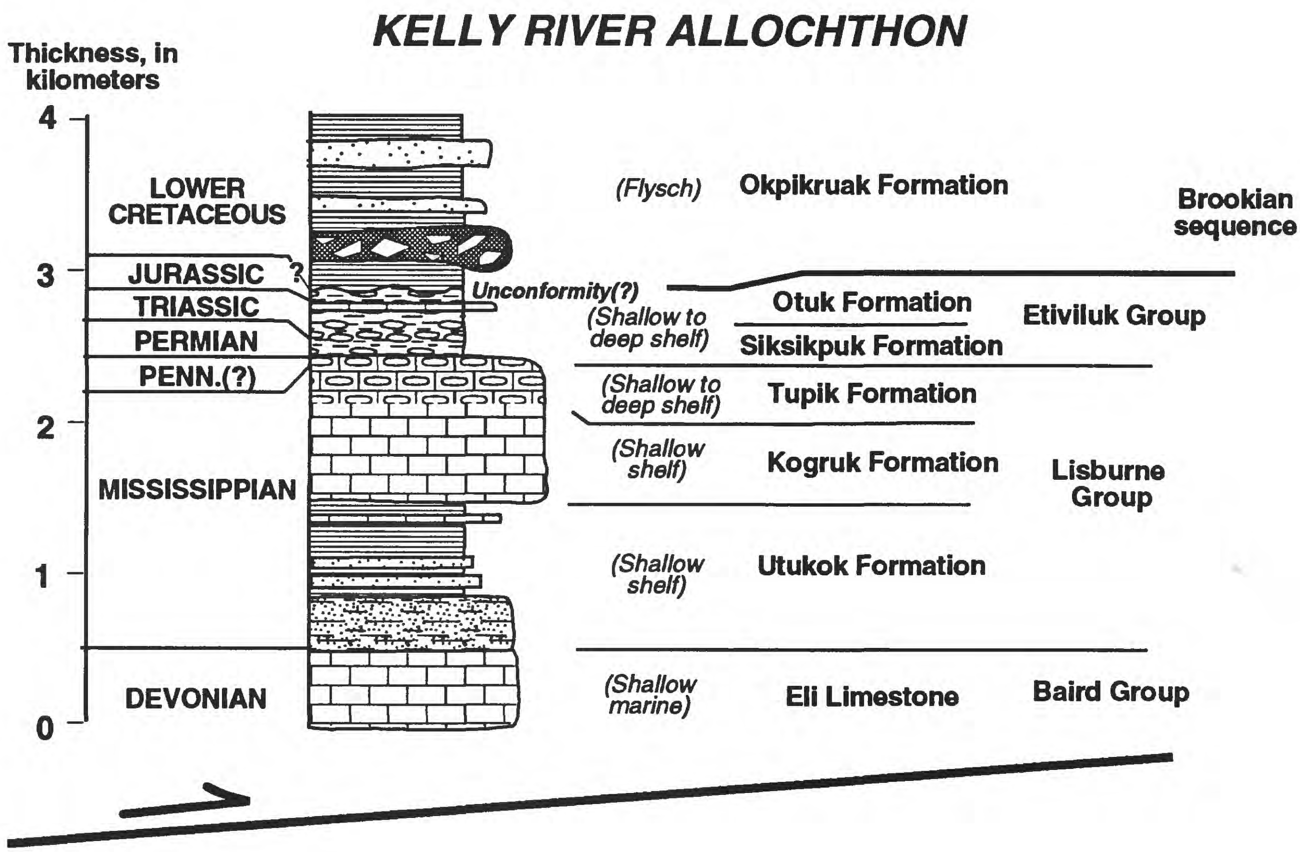
The Ipewik unit is a condensed section deposited in a quiescent marine basin. The widespread coquinoid limestone is commonly interpreted as a relatively shallow-water unit deposited on an intrabasin medial sill or ridge (Jones and Grantz, 1964; Tailleur and Brosgé, 1970; Molenaar, 1988), although the 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. The quartzose composition of the Tingmerkpuk member is more similar to that of the upper Ellesmerian sequence rocks of the North Slope subterrane rather than the lithic-rich graywacke sandstones of the nearly coeval Brookian deposits of the Endicott Mountains subterrane (Molenaar, 1988) (see below).

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 1,000 m thick. Conglomerate is locally prominent and contains rounded cobbles and boulders of chert, limestone, granitic rocks, dacite, diabase, and gabbro. These rocks 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 mélange, whose structural position 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; Mull and others, in press).

De Long Mountains subterrane

The De Long Mountains subterrane, the structually 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 (figs. 24 and 25). 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. The De Long Mountains subterrane is best exposed in the De Long Mountains of the western Brooks Range (fig. 26). 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 mapped as the Sheenjek terrane by Jones and others (1987) (see below). 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,



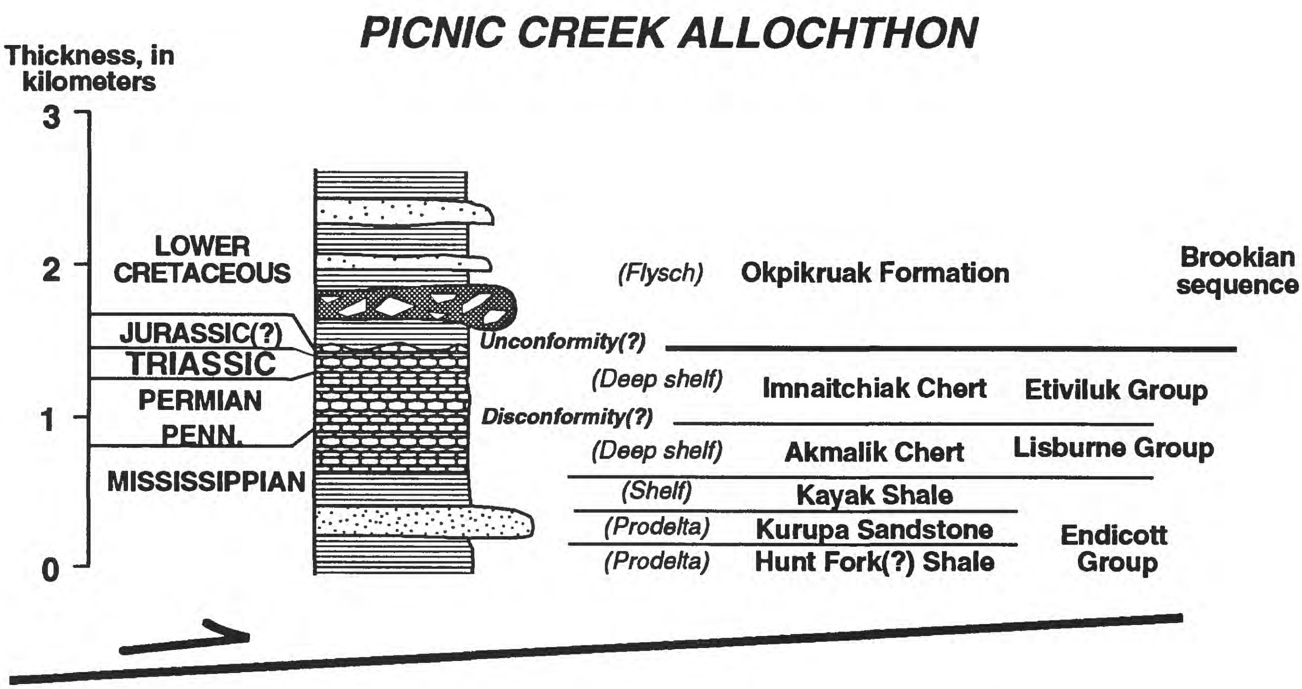


Figure 24. Generalized stratigraphy for Picnic Creek and Kelly River allochthons of De Long Mountains subterrane. Thrust symbol indicates relative northward movement between allochthons. See figure 5 for lithologic symbols.

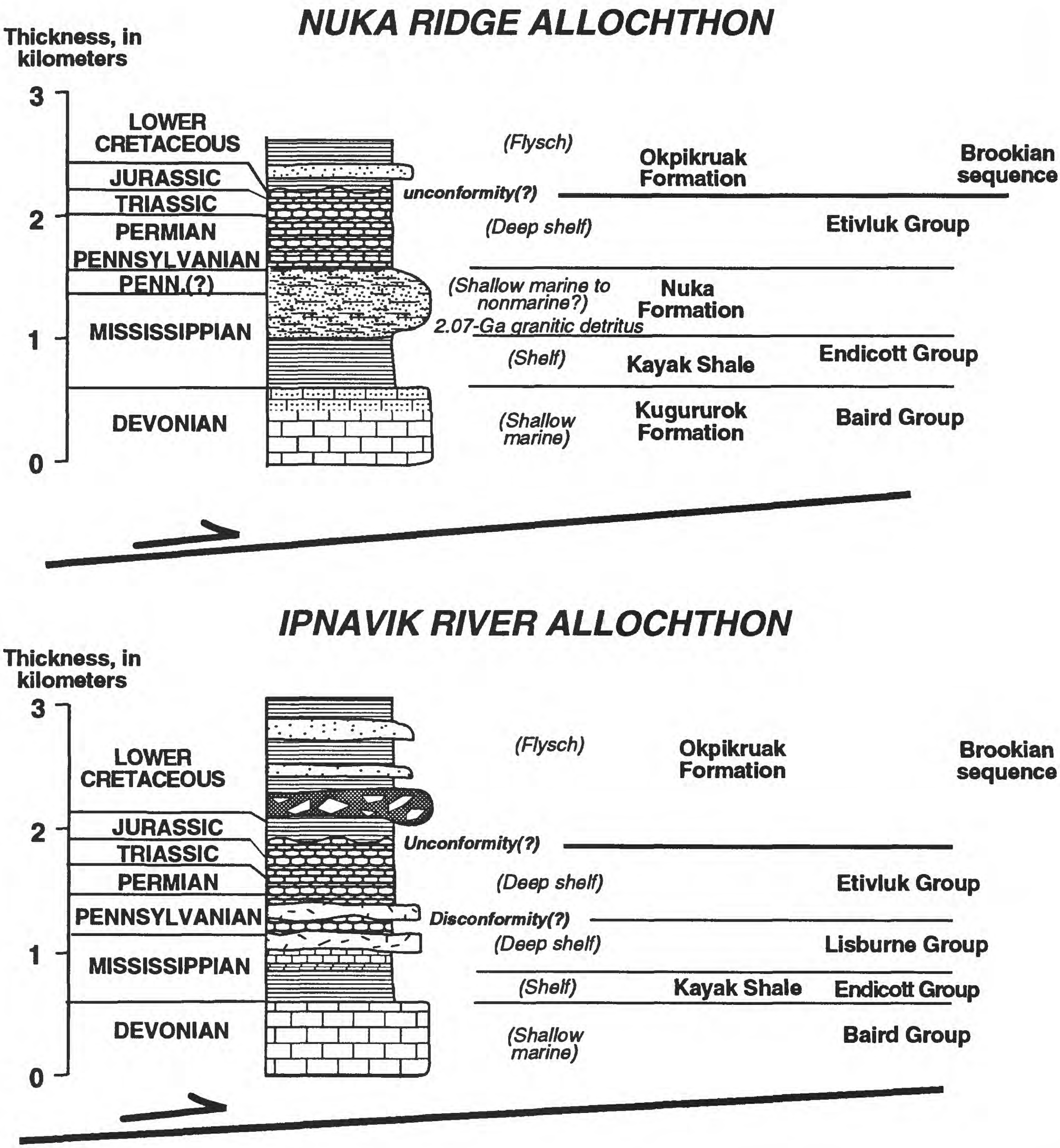


Figure 25. Generalized stratigraphy for Ipnavik River and Nuka Ridge allochthons of De Long Mountains subterrane. Thrust symbol indicates relative northward movement between allochthons. See figure 6 for lithologic symbols.

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. 24). The thickness of pre-Cretaceous strata of the Picnic Creek allochthon is less than 1,000 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) have 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. The Kurupa Sandstone consists of thin- to medium-bedded medium- to coarse-grained sandstone, siltstone, and contains minor granule and pebble conglomerate. Sandstone in the unit contains quartz (80-85%), chert (5-10%), and feldspar (3-10%), with sparse rock fragments (Mull and others, 1987b). The Kurupa Sandstone displays incomplete Bouma sequences near its base, but thickens and coarsens upward into strata containing complete Bouma sequences and comprising amalgamated bodies of sandstone. Bioturbation and slump structures are common, but features indicative of channelization apparently are absent in the unit. 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). Spicer and Thomas (1987) described plant fossils from the unit that previously had been found in Mississippian units of eastern Siberia.

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 shaley 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, 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 basal clastic unit rests disconformably on the Akmalik Chert (Mull and others, 1987b) and has the composition $Q_{36}F_{23}L_{41}$. Lithic fragments in the sandstones are largely sedimentary or metasedimentary and volcanic; potassium feldspar is the dominant feldspar (Siok and Mull, 1987).

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).

In the western Brooks Range, the strata of the Etivluk Group in the Picnic Creek allochthon are siliceous, but have locally been assigned to the Siksikpuk and Otuk Formations based on their color, stratigraphic position, and fossils (Curtis and others, 1984; Mayfield and others, 1987; Ellersieck and others, 1983). Further work may conclude that that the Late Paleozoic parts of these sequences should be reassigned to the Imnaitchiak Chert. Radiolarian and conodont assemblages in these rocks indicate the base of the Etivluk Group is Early Pennsylvanian (Morrowan) and is at least as young as Middle Triassic (Ladinian) and may extend into the Jurassic (Ellersieck and others, 1983; 1984).

Kelly River allochthon.

The Kelly River allochthon (fig. 24), 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 1,500 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. This allochthon is distinguished by the presence of carbonate of the Devonian Baird Group, the apparent absence of the clastic strata of the Upper Devonian to Lower Mississippian Endicott Group, and the presence of calcareous sandstone, limestone, and chert of the Carboniferous Lisburne Group and fine-grained clastic rocks in the Pennsylvanian to Triassic Etivluk Group.

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). Besides their older age and stratigraphic position, these rocks are generally distinguished from carbonate rocks of the Lisburne Group by the general absence of chert nodules and zones of silicification. 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. These rocks, originally thought to compose a lower part of the Kugururok Formation by Sable and Dutro (1961), were distinguished from that unit by Curtis and others (1984). 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.

Typically, the carbonate rocks of the Baird Group of the Kelly River allochthon 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 (westcentral Baird Mountains sequence), exposed immediately to the east, excepth that they lack 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). The Eli was probably deposited on a shallow-water shelf or platform receiving a significant amount of clay-rich clastic detritus (J.A. Dumoulin, personal communication, 1988).

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 the Misheguk Mountain quadrangle, consists of interbedded and reddish-brown-weathering, fine-grained, quartzose sandstone, sandy limestone, and gray, calcareous shale. The Utukok Formation is nearly 1,000 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, written commun., 1988; 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 Utukok was deposited in a shallow-marine shelf or platform environment.

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, 1987b; J.A. Dumoulin, written commun., 1988).

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 unresistant 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. The Siksikpuk Formation of the Kelly River allochthon is estimated to be 20 to 40 m thick (Curtis and others, 1984; Ellersieck and others, 1984; and Mayfield and others, 1984), but sections commonly are tectonically thickened.

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 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, but the Otuk in the Kelly River allochthon may include strata as young as Middle Jurassic.(Mayfield and others, 1984, 1987).\

Ipnavik River allochthon

The Ipnavik River allochthon (fig. 25), named for extensive exposures in the disturbed belt in the Howard Pass quadrangle (c), comprises the Baird Group, the Endicott Group, the Lisburne Group, the Etivluk Group, and the Okpikruak Formation. The allochthon is distinguished by many reddish-brown-weathering diabase sills that intrude black chert and limestone of the Lisburne and lower Etivluk Groups. It is also distinguished by the presence of Devonian carbonate rocks of the Baird Group and Pennsylvanian and Permian siliceous shale and chert similar to the Imnaitchiak Chert of the Picnic Creek allochthon (Curtis and others, 1984; Ellersieck and others, 1984; and Mayfield and others, 1984, 1990). Scattered outcrops of basalt or diabase and associated silicified limestone and chert indicate that thrust slices of this allochthon are present as far east as the Chandler Lake quadrangle. Its similarity to the Sheenjek subterrane of the eastern Brooks Range (see below) suggest that it may once have extended along most of the length of the Brooks Range. 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 are also 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 percent 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 (Ellersieck and others, 1984; Mayfield and others, 1984). The abundance of chert interstratified with thin-bedded, fine-grained limestone, locally with turbiditite sedimentary structures, 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 total 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. Sparse to numerous diabase sills intrude the Lisburne Group and lower Etivluk Group of the Ipnavik River allochthon. The sills are up to 100 m thick and consist of fine- to coarse-grained, microporphyritic clinopyroxene-plagioclase 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). Sable and others (1984a,b) reported that diabase sills intrude Triassic rocks and "show contact effects" in parts of the Jurassic and Lower Cretaceous Okpikruak Formation, although the latter rocks may have been confused with olistoliths of mafic rocks of similar composition in the Okpikruak Formation. No definitive radiometric dates have been obtained from these igneous rocks; therefore their age, post Early Mississippian, can be constrained 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. 25). Although extensive exposures of the allochthon are limited to the Nuka Ridge and Mount Bastille klippen in the Misheguk Mountain quadrangle (fig. 26), 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.

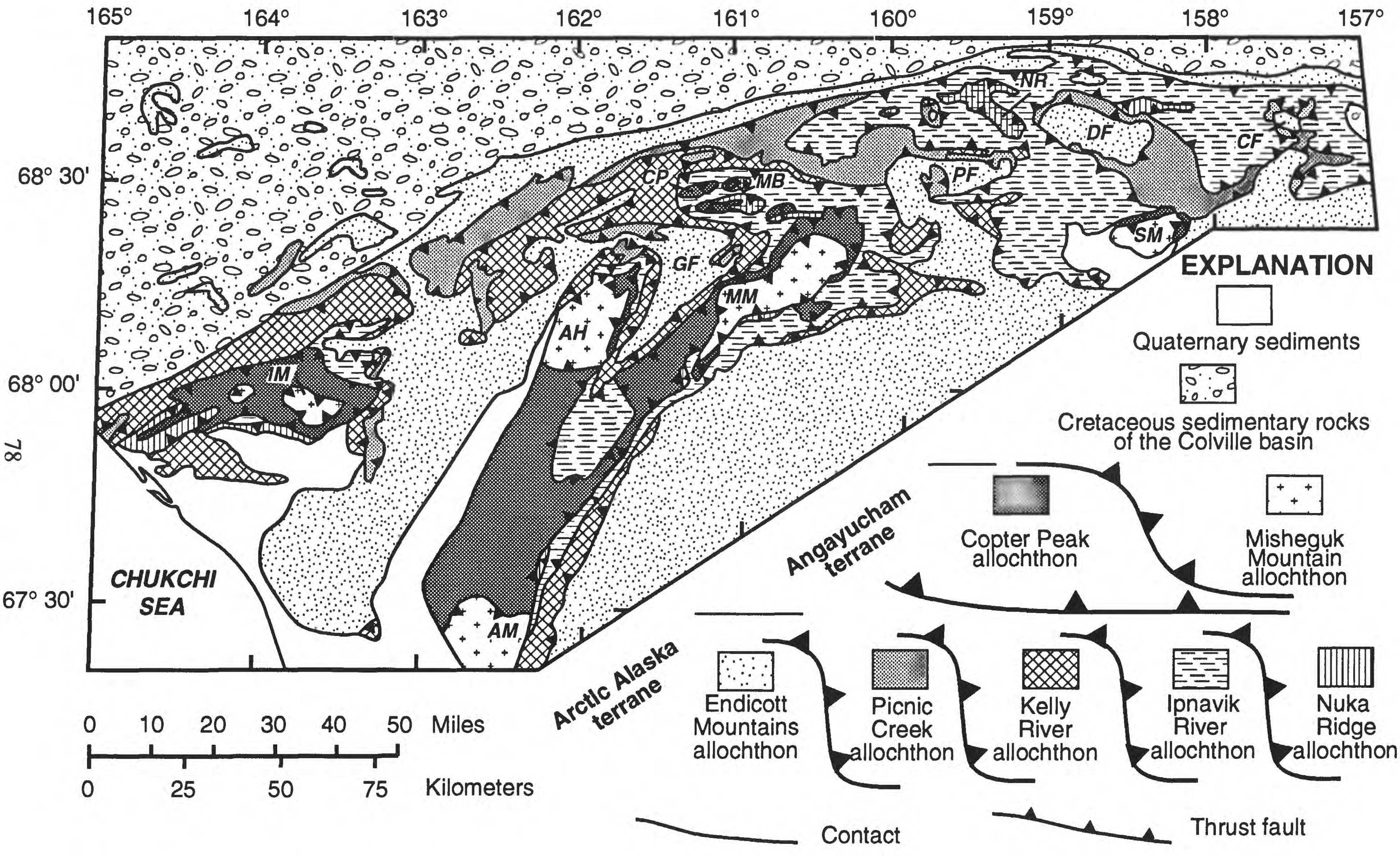


Figure 26. Map showing exposure of allochthons in the De Long Mountains, western Brooks Range (modified from Mayfield and others, 1988). Abbreviations: CF - Cutaway fenster; DF - Drinkwater fenster; GF - Ginny fenster; PF - Picnic Creek fenster; AH - Avan Hills klippe; AM - Asik Mountain klippe; CP - Copter Peak klippe; IM - Iyikrok Mountain klippe; MM- Misheguk Mountain klippe; NR - Nuka Ridge klippe; SM - Siniktanneyak Mountain klippe.

Baird Group. In the Nuka Ridge allochthon, the Baird Group consists of the **Kugururok Formation** (Devonian) (Sable and Dutro, 1961), . The Kugururok was divided into three informal members by Sable and Dutro (1961) and is 450 m thick as defined. The lowest member is 125 m thick and consists largely of clastic rocks, including shale with interbedded sandstone, granule conglomerate, siltstone, and limestone. This member was reassigned to the Jurassic and Lower Cretaceous Okpikruak Formation by Ellersieck and others (1984), who mapped a thrust fault at the top of the unit. 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 percent 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). Sable and Dutro (1961) reported latest Devonian ages from the Kugururok outside of the type area, but these rocks were later related to the Eli Limestone of the Kelly River allochthon by Curtis and others (1984). 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. The Kugururok Formation was probably deposited on a shallow-marine carbonate shelf or platform that received clastic detritus from a granitic source area.

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 rests 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- 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. The Nuka locally contains gray shale (Mayfield and others, 1987).

Abundant megafossils in the Nuka Formation were originally interpreted to range from Mississippian to Permian in age, with the characteristic coarse clastic rocks of the Nuka interpreted to be Permian (Tailleur and Sable, 1963). Later, Tailleur and others identified thrust faults within the section as defined by Tailleur and Sable (1963) and restricted the Nuka to the clastic rocks. More recently, foraminiferas and conodonts from the type area indicate that the Nuka is Late Mississippian (late Chesterian) to Early Pennsylvanian (early Morrowan) (Mayfield and others, 1984). Elsewhere, microfossils indicate that the Nuka ranges in age from Late Mississippian (late Meramecian) to Early Pennsylvanian (early-middle Morrowan) (Mayfield and others, 1984, 1987, 1990).

Sandstone and limestone of the Nuka Formation contain abundant, unweathered, coarse-grained, subangular potassium feldspar grains indicative of a nearby granitic source area. Sandstone from the Nuka Formation its type area contains about 30 percent potassium feldspar, 50 percent quartz grains, and 10 percent plagioclase with granitic and rare quartzite lithic grains. 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. A minor population of dark zircons yielded a minimum age of 2.2 Ga, which may reflect the age of country rocks or the source region of the granitic rocks. The unidentified source region for the Nuka Formation has been inferred to be an extensive southern paleohighland called "Nukaland" (Mayfield and others, 1988).

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. Typically, the chert is 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, unpub. data, 1985). 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 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 are 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 1,000 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).

Siok (1989) estimated that sandstone-to-shale ratios for Okpikruak exposures of the Picnic Creek allochthon in the Chandler Lake quadrangle as being 1:3 to 5:1 . He also reported that turbidite facies D and E of Mutti and Ricci Lucchi (1978) predominate in these exposures, but also wrote that facies F, C, and B are locally present. Based on its sedimentary facies and trace fossils, Siok (1989) inferred deposition at bathyal to abyssal depths in a middle or outer submarine-fan environment for these rocks.

Sandstone of the Okpikruak Formation in the Picnic Creek allochthon in the Killik River and Chandler Lake quadrangles has an average composition of $Q_{47}F_{20}L_{33}$,whereas Okpikruak sandstone in the Chandler Lake quadrangle has an average composition of $Q_{29}F_{13}L_{58}$ (Wilbur and others, 1987; Siok, 1989). These sandstones 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).

Olistostromes, locally present in the Okpikruak Formation in all except the Nuka Ridge allochthon, are 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 allochthons (Mayfield and others, 1988). Most workers have explained the diachronous nature of the Okpikruak Formation as a product of its derivation from northward advancing thrust-front of the Brooks Range orogen in Jurassic and Early Cretaceous time (Mull, 1985; Mayfield and others, 1988; Molenaar, 1988).

Sheenjek subterrane

The Sheenjek terrane of Jones and others (1987) in the Coleen quadrangle, southeast Brooks Range (fig 3) is here considered to be a small subterrane of the Arctic Alaska terrane. It consists of Mississippian limestone and shale, Permian(?) and Triassic(?) chert, argillite, and graywacke intruded by diabase sills. These rocks were originally included as part of the Christian mafic and ultramafic complex (Angayucham or Tozitna terrane) by Brosgé and Reiser (1969), but were distinguished from that terrane by Jones and others (1987) because of their different lithology, overlap in age, and the unknown structural relationship between the two terranes. The Sheenjek subterrane is structurally underlain by the Endicott Mountains and Venetie subterranes to the north and, by rocks probably belonging to the North Slope subterrane to the east. To the south, the Sheenjek subterrane is juxtaposed against the Porcupine terrane of the east-central Alaska region. This contact is poorly exposed, its nature is controversial, but has been interpreted as a major tectonic boundary (Brosgé and Reiser, 1969; Nilsen, 1981; Churkin and Trexler, 1981; Jones and others, 1986; Oldow and others, 1987b). The Angayucham (Tozitna) terrane is inferred to overlie the Sheenjek subterrane, although this contact is not well constrained in the field.

The Sheenjek subterrane is a stratigraphic succession consisting of three principle units (Brosgé and Reiser, 1969). These are, from base to top, a black shale and chert unit, a gray limestone with black chert unit, and a red and green argillite, chert and sandstone unit. The basal black shale and chert unit is less than 200 m thick and contains thin beds of laminated very fine- to fine-grained quartzite. No fossils have been recovered from this unit. The black shale is overlain conformably by thin-bedded bioclastic limestone which contains a rich assemblage of megafossils and foraminifera that yield Late Mississippian ages (Brosgé and Reiser, 1969). The limestone, less than 35 m thick, also contains abundant beds of black laminated chert which displays textures suggestive of replacement of limestone by silica. The uppermost unit may total as much as 700 m thick and consists of interbedded black siltstone and shale, red and green argillite, red, green and black chert, and fine-grained, calcareous quartzose sandstone. The sandstone in this unit contains a small amount of potassium feldspar. Brosgé and Reiser (1969) reported one possible conodont of Permian or Triassic age in red argillite, whereas sandstone in the unit contains crinoid fragments, suggesting a Permian age for the unit.

The Sheenjek subterrane is distinctive because of the presence of abundant diabase and gabbro sills that intrude all three of its units. Individual diabase sills in the subterrane are as much as 200 m thick and can be traced over distances of more than 10 km. The sills, which may compose as much as 20 percent of the subterrane, have not been dated, but are inferred to be Jurassic by Brosgé and Reiser (1969) because of their proximity to Jurassic diabase in the nearby Angayucham (Tozitna) terrane.

The general similarity of the above stratigraphic succession to the sequence of the Endicott Mountains and De Long Mountains subterranes (the Kayak Shale followed in turn by the Lisburne Group and the Siksikpuk Formation) supports our view that the Sheenjek is part of the Arctic-Alaska terrane. The thin-bedded character of the Mississippian limestone, the presence of abundant diabase sills, and its inferred structural position above the Endicott Mountains subterrane and below the Angayucham terrane, however, suggest that it is most analogous to the Ipnavik River allochthon of the De Long Mountains subterrane, although the potassium feldspar-bearing sandstone of the Sheenjek subterrane may argue for possible correlation with the Nuka Ridge allochthon of the De Long Mountains subterrane. We therefore recommend that the rocks of the Sheenjek terrane of Jones and others (1987) be reassigned to the De Long Mountains subterrane or be designated as a separate subterrane of the Arctic Alaska terrane.

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 (fig. 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 inhomogenous, 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. 27). As presently mapped, the Hammond underlies the Endicott Mountains subterrane, but overlies the North Slope subterrane to the north and underlies the Coldfoot subterrane to the south. However, Oldow and others (1987c) interpreted the northeastern part of subterrane as overlying the Endicott Mountains subterrane, showing that the nature and position of these boundaries are inexact and/or controversial.

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)

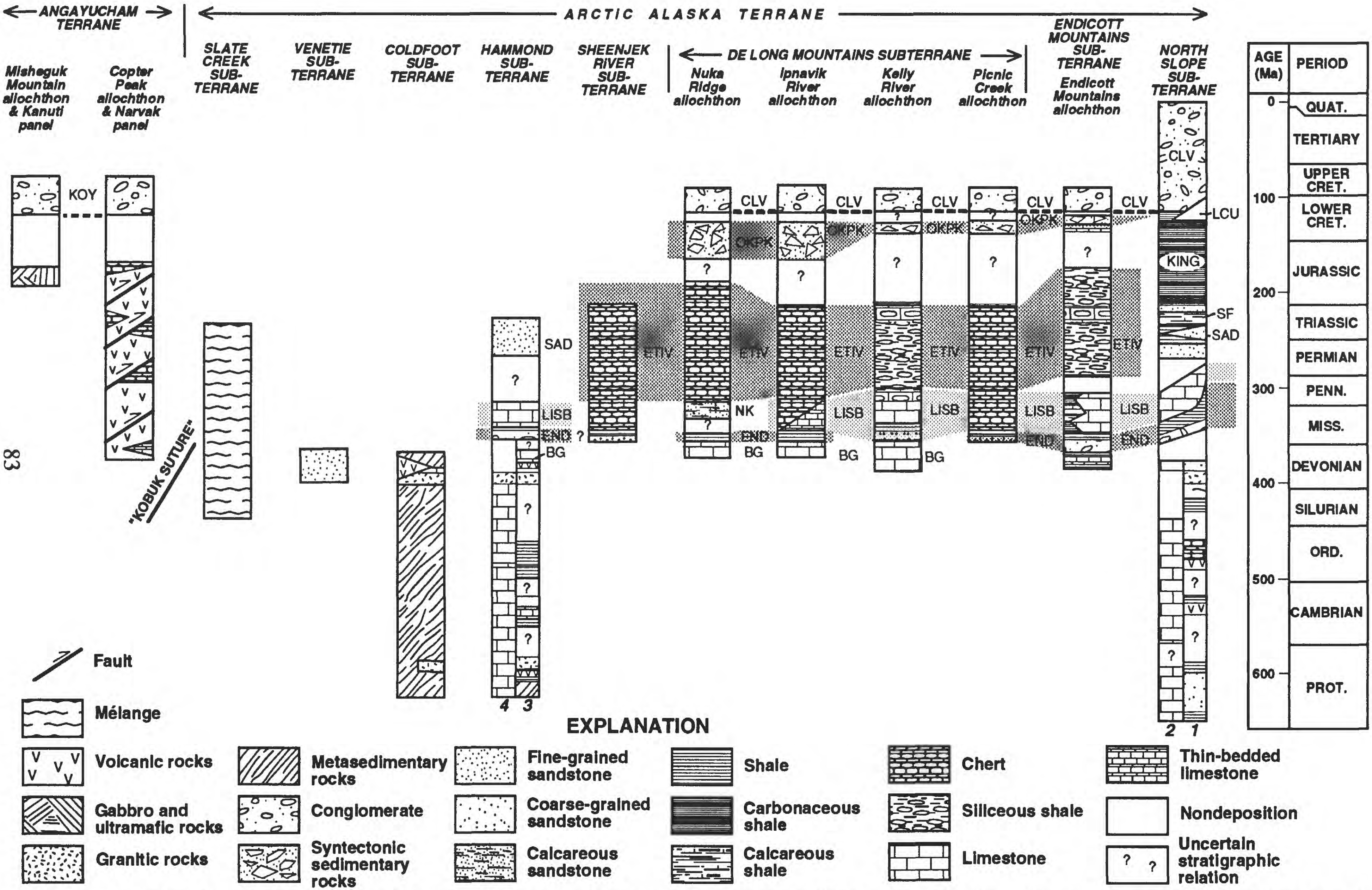


Figure 27. Time-stratigraphic columns for the Arctic Alaska and Angayucham terranes. Pre-Mississippian rocks are shown for the North Slope subterrane in the northeastern salient of the Brooks Range in subcolumns 1 (composite for areas with little stratigraphic control) and 2 (carbonate succession in the Sadierochit and Shublik Mountains) and for the Hammond subterrane in subcolumns 3 (composite for areas with little stratigraphic control) and 4 (Baird Group in the Baird Mountains quadrangle). All subterranes and terranes are shown in present relative positions; allochthons of the De Long Mountain subterrane are shown in the restored position hypothesized by Mayfield and others (1988). Note general stratigraphic similarity of North Slope and Hammond subterranes. Abbreviations: BG - Baird Group; CLV - Brookian sequence in Colville basin; END - Endicott Group; ETIV - Etivluk Group; KING - Kingak Shale; KOY - sedimentary rocks of the Koyukuk basin; LCU - Lower Cretaceous unconformity; LISB - Lisburne Group; NK - Nuka Formation; OKPK - Okpikruak Formation;SAD - Sadlerochit Group; SF - Shublik Formation. Absolute time scale used in this figure is from Palmer and others (1983). Shaded regions highlights correlative units; dashed line indicates base of overlapping sedimentary rocks of the Colville and Koyukuk basins.

