DALTON HIGHWAY, YUKON RIVER TO PRUDHOE BAY, ALASKA

Bedrock geology of the eastern Koyukuk basin, central Brooks Range, and eastcentral Arctic Slope

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Division of Geological & Geophysical Surveys
Guidebook 7
Volume 1

Field conference, May 25-28, 1985
60th Annual Meeting
AAPG-SEPM-SEG, Pacific Section
Anchorage, Alaska, U.S.A.

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Dedication

This volume is dedicated to W.P. (Bill) Brosgé and H.N. (Hill) Reiser of the U.S. Geological Survey (USGS). Brosgé and Reiser mapped the entire eastcentral and eastern Brooks Range and are senior authors of 10 1:250,000-scale geologic quadrangle maps of the area. Brosgé arrived in northern Alaska in 1949 and began mapping with the USGS Navy Oil Unit on the central Arctic Slope in Naval Petroleum Reserve No. 4 (now National Petroleum Reserve in Alaska). Reiser arrived in 1950 for a field season in the foothills of the central Brooks Range and soon after formed a partnership with Brosgé that lasted over 30 years. Along with J.T. (Tom) Dutro, Jr., R.L. (Bob) Detterman, M.D. (Marv) Mangus, I.L. (Irv) Tailleur, W.W. (Bill) Patton, E.G. (Ed) Sable, A.S. (Sam) Keller, A.L. (Art) Bowsher, R.H. (Bob) Morris, E.H. (Ernie) Lathram, George Gryc, and others of the Navy Oil Unit, Brosge and Reiser helped establish the stratigraphic framework and unravel the structural complexities of the Brooks Range and Arctic Slope. We who have followed in their footsteps could not have pursued our stratigraphic studies and tectonic reconstructions without the benefit of their pioneering studies.

C.G. Mull and K.E. Adams

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FOREWORD

The first geologic road log of the Dalton Highway, Guidebook 4, was published in 1983 by the Alaska Division of Geological and Geophysical Surveys (DGGS) as one in a series of six guidebooks written for field trips conducted during the Fourth International Conference on Permafrost. Guidebook 4 emphasizes permafrost and related geologic features along the Elliott and Dalton Highways from Fox to Prudhoe Hay, Alaska.

In 1985, DGGS expanded the contents of Guidebook 4 lo include the bedrock geology along the same route, as a contribution to the program of the 1985 meeting of the Pacific Section of the American Association of Petroleum Geologists (AAPG), the Society of Economic Paleontologists and Mineralogists (SEPM), and the Society of Exploration Geophysicists (SEG). This publication emphasizes the stratigraphy, structure, and tectonic history of the eastern Koyukuk basin, Brooks Range, and Arctic Slope, thus complimenting the content of Guidebook 4.

In the years following the 1985 AAPG-SEPM-SEG meeting, geologic knowledge of this region has been further enriched by ongoing work of geologists from various agencies, who have agreed to collaborate on the two-volume work that follows.

DGGS is pleased to have been the catalyst in this effort, and I wish to thank the authors, who are from universities, federal and state agencies, and industry for the collective enthusiasm that led to the publication of this guidebook.

Geologists and geophysicists were tho lead players in the discovery of the Prudhoe Bay oil field, a find that led to the construction of the Trans-Alaska Pipeline and the Dalton Highway. Their geologic investigations have been conducted in this region for over 80 years; many of the papers in these volumes arc based on the geologic foundation constructed by these earlier workers, and we gratefully acknowledge their contributions.

Ross Schaff, former State Geologist from 1976 to 1986, played an essential role in the guidebook project, which led lo the publication of these volumes. His foresight and enthusiasm were essential to the success of this project.

Robert B. Forbes
Director and State Geologist
Alaska Division of Geological and
Geophysical Surveys

CHAPTER 1.

INTRODUCTION

By C.G. Mull and K.E. Adams[1]

OVERVIEW

Following on the heels of early prospectors, geologists have been exploring the Brooks Range and its flanking basins since the turn of the century; most of these were members of the U.S. Geological Survey. Following the 1957 discovery of oil in southcentral Alaska by Richfield Oil Corporation and later the discovery of major copper deposits on the south flank of the Brooks Range by mining companies, petroleum and mining geologists became increasingly interested in the geology of northern Alaska.

By 1960, oil-industry geologists were actively studying the geology of the Brooks Range and Arctic Slope. This activity culminated with the 1968 discovery of the super-giant Prudhoe Bay oil field by Atlantic Richfield Company (successor to Richfield Oil Corporation) and Exxon Company, USA. The vastly increased geological activity stimulated by the Prudhoe Bay discovery resulted in a geological seminar on the geology of the North Slope. This meeting, sponsored by the Pacific Section of the American Association of Petroleum Geologists and the U.S. Geological Survey, was held in San Francisco, California, in 1970.

Fifteen years later, on May 22-24, 1985, North Slope Seminar II was sponsored by the Alaska Geological Society as part of the annual meeting of the Pacific Section of the American Association of Petroleum Geologists and the Society of Economic Paleontologists and Mineralogists. As part of a series of geologic field trips held in conjunction with this meeting, a trip was conducted along the Dalton Highway (Trans-Alaska Pipeline System haul road) from the Yukon River northwest to Prudhoe Bay (fig. 1). Each of the 40 participants on the field trip was provided with an illustrated geologic road log and a series of up-to-date papers on the geology of the eastern Koyukuk basin, the eastcentral Brooks Range, and the eastern Arctic Slope.

Since 1985, the road log, geologic papers, and accompanying maps and cross sections have been revised for publication in this two-volume format. Volume I contains the road log, complete with detailed geologic maps of the route, and summary papers that discuss the physiography, stratigraphy, structure, and petroleum development of the area. Volume II contains technical papers that give a more thorough account of the geology in the vicinity of the Dalton Highway corridor from the south flank of the Brooks Range to its northern foothills. Many of the papers in the volumes are previously unpublished works by members of the Alaska Division of Geological and Geophysical Surveys (DGGS), the University of Alaska, the U.S. Geological Survey, and the oil industry. This guide emphasizes bedrock geology along the highway. A companion guide, 'Guidebook to permafrost and related features along the Elliott and Dalton Highways, Fox to Prudhoe Bay, Alaska' (Brown and Kreig, 1983) focuses on permafrost and surficial geology.

ACKNOWLEDGMENTS

These volumes are the result of efforts of a large number of individuals, in addition to the authors of the technical papers. First, our appreciation to Dr. Ross Schaff, former director of DGGS, for approving the original concept of a guide to this important area of northern Alaska and to Dr. Robert Forbes, present director of DGGS, for enthusiastically supporting the completion of the project. C.L. Daniels and later G.M. Laird (DGGS) supervised the production of the guidebook. A.L. Schell (DGGS) served as project coordinator, directed the cartographic process, and designed the layout and most of the figures. W.G. Gilbert, G.H. Pessel, D.H. Solie, and A.A. Bakke (DGGS) and J.T. Dutro, Jr., and W.P. Brosgé (U.S. Geological Survey) reviewed the manuscripts. K.E. Adams (DGGS) and A.F. Seward (DGGS) edited and proofread the volumes. E.E. Harris (DGGS) drafted the geologic strip maps and many other figures along with N.D. Bowman, K.S. Pearson, and K.L. Crowder (DGGS). Harris, A.G. Sturmann (DGGS), and Laird did much of the darkroom work. R.A. Mann (DGGS) typed many drafts of the chapters during the writing and editorial process and was assisted by K.E. Ohland (DGGS) during the early stages of the project. J.A. Outten assembled the camera-ready

[1]DGGS, 3700 Airport Way, Fairbanks, Alaska 99709.

copy. Daniels and V.L. Reger (DGGS) edited and supervised the production of the preliminary edition. W.W. Patton and T.H. Nilsen (U.S. Geological Survey), J.T. Dillon and C.G. Mull (DGGS), and R.K. Crowder (University of Alaska) served as guides for the 1985 field trip, and Katherine Engle (Marathon Oil Company) arranged the logistics. We also appreciate the contribution of Standard Alaska Production Company, which provided maps, information, and a guided tour of the Prudhoe Bay oil field; and the Atlantic Richfield Company, which provided a regional seismic line. Finally, our gratitude to Mose Car (Aurora Helicopters) for safely escorting us to the peaks and ridges of the central Brooks Range during several years of field work.

HISTORY AND DEVELOPMENT ALONG THE ELLIOTT AND DALTON HIGHWAYS[2]

ELLIOTT HIGHWAY

The Elliott Highway begins at the Steese Highway in Fox, 11 mi north of Fairbanks, and extends northwest to Livengood and then west to Manley Hot Springs, a total of 145 mi (233 km). The route of the Elliott Highway dates from the early days of gold mining in 1902, when Felix Pedro and Tom Gilmore discovered gold north of Fairbanks. By 1903, mining communities had sprung up north of Fairbanks at Fox, Olnes, Gilmore, and Chatanika. The narrow-gauge Tanana Valley Mines Railroad was constructed in 1905 to haul freight from the mouth of Chena Slough, on the navigable Tanana River, north 21 mi (34 km) to Gilmore and Pedro Creeks. During the same period, a railroad branch, 5 mi (8 km) long, was built to Fairbanks. Two years later, the Tanana Valley Mines Railroad was extended 20 mi (32 km) to Chatanika. In 1917, the Tanana Valley line was incorporated into the federally owned Alaska Railroad. Train service was discontinued to Chatanika in 1931; however, a portion of the line close to Fairbanks was modernized and is now part of the Alaska Railroad.

In 1914, Jay Livengood and N.R. Hudson discovered gold near what is now the community of Livengood. A year later, the Alaska Road Commission constructed a 54-mi (87-km) sled road from Olnes to Livengood to serve the promising new communities. The route for the sled road was located by R.A. Jackson; the Fairbanks Commercial Club helped finance its construction. The sled road became less traveled in the 1920s, when the Alaska Road Commission built the Dunbar-Brooks sled road to the west of the Olnes-Livengood route through more level country in the Minto Flats area.

In the early 1930s, the Alaska Road Commission decided to improve the original sled road from Olnes to Livengood to accommodate wagon traffic. The road was called the Elliott Highway after Malcolm Elliott, president of the Alaska Road Commission, and was extended 71 mi (114 km) from the Steese Highway near Fox to Livengood. By 1936, about 40 mi (64 km) of the road was suitable for automobile travel. Two vears later. the road was surfaced with gravel and became an all-weather highway. It was not completed to Manley Hot Springs until 1958. Since 1960, the road has been improved between Fox and Livengood, particularly the first 20 mi (32 km), which have been paved.

[2]Modified from Brown and Kreig (1983).

HICKEL HIGHWAY

In 1970, 2 yr after oil was discovered at Prudhoe Bay, an ice road was built from Livengood to the North Slope. It was used during the winters of 1970-72. The road was called the Hickel Highway (after Walter Hickel, former governor of Alaska) but was actually a bulldozed trail. The road passed over the Yukon River by way of an ice bridge in the Yukon Flats 7 mi (11 km) upstream from Stevens Village. After crossing the Yukon and Kanuti Flats, the road traversed the present Dalton Highway just north of Old Man Camp and trended northwest to Bettles. Beyond Bettles, the road extended up the John River through Anaktuvuk Pass in the Brooks Range and on to Prudhoe Bay on the Arctic Ocean west of the mouth of the Sagavanirktok River. Spur roads were built to Dietrich, Coldfoot, and Prospect Camps on the south side of the Brooks Range and to Galbraith Lake on the north side. Because the surface organic mat was disturbed in places, substantial thawing occurred during the summer, leaving parts of the trail permanently scarred.

DALTON HIGHWAY

The Dalton Highway begins at Mile 73.1 (118 km) on the Elliott Highway, several miles west of Livengood. It was built by the Alyeska Pipeline Service Company in two sections. The first section, constructed between August 1969 and July 1970, extends 56 mi (90 km) from Livengood to the Yukon River. This section was referred to as the 'TAPS Road.' Construction camps for the second section, a 359-mi (575-km) haul road between the Yukon River and Prudhoe Bay, were established in 1971, and equipment was moved into place. Construction, however, was soon halted by the courts. When finally begun, the road was built in seven segments and completed between between April and September 1974. Road signs mark the sites where the segments are joined. The haul road was formally named the Dalton Highway, after James Dalton, by the Alaska Legislature in 1981. Dalton was a member of a pioneer Alaska family and, during the 1940s and 1950s, worked on construction projects in Naval Petroleum Reserve No. 4 (NPR-4) in northwestern Alaska and on the DEW Line (Distant Early Warning Line) of radar sites along the northern coast of Alaska. For a detailed account of the early history of the road, see Laycock (1979).

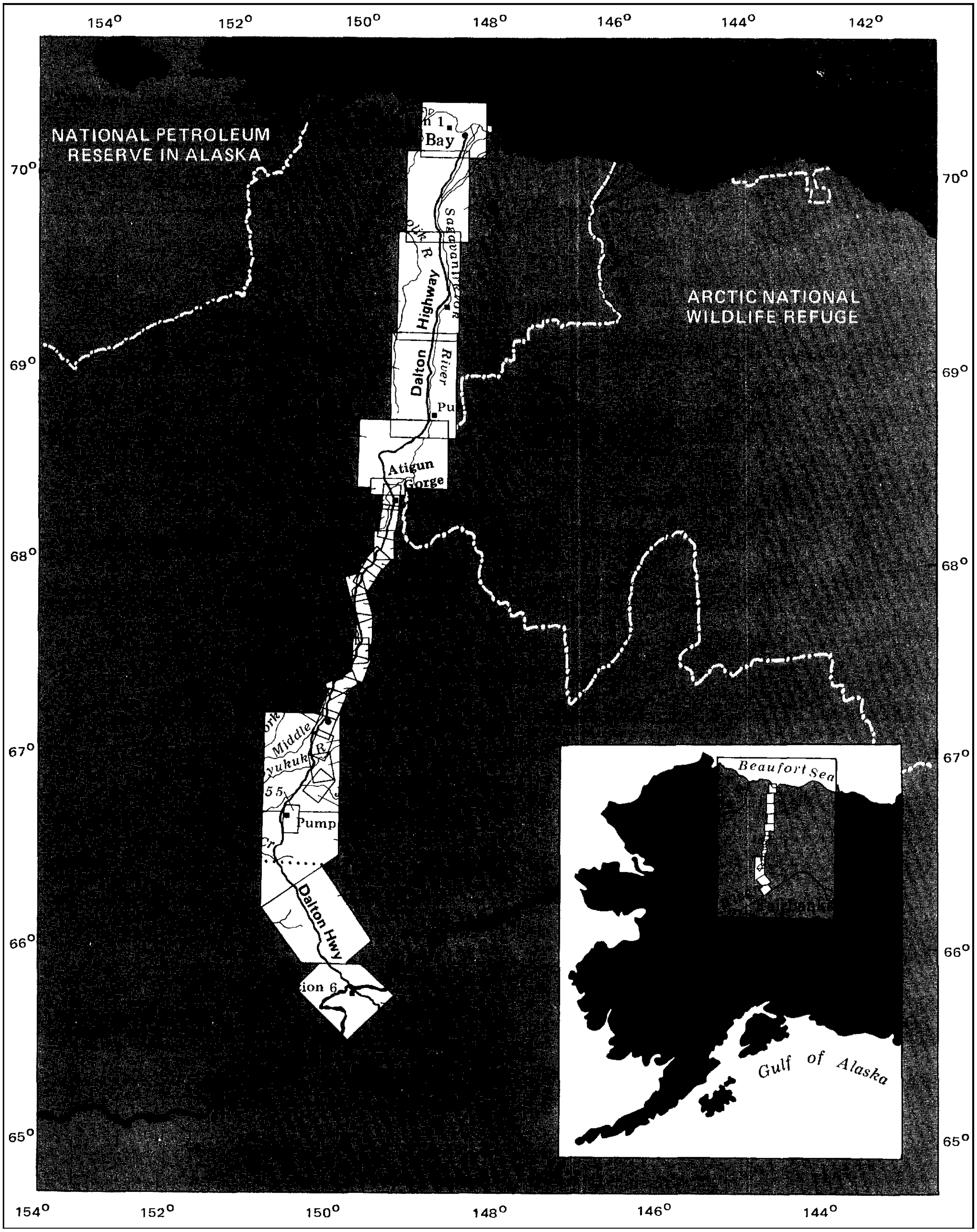
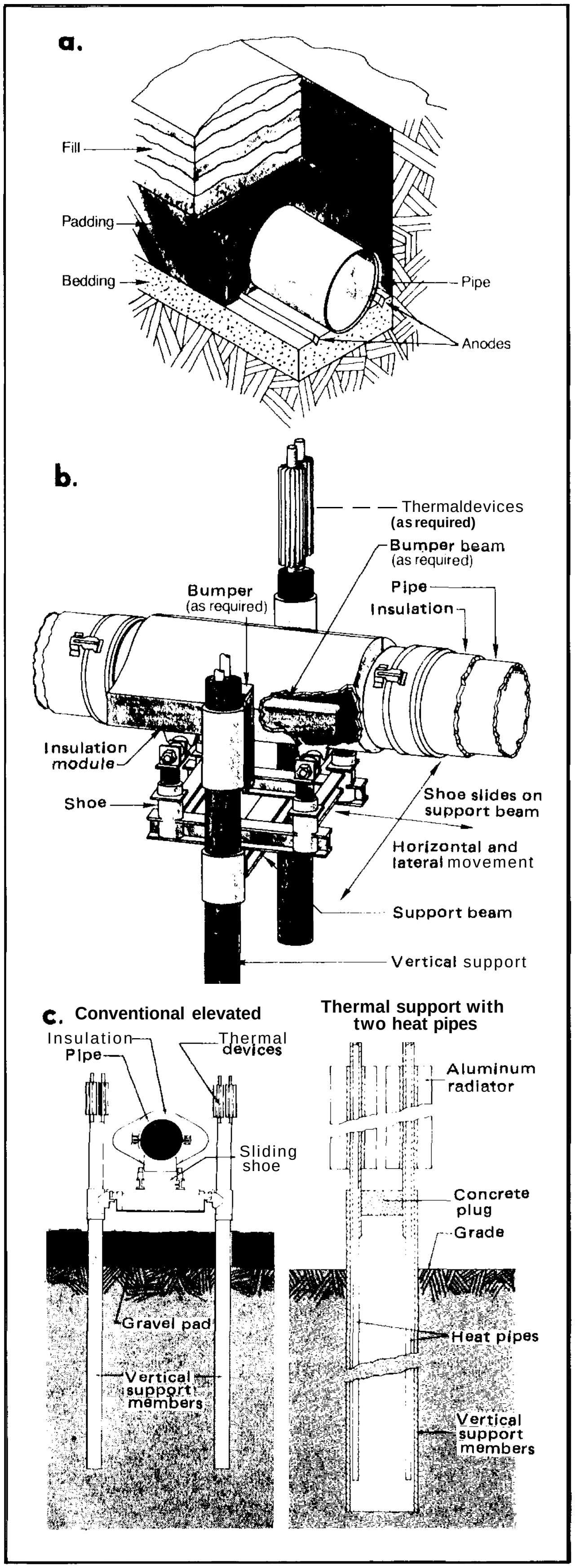


Figure 1. Map of field-trip route along Dalton Highway and Trans-Alaska Pipeline System (TAPS) corridor from Yukon River to Prudhoe Bay. Highlighted areas designate regions shown on geologic maps in road log.



Although the Elliott and Dalton Highways are state owned and maintained, they pass through land that has a variety of owners. The largest portion of land, managed by the U.S. Bureau of Land Management (BLM), is a strip called the utility corridor. This strip of land was withdrawn by Public Land Order 5150 in 1971 to provide for pipelines, transmission lines, and transportation. The corridor, 12 to 23 mi (19 to 37 km) wide, extends from Washington Creek, on the Elliott Highway, to Pump Station 2, about 60 mi (100 km) south of Prudhoe Bay; the remaining section of road frorn Pump Station 2 to Prudhoe Bay crosses state lands. Federal property bordering the utility corridor is managed by the U.S. National Park Service (Gates of the Arctic National Park and Preserve) and the U.S. Fish and Wildlife Service (including Yukon Flats National Wildlife Refuge). Only a few private individuals own land along the Dalton Highway, although there are numerous mining claims in the Koyukuk River valley near the old mining towns of Coldfoot and Wiseman.

In 1980, the Alaska State Legislature authorized public summer (June 1 to September 1) use of the Dalton Highway north of the Yukon River, but only to Chandalar Camp at Mile 239. North of Chandalar Camp, and during other times of the year, travel is limited to holders of permits. These are issued only to industrial and commercial users, researchers, and residents of the area.

TRANS-ALASKA PIPELINE SYSTEM (TAPS)

The Elliott and Dalton Highways parallel more than 497 mi (800 km) of the Trans-Alaska Pipeline System (TAPS), providing an excellent view of the pipeline and its support facilities. The system was built, and is presently operated, by the Alyeska Pipeline Service Company. (Alyeska is owned by eight oil companies, all of which have holdings in the Prudhoe Bay oil field.) The 48-in.-diam (1.2 m) pipeline went on-line on August 1, 1977, and transports up to 2 million barrels of crude oil a day from Prudhoe Bay to Valdez, 808 mi (1,300 km) to the south. By the end of 1988, over six billion barrels of oil had been shipped through the system.

The pipeline was constructed between 1975 and 1977, following 6 yr of intensive engineering design, environmental planning, and mobilization. Most of the line was built from gravel work pads, but some sections were constructed from short, experimental snow-and-ice pads. A total of 36 million yd^3 (26.4 million m^3) of gravel was used in constructing the work pads and related facilities.

The pipeline was either elevated or buried, depending on anticipated effects of the hot oil line on permafrost along the route. (Oil temperature as it enters the

Figure 2. Buried and elevated configuration of Trans-Alaska Pipeline System (TAPS): (a) buried, in bedrock or thaw-stable permafrost, or where ground was thawed; and (b) elevated, where thawing of permafrost would have created unstable conditions. Diagram (c) shows vertical support members (VSMs) and horizontal support beam. Illustrations courtesy of Alyeska Pipeline Service Company.

line is about 145 °F [62 °C] at Prudhoe Bay and 90 to 95 °F [32 to 35 °C] at Valdez.) Conventional burial, which offsets thermal stresses and high internal pressure in the pipe, was used in thawed or thaw-stable soils and in bedrock and was also allowed where thawing of the permafrost would not cause loss of soil support for the pipe (fig. 2a). Where thawing of the permafrost would have created unstable conditions, the pipeline was elevated, except for animal and highway crossings where special refrigerated sections were used. Because of permafrost, more than half of the pipeline north of the Yukon River is above ground.

The elevated sections are supported by two vertical support members (VSMs) and a horizontal beam that allows for expansion or contraction of the pipe as temperature changes (fig. 2b). To permit further lateral movement, the sections are built in a zigzag configuration, and, north of the Yukon River, some VSMs are tilted outward. The sections are anchored every 820 to 1,800 ft (250 to 550 m) to platforms supported by four VSMs.

VSMs are of three general types: a) thermal (corrugated with heat pipes); b) adfreeze (without heat pipes); and c) end bearing. Thermal VSMs keep the surrounding soil frozen by heat pipes equipped with radiators (fig. 2c). Each pipe contains both liquid and vapor ammonia. The tops of the pipes extend above the VSM and are fitted with aluminum cooling fins (radiators), either 4 or 6 ft (1.2 or 1.8 m) long, depending on the length of the pipe. In winter, as vapor cools in the top of the pipe, it condenses and flows to the bottom where it absorbs heat, turns back to vapor, and rises to the top, forming a continuous, nonmechanical heat-removal system. The process ceases when the air becomes warmer than the ground. The net result is removal of heat from the ground, which promotes refreezing around the VSMs.

North of Atigun Pass, heat pipes are not generally needed because insulated work pads are designed to prevent the permafrost from thawing. If massive ice is present, however, heat pipes are used to cool the ice below its natural temperature. This process increases the load-carrying capacity of the ice.

End-bearing VSMs were designed to support the pipe in areas where material, such as bedrock or massive gravel deposits, is found at shallow depths. Most end-bearing VSMs do not require freezeback for additional stability.

Seven pump stations are located along the pipeline north of Fairbanks. Pump Stations 1, 2, 3, 5, and 6 were built on ice-rich permafrost; thus they have refrigerated foundations. This situation may cause the structures to settle at different rates. A microwave system with a satellite backup links Pump Stations 1, 4, and 5, and the Valdez terminal. To further regulate the flow of oil, gate and check valves are located at several spots along the pipeline, typically at stream crossings and major elevated sections.

For additional information on the geotechnical aspects of the pipeline, see Liguori and others (1979), Luscher (1981), or any of the numerous publications of Alyeska Pipeline Service Company.

PHYSIOGRAPHY[3]

The southern end of the Dalton Highway traverses parts of the Yukon-Tanana Upland and the Ruby geanticline near the margin of the Koyukuk basin and Kanuti Flats (fig. 3). The uplands consist of even-topped, rounded ridges (fig. 4) that range in elevation from 2,000 to 4,000 ft (600 to 1,200 m). North of Kanuti Flats in the area of the South Fork Koyukuk River (Mile 156), the terrain is more rugged. The topography is dominated by a discontinuous line of rough to gently irregular ridges that range from 3,000 to 4,600 ft (900 to 1,400 m) high. Between the South Fork and the southern margin of the Brooks Range (Mile 165) lies a region of lowlands, 200 to 2,000 ft (60 to 600 m) in elevation, that contains northeast-southwest-trending ridges 2,000 to 3,000 ft (600 to 900 m) high (fig. 5).

East-west-trending topography dominates the Brooks Range (fig. 6), which begins abruptly near the small community of Coldfoot (Mile 175). The range comprises rugged, glacially sculptured peaks of sedimentary and metamorphic rock that are about 4,300 to 6,600 ft (1,300 to 2,000 m) high in the south and 7,600 to 8,900 ft (2,300 to 2,700 m) high in the north. Where bedrock has been glaciated, cliff and bench slopes have formed. Major rivers throughout the range flow north and south in the flat-floored, glaciated valleys (fig. 7).

North of the Brooks Range are the hills and lowlands of the Arctic Foothills. The southern part of the foothills (beginning about Mile 272) varies in elevation from about 1,100 to 3,500 ft (350 to 1,050 m) and includes irregular buttes, knobs, mesas, east-west-trending ridges, and intervening, gently irregular tundra uplands (fig. 8). The northern part of the Arctic Foothills (beginning about Mile 310) decreases in elevation from about 1,100 ft (350 m) in the south to 600 ft (180 m) in the north and is characterized by rolling uplands and broad, east-west-trending ridges (fig. 9).

Finally, near the confluence of the Sagavanirktok and Ivishak Rivers (Mile 361), the road crosses onto the Arctic Coastal Plain (fig. 10), which slopes gently to the Arctic Ocean. The flat topography of the coastal plain is broken by scattered pingos (ice-cored mounds) (fig. 11), low hills of Tertiary rock, and river terraces in Quaternary deposits. The coastal plain is poorly drained, and a significant part is covered by elongate, oriented thaw lakes (fig. 12) and marshy thaw-lake basins.

[3]Modified from Brown and Berg (1980).

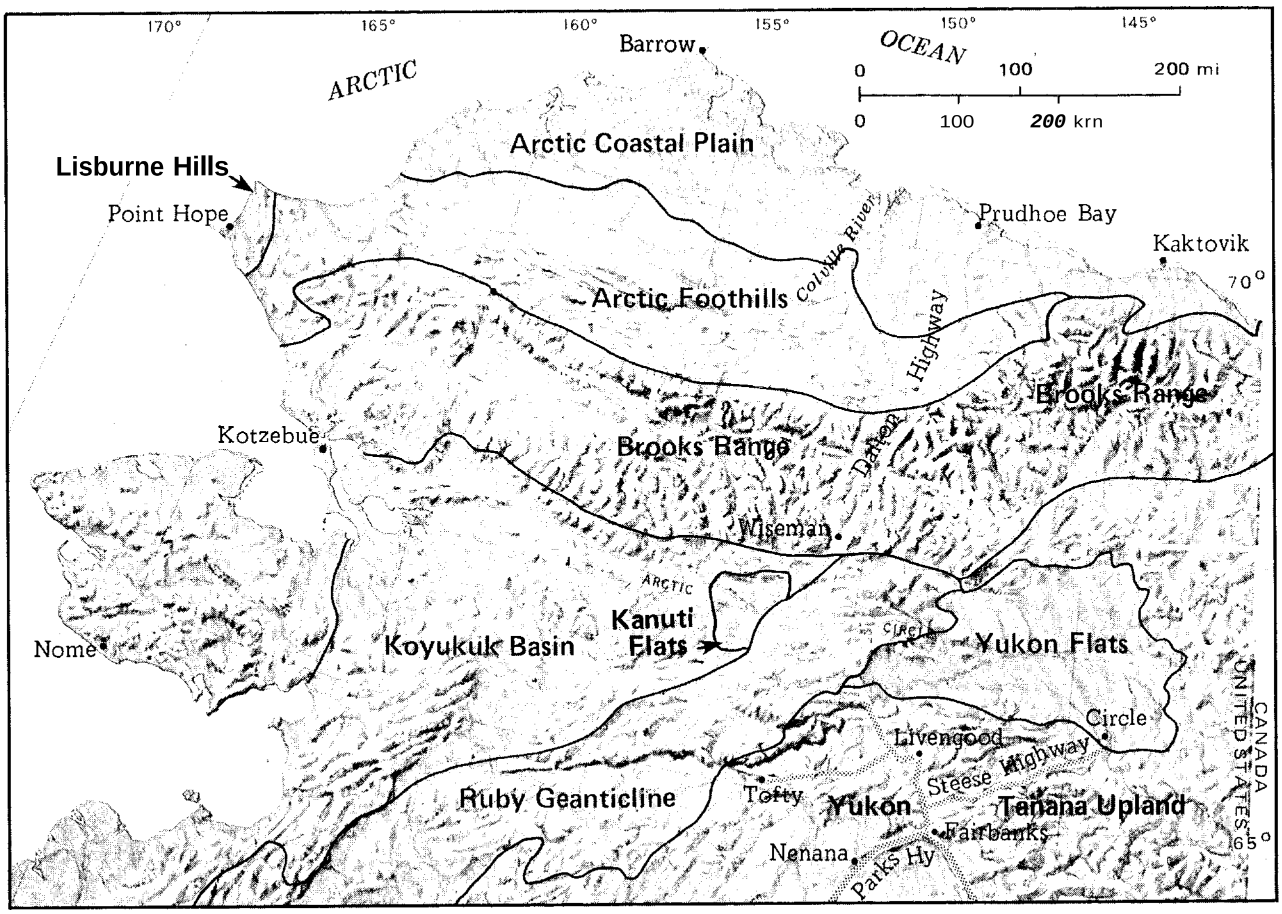


Figure 3. Major geologic and physiographic provinces of northern Alaska. Map modified from Wahrhaftig (1965) and *Raisz* (1966).

VEGETATION[4]

From the beginning of the Dalton Highway to treeline in the upper Dietrich River valley, the guidebook route runs primarily through forested areas interrupted occasionally by treeless bogs in the lowlands and alpine tundra on some of the higher ridges. The two major units of vegetation are tundra and taiga (boreal forest).

The distribution of vegetation in the Yukon-Tanana Upland between Fairbanks and Wickersham Dome on the Elliott Highway can serve as a rough guide for discerning the relation between vegetation and permafrost from the Yukon River to the Brooks Range, even though permafrost, and black spruce on south-facing slopes, become much more widespread north of the Yukon River.

Along actively meandering rivers, point bars usually show a distinct sequence of vegetation on freshly formed alluvium. Productive willow, balsam poplar, and white spruce occur in narrow, generally permafrost-free bands along the rivers. Bogs and black spruce are dominant on older terraces cut back from the river and on the outside of meandering rivers underlain by a high permafrost table.

On south-facing slopes underlain by thick loess, highly productive aspen, birch, and white spruce are abundant to elevations of about 1,300 ft (400 m). On north-facing slopes, in areas of thin loess, and in areas above 1,300 ft, black spruce, in all stages of postfire recovery, is the dominant forest cover. At altitudinal treeline, about 2,500 ft (750 m), mixed black and white spruce stands are open and dominated by nearly continuous shrub layers of shrub birch and alder.

For general mapping and descriptive purposes, the forest types can be subdivided into bottomland spruce-poplar forests, upland spruce-hardwood forests, and lowland spruce-hardwood forests. The tundra can be divided into barren ground; and wet, moist, and alpine tundras. Low and high shrub communities are also recognized (Selkregg, 1975a,b).

[4]Modified from L.A. Viereck (1983).

Figure 4. View northwestward toward Dalton Highway at Yukon River crossing. Uplands in distance are underlain by Cretaceous granitic pluton; Fort Hamlin Hills, forming lower ridge in upper center, are underlain by volcanic rock, chert, and limestone.

CLIMATE[5]

The interior of Alaska is a zone of temperature extremes and relatively high precipitation, compared with the Arctic region of Alaska. Alpine areas in the interior typically have less extreme temperatures, but more precipitation, than forested areas at lower elevations. Most precipitation in the interior occurs during the summer when storms track through the area from the south,or southwest. During the winter, the interior is dominated by relatively dry, continental polar-air masses; although infrequently, maritime air intrudes the area from the west or southwest, causing major snowstorms and, occasionally, winter rain. Overall, precipitation in the interior is convectional, widely scattered, and variable.

North of the Continental Divide in the Arctic region of Alaska is an area of extremely low winter temperatures, low summer temperatures, and relatively low precipitation. Unlike the interior of Alaska, wind is a major environmental factor throughout much of the year, reaching velocities of **30** mph (48 kph) on the Arctic Coastal Plain (Wahrhaftig, 1965). The winds cause severe wind-chill factors, and extremely poor visibility from drifting snow.

During July and August, breezes from the Arctic Ocean dominate the climate along the Arctic coastline. Colder air from the ice-dominated Arctic Ocean moves inland in response to a decrease in local pressure as the surface of the tundra is heated. The resulting north-easterly wind often causes cloudiness and coastal fog that sometimes extends inland for many miles and persists until the air is warmed. Ranges in temperature and precipitation in the major physiographic areas along the route are summarized in table **1** (Haugen, 1982); estimated mean annual air temperatures are shown in figure 13.

TEMPERATURE

Temperature regimes in the area of the Dalton Highway include some of the most extreme ranges found on the North American continent. The all-time low

[5]Modified from Brown and Kreig (1983)

Figure 5. View norlheastward from near Mile 153 toward valley of South Fork Koyukuk River. Hills in distance (north of South Fork) are about 2,500 ft (830 m) in elevation.

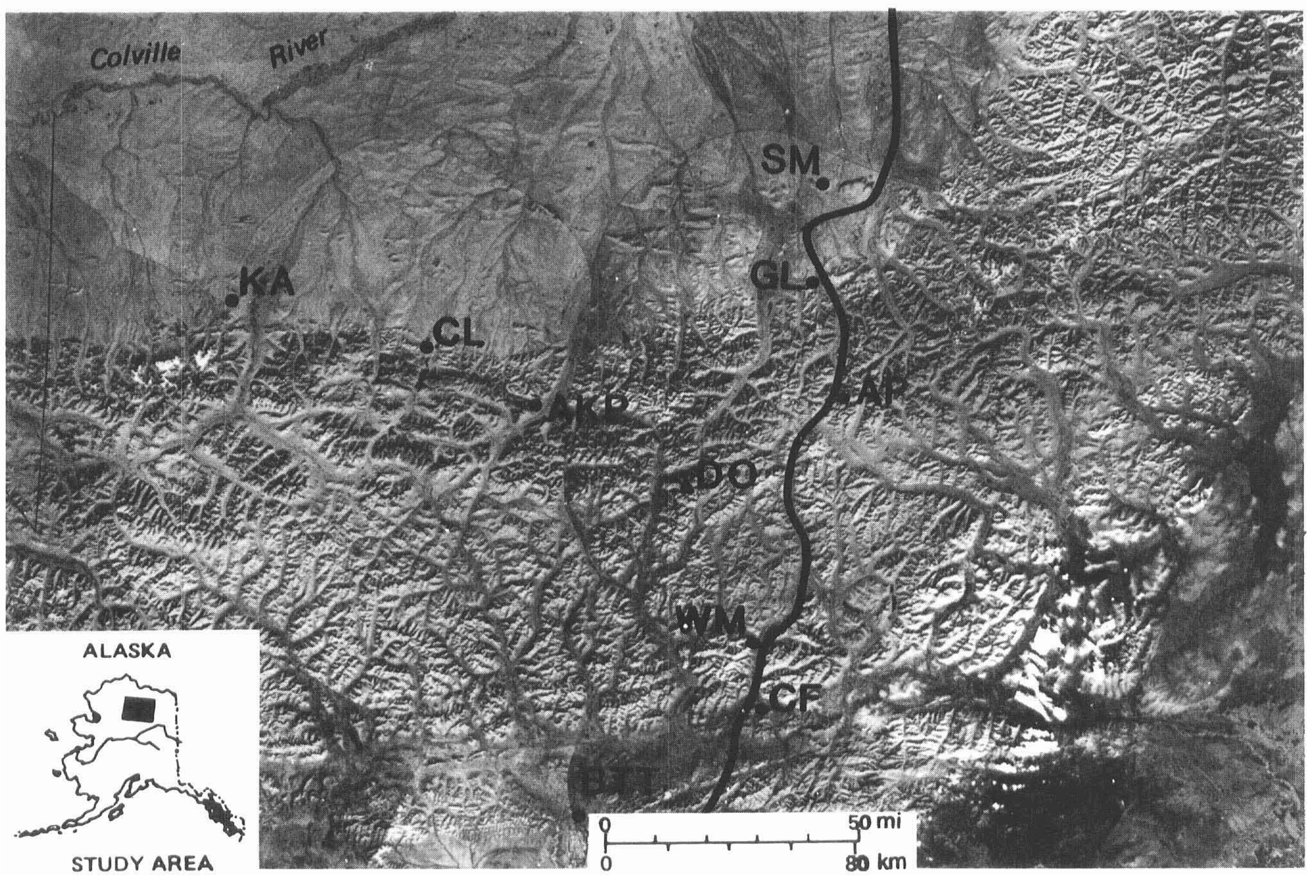


Figure 6. Composite Landsat image of central Brooks Range. Geographic features: AKP, Anaktuvuk Pass; AP, Atigun Pass; RTT, Bettles; CF, Coldfoot; CL, Chandler Lake; DO, Mount Doonerak; GL, Galbraith Lake; KA, Killik airstrip; SM, Slope Mountain; WM, Wiseman.