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 Formationand the Hunt Fork Shale; (4) upper Paleozoic carbonate and metaclastic rocks assigned to the Endicott, Lisburne, and Sadlerochit(?) Groups; and (5) metagranitic rocks. Stratigraphic relations within and between the various assemblages are controversial, and future work may indicate that the assemblage compose two or more tectonostratigraphic units.

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 quadrangles, 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 assembage 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., *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, oral commun., 1988; 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 that total 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; Tailleur and others, 1967; Oliver and others, 1975; Mayfield and Tailleur, 1978; Brosgé and others, 1979; 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 westcentral 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, midshelf 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 1,200-m-thick **westcentral 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 westcentral 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. Notably, Lower and Middle Ordovician strata of the westcentral carbonate sequence 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.

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.

However, recent mapping shows that an alternative interpretation of these rocks is possible (T.E., Moore, unpub. data, 1992). The trilobite-bearing limestone unit has ambiguous relationships with the structurally lower metaclastic rocks and may instead be a fault slice of the Skajit Limestone, to which it is juxtaposed. Similarly, the fine-grained black carbonaceous phyllite and limestone of Ordovician age may compose a basinal interval in a nearby imbricate of Skajit Limestone. This interval may be analogous to the Ordovician basinal interval of the Baird Group of the northeastern Baird Mountains quadrangle (see above). If these proposed relationships are correct, clastic rocks of Early Paleozoic age can only be documented in the Baird Mountains quadrangle, although huge regions of the Hammond subterrane are underlain by undated metaclastic rocks which may eventually prove to be Early Paleozoic.

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). Dillon and others (1987a) also included purple and green phyllite in the Beaucoup Formation. 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.

Although the Beaucoup Formation has only been mapped in the central and eastern Brooks Range (Brosgé and others, 1979; Brosgé and Reiser, 1964, 1965; Dillon and others, 1986), similar lithologies are present in the Hammond subterrane of the western Brooks Range. Nelson and Grybeck (1980) and Mayfield and Tailleur (1978) mapped calcareous, micaceous schist, phyllite and metasiltstone that may be correlative with the Beaucoup Formation rocks. Limestone associated with these rocks contain Middle to Late Devonian fossils (Nelson and Grybeck, 1980). Likewise, the Nakolik River unit of Karl and others (1989) in the Baird Mountains quadrangle is similar to the Beaucoup Formation, although it may compose the basal part of the Endicott Mountains subterrane instead of the Hammond subterrane (Karl and others, 1989).

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 (Reiser and Brosgé, 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.

Although depositionally similar to the Hunt Fork Shale of the Endicott Mountains subterrane, the Hunt Fork Shale of the Hammond subterrane is finer grained, commonly contains interlayered bodies of metadiabase, but lacks thin turbidites containing shallow-marine fossil debris that are locally present in the Endicott Mountains subterrane. It also displays a higher textural grade and a more complex structural style than does most of the Hunt Fork Shale of the Endicott Mountains subterrane. No stratigraphically higher rocks overlie the generally isolated exposures of the Hunt Fork Shale in the Hammond subterrane, so it is not known if it grades upwards into coarser grained strata related to the Noatak Sandstone and Kanayut Conglomerate of the Endicott Mountains subterrane.

The structural significance of rocks of the Hunt Fork Shale in the Hammond subterrane is also controversial. Dillon and others (1986) and Dillon (1987a, 1989) reported that the Beaucoup Formation in the Hammond subterrane is conformably overlain by the Hunt Fork Shale and represents an integral part of that subterrane. In contrast, Grantz and others (1991) hypothesized that exposures of the Hunt Fork Shale in the Hammond subterrane are klippen of the basal part of the Endicott Mountains subterrane that were structurally emplaced on the Hammond subterrane during an early part of the Brookian orogen. Recent work suggests that the Hunt Fork Shale of the Hammond subterrane differs lithologically and structurally from that of the Endicott Mountains subterrane, but may have once formed an older or more distal part of the clastic wedge of the Endicott Group in the Endicott Mountains subterrane (T.E. Moore, unpub. data, 1992).

Mississippian to Permian(?) rocks

The youngest strata included in the Hammond subterrane are the Endicott, Lisburne, and Sadlerochit(?) Groups which are exposed in several places in the Schwatka Mountains (fig. 22). 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. For these reasons, we include these upper Paleozoic rocks in the Hammond subterrane in this report, although we recognize that future work may indicate that these rocks should be reassigned to the North Slope subterrane.

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. Undeformed clasts in the conglomerate are well rounded and as large as 10 cm. 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. Exposures of the Lisburne Group in the Hammond subterrane are located in small synforms at Shishakshinovik Pass and at a locality 25 km to the north (Tailleur and others, 1977). 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, oral commun., 1988). 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 grade upward into black, phyllitic shale. These rocks are well bedded and overlie the Lisburne Group on a probable disconformity. The thickness of the Sadlerochit Group in these areas is difficult to estimate because of extensive tectonism, but is not more than a few tens of meters thick. 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 (table 1, pl. 1). 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 percent gabbro and leucogabbro and 30 percent 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 e_{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 (1,000-800 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). However, microprobe analysis indicates that the muscovite in some Devonian plutons in the Hammond subterrane may be partly or entirely metamorphic in origin (A.B. Till, oral comm., 1990). 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 Mountain 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) (table 1). Ribidium-strontium whole-rock isochrons indicate an age of 373 ±25 Ma (Late Devonian) for the Arrigetch Peak pluton (Dillon, 1989; Silberman and others, 1979), whereas K-Ar cooling ages for this pluton are 86-92 my (Late Cretaceous) (Brosgé and Reiser, 1971). Initial Sr-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). Dillon (1989) suggested that these plutons are satellite bodies to the larger Baby Creek S-type pluton which intrudes the Coldfoot subterrane a few miles to the south, but Newberry and others (1986) argued that compositional data precludes a comagmatic relationship. Based on age and compositional similarities, Dillon (1989) interpreted the felsitic metavolcanic rocks of the Upper Devonian Beaucoup Formation as the extrusive equivalents to the Devonian plutons of the Chandalar quadrangle. 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).

Metamorphism of the Hammond subterrane

Regionally, metamorphic mineral assemblages are variable, increasing from chlorite grade in the northern part of the subterrane to as high as amphibolite facies in the western part of the subterrane (Dusel-Bacon and others, 1989). Evidence of at least three metamorphic events can be identified within the rocks of the subterrane. The earliest is documented at Mount Angayukaqsraq (Baird Mountains quadrangle), where metabasite lenses containing amphibolite, blueschist, and greenschist facies mineral assemblages occur in a sequence of quartz-mica schist, quartzite and marble. A Late Proterozoic metamorphic age for amphibolite in this area is indicated by K-Ar muscovite and hornblende ages of 729 ±22 and 594 ±18 my, although Cretaceous K-Ar ages have also been determined from rocks of the same succession (Turner and others, 1979; Mayfield and others, 1982; Armstrong and others, 1986). Turner and others (1979) originally suggested that the K-Ar data indicate a Precambrian episode of blueschist facies metamorphism, but Till and others (1988) and Armstrong and others (1986) now explain the disparity of K-Ar ages in these rocks to be the result of Late Proterozoic amphibolite facies mineral assemblages partially overprinted by Cretaceous blueschist facies mineral assemblages. The regional extent of the Late Proterozoic metamorphic event(s) is not known, but they may also have affected the Late Proterozoic metasedimentary rocks in the Wiseman and Survey Pass quadrangles. Kyanite is reported from banded schist of probable Upper Proterozoic age near the Wiseman-Survey Pass quadrangle boundary (Brosgé, 1975; Nelson and Grybeck, 1980). Alternatively, the Late Proterozoic higher grade metamorphic episode may be restricted to contact metamorphic aureoles around Late Proterozoic orthogneiss plutons located at Mount Angayukaqsraq in the Baird Mountains quadrangle and Ernie Lake in the Wiseman quadrangle (Dillon and others, 1986).

A second metamorphic episode is represented by metamorphic aureoles around Middle Devonian orthogneiss plutons in the Chandalar, Survey Pass, and Baird Mountains quadrangles (Dusel-Bacon and others, 1989). These contact metamorphic aureolas are up to several kilometers in width (Newberry and others, 1986). Mineral assemblages in calcareous country rocks in the aureoles vary from hornblende hornfels to albite-epidote hornfels facies and demonstrate decreasing temperatures away from intrusive contacts (Newberry and others, 1986). The contact metamorphic aureoles 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). The country rocks in areas outside the contact metamorphic aureoles commonly contain greenschist facies mineral assemblages (albite-chlorite-muscovite-epidote) and dynamothermal textures.

Higher grade garnet and biotite-bearing metasedimentary rocks are associated with the Devonian orthogneiss plutons in the Survey Pass quadrangle (Nelson and Grybeck, 1981) and may represent a deeper level of exposure of the regional Cretaceous metamorphic overprint or relict assemblages associated with higher grade prograde metamorphism developed at the time of emplacement of the plutonic rocks (Nelson and Grybeck, 1981; S.W. Nelson, personal communication, 1988). Newberry and others (1986) suggest that Cretaceous K-Ar ages from these rocks and dynamothermal metamorphism of the Devonian plutons indicate that the regional metamorphism is Cretaceous and that Devonian metamorphism is restricted to the contact aureoles of the plutons.

Regional metamorphism of the Hammond subterrane is largely lower greenschist facies, especially in the eastern part of the subterrane. Typical mineral assemblages in pelitic rocks include chlorite, quartz, albite, white mica, and epidote with biotite and garnet appearing in higher grade rocks in the Survey Pass quadrangle (Nelson and Grybeck, 1980). Calcareous schists in the southern part of the subterrane contain mineral assemblages including calcite, dolomite, quartz, white mica, albite, chlorite, actinolite, epidote, and sphene and metabasites contain the assemblage actinolite, albite, epidote, and chlorite (Nelson and Grybeck, 1980). In the western part of the subterrane, blueschist facies assemblages are also reported in metasedimentary rocks and metabasite at Mount Angayukaqsraq in the Baird Mountains quadrangle (Turner and others, 1979; Mayfield and others, 1982; Armstrong and others, 1986; Till and others, 1988). These rocks contain crossite-epidote assemblages and are interleaved with greenschist facies rocks. Till (1988) suggested that the high-pressure assemblages of the Hammond subterrane differ from those of the Coldfoot subterrane in that they are (1) regionally less extensive; (2) are younger; and (3) were metamorphosed at somewhat lower pressure. Potassium-argon cooling ages for white mica in the Hammond subterrane are 100 - 86 Ma (Turner and others, 1979; Till, 1988), but it is unclear if these ages indicate a younger age of high-pressure metamorphism in the Hammond subterrane.

Coldfoot subterrane

The Coldfoot subterrane consists largely of fine- to coarse-grained metasedimentary rocks that form the schist belt, a continuous 15- to 25-km-wide belt that stretches 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. 3, 27). 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. Jones and others (1987) originally restricted the Coldfoot subterrane to the central and eastern Brooks Range, but Dillon (1987a) pointed out that similar metamorphic rocks extend west through the Survey Pass, Ambler River, and Baird Mountains quadrangle without a significant break. We therefore have modified the Coldfoot subterrane of Jones and others (1987) by including the rocks of the schist belt in the western Brooks Range.

The Coldfoot subterrane is bounded to the south by the Slate Creek subterrane, and to the north by the Hammond subterrane, along boundaries 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 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 2,500 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 may 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 a 1,000 m thick, contain prominent, 5- to 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, written commun., 1989). 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. Typically, 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) 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 percent interlayered pelitic schist, quartz-rich schist, and paragneiss and about 5 percent 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 sediments (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 respective interstratified metavolcanic rocks.

Bornite carbonate sequence

The Bornite carbonate sequence of Hitzman and others (1986) consists of about 1,000 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, oral commun., 1990). Conodonts from one locality in the unit indicate a Silurian age (A.G. Harris and J.A. Dumoulin, unpub. data, 1987); 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 percent 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- to 1,850-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 percent metavolcanic and volcaniclastic rocks, 25 percent marble, and 15 percent 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 metavolcanic rocks of the Ambler sequence (Hitzman and others, 1986).

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, oral commun., 1990). 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 are 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 (table 1). 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).

Metamorphism of the Coldfoot subterrane

Regionally, the Coldfoot subterrane displays lower greenschist facies mineral assemblages, but blueschist and eclogite facies assemblages have been reported locally over most of its length and are especially prominent in the Ambler mineral district in the Ambler River quadrangle (Dusel-Bacon and others, 1989). Rocks of the subterrane are characterized by complicated parageneses as indicated by (1) the presence of unstable mineral assemblages (2) abundant textural evidence of replacement textures, and (3) multiple fabrics associated with different metamorphic assemblages. Although few detailed petrologic investigations of these rocks have been completed to date, most workers agree that at least two metamorphic episodes can be recognized regionally within the subterrane: an older high-pressure episode and a relatively younger lower pressure episode. The timing and tectonic significance of these metamorphic episodes presently is controversial, but they commonly are assumed to be related to the Brookian orogenic event in Jurassic and Early Cretaceous time (Hitzman and others, 1986). Pre-Mesozoic metamorphism has also been suggested for parts of the quartz-mica schist assemblage on the basis of coarser crystallinity, relict epidote-amphibolite metamorphic assemblages, and a more complex structural fabric (Hitzman and others, 1982; Dillon, 1989; Dusel-Bacon and others, 1989), but the regional extent and age of this metamorphism are uncertain. If present, pre-Mesozoic metamorphism may be explained as the product of dynamothermal metamorphism associated with Devonian magmatism or subduction zone metamorphism associated with Paleozoic convergence.

Blueschist facies assemblages are largely obliterated by younger assemblages in most areas, but are well preserved in metabasites in the southern Ambler River quadrangle and in other locations in the Baird Mountains, Survey Pass, Wiseman, and Chandalar quadrangles (Turner and others, 1979; Nelson and Grybeck, 1981; Hitzman and others, 1982, 1986; Gottschalk, 1987; Gottschalk and Oldow, 1988; Till and others, 1988; Zayatz, 1987; Reiser and others, 1979). In metabasites, the high-pressure assemblage typically contain glaucophane, epidote, garnet, and albite, with sphene and paragonite, whereas pelitic rocks typically have the assemblage garnet-chloritoid ± glaucophane (Hitzman and others, 1986; Gottschalk, 1987; Zayatz, 1987; Till, 1988). In most areas, such as near the Dalton Highway, relict blue amphibole is rare, but pseudomorphs after blue amphibole are common (Gottschalk, 1987). Recently, A.B. Till (written communication, 1988) has recognized pseudomorphs after lawsonite of clinozoisite, paragonite, and albite within garnet in many of the metasedimentary rocks of the Baird Mountains, Ambler River, and Wiseman quadrangles. Rare, higher grade assemblages have also been reported in the subterrane, including (1) a jadeite-bearing metagraywacke present in the Ambler River quadrangle (Turner and others, 1979) and (2) a metabasite lense near the Dalton Highway with coarse almandine garnet and sodic augite which Gottschalk (1987) interpreted as an eclogite facies assemblages. However, the age and structural relationship of these higher grade rocks to the surrounding lower grade rocks of the quartz-mica schist assemblage in which they occur is uncertain.

The wide distribution of pseudomorphs of high pressure mineral phases suggests that the entire subterrane underwent high-pressure metamorphism. Till (1988) reported that these assemblages record an earlier lower temperature phase characterized by lawsonite and a younger higher temperature phase characterized by epidote. Dusel-Bacon and others (1989) interpreted the high-pressure assemblages as evidence that metamorphism occurred at high pressure with temperature increasing over time. Near Wiseman, Gottschalk (1987) and Gottschalk and Oldow (1988) interpreted early metamorphism to have occurred at pressures between 7.6 and 9.8 kb and at temperatures around 475^{o}C. These data suggest that peak metamorphism in the Coldfoot subterrane occurred at depths in excess of 25 km.

The younger, lower pressure metamorphic assemblages are widespread in the Coldfoot subterrane and are the typical assemblage observed in the subterrane. These assemblages are commonly described as a mild to pervasive retrogradation to lower greenschist facies assemblages (e.g., Dusel-Bacon and others, 1989). Metapelites typically display the assemblage quartz-white mica-chlorite-albite, locally accompanied by chloritoid, calcite, biotite, garnet, and epidote, whereas metabasites contain albite-chlorite-sphene, locally accompanied by amphibole, epidote, quartz, pyrite, and magnetite. These minerals typically are oriented along well defined fabric in pelitic rocks, but late postkinematic, helicitic albite porphyroblasts, randomly oriented biotite, and partial to total replacement of garnet by chlorite are widespread (Dusel-Bacon and others, 1989).

Dusel-Bacon and others (1989) concluded that the conditions of metamorphism of the Coldfoot subterrane in Mesozoic time followed a "clockwise" pressure-temperature path that evolved from low- to high-temperature subfacies of the blueschist facies, followed by greenschist facies. The high pressure-low temperature metamorphism is interpreted to have been caused by subduction of the Arctic Alaska terrane, whereas the later greenschist facies metamorphism was probably due to later thermal recovery and decreasing pressure associated with uplift of the Brooks Range in Cretaceous time.

Potassium-argon cooling ages of white-mica in the Coldfoot subterrane are 130-100 Ma (Till, 1988) and are generally interpreted to date cooling of the later lower pressure greenschist facies assemblages. Most workers suggest that these dates reflect uplift of the southern Brooks Range in late Early Cretaceous time as recorded by the lithic composition of the Colville basin fill (e.g., Turner and others, 1979; Till, 1988). Whether this uplift was produced by convergent deformation involving structural basement (Oldow and others, 1987d) or by continent-scale crustal extension (Miller and and Hudson, 1991) is uncertain. The age of the earlier higher pressure metamorphic assemblages is more difficult to constrain isotopically because these minerals have not been directly dated or have reequilibrated during lower pressure metamorphism. Estimates of the age high-pressure metamorphism vary from 130 Ma to as old as 180 Ma, but commonly are compared with 160 Ma-blueschist reported from the Seward Peninsula (Armstrong and others, 1986).

Slate Creek subterrane

The southern part of the Coldfoot subterrane as mapped by Jones and others (1984) included the 5 to 10-km-wide phyllite belt which extends for over 500 km along the foothills of the southern Brooks Range. This topographically recessive belt, locally metamorphosed to lower greenschist facies, consists of phyllite, phyllonite, and metagraywacke. (Despite its texturally mature compositon, sandstone of the Slate Creek and Venetie subterranes has been described as "graywacke" because of dark green to gray coloration and chert-rich lithic composition). Patton and Box (1989) distinguished the phyllite belt from the Coldfoot as a separate tectonostratigraphic unit because of its probable tectonic contact with the Coldfoot subterrane, but linked it to the Angayucham terrane as"Slate Creek thrust panel of the Angayucham subterrane" because of it close association with that terrane. We agree with Patton and Box (1989) that the phyllite-metagraywacke belt should be distinguished as a separate tectonostratigraphic unit, but because of its quartz-rich composition and published interpretations of its origin as part of the Arctic Alaska terrane (e.g., Murphy and Patton, 1988), we describe it here as the Slate Creek subterrane of the Arctic Alaska terrane. This unit includes the Rosie Creek allochthon of Oldow and others (1987d).

The Slate Creek subterrane is structurally overlain to the south along the Angayucham fault by imbricated basalt, chert, and diabase of the Angayucham terrane (fig 28). The subterrane locally is depositionally overlapped by Albian and younger sedimentary rocks of the Koyukuk basin, beneath which the subterrane disappears to the west. The Slate Creek subterrane is truncated by the South Fork-Malamute fault system to the east, but is lithologically correlative with the Venetie subterrane in the southeastern Brooks Range (D.L. Jones, pers, comm., 1987; W.P. Brosgé, pers. comm., 1988). To the north, the subterrane overlies the Coldfoot subterrane along a south-dipping fault contact marked by mylonite (Gottschalk and Oldow, 1988; Dillon, 1986, 1989) near the Dalton Highway. In the Ambler district (Ambler River and Survey Pass quadrangles), where the Slate Creek subterrane is represented by the **Beaver Creek phyllite**, Hitzman and others (1982) interpreted the contact with the Coldfoot subterrane as a conformable gradational metamorphic boundary. Elsewhere, local mylonitic zones have been recognized along the northern margin of the subterrane and these may represent important zones of dislocation (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.

The Slate Creek subterrane consists of brown, dark gray, and black metamorphosed fine- to medium-grained sandstone, siltstone, shale, with radiolarian chert. At one location in the Ambler River quadrangle, Murphy and Patton (1988) reported that the assemblage contains impure limestone turbidites with coarse-grained carbonate platform and mafic volcanic debris, but other workers believe these strata may be in tectonic contact with the unit. No mappable internal stratigraphy has been recognized in the unit, but local zones of tectonic melange and broken formation are present along its southern margin near the Dalton Highway (Gottschalk, 1987; Dillon, 1989)

Where sedimentary structures are preserved, sandstone:shale ratios for the unit are typically about 1:4. Sandstone beds are thin- to medium-bedded and display erosive bases, shale ripup clasts, normal grading and well developed Bouma sequences (Murphy and Patton, 1988). Based on these observations, Murphy and Patton (1988) suggested that the subterrane consists largely of turbidites that may have been deposited in a deep-marine, possibly continental-slope environment. Gottschalk (1987), however, reported oscillation ripples and hummocky cross-stratification within the turbiditic strata and inferred shallow-water deposition for at least part of the unit. Flute casts and bottom markings indicate southward sediment transport east of the Dalton Highway (Gottschalk, 1987). Metagabbro dikes locally intrude these rocks (Nelson and Grybeck, 1980; Dillon and others, 1986; Dillon, 1989; Karl and others, 1989).

Point counts of seven sandstone samples from the Slate Creek subterrane by Murphy and Patton (1988) show that the graywacke protolith is compositionally mature, but texturally immature. These sandstones consist predominantly of angular to subangular, moderately sorted quartz and

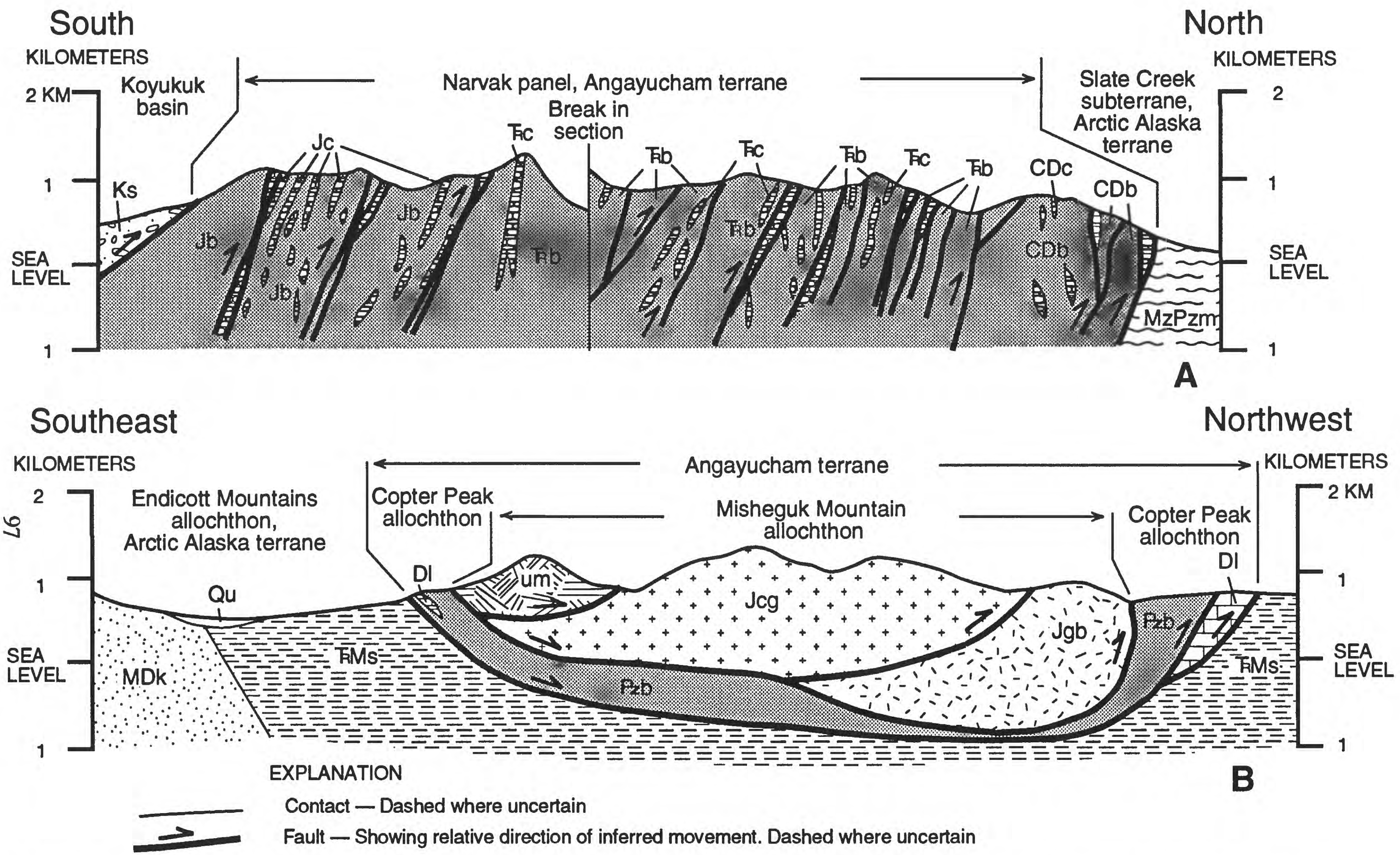


Figure 28. Relations of sections (no verical exaggeration) across Angayucham terrane. **A**, Greenstone belt in Angayucham Mountains, Hughes quadrangle (modified from Pallister and others, 1989). Note imbricate structure and progressively younger age of rocks in fault slabs from structural base to top in Nrvak panel. Abbreviations: Qu - Quaternary deposits, undivided Ks - Cretaceous sedimentary rocks; Jb - Jurassic pillow basalt, diabase, and microgabbro; Jc - Jurassic chert; TRb - Triassic pillow basalt, diabase, and microgabbro; TRc - Triassic chert; CDb - Devonian and Carboniferous pillow basalt, diabase, and microgabbro; CDc - Devonian and Carboniferous chert; MzPzm - Paleozoic and Mesozoic mélange. **B**, Crestal belt at Siniktanneyak Mountain, Howard Pass quadrangle (modified from Nelson and Nelson, 1982). Abbreviations: TRMs - Mississippian to Triassic fine-grained sedimentary rocks of undivided Kayak Shale and Lisburne and Etivluk Groups; MDk - Devonian and Mississippian(?) clastic sedimentary rocks of the Kanayut Conglomerate; Dl - fossiliferous Devonian carbonate rocks; Pzb - Paleozoic diabase and pillowed volcanic rocks; um - dunite, harzburgite, and pyroxenite; Jcg - Jurassic(?) cumulate gabbro ; Jgb- Jurassic(?) isotropic gabbro with plagiogranite dikes and stocks.

chert grains with sparse feldspar (average $Q_{74}F_9L_{17}$; $Qm_{21}F_9L_{70}$). Metamorphic rock fragments (7%) are the most abundant lithic grain type after chert, but sedimentary (4%) and volcanic rock fragments (6%) are common in these rocks. Matrix is abundant (10%) in the samples, suggesting partial derivation from poorly indurated lithic grains during diagenesis. Murphy and Patton (1988) concluded that the provenance of the subterrane is continental in character and included granitic, quartzose metamorphic, unfoliated sedimentary, and minor volcanic rocks. They further suggested that these lithologies were unroofed during a mid-Paleozoic continental-rifting event.

An Early Cretaceous or older age for the Slate Creek subterrane is indicated by Albian sedimentary rocks which unconformably overlie it, but the age of the assemblage is otherwise poorly known. The Beaver Creek phyllite in the Ambler district is assigned an Early Mississippian age by Hitzman and others (1986) because of its inferred gradational contact with structurally underlying Devonian to Mississippian rocks, but no fossils have been reported from this unit and the actual contact relationships are not well known. Palynomorphs in phyllite near the Dalton Highway indicate a late-Early Devonian (Siegian-Emsian) age (Gottschalk, 1987). However, Devonian palynomorphs are durable and are commonly reworked into younger deposits (e.g., Cretaceous Nanushuk Group rocks in NPRA; Quaternary sediments of the Arctic Ocean), indicating that an age as young as Early Cretaceous cannot be precluded for the unit (I.L. Tailleur, personal communication., 1988). Chert interbedded with graywacke, also near the Dalton Highway, contains Mississippian and Triassic radiolarian assemblages (Dillon and others, 1986) and nearby fault slivers of chert contain Mississippian and Triassic-Early Jurassic assemblages (D.L. Jones, in Murphy and Patton, 1988). Because it is unlikely that a clastic depositional environment would persist unchanged from Devonian through Triassic time, however, many workers believe that the chert ages are fault blocks of the Angayucham terrane that have been tectonically incorporated into the Slate Creek subterrane. In the Ambler River quadrangle, shallow-water conodonts reworked into limestone turbidites yield Devonian and Late Mississippian or Pennsylvanian (?) ages (A.G. Harris, 1984, in Murphy and Patton, 1988), but these ages may also be from a tectonic sliver incorporated along the faulted southern margin of the terrane.

Based on their review of the above data, Murphy and Patton (1988) favored a Devonian age for the rocks of the subterrane. These workers also proposed a correlation of the rocks of the subterrane to metagraywacke of similar age in the Venetie subterrane and suggested that they are the deep-marine equivalents of the Upper Devonian chert-rich clastic rocks of the Endicott Group in the Endicott Mountains subterrane. Oldow and others (1987d), on the other hand correlated the rocks of the Slate Creek subterrane with older Devonian rocks of the Hammond subterrane.

The Slate Creek subterrane displays incipient to pervasive development of white mica and chlorite along foliation surfaces and is interpreted to have undergone lower greenschist facies metamorphism, especially along its northern margin (Murphy and Patton, 1988; Gottschalk and Oldow, 1988; Dusel-Bacon and others, 1989). Dillon (1989) explained this foliation as the product of a single metamorphic episode and contrasted it with polymetamorphosed, higher grade rocks in the Coldfoot subterrane to the north. Gottschalk (1987), however, reported that the Slate Creek subterrane displays evidence for the same deformational events as the higher grade rocks of the underlying Coldfoot subterrane, but inferred that deformation occurred at a shallower depth and hence, at a lower metamorphic grade, then did deformation of the Coldfoot subterrane.

Venetie subterrane

Jones and others (1987) defined the Venetie terrane as consisting of a structurally complex assemblage of graywacke, phyllite, and chert that mostly structurally overlies the Ruby terrane in central Alaska, but extends northeastward into the Christian and Arctic quadrangles in the southeastern Brooks Range. Rocks of the Venetie terrane appear to cross an important structural boundary where the Ruby and Arctic Alaska terranes abut in the southern Chandalar quadrangle (Jones and others, 1986; Grantz and others, 1991). Rocks like those assigned to the Venetie subterrane can be traced southwestward along the southern edge of the Brooks Range through a series of scattered exposures in the southern Chandalar quadrangle into the Slate Creek subterrane.

Although Venetie subterrane may possibly be distinguished from the Slate Creek subterrane by its lesser metamorphic grade, its more easterly position, and the greater width of its belt of exposure, many workers consider these two units to be lithologically correlative (e.g., Murphy and Patton, 1988). Because the part of the Venetie terrane of Jones and others (1987) in the Brooks Range may be significantly displaced from the remainder of that terrane to the south, we believe that the Brooks Range part should be distinguished from the major part of the Venetie. For these reasons, in this paper we treat the Venetie rocks in the southeastern Brooks Range as a subterrane of the Arctic Alaska subterrane comparable to the Slate Creek subterrane.

The Venetie subterrane structurally overlies the Endicott Mountains subterrane to the north, the Hammond subterrane to the west, and the Coldfoot subterrane to the southwest. The mafic and ultramafic rocks of the Christian complex of the Angayucham (Tozitna) terrane structurally overlie the Venetie subterrane on the east, and the Venetie subterrane is separated by a fault from the Ruby terrane to the south. The stratigraphy of the Venetie subterrane has not been described in detail, although Howell and others (1986, fig. 2) estimate its structural thickness to be about 3 km. The following general description is from Brosgé and Reiser (1962), W.P. Brosgé (pers. comm., 1988), and D.L. Jones (pers. comm., 1987).

The Venetie subterrane is composed largely of micaceous fine- to medium-grained, gray-green lithic sandstone and interbedded shale with bedding thicknesses generally less than 1 m. In the western part of the terrane, these clastic rocks display low-grade metamorphic assemblages and phyllitic to schistose fabrics. Fine-grained quartzite beds locally interdigitate with the graywacke and appear to become more abundant higher in the section (Brosgé and Reiser, 1962). The stratigraphic thickness of this clastic is estimated to be more than 600 m, although the structural thickness of the sequence is likely to be much larger. Sandstone:shale ratios average about 3:1 in the graywacke-rich lower part unit, but may be higher where quartzite is present in higher parts of the section. Sedimentary structures indicate that this clastic sequence consists largely of turbidites (D.L Jones, pers. comm., 1987; W.P Brosgé, pers. comm., 1988). Murphy and Patton (1988) reported point counts of two sandstones from the Venetie subterrane which show that the rocks are enriched in quartz and depleted in feldspar (average composition of Q_{87} F_0 L_{13} and Qm_{37} F_0 Lt_{63}). Lithic fragments are dominated by chert (14% of total grain population), but metamorphic (12%) and sedimentary rock fragments (average 3%) are also present. Volcanic lithic grains are rare. Matrix comprises as much as 20 percent of these rocks, suggesting partial derivation from poorly indurated lithic grains modified by diagenesis. Brosgé and Reiser (1962) reported that the clastic rocks are interbedded with less than 100 m of thinly bedded red, green, and black radiolarian chert, siliceous argillite, and argillite. These rocks may alternatively be fragments of the siliceous Upper Paleozoic rocks of the De Long Mountains (Sheenjek) subterrane, implying tectonic juxtaposition with the structurally lower clastic rocks of the Venetie subterrane.