Table I. Summary of annual *climatic* values *at* selected stations in northcentral Alaska, 1975-79
[Haugen, 1982]

	Interior plains	Brooks Range	Arctic Foothills	Arctic Coastal Plain
Degree-days[a]				
Thawing	1,182 - 1,904	453 - 1,189	760 - 1,125	318 - 897
Freezing	2,767 - 4,513	3,173 - 3,888	4,225 - 5,412	4,409 - 5,642
Thaw season				
Length (days)	123 - 168	87 - 131	104 - 139	91 - 128
Starting dates	Apr 18 - June 1	May 3 - June 10	May 18 - June 27	May 25 - July 9
Precipitation (mm)				
Frozen		57 - 181	87 - 110	125 - 142
Unfrozen	84 - 367	117 - 292	52 - 157	58 - 81
Total	168 - 445	295 - 450	140 - 267	183 - 225
Temperature (°C)				
Mean	-6.9 - -3.7	-6.9 - -5.9	-11.1 - -6.2	-12.8 - -10.3
Range (mean diurnal)	12.8 - 14.6	10.8 - 12.6	7.6 - 11.6	7.6 - 9.6
Range (extremes)	-53.3 - +33	-37.8 - +26.1	-53.3 - +30	-50.6 - +28.9

[a]A measure of the difference between the mean daily temperature and an arbitrary temperature, such as 18.3 °C (65 °F), as used by heating engineers. It is normally applied **to mean temperatures that are below the standard. (Definrtion from Bates and Jackson, 1987, P. 172.)**
- - No data

temperature for the United States, -79 °F (-62 °C), was recorded at Prospect Creek Camp (Mile 135) on January 24, 1971. Many locations have extreme minimum temperatures below -58 °F (-50 °C), and at least half the stations have summer maximum temperatures above 86 °F (30 °C), a range of more than 144 °F (80 °C). Average annual air temperatures range from about 11 °F (-11.6 °C) at Prudhoc Bay to 25 °F (-4 °C) at some of the stations south of Dietrich Camp (fig. 13). Extremely low temperatures recorded at valley stations (for example, Prospect [Mile 135], Coldfoot [Mile 175], and Dietrich Camps [Mile 209.31) result from inversion of the vertical temperature profile as cold air drains downslope. Areas at higher elevations, such as Gobbler's Knob (Mile 132) and Chandalar Shelf (Mile 238), are above the average height of the inversion and therefore have higher average winter temperatures. Lower summer temperatures at higher elevations reflect a normal temperature decrease with elevation increase.

Areas at the same latitude and elevation with a similar summer temperature gradient may have a similar vegetation pattern. The 'Nordenskjold formula' takes this premise into account; thus it can be used to determine temperatures at tree line (Haugen and Brown, 1978). The limit of the white spruce forest is about 2,375 ft (720 m) elevation near Finger Mountain (Mile 98) and Gobbler's Knob (Mile 132) and in the area 25 mi (40 km) north of Dietrich Camp (Mile 209.3). The formula gives a calculated approximate July mean temperature of 54 °F (12 °C), which is in the same range as temperatures measured at tree iine in those areas (Densmore, 1980).

Temperature patterns along the entire route typify a continental climate, except for the maritime influence on summer temperatures north of Happy Valley Camp (Mile 335). An index of continentality is the mean annual diurnal range of temperatures (amplitude multiplied by 2). This averages <46 °F (8 °C) north of Happy Valley Camp and >50 °F (10 °C) south of the camp. Values of 54 to 55 °F (12 to 13 °C) are common between Happy Valley Camp and the Brooks Range and at stations at low elevations in the interior of Alaska. The highest mean annual diurnal temperature is 57 °F (13.7 °C) at Fivemile Camp (Mile 67).

PRECIPITATION

Annual precipitation ranges from 5.5 in. (140 mm) at Sagwon (Mile 350) to more than 16 in. (400 mm) in the Atigun Pass-Chandalar Shelf area. The 30-yr normal-precipitation value of 14 in. (360 mm) at Bettles probably represents all precipitation values, except those for higher elevations, from treeline near the head of the Dietrich River in the Brooks Range south to Old Man Camp (Mile 107). From Old Man Camp south to the Yukon River, total precipitation distinctly decreases, generally to >12 in. (300 mm) at Fivemile Camp. The greatest amount of precipitation recorded during a single day was 3.6 in. (89 mm) at Chandalar on July 27, 1975, followed by 2 in. (52 mm) at Prospect Camp on July 24, 1977.

During most years, rain is the dominant form of precipitation, particularly along the southern part of the route, where the thaw season is long and the percentage of precipitation that falls as rain is therefore greater. About two-thirds of the annual precipitation south of Chandalar is rain. South of the Continental Divide, thunderstorms produce intense precipitation; north of the divide, the storms are less common.

In the Arctic, weak low-pressure centers pass from west to east, often along the boundary of the summer Maritime Polar Front. These are responsible for about

Figure 7. View rzorlheastward toward Middle Fork Koyukuk River and Sukakpak Mountain (elevation 4,459 ft; 1,359 m) near Mile 200, central Brooks Range.

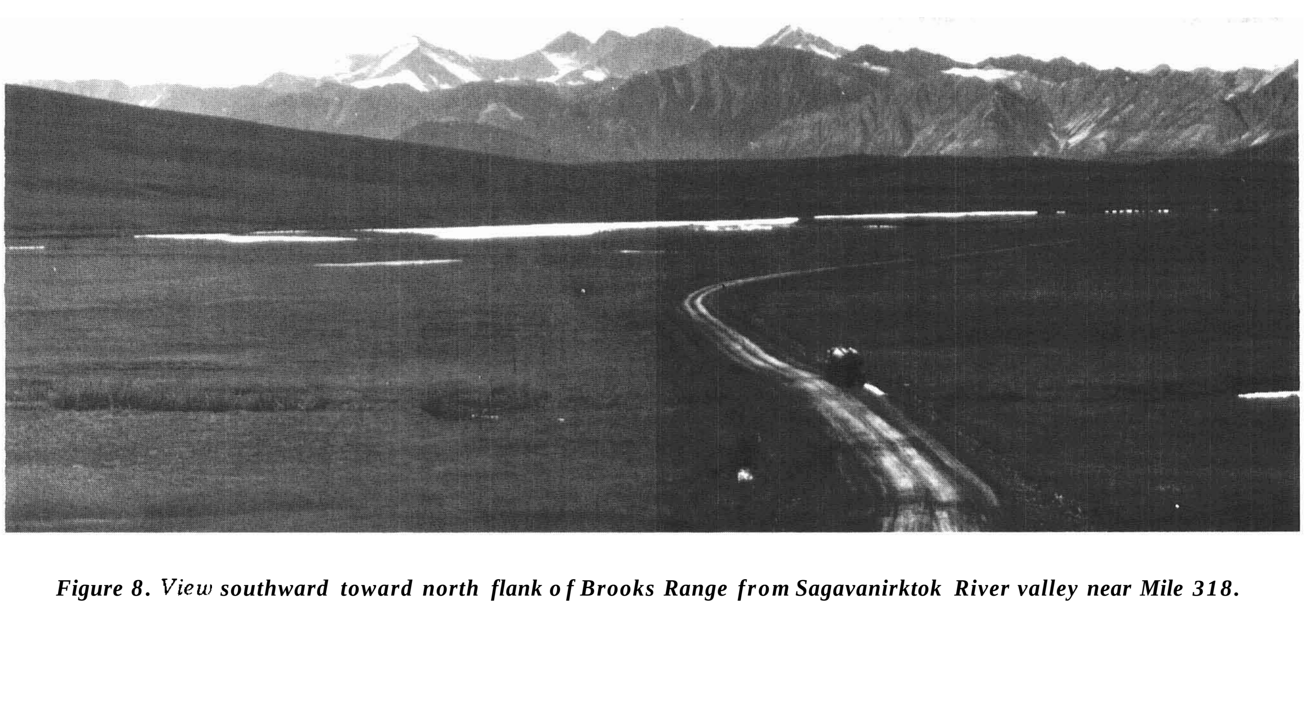


Figure 8. View southward toward north flank of Brooks Range from Sagavanirktok River valley near Mile 318.

Figure 9. View southward along Dalton Highway as it crosses uplands at northern edge of Arctic Foothills near Mile 354.

half the summer precipitation in the region. The coastal area, however, is usually influenced by maritime air that causes more frequent, but lighter, precipitation than that to the south. Benson (1982) reported that the amount of snowfall on the Arctic Slope may be underestimated by a factor of three because of inaccurate measuring techniques.

PERMAFROST AND GROUND ICE[6]

Perennially frozen ground, or permafrost, is defined as a thickness of soil or other superficial deposit (or even of bedrock) that has been colder than 32 °F (0 °C) for at least 2 yr (Muller, 1947). Permafrost is continuous north of Atigun Pass and is cliscontinuous in much of interior Alaska, including areas in valleys south of the Continental Divide in the Brooks Range (Ferrians, 1965; Ferrians and others, 1969). The term 'continuous permafrost' implies that permafrost underlies all or nearly all the landscape, including small ponds and streams, and has a temperature lower than 23 °F (-5 °C) at the depth of zero annual seasonal change, which is about 50 ft (15 m). In the zone of discontinuous permafrost, ground temperatures are higher than 23 °F (-5 °C) and most north-facing and low areas are underlain by permafrost; south-facing slopes and areas beneath bodies of water may be permafrost free.

Although permafrost soils may be nearly ice free in coarse, unsaturated material, they may contain more than 50 percent ice in fine-textured soils. The ice forms where water separates from saturated soils during the freezing process. Distribution of ground ice is highly variable. It occurs as films, lenses, layers, pore fillings, and other small, segregated masses as thick as 6 in. (15 cm). Ground ice occurs also in massive form as large sheets, and as dome-shaped intrusions in peat mounds and pingos. Vertical ice wedges (fig. 14), which commonly are <3 ft (1 m) wide at the top, have formed over many centuries in the permafrost and are actively growing in the colder, continuous permafrost zone. The wedges are responsible for polygonal ground (fig. 15) in treeless tundra (Leffingwell, 1919; Lachenbruch, 1962); however, it is not uncommon for ice wedges to show virtually no polygonal surface expression. Pond ice, buried icings, sheets of injected ice, and possibly buried glacial ice (Hamilton, 1982) are also found in permafrost soils.

The pipeline is elevated where it is underlain by frozen, or possibly frozen, fine-grained soil likely to contain significant amounts of ground ice. In the northern section of the pipeline, vertical support members (VSMs) with heat pipes indicate the presence of massive

[6]Modified from Brown and Berg (1980).

Figure 10. View northeastward from near Mile 388 down Sagavanirktok River valley on Arctic Coastal Plain. Tertiary Sagavanirktok Formation exposed on right at northern end of Franklin Bluffs.

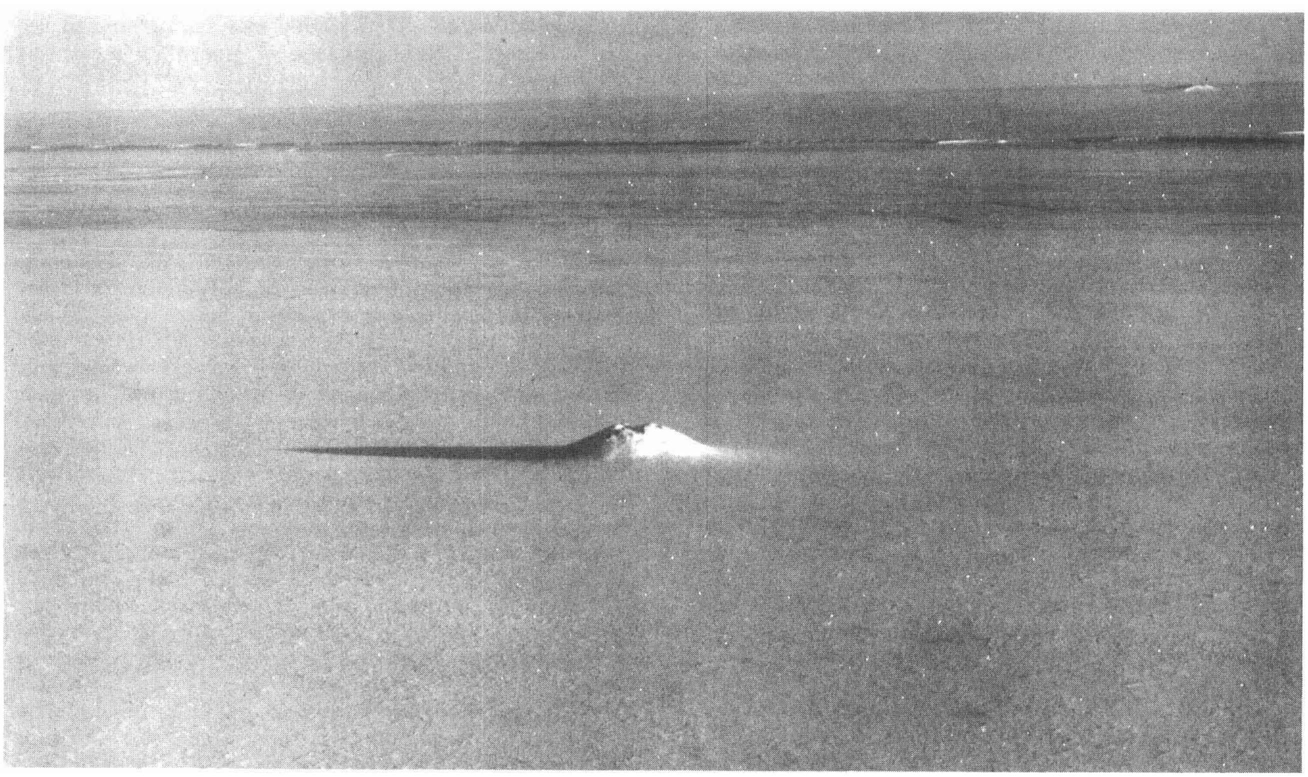


Figure 11. Pingo in November on Arctic Coastal Plain in Kadleroshilik River area, southeast of Prudhoe Bay

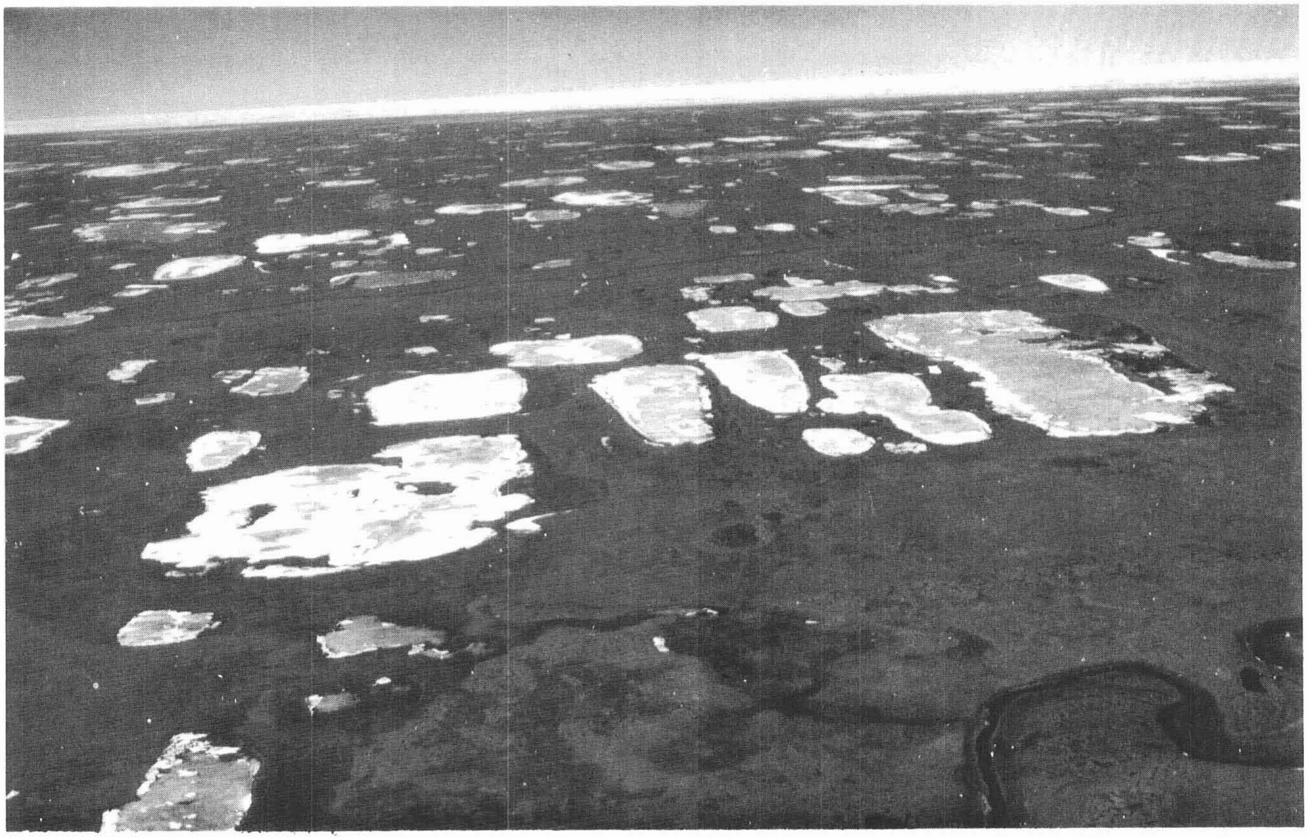


Figure 12. View northward toward oriented lakes in June on Arctic Coastal Plain south of Prudhoe Bay. Pack ice in distance.

ice. Insulated, gravel-covered berms around some VSMs maintain or reduce the thickness of the active layer, the soil horizon above permafrost that thaws and freezes each year. Buried portions of the pipeline (except where special designs were used) are in locations where unconsolidated deposits are relatively free of excess ground ice, in competent bedrock, or in nonpermafrost terrain.

South of the Brooks Range, the presence of permafrost and the thickness of the active layer are closely related to aspect, drainage, vegetation, slope angle, and thermal properties of parent material. Bogs, larch, and black spruce generally indicate the presence of permafrost within 24 in. (0.6 m) of the surface. White spruce and aspen usually indicate an area that is free of permafrost or that has an active layer *3* ft (1 m) or more thick. Pure stands of paper birch are found on sites free of permafrost or where the active layer has been temporarily deepened by burning or clearing. Generally, well-drained, south-facing slopes and sediments beneath the active channels of large streams are free of permafrost. Valley bottoms, north-facing slopes, and wet lower slopes are usually underlain by permafrost with an active layer 20 to 40 in. (0.5 to 1 m) thick. In perennially frozen areas, thaw bulbs exist beneath smailer streams. The overall thickness and lateral continuity of permafrost generally increase northward.

North of the Continental Divide, the Brooks Range is within the continuous permafrost zone; south of the divide, the range is within the discontinuous zone.