The age of the Venetie subterrane is poorly constrained. Palynomorphs from shale beds at two localities in the graywacke unit yield Early(?) Devonian (J.M. Schopf, written comm. to W.P. Brosgé, 1973) and Middle or Late Devonian ages (R.A. Scott, written comm. to W.P. Brosgé, 1965) and plant fossils from the latter locality indicate a Late (?) Devonian age (S.H. Mamay, 1962 and written comm. to W.P. Brosgé, 1962). Radiolarians recovered from the chert thought to be interbedded with graywacke include Mississippian assemblages, whereas radiolarians contained in bedded chert near the structural top of the terrane have been identified as Triassic and Permian in age (D.L. Jones, pers. comm., 1987). Mississippian radiolarian ages (B.K. Holdsworth, written communication to W.P. Brosgé, 1978; 1979), a probable Mesozoic radiolarian age (D.L. Jones and B.L Murchey, written communication to W.P. Brosgé , 1981), and a possible Permian conodont age Bruce Wardlaw, personal. communication to W.P. Brosgé, 1979) were also obtained from chert associated with the Venetie subterrane.

Assuming the Upper Paleozoic siliceous sedimentary rocks are part of the Venetie subterrane, a stratigraphy may be inferred for the subterrane consisting from base to top, of Middle and/or Upper Devonian and Mississippian quartz- and chert -rich graywacke, quartzose clastic rocks of undetermined age, and bedded chert of Mississippian, Permian and Triassic age. The age, lithologies and composition of this inferred sequence is similar to the Endicott Mountains or De

Long Mountains subterranes in the western Brooks Range. However, the Devonian clastic rocks of the Venetie subterrane appear to be composed of deeper marine clastic deposits than the coeval clastic rocks of these subterranes. These features may suggest that the Venetie subterrane is a more distal facies, possibly as a continental-rise succession, of the Arctic Alaska terrane.

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 (figs. 3, 26, and 28). Jones and others (1986, 1987) assigned most of the rocks of both areas to the Angayucham terrane, a terrane which also includes similar rocks resting on the Ruby terrane in central Alaska. However, Jones and others (1987) assigned lithologically correlative rocks in the eastern Brooks Range (Christian quadrangle) to the Tozitna terrane, a terrane in central Alaska lithologically similar to the Angayucham terrane, but distinguished by the presence or absence of certain key lithologies (e.g., andesitic breccia units in the Tozitna terrane). In this paper, we modify the terminology Jones and others (1987) in order to reflect a possibly major crustal boundary at the intersection of the Ruby and Arctic Alaska terranes in the southern Chandalar quadrangle by restricting the Tozitna terrane to mafic and ultramafic rocks resting structurally on the Ruby terrane and the Angayucham terrane to mafic and ultramafic rocks resting structurally on the Arctic Alaska terrane. Therefore, in our terrane nomenclature, the Angayucham terrane is restricted to northern Alaska.

Within northern Alaska, the mafic rocks of the Angayucham terrane have been divided into two major structural packages (fig. 27). 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 over 500 km along the southern margin of the Brooks Range. This belt consists principally of imbricated Paleozoic and Mesozoic diabase and mafic volcanic rocks with local gabbro and ultramafic rocks and is exposed in the southern foothills of the Brooks Range (Wiseman, Survey Pass, Hughes, and Ambler River quadrangles). 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. Patton and Box (1989) also included the Venetie and Slate Creek subterranes of the Arctic Alaska terrane in their Angayucham-Tozitna terrane as the Slate Creek thrust panel based on their spatial association with those rocks, but as explained above we believe that these sedimentary units display greater compositional affinity to the Arctic-Alaska terrane than to the Angayucham terrane.

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. 28). 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 mélange, cataclasite, and mylonite (Hitzman and others, 1986; Dillon, 1989). Hitzman and others (1982,1986) referred to this fault as the Angayucham thrust fault in the Ambler River quadrangle, whereas near the Dalton Highway, Gottschalk (1987) and Gottschalk and Oldow (1988) named it the Cathedral Mountain fault zone. 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, oral. commun., 1988; 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 aphyric. 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 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, written commun., 1987). 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 1,500 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 rare-earth-elements (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 Mountains 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 anomolies 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 (fig. 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 constrast with the largely ultramafic rocks and gabbro of the Misheguk Mountain allochthon.

Important bodies comprising this belt include massifs at Iyikrok Mountain, Asik Mountain, Maiyumerak Mountains, Avan Hills, Copter Peak, Misheguk Mountain, Pupik Hills, Siniktanneyak Mountain, and Kikiktat Mountain (Baird Mountains, DeLong Mountains, Misheguk Mountain, Howard Pass, and Killik River quadrangles) (fig.26). In the southeastern Brooks Range, the belt of klippen is represented by the extensive Christian massif (Christian quadrangle) which was included in the Tozitna terrane by Jones and others (1987). Where mapped, the maximum thickness of the klippen is estimated to be about 5 km (Ellersieck and others, 1984; Nelson and Nelson, 1982). A gravity high over the Maiyumerak Mountains has been suggested to require a much greater thickness for that body (D. Barnes, pers. comm., 1988; K.R. Wirth, oral comm., 1987), but may also be explained as the product of its steep northwesterly dip.

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. 28). 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. Rare-earth-element patterns for most of the mafic rocks show moderate enrichment in light rare-earth elements, whereas others ar 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 levels.

Age and structural relations of the rocks of the Copter Peak allochthon are constrained largely 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, oral. commun., 1987; B.L. Murchey, written commun., 1987; Mull and others, in press). 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. 28). The ultramafic rocks consists largely of dunite with chromitite layers and subordinate harzburgite, wehrlite, and pyroxenite (Zimmerman and Soustek, 1979; Bird and others, 1985). Isoclinal folds and other evidence of folding while in a ductile state are common. 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 uralitized clinopyroxene and commonly displays large 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). Dikes and stocks of potassium feldspar-granitic rocks have been reported to intrude ultramafic rocks and gabbro in a number of the massifs and may represent a later plutonic episode (Nelson and Nelson, 1982; Zimmerman and others, 1981) or partial melts generated during emplacement of the bodies while hot (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 textures (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 (Tailleur, 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; and (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 and low pressures 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; Mull and others, in press). 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).

The structurally lower Narvak panel and the Copter Peak allochthon have been interpreted by many workers to be an imbricated assemblage of mainly oceanic plateau and island basalts possibly assembled in the forearc region of an oceanic subduction zone (Box, 1985; Patton and Box, 1989; Barker, 1988; Pallister and others, 1987, Grantz and others, 1991). Based on its geologic setting, geochemistry, sedimentary debris in the syntectonic Okpikruak Formation (Mayfield and others, 1978), and the local presence of potassium-feldspar-bearing intrusive units, on the other hand, the Kanuti thrust panel and Misheguk Mountain allochthon may represent the subcrustal portions of an ophiolite that once lay beneath a contemporaneous volcanic arc. The two allochthonous sequences may therefore represent contiguous forearc elements of a mid-Mesozoic intraoceanic arc-trench system that were assembled in the Middle Jurassic and later emplaced together onto the Arctic-Alaska terrane during the Early Cretaceous (Box, 1985). The Misheguk Mountain allochthon is unusual for Cordilleran ophiolites in that (1) it rests structurally above continental sedimentary rocks of the Arctic Alaska terrane rather than above graywacke flysch; and (2) its basal contact is marked by narrow zones of amphibolite rather than blueschist facies metamorphic rocks. These features instead suggest an affinity with ophiolites of the Mediterranean realm (Coleman, 1984).

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 1,000 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 pre-orogenic 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. Further, 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 post-orogenic 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. 29). These provinces are defined by their

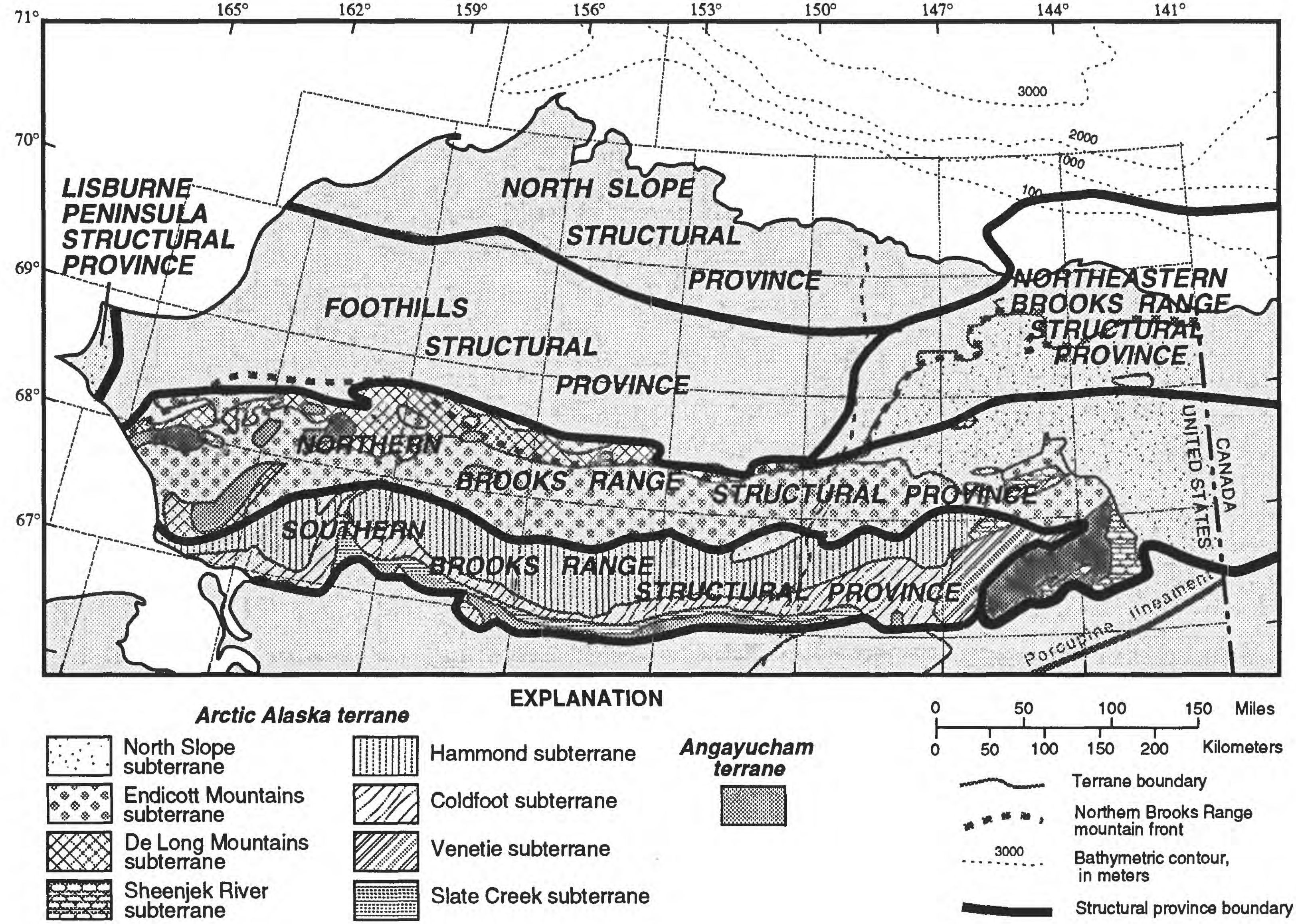


Figure 29. Structural province map for northern Alaska.

structural characteristics (table 2), but they coincide approximately with the physiographic 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 (fig. 29) 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. To the south, rocks of the province dip to the south beneath the Koyukuk 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 greenstone belt of the 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 (pl. 1, 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 than10-km-thick imbricate stack of 1- to 3-km-thick thrust sheets (Oldow and others, 1987d; 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, 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).

Table 2. Characteristics of the structural provinces of northern Alaska [structural provinces shown on figure 29]

Structural province	Southern Brooks Range	Northern Brooks Range	Foothills
Terrane nomenclature	–	Arctic Alaska terrane: North Slope, Endicott Mountains, and De Long Mountains subterranes. Angayucham terrane (crestal belt).	Arctic Alaska terrane: North Slope subterrane and overlying Albian and younger foredeep deposits.
Stratigraphy	Arctic Alaska terrane: metamorphosed clastic, carbonate, volcanic, and plutonic rocks. Mainly Proterozoic to Late Devonian age, only locally younger. Angayucham terrane: Devonian to Jurassic basalt and subordinate chert, limestone, and argillite.	North Slope subterrane: Stratified clastic and carbonate rocks; mainly Mississippian through Triassic age, pre-Mississippian rocks only locally. Endicott Mountains, De Long Mountains, & Slate Creek subterrane: Stratified clastic and carbonate rocks; mainly Late Devonian through Early Cretaceous age. Angayucham terrane: Devonian to Triassic basalt and Jurassic(?) peridotite and gabbro.	Albian and younger clastic rocks shed northward and eastward from the Brooks Range into the Colville basin. Deposited on gently south-dipping pre-orogenic deposits.
Boundaries	Northern, eastern, and western: Separated by thrust fault dipping beneath structurally higher northern Brooks Range province. Southern: Depositionally overlapped by Cretaceous of Koyukuk basin. Internal: Thrust faults separate North Slope from Hammond and Hammond from Coldfoot. Thrust and(or) normal faults separate Coldfoot from Slate Creek and Slate Creek from Angayucham.	Northern and western: Depositional overlap by mid-Cretaceous 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: Structurally overlies southern Brooks Range province on thrust fault. Internal: Constituent allochthons underlain by thrust faults.	Northern: Separated by northern front of compressional deformation from North Slope province. Eastern: Zone of transition to similar, but probably younger, structures of the northeastern Brooks Range province. Southern: Mid-Cretaceous foredeep deposits of the foothills province depositionally overlap rocks of the northern Brooks Range province. Boundary modified by late Brookian deformation. Western: Overthrust by Lisburne Hills province.
Early Brookian structural characteristics	North Slope, Hammond, and Coldfoot subterranes: Penetratively poly-deformed. Dominantly north-vergent. Large thrust-bounded fault slices. Major and minor tight to isoclinal folds associated with thrusting. At least two generations of minor fold and associated foliation. Thrusting outlasted ductile deformation. Slate Creek subterrane: Polydeformed, but monometamorphic. Major thrust faults. Angayucham terrane: Brittle major and minor imbricate thrust faults	All units: Dominantly north-vergent folding and thrusting. Penetrative structures and metamorphic overprint occur only locally, mainly associated with major thrust faults. North Slope subterrane: Closely spaced north-vergent folds and imbricate thrust faults. Endicott and De Long Mountains subterranes: Apparent structural stack of up to five regionally extensive, but commonly laterally discontinous thrust packages or "allochthons". Apparently consistent structural stacking order. Common intra-allochthon deformation in the form of folds and duplexes; character and intensity varies according to location and stratigraphic character. Angayucham terrane: Comprises the two structurally highest allochthons, which appear to have behaved as coherent thrust sheets with little internal deformation.	Not affected by early Brookian deformation.
Early Brookian metamorphism	North Slope subterrane: Lower greenschist to prehnite-pumpellyite. Hammond and Coldfoot subterranes: Lower to upper greenschist facies and blueschist facies; grade increases southward. Slate Creek subterrane: Lower greenschist facies. Angayucham terrane: Lower greenschist to prehnite-pumpellyite facies.	Incipient metamorphism to lower greenschist facies. Conodont color alteration index (CAI) values indicates metamorphism at <300°.	Not affected by early Brookian metamorphism.
Late Brookian structural characteristics	North Slope, Hammond, Coldfoot subterranes: Uplift and locsl south-vergent folding and faulting. All units: Broad ENE- to WSW-trending doubly plunging open folds. All units (but mainly Slate Creek subterrane and Angayucham terrane): South-dipping low-angle normal faults. East-trending high-angle faults, south side down, probable major right-lateral strike-slip displacement.	All units: Apparent regional west plunge with progressively deeper structural levels exposed eastward. This and a local structural low in the southeastern Brooks Range may be due to regional changes in structural relief as a result of late Brookian deformation. North Slope subterrane: No apparent basis for distinguishing early and late Brookian structures. Endicott and De Long Mountains subterranes and Angayucham terrane: Broad anticlines and synclines superimposed on early Brookian allochthons largely define regional structural trends. Smaller late Brookian folds and faults probably present but difficult to distinguish from earlier structures. Range-front structure postdates emplacement of allochthons and mid-Cretaceous foredeep deposition; defined by abrupt northward decrease in structural relief.	North-vergent folding and thrusting mainly above detachment in Torok Formation; stratigraphically lower units locally involved in deformation to the south. Broad synclines and narrow anticlines commonly associated with thrust faults. Structural relief and intensity of deformation decreases gradually northward.
Structural characteristics of Canada basin rifting	Probably not significantly affected by rifting in Canada basin.	Not significantly affected by rifting in Canada basin.	Not significantly affected by rifting in Canada basin.

Table 2. Characteristics of the structural provinces of northern Alaska (continued).

Structural province	Lisburne Peninsula	Northeastern Brooks Range	North Slope
Terrane nomenclature	Arctic Alaska terrane: North Slope(?) subterrane.	Arctic Alaska terrane: North Slope subterrane. Also includes overlying Albian and younger foedeep deposits in the foothills and Arctic coastal plain.	Arctic Alaska terrane: North Slope subterrane. Also includes overlying Albian and younger foredeep deposits in the foothills and Arctic coastal plain.
Stratigraphy	Pre-Mississippian clastic rocks unconformably overlain by Mississippian to Lower Cretaceous carbonate and clastic sequence.	Heterogeneous assemblage of sedimentary and igneous rocks deformed in pre-Mississippian time; Mississippian to Lower Cretaceous carbonate and clastic sequence; Albian and younger foredeep deposits.	Mainly argillitic pre-Mississippian rocks erosionally overlain by northward thinning Mississippian to Lower Cretaceous south-facing clastic and carbonate continental margin succession. Progradational Albian and younger 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.
Boundaries	Northern and eastern: Thrust over foredeep deposits of the foothills province. Northwestern: Offshore continuation (Herald arch) thrust over foredeep deposits. Southern and western: Depositionally overlapped offshore by deposits of younger Hope basin.	Northern and northeastern: Separated from rocks of Canada basin by northern front of compressional deformation. Northwestern: Separated from North Slope province by northern front of compressional deformation. Eastern: Transitional to north-trending structural low in Canasda. Western: Transitional from similar, but probably older structures of foothills province. Southern: Transitional in structural style to northern Brooks Range province.	Northern: Separated from rocks of Canada basin by tectonic hinge line marked by zone of significant down-bowing 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 down-bowing of pre-Albian rocks.
Early Brookian structural characteristics	Probably not significantly affected by early Brookian deformation.	Probably not significantly affected by early Brookian deformation.	Not affected by early Brookian deformation.
Early Brookian metamorphism	Little or no early Brookian metamorphism.	Little or no early Brookian metamorphism.	Not affected by early Brookian metamorphism.
Late Brookian structural characteristics	East-vergent thrust faults and associated folds. Related east-vergent structures probably have been superimposed on adjacent parts of the foothills and northern Brooks Range provinces.	Northward-convex, north-vergent arcuate foldbelt. 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. Foothills and coastal plain: Sharp northward decrease in structural relief from mountains, although similar structures probably present in subsurface. Foredeep deposits display broad synclines and narrow anticlines at the surface, probably underlain by complex north-vergent imbricate thrust faults at depth. Structural relief and intensity of deformation decreases gradually northward.	Not affected by late Brookian deformation.
Structural characteristics of Canada basin rifting	Not significantly affected by rifting in Canada basin.	Jurassic to Cretaceous extensional faulting (Dinkum graben); northward down-bowing of south-dipping pre-Cretaceous continental margin deposits (the Barrow arch); local uplift and erosion along Barrow arch in late Neocomian time. Overprinted by late Brookian compressional structures.	Jurassic to Cretaceous extensional faulting (Dinkum graben); listric faulting offshore; minor extensional faulting in subsurface; northward down-bowing of pre-Cretaceous south-dipping continental margin deposits (the Barrow arch); local uplift and erosion along Barrow arch in late Neocomian time.

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 (1986) suggested that narrow metamorphic aureoles around these plutons indicate emplacement at a high structural level. Late 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, oral commun., 1992). Although presently there is considerable discussion about the timing and significance of some of these fabrics, particularly in the Coldfoot and Slate Creek subterranes (for example, Miller and others, 1990), 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 at all scales, from thin-section to map 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 and also present in the North Slope subterrane in the Mt. Doonerak fenster, 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 two sets of structures are attributed by Gottschalk (1990) to progressive deformation and metamorphism of the Brookian orogeny under conditions of top-to-the-north ductile shear, but was attributed by Dillon (1989) to pre-Devonian deformation. 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 presently unclear if structures of the Dalton Highway area are representative of structures along strike. A.B. Till (written comm., 1990) 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) underwent a structural history comparable to that of rocks of the Coldfoot subterrane in the Dalton Highway area. In the Ambler River quadrangle, Hitzman and others (1986) described three generations of folds formed during Brookian metamorphism in the Coldfoot subterrane. They reported that early folds are tight, north-trending F_2 folds with axial planar schistosity and were followed by recumbent, tight to isoclinal F_3 folds with west-northwest trending axes formed during the highest pressure phase of metamorphism. This later phase represented a major deformational event, with folds ranging from microscopic scale to several kilometers in wavelength. Open to tight F_4 folds are subparallel with F_3 axes, but dip more steeply and were formed during lower pressure retrograde metamorphism. A number of thrust faults occur within the area and generally parallel F_3 axial surfaces. These faults cut F_2 through F_4 folds. In the Survey Pass quadrangle, Grybeck and Nelson (1981) described polyphase folding and thrust-faulting in the Hammond subterrane, but did not recognize a regionally consistent deformation as sequence. Most of the folds reported by them are isoclinal, commonly recumbent, and range from microscopic to amplitudes in the hundreds of meters. Fold axes vary in orientation, but most are east-trending with gently dipping axial surfaces.

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 as both 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. 30). In the Ambler River and Survey Pass quadrangles, 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 which 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** (fig. 30), 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) (pl. 1, section *B-B'*). 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 (pl. 1, 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

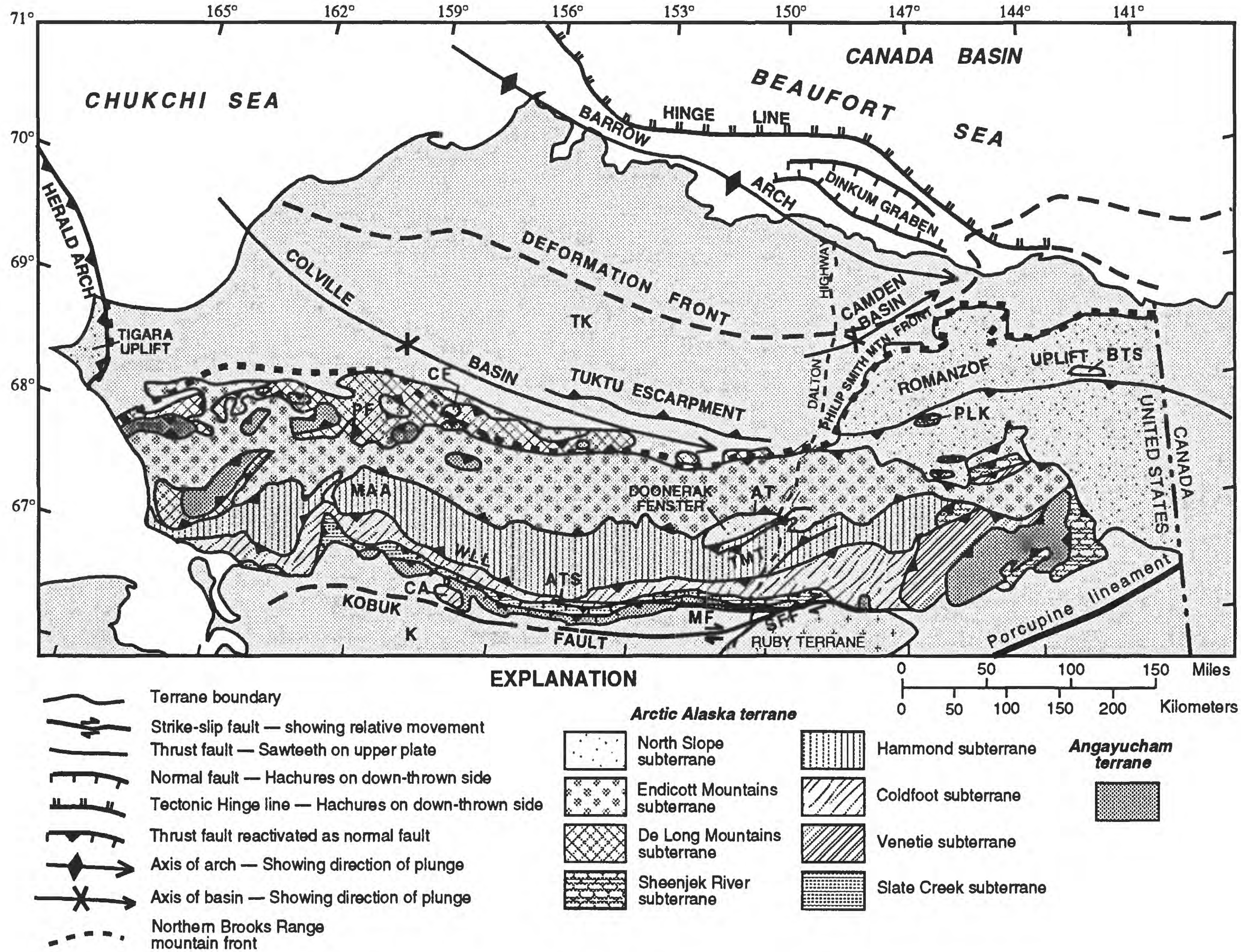


Figure 30. Map showing major tectonic features of northern Alaska. Abbreviations: TK--Cretaceous and Tertiary rocks of the Brookian sequence; K--Cretaceous rocks of Koyukuk basin; AT--Amawk thrust; ATS-- Angayucham "thrust" system; BTS--Bathtub syncline; CA--Cosmos arch; CR--Cutaway fenster; MAA--Mount Angayukaqsraq antiform; MF--Malamute fault; PF--Picnic Creek fenster; PLK--Porcupine Lake klippe; SFF--South Fork fault; TMT--Table Mountain thrust fault; WLL Walker Lake lineament.

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) consider this boundary a north-dipping 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 kb) metamorphism in a crustal-scale, north-vergent duplex that was bounded above by a décollement. Above the décollement, which acted as the roof thrust of the duplex, rocks of the Hammond subterrane were imbricated under lower pressure (< 5-6 kb) conditions. Later, the décollement was 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 and Venetie subterranes. 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 others (1990), 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.

Hitzman and others (1982) interpreted the contact between the Coldfoot and Slate Creek subterranes in the Ambler River quadrangle as lithologically gradational, but representing an abrupt southward decrease in metamorphic grade. Elsewhere, however, the contact is a moderately south-dipping fault (Mull and others, 1987c; Oldow and others, 1987d; Dillon, 1989; Grantz and others, 1991) marked by a significant decrease in metamorphic grade from the footwall to the hangingwall. According to Dillon (1989), this fault is marked by a mylonite zone and is the structurally lowest of three parallel strands of what he calls the "Angayucham thrust system". The middle strand separates two major thrust panels within the Slate Creek subterrane (an upper metagraywacke panel and a lower phyllite panel), and is marked by a zone of broken formation. The upper strand is represented by melange separating the Slate Creek subterrane from the structurally overlying Angayucham terrane.

Greenstone belt of the Angayucham terrane. The Angayucham terrane dips gently to moderately southward, and its base is defined by a complex fault zone, commonly a unit of mélange (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 instance, Pallister and others (1989) described multiple 1-km-thick fault slabs of mostly basalt, as well as a complex mélange 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).

Timing of early Brookian deformation in the southern Brooks Range province. Major early Brookian north-vergent deformation and associated metamorphism occurred within the southern Brooks Range during Late Jurassic to Early Cretaceous time (Hitzman and others, 1986; Dillon, 1989). Metamorphism and associated penetrative structures (S_2 and S_3) overprint rocks at least as young as Upper Devonian in the Hammond and Coldfoot subterranes and at least as young as Triassic in the North Slope subterrane in the Doonerak window (Dillon, 1989). Late metamorphism and penetrative structures (S_3) overprint the Slate Creek subterrane, which includes rocks at least as young as Devonian (Oldow and others, 1987c, Dillon, 1989). Faults of the Angayucham thrust system cut rocks as young as lower Jurassic in the southern portion of the Angayucham terrane (Dillon, 1989). It should be noted, however, that at least some of these faults may have formed originally or been reactivated as normal faults after the major early Brookian phase of thrusting (Carlson, 1985; Box, 1987; Miller, 1987; Oldow and others, 1987a,b,c).

Major thrust displacements predate the onset of Albian to Cenomanian marine to non-marine deposition in the Koyukuk basin (Fig. 30). This is indicated because these deposits unconformably overlie rocks of the southern portion of the Angayucham terrane and faults which cut it (Patton and others, 1977; Dillon and Smiley, 1984; Dillon, 1989). In addition, Dillon (1989) suggested that upward changes in clast composition within these deposits reflect progressive unroofing of deeper thrust sheets within the southern Brooks Range structural province.

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). 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 kb (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 pressure-temperature path that evolved from low- to high-temperature 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, oral commun., 1992). 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 that were 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 constrain 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 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 to100 Ma (Turner and others, 1979; Mull, 1982; Dillon, 1989; Blythe and others, 1990). 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. Previously, uplift in the core of the range was 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). North-vergent late Brookian shortening probably has also contributed to the exposure of deeper structural levels in the southern Brooks Range. This is best documented for the Doonerak window, where uplift has been attributed largely to shortening and structural thickening of rocks of the North Slope subterrane in a north-vergent duplex beneath the structurally overlying Endicott Mountains and Hammond subterranes (Oldow and others, 1987c). Recent work also suggests that a genetic relationship is likely between extension and uplift in the core of the range (Oldow and others, 1987a,b,c), although it is not yet clear whether extension was the cause or the consequence of uplift.

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; pl. 1). 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 a number of workers (Carlson, 1985; Box, 1987; Miller, 1987; Oldow and others, 1987a, c, d; Gottschalk and Oldow, 1988; Miller and others, 1990) 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 others (1990) reported that kinematic indicators support down-to-the-south displacement on gently south-dipping faults in the Ambler and Wiseman quadrangles. Miller and others (1990) 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 pre-existing 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.

If major extension has occurred along the south flank of the Brooks Range, a number of major tectonic problems in the Brooks Range may be resolved. Extension would have caused rapid tectonic denudation of the now most highly uplifted portion of the Brooks Range, the Hammond and Coldfoot subterranes. Denudation and associated uplift could account for both the local preservation of high P/T metamorphic assemblages, and their widespread overprinting by lower P/T metamorphism. Tectonic denudation could also account for the large amount of structural section missing above the metamorphic rocks of the core of the range, as indicated by the abrupt upward and southward decrease in metamorphic grade across some faults on the southern flank of the range. Major extension could also help explain the apparent absence of stratigraphic basement for many of the allochthons of the northern Brooks Range structural province. The missing structural section may have been displaced down and southward beneath the Yukon-Koyukuk basin during extensional faulting. The extension could account for the origin of theKoyukuk basin filled with mid-Cretaceous sedimentary detritus that was shed southward into the hinterland of the Brooks Range orogen and for the structurally low position of the structurally highest elements of the Brooks Range (i.e., the Angayucham terrane) beneath the sedimentary rocks of the Koyukuk basin.

South-vergent structures in the Hammond and Coldfoot subterranes. Structural vergence in the southern Brooks Range province is most commonly to the north, but relatively late south-vergent structures are widespread, particularly in the southern part of the Hammond and Coldfoot subterranes. Penetrative south-vergent small folds and crenulation cleavage have been described by Seidensticker and others (1987) and are interpreted to have formed during dominantly northward tectonic transport. Larger south-vergent structures have been recognized in the southern part of the range (Fig. 30). The most common south-vergent structures are folds (Mull, 1977; Hitzman and others, 1986), but south-vergent thrust faults have been recognized locally (Nelson and Grybeck, 1980). The cause of this south-vergent deformation has been variously attributed to a shift from southward to incipient northward subduction (Mull, 1977), vertical uplift due to isostatic rebound (Mull, 1982), or formation of structures which are conjugate to the dominant gently south-dipping, north-vergent structures (Seidensticker and others, 1987). The age of the south-vergent structures is poorly constrained except that they post-date early Brookian north-vergent structures and thus formed during or after major uplift in the southern Brooks Range. Similar late and antithetic structures are common in the hinterland portions of many orogenic belts in the world.

Folding in the southern Brooks Range. Post-metamorphic 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 in the 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 map-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, Kalurivik arch of Hitzman and others, 1982). Although these folds generally cannot be demonstrably related 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.

Early Brookian folds, faults, and penetrative structures have been overprinted by this generation of structures (Dillon, 1989). Albian clastic deposits along the southern flank of the Brooks Range display upright to north-overturned folds of this generation (Dillon, 1989). Gently dipping faults beneath Cretaceous clastic rocks in the Ambler district are considered to be thrust faults by Hitzman and others (1982) presumably belong to this generation of structures, though younger-over-older relationships across many of these faults suggests the possibility that they may be low-angle normal faults. No upper limit on the age of late folding has been established in the southern Brooks Range.

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. 30). 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 southern foothills belt 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) suggested that large-magnitude, right-lateral strike-slip displacement has occurred along the Malamute-South Fork fault system. In one place, strands of the Angayucham thrust system show 40 km right-separation across the Malamute fault. In another, hornfelsed phyllite within the Malamute-South Fork fault system is separated to the right 90 km from its probable source, a Cretaceous pluton north of the Malamute fault. Considerably greater right-lateral displacement is required if the pluton is offset from the nearest Cretaceous pluton south of the South Fork fault, in the Ruby geanticline. 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. The youngest rocks cut by right-lateral faults in the southern Brooks Range are Albian to Cenomanian clastic deposits of the Koyukuk basin which are cut by the Malamute-South Fork fault system. Dillon (1989) suggested that abrupt facies changes parallel to the fault system and chaotic mass-flow deposits indicate that deposition may have been synchronous with faulting.