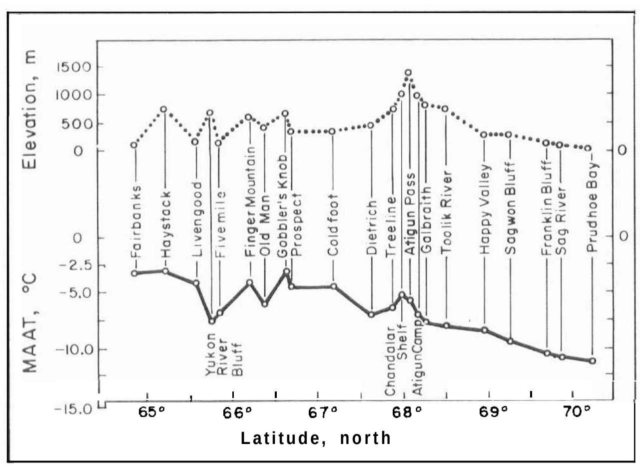


Figure 13. Estimated mean annual air temperature (MAAT) along field-trip route as function of elevation and latitude. Diagram by R.K. Haugen, U.S. Cold Regions Research and Engineering Laboratory, 1983.

Although thickness of the permafrost is extremely variable throughout the range, bedrock and unconsolidated deposits on slopes are generally perennially frozen, except for those on south-facing slopes south of the

Figure 14. Ice wedge and ice lens in unconsolidated Quaternary sediments, Chandler River, Arctic Foothills.

Figure 15. Polygonal ground, Arctic Coastal Plain southwest of Prudhoe Bay. Shallow tundra depressions are bordered by 1- to 2-ft-high (0.3 to 0.6 m) sod dikes that overlie ice wedges similar to those in figure 14. Shallow troughs along crests of dike systems indicate actively growing ice wedges. Polygons and ice wedges are analogous to dessication cracks but are formed by contraction during times of intense cold and grow slowly over many years.

divide. Coarse-textured, freely drained material on upper slopes has a deep active layer, whereas wet, fine-grained material on lower slopes has a shallow active layer, commonly only 20 to 40 in. (0.5 to 1 m) thick. Beneath the flood plains, the permafrost is generally discontinuous. South of the divide, permafrost is probably absent in most places beneath the active channels of larger rivers, such as the Chandalar, Dietrich, and Middle Fork Koyukuk Rivers. Thaw bulbs are present beneath the small drainages. Fine-grained deposits of the Brooks Range usually contain numerous ice wedges; coarse-grained material contains ice in voids, as coatings on individual particles, or as massive bodies in mudflow cones, rock glaciers, and some talus deposits.

North of the Brooks Range, primary causes of changes in permafrost thickness are differences in thermal conductivity of the rocks and increased heat flow. Permafrost is thickest in the highly porous Tertiary and Quaternary deposits, successively thinner in the less porous Upper Cretaceous rocks, and thinnest in the least porous Lower Cretaceous rocks. The active layer is generally less than 20 in. (0.5 m) thick in fine-grained soils. Unfrozen zones are generally limited to deep river channels and large, deep lake basins. Perennial springs indicate zones of unfrozen bedrock which provide avenues for recharge and discharge of ground-water systems.

The Arctic Foothills and Arctic Coastal Plain are underlain by a thick zone of permafrost that reaches a maximum depth of about 2,000 ft (600 m) at Prudhoe Bay (Gold and Lachenbruch, 1973). Throughout the foothills and plains, ice-wedge polygons (fig. 15) are conspicuous in poorly drained depressions and drained lake basins. Closedsystem pingos have developed in some refrozen lake-basin sediments of various ages. Where pingos or ice-wedge polygons are not evident, thermokarst ponds indicate the presence of ground ice. Other forms of massive ice show little surface expression. Ground ice was observed and logged by Alyeska in many VSM borings, in fuel-line trenches, and in the pipeline trench in areas where the pipe was placed in thaw-stable gravel beneath a silty, ice-rich surface layer.

ICINGS

Icings (aufeis) are sheets of surface ice formed during successive overflows on broad, braided-river flood plains, narrow channels of small streams, or downstream from seasonal or perennial springs (fig. 16). In rivers, icings generally form when water is forced to discharge at the surface because freezing has blocked the stream flow in the channel or the thaw bulb beneath it. Icings are fed not only by river water and underflow but also by discharge of ground water, stored in unfrozen, unconsolidated deposits of tributary alluvial fans, and by water discharged from bedrock through joints, faults, and solution channels.

Larger icings occur annually, but their size and

Figure 16. Aufeis field on Echooka River at Philip Smith Mountains front in early June. Field is about 2 mi (3.2km) wide and is fed by springs from Mississippian Lisburne Croup carbonate rocks that form mountain front.

thickness may vary, depending on meteorologic and hydrologic conditions. Most of the icings between Fox and the Middle Fork Koyukuk River are confined to small stream channels. The Middle Fork has icings that are generally limited to the main channel and probably form by constriction of channel flow and underflow by freezing. On the Dietrich and Atigun Rivers, broad icings occupy the entire braided flood plain. These icings seem to be supplied by water stored in the unfrozen gravel of tributary alluvial fans, by freezing of the river and its bed, and possibly by discharge of water from bedrock. East of the highway route, along lhe north flank of the Brooks Range, there are more than 50 spring-fed icings, some of which grow to be >16 ft (5 m) thick. Several of the larger icings (for example, those on the west side of Galbraith Lake and on the Kongakut, Echooka [fig. 16], and Ivishak Rivers) melt completely some years but persist throughout the summer and winter during other years (Childers and others, 1977).

PINGOS

Pingos are perennial, conical, ice-cored mounds that form under periglacial conditions. The largest pingos, in exceplional cases up to 200 fl (60 m) high and 3,200 ft (1,000 m) diam (Mackay, 1979), are concentrated on the Arctic Coastal Plain, where they dominate the flat terrain (fig. 11). A few of lhcse can be seen along the Dalton Highway west of Franklin Bluffs.

Leffingwell (1919) and Porsild (1938) were among the first to mention the presence of pingos on the Arctic Coastal Plain. To date, more than 1,000 have been catalogued in that area (Galloway and Carter, 1978; O.J. Ferrians, Jr., written commun., 1983). In the discontinuous permafrost zone of central Alaska, nearly 300 pingos and pingolike mounds have been located (Holmes and others, 1968); 74 have been reported in the Brooks Range (Hamilton and Obi, 1982).

Studies of pingos in Alaska have been largely restricted to description and classification in open- and closed-system categories (following Muller, 1959). Open-system pingos are characteristic of interior Alaska and many of the southern valleys of the Brooks Range. They form on lower slopes, where artesian pressure is likely to be greatest and artesian flow is blocked or localized (Holmes and others, 1968), either in alluvial aquifers buried by fine-grained deposits or in bedrock, as shown hy the alignment of pingos along rock fractures and by the inclusion of bedrock fragments in pingo sediments. Most pingos in the inlerior are of Holocene age, for the youngest sedimenls that have been deformed are no older than 7,000 yr (Holmes and others, 1968). In the Brooks Range (Hamilton and Obi, 1982), pingos postdate the Late Wisconsin glaciation.

Closed-system pingos are present in regions of continuous permafrost and are formed by hydrostatic pressure caused by freezing of water-saturated sediments in the thaw bulb beneath recently drained lakes (Mackay, 1979) (fig. 17). Pingos of the Arctic Coastal Plain and those reported (Hamilton and Obi, 1982) from a valley on the north side of the Brooks Range and from the valley of the Noatak River are all closed-system pingos. Hall and Roswell (1981), however, believe that several pingos localed in an area devoid of drained, deep lakes near the Shaviovik River icing may be open-system pingos supplied from an artesian system that perforates the permafrost.

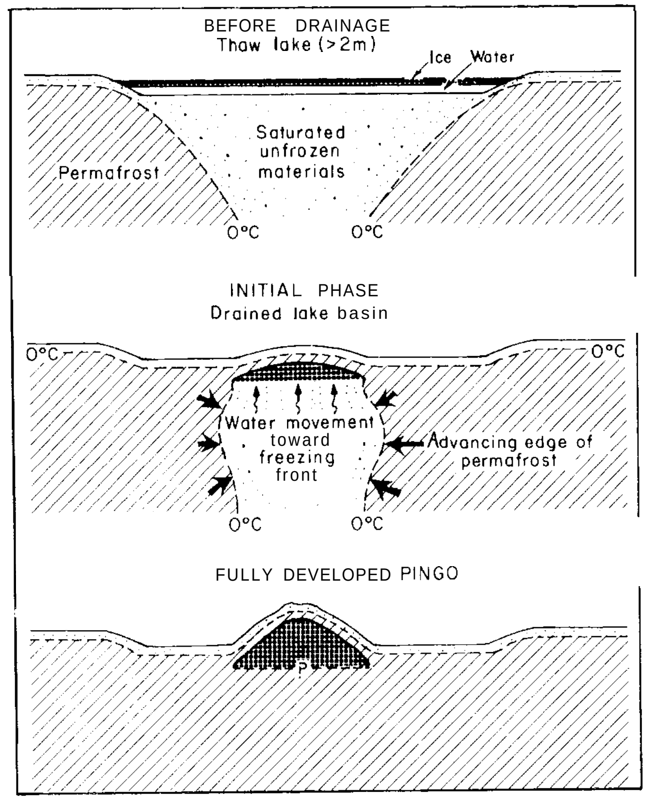


Figure 17. Schematic diagram of closed-system pingo development. From Walker and others (1980).

Pingo growth may continue for many centuries, as in the case of some of the very large pingos that are 185 It (60 m) high in the Mackcnzie River delta east of Prudhoe Bay. In the Prudhoe Bay area, the active-growth phase of pingos may last only decades. Growth ceases when the ground-water source is depleted or cut off by the downward and lateral extension of permafrost. The ice core may be maintained for long periods if the insulating sediment and organic material remain undisturbed and the regional climate does not warm appreciably.

CHAPTER 2.

A BRIEF HISTORY OF EIGHTY YEARS OF GEOLOGICAL EXPLORATION IN THE CENTRAL BROOKS RANGE, NORTHERN ALASKA

By J. Thomas Dutro, Jr.[1]

INTRODUCTION

Geologic exploration and mapping in the central Brooks Range and North Slope along the route of the Dalton Highway can be divided into three phases. The earliest, and longest, was the exploration phase, extending from military expeclitions in the 1880s until the onset of World War II. These expeditions were performed under the most difficult physical conditions, without the advantage of topographic base maps. Topographers produced route maps at the same time the geologists were making their observations. Travel was by pack train, canoe, dogsled, or foot.

The second, or reconnaissance, phase began with the second Naval Petroleum Reserve No. 4 (NPR-4) program in 1943. For nearly a decade, a prodigious amount of geologic and geophysical information was gathered by dozens of scientists. Airplanes and tracked, self-propelled vehicles (weasels) facilitated regional field studies, although a great deal of the field work was still done by boat and foot traverses. Accurate base maps remained a problem, even though planimetric maps were prepared from trimetrogon photographs taken during the 1940s.

The reconnaissance phase continued through the 1950s and 1960s as logistics were upgraded through the use of helicopters, and better topographic base maps produced by the U.S. Geological Survey. The existence of the pipeline haul roacl (now the Dalton Highway), and the availability of road construction camps and airstrips even before the road was completed, provided access to country that was previously unreachable.

First-order triangulation was not completed until the early 1960s. Inch-to-mile topographic maps became available during the 1970s, but parts of the Brooks Range do not yet have inch-to-mile coverage. Availability of accurate, large-scale topographic maps, and the start of a third, intensive study of the Petroleum Reserve in 1974, initiated the detailed mapping phase that continues to the present.

EXPLORATORY PHASE

Gold first brought white men into the central Brooks Range, and the hope of striking it rich has kept them there for nearly 100 yr. As many as 1,000 gold seekers arrived on the upper Koyukuk River in 1898, but, as most were inexperienced, they soon became discouraged and left for greener pastures. Although the population fluctuated over the years, probably no more than 200 people continued mining for gold during the first five decades of this century.

Before the gold boom, two military exploration parties had reached the region. Lt. H.T. Allen's 1885 Army expedition brought him to the upper Koyukuk River, which he traversed as far north as the mouth of the John River (Allen, 1887). In 1886, Lt. G.M. Stoney of the U.S. Navy explored the upper Alatna drainage and crossed the range to Chandler Lake (Stoney, 1900).

Until recently, most of the geological exploration and mapping in northern Alaska was done by the U.S. Geological Survey. The first geological work in the central Brooks Range was carried out by F.C. Schrader. In 1899, Schracler's party traversed from the Yukon River up the Chandalar River to the Koyukuk River and then descended the Koyukuk to its mouth. Schrader was also the first geologist to transect the Brooks Range. In 1901, his party ascended the John River, crossed

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through Anaktuvuk Pass, and descended the Anaktuvuk and Colville Rivers to the Arctic Coast. Schrader's 1904 reconnaissance report of the geology of that transect is the earliest account of the geology of the region. He named the Skajit and Lisburne limestones, differentiated the Stuver Series, mapped Cretaceous rocks on both flanks of the Brooks Range, and recognized the faulted nature of the north front of the range.

The first geologic map of the Brooks Range in the region crossed by the southern part of the Dalton Highway was published by A.G. Maddren in 1913 as part of his report on the gold fields of the Nolan-Coldfoot area. Maddren drew largely on the earlier geologic work of Schrader (1900, 1904) and W.C. Mendenhall (1902).

Although E. de K. Leffingwell did not map in the central Brooks Range, his pioneer work in the eastern part of the range (Leffingwell, 1919) established a stratigraphic sequence and provided geologic interpretations that were used throughout northern Alaska for several decades.

J.B. Mertie spent most of the summer of 1923 in the Chandalar district, where he examined gold prospects and produced a geologic map of the region (Mertie, 1925). Mertie was the first to recognize the Paleozoic age of most of the metamorphic rocks in the area. He differentiated Silurian limestone and Devonian slate belts and mapped the main outlines of granites, which he correctly assigned to the Paleozoic.

In their report of the Survey's first exploration of NPR-4 (1923-26), Bulletin 815, P.S. Smith and Mertie (1930) included a geologic map that covered an area as far east as the John and Anaktuvuk river valleys. Among other contributions, the report provides an excellent summary of earlier explorations (fig. 18) and includes an analysis by G.H. Girty of Carboniferous faunas from the Lisburne limestone, largely correcting the earlier, but erroneous, Devonian age assigned to the formation.

Many topographic features in the southcentral Brooks Range were named by Robert Marshall who was in the Wiseman and Mt. Doonerak areas during the summers of 1929, 1930, and 1931, and through the winter of 1930-31. Marshall was studying the vegetation of the area, but he prepared a sketch map of the drainages, major passes, and mountains, which was published by the U.S. Geological Survey in 1934. Marshall also conducted sociological studies at Wiseman, including his unique correlation of gold production in the district with the number of prostitutes in town (Marshall, 1933).

Irving McK. Reed visited and described all the gold placers in the Upper Koyukuk district during the 1930s and prepared a report for the Territorial Department of Mines (Reed, 1938). Although this report was never published, several copies exist and it has been referred to by later geologists.

P.S. Smith (1939) summarized all that was known of Alaska geology before World War II in U.S. Geological Survey Professional Paper 192, which includes a generalized geologic map that incorporates the central Brooks Range traverses of Schrader in 1901, Mertie in 1923, and Smith and Mertie in 1924. Most of the Wiseman Quadrangle and the country north of the Continental Divide, along what is now the Dalton Highway, had not yet been geologically examined. No further geologic work was done in this region until the postwar Navy Petroleum project of the U.S. Geological Survey.

RECONNAISSANCE PHASE

With the onset of World War II, the U.S. Geological Survey again became involved in a program to investigate the petroleum potential of NPR-4. This work is documented in detail by John C. Reed (1968) in his Professional Paper on the history of exploration of northern Alaska during the years 1943-53 (fig. 19). Wide-ranging geologic field work was done during each of the ten summers of the program; most of the U.S. Geological Survey geologists who have contributed to the geology of northern Alaska during the past quarter century got their start in the NPR-4 program. For instance, George Gryc, who later became chief of the Branch of Alaskan Geology, head of the third major program in the petroleum reserve, and assistant director for the U.S. Geological Survey western region, took part in field work along the Colville River near Umiat during the summer of 1944, the first field season of the program.

In 1945, three parties of U.S. Geological Survey geologists traversed the Anaktuvuk, Chandler, and Killik river valleys by boat. They collected data mostly on the Paleozoic and lower Mesozoic rocks of the foothills belt and recognized, for the first time, the structural complexities of the range front and foothills belt. These traverses also provided the basis for the Cretaceous stratigraphy that is used by geologists on the North Slope today (Gryc and others, 1951). In 1946, R.M. Chapman, E.H. Lathram, C.L. Whittington, Karl Stefansson, and Gryc were among those who made up five field parties, centered mostly north of the range. In 1947, there were again five parties in the field. Among those who studied the foothills and Brooks Range-front geology that year were R.L. Detterman, M.D. Mangus and, again, George Gryc. There were only three field parties in the summer of 1948, and these included W.W. Patton, Jr., E.G. Sable, Whittington, Stefansson and E.J. Webber, in addition to Detterman and Mangus.

In 1949, six parties were in the field, largely concentrating on the central part of the range. This was the season that W.P. Brosgé, A.S. Keller, I.L. Tailleur, A.H. Lachenbruch, M.C. Lachenbruch, A.L. Bowsher, and J.T. Dutro, Jr., were added to the NPR-4 crew. Patton and Tailleur used weasels in their work in the foothills belt in the Okpikruak-Kiruktagiak Rivers area. Bowsher and Dutro did detailed stratigraphic and paleontologic work on the Lisburne and related rocks in the Kanayut, Nanushuk, and Itkillik Lakes areas. Detterman, Mangus, and the Lachenbruchs traversed the Etivluk and Killik Rivers southward beyond the mountain front.

The summer of 1950 was the time of greatest field activity during this second NPR-4 program. Seven parties were in the field, several within the Brooks Range. Helicopters were used for the first time, albeit with

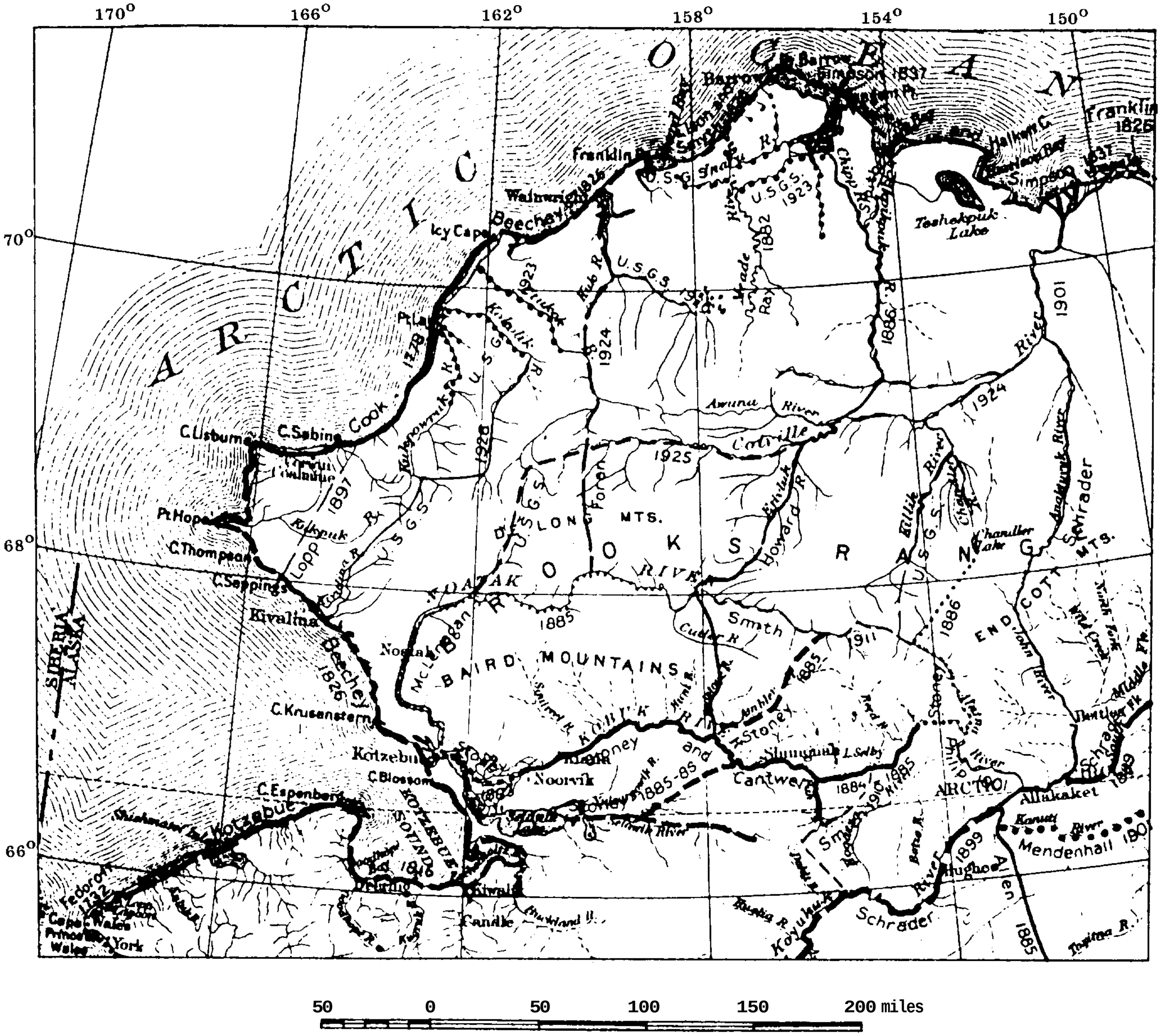

Figure 18. Sketch map showing progress of investigations in northwestern Alaska. Modified by Gryc (1985) from Smith and Mertie (1930).

minimal success, and five parties were weasel supported. Range-front and foothills structures were studied in the upper Utukok and Kokolik river valleys by Patton and Keller; in the Killik-Etivluk valleys by Chapman and G.D. Eberlein; and in the Etivluk-Kiligwa valleys by Tailleur. Dutro and the two Lachenbruch brothers made a boat traverse of the Nimiuktuk-Kugururok-Noatak Rivers in the western part of the range. Brosgé, Bowsher, Reiser, and others continued Lisburne stratigraphic studies in the northcentral part of the range.

In 1951, there was a cutback in field activity; only four parties were sent out. Keller and Detterman worked the Shaviovik-Sagavanirktok Rivers area; Patton, Mangus, and Brosgé traversed the Okokmilaga-John Rivers area; Tailleur, Reiser, and B.H. Kent worked the Ipnavik-eastern De Long Mountains area; and Sable, Dutro, and Morris traversed the western De Long Mountains. These last three parties reached or crossed the Brooks Range divide by weasel. Sable and Mangus had previously crossed the divide by weasel, in the upper Utukok area, in the summer of 1950. Gryc, Lathram, and L.A. Spetzman returned the Patton party weasels to Umiat by way of Anaktuvuk Pass. These were the first motorized vehicles to traverse that well-known pass.

Further cutbacks in field work resulted in only three field parties during the summer of 1952. Keller worked the Canning-Shaviovik Rivers area; Detterman's party worked the northern foothills from the ,Chandler River to the Anaktuvuk River; and Brosgé , Dutro, Mangus, and Reiser surveyed a large part of the eastern Brooks Range with float-plane support. Mangus and Dutro also worked at Wild Lake.

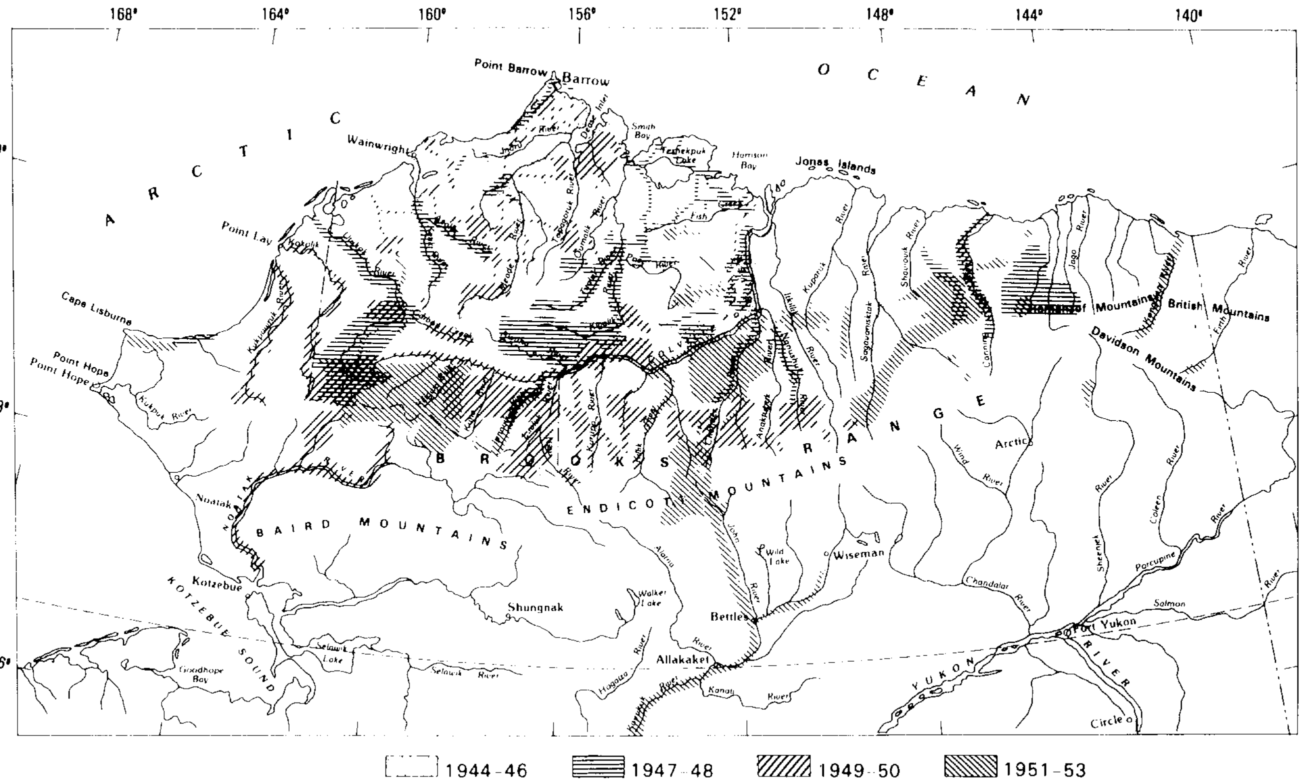

Figure 19. Sketch map showing progress of geologic exploration of northern Alaska from 1944 to 1953. Modified by Gryc (1985) from Reed (1958).

The last field season for the NPR-4 program was in 1953. Seven parties were in the field, but most of these were involved with completing mapping and sampling in areas already traversed. Of particular interest is the work of Patton, Tailleur, and others, who carried out detailed studies of the Carboniferous and Triassic in the northcentral part of the Brooks Range, crossed the range to Bettles, and descended the Koyukuk River to the Hog River.

By the mid-1950s, the broad outlines of the geology of the central Brooks Range were beginning to appear. The results of the NPR-4 program were released in a series of open-file reports at the end of the program, and much of the geology and geophysics was published during the decade that followed in a series of U.S. Geological Survey Professional Papers (see, especially, Professional Papers 302A-D, 303A-H, and 304, all published between 1956 and 1966).

For the most part, the work of the Navy Oil geologists was compiled on planimetric maps that had been made from trimetrogon photography taken for the Topographic Division of the U.S. Geological Survey during the period 1943-50. During the early years of the program, precise map location remained a problem; in some local areas, plane-table mapping provided the only topographic control. Left for the next three decades were further reconnaissance and detailed geologic mapping, as modern topographic base maps became available.

Thus, the stage was set for further geologic investigations. Many members of the Navy Oil Unit stayed with the Survey and continued geologic work in northern Alaska for the next two decades. Chief among these: particularly in the central Brooks Range, were Brosge and Reiser. During the late 1950s, they turned to the Chandalar Quadrangle and produced a 1:250,000-scale geologic map (Brosgé and Reiser, 1964) of the old gold-field area that had not been geologically surveyed since the early reconnaissance work of Maddren and Mertie. Another product of that project was a geochemical reconnaissance, of the Wiseman and Chandalar Quadrangles (Brosge and Reiser, 1972). The Chandalar project proved to be the prototype for the Alaska Mineral Resource Assessment Program (AMRAP), which continues today as a major activity of the U.S. Geological Survey in Alaska.

Brosgé and Reiser extended their reconnaissance westward to the Wiseman and Survey Pass Quadrangles, and their preliminary maps of that vast area were basic to later, more complete mapping (Brosgé and Reiser, 1960, 1971). Similar work, near the end of the reconnaissance phase, was completed by Patton and T.P. Miller in the Bettles and southern part of the Wiseman Quadrangles (Patton, 1973; Patton and Miller, 1973).

Major, regional stratigraphic and biostratigraphic syntheses, completed at about this time, summarized three decades of intensive reconnaissance work. Of particular interest are the publications of Detterman (1974, 1976a) and Detterman and others (1975) on the Sadlerochit Group (Permian and Lower Triassic) and A.K. Armstrong and B.L. Mamet (1977) on the Lisburne Group (Mississippian and Pennsylvanian).

DETAILED MAPPING PHASE

The discovery of oil at Prudhoe Bay in 1968 resulted in the construction of the pipeline haul road (now the Dalton Highway), the initiation of a third, detailed examination of the petroleum reserve (now called the National Petroleum Reserve in Alaska--NPRA; see Gryc, 1985), and the reorientation of the fledgling AMRAP program.

The Philip Smith Mountains AMRAP Quadrangle was completed by Brosge and others (1979a), and work was extended into the Survey Pass Quadrangle by Brosgé and G.H. Pessel (1977). Two major small-scale maps summarized the work of both the NPRA and AMRAP programs. A bedrock geologic map of the southern half of NPRA was completed by C.F. Mayfield, Tailleur, C.G. Mull, and Sable (1978), and a map of northern Alaska was compiled by H.M. Beikman and Lathram (1976).

Detailed regional stratigraphic work was a feature of the NPRA program, including the study of Devonian clastic rocks in the Brooks Range by Brosgé, Reiser, Dutro, and T.H. Nilsen (1979b). Nilsen continued research on the clastic rocks for several years and produced a number of papers on the sedimentological significance of the sequence. A more complete map of the Survey Pass Quadrangle was published by S.W. Nelson and D.J. Grybeck (1980). A revision of the upper Paleozoic and lower Mesozoic sequence in the central and western Brooks Range by Mull, Tailleur, and others (1982) added new dimensions to the stratigraphic and structural studies. Modern studies of surficial deposits and glacial history along the highway route by T.D. Hamilton (1978a,b) enhanced our understanding of the region's geologic history.

The Wiseman Quadrangle became the first U.S. Geological Survey-State of Alaska cooperative AMRAP quadrangle. The preliminary geologic map by J.T. Dillon, Brosgé, and Dutro (1986) incorporates detailed inch-to-mile mapping by Dillon and a number of associates of the Alaska Division of Geological and Geophysical Surveys (DGGS). This mapping was possible only because inch-to-mile topographic maps became available in the 1970s.

THE FUTURE

By the mid-1980s, the stage was set for a fourth phase of geological work in northern Alaska. As in each of the other phases, it will build on the work of earlier geologists. Modern detailed research is now being carried out by many people from DGGS, the University of Alaska and other academic institutions, and industry, in addition to a new generation of U.S. Geological Survey geologists. Some of their results are a part of the Dalton Highway geologic guide.

ACKNOWLEDGMENTS

I would like to thank W.P. Brosgé, George Gryc, and M.D. Mangus for their helpful reviews of this paper. All three provided comments and suggestions that improved the final version by pointing out certain errors of both omission and commission.

CHAPTER 3.

GLACIAL GEOLOGY OF THE BROOKS RANGE[1]

By T.D. Hamilton[2]

INTRODUCTION

The physiography of the Brooks Range has been strongly modified by repeated glacial advances during late Tertiary and Quaternary times (fig. 20). Glaciation has also been responsible for many of the surficial deposits within the range and in the foothills to the north and south. During the Late Pleistocene, glaciers originated mainly within a belt of cirques (fig. 21), about 18 mi (30 km) wide, that was centered north of the Continental Divide. Ice flowed north along relatively short, steep glacial troughs with cirque-headed tributaries. The ice streams extended beyond the range front to form the coalescing piedmont drift sheets that now dominate the surficial geology north of the range. As glaciers retreated, basins formed behind the end moraines and filled rapidly with sandy sediment. Glacial valleys south of the divide are typically longer and have gentler gradients. Many of their tributaries were unglaciated during younger ice advances. This relationship created complex flow patterns in which main valley glaciers extended varying distances up the lower courses of tributary valleys. As these glaciers retreated, they formed irregularly shaped basins to 30 mi (50 km) long, which filled slowly with clay- and silt-rich sediments. Glacier tongues that extended beyond the south flank of the range remained confined within the Chandalar and Koyukuk drainages. Deep erosion along parts of these river systems has exposed sections of Quaternary deposits as thick as 125 to 275 ft (40 to 90 m). The sections commonly contain successive tills separated by alluvial and lacustrine sediments beneath peat, loess, and thaw-lake deposits. Older glacial advances were more extensive both north and south of the range, but little remains of their landforms or deposits in the mountain valleys. Glacier expansions of late Holocene (Neoglacial) age are confined to cirques above about 4,800 ft (1,500 m) in elevation.

BROOKS RANGE GLACIAL SEQUENCE

The Brooks Range glacial sequence was defined initially by R.L. Detterman (1953) and has been modified subsequently by Detterman and others (1958), Williams (1962), Porter (1964, 1966a), Hamilton and Porter (1975), and Hamilton (1978a, 1979a, 1982, 1986). Four major phases of glaciation are recognized (fig. 22). The youngest phase is divisible into two or three separate episodes of valley-glacier advance, which were followed by cirque-glacier expansion during the last 4,000 to 5,000 yr (Ellis and Calkin, 1984).

The oldest interval of glaciation is represented by the informally named Gunsight Mountain erratics, which consists of large, 3- to 6-ft (1 to 2 m) boulders of highly resistant Kanayut Conglomerate. The boulders were deposited during one or more glacial advance of probable late Tertiary age (Hamilton and Hopkins, 1982). Later, they accumulated as lag deposits in alluvium during a long interval of stream erosion and pedimentation that took place when streams north of the range flowed 150 to 300 ft (50 to 100 m) above their modern levels. The Gunsight Mountain erratics and correlative deposits are restricted to piedmont zones and uplifted plateaus along mountain fronts and cannot be traced to existing mountain valleys. Extensive erosion surfaces of post-Gunsight Mountain age are overlapped by drift of the Anaktuvuk River Glaciation, indicating that a long interval separated these two glacial phases.

During the Anaktuvuk River Glaciation (Detterman and others, 1958), ice streams occupied major mountain valleys of the present Brooks Range but typically flowed 300 ft (100 m) or more above their modern floors. Extensive moraines formed beyond the mountains. These are fairly continuous but subdued, exhibiting slope angles of generally only 1° to 2°. Between the morainal ridges are concentric series of arcuate drainage courses, representing either individual glacial advances or merely recession of a single ice tongue. Other drainage networks are maturely developed, and complex thaw-

[1]The original version of this paper appears in the volume 'Elliott and Dalton Highways, Fox to Prudhoe Bay, Alaska: Guidebook to Permafrost and Related Features' (Brown and Kreig, 1983). The revised draft has been approved for publicalion by Director, U.S. Geological Survey.
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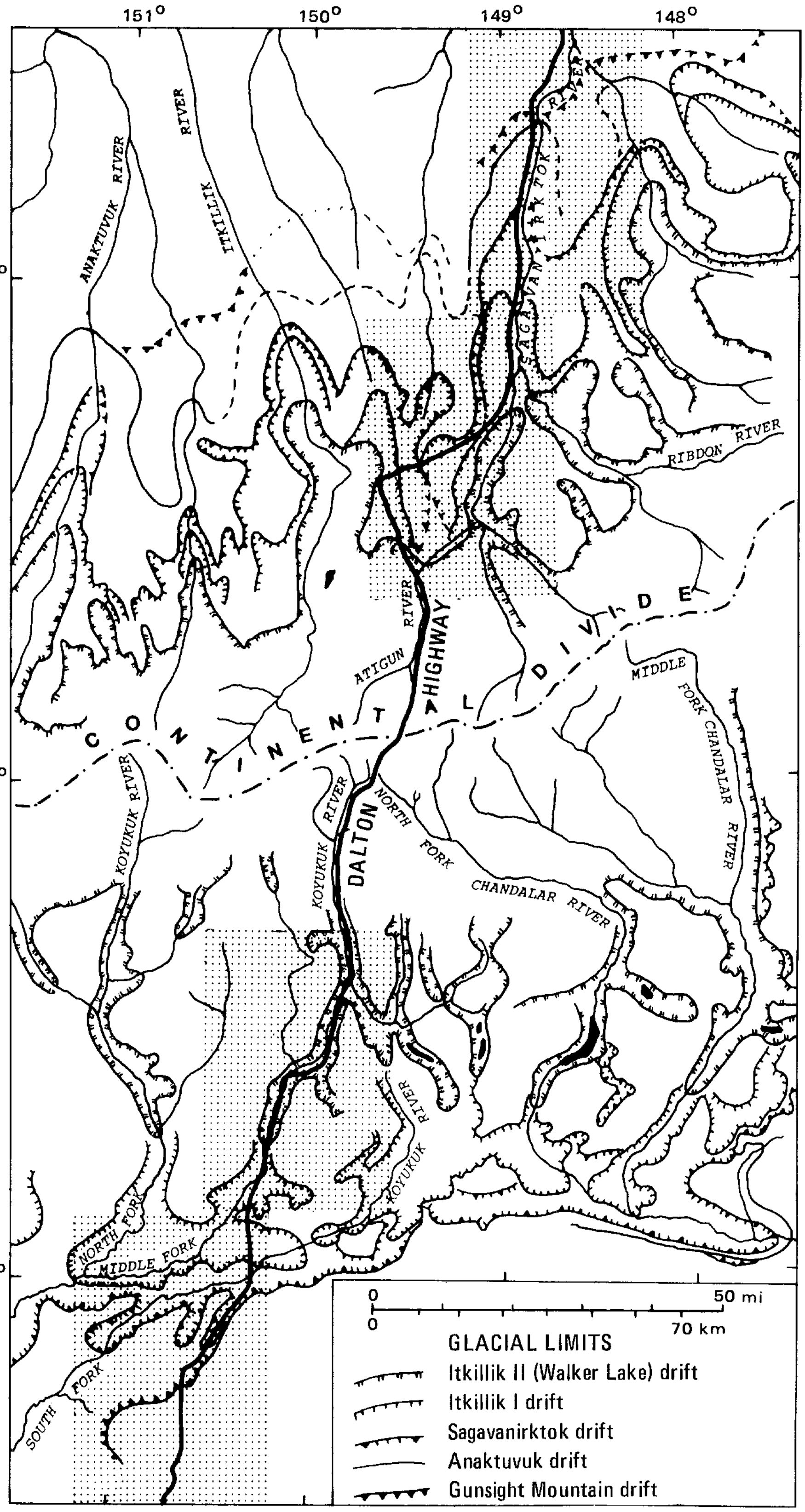

Figure 20. Glacial geology along Dalton Highway from about Mile 120 to Mile 207 (Hamilton, 1978b,c, 1979c, 1982). Stippled areas shown in greater detail in figures 54 and 103.