Down-to-the-south apparent offset is characteristic both of the Kobuk and Malamute-South Fork fault systems and the other minor faults to the north, suggesting that a component of normal dip-slip displacement. Box (1987) suggested that right-lateral displacement on the Kobuk fault system and extension in the southern Brooks Range may reflect a single transtensional event. Dillon (1989), on the other hand, suggested the possibility that post-metamorphic broad folds, regional uplift, and right-lateral strike-slip displacement on the Kobuk and Malamute-South Fork fault system may reflect a single transpressive event.

A major northeast-striking lineament, called the **Porcupine lineament** by Grantz (1966), parallels the Porcupine River southeast of the Brooks Range (fig. 30). 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 eastcentral Alaska and is widely 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 2,000 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. 30). 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 (fig. 29), containing much of the preserved superstructure of the main axis of the Brooks Range orogen, 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 (pl. 1). It consists of the Endicott Mountains, De Long Mountains, and Sheenjek subterranes of the Arctic-Alaska terrane, the southern, highly deformed part of the North Slope subterrane, and the northern belt of klippe of the Angayucham terrane. It is characterized by a stack of extensive, far-traveled, but internally deformed thrust packages defined by distinctive sequences of stratified Upper Devonian to Lower Cretaceous rocks. 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.

For the most part, the boundary between the southern and northern Brooks Range provinces is a thrust fault dipping beneath the structurally higher northern Brooks Range province. To the north and west, on the other hand, the province is bounded over much of its length by the foothills structural province, a relative structural low containing deformed foredeep deposits derived from the orogen itself. The boundary is defined by depositional overlap by the mid-Cretaceous and younger foredeep deposits, though this depositional boundary has been modified by late Brookian deformation in many places. To the northeast, the province is bounded by the northeastern Brooks

Range structural province, which was deformed and uplifted late in the tectonic evolution of the region, after early Brookian major shortening in the northern Brooks Range structural province. This boundary is a zone of transition between the structural styles characteristic of the two provinces.

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. 26 and 30), seven allochthonous sequences have been recognized (fig. 26). 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. As described in earlier parts of this paper, 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 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 autochthonous to parautochthonous relative to the above units are those of the North Slope and the Hammond subterranes. 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. 30, pl. 1). 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 differs markedly from the coeval sequence in the structurally overlying Endicott Mountains allochthon (fig. 27). 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,c; 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 percent shortening to account for thrust imbrication and macroscopic folding within the allochthon.

Much of the southern Brooks Range structural province (for example, Mt. Doonerak fenster and Schwatka Mountains) and the deformed parts of the North Slope subterrane in the eastern and northeastern Brooks Range have been referred to as "autochthonous" or "parautochthonous" because of their stratigraphic affinity to rocks in the subsurface of the North Slope (Mull, 1982; Mayfield and others, 1988). However, these rocks have been transported northward above thrust faults, and hence, they are allochthonous in the strict sense (Oldow and others, 1987d; Till and others, 1988). They are referred to here as "parautochthonous" to distinguish them clearly from the more highly displaced allochthonous rocks that structurally overlie them and from the undisplaced, and hence truly autochthonous, rocks of the North Slope subsurface to which they appear stratigraphically related.

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. 30). 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 (pl. 1). 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.

Synorogenic deposits of the Okpikruak Formation are thick, incompetent, and relatively homogeneous. They consist mostly of shale to siltstone with subordinate more competent sandstone interbeds. Consequently, they are prone to an incoherent, broken-formation style of deformation, and probably have been structurally thickened in many places. Some of these deposits are olistostromes, so at least some of the stratal disruption is syndepositional (Mull and others, 1976). However, a post-depositional deformational overprint probably has affected most of these 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, 1987b; Kelley and Bohn, 1988; Handschy and Oldow, 1989). The shorter, steep to overturned limb 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 decreases 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 1,000 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 poorly constrained.

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 post-emplacement 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 rangefront 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. 30). 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 roughly corresponds 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, and 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, which 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. 30). 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 30). The klippe, composed of De Long Mountain 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. 30), 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).

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 mountain 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. 29) 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 percent) 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 (pl. 1, 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 pebble-shale-unit reflector (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 homoclinally 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 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 hence 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, with 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. 30), 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 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 Okpiruak 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 and display a northerly structural trend in sharp contrast with the trend of the other structural provinces of northern Alaska (fig. 30). These pre-Cretaceous and overlying lower Cretaceous deposits are deformed by west-dipping imbricate thrust faults and associated folds, which 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 map-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, 1975, 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 precisely constrained. 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). Minimum age of thrusting is constrained 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 oroclinally bent (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 (fig. 29) consists the eastern part of the the Arctic Coastal Plain and a prominent northward-convex arcuate topographic and structural salient, with respect to the northern Brooks Range structural province (fig. 30). 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 extensively exposed. 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; Wallace and Hanks, 1990; Howell and others, 1992; pl. 1). 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 all the way north to the continental margin. Because the salient represents a younger deformational belt, it is known by the separate term, the Romanzof uplift (fig. 30).

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). Further, 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 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); and (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 (pl. 1). 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 percent) 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 ANWR. Seismic reflection profiles suggest that these antiforms probably were 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 horsesin 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 probably was 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 sourced 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 lower 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. 30). 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. 2, 30).

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. 29) is characterized by nearly flat-lying strata of Mississippian and younger age and 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, Endicott) of the North Slope subterrane (figs. 10, 12). 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). 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 (e.g., Dinkum graben) (fig. 30) 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 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. 30). 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. East of Prudhoe Bay, the crest of inflection defining the Barrow arch plunges eastward beneath the northern part of the ANWR coastal plain, and not southeastward toward the Brooks Range as shown by Craig and others (1985, fig. 1) or as described by Mull (1985, p. 19) on the basis of exposures of the Lower Cretaceous unconformity.

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. For this reason, the Barrow arch has been called the "Barrow inflection" by Ehm and Tailleur (1985) and the "Beaufort sill" by Mull (1985) and Mull and others (1987c). The southern flank of the Barrow arch was established by late Paleozoic 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) . Rift-flank uplift adjacent to the nascent Canada basin resulted in exposure of the Barrow arch above sea-level an erosion in Valanginian to Albian time, producing the Lower Cretaceous unconformity. 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.

Cenozoic normal faults

Along the mid- to outer continental shelf, large-scale, listric normal faults, down-thrown to the north, are common (Grantz and May, 1983). These faults are interpreted as growth faults related to development of rotational megaslumps in Late Cretaceous and Cenozoic strata overlying and detached from rift-margin structures. Small-displacement normal faults of Cenozoic age with northwest or uncertain trends are observed in Harrison Bay (Craig and Thrasher, 1982), the Kuparuk oil field area (Werner, 1987), and in northeastern NPRA.

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 first discuss the evidence for post-Devonian linkage of the Arctic Alaska superterranes. We then 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. Finally, we 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.

Evidence of common origin for the Arctic Alaska subterranes

The division of northern Alaska into a series of terranes and subterranes by Jones and others (1987) allowed the possibility that northern Alaska may be composed of a number of unrelated crustal fragments. Most workers agree that the Angayucham and Tozitna terranes may be exotic to northern Alaska because of their possibly oceanic origin, the pelagic character of its associated sedimentary rocks, and because of its structural position separating the continental Arctic Alaska subterranes from the Jurassic and Lower Cretaceous island-arc rocks of the Koyukuk terrane to the south (e.g., Box, 1985; Mull, 1985; Patton and Box, 1989; Mayfield and others, 1988). The Arctic-Alaska subterranes, on the other hand, display a number of stratigraphic similarities that lead many workers to consider them as structurally disjunct fragments of the same continental mass, at least in post-Devonian time. These lines of evidence for stratigraphic linkage of the Arctic-Alaska subterranes are as follows: (1) the quartz-mica schist assemblage of the Coldfoot subterrane is lithologically similar to, and may be correlative with schists of probable Proterozoic age in the

Hammond subterrane based on their similar protolith compositions and absence of a marked boundary (Hitzman and others, 1986; Dillon, 1989); (2) the North Slope, Hammond, and Coldfoot subterranes have all been intruded by granitic plutons of similar composition that yield similar Devonian U-Pb crystallization ages (Dillon and others, 1987b), indicating these subterranes were linked by Devonian time; (3) the Hammond and Coldfoot subterranes each contain similar units of metamorphosed felsic volcanic rocks of Devonian age that may be extrusive equivalents of the Devonian plutons (Dillon and others, 1987b); (4) the lower Paleozoic rocks in both the North Slope and Hammond subterranes are overlain by a sub-Mississippian unconformity; (5) Upper Devonian and Lower Mississippian chert-clast-rich siliciclastic strata of the Endicott Group occur in the North Slope, Endicott Mountains, Hammond, and De Long Mountains (Picnic Creek allochthon) subterranes. Siliciclastic strata inferred to be related to these strata also compose much of the Venetie and Coldfoot subterranes (Murphy and Patton, 1988). Dillon and others (1986) also consider a metapelite units in the quartz-mica-schist assemblage of the Coldfoot subterrane to be correlative with the Beaucoup Formation and the Hunt Fork Shale of the Endicott Group in the Endicott Mountains subterrane; (6) black shale of Mississippian age (generally mapped as the Kayak Shale) occurs in the North Slope, Endicott Mountains, Hammond, Sheenjek, and De Long Mountains subterranes; (7) Carboniferous platform carbonate rocks of the Lisburne Group (Carboniferous) occur in the North Slope, Endicott Mountains, Hammond, and De Long Mountains (Kelly River and Nuka Ridge allochthons) subterranes. Black chert and shale interpreted to be the basinal equivalent of the platform carbonate of the Lisburne Group occur in the North Slope (Tupik Formation of the Lisburne Peninsula), Endicott Mountains (Kuna Formation), and De Long Mountains (Akmalik chert and equivalent units in the Picnic Creek, Kelly River, and Ipnavik River allochthons) subterranes; and (8) coarse to fine-grained siliciclastic strata of Permian and Triassic age (Sadlerochit Group and Shublik Formation) occur in the North Slope and Hammond subterranes. The Endicott Mountains, De Long Mountains, and Sheenjek subterranes each contain age-correlative finer grained rocks (Etivluk Group) consisting of various proportions of siltstone, argillite, pelagic limestone, siliceous shale and chert, which are considered to be the basinal equivalents of the siliciclastic deposits of the Sadlerochit Group and Shublik Formation.

Together, the above characteristics argue strongly for facies relationships and hence, for the stratigraphic linkages among the North Slope, Endicott Mountains, De Long Mountains, Hammond, and Sheenjek subterranes at least by post-Devonian time. The evidence for linkage is somewhat less certain for the Coldfoot, Venetie, and Slate Creek subterranes, but the age, stratigraphic, and compositional compatibility of these to parts of the other subterranes are suggestive such a linkage. None of the Arctic-Alaska subterranes are separated from each other by rocks of oceanic character (i.e., ophiolites) that may be indicative of suturing of originally widely separated terranes. However, all of the Arctic-Alaska subterranes occur to the north of and structurally beneath the rocks of Angayucham terrane, implying their derivation from positions north of or landward of the ocean basin represented by the rocks of the Angayucham terrane. These stratigraphic threads provide the basis for reconstructing pre-Cretaceous paleogeographic relationships among the subterranes of the Arctic-Alaska terrane.

Although the combined evidence argues against an exotic origin for the post-Devonian rocks of the Arctic-Alaska subterranes, two general features indicate that large-scale displacements may have occurred between the subterranes during Brookian orogenesis. These are: (1) widespread evidence of strain in the rocks of the subterranes, including folding and thrust faulting at all scales and penetrative deformation in the southern Brooks Range; and (2) the structural superposition over large ares of distinct, but coeval facies of the Arctic Alaska terrane. Palinspastic restorations to date have tended to focus on either reconstruction by restoration of facies patterns or geometric unfolding across known structures, resulting in widely variable paleogeographic models and estimates of the amount of Brookian shortening.

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 -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 as well. 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 mélange and coherent masses in the North Slope subterrane. They are abundant in the northeastern and southcentral 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 eastcentral 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 southcentral and eastern Brooks Range, Moore and others (1985a), Moore (1986), and Grantz and others (1991) have 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, oral commun., 1988). 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 uncomformity 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) whose direction of structural transport 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 and 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). Similarly, 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 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 sometime 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 Pennsylvannian(?) 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 is 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 southwestly 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

From latest Devonian to Jurassic time, the Arctic Alaska terrane became the site of depositional processes that were active over widespread areas. Many of the rocks of this stratigraphic interval were deposited in shallow-marine to nonmarine environments and consist of platform carbonate rocks or compositionally mature siliciclastic strata, indicating that large parts of the terrane behaved as a continental platform or shelf. Reconstruction of the paleogeography of the terrane during this period of time is therefore simplified by the relatively predictable stratigraphic patterns related to sedimentation on a stable continental platform, the large database consisting of seismic, well, and outcrop data for this stratigraphic interval, the restriction of complicated Brookian deformational overprints to the southern part of the Arctic-Alaska terrane, and the absence of geologic structures related to older orogenic events. Palinspastic restorations for this interval are uncertain, however, due to the poorly known structural kinematics of the Brookian orogeny and the apparent absence of rocks of this stratigraphic interval throughout much of the southern Brooks Range.

Two contrasting paleogeographic reconstructions of the Arctic Alaska terrane have been suggested for latest Devonian (Fammenian) 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 structurally overlies. 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 atop 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) considered 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 require 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 presently 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 in part 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).

Figures 31 to 36 shows a series of block diagrams illustrating paleogeographic reconstructions for Mississippian 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. It is important to 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.

During latest Devonian and earliest Mississippian time (fig. 31), the regional sub-Mississippian unconformity shows that 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

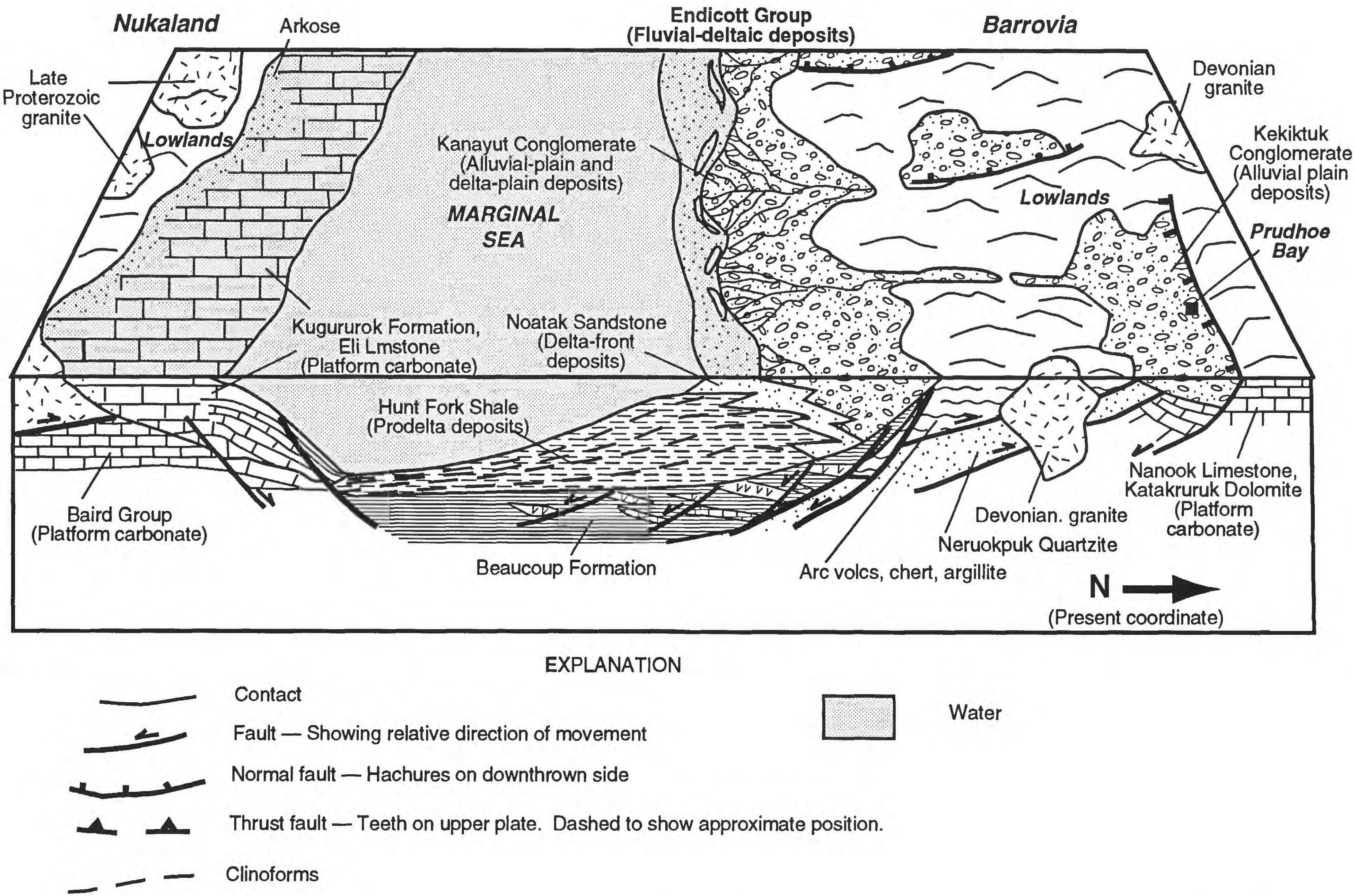


Figure 31. Paleogeographic model of Arctic Alaska terrane for the latest Devonian (Fammenian) and earliest Mississippian. See figures 6 and 28 for lithologic symbols.

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 1,500 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. Because of their structurally high position and inferred restoration to more southern positions, 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. 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. 32). 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 to 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, perhaps a fault block, within the epicontinental basin separating Barrovia and Nukaland.

During the Pennsylvanian, Lisburne Group carbonate platform deposition transgressed progressively northward, depositionally onlapping the Endicott Group clastic rocks and older rocks of the Hammond and North Slope subterranes. By Early Permian time, platform carbonate rocks of the Lisburne Group had been deposited as a diachronous sheet across most of the Endicott Mountains and North Slope subterranes, and by inference, the intervening Hammond subterrane. Upper Pennsylvanian and Lower Permian Lisburne Group carbonate rocks, however, are

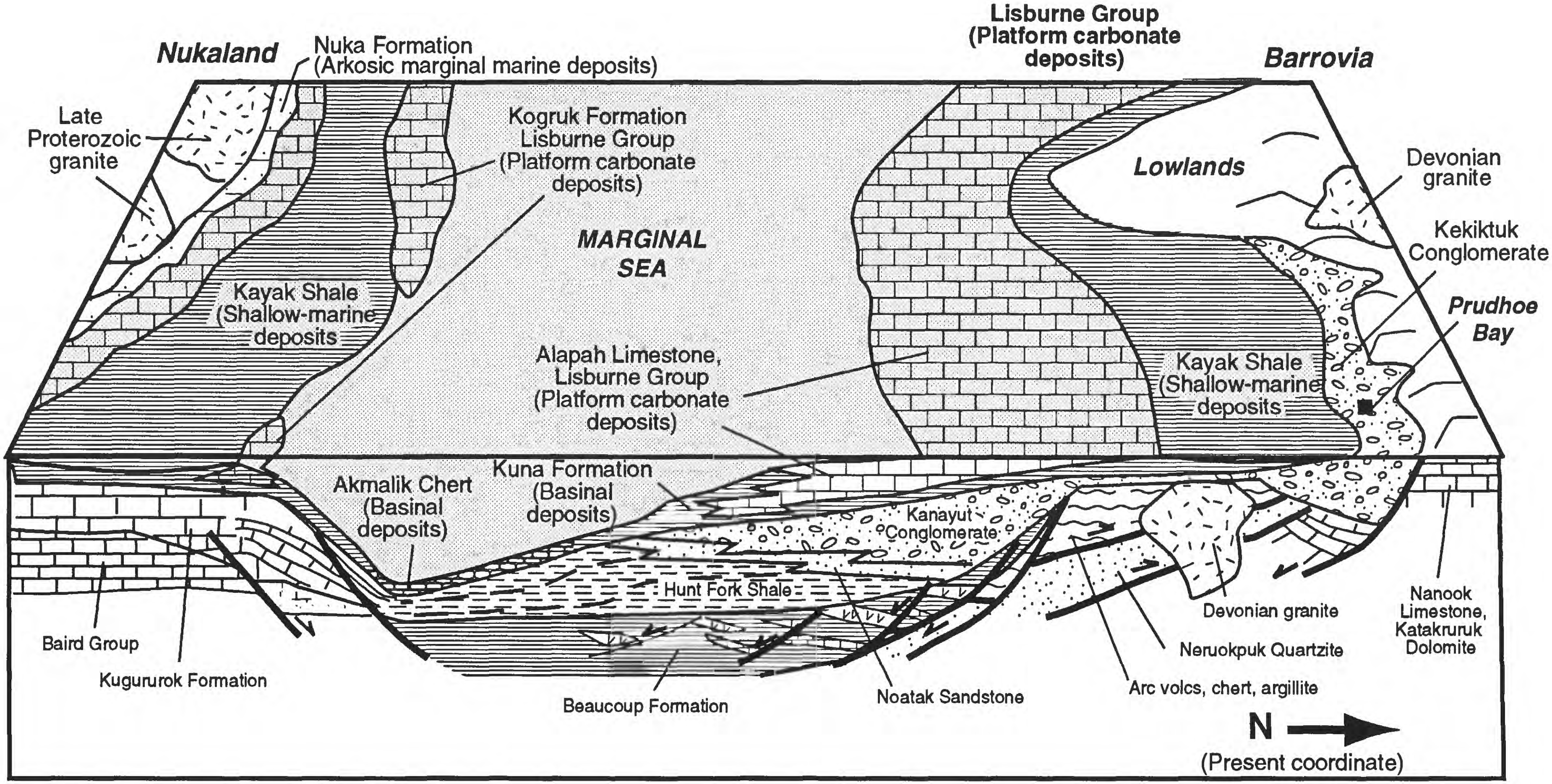


Figure 32. Paleogeographic model of Arctic Alaska terrane for the early Late Mississippian (Meramecian). See figures 6, 28, and 34 for lithologic symbols.

restricted to the North Slope subterrane and have not been identified in the Endicott Mountains and Hammond subterranes suggesting a regional disconformity or depositional hiatus during this time.

In the allochthons of the De Long Mountains subterrane, Pennsylvanian and Permian time is everywhere represented by radiolarian chert and siliceous shale of the Etivluk Group (Mull and others, 1987c; Siok and Mull, 1987; Curtis and others, 1984; Mayfield and others, 1984). In the Nuka Ridge allochthon, spiculitic chert of Pennsylvanian to Permian age reportedly rests depositionally on arkose of the Nuka Formation. Mayfield and others (1988) suggest that this relationship indicates subsidence of the southern highlands region (Nukaland) to below wavebase by Pennsylvanian time, and speculate that its subsidence may be related to rifting and continental breakup along the southern margin of the Arctic-Alaska terrane. The presence of numerous diabasic rocks into Permian and older strata of the Ipnavik River allochthon may be explained by rifting at this time.

By Permian time (fig. 33), 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 chert-rich sequences in most of the De Long Mountains subterrane (Imnaitchiak Chert, part). 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. 34) 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. 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, oral commun., 1988) 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. 15) 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. 35) indicates that the Shublik Formation was deposited on a broad, southward-sloping, low-gradient shelf (Fraser and Clark, 1976). Further, 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

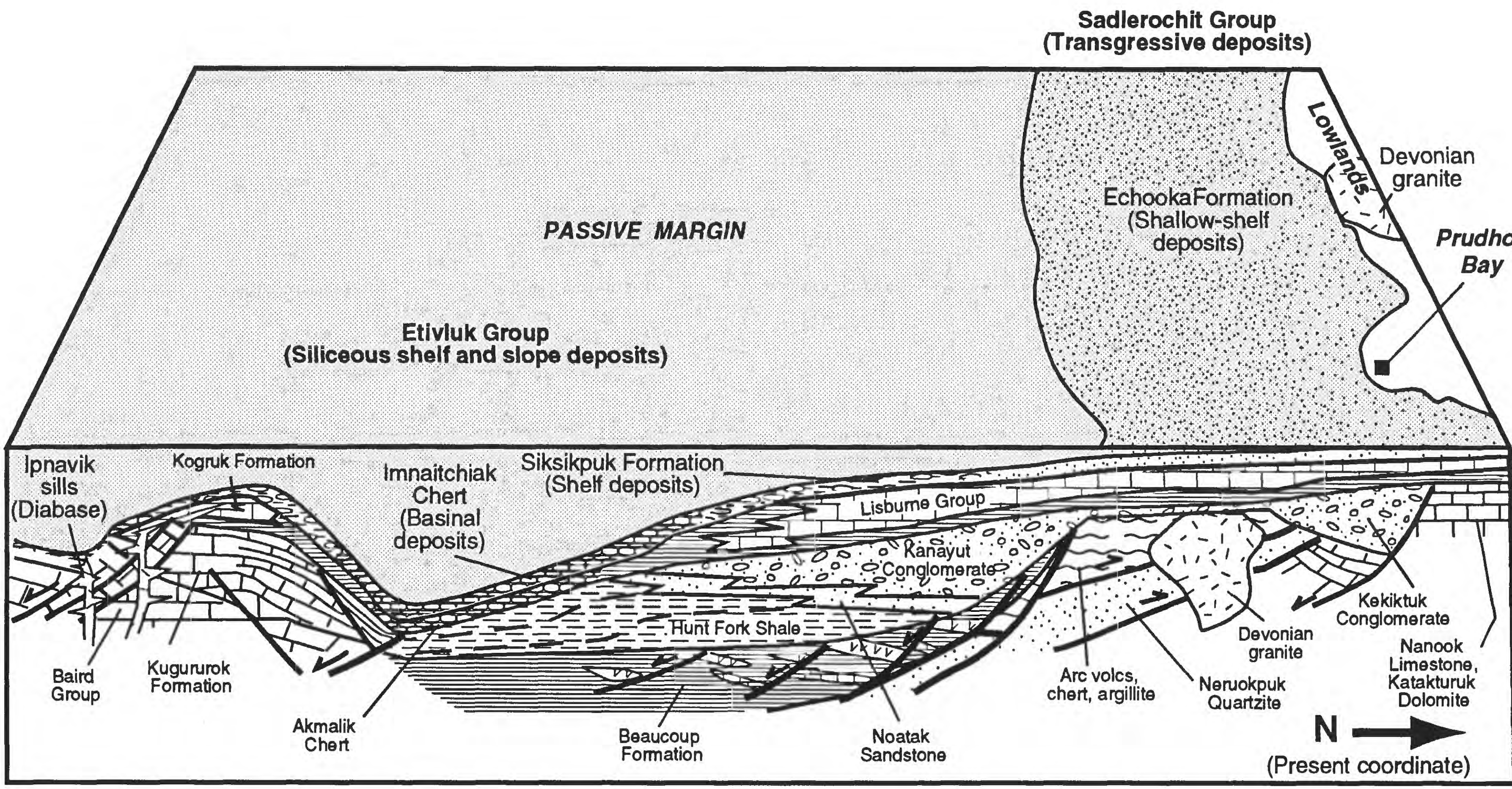


Figure 33. Paleogeographic model of Arctic Alaska terrane for the Late Permian. See figures 6, 28, and 34 for lithologic symbols.

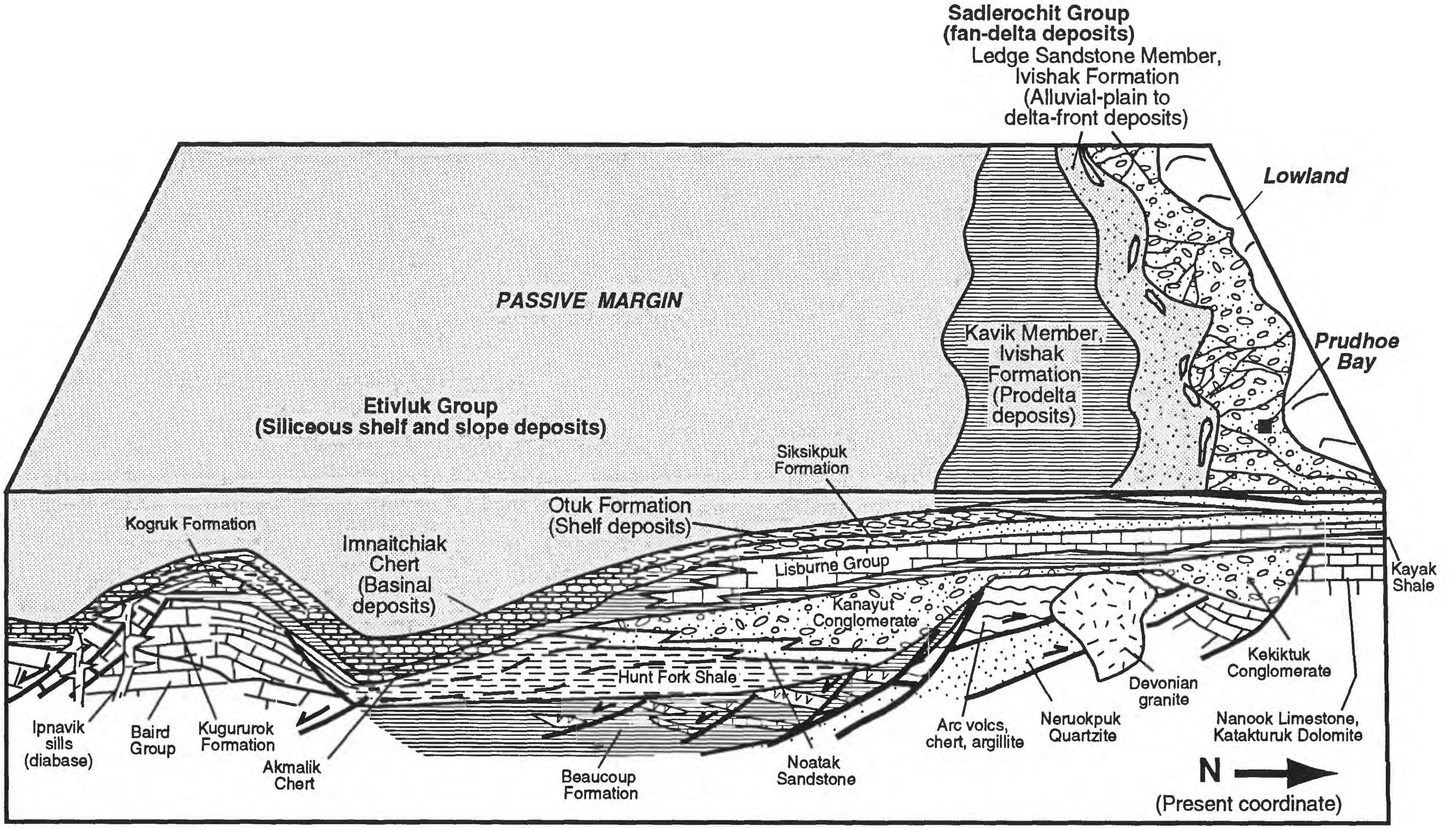


Figure 34. Paleogeographic model of Arctic Alaska terrane for the Early Triassic. See figures 6, 28, and 34 for lithologic symbols.

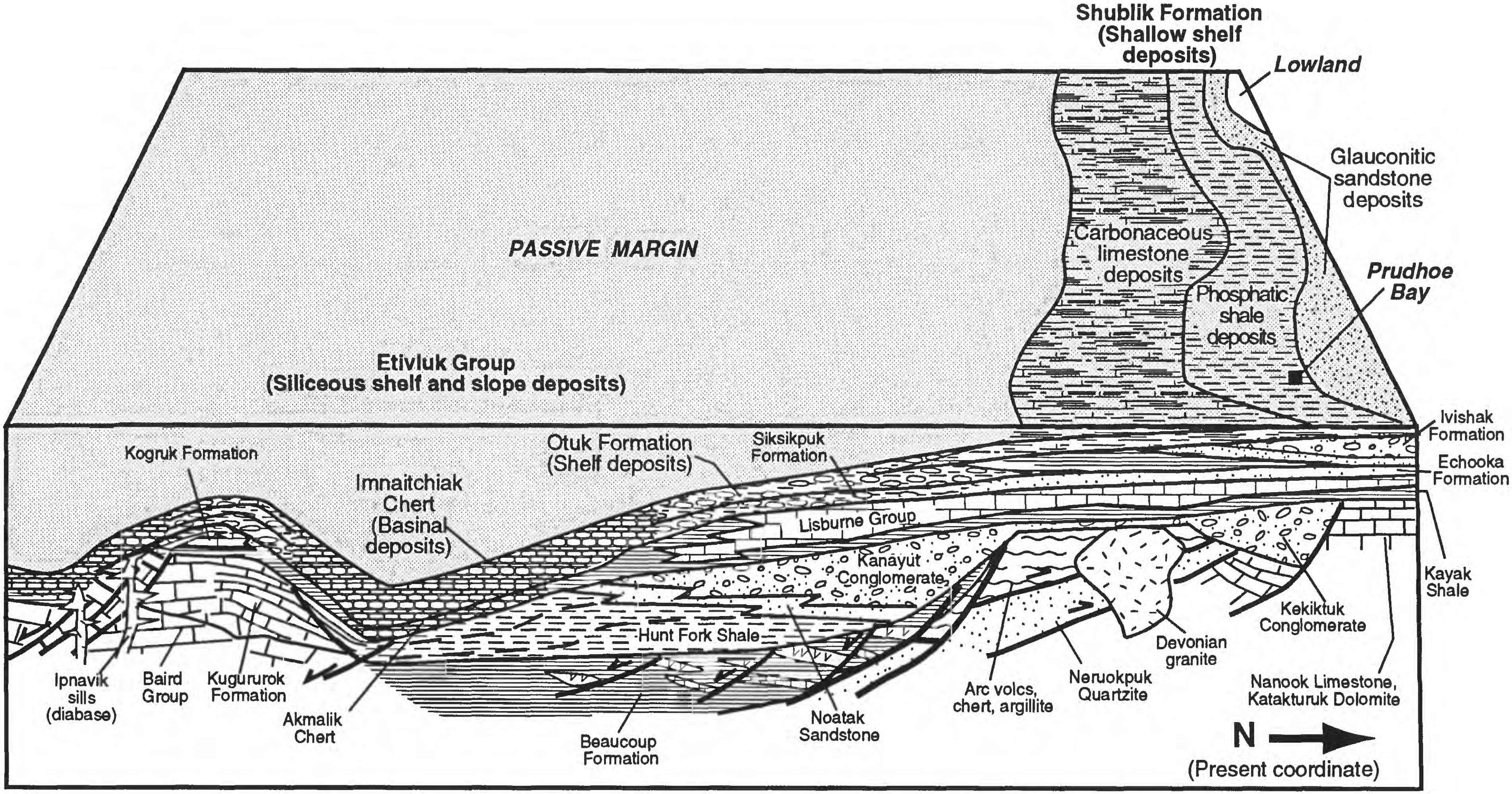


Figure 35. Paleogeographic model of Arctic Alaska terrane for the Late Triassic. See figures 6, 28, and 34 for lithologic symbols.

of dark, organic-rich, locally bioturbated shale and minor siltstone and sandstone that were derived from the north (Kingak Shale, part). 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 consists of condensed basin deposits (Blankenship Member, 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. 36). 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 which 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 (e.g., Kemik Sandstone and upper part of the Kuparuk Formation) and in widespread deposition of the pebble shale unit onto shelf areas.

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; Patton and Box, 1989). 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 constrained 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 they are, in turn, underlain by the pillowed basalts and diabase of the Copter Peak allochthon (Angayucham terrane), which, in turn, 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

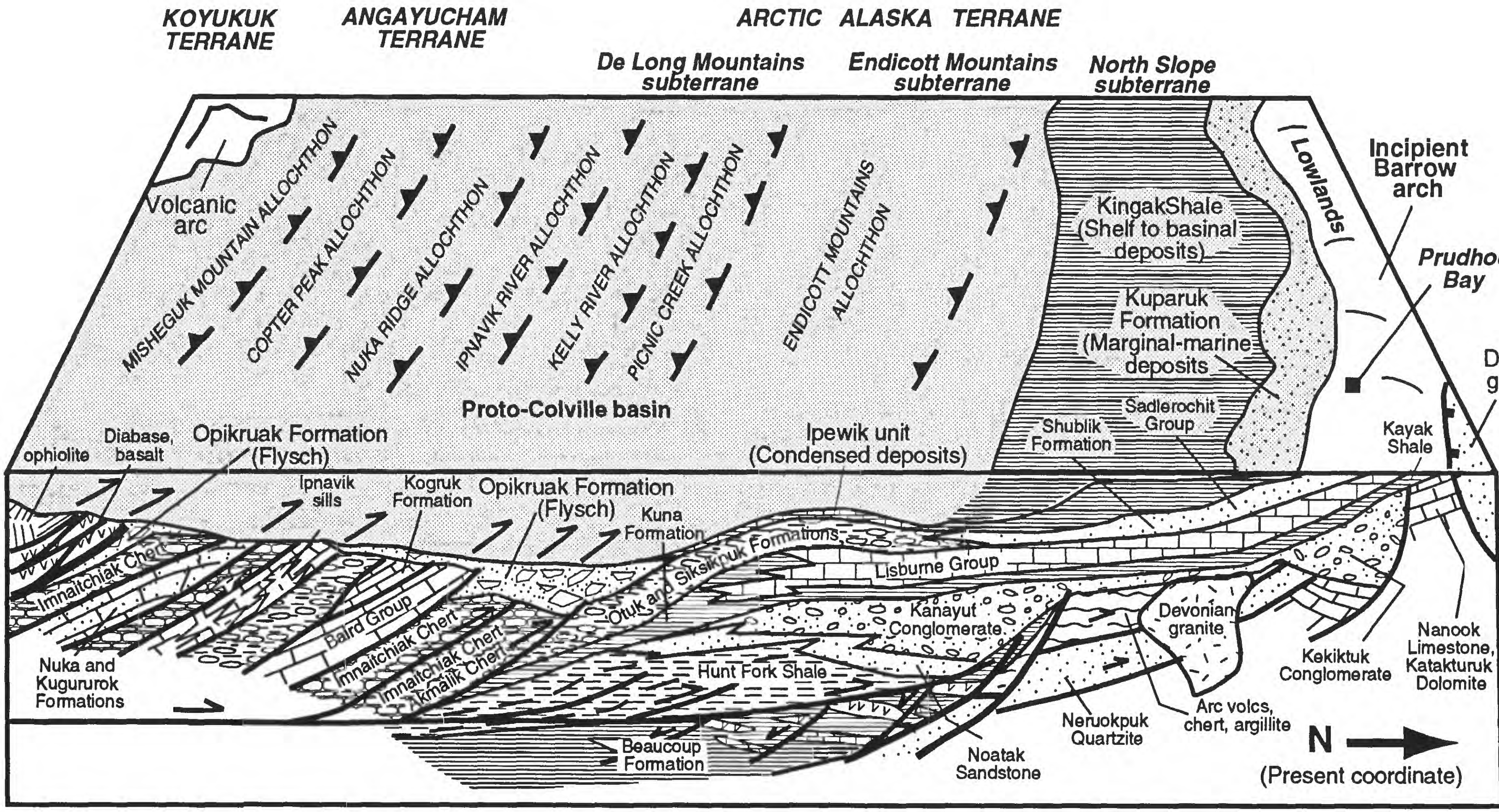


Figure 36. Paleogeographic model of Arctic Alaska terrane for the Early Cretaceous (Valanginian). See figures 6, 28, and 34 for lithologic symbols.

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 likely a remnant of an intra-oceanic arc accreted to Alaska in Early Cretaceous time (Box, 1985; Patton and Box, 1989); and (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 and presumably northward 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 constrained, 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' paleogeographic reconstruction, neglecting shortening across most intra-allochthon map-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 37. 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 intra-oceanic arc (Koyukuk terrane) was established on oceanic crust (Kanuti panel, Misheguk Mountain allochthon) (fig. 37*A*). Subduction of the oceanic crust flooring the basin resulted in construction 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. 37*B*). 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). 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 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. 37*C*). 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. 37*D*). 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 Koyukuk 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. 37*E,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 andAngayucham terranes (fig. 37*F*), 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 others, 1991).

Origin of the northern Alaska continental margin

The Canada basin, adjoining the northern margin of the Arctic Alaska terrane, is an ocean basin with an abyssal plain that lies at a depth of about 4,000 m. This basin is underlain by more than 6 km of sediments and has a lower crustal basement thickness of 6 -8 km (Grantz and others, 1990b). Using seismic refraction methods, Mair and Lyons (1981) identified layers 2 and 3 within the lower crustal rocks of the basin and estimated their seismic velocities at 6.6 and 7.5 km/sec, respectively. These data are similar to those from other modern ocean basins and are accepted by most workers as strong evidence that the Canada Basin is underlain by oceanic crust. Magnetic anomaly patterns in the basin are ambiguous, and there is no stratigraphic control on the age older sedimentary fill. Consequently, the age of the oceanic crust underlying the basin can be dated only as pre-Albian (late Early Cretaceous) by inference from the available seismic reflection and well data from the basin margins. The age of the basin has therefore been estimated from bathymetry, heat flow data, evidence from the basin margins, and comparison with other ocean basins. These data indicate that the Canada Basin was formed by sea-floor spreading in Early Cretaceous time (Grantz and May, 1983).

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 (1969b, 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 seismic reflection profiles across this margin and identified Early Cretaceous to Quaternary unconformities, subsidence hinge lines, oceanward (northward) progradational sedimentary prisms, down-to-basin normal faults, large-scale slumps, growth faults and other features that typically characterize passive margins. These workers also described the 10-40 km-wide and 170 km-long Dinkum graben beneath the Beaufort Sea shelf and interpreted it as a fossil rift valley containing Jurassic and Cretaceous sedimentary rocks. Volcanic rocks that can be related to Mesozoic rifting have not been identified in the stratigraphy of the region, however.

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 185-190 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 unconformitys 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. Rift-related uplift followed by post-rift subsidence along the newly formed continental margin therefore resulted in development of a tectonic hinge line and the Barrow arch. The tectonic hinge line is the boundary north of which thinned pre-rift continental crust dips sharply seaward toward transitional and oceanic crust, whereas the Barrow arch is defined by the line of inflection at which the regionally south-dipping

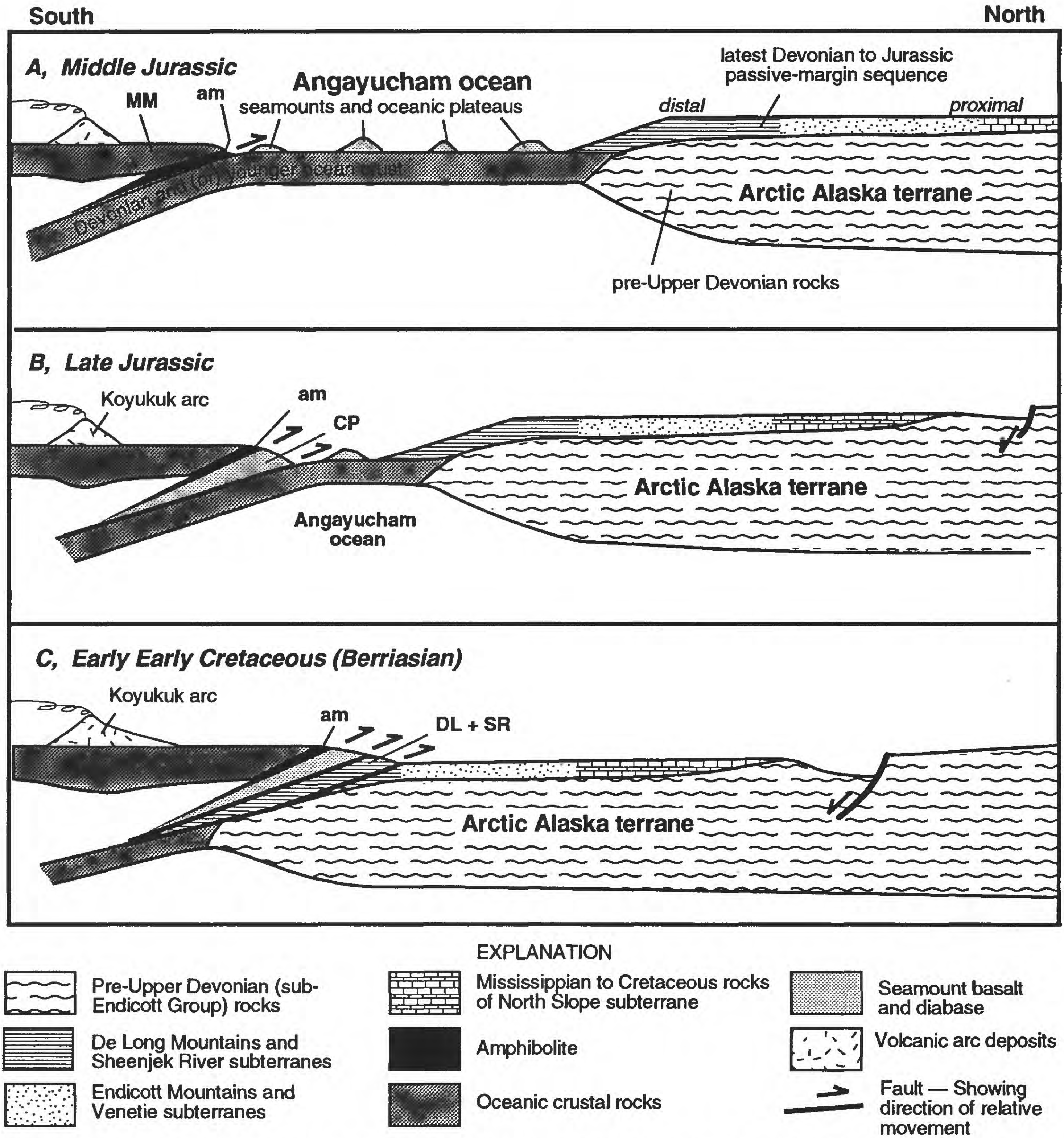


Figure 37. Tectonic model for Brookian orogeny. A, Subduction of late Paleozoic and early Mesozoic oceanic crust initiated in Middle Jurassic and amphibolitic metabasite (am) was produced by underthrusting of ocean crust beneath young and hot oceanic crust (MM); B, Subduction of oceanic crust nearly complete and ocean basin mostly closed; subduction complex consists mostly of fragments of seamounts and oceanic plateaus off-scraped from subducted ocean crust (CP). Failed rifting associated with development of Dinkum graben in Jurassic time is shown at right; C, Subduction of seaward part of Arctic Alaska terrane begins in latest Jurassic or earliest Cretaceous time; outboard sedimentary cover (DL) detached from basement and imbricated. Abbreviations: Angayucham terrane: MM - Misheguk Mountain allochthon and Kanuti panel, CP - Copter Peak and Narvak panel; Arctic Alaska terrane: DL + SR - De Long Mountains and Sheenjek River subterranes, En + V - Endicott Mountains and Venetie subterranes, Hm - Hammond subterrane, NS - North Slope subterrane, Cf - Coldfoot subterrane; SC - Slate Creek subterrane; am - amphibolite; bs - high pressure metamorphic rocks.

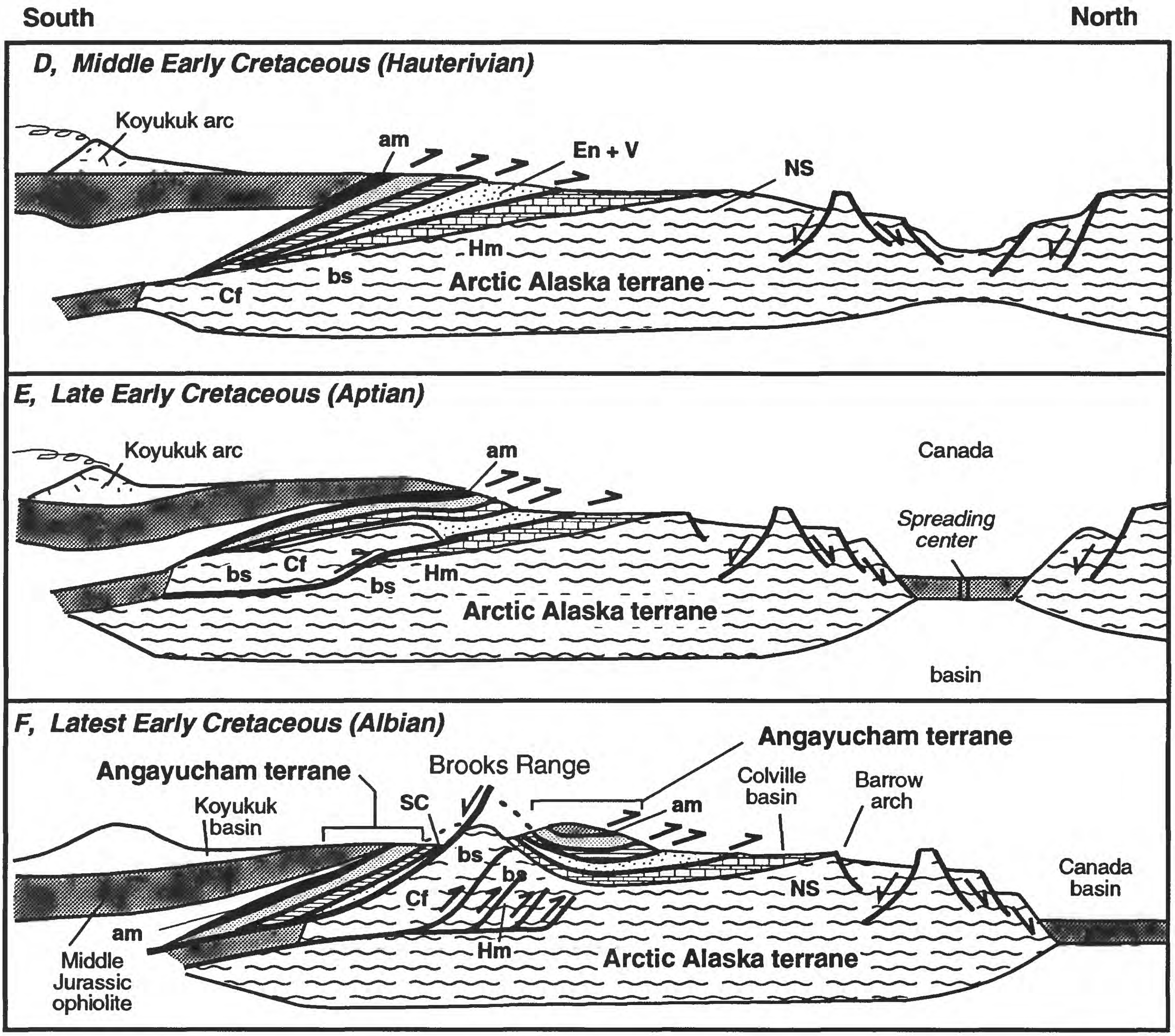


Figure 37 (continued). Tectonic model for Brookian orogeny (continued). D, Subduction of continental substructure to sufficient depth to produce blueschist-facies metamorphism (bs); medial sedimentary cover (En + V) detached from basement, imbricated, and underthrust by inboard sedimentary cover and basement (NS + Hm); rifting and continental break up occurs along northern margin of Arctic Alaska terrane; E, Continental substructure rocks containing blueschist facies assemblages uplifted and emplaced at higher structural levels by large-scale out-of-sequence faulting, imbrication, duplexing, and crustal thickening of lower crust (Cf); Canada basin opened and Barrow arch formed; F, Continued contraction thickened middle and lower crustal rocks; coeval or later crustal attenuation thins imbricated crustal superstructure along down-to-the south normal faults, especially in southern Brooks Range (SC). Resulting uplift and erosional unroofing produced huge volumes of clastic detritus shed southward into the Koyukuk basin and northward into the Colville basin. Abbreviations: Angayucham terrane: MM - Misheguk Mountain allochthon and Kanuti panel, CP - Copter Peak and Narvak panel; Arctic Alaska terrane: DL + SR - De Long Mountains and Sheenjek River subterranes, En + V - Endicott Mountains and Venetie subterranes, Hm - Hammond subterrane, NS - North Slope subterrane, Cf - Coldfoot subterrane; SC - Slate Creek subterrane; am - amphibolite; bs - high pressure metamorphic rocks.

Ellesmerian rocks are downwarped and downfaulted to the north in response to rifting and later subsidence.

By middle Albian time (105 my), clastic deposits from the ancestral Brooks Range prograded northward across the Colville basin and overtopped the subsiding continental margin. Continued subsidence coupled with continued influx of clastic materials from southerly sources resulted in the deposition of post-breakup progradational sedimentary prisms, which formed continental terraces on the Beaufort Sea shelf during Late Cretaceous and Cenozoic time.

Relation between Early Cretaceous convergent deformation and rifting

The geologic relationships summarized above suggest that the opening of the Canada basin by rifting and eventual seafloor spreading in Jurassic and Early Cretaceous time was coeval with Brookian convergent deformation and southward subduction of the Arctic Alaska terrane. These coeval tectonic events affecting the northern and southern margins of the Arctic Alaska terrane have been suggested to be genetically linked by Tailleur (1973a), Mull (1982), and Mayfield and others (1988). These workers suggest that the Canada basin was opened by seafloor spreading about a pole of rotation in the MacKenzie delta as hypothesized by Carey (1958) and argued by Grantz and May (1983) and that compressional shortening along the leading edge of the southward-rotating Arctic Alaska terrane was the cause of Brookian convergent deformation. About 67 degrees of counterclockwise rotation of the Arctic Alaska terrane is required by the rotational model of origin for the Canada Basin. Because not all of the allochthonous sequences of the De Long Mountains subterrane in the western Brooks Range have been identified in the eastern Brooks Range, Mull (1982) and Mayfield and others (1988) estimated that the amount of north-vergent shortening decreases from the western to the eastern Brooks Range. This hypothesized eastward decrease in Brookian shortening was explained by a decrease in the amount of seafloor spreading approaching the proposed pole of rotation in the Mackenzie delta. This hypothesis therefore related subduction and convergent deformation at the leading-edge of the Arctic Alaska terrane to counterclockwise rotation of the terrane and implied that the Early Cretaceous tectonism was driven by seafloor spreading (ridge-push) in the Canada basin.

An alternative view is proposed by Grantz and May (1983), who pointed out that seafloor spreading in the Canada basin was initiated in Early Cretaceous time, whereas Brookian convergent deformation began much earlier in Middle Jurassic time. They therefore suggest that southward subduction of the Arctic Alaska terrane was not genetically linked to opening of the Canada basin, but that each was driven by separate tectonic 'engines'. This is supported by the observation by Mayfield and others (1988) that convergent deformation of similar character, timing, and displacement geometry occurred in the Canadian Cordillera and cannot be easily linked to the hypothesized opening of the Canada basin. Moreover, Rattey (1985) and Oldow and others (1987d) observed that Brookian deformational structures in the eastern Brooks Ranges suggest amounts of shortening comparable to those in the central and western Brooks Range The local presence of klippen of mafic-ultramafic rocks (Christian complex, Angayucham terrane) and fine-grained late Paleozoic and early Mesozoic facies (Sheenjek subterrane) in the eastern Brooks Range argue that similar amounts of shortening occurred in both the eastern and western parts orogenic belt. Greater uplift and a deeper level of erosion caused by Late Cretaceous and Cenozoic deformation may have stripped away the allochthonous sequences analogous to the De Long Mountains subterrane and Angayucham terrane throughout most of the eastern Brooks Range, so that the total amount of shortening is not as easily documented.

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). 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 extension 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 likely 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 prodelta-shale and thin-bedded turbidite deposits 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 (e.g., 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. 19; 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 younger 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). 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, written commun., 1990).

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 and 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, 1983). 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 further amplified 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 resticted 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 Mount 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 constrained, 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 by-product 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. To the east, Plumley and Vance (1988) reported that extensional tectonism along the Porcupine lineament probably took place in Paleogene time. The change from convergence to extensional and translational tectonism also 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 may be related to deformation in the western Brooks Range (Karl and Long, 1987), probably is 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 continetal-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. Consequent deformation led to northward displacement and 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.

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 constrain 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 (Lawver and Scotase, 1990). Although the Arctic region has been reconstructed in many ways, the Arctic Alaska terrane is typically restored to one of four general positions (fig. 38).

The first class of models for the Arctic region restores the Arctic Alaska terrane in Paleozoic to middle Mesozoic time to nearly its present position relative to North America (for example, Bogdanov and Tilman, 1964). Churkin and Trexler (1980, 1981) proposed that early Mesozoic oceanic lithosphere, travelling northward from the Pacific Ocean, became trapped in the Arctic region by mid-Cretaceous closure between North America, Eurasia, and the Kolyma terrane of the Russian Far East. This model requires a Jurassic or older age for the Canada basin sea floor, does not account for a northern source region (Barrovia) from which strata of the Ellesmerian sequence were derived, and implies substantial subduction around the margins of the Canada basin, for which there is little evidence. Herron and others (1974), in contrast, proposed that the Canada basin was created by in situ sea-floor spreading oriented at a high angle to the northern margin of Alaska. Opening of the Canada basin in this model involved left-lateral transform displacement of a large continental terrane such as Kolyma (Herron and others,1974) or the Chukchi borderlands (Rowley and others, 1985) along the northern Alaska continental margin from an original position adjacent to the Canadian Arctic Islands (fig. 38A). Because there is no recognized record of translation along the northern margin of the Arctic Alaska terrane, most workers now favor a passive-margin origin for the margin in Early Jurassic time (for example, Grantz and May, 1983).

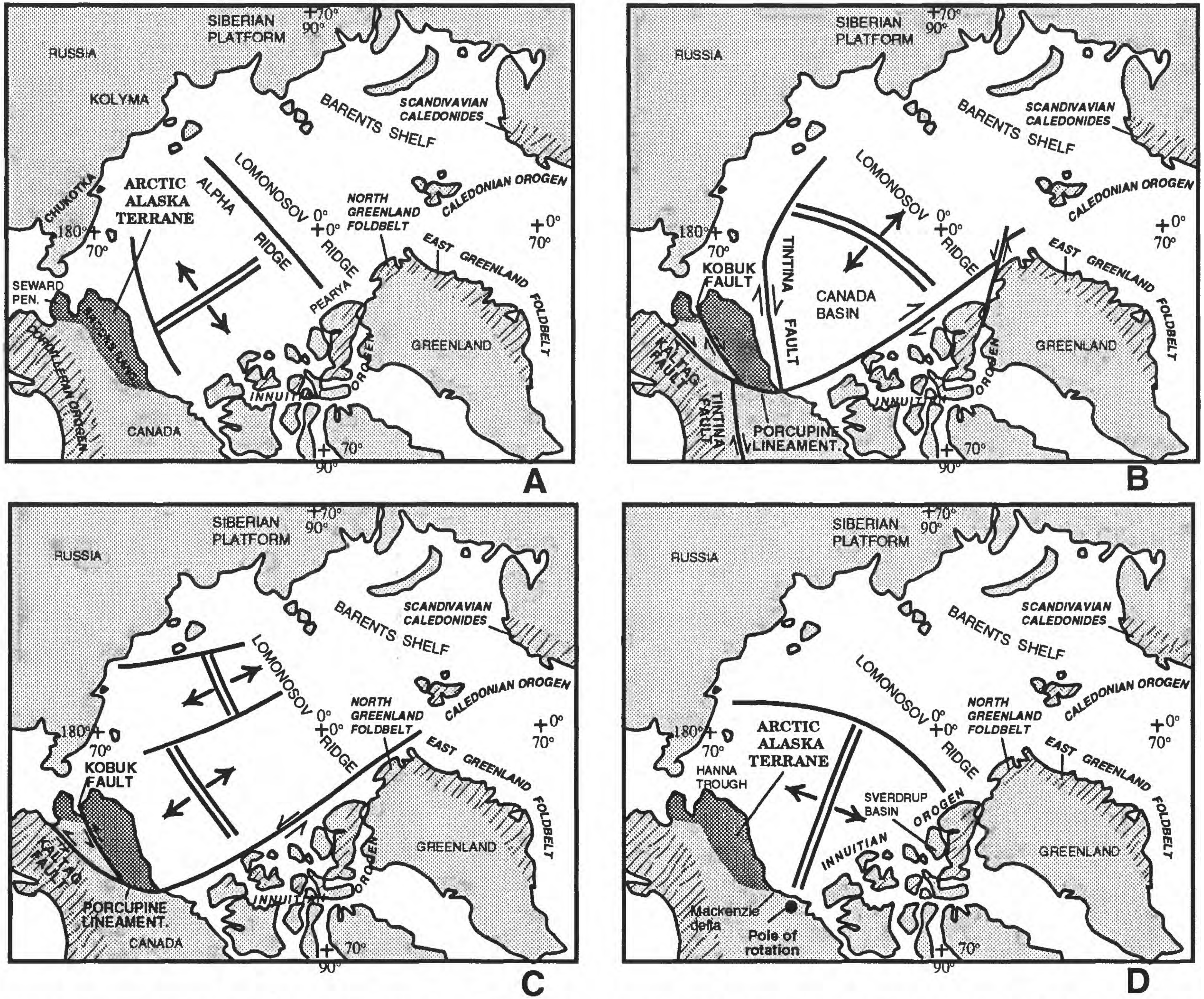


Figure 38. Paleotectonic maps showing possible restorations of the Arctic Alaska terrane to positions in Cordilleran, Innuitian, and Caledonian orogens. A, in situ origin: Arctic Alaska terrane not rotated or translated; B, Yukon origin: Arctic Alaska terrane translated by large-scale right-slip along Tintina fault from position in northern Canadian part of Cordilleran orogen and offset right laterally along Porcupine lineament; C, Barents shelf origin: Arctic Alaska terrane 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; D, Canadian Arctic Islands origin: Arctic Alaska terrane rotated oroclinally from Innuitian orogen about a pole of rotation near present Mackenzie Delta.

A second restoration (fig. 38*B*) involves northward right-lateral motion of the Arctic Alaska terrane along the Tintina fault from a position originally within the northern Canadian part of the Cordilleran orogen (Jones, 1982b). According to this model, the terrane was later displaced to the northeast by right-lateral motion along the Porcupine lineament. This model (1) accounts for similarities in the pre-Mississippian rocks of the northeastern part of the Arctic Alaska terrane and the northern Cordilleran orogen (Norris, 1985), (2) restores the Devonian granitic batholiths of the terrane to a position within the Devonian magmatic belt of the Cordillera (Rubin and others, 1990), (3) relates the Devonian clastic wedge to the nearly coeval Antler belt of chert-rich clastic rocks (Gordey and others, 1987; Gordey, 1988), and (4) accounts for apparent correspondence between the Mississippian through Upper Cretaceous facies patterns and mineralization of the two regions (Einaudi and Hitzman, 1986; Schmidt, 1987). The disadvantages of the model are that it requires a transform, rather than passive, northern margin for the Arctic Alaska terrane and a Paleozoic, rather than a Mesozoic, age for the Tintina fault. The model also assumes a late Paleozoic or early Mesozoic age for the Canada basin and places the thick Devonian fluvial deposits of the Endicott Mountains subterrane adjacent to the deep-marine clastic rocks of the Antler belt (Nilsen, 1981).

A third class of reconstructions (fig. 38*C*) restores the northern margin of the Arctic Alaska terrane to a position adjacent to the Lomonosov Ridge and Barents shelf and makes the Arctic Alaska terrane part of the northern Laurussian continental margin in pre-Jurassic time (Dutro, 1981; Nilsen, 1981; Oldow and others, 1987b; Smith, 1987). These reconstructions require as much as 2,000 km of left slip on a transform fault along the linear continental margin of northern Canada and its southwestward projection through the Mackenzie delta and onward along the Porcupine lineament to either the present-day Kaltag fault or Kobuk fault along the south edge of the Brooks Range. This reconstruction was suggested by Oldow and others (1987b) who reported that the direction of tectonic transport in pre-Mississippian rocks in the northeastern Brooks Range is compatible with that of the Ellesmerian orogeny in the Canadian Arctic Islands if restored by large-scale left slip. A plate-tectonic explanation for this restoration is provided by Smith (1987), who suggested that the Canada basin opened along a spreading center oriented normal to the straight extent of the northern Canadian continental margin north of the Canadian Arctic Islands. In this reconstruction, Brookian deformation resulted from interactions with plates of the paleo-Pacific ocean during translation toward the southwest. The advantages of this class of models is that it (1) provides for a Cretaceous age for the Canada basin, (2) accounts for a northern source region (Barrovia) for the strata of the Ellesmerian sequence, (3) explains the linear character of the northern Canadian continental margin, and (4) relates the large outpouring of clastic rocks in the Late Devonian and Early Mississippian to the thick clastic deposits shed from the Ellesmerian orogeny in the Innuitian orogen or possibly to trans-tensional deposits of the Upper Old Red Series of the East Greenland fold belt. Major disadvantages of these models are that they propose extremely large amounts of left slip across the Porcupine lineament and the Kaltag or other faults, which presently display only small to moderate amounts of right slip, and that they require an older age of movement than that documented on the faults. Further, the Devonian clastic wedges of the Arctic Alaska terrane and the Innuitian fold belt differ somewhat in age so may not be directly correlative.

The fourth, and 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. 38*D*) (Carey, 1958; Rickwood, 1970; Tailleur, 1973a; 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, oral commun., 1988). 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 1,500 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 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).

CONCLUSION

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 coastal-plain to continental-shelf and carbonate-platform deposits in the Late Devonian to Pennsylvanian and neritic to bathyal deposits in theTriassic to Jurassic. Gradual deepening was accompanied by waning clastic input from the north, resulting in deposition of condensed basinal deposits of shale, pelagic 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 once have 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 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-prrograding 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.

ACKNOWLEDGMENTS

This manuscript incorporates many published and unpublished ideas and data contributed by K.E. Adams, W.P. Brosgé, J.A. Dumoulin, A. Grantz, A.G. Harris, D.G. Howell, D.L. Jones, E.L. Miller, W.J. Nokleberg, J.S. Oldow, R.R. Reifenstuhl, I.L. Tailleur, and A.B. Till. We are grateful to reviewers D.C Bradley and A.B Till for their careful reading of the manuscript and thoughtful suggestions for its improvement. We also thank K.E. Adams, who graciously edited large parts of the text.

REFERENCES CITED

Adams, K.E., 1989, Permian sedimentatin in the northcentral Brooks Range, Alaska: implications for tectonic reconstructions (M.S. thesis): Fairbanks, Alaska, University of Alaska, 122 p.

Adams, K.E., and Siok, J.P., 1989, Permian stratigraphy in the Atigun Gorge area: a transition between the Echooka and Siksikpuk Formations, in Mull, C.G., and Adams, K.E., eds., Dalton Highway, Yukon River to Prudhoe Bay, Alaska: Alaska Division of Geological and Geophysical Surveys Guidebook 7, v. 2, p. 267-276.

Adkison, W.L., and Brosgé, M.M., eds., 1970, Proceedings of the geological seminar on the North Slope of Alaska: Pacific Section, American Association of Petroleum Geologists, Los Angeles, Calif.

Ahlbrandt, T.S., Huffman, A.C., Fox, J.E., and Pasternack, Ira, 1979, Depositional framework and reservoir-quality studies of selected Nanushuk Group outcrops, North Slope, Alaska, in Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Grousp Rocks, North Slope, Alaska: U.S.Geological Survey Circular 794, p. 14-31.

Anderson, A.V., 1987, Provenance and petrofacies, Upper Devonian sandstones, Philip Smith Mountains and Arctic quadrangles, Brooks Range, Alaska (M.S. thesis): University of Arizona, Tucson AZ, 113 p.