Figure 21. Cirque glacier on north side of Continental Divide in eastern Endicott Mountains at head of West Fork Atigun River, 10 mi (16 km) west of Atigun Pass. Continental Divide is about 6,500 ft (2,000 m) in elevation. Photograph by C.G. Mull, August 1985.

lake basins demonstrate repeated cycles of lake formation. Erratics are generally sparse and, despite their large size (4.5 to 6 ft; 1.5 to 2 m), are typically buried nearly flush with the ground surface. Piedmont drift sheets have been dissected by streams that flowed 125 to 400 ft (40 to 66 m) above their modern levels and eroded valleys up to 6 mi (10 km) long. Deglaciation was followed by a long interval of valley enlargement and pedimentation.

The youngest complex of drift sheets occurs on or close to modern valley floors and extends into valley centers, where the sheets generally stand within 125 ft (40 m) of modern stream levels. Drift from separate glacial advances within the complex differ markedly in weathering, soil development, and sharpness of surface morphology. The oldest drift sheet of this complex, assigned to the Sagavanirktok River Glaciation (Detterman and others, 1958), is relatively highly weathered, subdued by mass wastage, and dissected by streams. Slope angles rarely exceed 4°, except where surfaces have been steepened by postglacial downcutting.

A much younger appearing drift, assigned to the Itkillik Glaciation of Detterman and others (1958), was assumed to be entirely of late Wisconsin age (Porter, 1964; Hamilton and Porter, 1975). However, subsequent radiocarbon dating and stratigraphic studies have shown that initial glacial advances of Itkillik age took place prior to 50,000 radiocarbon years B.P. (Hamilton, 1979b, 1982, 1986). On the other hand, deposits formed during these advances are morphologically similar to and continuous with drift sheets that date from late Wisconsin time, and they may still be ice-cored in places. For these reasons, the outermost Itkillik deposits are believed to be of early Wisconsin age, postdating the last major Pleistocene interglaciation (Hamilton and Hopkins, 1982).

Younger deposits of Itkillik age, dated between about 25,000 and 10,000 yr B.P. in the southcentral Brooks Range (fig. 23), are morphologically fresh and still ice-cored in some valleys. These drift sheets, equivalent in age to deposits of the late Wisconsin substage, were assigned to the Walker Lake glacial advance in the southern Brooks Range (Hamilton, 1982). The term 'Itkillik II' of Hamilton and Porter (1975), however, is generally preferable because "glaciers may not have retreated from most mountain valleys between major advances of Itkillik age...[and] drift of the several advances cannot be separated in those localities" (Hamilton, 1986, p. 43).

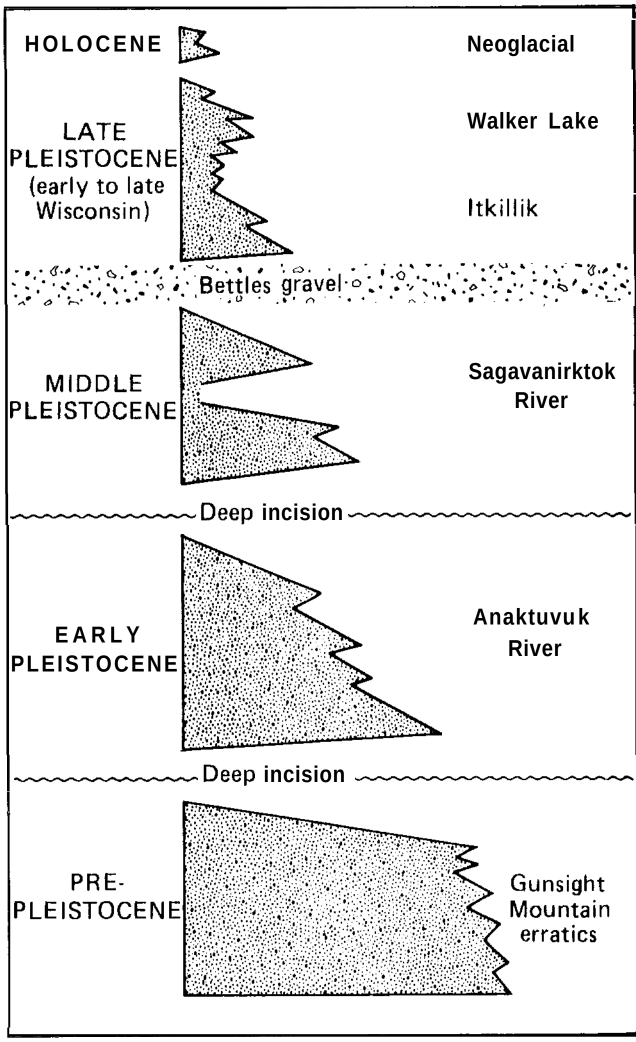

Figure 22. Time-distance diagram showing late Cenozoic glacial fluctuations in the central Brooks Range

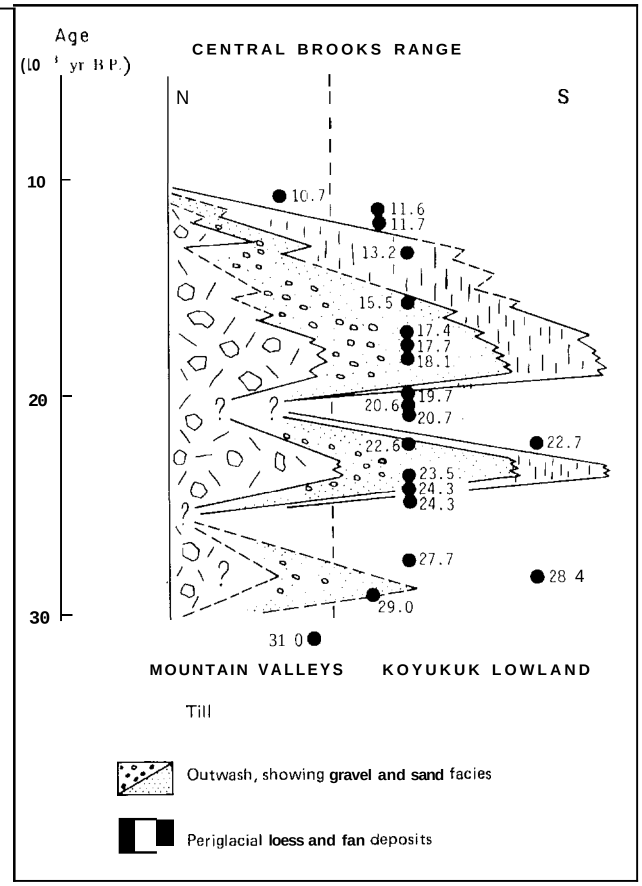

Figure 23. Time-distance diagram showing glacial and proglacial deposits of Itkillik II glacial advance (Walker Lake age) in the southcentral Brooks Range. Black dots mark radiocarbon dates (thousands of years B.P.). Modified from Hamilton (1982).

CHAPTER 4.

FRAMEWORK GEOLOGY: YUKON RIVER TO BROOKS RANGE[1]

By W.W. Patton, Jr.[2]

RUBY GEANTICLINE

From the Yukon crossing north to about Mile 150, the Dalton Highway traverses the Ruby geanticline, a linear uplift of pre-Cretaceous rocks that diagonally crosses central Alaska along the southeastern side of the Cretaceous Yukon-Koyukulc basin. The geanticline is composed of two distinctly different rock assemblages (fig. 24): 1) autochthonous Proterozoic(?)and Paleozoic metamorphic rocks assigned to the Ruby lithotectonic terrane of Jones and others (1984a); and 2) allochthonous late Paleozoic to early Mesozoic mafic volcanic and intrusive rocks, ancl locally abundant chert and argillite, assigned to the Tozitna and Angayucham lithotectonic terranes of Jones and others (1984a). Both of these assemblages are intruded by mid-Cretaceous granitic rocks and locally mantled by small patches of early Tertiary calc-alkalic volcanic rocks and late Cenozoic basalt flows.

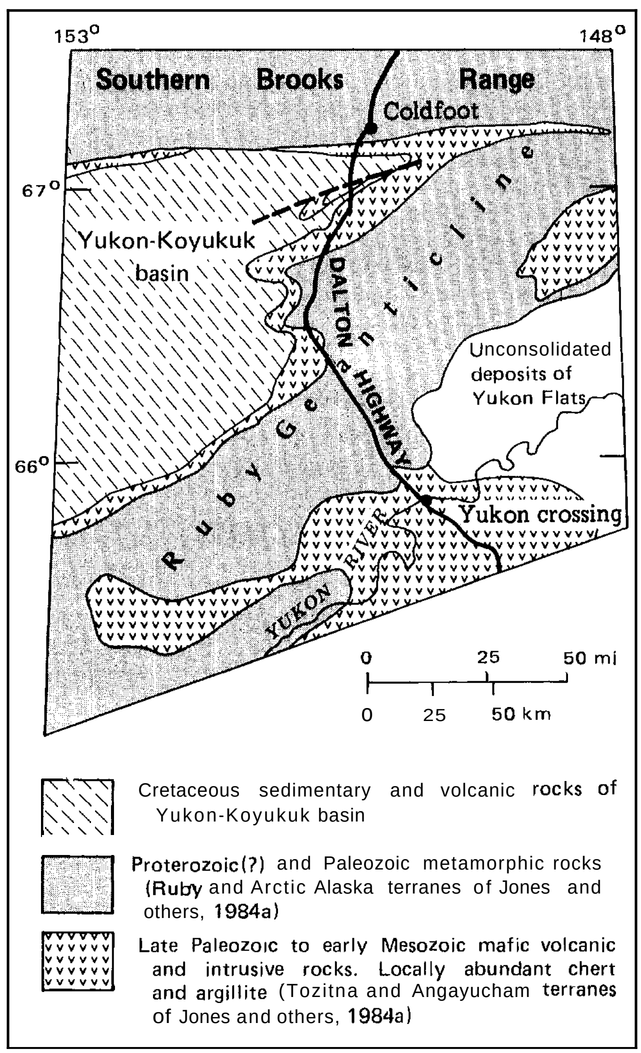

Figure 24. Skelch map showing major geologic elements along the Dalton Highway between Yukon crossing (Mile 56) and Coldfoot (Mile 176).

PROTEROZOIC(?) AND PALEOZOIC METAMORPHIC ROCKS (RUBY TERRANE)

The metamorphic core of the Ruby geanticline consists of pelitic schist, quartzite, greenstone, carbonate rocks, and quartzo-feldspathic gneiss. These rocks appear to represent a Proterozoic(?) and early Paleozoic miogeoclinal assemblage that was metamorphosed in Early Cretaceous time. Overall, the assemblage is of greenschist facies but locally ranges from lower greenschist to almandine-amphibolite facies. Glaucophane-bearing blueschist mineral assemblages have been identified at several localities along the northwest flank of the geanticline. All of the metamorphic rocks are widely intruded by Cretaceous granitic rocks and thermally altered to andalusite-cordierite hornfels, hornblende hornfels, and contact marble. Also included with the metamorphic rocks is an undated sequence of phyllite and meta-

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graywacke that displays a generally lower metamorphic grade than the pelitic schist. The sequence is exposed at several localities along the highway and is spatially associated with the late Paleozoic to early Mesozoic mafic volcanic and intrusive rocks. Along the northwest flank of the geanticline, the sequence occupies a structural position above the autochthonous schist and below the allochthonous mafic volcanic and intrusive rocks. The sequence represents a separate thrust sheet.

The Proterozoic(?) and Paleozoic metamorphosed miogeoclinal rocks of the Ruby geanticline may represent a slice of the southern Brooks Range that was rotated or displaced in Mesozoic time by rifting, oroclinal bending, or strike-slip faulting (Carey, 1958; Patton, 1970; Churkin and Carter, 1979; Tailleur, 1980). Precise correlations between rocks of the Ruby geanticline and those of the southern Brooks Range have not been firmly established, however, because protolith ages, stratigraphy, and internal structure are poorly known, particularly for the metamorphic rocks of the Ruby geanticline. In that area, Paleozoic fossils have been found only at a few scattered localities. The best evidence for correlation between rocks of the Ruby geanticline and southern Brooks Range comes from recent U-Pb zircon dating of granite gneiss in the central Brooks Range (Dillon and others, 1980), and in the Ray Mountains of the Ruby geanticline (Patton and others, 1987). The zircon ages (about 335 to 375 Ma, or Late Devonian to Late Mississippian) provide evidence of a major plutonic event that occurred in both belts during mid-Paleozoic time. Both regions also yield similar Cretaceous metamorphic-mineral K-Ar ages (zbout 85 to 135 Ma, or Early to Late Cretaceous), which are probably related to Early Cretaceous overthrusting of the late Paleozoic to early Mesozoic mafic volcanic and intrusive rocks (Patton and others, 1984; Turner, 1984).

LATE PALEOZOIC TO EARLY MESOZOIC MAFIC VOLCANIC AND INTRUSIVE ROCKS (TOZITNA AND ANGAYUCHAM TERRANES)

This assemblage of rocks crops out in large, synformal masses along the southeastern flank of the Ruby geanticline, where it has been assigned to the Tozitna lithotectonic terrane of Jones and others (1984a). It is also present in a narrow belt of slab-like bodies that dip beneath the Yukon-Koyukuk basin along the northwestern flank of the geanticline; in this region, it has been assigned to the Angayucham lithotectonic terrane (fig. 24) of Jones and others (1984a). Both terranes appear to comprise erosional remnants, or klippen, of allochthonous sheets of ophiolites and allied oceanic crustal rocks that were thrust over the Proterozoic(?) and Paleozoic miogeoclinal rocks of the Ruby geanticline in late Mesozoic time (Patton and others, 1977). In both terranes, two distinct allochthons are recognizable: 1) a lower allochthon composed of multiple thrust sheets of pillow basalt, nonlayered gabbro, and radiolarian chert, with lesser amounts of argillite, volcaniclastic rocks, and carbonate rocks; and 2) a higher allochthon composed of harzburgite tectonite and cumulate peridotite and gabbro. A thin layer of garnet amphibolite commonly marks the base of the upper allochthon. The lower allochthon yields fossils that range from Mississippian to Triassic in age; the upper allochthon yields Middle and Late Jurassic (about 140 to 170 Ma) K-Ar ages.

Although most workers agree that this assemblage of oceanic rocks is allochthonous, relative to the metamorphic core of the Ruby geanticline, no consensus exists on where the thrust sheets came from or in what direction they moved. Patton and others (1977) suggested that the thrust sheets were rooted along the margin of the Yukon-Koyukuk basin and were transported southeastward across the Ruby geanticline. Coney (1984) interpreted the oceanic crustal rocks as remnants of huge nappes that overrode much of central Alaska from a former ocean basin that lay to the south. Gemuts and others (1983) envisaged the oceanic rocks as generated in local rifts in the Proterozoic(?) and Paleozoic metamorphic rocks and subsequently thrust onto the metamorphic rocks during a later compressional event.

MID-CRETACEOUS GRANITIC ROCKS

Both the metamorphic rocks of the Ruby terrane and the allochthonous oceanic crustal rocks of the Angayucham terrane are intruded by large granitic plutons (fig. 25). The plutonic rocks are chiefly coarsely porphyritic biotite granite but locally include granodiorite and monzonite. K-Ar mineral and U-Pb zircon ages from the plutons range from 104 to 112 Ma (late Early Cretaceous-Albian). High initial $^{87}Sr/^{86}Sr$ ratios; an abundance of lithophile elements, such as potassium, uranium, thorium, tungsten, and tin; and the presence of two-mica peraluminous phases in the granite suggest that these intrusives are, in large part, a product of crustal melting generated within the Proterozoic(?) and Paleozoic miogcociinal rocks.

TERTIARY VOLCANIC ROCKS

Calc-alkalic extrusive rocks and related hypabyssal rocks of early Tertiary (47 to 65 Ma) age are widely distributed along the southeastern side of the Yukon-Koyukuk basin and locally overlap onto the Ruby geanticline. The tectonic significance of these rocks is discussed in the following section on the Yukon-Koyukuk basin.

LATE CENOZOIC BASALT

Small patches of flat-lying, vesicular to massive, subaerial olivine-basalt flows are exposed in the heavily alluviated lowlands of the Ray River. The precise age of these flows is not known. Similar undated basalt flows are present around the margins of the Yukon Flats that border the east side of the Ruby geanticline. The presence of a deep gravity low beneath the flats suggests that the flats may be underlain by a thick late Cenozoic sedimentary basin. Extrusion of the basalt may have accompanied downfaulting on the basin margins.

YUKON-KOYUKUK BASIN

Although the Dalton Highway crosses only the northeasternmost tip of the Yukon-Koyukuk basin (fig. 24), a brief review of the broad stratigraphic and structural features of the basin is presented here as background for the tectonic history of interior Alaska. The basin covers much of western Alaska and is a structurally complex depression composed of several smaller subbasins and interbasin highs. The Cretaceous rocks that fill the depression can be divided into two suites: 1) a lower volcanic suite composed of andesitic volcaniclastic rocks and flows; and 2) an upper suite composed of terrigenous sedimentary rocks that range from deep-water turbidites to shallow-marine and fluvial deposits.

Figure 25 *View* northwestward from *Finger Mountain (Mile* 98 1) across shoulder of *Caribou Mountain* to *Little Kanuti* Flats *and Kanuti pluton (right center) Caribou Mountain is underlain* by *harzburgite* and gabbro *of Angayucham terrane Photograph by C G* Mull *November* 1984

VOLCANIC SUITE

The volcanic suite is exposed on a broacl uplift, the Hogatza trend, in the northcentral part of the basin and on small structural highs along the southeastern side of the basin. On the Koyukuk River near Hughes, the volcanic suite is well exposed and is at least 5,000 ft (1,500 m) thick; near Ohogamiut on the lower Yukon River the volcanic suite is at least 10,000 ft (3,000 m) thick. Volcaniclastic rocks compose the bulk of the suite and range from coarse breccia and agglomerate to fine crystal and lithic tuffs. Flows, chiefly pillowed anclesite and basalt, are locally intercalated with the volcaniclastic rocks. The volcanic suite petrographically and chemically appears to fit the definition of an orogenic andesite (Gill, 1981) and is generally considered to represent a volcanic-arc assemblage. Fossils and K-Ar mineral-separate determinations from widely distributed localities throughout the basin yield ages from Early Cretaceous (Berriasian) to late Early Cretaceous (Aptian). The base of the suite has not been observed.