Anderson, A.V., 1991, Geologic map and cross sections, headwaters of the Kongakut and Aichilik Rivers, Demarcation Point A-4 and Table Mountain D-4 quadrangles, eastern Brooks Range, Alaska: Alaska Division of Geological and Geophysical Surveys Public Data File 91-3, 24 p., 1:25,000, 2 sheets.

Anderson, A.V., and Wallace, W.K., 1990, Middle Devonian to Lower Mississippian clastic depositional cycles southwest of Bathrub Ridge, northeastern Brooks Range, Alaska [abs.]: Program with Abstracts for Annual Meeting of Geological Association of Canada/Mineralogical Association of Canada, v. 15, p. A2.

Armstrong, A.K., 1970, Carbonate facies and the lithostrotionoid corals of the Mississippian Kogruk Formation, De Long Mountains, northwestern Alaska: U.S. Geological Survey Professional Paper 664, 38 p., 14 pls.

Armstrong, A.K., 1972, Pennsylvanian carbonates, paleoecology, and rugose colonial corals, north flank, eastern Brooks Range, Arctic Alaska: U.S. Geological Survey Professional Paper 747, 21 p., 8 pls.

Armstrong, A.K., 1974, Carboniferous carbonate depositional models, preliminary lithofacies and paleotectonic maps, Arctic Alaska: American Association of Petroleum Geologists Bulletin, v. 58, p. 621-645.

Armstrong, A.K., and Bird, K.J., 1976, Carboniferous environments of deposition and facies, Arctic Alaska, in Miller, T.P., ed., Symposium on recent and ancient sedimentary environments in Alaska: Anchorage, Alaska Geological Society Symposium Proceedings, p. A1-A16.

Armstrong, A.K., and Mamet, B.L., 1975, Carboniferous biostratigraphy, northeastern Brooks Range, Arctic Alaska: U.S. Geological Survey Professional Paper 884, 29 p.

Armstrong, A.K., and Mamet, B.L., 1977, Carboniferous microfacies, microfossils, and corals, Lisburne Group, Arctic Alaska: U.S. Geological Survey Professional Paper 849, 144 p., 39 pls.

Armstrong, A. K., and Mamet, B.L., 1978, Microfacies of the Carboniferous Lisburne Group, Endicott Mountains, Arctic Alaska, in Stelck, C.R., and Chatterton, B.D.E., eds., Western and Arctic biostratigraphy: Geological Association of Canada Special Paper 18, p. 333-394.

Armstrong, A.K., Mamet, B.L., Brosgé, W.P., and Reiser, H.N., 1976, Carboniferous section and unconformity at Mount Doonerak, Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 60, p, 962-972.

Armstrong, A.K., Mamet, B.L., and Dutro, J.T., Jr., 1970, Foraminiferal zonation and carbonate facies of Carboniferous (Mississippian and Pennsylvanian) Group, central and eastern Brooks Range, Arctic Alaska: American Association of Petroleum Geologists Bulletin, v. 54, p. 687-698.

Armstrong, A.K., Mamet, B.L., and Dutro, J.T., Jr., 1971, Lisburne Group, Cape Lewis-Niak Creek, northwestern Alaska, Chap B, in Geological Survey research, 1971: U.S. Geological Survey Professional Paper 750-B, p. B23-B34.

Armstrong, R.L., Harakal, J.E., Forbes, R.B., Evans, B.W., and Thurston, S.P., 1986, Rb-Sr and K-Ar study of metamorphic rocks of the Seward Peninsula and southern Brooks Range, in Evans, B.W., and Brown, E.H., eds., Blueschists and eclogites: Boulder, Colorado, Geological Society of America Memoir 164, p. 185-203.

Atkinson, C.D., Trumbly, P.N., and Kremer, M.C., 1988, Sedimentology and depositional environments of the Ivishak Sandstone, Prudhoe Bay field, North Slope, Alaska, in Lomando, A.J., and Harris, P.M., eds., Giant oil and gas fields, a core workshop: Society of Economic Paleontologists and Mineralogists Core Workshop No. 12, Tulsa, Oklahoma, p. 561-613.

Bader, J.W., and Bird, K.J., 1986, Geologic map of the Demarcation Point, Mount Michelson, Flaxman Island, and Barter Island quadrangles, northeastern Alaska, U.S. Geological Survey Miscellaneous Investigations Map I-1791, scale 1:250,000, 1 sheet.

Barker, Fred, Jones, D.L., Budahn, J.R., and Coney, P.J., 1988, Ocean plateau-seamount origin of basaltic rocks, Angayucham terrane, central Alaska: Journal of Geology, v. 96, p. 368-374.

Barker, J.C., 1982, Reconnaissance of rare-metal occurrences associated with the Old Crow batholith, eastern Alaska-northwestern Canada: Short notes on Alaska Geology - 1981, Alaska Division of Geological and Geophysical Surveys Geologic Report 73, p. 43-49.

Barnes, D.A., 1987, Reservoir quality in the Sag River Formation, Prudhoe Bay field Alaska: depositional environment and diagenesis, in Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 50, Bakersfield, California, p. 85-94.

Barnes, D.F., 1970, Gravity and other regional geophysical data from northern Alaska, in Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska: American Association of Petroleum Geologists Pacific Section Meeting, Los Angeles, p. I1-I19.

Barnes, D.F., 1977, Bouguer gravity map of northern Alaska: U.S. Geological Survey Open-File map OF 77-166A, scale 1:1,000,000.

Bartsch-Winkler, Susan, 1979, Textural and mineralogical study of some surface and subsurface sandstones from the Nanushuk Group, western North Slope, Alaska, in Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group Rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 61-76.

Bergquist, H.R., 1966, Micropaleontology of the Mesozoic rocks of northern Alaska: U.S. Geological Survey Professional Paper 302-D, p. 93-227.

Bird, J.M., Wirth, K.R., Harding, D.J., and Shelton, D.H., 1985, Brooks Range ophiolites reconstructed [abs.]: Eos (Transactions of the American Geophysical Union), v. 46, p. 1129.

Bird, K.J., 1978, New information on the Lisburne Group (Carboniferous and Permian) in the National Petroleum Reserve in Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 62, p. 880.

Bird, K.J., 1982, Rock-unit reports of 228 wells drilled on the North Slope, Alaska: U.S. Geological Survey Open-File Report 82-278, 106 p.

Bird, K.J., 1985, The framework geology of the North Slope of Alaska as related to oil-source rock correlations, in Magoon, L.B., and Claypool, G.E., eds., Alaskan North Slope oil/rock correlation study: American Association of Petroleum Geologists Studies in Geology, no. 20, p. 3-29.

Bird, K.J., 1987, The framework geology of the North Slope of Alaska as related to oil-source rock correlations, in Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope Geology: Bakersfield, Calif., Pacific Section of Society of Economic Paleontologists and Mineralogists and the Alaska Geological Society, Book 50, v. 1, p. 121-143.

Bird, K.J., 1988a, Alaskan North Slope stratigraphic nomenclature and data summary for government-drilled wells, Chap. 15, in Gryc, George, ed., Geology and exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, p. 317-353.

Bird, K.J., 1988b, Structure-contour and isopach maps of the National Petroleum Reserve in Alaska, Chap 16, in Gryc, George, ed., Geology and exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, p. 355-377.

Bird, K.J., and Andrews, Jack, 1979, Subsurface studies of the Nanushuk Group, in Ahlbrandt, T.S., ed., Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group Rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 32-41.

Bird, K.J., Connor, C.L., Tailleur, I.L., Silberman, M.L., and Christie, J.L., 1978, Granite on the Barrow Arch, northeast NPRA, in Johnson, K.M., ed., The United States Geological Survey in Alaska: accomplishments during 1977: U.S. Geological Survey Circular 772-B, p. B24-B25.

Bird, K.J., Griscom, S.B., Bartsch-Winkler, Susan, and Giovannetti, D.M., 1987, Petroleum reservoir rocks, Chap. 7, in Bird, K.J., and Magoon, L.B., eds., Petroleum geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska: U.S. Geological Survey Bulletin 1778, p. 79-99.

Bird, K.J., and Jordan, C.F., 1977, Lisburne Group (Mississippian and Pennsylvanian), potential major hydrocarbon objective of Arctic Slope, Alaska: American Association of Petroleum Geologists Bulletin, v. 61, p. 1493-1512.

Bird, K. J., and Magoon, L.B., eds., 1987, Petroleum geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska: U.S. Geological Survey Bulletin 1778, 329 p., 5 plates.

Bird, K.J., and Molenaar, C.M., 1987, Stratigraphy, Chap.5, in Bird, K.J., and Magoon, L.B., eds., Petroleum geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska: U.S. Geological Survey Bulletin 1778, p. 37-59.

Black, R.F., 1964, Gubik Formation of Quaternary age in northern Alaska: U.S. Geological Survey Professional Paper 302-C, p. 59-91.

Blanchard, D.C., and Tailleur, I.L., 1983, Pebble shale (Early Cretaceous) depositional environments in National Petroleum Reserve in Alaska (NPRA)[abs.]: American Association of Petroleum Geologists Bulletin, v. 67, p. 424-425.

Blodgett, R.B., Clough, J.G., Dutro, J.T., Jr., Ormiston, A.R., Palmer, A.R., and Taylor, M.E., 1986, Age revisions for the Nanook Limestone and Katakturuk Dolomite, northeastern Brooks Range, in Bartsch-Winkler, Susan, and Reed, K.M., eds., Geologic studies in Alaska by the U.S. Geological Survey during 1985: U.S. Geological Survey Circular 978, p. 5-10.

Blodgett, R.B., Clough, J.G., Harris, A.G., and Robinson, M.S., 1991, The Mount Copleston Limestone, a new Lower Devonian formation in the Shublik Mountains, northeastern Brooks Range, Alaska, in Bradley, D.C., and Ford, A., eds., Geologic studies in Alaska by the U.S. Geological Survey in 1990: U.S. Geological Survey Bulletin 1999, p. 1-5.

Blodgett, R.B., Rohr, D.M., Harris, A.G., and Jia-yu, Rong, 1988, A major unconformity between Upper Ordovician and Lower Devonian strata in the Nanook Limestone, Shublik Mountains, northeastern Brooks Range, Chap. 33, in Hamilton, T.D., and Galloway, J.P., eds., Geologic studies in Alaska by the U.S. Geological Survey during 1987: U.S. Geological Survey Circular, p. 18-23.

Blome, C.D., Reed, K.M., and Tailleur, I.L., 1988, Radiolarian biostratigraphy of the Otuk Formation in and near the National Petroleum Reserve in Alaska, Chap. 33, in Gryc, George, ed., Geology and Exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, p. 725-751.

Blythe, A.E., Wirth, K.R., and Bird, J.M., 1990, Fission track and 40Ar/39Ar ages of metamorphism and uplift, Brooks Range, northern Alaska [abs.]: Geological Association of Canada, Program and Abstracts, v. 15, p. A-12.

Boak, J.M., Turner, D.L., Henry, D.J., Moore, T.E., and Wallace, W.K., 1987, Petrology and K-Ar ages of the Misheguk igneous sequence -- an allochthonous mafic and ultramafic complex -- and its metamorphic aureole, western Brooks Range, Alaska, in Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 50, Bakersfield, California, p. 737-745.

Bodnar, D.A., 1984, Stratigraphy, age, depositional environments, and hydrocarbon source rock evaluation of the Otuk Formation, north-central Brooks Range, Alaska (M.S. thesis): University of Alaska, Fairbanks, Alaska, 232 p.

Bodnar, D.A., 1989, Stratigraphy of the Otuk Formation and Cretaceous coquinoid limestone and shale unit, in Mull, C.G., and Adams, K.E., eds., Dalton Highway, Yukon River to Prudhoe Bay, Alaska: Alaska Division of Geological and Geophysical Surveys Guidebook 7, v. 2, p. 277-284

Bogdanov, N.A., and Tilman, S.M., 1964, Similarities in the development of the Paleozoic structure of Wrangell Island and the western part of the Brooks Range (Alaska), in Soreshchanie po Problem Tektoniki: Skladchatye oblasti Evrazil, Materialy, Moskva, Nauka, p. 219-230.

Bowsher, A.L., and Dutro, J.T., Jr., 1957, The Paleozoic section in the Shainin Lake area, central Brooks Range, Alaska, in Pt. 3, Areal geology, of Exploration of Naval Petroleum Reserve No. 4 and adjacent areas, northern Alaska, 1944-53: U.S. Geological Survey Professional Paper 303-A, p. 1-39.

Box, S.E., 1985, Early Cretaceous orogenic belt in northeastern Alaska: Internal organization, lateral extent, and tectonic interpretation, in Howell, D.G., ed., Tectonostratigraphic terranes of the circum-Pacific region: Circum-Pacific Council for Energy and Mineral Resources (American Association of Petroleum Geologists), Earth Science series, no. 1, p. 137-145.

Box, S.E., 1987, Late Cretaceous or younger SW-directed extensional faulting: Cosmos Hills, Brooks Range, Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 19, no. 6, p. 361.

Box, S.E., and Patton, 1989, Igneous history of the Koyukuk terrane, western Alaska: constraints on the origin, evolution, and ultimate collision of an accreted island-arc terrane: Journal of Geophysical Research, v. 94, p. 15,843-15,867.

Brosgé, W.P., 1975, Metamorphic belts in southern Brooks Range, in Yount, M.E., ed., United States Geological Survey Program, 1975: U.S. Geological Survey Circular 722, p. 40-41.

Brosgé, W.P., and Dutro, J.T., Jr., 1973, Paleozoic rocks of northern and central Alaska, in Pitcher, M.G., ed., Arctic geology: American Association of Petroleum Geologists Memoir 19, p. 361-375.

Brosgé, W.P., Dutro, J.T., Jr., Mangus, M.D., and Reiser, H.N., 1962, Paleozoic sequence in eastern Brooks Range, Alaska: American Association Petroleum Geologists Bulletin, v. 46, p. 2,174-2,198.

Brosgé, W.P., Nilsen, T.H., Moore, T.E., and Dutro, J.T., Jr., 1988, Geology of the Upper Devonian and Lower Mississippian(?) Kanayut Copnglomerate in the central and eastern Brooks Range, in Gryc, George, ed., Geology and exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, p. 299-316.

Brosgé, W.P., and Reiser, H.N., 1962, Preliminary geologic map of the Christian quadrangle, Alaska: U.S. Geological Survey Open-File Report 62-229, scale 1:250,000.

Brosgé, W.P., and Reiser, H.N., 1964, Geologic map and section of the Chandalar quadrangle, Alaska: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-375, scale 1:250,000.

Brosgé, W.P. and Reiser, H.N., 1965, Preliminary geologic map of the Arctic quadrangle, Alaska: U.S. Geological Survey Open-File Report OF 65-22, scale 1:250,000.

Brosgé, W.P., and Reiser, H.N., 1969, Preliminary geologic map of the Coleen quadrangle, Alaska: U.S. Geological Survey Open-File Report OF 69-370, scale 1:250,000.

Brosgé, W.P., and Reiser, H.N., 1971, Preliminary bedrock geologic Map, Wiseman and eastern Survey Pass quadrangles, Alaska: U. S. Geological Survey Open-File Report OF 71-56, scale 1:250,000.

Brosgé, W.P., Reiser, H.N., Dutro, J.T., Jr., and Detterman, R.L., 1979, Bedrock geologic Map of the Philip Smith Mountains quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-897B, scale 1:250,000.

Brosgé, W.P., and Tailleur, I.L., 1970, Depositional history of northern Alaska, in Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska: American Association of Petroleum Geologics Pacific Section Meeting, Los Angeles, p. D1-D18.

Brosgé, W.P., and Tailleur, I.L., 1971, Northern Alaska petroleum province, in Cram, I.H., ed., Future petroleum provinces of the United States--their geology and potential: American Association of Petroleum Geologists Memoir 15, p. 68-99.

Brosgé, W.P., Whittington, C.L., and Morris, R.H., 1966, Geology of the Umiat-Maybe Creek region, Alaska, Chap. H of Pt. 3, Areal geology, of Exploration of Naval Petroleum Reserve No. 4 and adjacent areas, northern Alaska, 1944-53: U.S. Geological Survey Professional Paper 303-H, p. 501-638.

Bruns, T.R., Fisher, M.A., Leinbach, W.J., Jr., and Miller, J.J., 1987, Regional structure of rocks beneath the coastal plain, Chap. 19, in Bird, K.J., and Magoon, L.B., eds., Petroleum geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska: U.S. Geological Survey Bulletin 1778, p. 249-254.

Bruynzeel, J.W., Guldenzopf, E.C., and Pickard, J.E., 1982, Petroleum exploration of NPRA, 1974-1981, Final Report: Houston, Tetra Tech, 130 p.

Buckingham, M.L., 1987, Fluvio-deltaic sedimentation patterns of the Upper Cretaceous to Lower Tertiary Jago River Formation, Arctic National Wildlife Refuge (ANWR), northeastern Alaska, in Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 50, Bakersfield, California, p. 529-540.

Cady, J.W., 1989, Geologic implications of topographic, gravity, and aeromagnetic data in the northern Yukon-Koyukuk province and its borderlands, Alaska: Journal of Geophysical Research, v. 94, p. 15,821-15,841.

Campbell, R.H., 1967, Areal geology in the vicinity of the Chariot site, Lisburne Peninsula, northwest Alaska: U.S. Geological Survey Professional Paper 395, 71 p.

Carey, S.W., 1958, A tectonic approach to continental drift, in Carey, S.W., ed., Continental drift. A symposium: Hobart, Tasmania University, p. 177-355.

Carlson, C., 1985, Large-scale south-dipping, low-angle normal faults in the southern Brooks Range, Alaska: Eos (Transactions of the American Geophysical Union), v. 66, p. 1074.

Carman, G.J., and Hardwick, P., 1983, Geology and regional setting of the Kuparuk oil field, Alaska: American Association of Petroleum Geologists Bulletin, v. 67, p. 1014-1031.

Carter, Claire, and Laufeld, Sven, 1975, Ordovician and Silurian fossils in well cores from North Slope of Alaska: American Association of Petroleum Geologists Bulletin, v. 59, p. 457-464.

Carter, Claire, and Tailleur, I.L., 1984, Ordovician graptolites from the Baird Mountains, western Brooks Range, Alaska: Journal of Paleontology, v. 58, p. 40-57.

Carter, L.D., 1981, A Pleistocene sand sea on the Alaskan Arctic Coastal Plain: Science, v. 211, no. 4480, p. 381-383.

Chapman, R.M., Detterman, R.L., and Mangus, M.D., 1964, Geology of the Killik-Etivluk Rivers region, Alaska: U.S. Geological Survey Professional Paper 303-F, p. 325-407.
Chapman, R. M., and Sable, E.G., 1960, Geology of the Utukok-Corwin region, northwestern Alaska: U.S. Geological Survey Professional Paper 303-C, p. 47-167.
Churkin, Michael, Jr., 1975, Basement rocks of Barrow arch, Alaska, and circum-Arctic Paleozoic mobile belt: American Association Petroleum Geologists Bulletin, v. 59, p. 451-456.
Churkin, M., Jr., Nokleberg, W.J., and Huie, C., 1979, Collision-deformed Paleozoic continental margin, western Brooks Range, Alaska: Geology, v. 7, p. 379-383.
Churkin, Michael, Jr., and Trexler, J.H., Jr., 1980, Circum-Arctic plate accretion-isolating part of a Pacific plate to form the nucleus of the Arctic Basin: Earth and Planetary Science Letters, v. 49, p. 356-362.
Churkin, Michael, Jr., and Trexler, J.H., 1981, Continental plates and accreted oceanic terranes in the Arctic, in Nairn, A.E.M., Churkin, Michael, Jr., and Stehli, F.G., eds., the Arctic Ocean: The ocean basin and margins, v. 5, New York, Plenum Publishing Corp., p. 1-20.
Clough, J.G., Blodgett, R.B., Imm, T.A., and Pavia, E.A., 1988, Depositional environments of Katakturuk Dolomite and Nanook Limestone, Arctic National Wildlife Refuge, Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 72, p. 172.
Clough, J.G., Robinson, M.S., Pessel, G.H., Imm, T.A., Blodgett, R.B., Harris, A.G., Bergman, S.C., and Foland, K.A., 1990, Geology and age of Franklinian and older rocks in the Sadlerochit and Shublik Mountains, Arctic National Wildlife Refuge, Alaska [abs.]: Geological Association of Canada, Program with Abstracts, v. 15, p. A25.
Coleman, R.G., 1984, The diversity of ophiolites: Geologie en Mijnbouw, v. 63, p. 141-150.
Collier, A.J., 1906, Geology and coal resources of the Cape Lisburne region, Alaska: U.S. Geological Survey Bulletin, no. 278, 54 p.
Collins, F.R., 1958, Test wells, Topagoruk area, Alaska, Chap. D in Pt. 5, Subsurface geology and engineering data, of Exploration of Naval Petroleum Reserve No. 4 and adjacent areas, northern Alaska, 1944-53: U.S. Geological Survey Professional Paper 305-D, p. 265-316.
Collins, F.R., 1961, Core test and test wells, Barrow area, Alaska, in Pt. 5, of Exploration of Naval Petroleum Reserve No. 4 and adjacent areas, northern Alaska, 1944-53: U.S. Geological Survey Professional Paper 305-K, p. 569-644.
Coney, P.J., and Jones, D.L., 1985, Accretion tectonics and crustal structure in Alaska: Tectonophysics, v. 119, p. 265-283.
Craig, J.D., Sherwood, K.W., and Johnson, P.P., 1985, Geologic report for the Beaufort Sea planning area, Alaska: Minerals Management Service OCS Report MMS 85-0111, 192 p.
Craig, J.D., and Thrasher, G.P., 1982, Environmental geology of Harrison Bay, northern Alaska: U.S. Geological Survey Open-File Report 82-35, 25p.
Crane, R.C., 1980, Comment on "Collision-deformed Paleozoic continental margin, western Brooks Range, Alaska", by Churkin, M., Jr., Nokleberg, W.J., and Huie, C.: Geology, v. 8, no. 8, p. 354.
Crane, R.C., 1987, Cretaceous olistostrome model, Brooks Range, Alaska, in Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 433-440.
Crane, R.C., and Mull, C.G., 1987, Structural style - Brooks Range mountain front, Alaska, in Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 631-638.
Crane, R.C. and Wiggins, V.D., 1976, The Ipewik Formation, a significant Jurassic-Neocomian map unit in the northern Brooks Range fold belt [abs.]: American Association Petroleum Geologists, Pacific Section, Program and abstracts for 51st Annual Meeting, p. 25-26.
Crowder, R.K., 1987, Cretaceous basin to shelf transition in northern Alaska; deposition of the Fortress Mountain Formation, in Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 449-458.

Crowder, R.K., 1989, Deposition of the Fortress Mountain Formation, in Mull, C.G., and Adams, K.E., eds., Dalton Highway, Yukon River to Prudhoe Bay, Alaska: Alaska Division of Geological and Geophysical Surveys Guidebook 7, v. 2, p. 293-301.

Curtis, S.M., Ellersieck, Inyo, Mayfield, C.F., and Tailleur, I.L., 1984, Reconnaissance geologic map of southwestern Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations series Map I-1502, scale 1:63,360.

Curtis, S.M., Ellersieck, Inyo, Mayfield, C.F., and Tailleur, I.L., 1990, Reconnaissance geologic map of the De Long Mountains A1 and B1 quadrangles and part of the C2 quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1930, scale 1:63,360.

Decker, J. E., and Dillon, J.T., 1984, Interpretation of regional aeromagnetic signatures along the southern margin of the Brooks Range, Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 16, no. 5, p. 278.

Decker, John, and Karl, S.M., 1977, Aeromagnetic map of the Brooks Range and Arctic Slope, Alaska: U.S. Geological Survey Open-File Report OF 77-166E, scale 1:1,000,000.

Detterman, R.L.,1973, Mesozoic sequence in Arctic Alaska, in Pitcher, M.G., ed., Arctic geology: American Association of Petroleum Geologists Memoir 19, p. 376-387.

Detterman, R.L., 1970, Sedimentary history of Sadlerochit and Shublik Formations in northeastern Alaska, in Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska: Los Angeles, Calif., American Association of Petroleum Geologists, Pacific Section, p. O1-O13.

Detterman, R.L., Bickel, R.S., and Gryc, George, 1963, Geology of the Chandler River region, Alaska: U.S. Geological Survey Professional Paper 303-E, p. 223-324.

Detterman, R.L., Reiser, H.N., Brosgé, W.P., and Dutro, J.T., Jr., 1975, Post-Carboniferous stratigraphy, northeastern Alaska: U.S. Geological Survey Professional Paper 886, 46 p.

Dillon, J.T., 1987, Root zone of the Endicott allochthon, Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 19, no. 6, p. 372.

Dillon, J.T., 1989, Structure and stratigraphy of the southern Brooks Range and northern Koyukuk basin near the Dalton Highway, in Mull, C.G., and Adams, K.E., eds., Dalton Highway, Yukon River to Prudhoe Bay, Alaska: Alaska Division of Geological and Geophysical Surveys Guidebook 7, v. 2, p. 157-187.

Dillon, J.T., Brosgé, W.P., and Dutro, J.T., Jr., 1986, Generalized geologic map of the Wiseman quadrangle, Alaska: U.S. Geological Survey Open-File Report OF 86-219, scale 1:250,000.

Dillon, J.T., Harris, A.G., and Dutro, J.T., Jr., 1987a, Preliminary description and correlation of Lower Paleozoic fossil-bearing strata in the Snowden Mountain area of the south-central Brooks Range, Alaska, in Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 337-345.

Dillon, J.T., Pessel, G.H., Chen, J.A., Veach, N.C., 1980, Middle Paleozoic magmatism and orogenesis in the Brooks Range, Alaska: Geology, v. 8, p. 338-343.

Dillon and Smiley, C.J., 1984, Clasts from the Early Cretaceous Brooks Range orogen in Albian to Cenomanian molasse deposits of the northern Koyukuk basin [abs.]: Geological Society of America Abstracts with Programs, v. 16, no. 5, p. 279.

Dillon, J.T., Tilton, G.R., Decker, John, and Kelly, M.J., 1987b, Resource implications of magmatic and metamorphic ages for Devonian igneous rocks in the Brooks Range, in Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 713-723.

Dinter, D.A., 1985, Quaternary sedimentation of the Alaskan Beaufort shelf: influence of regional tectonics, flucturating sea levels, and glacial sedimnt sources: Tectonophysics, v. 114, p. 133-161.

Dinter, D.A., Carter, D.L., and Brigham-Grette, Julie, 1990, Late Cenozoic geologic evolution of the Alaskan North Slope and adjacent continental shelves,in Grantz, A., Johnson, L., and Sweeney, J.F., eds., The Arctic Ocean region: Boulder, Colo., Geological Society of America, The Geology of North America, v. L., p. 459-490.

Drummond, K.J., 1974, Paleozoic Arctic margin of North America, in Burk, C.A., and Drake, C.L., eds., The geology of continental margins: New York, Springe-Verlag, p. 797-810.

Dumoulin, J.A., 1988, Stromatolite- and coated-grain-bearing carbonate rocks of the western Brooks Range, in Galloway, J.P. and Hamilton, T.D., eds., Geologic Studies in Alaska by the U.S. Geological Survey in 1987, U.S. Geological Survey Circular 1016, p. 31-34.

Dumoulin, J.A., and Harris, A.G., 1987, Lower Paleozoic carbonate rocks of the Baird Mountains quadrangle, western Brooks Range, Alaska, in Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 311-336.

Dusel-Bacon, Brosgé, W.P., Till, A.B., Doyle, E.O., Mayfield, C.F., Reiser, H.N., and Miller, T.P., 1989, Distribution, facies, ages, and proposed tectonic associations of regionally metamorphosed rocks in northern Alaska: U.S. Geological Survey Professional Paper 1497-A, 44 p, scale 1:1,000,000, 2 sheets.

Dutro, J.T., Jr., 1952, Stratigraphy and paleontology of the Noatak and associate formations, Brooks Range, Alaska: U.S. Geological Survey Geological Investigations, Naval Petroleum Reserve No. 4, Alaska, Special Report 33, 154 p.

Dutro, J.T., Jr., 1953, Stratigraphy and paleontology of the Noatak and associated formations, Brooks Range, Alaska (Ph.D. thesis): Yale University, New Haven, Conn., 154p.

Dutro, J.T., Jr., 1970, Pre-Carboniferous carbonate rocks, in Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska: American Association of Petroleum Geologists Pacific Section Meeting, Los Angeles, p. M1-M17.

Dutro, J.T., Jr., 1980, Comment on "Collision-deformed Paleozoic continental margin, western Brooks Range, Alaska", by Churkin, M., Jr., Nokleberg, W.J., and Huie, C.: Geology, v. 8, no. 8, p. 355-356.

Dutro, J.T., Jr., 1981, Geology of Alaska bordering the Arctic Ocean, in Nairn, A.E.M., Churkin, Michael Jr., and Stehli, F.G., eds., The ocean basins and margins, vol. 5: the Arctic Ocean: New York, Plenum Press, p. 21-36.

Dutro, J.T., Jr., 1987a, A brief history of eighty years of geological exploration in the central Brooks Range, northern Alaska, in Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 50, p. 7-11.

Dutro, J.T., Jr., 1987b, Revised megafossil biostratigraphic zonation for the Carboniferous of northern Alaska, in Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 359-364.

Dutro, J.T., Jr., Brosgé, W.P., Reiser, H.N., and Detterman, R.L., 1979, Beaucoup Formation, a new Upper Devonian stratigraphic unit in the central Brooks Range, northern Alaska, in Sohl, N.F., and Wright, W.B., eds., Changes in stratigraphic nomenclature by the U.S. Geological Survey: U.S. Geological Survey Bulletin 1482-A, p. A63-A69.

Dutro, J.T., Jr., Brosgé, W.P., Lanphere, M.A., and Reiser, H.N., 1976, Geologic significance of Doonerak structural high, central Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 60, p. 952-961.

Dutro, J.T., Jr., Brosgé, W.P., and Reiser, H.N., 1972, Significance of recently discovered Cambrian fossils and reinterpretation of Neruokpuk Formation, northeastern Alaska: American Association of Petroleum Geologists Bulletin, v. 56, p. 808-815.

Dutro, J.T., Jr., Palmer, A.R., Repetski, J.E., and Brosgé, W.P, 1984, Middle Cambrian fossils from the Doonerak anticlinorium, central Brooks Range, Alaska: Journal of Paleontology, v. 58, p. 1364-1371.

Eckelmann, W.R., Fisher, W.L., and DeWitt, R.J., 1976, Prediction of fluvial-deltaic reservoir, Prudhoe Bay filed, Alaska, in Miller, T.P., ed., Symposium on recent and ancient sedimentary environments in Alaska: Symposium Proceedings of the Alaska Geological Society, Anchorage, Alaska, p. B1-B8.

Ehm, Arlen, and Tailleur, I.L., 1985, Refined names for Brookian elements in northern Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 69, p. 664.

Einaudi, M.T., and Hitzman, M.W., 1986, Mineral deposits in northern Alaska: introduction: Economic Geology, v. 81, p. 1583-1591.

Ellersieck, Inyo., Curtis, S.M., Mayfield, C.F., and Tailleur, I.L., 1984, Reconnaissance geologic map of south-central Misheguk Mountain quadrangle: U.S. Geological Survey Miscellaneous Investigations Series map I-1504, scale 1:63,360.

Ellersieck, I., Mayfield, C.F., Tailleur, I.L., and Curtis, S.M., 1979, Thrust sequences in the Misheguk Mountain quadrangle, Brooks Range, Alaska: U.S. Geological Survey Circular 804-B, p. B8-B9.

Ellersieck, Inyo., Curtis, S.M., Mayfield, C.F., and Tailleur, I.L., 1990, Reconnaissance geologic map of the De Long Mountains A2 and B2 quadrangles and part of the C2 quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1931, scale 1:63,360.

Forbes, R.B., Hamilton, T., Tailleur, I.L., Miller, T.P., and Patton, W.W., 1971, Tectonic implications of blueschist facies metamorphic terranes in Alaska: Nature Physical Sciences, v. 234, p. 106-108.

Fraser, G.S., and Clark, R.H., 1976, Transgressive-regressive shelf deposition, Shublik Formation, Prudhoe Bay area, Alaska [abs.]: Bulletin of the American Association of Petroleum Geologists, v. 60, p. 672.

Fritts, C.E., Eakins, G.R., and Garland, R.E., 1971, Geology and geochemistry near Walker Lake, southern Survey Pass quadrangle, Arctic Alaska: Alaska Division of Geological and Geophysical Surveys Annual Report, p. 19-27.

Fujita, Kazuya, and Newberry, J.T., 1982, Tectonic evolution of northeastern Siberia and adjacent regions: Tectonophysics, v. 89, p. 337-357.

Gaynor, G.C., and Scheihing, M.H., 1988, Shelf depositional environments and reservoir characteristics of the Kuparuk River Formation (Lower Cretaceous), Kuparuk Field, North Slope, Alaska, in Lomando, A.J., and Harris, P.M., eds., Giant oil and gas fields, a core workshop: Society of Economic Paleontologists and Mineralogists Core Workshop No. 12, Tulsa, Okla., p. 333-389.

Gautier, D.L., 1987, Petrology of Cretaceous and Tertiary reservoir sandstones in the Point Thompson area, Chap. 9, in Bird, K.J., and Magoon, L.B., eds., Petroleum geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska: U.S. Geological Survey Bulletin 1778, p. 117-122.

Gordey, S.P., 1988, Devono-Mississippian clastic sedimentation and tectonism in the Canadian Cordilleran miogeocline, in McMillan, N.J., Embry, A.F., and Glass, D.J., eds., Devonian of the World, volume II: sedimentation: Canadian Society of Petroleum Geologists Memoir 14, Calgary, Canada, p. 1-14.

Gordey, S.P., Abbott, J.G., Tempelman-Kluitt, D.J., and Gabrielse, H., 1987, "Antler" clastics in the Canadian Cordillera: Geology, v. 15, p. 103-107.