TERRIGENOUS SEDIMENTARY SUITE

The volcanic suite is unconformably overlain by terrigenous sedimentary rocks derived from the pre-Cretaceous borderlands that surround the Yukon-Koyukuk basin and from the underlying volcanic suite. The thickness of the sedimentary section varies considerably but locally may be as much as 26,000 ft (8,000 m). In general, the lower part of the suite is composecl of turbidites rich in volcanic-rock debris, and the upper part is composed of turbidites and shallow-metamorphic-rock debris. Thick accumulations of marginal conglomerates around the basin's periphery are characterized by an abundance of mafic-rock debris from the Angayucham terrane in the lower part and quartz- and metamorphic-rock debris from the Arctic Alaska (southern Brooks Range) and Ruby terranes in the upper part. Much of the terrigenous sedimentary suite has defied rigorous stratigraphic analyses because of complex structure and lack of fossil data, particularly in the thick turbiditc assemblages. Fossil ages from these rocks are generally late Early Cretaceous (Albian) to early Late Cretaceous (Cenomanian).

CRETACEOUS GRANITIC ROCKS

Both the volcanic suite and terrigenous sedimentary suite are widely intruded by plutonic rocks. Plutons in the northeastern part of the basin are Late Cretaceous (80 to 84 Ma) in age and are composctl chiefly of a compositionally expanded suite of granodiorite and tonalite (Miller, 1984). Initial $^{87}Sr/^{86}Sr$ ratios are low (0.7038 to 0.7047) and suggest that the Proterozoic(?) and early Paleozoic metamorphic rocks of the Ruby geanticline do not extend beneath this part of the basin (Arth and others, 1984). Plutons in the western part of the basin are Early Cretaceous in age (99 to 110 Ma, or Albian) and are composed of monzonite, syenite, quartz monzonite, and subsilicic-alkaline complexes. No isotope data for these plutons are presently available, and the character of the basement beneath this part of the basin is uncertain.

TERTIARY VOLCANIC ROCKS

Calc-alkalic extrusive rocks and related hypabyssal rocks of early Tertiary (47 to 65 Ma, or Paleocene to Eocene) age are widely distributed along the southeastern side of the basin. These rodks include flows, volcaniclastic rocks, sills, dikes, and plugs of basalt, andesite, dacite, and rhyolite. The petrology and chemical composition of these rocks suggest that they are subduction related, but the position and polarity of the subduction zone are uncertain (Moll and Patton, 1984). An areally less widespread assemblage of younger Tertiary (40 Ma, or late Eocene) volcanic rocks has also been identified along the southeastern side of the basin (Miller and Lanphere, 1981). The bimodal basalt-rhyolite composition and structural setting of this assemblage indicate emplacement during an extensional regime.

STRUCTURE

All Cretaceous volcanic and sedimentary rocks in the basin are intensely deformed. In the western and central parts of the basin, the rocks are characterized by isoclinal folds and closely spaced, high-angle faults. Juxtaposition of shallow-marine and deep-sea-fan deposits, in the absence of intermediate-slope deposits, suggests large-scale shortening by thrust faulting (Nilsen and Patton, 1984). In the eastern and southeastern parts of the basin, folding is less intense, but flank dips, except locally, are $>30^{\circ}$. Early Tertiary volcanic rocks along the southeastern side of the basin rest unconformably on the Cretaceous sedimentary and volcanic rocks and have flank dips generally $<30^{\circ}$.

The west- to southwest-trending Kaltag fault, a major strike-slip fault that crosses the basin between Ruby on the Yukon River and Unalakleet on the Bering Sea coast, provides well-documented evidence of 75 to 100 mi (120 to 160 km) of right-lateral offset of the southeast margin of the basin in post-middle Late Cretaceous time (Patton and Hoare, 1968; Patton and others, 1984). The Kobuk fault zone along the northern margin of the basin may also have major strike-slip movement (Grantz, 1966; Dillon, chap. 10), but convincing evidence is lacking.

CHAPTER 5.

GENERALIZED STRATIGRAPHY AND STRUCTUREOFTHE BROOKS RANGE AND ARCTIC SLOPE

By C.G. Mull[1]

INTRODUCTION

The structure and stratigraphy of the Brooks Range and Arctic Slope are illustrated on sheet 1, a generalized geologic map and cross section that portrays relationships that resulted From the Late Jurassic and Cretaceous evolution of the Brooks Range orogenic belt (also see fig. 26; Mull and others, 1987a). The cross section depicts features of the compressional and extensional margins of the Arctic Alaska plate (Mull, 1982), a small lithospheric plate composed dominantly of continental rocks. Most of the structural relationships exposed in the Brooks Range and central Arctic Slope have resulted from compressional interaction of this plate with oceanic rocks exposed along the south flank of the Brooks Range and margins of the Koyukuk basin.

The interpretations below are the product of many years of reconnaissance studies, combined with detailed U.S. Geological Survey studies and contributions of other workers from DGGS, the University of Alaska, and the oil and mining industry. Ongoing and sometimes lively discussions with I.L. Tailleur (U.S. Geological Survey), H.S. Sonneman (Exxon Company, U.S.A.), G.H. Pessel and J.T. Dillon (DGGS), and, more recently, T.S. Moore and S.K. Karl (U.S. Geological Survey) and R.K. Crowder and W.J. Wallace (University of Alaska) were of great value in the development of interpretations presented here, which, although my own, are not necessarily unique. The line between innovation, rediscovery, and unconscious adoption of other geologists' concepts becomes vague after a time, and thus those named above have contributed, even though they may not agree with some of the concepts.

TERRANE AND ALLOCHTHON CONCEPTS

A major recent advance in understanding Alaska geology is the concept that Alaska is composed of many accreted blocks, or terranes. These blocks have been called microplates (Beck and others, 1980), suspect terranes (Coney and others, 1980), tectonostratigraphic terranes (Jones and others, 1981), and lilhotectonic terranes (Silberling and Jones, 1984; Jones and others, 1987). Defined as a fault-bounded geologic entity usually of regional extent, a tectonostratigraphic or lithotectonic terrane is characterized by a distinctive stratigraphic sequence or rock assemblage that differs markedly from those of partly or entirely coeval neighbors (Jones and others, 1981). Jones and his co-workers have suggested that many accreted terranes are exotic to North America and that large-scale, horizontal translations by conventional plate-tectonic processes resulted in collision with the North American plate, a process which formed Alaska and much of the west coast of North America. Although some geologists question the magnitude or style of some dislocations (for example, see Ernst, 1984), the terrane concept provides a useful way to view the geology of northern Alaska.

The Brooks Range and Arctic Slope are composed of two major terranes (fig. 26; sheet 1; Mull and others, 1987a): a) the Angayucham terrane of dominantly oceanic character on the south, and b) the Arctic Alaska terrane of dominantly continental character to the north. These two distinctly different terranes are in fault contact near the southern margin of the Brooks Range at the Kobuk suture zone (Mull, 1982); this boundary is described in detail by Dillon (chap. 10). The Dalton Highway crosses both the Angayucham and Arctic Alaska terranes.

The similarity of the stratigraphic sequences of the Arctic Alaska terrane to rocks of the northwestern Canada cordillera and to the Sverdrup basin in Arctic Canada--rocks that seem to be firmly tied to the North American craton--suggests that the Arctic Alaska terrane

[1]DGGS, 3700 Airport Way, Fairbanks, Alaska 99709.

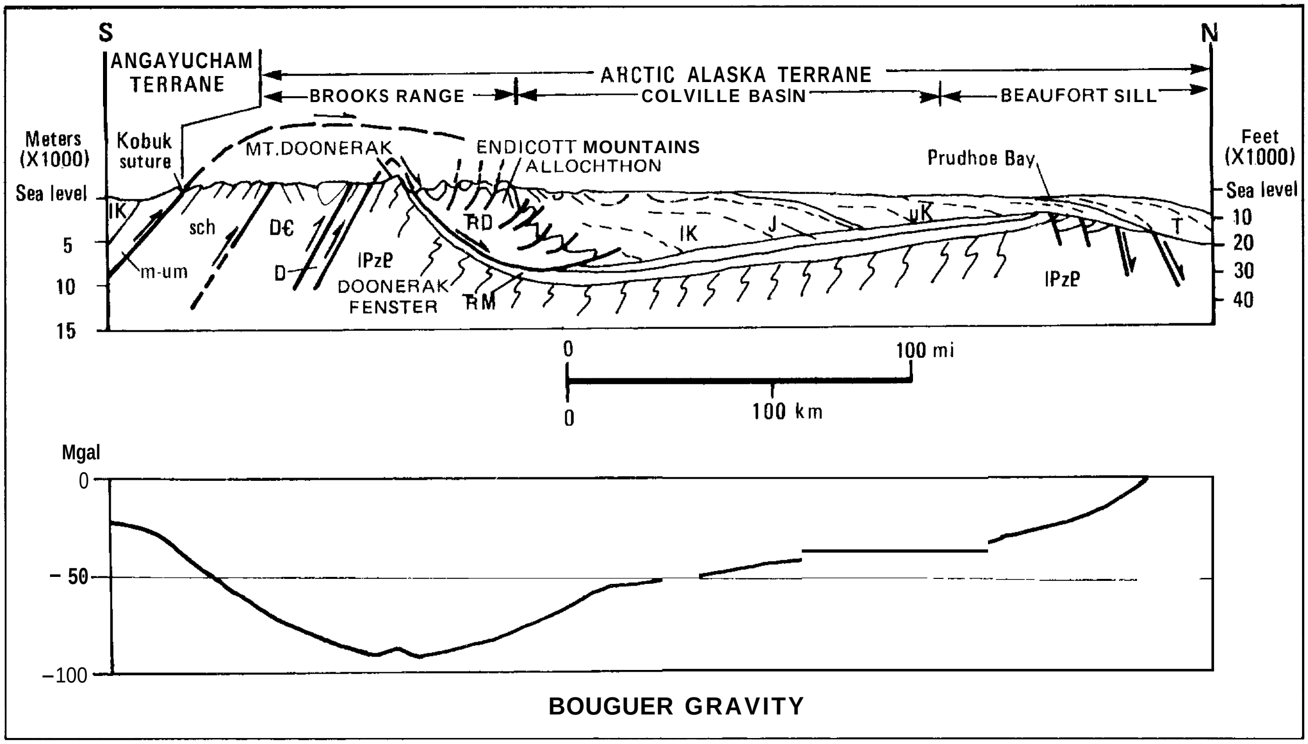


Figure 26. Diagrammatic north-south cross section of Brooks Range and Arctic Slope near Dalton Highway. Geologic units: sch, lower Paleozoic to Proterozoic rocks of schist belt; lPzP, lower Paleozoic to Proterozoic rocks; DЄ, Devonian to Cambrian metamorphic rocks; D, Devonian rocks; m-um, Jurassic to Mississippian mafic and ultramafic rocks; ŦD, Triassic to Devonian rocks; ŦM, Triassic to Mississippian rocks; J, Jurassic rocks; lK, Lower Crelaceous rocks; uK, Upper Cretaceous rocks; T, Tertiary rocks.

is not exotic to North America, as some other Alaskan terranes (including the Angayucham terrane) may be. However, close affinity of Mississippian floras (Spicer, 1985) and microfaunas (Armstrong and others, 1970) and Cambrian trilobites (Dutro and others, 1984b) to Siberian flora and fauna suggests a Paleozoic link to Siberian terranes.

Another aid in deciphering the geology of the Brooks Range is the differentiation and mapping of allochthons within terranes (Mull, 1982, 1985; Mayfield and others, 1983). Originally called thrust sequences (Tailleur and others, 1966; Martin, 1970; Mull, 1979), allochthons are discrete thrust-bounded stratigraphic sequences consisting of several rock units that have collectively been translated northward and juxtaposed with adjacent sequences by thrust faulting. In many cases, adjacent allochthons have similar stratigraphic sequences but exhibit distinctive differences in coeval formations. Although facies changes are recognized, the formations within an individual allochthon generally have a consistency that enables the allochthon to be recognized over a wide area, whereas formations and stratigraphic sequences in differing allochthons are distinct enough to characterize one allochthon from another. Within allochthons, numerous thrust faults are also common, but these intra-allochthon thrust faults juxtapose rocks that are generally similar lithologically and stratigraphically. The similarity in stratigraphic sequences on allochthons of the Arctic Alaska terrane suggests that they are fragments of an originally continuous depositional basin.

Recognition of allochthons has made it possible to distinguish regional structural patterns that are obscured by local structure. In the De Long Mountains of the western Brooks Range, seven allochthons are recognized by Mayfield and others (1983): five are allochthons of the Arctic Alaska terrane and composed largely of sedimentary rocks, and two are allochthons of the Angayucham terrane and largely mafic or ultramafic rock. In the Brooks Range, the vertical sequence of stacked allochthons is usually consistent; for example, allochthon 3 structurally overlies allochthon 2 or allochthon 1; a reversal of stacking order is rare. Palinspastic restoration of the allochthons to their prethrusted positions allows an approximate reconstruction of the depositional basins of the various formations. The minimum crustal shortening during deformation of the Brooks Range thrust belt can also be estimated.

In the northcentral and northwestern Brooks Range, the allochthons presently recognized (Mayfield and others, 1983; Mull, 1985) consist dominantly of unmetamorphosed rock. The northern Endicott Mountains are composed entirely of one allochthon, the Endicott Mountains allochthon (Mull, 1982); some of the higher allochthons have limited distribution in the disturbed belt north of the mountain front. Dillon (chap. 10) has

ARCTIC ALASKA TERRANE

The Arctic Alaska terrane comprises most of the Brooks Range and Arctic Slope; it extends northward to the Beaufort Sea continental margin and westward beneath the Chukchi Sea an unknown distance. The eastern limit of the Arctic Alaska plate is probably in northern Yukon Territory, Canada, near the Blow River, which separates the Barn Mountains and eastern Brooks Range from the northern Richardson Mountains.

The Brooks Range can be divitlecl into four major belts or provinces that are distinguished by their stratigraphy ancl general structural setting (fig. 26; sheet 1):

1. Southern flank of Baird, Schwatka, and Endicott Mountains--lower Paleozoic polymetamorphic schist and related rocks commonly called 'the schist belt,' which constitutes fault panel 9 of Dillon (chap. 10). Where this belt cropsout near the Dalton Highway, Silberling and Jones (1984) ancl Jones and others (1987) refer to it as the Coldfoot subterrane.
2. Core of Brooks Range in Baird, Schwatka, and southern Endicott Mountains--Middle Devonian and older metasedimentary and metavolcanic rocks and several small to medium granitic plutons. The province is here referred to as the internal metamorphic and plutonic belt and is characterized by generally ductile deformation. Dillon (chap. 10) has delineated seven fault panels within this belt. Silberling and Jones (1984) and Jones and others (1987) included most of these rocks in their Hammond subterrane; rocks in the Doonerak fenster are included in their North Slope subterrane.
3. Northern Brooks Range province, De Long and Endicott Mountains--a series of major allochthons of Middle, or Upper, Devonian through Lower Cretaceous sedimentary rocks. The allochthons are commonly characterized by abundant intra-allochthon thrusting and north-vergent folding. Brittle deformation predominates in this belt. Silberling and Jones (1984) and Jones and others (1987) include these rocks in their De Long and Endicott Mountains subterranes.
4. Northeastern Brooks Range province, Sadlerochit, Shublik, Romanzof, British, and northern Philip Smith Mountains--mostly autochthonous or parautochthonous upper Paleozoic and lower Mesozoic sedimentary rocks that unconformably overlie lower Paleozoic metamorphic rocks and three granitic plutons. Similar rocks are present in the subsurface of the Arctic Slope and are also exposed in the Doonerak fenster in the Endicott Mountains (fig. 27) and near the

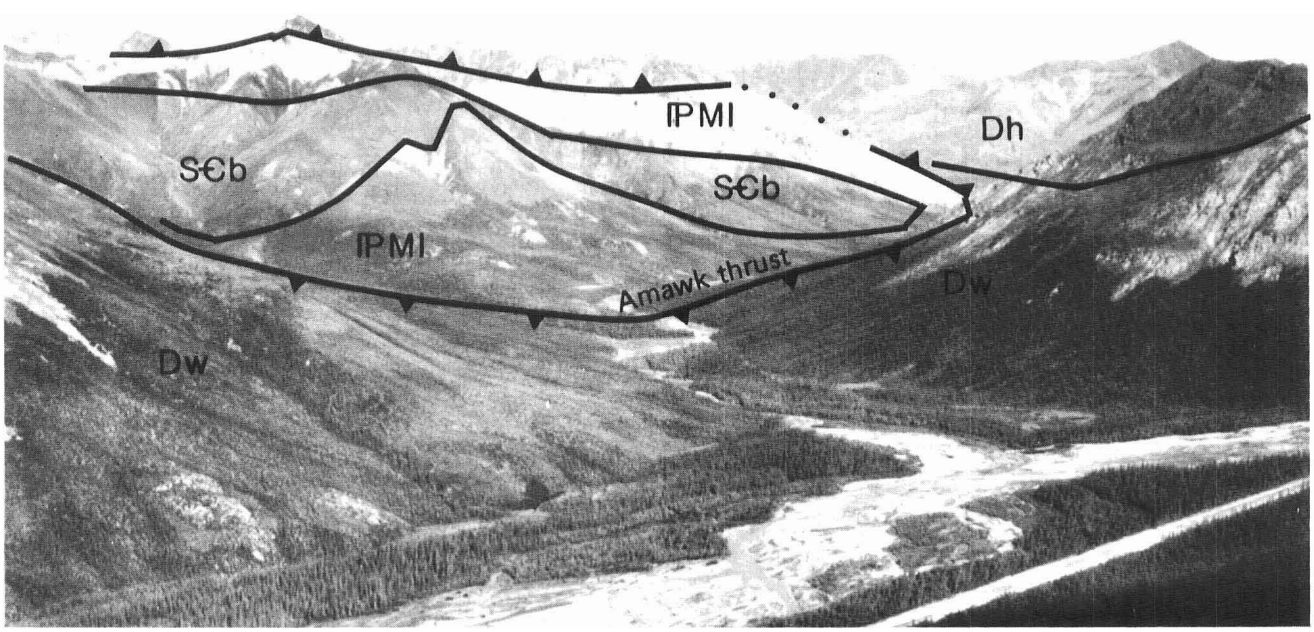


*Figure 27. View northwestward from near Mile **225** up Koyuktuvuk Creek to east end of Doonerak fenster. Dark lower Paleozoic rocks (SЄb) are stratigraphically overlain by light-colored Mississippian to Lower Pennsylvanian Lisburne Group limestone (lPMl). These units are structurally overlain by Devonian Whiteface Mountain oolcanic rocks (Dw) and Hunt Forh Shale (Dh) above Amawk thrust.*

delineated 13 major fault-bounded panels in the southern Brooks Range and northern flank of the Koyultuk basin that are probably similar to allochthons. However, in the interior of the range, metamorphic overprints and a scarcity of fossil control hinder the dating of stratigraphic units; therefore, further work is needed to delineate allochthons as precisely as they are elsewhere in the Brooks Range.

Silberling and Jones (1984) and Jones and others (1987) have divided the Arctic Alaska terrane into a number of subterranes that consist of several combinations of allochthons, fault panels, and autochthonous and parautochthonous rock. Because of the ambiguity in the definition of subterranes, many workers do not use the subterrane nomenclature.