Gottschalk, R.R., Jr., 1987, Structural and petrologic evolution of the southern Brooks Range near Wiseman, Alaska (Ph.D. thesis): Houston, Texas, Rice University, 263 p.

Gottschalk, R.R., Jr., 1990, Structural evolution of the schist belt, south-central Brooks Range fold and thrust belt, Alaska: Journal of Structural Geology, v. 12, p. 453-469.

Gottschalk, R.R., Jr., and Oldow, J.S., 1988, Low-angle normal faults in the south-central Brooks Range fold and thrust belt, Alaska: Geology, v. 16, p. 395-399.

Grantz, A., 1966, Strike-slip faults in Alaska: U.S. Geological Survey Open-file Report OFR-267, 82 p.

Grantz, Arthur, Dinter, D.A., and Biswas, N.N., 1983a, Holocene faulting, warping, and earthquake epicenters on the Beaufort Shelf north of Alaska: U.S. Geological Survey Miscellaneous Investigations Map I-1189C, 7 p, scale 1:500,000, 3 sheets.

Grantz, Arthur, Dinter, D.A., and Culotta, R.C., 1987, Structure of the continental shelf north of the Arctic National Wildlife Refuge, Chap. 21, in Bird, K.J., and Magoon, L.B., eds., Petroleum geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska: U.S. Geological Survey Bulletin 1778, p. 271-276.

Grantz, Arthur, Eittreim, Stephen, and Whitney, O.T., 1981, Geology and physiography of the continental margin north of Alaska and implications for the origin of the Canada basin, in Nairn, A.E.M., Churkin, Michael, and Stehli, F.G., eds., The ocean basins and margins: Plenum Publishing Corporation, New York, v. 5, p. 439-492.

Grantz, Arthur, and May, S.D., 1983, Rifting history and structural development of the continental margin north of Alaska, in Watkins, J.S., and Drake, C.L., eds., Studies in continental margin geology: American Association of Petroleum Geologists Memoir 34, p. 77-100.

Grantz, Arthur, and May, S.D., 1987, Regional geology and petroleum potential of the United States Chukchi shelf north of Point Hope, in Scholl, D.W., Grantz, Arthur, and Vedder, J.G., eds.,Geology and resource potential of the continental margin of western North America and adjacent ocean basins -- Beaufort Sea to Baja California: Circum-Pacific Council for Energy and Mineral Resources Earth Science Series, v. 6, p. 37-58.

Grantz, Arthur, May, S.D., and Hart, P.E., 1990a, Geology of the Arctic continental margin of Alaska, in Grantz, A., Johnson, L., and Sweeney, J.F., eds., The Arctic Ocean region: Boulder, Colo., Geological Society of America, The Geology of North America, v. L., p. 257-288.

Grantz, Arthur, May, S.D., Taylor, P.T., and Lawver, L.A., 1990b, Canada basin, in Grantz, A., Johnson, L., and Sweeney, J.F., eds., The Arctic Ocean region: Boulder, Colo., Geological Society of America, The Geology of North America, v. L., p. 379-402.

Grantz, Arthur, Moore, T.E., and Roeske, S.M., 1991, Continent-ocean transect A-3: Gulf of Alaska to Arctic Ocean: Boulder, Colo., Geological Society of America, scale 1:500,000, 3 sheets.

Grantz, Arthur, Tailleur, I.L., and Carter, Claire, 1983b, Tectonic significance of Silurian and Ordovician graptolites, Lisburne Hills, northwest Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 274.

Grantz, A., Wolf, S.C., Breslau, L, Johnson, T.C., and Hanna, W.F., 1970, Reconnaissance geology of the Chukchi Sea as determined by acoustic and magnetic profiles, in Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska: American Association of Petroleum Geologists Pacific Section Meeting, Los Angeles, p. F1-F28.

Grybeck, Donald, Beikman, H.M., Brosgé, W.P., Tailleur, I.L., and Mull, C.G., 1977, Geologic map of the Brooks Range, Alaska: U.S. Geological Survey Open-File Report OF 77-166B, scale 1,000,000.

Grybeck, D., and Nelson, S.W., 1981, Structure of the Survey Pass quadrangle, Brooks Range, Alaska: U.S. Geological Survey Miscellaneous Geologic Investigations Map MF-1176B, 8 p., scale 1:250,000.

Gryc, George, 1970, History of petroleum exploration in northern Alaska, in Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska: Pacific Section, American Association of Petroleum Geologists, Los Angeles, CA, p. C1-C10.

Gryc, George, 1988, ed., Geology and exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, 940p.

Gryc, G., Patton, W.W., Jr., and Payne, T.G., 1951, Present Cretaceous stratigraphic nomenclature of northern Alaska: Washington Academy of Science Journal, v. 41, p. 159-167.

Gutman, S.I., Goldstein, A., and Guldenzopf, E.C., 1982, Gravity and magnetic investigations of the National Petroleum Reserve in Alaska: Houston, Tetra Tech, 88 p.

Halgedahl, S.L., and Jarrard, R.D., 1987, Paleomagnetism of the Kuparuk River Formation from oriented drill core: evidence for rotation of the Arctic Alaska plate, in Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 581-617.

Hamilton, T.D., 1986, Late Cenozoic glaciation of the central Brooks Range, in Hamilton, T.C., Reed, K.M., and Thorson, R.M., eds., Glaciation in Alaska; the geologic record: Anchorage, Alaska Geological Society, p. 9-50.

Handschy, J.W., and Oldow, J.S., 1989, Strain variation in the Endicott Mountains allochthon, central Brooks Range, Alaska [abs]: Geological Society of America Abstracts with Program, v. 21, no. 5, p. 89.

Handschy, J.W., Oldow, J.S., and Avé Lallemant, H.G., 1987b, Fold-thrust kinematics and strain distribution in the Endicott Mountains allochthon, Brooks Range, Alaska: Eos (Transactions of the American Geophysical Union), v. 68, p. 1457.

Handschy, J.W., Oldow, J.S., Phelps, J.C., and Ave Lallemant, H.G., 1987a, Stratigraphy and facies relationships of the Endicott Group between Atigun Pass and the eastern Doonerak window, central Brooks Range, Alaska (abs.): Geological Society of America Abstracts with Programs, v. 19, p. 386.

Harris, A.G., Repetski, J.E., and Dumoulin, J.A., 1988, Ordovician carbonate rocks and conodonts from northern Alaska [abs.]: Program and Abstracts for the Fifth International Symposium on the Ordovician System, St. Johns, Newfoundland, Canada, p. 38.

Harris, R.A., 1988, Origin, emplacement, and attenuation of the Misheguk Mountain allochthon, western Brooks Range, Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 20, no. 7, p. A112.

Hemming, Sidney, Sharp, W.D., Moore, T.E., and Mezger, Klaus, 1989, Pb/U dating of detrital zircons from the Carboniferous Nuka Formation, Brooks Range, Alaska: evidence for a 2.07 Ga Provenance [abs.]: Geological Society of America Abstracts with Programs, v. 21, no. 6, p. A190.

Henning, M.W., 1982, Reconnaissance geology and stratigraphy of the Skajit Formation, Wiseman B-5 quadrangle, Alaska: Alaska Division of Geological and Geophysical Surveys Open-File Report AOF-147, scale 1:63,360, 1 sheet.

Herron, E.M., Dewey, J.F., and Pitman, W.C., 1974, Pl. tectonics model for the evolution of the Arctic: Geology, v. 2, p. 377-380.

Hillhouse, J.W., and Grommé, C.S., 1988, Cretaceous remagnetization of Paleozoic sedimentary rocks in the Brooks Range, Alaska, Chap. 27, in Gryc, George, ed., Geology and Exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, p. 633-644.

Hitzman, M.W., Proffett, J.M., Jr., Schmidt, J.M., and Smith, T.E., 1986, Geology and mineralization of the Ambler district, northwestern Alaska: Economic Geology, v. 81, p. 1592-1618.

Hitzman, M.W., Smith, T.E., and Proffett, J.M., Jr., 1982, Bedrock geology of the Ambler district, southwestern Brooks Range, Alaska, Alaska Division of Geological and Geophysical Surveys Geologic Report 75, scale 1:125,000, 2 sheets.

Holdsworth, B.K., and Murchey, B.L., 1988, Paleozoic radiolarian biostratigraphy of the northern Brooks Range, Alaska, Chap. 34, in Gryc, George, ed., Geology and Exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, p. 777-797.

Howell, D.G., Bird, K.J., Huafu, Lu, and Johnsson, M.J., 1992, Tectonics and petroleum potential of the Brooks Range fold and thrust belt—a progress report, in Bradley, D.C., and Ford, A.B., Geologic studies in Alaska by the U.S. Geological Survey, 1990: U.S. Geological Survey Bulletin 1999, p. 112-126.

Howell, D.G., Jones, D.L., and Coney, P.J., 1986, Convergent-margin geologic characterization for deep source hydrocarbon potential, in Deep source gas/gas hydrates: U.S. Geological Survey Quarterly Report (Annual Summary) for Department of Energy, Contract number DE-AI21-83-MC20422, 11 p.

Howell, D.G., Jones, D.L., and Schermer, E.R., 1985, Tectonostratigraphic terranes of the circum-Pacific region, in Howell, D.G., ed., Tectonostratigraphic terranes of the circum-Pacific region: Circum-Pacific Council for Energy and Mineral Resources,Houston, Texas, Earth Science Series, no. 1, p. 3-30.

Howell, D.G., and Wiley, T.J., 1987, Crustal evolution of northern Alaska inferred from sedimentology and structural relations of the Kandik area: Tectonics, v. 6, p. 619-631.

Hubbard, R.J., Edrich, S.P., and Rattey, R.P., 1987, Geologic evolution and hydrocarbon habitat of the Arctic Alaska microplate, in Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 797-830.

Huffman, A.C., Jr., Ahlbrandt, T.S., Pasternac, Ira, Stricker, G.D., and Fox, J.E., 1985, Depositional and sedimentologic factors affecting the reservoir potential of the Cretaceous Nanushuk Group, central North Slope, Alaska, in Huffman, A.C., Jr., ed., Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 61-74.

Hunter, R.E., and Fox, J.E., 1976, Interpretation of depositional environments in the Fortress Mountain Formation, central Arctic Slope, in Cobb, E.H., ed., The United States Geological Survey in Alaska: accomplishments during 1975: U.S. Geological Survey Circular 733, p. 30-31.

Jamison, W.R., 1987, Geometric analysis of fold development in overthrust terranes: Journal of Structural Geology, v. 9, p. 207-219.

Jamison, H.C., Brockett, L.D., and McIntosh, R.A., 1980, Prudhoe Bay--a 10-year perspective, in Giant oil and gas fields of the decade 1968-1978: American Association of Petroleum Geologists Memoir 30, p. 289-314.

Jones, D.L., 1983, Recognition, character, and analysis of tectonostratigraphic terranes in western North America, in Hashimoto, M., and Uyeda, S., eds., Accretion tectonics in the circum-Pacific regions: Boston, D. Reidel Publishing Co., p. 21-36.

Jones, D.L., and Coney, Peter, 1989, Regional decollement at base of Hunt Fork Shale, eastern Brooks Range, Alaska, [abs.]: Geological Society of America Abstracts with Programs, v. 21, no. 5, p. 99.

Jones, D.L., Coney, P.J., Harms, T.A., and Dillon, J.T., 1988, Interpretive geologic map and supporting radiolarian data from the Angayucham terrane, Coldfoot area, southern Brooks Range, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1993, 1 sheet, scale 1:63,360.

Jones, D.L., and Grantz, A., 1964, Stratigraphic and structural significance of Cretaceous fossils from Tiglukpuk Formation, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 48, p. 1462-1474.

Jones, D.L., Silberling, N.J., and Coney, P.J., 1986, Collision tectonics in the Cordillera of western North America: examples from Alaska, in Coward, M.P., and Ries, A.C., (eds.), Collision Tectonics: Geological Society of London Special Publication no. 19, p. 367-387.

Jones, D.L., Silberling, N.J., Coney, P.J., and Plafker, George, 1987, Lithotectonic terrane map of Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1874A, scale 1:2,500,000, 1 sheet.

Jones, H.P., and Speers, R.G., 1976, Permo-Triassic reservoirs of the Prudhoe Bay gas fields: American Association of Petroleum Geologists Memoir 24, p. 23-50.

Jones, P.B., 1980, Evidence from Canada and Alaska on plate tectonic evolution of the Arctic Ocean basin: Nature, v. 285, p. 215-217.

Jones, P.B., 1982a, Oil and gas beneath east-dipping underthrust faults in the Alberta foothills, in Powers, R.B., ed., Geologic studies of the Cordilleran thrust belt: Geologic studies of the Cordilleran thrust belt: Rocky Mountain Association of Geologists, Denver, Colo., v.1, p. 61-74.

Jones, P.B., 1982b, Mesozoic rifting in the western Arctic Ocean basin and its relationship to Pacific seafloor spreading, in Embry, A.F., and Balkwill, H.R., eds., Arctic geology and geophysics: Canadian Society of Petroleum Geologists Memoir 8, p. 83-99.

Julian, F.E., 1989, Structure and stratigraphy of Lower Paleozoic rocks, Doonerak window, central Brooks Range, Alaska (Ph.D. dissertation): Houston, Texas, Rice University, 127 p, scale 1:31,680, 1 sheet.

Julian, F.E., 1986, Stratigraphy and tectonic provenance of Lower Paleozoic rocks, Doonerak structural high, Brooks Range, Alaska (abs.): Geological Society of America Abstracts with Programs, v. 18, p. 123.

Karl, S.M., 1989, Paleoenvironmental implication of Alaskan siliceous deposits, in Hein, J.R., and Obradovic, Jelena, eds., Siliceous deposits of the Tethys and Pacific regions: New York, Springer-Verlag, p. 169-200.

Karl, S.M., 1991, Arc and extensional basin geochemical and tectonic affinities for the Maiyumerak basalts in the western Brooks Range, in Bradley, D.C., and Ford, A.B., eds., Geologic studies in Alaska by the U.S. Geological Survey, 1990: U.S. Geological Survey Bulletin 1999, p. 141-155.

Karl, S.M., and Dickey, C.F., 1989, Geology and geochemistry indicate belts of both ocean floor and arc basalt and gabbro in the Maiyumerak Mountains, northwestern Brooks Range, Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 21, no.5, p. 100.

Karl, S.M., and Long, C.L., 1987, Evidence for tectonic truncation of regional east-west trending structures in the central Baird Mountains quadrangle, western Brooks Range, Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 19, no.6, p. 392.

Karl, S.M., and Long, C.L., 1990, Folded Brookian thrust faults: implications of three geologic/geophysical transects in the western Brooks Range: Journal of Geophysical Research v. 95, p. 8581-8592.

Karl, S.M., Dumoulin, J.A., Ellersieck, Inyo, Harris, A.G., and Schmidt, J.M., 1989, Preliminary geologic map of the Baird Mountains quadrangle, Alaska: U.S. Geological Survey Open-File Report 89-551, 65 p., scale 1:250,000, 1 sheet.

Keller, A.S., Morris, R.E., and Detterman, R.L., 1961, Geology of the Shaviovik and Sagavanirktok Rivers region, Alaska: U.S. Geological Survey Professional Paper 303-D, p. 169-219.

Kelley, J.S., 1988, Preliminary geologic map of the Chandler Lake quadrangle, Alaska: U.S. Geological Survey Open File Report 88-42, scale 1:125,000, 2 sheets.

Kelley, J.S., and Bohn, D., 1988, Décollements in the Endicott Mountains allochthon, north-central Brooks Range, in Galloway, J.P., and Hamilton, eds., Geologic Studies in Alaska by the U.S. Geological Survey during 1987: U.S. Geological Survey Circular 1016, p. 44-47.

Kelley, J.S., and Foland, R.L., 1987, Structural style and framework geology of the coastal plain and adjacent Brooks Range, Chap. 20., in Bird, K.J., and Magoon, L.B., eds., Petroleum geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska: U. S. Geological Survey Bulletin 1778, p. 255-270.

Kelley, J.S., and Molenaar, C.M., 1985, Detachment tectonics in Sadlerochit and Shublik Mountains and applications for exploration beneath coastal plain, Arctic National Wildlife Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 69, p. 667.

Kelley, J.S., Brosgé, W.P., and Reynolds, M.W., 1985, Fold-nappes and polyphase thrusting in the north-central Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 65, p. 667.

Kindle, E.M., 1909, The section at Cape Thompson, Alaska: American Journal of Science: Fourth series, v. 28, p.520-528.

Kirschner, C.E., Gryc, G., and Molenaar, C., 1983, Regional seismic lines in the National Petroleum Reserve in Alaska, in Bally, A.W., ed., Seismic expression of structural styles, volume 1: American Association of Petroleum Geologists Studies in Geology, Series No. 15, p. 1.2.5-1-14 to 1.2.5-14.

Kirschner, D.E., and Rycerski, B.A., 1988, Petroleum potential of representative stratigraphic and structural elements in the National Petroleum Reserve in Alaska Chap. 9, in Gryc, George, ed., Geology and Exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, p. 191-208.

Knock, D.G., 1987, Depositional setting and provenance of upper Neocomian Kemik Sandstone, Arctic National Wildlife Refuge (ANWR), northeastern Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 19, no. 6, p. 395.

Lane, L.S., 1991, The pre-Mississippian "Neruokpuk Formation," northeastern Alaska and northwestern Yukon: review and new regional correlation: Canadian Journal of Earth Science v. 28, p.1521-1533.

Lane, L.S. and Cecile, M.P., 1989, Stratigraphy and structure of the Neruokpuk Formation, northern Yukon, in Current Research, Part G: Geological Survey of Canada, Paper 89-1G, p. 57-62.

Lathrum, E.H., 1965, Preliminary geologic map of northern Alaska: U.S. Geological Survey Open-file Report 65-96, 2 sheets, scale 1:1,000,000.

Lawton, T.F., Geehan, G.W., and Voorhees, B.J., 1987, Lithofacies and depositional environments of the Ivishak Formation, Prudhoe Bay field, in Tailleur, I.L, and Weimer, Paul, eds., Alaskan North Slope Geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 61-76.

Lawver, L.A., and Scotese, C.R., 1990, A review of tectonic models for the evolution of the Canada basin, in Grantz, A., Johnson, L., and Sweeney, J.F., eds., The Arctic Ocean region: Boulder, Colo., Geological Society of America, The Geology of North America, v. L., p. 593-618.

Leffingwell, Ernest, de K., 1919, The Canning River region, northern Alaska: U.S. Geological Survey Professional Paper 109, 251 p.

Lerand, Monti, 1973, Beaufort Sea, in McCrossam, R.G., ed., The future petroleum provinces of Canada -- their geology and potential: Canadian Society of Petroleum Geology Memoir 1, p. 315-386.

Leiggi, P.A., 1987, Style and age of tectonism of the Sadlerochit Mountains to Franklin Mountains, Arctic National Wildlife Refuge, Alaska, in Tailleur, I.L., and Weimer, P., eds., Alaskan North Slope geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 749-756.

Leiggi, P.A., and Russell, B.J., 1985, Style and age of tectonism of Sadlerochit Mountains to Franklin Mountains, Arctic National Wildlife Refuge (ANWR), Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 69, p. 668.

LePain, D.L., and Crowder, R.K., 1990, Deposition of the Endicott Group (Mississippian) in the northeastern Brooks Range, Alaska [abs.]: Geological Association of Canada, Program with Abstracts, v. 15, p. A76.

Loney, R.A., and Himmelberg, G.R., 1985, Ophiolitic ultramafic rocks of the Jade Mountains - Cosmos Hills area, southwestern Brooks Range, in Bartsch-Winkler, Susan, ed., Geologic studies in Alaska by the U.S. Geological Survey during 1985: U. S. Geological Survey Circular 967, p. 13-15.

Maddren, A.G., 1912, Geologic investigations along the Canada-Alaska boundary: U.S. Geological Survey Bulletin 520, p. 297-314.

Maddren, A.G., 1913, The Koyukuk-Chandalar region: U.S. Geological Survey Bulletin 532, 119 p.

Mair, J.A., and Lyons, J.A., 1981, Crustal structure and velocity anisotrophy beneath the Beaufort Sea: Canadian Journal of Earth Science, v. 18, p. 724-741.

Marinai, R.K., 1987, Petrography and diagenesis of the Ledge Sandstone Member of the Triassic Ivishak Formation, in Bird, K.J., and Magoon, L.B., eds., Petroleum geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska: U.S. Geological Survey Bulletin 1778, p. 101-115.

Martin, A.J., 1970, Structure and tectonic history of the western Brooks Range, De Long Mountains, and Lisburne Hills, northern Alaska: Geological Society of America Bulletin, v. 81, p. 3605-3622.

Martin, G.C., 1926, The Mesozoic stratigraphy of Alaska: U.S. Geological Survey Bulletin 776, 493 p.

Masterson, W.D., and Paris, C.E., 1987, Depositional history and reservoir description of the Kuparuk River Formation, North Slope, Alaska, in Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope Geology: Bakersfield, Calif., Pacific Section of Society of Economic Paleontologists and Mineralogists and the Alaska Geological Society, Book 50, p. 95-107.

Mayfield, C.F., 1980, Comment on "Collision-deformed Paleozoic continental margin, western Brooks Range, Alaska", by Churkin, M., Jr., Nokleberg, W.J., and Huie, C.: Geology, v. 8, p. 357-359.

Mayfield, C.F., Curtis, S.M., Ellersieck, Inyo, and Taillieur, I.L., 1990, Reconnaissance geologic map of the De Long Mountains A3 and B3 quadrangles and parts of the A4 and B4 quadrangles: U.S. Geological Survey Miscellaneous Investigations Series Map I-1929, scale 1:63,360.

Mayfield, C.F., Curtis, S.M., Ellersieck, Inyo, and Taillieur, I.L., 1984, Reconnaissance geologic map of southeastern Misheguk Mountain quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations series Map I-1503, scale 1:63,360.

Mayfield, C.F., Ellersieck, Inyo, and Tailleur, I.L., 1987, Reconnaissance geologic map of the Noatak C5, D5, D6, and D7 quadrangles, Alaska: U.S. Geological Survey Miscellaneous Investigation Series Map I-1814, scale 1:63,360, 1 sheet.

Mayfield, C.F., Silberman, M.L., and Tailleur, I.L., 1982, Precambrian metamorphic rocks from the Hub Mountain terrane, Baird Mountains quadrangle, Alaska, in Coonrad, W.L., ed., The United States Geological Survey in Alaska: accomplishments during 1980: U.S. Geological Survey Circular 844, p. 18-22.

Mayfield, C.F., and Tailleur, I.L., 1978, Bedrock geology map of the Ambler River quadrangle, Alaska: U.S. Geological Survey Open-File Map 78-120A, scale 1:250,000, 1 sheet.

Mayfield, C.F., Tailleur, I.L., and Ellersieck, Inyo, 1988, Stratigraphy, structure, and palinspastic synthesis of the western Brooks Range, northwestern Alaska, Chap 7, in Gryc, George, ed., Geology and Exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, p. 143-186.

Mayfield, C.F., Tailleur, I.L., Mull, C.G., and Silberman, M.L., 1978, Granitic clasts from Upper Cretaceous conglomerate in the northwestern Brooks Range, in Johnson, K.M., ed., The United States Geological Survey in Alaska: accomplishments during 1977: U.S. Geological Survey Circular 772-B, p. B11-B13.

McCulloch, D.S., 1967 Quaternary geology of the Alaskan shore of Chukchi Sea, in Hopkins, D..M., ed., The Bering Land Bridge: Stanford, CA, Stanford University Press, p. 91-120.

McWhae, J.R., 1986, Tectonic history of northern Alaska, Canadian Arctic, and Spitsbergen regions since Early Cretaceous: American Association of Petroleum Geologists Bulletin, v. 70, p. 430-450.

Melvin, John, 1987, Fluvio-paludal deposits in the lower Kekiktuk Formation (Mississippian), Endicott Field, northeast Alaska, in Ethridge, F.G., Flores, R.M., and Harvey, M.D., eds., Recent developments in fluvial sedimentology: contributions from the Third International Fluvial Sedimentology Conference: Society of Economic Paleontologists and Mineralogists Special Publication No. 39, p. 343-352.

Melvin, John, and Knight, A.S., 1984, Lithofacies, diagenesis and porosity of the Ivishak Formation, Prudhoe Bay area, Alaska, in McDonald, D.A., and Surdam, R.C., eds., Clastic Diagenesis: American Association of Petroleum Geologists Memoir 37, p. 347-365.
Mendenhall, W.C., 1902, Reconnaissance from Fort Hamlin to Kotzebue Sound, Alaska: U.S. Geological Survey Professional Paper 10, 68 p.
Mertie, J.B., Jr.,1925, Geology and gold placers of the Chandalar district: Geological Survey Bulletin 773, p. 215-264.
Mertie, J.B., Jr., 1929, The Chandalar-Sheenjek district, Alaska: U.S. Geological Survey Bulletin 810, p. 87-139.
Metz, P.A.., 1980, Comment on "Collision-deformed Paleozoic continental margin, western Brooks Range, Alaska", by Churkin, M., Jr., Nokleberg, W.J., and Huie, C.: Geology, v. 8, no. 8, p. 360.
Metz, P.A., Egan, Alyce, and Johanson, Otto, 1982, Landsat linear features and incipient rift system model for origin of base-metal and petroleum resources in northern Alaska, in Embry, A.F., and Balkhill, H.R., eds., Arctic geology and geophysics: Canadian Society of Petroleum Geologists Memoir 8, p. 101-112.
Mickey, M.B., and Haga, Hideyo, 1983, Jurassic-Neocomian seismic stratigraphy, NPRA: Item TGY-0220-BL, National Geophysical Data Center, Boulder, Colorado, 2 volumes, 133p.
Miller, E.L., 1987, Dismemberment of the Brooks Range orogenic belt during middle Cretaceous extension: Geological Society of America Abstracts with Programs, v. 19, p. 432.
Miller, E.L., 1990, Structural studies in the southernmost Brooks Range, Alaska [abs.]: Geological Association of Canada, program with Abstracts, v. 15, p. A-89.
Miller, E.L., and Hudson, T.L., 1991, Mid-Cretaceous extensional fragmentation of a Jurassic-Early Cretaceous compressional orogen, Alaska: Tectonics, v. 10, p. 781-796.
Molenaar, C.M., 1983, Depositional relations of Cretaceous and Lower Tertiary rocks, northeastern Alaska: American Association of Petroleum Geologists Bulletin, v. 67, p. 1066-1081.
Molenaar, C.M., 1985, Subsurface correlations and depositional history of the Nanshuk Group and related strata, North Slope, Alaska, in Huffman, A.C., Jr., ed., Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 37-59.
Molenaar, C.M., 1988, Depositional history and seismic stratigraphy of Lower Cretaceous rocks in the National Petroleum Reserve in Alaska and adjacent areas, Chap. 25, in Gryc, George, ed., Geology and Exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, p. 593-621.
Molenaar, C.M., Bird, K.J., and Collett, T.S., 1986, Regional correlation sections across the North Slope of Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1907 (chart with four correlation sections).
Molenaar, C.M., Bird, K.J., and Kirk, A.R., 1987, Cretaceous and Tertiary stratigraphy of northeastern Alaska, in Tailleur, I.L, and Weimer, Paul, eds., Alaskan North Slope Geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 513-528.
Molenaar, C.M., Egbert, R.M., and Krystinik, L.F., 1988, Depositional facies, petrography, and reservoir potential of the Fortress Mountain Formation (Lower Cretaceous), central North Slope, Alaska, Chap. 12, in Gryc, George, ed., Geology and Exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, p. 257-280.
Molenaar, C.M., Kirk, A.R., Magoon, L.B., and Huffman, A.C., 1984, Twenty-two measured sections of Cretaceous - Lower Tertiary rocks, eastern North Slope, Alaska: U.S. Geological Survey Open-File Report 84-695, 19 p.
Moore, D.W., Young, L.E., Modene, J.S., and Plahuta, J.T., 1986, Geologic setting and genesis of the Red Dog zinc-lead-silver deposit, western Brooks Range, Alaska: Economic Geology, v. 81, p. 1696-1727.

Moore, T.E., 1984, Endicott-North Slope terrane boundary in the central Brooks Range, Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 16, no. 5, p. 322.

Moore, T.E., 1986, Stratigraphic framework and tectonic implications of pre-Mississippian rocks, northern Alaska [abs.]: Geological Society of America, Abstracts with Programs, v. 18, no. 2, p. 159.

Moore, T.E., 1987a, Geochemistry and tectonic setting of some volcanic rocks of the Franklinian Assemblage, central and eastern Brooks Range, in Tailleur, I.L, and Weimer, Paul, eds., Alaskan North Slope Geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 691-710.

Moore, T.E., 1987b, Geochemical and tectonic affinity of basalts from the Copter Peak and Ipnavik River allochthons, Brooks Range, Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 19, no. 6, p. 434.

Moore, T.E., Brosgé, W.P., Churkin, Michael, Jr., and Wallace, W.K., 1985a, Pre-Mississippian accreted terranes of northeastern Brooks Range, Alaska [abs.]: American Association of Petroleum Geologists, v. 69, p. 670.

Moore, T.E., and Churkin, Michael, Jr., 1984, Ordovician and Silurian graptolite discoveries from the Neruokpuk Formation (sensu lato), northeastern and central Brooks Range, Alaska: Paleozoic geology of Alaska and northwestern Canada Newsletter, no. 1, p. 21-23.

Moore, T.E., and Mull, C.G., 1989, Geology of the Brooks Range and North Slope, in Schmidt, R.A.M., Nokleberg, W.J., and Page, R.A., Alaska geological and geophysical transect, Valdez to Coldfoot Alaska: American Geophysical Union, Field Trip Guidebook T104, p. 107-131.

Moore, T.E., and Nilsen, T.H., 1984, Regional sedimentological variations in the Upper Devonian and Lower Mississippian (?) Kanayut Conglomerate, Brooks Range, Alaska: Sedimentary Geology, v. 38, p. 464-498.

Moore, T.E., and Nilsen, T.H., 1985, Sedimentology of meandering-stream cycles, upper part of the Ear Peak Member of the Kanayut Conglomerate, central Brooks Range, in Bartsch-Winkler, Susan, ed., The United States Geological Survey in Alaska: accomplishments during 1984: U.S. Geological Survey Circular 967, p. 15-19.

Moore, T.E., Nilsen, T.H., Grantz, A., and Tailleur, I.L., 1984, Parautochthonous Mississippian marine and non-marine strata, Lisburne Peninsula, Alaska, in Reed, K.M., and Bartsch-Winkler, Susan, eds., The United States Geological Survey in Alaska: accomplishments during 1982: U.S. Geological Survey Circular 939, p. 17-21.

Moore, T.E., Wallace, W.K., Bird, K.J., Karl, S.M., Mull, C.G., and Dillon, J.T., in press, Geology of northern Alaska, in Plafker, George, and Berg, H.C., eds., The geology of Alaska: Decade of North American Geology, v. G1, Geological Society of America, Boulder, Co.

Moore, T.E., Wallace, W.K., and Jones, D.L., 1991, TACT geologic studies in the Brooks Range: preliminary results and implications for crustal structure [abs.]: Geological Society of America Abstracts with Programs, v. 23, no. 2, p. 80.

Moore, T.E., Whitney, J.W., and Wallace, W.K., 1985b, Cenozoic north-vergent tectonism in northeastern Alaska: indentor tectonics in Alaska [abs.]: Eos (Transactions of the American Geophysical Union), v. 66, p. 862.

Morgridge, D.L., and Smith, W.B., 1972, Geology and discovery of Prudhoe Bay field, eastern Arctic Slope, Alaska, in King, R.E., ed., Stratigraphic oil and gas fields—classification, exploration methods, and case histories: American Association of Petroleum Geologists Memoir 16, p. 489-501.

Mull, C.G., 1977, Apparent south vergent folding and possible nappes in Schwatka Mountains: U.S. Geological Survey Circular 751-B, p. 29-31.

Mull, C.G., 1979, Nanushuk Group deposition and the Late Mesozoic structural evolution of the central and western Brooks Range and Arctic Slope, in Ahlbrandt, T.S. ed., Preliminary geologic, petrologic, and paleontologic results of the Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 5-13.

Mull, C.G., 1980, Comment on "Collision-deformed Paleozoic continental margin, western Brooks Range, Alaska", by Churkin, M., Jr., Nokleberg, W.J., and Huie, C.: Geology, v. 8, p. 361-362.
Mull, C.G., 1982, The tectonic evolution and structural style of the Brooks Range, Alaska: an illustrated summary, in Powers, R.B., ed., Geological studies of the Cordilleran thrust belt: Denver, Colo., Rocky Mountain Association of Geologists, v. 1, p. 1-45.
Mull, C.G., 1985, Cretaceous tectonics, depositional cycles, and the Nanushuk Group, Brooks Range and Arctic Slope, Alaska, in Huffman, A.C., Jr., ed., Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 7-36.
Mull, C.G., 1987, Kemik Sandstone, Arctic National Wildlife Refuge, northeastern Alaska, in Tailleur, I.L., and Weimer, P., eds., Alaskan North Slope geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, and Alaska Geological Society, v. 50, p. 405-431.
Mull, C.G., 1989, Generalized stratigraphy and structure of the Brooks Range and Arctic Slope, in Mull, C.G., and Adams, K.E., eds., Dalton Highway, Yukon River to Prudhoe Bay, Alaska: Alaska Division of Geological and Geophysical Surveys Guidebook 7, v. 1, p. 31-46.
Mull, C.G., Harris, E.E. and Tailleur, I.L., in press, Preliminary geologic map of the Killik River quadrangle: U.S. Geological Survey Open-File Report, scale 1:125,000, 1 sheet.
Mull, C.G., Adams, K.E., and Dillon, J.T., 1987a, Stratigraphy and structure of the Doonerak fenster and Endicott Mountains allochthon, central Brooks Range, Alaska, in Tailleur, I.L., and Weimer, P., eds., Alaskan North Slope geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 663-679.
Mull, C.G., Crowder, Keith, Adams, K.E., Siok, J.P., Bodnar, D.A., Harris, E.E., and Alexander, R.A., 1987b, Stratigraphy and structural setting of the Picnic Creek allochthon, Killik River quadrangle, central Brooks Range, Alaska: a summary, in Tailleur, I.L, and Weimer, Paul, eds., Alaskan North Slope Geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 649-662.
Mull, C.G., and Mangus, M.D., 1972, Itkilyariak Formation: new Mississippian formation of Endicott Group, Arctic Slope of Alaska: American Association of Petroleum Geologists Bulletin, v. 56, p. 1364-1369.
Mull, C.G., Roeder, D.H., Tailleur, I.L., Pessel, G.H., Grantz, Arthur, and May, S.D., 1987c, Geologic sections and maps across Brooks Range and Arctic Slope to Beaufort Sea: Geological Society of America Map and Chart series, MC-28S, scale 1:500,000.
Mull, C.G., and Tailleur, I.L., 1977, Sadlerochit(?) Group in the Schwatka Mountains, south-central Brooks Range, in Blean, K.M., ed., The United States Geological Survey in Alaska: accomplishments during 1976: U.S. Geological Survey Circular 751-B, p. B27-B29.
Mull, C.G., Tailleur, I.L., Mayfield, C.F., and Pessel, G.H., 1976, New structural and stratigraphic interpretations, central and western Brooks Range and Arctic Slope, in Cobb, E.H., ed., The United States Geological Survey in Alaska: accomplishments during 1975: U.S.Geological Survey Circular 733, p. 24-26.
Mull, C.G., Tailleur, I.L., Mayfield, D.F., Ellersieck, I.F., and Curtis, S., 1982, New Upper Paleozoic and lower Mesozoic stratigraphic units, central and western Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 66, p. 348-362.
Murchey, B.L., and Harris, A.G., 1985, Devonian to Jurassic sedimentary rocks in the Angayucham Mountains of Alaska: possible seamount or oceanic plateau deposits [abs.]: Eos (Transactions of the American Geophysical Union), v. 66, p. 1102.
Murchey, B.S., Jones, D.L., Holdsworth, B.K., and Wardlaw, B.R., 1988, Distribution patterns of facies, radiolarians, and conodonts in the Mississippian to Jurassic siliceous rocks of the north Brooks Range, Alaska, Chap. 32, in Gryc, George, ed., Geology and Exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, p. 697-724.

Murphy, J.M., Moore, T.E., Patton, W.W., Jr., and Saward, S.E., 1989, Stratigraphy of Cretaceous conglomerates, northeastern Koyukuk basin, Alaska: unroofing of southeastern Brooks Range, Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 21, no. 5, p. 120.

Murphy, J.M., and Patton, W.W., Jr., 1988, Geologic setting and petrography of the phyllite and metagraywacke thrust panel, north-central Alaska, in Galloway, J.P., and Hamilton, T.D., eds., Geologic studies in Alaska by the U.S. Geological Survey during 1987: U.S. Geological Survey Circular 1016, p 104-108.

Namson, J.S., and Wallace, W.K., 1986, A structural transect across the northeastern Brooks Range, Alaska: Geological Society of America Abstracts with Programs, v. 18, p. 163.

Nelson, B.K, Nelson, S.W., and Till, A.B., 1989, Isotopic evidence of an Early Proterozoic crustal source for granites of the Brooks Range, northern Alaska: Geological Society of America Annual Meeting Abstracts with Programs, v. 21, p. A105.

Nelson, S.W., and Grybeck, Donald, 1980, Geologic map of the Survey Pass quadrangle, Brooks Range, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1176A, scale 1:250,000.

Nelson, SW., and Grybeck, D.G., 1981, Metamorphic rocks of the Survey Pass quadrangle, U.S. Geological Survey Miscellaneous Field Studies Map MF-1176C, scale 1:250,000.

Nelson, S.W., and Nelson, W.H., 1982, Geology of the Siniktanneyak Mountain ophiolite, Howard Pass quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1441, scale 1:63,360.

Newberry, R.J., Dillon, J.T., and Adams, D.D., 1986, Regionally metamorphosed, calc-silicate-hosted deposits of the Brooks Range, northern Alaska: Economic Geology, v. 81, p. 1728-1752.

Newman, G.W., Mull, C.G., and Watkins, N.D., 1977, Northern Alaska paleomagnetism, plate rotation, and tectonics, in Sisson, Alexander, ed., The relationship of plate tectonics to Alaskan geology and resources: Proceedings of the Sixth Alaska Geological Society Symposium, Alaska Geological Society, Anchorage Alaska, p. C1-C7.

Nilsen, T.H., 1981, Upper Devonian and Lower Mississippian redbeds, Brooks Range, Alaska, in Miall, A.D., ed, Sedimentation and tectonics in alluvial basins: Geological Association of Canada Special Paper 23, p. 187-219.

Nilsen, T.H., Brosgé, W.P., Dutro, J.T., Jr., 1985, New reference section of the Noatak Sandstone, Nimiutuk River, Misheguk Mountain quadrangle, central Brooks Range, in Bartsch-Winkler, Susan, and Reed, K.M., eds., The United States Geological Survey in Alaska: accomplishments during 1983: U.S. Geological Survey Circular 945, p. 10-13.

Nilsen, T.H., and Moore, T.E., 1984a, Stratigraphic nomenclature for the Upper Devonian and Lower Mississippian(?) Kanayut Conglomerate, Brooks Range, Alaska: U.S. Geological Survey Bulletin 1529-A, p. A1-A64.

Nilsen, T.H., and Moore, T.E., 1984b, The Kanayut Conglomerate in the westernmost Brooks Range, Alaska, in Coonrad, W.L., and Elliot, R.L., eds., The United States Geological Survey in Alaska: accomplishments during 1981: U.S. Geological Survey Circular 868, p. 12-16.

Nilsen, T.H., Moore, T.E., Balin, D.F., and Johnson, S.Y., 1982, Sedimentology and stratigraphy of the Kanayut Conglomerate, central Brooks Range, Alaska -- report of 1980 field season: U.S. Geological Survey Open-File report 82-199, 80 p.

Nilsen, T.H., Moore, T.E., Brosgé, W.P., and Dutro, J.T., Jr., 1981, Sedimentology and stratigraphy of the Kanayut Conglomerate and associate units, central and eastern Brooks Range, Alaska -- report of the 1979 field season: U.S. Geological Survey Open-File report 81-506, 39 p.

Nilsen, T.H., Moore, T.E., Dutro, J.T., Jr., Brosgé, W.P., and Orchard, D.M., 1980, Sedimentology and stratigraphy of the Kanayut Conglomerate and associate units, central and eastern Brooks Range, Alaska -- report of the 1978 field season: U.S. Geological Survey Open-File report 80-888, 40 p.

Nokleberg, W.J., and Winkler, G.R., 1982, Stratiform zinc-lead deposits in the Drenchwater Creek area, Howard Pass quadrangle, northwestern Brooks Range, Alaska: U.S. Geological Survey Professional Paper 1209, 22p., 2 sheets, scale 1:19,800.

Norris, D.K., 1985, The Neruokpuk Formation, Yukon Territory and Alaska: Current Research, Part B, Geological Survey of Canada Paper 85-1B, p. 223-229.

Norris, D.K., and Yorath, C.J., 1981, The North American plate from the Arctic archipelago to the Romanzof Mountains in Nairn, A.E.M., Churkin, Michael Jr., and Stehli, F.G., eds., The ocean basins and margins, volume 5: the Arctic Ocean: Plenum Press, New York, p. 37-103.

North Slope Stratigraphic Committee, Alaska Geological Society, 1970, The Sag River Sandstone and Kuparuk River sands, two important subsurface units in the Prudhoe Bay field, in Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska: Los Angeles, Calif., American Association of Petroleum Geologists, Pacific Section, p. P1-P3.

Nunn, J.A., Czerniak, M., and Pilger, R.H., Jr., 1987, Constraints on the structure of Brooks Range and Colville basin, northern Alaska, from flexure and gravity analysis: Tectonics, v. 6, p. 603-617.

Oldow, J.S., and Avé Lallemant, H.G., 1989, Tectonic elements of eastern Arctic Alaska and Northwestern Canada [abs.]: Eos (Transactions of the American Geophysical Union), v. 70, p. 1337-1338.

Oldow, J.S., Avé Lallemant, H.G., and Gottschalk, R.R., 1987a, Large-scale extension within a contractional orogen: south-central Brooks Range, Alaska: Eos (Transactions of the American Geophysical Union), v. 68, p. 1457.

Oldow, J.S., Avé Lallemant, H.G.A., Julian, F.E., and Seidensticker, C.M., 1987b, Ellesmerian(?) and Brookian deformation in the Franklin Mountains, northeastern Brooks Range, Alaska, and its bearing on the origin of the Canada basin: Geology, v. 15, p. 37-41.

Oldow, J.S., Gottschalk, R.R., and Avé Lallemant, H.G., 1987c, Low-angle normal faults: southern Brooks Range fold and thrust belt, northern Alaska: Geological Society of America Abstracts with Programs, v. 19, p. 438.

Oldow, J.S., Seidensticker, C.M., Phelps, J.C., Julian, F.E., Gottschalk, R.R., Boler, K.W., Handschy, J.W., and Ave Lallemant, H.G., 1987d, Balanced cross sections through the central Brooks Range and North Slope, Arctic Alaska: American Association of Petroleum Geologists publication, 19 p., 8 plates, scale 1:200,000.

Oliver, W.A., Jr., Merriam, C.W., and Churkin, Michael, Jr., 1975, Ordovician, Silurian, and Devonian corals of Alaska: U.S. Geological Survey Professional Paper 823-B, p. 13-44.

Orth, D.J., 1970, North Slope geographic name sources for geologic nomenclature, in Adkison, W.L., and Brosgé, M.M., [eds.], Proceedings of the geological seminar on the North Slope of Alaska: American Association of Petroleum Geologists, Pacific Section, p. R1-R10.

O'Sullivan, P.O., 1988, Preliminary results of 42 apatite fission track analyses of samples from Arctic National Wildlife Refuge, northeastern Alaska: Alaska Division of Geological and Geophysical Surveys, Public Data File Report 88-25A, 57 p.

O'Sullivan, P.O., Decker, John, and Bergman, S.C., 1989, Apatite fission track thermal history of Permian to Tertiary sedimentary rocks in the Arctic National Wildlife Refuge, northeastern Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 21, no. 5, p. 126.

Paige, Sidney, Foran, W.T., and Gilluly, James, 1925, A reconnaissance of the Point Barrow region, Alaska: U.S. Geological Survey Bulletin 772, 33 p.

Pallister, J.S., and Carlson, Christine, 1988, Bedrock geologic map of the Angayucham Mountains, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-2024, scale 1:63,360, 1 sheet.

Pallister, J.S., Budahn, J.R., and Murchey, B.L., 1989, Pillow basalts of the Angayucham terrane: oceanic-plateau and island crust accreted to the Brooks Range: Journal of Geophysical Research, v. 94, p. 15,901-15,923.

Palmer, A.R., 1983, The Decade of North American Geology 1983 time scale: Geology, v. 11, p. 503-504.

Palmer, A.R., Dillon, J.T., and Dutro, J.T., Jr., 1984, Middle Cambrian trilobites with Siberian affinities from the central Brooks Range, northern Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 16, no. 5, p. 327.

Parrish, J.T., 1987, Lithology, geochemistry, and depositional environment of the Triassic Shublik Formation, northern Alaska, in Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope Geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 391-396.

Patton, W.W., Jr., 1956, New and redefined formations of Early Cretaceous age, in Gryc, G., and others, Mesozoic sequence in Colville River region, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 40, p. 209-254.

Patton, W.W., Jr., 1957, A new Upper Paleozoic formation, central Brooks Range, Alaska, in Pt. 3, Areal geology, of Exploration of Naval Petroleum Reserve No. 4 and adjacent areas, northern Alaska, 1944-53: U.S. Geological Survey Professional Paper 303-B, p. 41-45.

Patton, W. W., Jr., 1973, Reconnaissance geology of the northern Yukon-Koyukuk province, Alaska, in Shorter contributrions to general geology: U.S. Geological Survey Professional Paper 774-A, p. A1-A17.

Patton, W.W., Jr., and Box, S.E., 1989, Tectonic setting of the Yukon-Koyukuk basin and its borderlands, western Alaska: Journal of Geophysical Research, v. 94, p. 15,807-15,820.

Patton, W.W., Jr., Miller, T.P., and Tailleur, I.L., 1968, Regional geologic map of the Shungnak and southern part of the Ambler River quadrangle, Alaska: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-554, scale 1:250,000.

Patton, W.W., Jr., and Tailleur, I.L., 1964, Geology of the Killik-Itkillik region, Alaska in Pt. 3, Areal geology, of Exploration of Naval Petroleum Reserve No. 4 and adjacent areas, northern Alaska, 1944-53: U.S. Geological Survey Professional Paper 303-G, p. 409-500.

Patton, W.W., Jr., and Tailleur, I.L., 1977, Evidence in the Bering Strait region for differential movement between North America and Eurasia: Geological Society of America Bulletin, v. 88, p. 1298-1304.

Patton, W.W., Tailleur, I.L., Brosgé, W.P., and Lanphere, M.A., 1977, Preliminary report on the ophiolites of northern and western Alaska: Oregon Department of Geology and Mineral Industries, Bulletin 95, p. 51-57.

Pavlis, T.L., 1989, Middle Cretaceous orogenesis in the northern cordillera: a Mediterranean analog of collision-related extensional tectonics: Geology, v. 17, p. 947-950.

Payne, J.H., 1987, Diagenetic variations in the Permo-Triassic Ivishak Sandstone in the Prudhoe Bay field and central-northeastern National Petroleum Reserve in Alaska, in Tailleur, I.L, and Weimer, Paul, eds., Alaskan North Slope Geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 77-83.

Payne, T.G., 1955, Mesozoic and Cenozoic tectonic elements of Alaska: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-84, scale 1:5,000,000.

Payne, T.G., and others, 1951, Geology of the North Slope of Alaska: U.S. Geological Survey Oil and Gas Investigations Map OM-126, scale 1:1,000,000, 3 sheets.

Pessel, G.H., Garland, R.E., Tailleur, I.L., and Eakins, G.R., 1973, Preliminary geologic map of southeastern Ambler River and southwestern Survey Pass quadrangles, Alaska: Alaska Division Geology and Geophysical Surveys Open-File Report 28, scale 1:63,360, 1 sheet.

Plumley, P. W., and Vance, Margaret, 1988, Porcupine River basalt field, northeastern Alaska: age, paleomagnetism, and tectonic significance [abs.]: Eos (Transactions of the American Geophysical Union), v. 44, p. 1458.

Porter, S.C., 1966, Stratigraphy and deformation of the Paleozoic section at Anaktuvuk Pass, central Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 50, p. 952-980.

Rattey, R.P., 1985, Northeastern Grooks Range Alaska -- new evidence for complex thin-skinned thrusting [abs.]: American Association of Petroleum Geologists Bulletin, v. 69, p. 676-677.

Reed, B.L., 1968, Geology of the Lake Peters area, northeastern Brooks Range, Alaska: U.S. Geological Survey Bulletin 1236, 132 p.

Reed, J.C., 1958, Exploration of Naval Petroleum Reserve No. 4 and adjacent areas, northern Alaska 1944-1953, pt 1, History of the exploration: U.S. Geological Survey Professional Paper 301, 192 p., 1 sheet, scale 1:48,000.

Reiser, H.N., Brosgé, W.P., Dutro, J.T., Jr., and Detterman, R.L., 1971, Preliminary geologic map of the Mount Michelson quadrangle, Alaska: U.S. Geological Survey Open-File Report 71-237, scale 1:250,000.

Reiser, H.N., Brosgé, W.P., Dutro, J.T., Jr., and Detterman, R.L., 1979, Upper Paleozoic volcanic rocks in the eastern and central Brooks Range, in Johnson, K.M., and Williams, J.R., eds., The United States Geological Survey in Alaska: Accomplishments during 1978: U.S. Geological Survey Circular 804-B, p. B25\-B27.

Reiser, H.N., Brosgé, W.P., Dutro, J.T., Jr., and Detterman, R.L., 1980, Geologic map of the Demarcation Point quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1133, scale 1:250,000.

Reiser, H.N., Norris, D.K., Dutro, J.T., Jr., and Brosgé, W.P., 1978, Restriction and renaming of the Neruokpuk Formation, northeastern Alaska, in Sohl, N.F., and Wright, W.B., eds., Changes in stratigraphic nomenclature by the U.S. Geological Survey, 1977, Chap. A of Contributions to stratigraphy: U.S. Geological Survey Bulletin 1457-A, p. A106-A107.

Repetski, J.E., Carter, Claire, Harris, A.G., and Dutro, J.T., Jr., 1987, Ordovician and Silurian fossils from the Coonerak anticlinorium, central Brooks Range, Alaska, in Hamilton, T.D., and Galloway, J.P., eds., Geologic studies in Alaska by the U.S. Geological Survey during 1986: U.S. Geological Survey Circular 998, p. 40-42.

Rickwood, F.K., 1970, The Prudhoe Bay field, in Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska: American Association of Petroleum Geologists, Pacific Section, p. L1-L11.

Robinson, F.M., 1959, Core tests, Simpson area, Alaska, Chap. L, in Pt. 5, Subsurface geology and engineering data, of Exploration of Naval Petroleum Reserve No. 4 and adjacent areas, northern Alaska, 1944-53: U.S. Geological Survey Professional Paper 305-L, p. 645-730.

Robinson, F.M., Rucker, F.P., and Bergquist, H.R., 1956, Two subsurface formations of Early Cretaceous age, in Gryc, G. and others, Mesozoic sequence in Colville River region, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 40, p. 223-233.

Robinson, M.S., Decker, John, Clough, J.G., Reifenstuhl, R.R., Dillon, J.T., Combellick, R.A., and Rawlinson, S.E., 1989, Geology of the Sadlerochit and Shublik Mountains, Arctic National Wildlife Refuge, northeastern Alaska: Alaska Division of Geological and Geophysical Surveys, Professional Report 100, scale 1:63,360, 1 sheet.

Roeder, Dietrich, and Mull, C.G., 1978, Tectonics of Brooks Range ophiolites, Alaska: American Association Petroleum Geologists Bulletin, v. 62, p. 1696-1702.

Rowley, D.B., Lottes, A.L., and Ziegler, A.M., 1985, North America-Greenland-Eurasia relative motions; implications for circum-Arctic tectonic reconstructions [abs.]: American Association of Petroleum Geologists Bulletin, v. 69, p. 303.

Rubin, C.M., Miller, M.M., and Smith, 1990, Tectonic setting of Cordilleran mid-Paleozoic volcano-plutonic complexes; evidence for convergent margin tectonism, in Harwood, D.S., and Miller, M.M., eds., Paleozoic and early Mesozoic paleogeographic relations; Sierra Nevada, Klamath Mountains, and related terranes: Boulder, Colorado, Geological Society of America Special Paper 255, p. 1-16.

Sable, E.G., 1977, Geology of the western Romanzof Mountains, Brooks Bange, northeastern Alaska: U. S. Geological Survey Professional Paper 897, 84 p., scale 1:63,360.

Sable, E.G., Chapman, R.M., and Tailleur, I.L., 1984a, Geologic map of the western Kukpowruk-Nuka Rivers region, northwestern Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF 1668, 2 sheets, scales 1:63,360 and 1:250,000.

Sable, E.G., and Dutro, J.T., Jr., 1961, New Devonian and Mississippian formations in De Long Mountains, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 45, p. 585-593.

Sable, E.G., Dutro, J.T., Jr., Morris, R.H., and Tailleur, I.L., 1984b, Geologic map of the eastern Kukpowruk-Nuka Rivers region, northwestern Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF 1671, 2 sheets, scale 1:63,360 and 1:250,000.

Sable, E.G., and Stricker, G.D., 1987, Coal in the National Petroleum Reserve in Alaska (NPRA): framework geology and resources, in Tailleur, I.L, and Weimer, Paul, eds., Alaskan North Slope Geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 195-215

Schmidt, J.M., 1987, Paleozoic extension of the western Brooks Range (WRB) continental margin - evidence from mineral deposits, igneous rocks, and sedimentary facies [abs.]: Geological Society of America Abstracts with Programs, v. 19, no. 6, p. 447.

Schrader, F.C., 1900, Preliminary report on a reconnaissance along the Chandalar and Koyukuk Rivers, Alaska, in 1899: Twenty-first Annual Report of the U.S. Geological Survey, Part II, p. 447-486.

Schrader, F.C., 1902, Geological section of the Rocky Mountains in northern Alaska: Geological Society of America Bulletin, v. 13, p. 233-252.

Schrader, F.C., 1904, A reconnaissance in northern Alaska: U.S. Geological Survey Professional Paper 20, 139 p.

Schrader, F.C., 1904, A reconnaissance in northern Alaska: U.S. Geological Survey Professional Paper 20, 139 p.

Seidensticker, C.M., Julian, F.E., Oldow, J.S., and Avé Lallemant, H.G., 1987, Kinematic significance of antithetic structures in the central Brooks Range, Alaska: Geological Society of America Abstracts with Programs, v. 19, no. 6, p. 449.

Silberman, M.L., Brookins, D.G., Nelson, S.W., and Grybeck, D., 1979, Rubidium-strontium and potassium-argon dating of emplacement and metamorphism of the Arrigetch Peaks and Mount Igikpak plutons, Survey Pass quadrangle, Alaska, in Johnson, K.M., and Williams, J.R., eds., U.S. Geological Survey in Alaska: accomplishments during 1978: U.S. Geological Survey Circular 804-B, p. 18-19.

Siok, J.P., 1985, Geologic history of the Siksikpuk Formation on the Endicott Mountains and Picnic Creek allochthons, north-central Brooks Range, Alaska (M.S. thesis): Fairbanks, Alaska, University of Alaska, 253 p.

Siok, J.P., 1989, Stratigraphy and petrology of the Okpikruak Formation at Cobblestone Creek, northcentral Brooks Range, in Mull, C.G., and Adams, K.E., eds., Dalton Highway, Yukon River to Prudhoe Bay, Alaska: Alaska Division of Geological and Geophysical Surveys Guidebook 7, v. 2, p. 285-292.

Siok, J.P., and Mull, C.G., 1987, Glauconitic phosphatic sandstone and oncolite deposition at the base of the Etivluk Group (Carboniferous) Picnic Creek allochthon, north-central Brooks Range, Alaska, in Tailleur, I.L, and Weimer, Paul, eds., Alaskan North Slope Geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 367-370.

Smiley, C.J., 1969, Cretaceous floras of Chandler-Colville region, Alaska—stratgraphy and preliminary floristics: American Association of Petroleum Geologists Bulletin, v. 53, p. 482-502.
Smith, D.G., 1987, Late Paleozoic to Cenozoic reconstructions of the Arctic, in Tailleur, I.L, and Weimer, Paul, eds., Alaskan North Slope Geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 785-795.
Smith, P. S., 1912, The Alatna-Noatak region: U.S. Geological Survey Bulletin 520, p 315-338.
Smith, P.S., 1913, The Noatak-Kobuk region, Alaska: U.S. Geological Survey Bulletin 536, 160 p.
Smith, P.S., 1939, Areal geology of Alaska: U.S. Geological Survey Professional Pater 192, 100p.
Smith, P.S., and Mertie, J.B., Jr., 1930, Geology and mineral resources of northwestern Alaska: U.S. Geological Survey Bulletin 815, 351p.
Smith, P.S., and Mertie, J.B., Jr., 1930, Geology and mineral resources of northwestern Alaska: U.S. Geological Survey Bulletin 815, 351 p.
Smith, T.E., Webster, G.D., Heatwole, D.A., Proffett, J.M., Kelsey, G., and Glavinovich, P.S., 1978, Evidence for mid-Paleozoic depositional age of volcanogenic base-metal massive sulfide occurrences and enclosing strata, Ambler district, northwest Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 10, no. 3, p. 148.
Snelson, Sigmund, and Tailleur, I.L., 1968, Large-scale thrusting and migrating Cretaceous foredeeps in western Brooks Range and adjacent regions of northwestern Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 52, p. 567.
Specht, R.N., Brown, A.E., and Seiman, C.H., and Carlisle, J.H., 1987, Geophysical case history, Prudhoe Bay field, in Tailleur, I.L, and Weimer, Paul, Alaskan North Slope geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 50, p 19-30.
Spicer, R.A., and Thomas, B.A., 1987, A Mississippian Alaska-Siberia connection: evidence from plant megafossils, in Tailleur, I.L, and Weimer, Paul, eds., Alaskan North Slope Geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., v. 50, p. 355-358.
Stewart, J.H., 1976, Late Precambrian evolution of North America: plate tectonics implication: Geology, v. 4, p. 11-15.
Sweeney, J.F., 1982, Mid-Paleozoic travels of Arctic Alaska: Nature, v. 298, p. 647-649.
Tailleur, I.L., 1965, Low-volatile bituminous coal of Mississippian age on the Lisburne Peninsula, northwestern Alaska: U.S. Geological Survey Professional Paper 525-B, p. B34-B38.
Tailleur, I.L., 1969, Rifting speculation of the geology of Alaska's North Slope: Oil and Gas Journal, v. 67, no. 39, p. 128-130.
Tailleur, I.L., 1973a, Probable rift origin of Canada basin, in Pitcher, M.G., ed., Arctic geology: American association of Petroleum Geologists Memoir 19, p. 526-535.
Tailleur, I.L., 1973b, Possible mantle-derived rocks in western Brooks Range, in Geological Survey research 1973: U.S. Geological Survey Professional Paper 850, p. 64-65.
Tailleur, I.L., 1980, A rationalization of the Koyukuk "crunch", northern and central Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 64, p. 792.
Tailleur, I.L, and Brosgé, W.P., 1970, Tectonic history of northern Alaska, in Adkison, W.L., and Brosgé, M.M., eds., Proceedings of the geological seminar on the North Slope of Alaska: American Association of Petroleum Geologists Pacific Section Meeting, Los Angeles, p. E1-E19.
Tailleur, I.L., Brosgé, W.P., and Reiser, H.N., 1967, Palinspastic analysis of Devonian rocks in northwestern Alaska, in Oswald, D.H., ed., International symposium on the Devonian system, v. 2: Alberta Society of Petroleum Geologists, Calgary, Canada, p. 1345-1361.
Tailleur, I.L., Kent, B.H., and Reiser, H.N., 1966, Outcrop geologic maps of the Nuka-Etivluk region, northern Alaska: U.S. Geological Survey Open File Report 66-128, scale 1:63,360, 7 sheets.

Tailleur, I.L., Mamet, B.L., and Dutro, J.T., Jr., 1973, Revised age and structural interpretation of Nuka formation at Nuka Ridge, northwestern Alaska: American Association of Petroleum Geologists Bulletin, v. 57, p. 1348-1352.

Tailleur, I.L., Mayfield, C.F., and Ellersieck, I.F., 1977, Late Paleozoic sedimentary sequence, southwestern Brooks Range, in Blean, K.M., ed., The United States Geological Survey in Alaska: accomplishments during 1976: U.S. Geological Survey Circular 751-B, p. B25-B27.

Tailleur, I.L., and Sable, E.G., 1963, Nuka Formation of Late Mississippian to Late Permian age, new formation in northern Alaska: American Association Petroleum Geologists Bulletin, v. 47, p. 632-642.

Tailleur, I.L., and Weimer, Paul, eds., 1987, Alaskan North Slope Geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 50, 874 p.

Thurston, D.K., and Theiss, L.A., 1987, Geologic report for the Chukchi Sea Planning Area, Alaska: Minerals management Service OCS Report MMS 87-0046, 193 p.

Till, A.B., 1988, Evidence for two Mesozoic blueschist belts in the hinterland of the western Brooks Range fold and thrust belt [abs.]: Geological Society of America, Abstracts with Program, v. 21, no. 7, p. A112.

Till, A.B., 1989, Proterozoic rocks of the western Brooks Range, in Dover, J.H., and Galloway, J.P., eds., Geologic Studies in Alaska by the U.S. Geological Survey, 1988: U.S. Geological Survey Bulletin 1903, p. 20-25.

Till, A.B., Schmidt, J.M., and Nelson, S.W., 1988, Thrust involvement of metamorphic rocks, southwestern Brooks Range, Alaska: Geology, v. 10, p. 930-933.

Turner, D.L., Forbes, R.B., and Dillon, J.T., 1979, K-Ar geochronology of the southwestern Brooks Range, Alaska: Canadian Journal of Earth Sciences, v. 16, p. 1789-1804.

Turner, R.F., Martin, G.C., Risley, D.E., Steffy, D.A., Flett, T.O., and Lynch, M.B., 1986, Geologic report for the Norton Basin planning area, Bering Sea, Alaska: Minerals Management Service OCS Report MMS 86-0033, 179 p.

Van Alstine, D.R., 1986, Normal- and reversed-polarity synfolding CRM along the Brooks Range mountain front, northern Alaska: Eos (Transactions of the American Geophysical Union), v. 67, p. 269-270.

Vann, I.R., Graham, R.H., and Hayward, A.B., 1986, The structure of mountain fronts: Journal of Structural Geology, v. 8, p. 215-227.

Wadman, D.H., Lamprecht, D.E., and Mrosovsky, Ivan, 1979, Joint geologic/engineering analysis of the Sadlerochit reservoir, Prudhoe Bay field: Journal of Petroleum Technology, v. 31, p. 933-940.

Wahrhaftig, Clyde, 1965, Physiographic divisions of Alaska: U.S. Geological Survey Professional Paper 482, 52 p.

Wallace, W.K., and Hanks, C.L., 1990, Structural provinces of the northeastern Brooks Range, Arctic National Wildlife Refuge, Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 74, p.1100-1118.

Wallace, W.K., Meigs, A.J., and Rogers, J.A., 1987, Relationships between stratigraphy and structural evolution of the Sadlerochit and Shublik Mountains, northeastern Brooks Range, Alaska [abs.]: Geological Society of America Abstracts with Programs, v.19, no. 6, p. 461.

Weimer, Paul, 1987a, Northern Alaska exploration -- the past dozen years, in Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope geology: Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, CA, v. 50, p. 31-37.

Weimer, P., 1987b, Seismic stratigraphy of three areas of lower slope failure, Torok Formation, northern Alaska, in Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope Geology: Bakersfield, Calif., Pacific Section of Society of Economic Paleontologists and Mineralogists and the Alaska Geological Society, book 50, p. 481-496.

Werner, M.R., 1987, West Sak and Ugnu sands: low-gravity oil zones of the Kuparuk River area, Alaskan North Slope, in Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope Geology: Bakersfield, Calif., Pacific Section of Society of Economic Paleontologists and Mineralogists and the Alaska Geological Society, Book 50, p. 109-118.

Wilbur, Steve, Siok, J.P., and Mull, C.G., 1987, A comparison of two petrographic suites of the Okpikruak Formation; a point count analysis, in Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope Geology: Bakersfield, Calif., Pacific Section of Society of Economic Paleontologists and Mineralogists and the Alaska Geological Society, Book 50, p. 441-447.

Wirth, K.R., Harding, D.J., and Bird, J.M., 1987, Basalt geochemistry, Brooks Range, Alaska [abs.]: Geological Society of America Abstracts with Programs, v. 19, no. 6, p. 464.

Wirth, K.R., and Bird, J.M., 1992, Chronology of ophiolite crystallization, detachment, and emplacement: evidence from the Brooks Range, Alaska: Geology, v. 20, p. 75-78.

Witmer, R.J., Haga, H., and Mickey, M.B., 1981, Biostratigraphic report of thirty-three wells drilled from 1975 to 1981 in National Petroleum Reserve in Alaska: U.S. Geological Survey Open-File Report 81-1166, 47 p.

Woidneck, K., Behrman, P., Soule, C., and Wu, J., 1987, Reservoir description of the Endicott field, North Slope, Alaska, in Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope Geology: Bakersfield, Calif., Pacific Section of Society of Economic Paleontologists and Mineralogists and the Alaska Geological Society, v. 50, p. 43-59.

Wolf, S.C., Barnes, P.W., Rearic, D.M., and Reimnitz, E., 1987, in Bird, K.J., and Magoon, L.B., eds., Petroleum geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska: U.S. Geological Survey Bulletin 1778, p. 61-78.

Wood, G.V., and Armstrong, A.K., 1975, Diagenesis and stratigraphy of the Lisburne Group limestones of the Sadlerochit Mountains and adjacent areas, northeastern Alaska: U.S. Geological Survey Professional Paper 857, 47 p.

Woolson, J.R., and others, 1962, Seismic and gravity surveys of Naval Petroleum Reserve No. 4 and adjoining areas, Alaska: U.S. Geological Survey Professional Paper 304-A, 25 p.

Zayatz, M.R., 1987, Petrography of the Baird Mountains schistose lithologies, northwestern Alaska: U.S. Geological Survey Circular 998, p. 49-52.

Ziegler, P.A., 1988, Laurussia--the Old Red Continent, in McMillan, N.J., Embry, A.F., and Glass, D.J., eds., Devonian of the World, volume I: Regional syntheses: Canadian Society of Petroleum Geologists Memoir 14, Calgary, Canada, p. 15-48.

Zimmerman, Jay, and Frank, C.O., 1982, Possible obduction-related metamorphic rocks at the base of the ultramafic zone, Avan Hills complex, De Long Mountains, in Coonrad, W.L., ed., The United States Geological Survey in Alaska; accomplishments during 1980: U.S. Geological Survey Circular 844, p. 27-28.

Zimmerman, Jay, Frank, C.O., and Bryn, Sean, 1981, Mafic rocks in the Avan Hills ultramafic complex, De Long Mountains, in Albert, N.R.D., and Hudson, Travis, eds., The United States Geological Survey in Alaska; accomplishments during 1979: U.S. Geological Survey Circular 823-B, p. B14-B15.

Zimmerman, Jay, and Soustek, P.G., 1979, The Avan Hills ultramafic complex, De Long Mountains, Alaska, in Johnson, K.M., and Williams, J.R., eds., The United States Geological Survey in Alaska: accomplishments during 1978: U.S. Geological Survey Circular 804-B, p. B8-B10.