ANGAYUCHAM TERRANE

The Angayucham terrane crops out discontinuously along a 300 mi (480 km) east-west-trending belt along the southern margin of the Brooks Range. The belt is crossed by the Dalton Highway from about Mile 165 to Mile 168 (fig. 62). The terrane also crops out in a series of isolated klippen in the De Long and western Endicott Mountains of the northwestern and central Brooks Range (sheet 1). In addition, a large klippe in the southeastern Brooks Range, the Christian complex, is considered here as part of the Angayucham terrane, although Silberling and Jones (1984) and Jones and others (1987) consider it part of a separate oceanic terrace, the Tozitna terrane. Although the Angayucham terrane constitutes only a small part of Arctic Alaska, an understanding of it and its relationship to the Arctic Alaska terrane is important in understanding the evolution of the Brooks Range orogenic belt.

Along the south flank of the range, the Angayucham terrane consists dominantly of mafic igneous rock, including pillow basalt, with subordinate chert and limestone. The mafic complex and associated sediments are unconformably overlain by Early and Late Cretaceous graywacke and igneous- and quartz-pebble conglomerate. A few small exposures of gabbro and serpentinite are also present along the south flank of the range.

In the De Long and western Endicott Mountains, the Angayucham terrane consists of klippen of pillow basalt and associated chert and limestone of the Copter Peak allochthon. Some basalt is structurally overlain by ultramafic to gabbroic rocks (Patton and others, 1977; Roeder and Mull, 1978; Zimmerman and Soustek, 1979; Nelson and Nelson, 1982) of the Misheguk Mountain allochthon (Mayfield and others, 1983). Together, the Copter Peak and Misheguk Mountain allochthons are the uppermost in the series of major allochthons that form the De Long and northern Endicott Mountains. Patton and Box (1989) have named the basalt and ultramafic to gabbroic sheets along the south side of the Brooks Range and in the Koyukuk basin the Narvak and Kanuti thrust panels, respectively.

The ultramafic, gabbroic, and fine-grained mafic rocks of the Angayucham terrane collectively can be considered part of a dismembered ophiolite, as defined by the 1972 Penrose Conference on ophiolites. The terrane has been interpreted as part of a volcanic-arc complex (Roeder and Mull, 1978; Box and others, 1985; Patton and Box, 1989) or oceanic plateau (Murchey and Harris, 1985; Pallister, 1985; Pallister and Budahn, 1989). Mapping by Dillon and others (1981a, 1986), Hitzman and others (1982), and Gottschalk (1987) shows that the Angayucham rocks, as well as the structurally underlying schist belt, dip regionally south along the south side of the Brooks Range (fig. 26; sheets 1 and 2).

In addition to the Narvak and Kanuti thrust panels, a third panel--the Slate Creek panel--which structurally underlies the Narvak panel, is also considered by some workers to be part of the Angayucham terrane (Dillon and others, 1986; Dillon, chap. 10; Patton and Box, 1989). This panel, which consists dominantly of phyllite and graywacke deposited as turbidites, is considered by other workers to be more closely associated with the Arctic Alaska terrane (Mull and others, 1987a; Moore and others, in press). Rocks of the Slate Creek panel are included by Silberling and Jones (1984) and Jones and others (1987) in the upper part of their Coldfoot subterrane. Limestone, mafic volcanic debris, and chert within the belt may represent tectonic slivers. On the basis of point count data, Murphy and Patton (1988) concluded that the provenance of the graywacke is continental and included granitic, quartzose metamorphic, sedimentary, and minor volcanic rocks. Hitzman and others (1982) inferred a depositional contact between the phyllite and graywacke of the Slate Creek panel and underlying rocks of the southern Brooks Range.

The Kobuk suture zone (fig. 26; sheet 1), the boundary between the Angayucham terrane and the Arctic Alaska terrane, consists of one or more thrust faults (Angayucham thrust system) along which the Angayucham terrane was obducted over the Arctic Alaska terrane. Albian conglomerate and graywacke unconformably overlie basalt of the Angayucham terrane, which suggests that the thrusting was pre-Albian in age. Dillon (chap. 10) mapped three strands of the Angayucham thrust system near the Dalton Highway (sheet 2). The southern strand of the system juxtaposes basalt of the Narvak panel over phyllite and graywacke of the Slate Creek panel. To the north, the middle strand of the Angayucham fault system is mapped within the Slate Creek panel. The northern strand of the system juxtaposes monometamorphic rocks of the Slate Creek panel against polymetamorphic rocks of the Brooks Range schist belt. Miller (1987) argued that a regional zone of down-to-the-south normal faults cuts and offsets the Angayucham thrust system. Gottschalk (1987) and Oldow and others (1987a,b) suggested that the faults of the Angayucham thrust system are late-stage, south-dipping normal faults that modify the earlier system of thrust faults.

Shishakshinovik pluton in the Schwatka Mountains of the westcentral Brooks Range. These rocks constitute the North Slope subterrane of Silberling and Jones (1984) and Jones and others (1987).

The Dalton Highway crosses the schist belt between Mile 172 and Mile 187 and the internal metamorphic and plutonic belt from Mile 187 to about Mile 233. In some areas, no definite boundary can be drawn between the metamorphic and plutonic belt and greenschist facies rocks of the allochthon belt to the north. However, northwest of the highway near Mile 226, the boundary between the metamorphic and plutonic belt and the Endicott Mountains allochthon is well exposed on the north flank and around the east plunge of the Doonerak fenster (figs. 26 and 27; sheet 1)--a significant area for understanding the structure and tectonic history of the central Brooks Range (see Mull and others, chap. 14). The Endicott Mountains allochthon, which forms the entire northern Endicott Mountains, is crossed by the Dalton Highway from Mile 233 to Mile 271. Autochthonous or parautochthonous rocks of the northwestern Brooks Range are not crossed by the highway but are visible to the east from about Mile 285 to Mile 310.

North of the central and western Brooks Range mountain front, the Arctic Alaska terrane is composed of the southern and northern foothills provinces and the Arctic Coastal Plain. The southern foothills (Mile 271 to Mile 300) include the disturbed belt, a zone of slivers from several allochthons; the northern foothills (Mile 300 to Mile 358) are underlain by a belt of detachment structures developed in Cretaceous rocks of the Colville basin, an asymmetrical basin that began to form in the Early Cretaceous (fig. 28). North of the foothills, the Arctic Coastal Plain (Mile 358 to Prudhoe Bay) is underlain by gently folded to nearly flat-lying Cretaceous rocks and gently south-dipping Mississippian to Jurassic rocks (figs. 26 and 28; sheet 1). To the east, the foothills and Arctic Coastal Plain north of the northeastern Brooks Range are underlain by Tertiary and older rocks.

Near the northern front of the Brooks Range, pre-Cretaceous rocks are probably present at depths near 30,000 ft (10 km), but they rise gradually northward to depths of 3,000 to 9,000 ft (1 to 3 km) near the Beaufort Sea (fig. 28; sheet 1). Beneath the Beaufort Sea and the northern Arctic Slope a shallow, stable platform separates the Colville basin on the south from the Canada basin of the Beaufort Sea on the north. This platform has been called the Barrow arch (Brosgé and Tailleur, 1969; Morgridge and Smith, 1972; Detterman, 1973), the Arctic platform (Payne, 1955; Brosgé and Tailleur, 1970), and the Beaufort sill (Mull, 1985). The Prudhoe Bay and Kuparuk oil fields and other subsidiary petroleum accumulations lie on or near the crest of this sill, and much of the major exploratory activity for hydrocarbons in northern Alaska has been conducted near this feature.

The northern flank of the Beaufort sill is characterized by extensional faulting of basement and overlying Paleozoic and Mesozoic sedimentary rocks. Seismic data indicate that pre-Cretaceous strata north of the coastline are broken by a series of normal faults which produce grabens and half grabens regionally downdropped to the north. This zone of normal faults marks the northern edge of the Arctic Alaska plate and appears to be an Atlantic-style extensional plate boundary; it has been mapped and discussed by Grantz and May (1983), illustrated by Mull and others (1987a), and is shown on sheet 1. The fault blocks along the rifted continental margin are truncated by a Lower Cretaceous unconformity and are unconformably overlain by sediments, derived from the Brooks Range, that prograde over the Beaufort sill and into the Canada basin.

GENERALIZED STRATIGRAPHY

Rocks of the Brooks Range and Arctic Slope are divided into three unconformity-bounded sequences: the

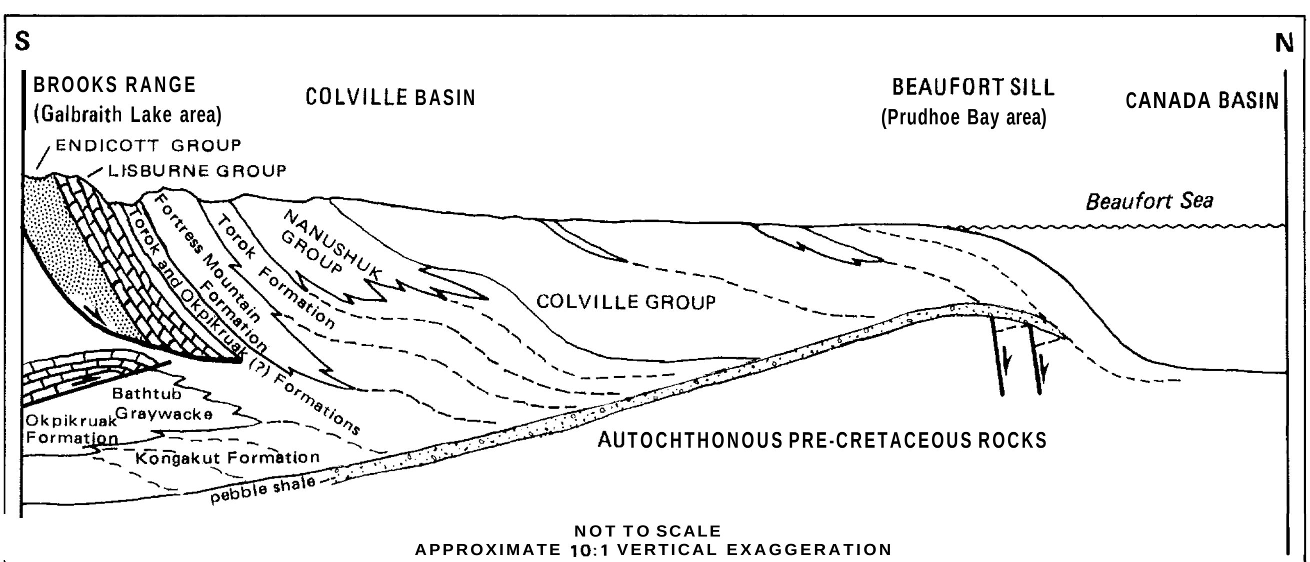


Figure 28. Diagrammatic north-south cross section of eastern Colville basin at end of Cretaceous time.

Franklinian, Ellesmerian, and Brookian sequences (figs. 29, 30, 31, and 32). This usage follows that of Lerand (1973), who applied the terms to similar rock sequences in the Canadian Arctic. Hubbard and others (1987) have suggested a fourth sequence, the Beaufortian, which is thought to be related to Jurassic and Early Cretaceous rifting of the Arctic margin near the Arctic coast. Dillon (chap. 10), Moore and others (chap. 15), Armstrong and Mamet (chap. 16), Adams and Siok (chap. 17), Bodnar (chap. 18), Siok (chap. 19), Crowder (chap. 20), and Huffman (chap. 21) discuss general aspects of the stratigraphy of many of the rock units in these sequences in volume 2.

FRANKLINIAN SEQUENCE

In Arctic Alaska, the lowest sequence, the Franklinian sequence, consists dominantly of Proterozoic to Middle Devonian rocks that are unconformably overlain by the Mississippian and younger Ellesmerian sequence. In the subsurface of the Arctic Slope, the Franklinian sequence is dominantly argillite (fig. 29); in the northeastern Brooks Range, several contrasting packages of argillite, limestone, dolomite, volcanic rock, phyllite, chert, and graywacke are also abundant and have been lumped together under the name Neruokpuk Formation (Brosgé and others, 1962). Some of the Franklinian sequence in these areas have been interpreted as volcanic-arc deposits that are associated with a variety of eugeoclinal sediments.

In the northeastern Brooks Range, mapping by Reiser and others (1980) shows that most of the Franklinian rocks dip southward beneath a pre-Mississippian angular unconformity; similar rocks are present beneath the pre-Mississippian unconformity in the Doonerak fenster. Most workers have assumed that the pre-Mississippian deformation was caused by a north-vergent compressional orogenic event--called the Innuitian or Ellesmerian orogeny in northern Canada--that telescoped the diverse rock units and generated several plutons of Devonian age. Alternatively, Oldow and others (1987c) have proposed a south-vergent event on the basis of detailed structural studies in the Franklin Mountains of the northeastern Brooks Range.

In the Baird, Schwatka, and Philip Smith Mountains, lower Paleozoic and Proterozoic rocks have not previously been referred to the Franklinian sequence, although they bear many similarities to the Franklinian sequence to the north. In the southern Endicott Mountains, Dillon recognized Franklinian rocks on the thrust panel that forms the schist belt and on six thrust panels in the internal metamorphic and plutonic belt (see chap. 10 for discussion of fault panels in the southern Brooks Range). In the schist belt, the Franklinian sequence consists dominantly of rocks of upper greenschist to amphibolite facies, including banded, graphitic schist and gneiss; calc-schist; marble; and felsic intrusive rocks. These are thrust northward over Franklinian rocks of the internal metamorphic and plutonic belt, which include ductilely deformed black argillite; purple and green phyllite; chloritic sandstone, siltstone, and conglomerate; gray to black limestone and marble; and a massive, white, cliff-forming marble unit known as the Skajit Limestone (figs. 69 and 73). The Skajit is thought to grade laterally and upward into the Whiteface Mountain and Ambler volcanics and the Beaucoup Formation, which grades upward into an Upper Devonian clastic wedge at the base of the Ellesmerian sequence. Metamorphic grade of the Franklinian rocks in the internal metamorphic and plutonic belt ranges from that of low greenschist facies to blueschist facies and, in general, increases to the south. A number of small- to medium-sized plutons intrude the Franklinian sequence in the southern Brooks Range, providing a link to the Franklinian sequence in the northeastern Brooks Range. Late Proterozoic dates have also been obtained from a few of the plutons.

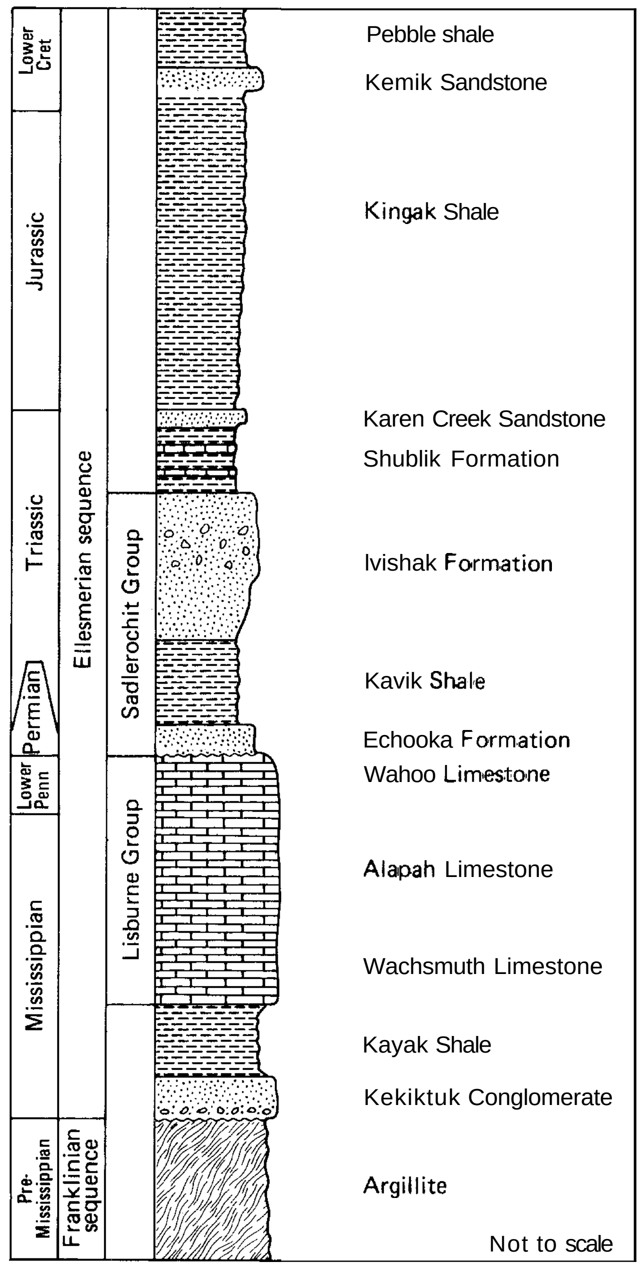


Figure 29. Generalized columnar section of autochthonous and parautochthonous Ellesmerian sequence of northeaslern Brooks Range and Arctic Slope.

ELLESMERIAN SEQUENCE

The Franklinian sequence in northern Alaska is overlain by the Ellesmerian sequence, which is present in three separate tectonic settings: 1) an autochthonous complex in the subsurface of the Arctic Slope; 2) an autochthonous or parautochthonous sequence in the northeastern Brooks Range (fig. 29), in which the rocks have been deformed by detachment folding (fig. 30) and moderate thrust faulting; and 3) an allochthonous complex in the western and central Brooks Range (fig. 31), characterized by thrust faulting with many tens of miles of displacement. Parautochthonous Ellesmerian rocks are also exposed in two significant areas near the core of the range: the Doonerak fenster in the Endicott Mountains (fig. 27) and near Shishakshinovik Pass in the Schwatka Mountains. Rocks of the Ellesmerian sequence were derived dominantly from northern sources and were deposited on a stable platform during two regional transgressive intervals punctuated by a regressive cycle.

AUTOCHTHONOUS AND PARAUTOCHTHONOUS ROCKS OF THE ELLESMERIAN SEQUENCE

In the northeastern Brooks Range and the subsurface of the Arctic Slope, the autochthonous and parautochthonous Ellesmerian sequence is composed of a dominantly sedimentary section of Mississippian to Lower Cretaceous rocks that overlies lower Paleozoic rocks at a regional angular unconformity. A similar section of Mississippian to Triassic rocks overlies the unconformity in the Doonerak fenster in the central Brooks Range (fig. 27; Mull and others, chap. 14). In the subsurface, the Ellesmerian sequence has an average thickness of 3,000 to 6,000 ft (925 to 1,850 m), except in local basins, where it may be over 12,000 ft (3,700 m) thick. In outcrop, the top of the sequence has been removed by Holocene erosion, and the sequence is thinner, except where imbricated by thrusting. Stratigraphic units assigned to the sequence include the Mississippian Kekiktuk Conglomerate and Kayak Shale, the Mississippian to Lower Pennsylvanian Wachsmuth, Alapah, and Wahoo Limestones of the Lisburne Group, the Permian to Triassic Echooka Formation, Kavik Shale, and Ivishak Formation of the Sadlerochit Group, the Triassic Shuhlik Formation and Karen Creek Sandstone, the Jurassic to Lower Cretaceous Kingak Shale, and the Lower Cretaceous Kemik Sandstone and pebble shale.

The Kekiktuk Conglomerate is the base of the lowest Ellesmerian transgressive interval. In most places, the Kekiktuk is a relatively thin (<300 ft; 100 m), northward transgressive, quartzitic sandstone that contains a basal chert- and quartz-pebble conglomerate; it is absent on local topographic highs, such as in the

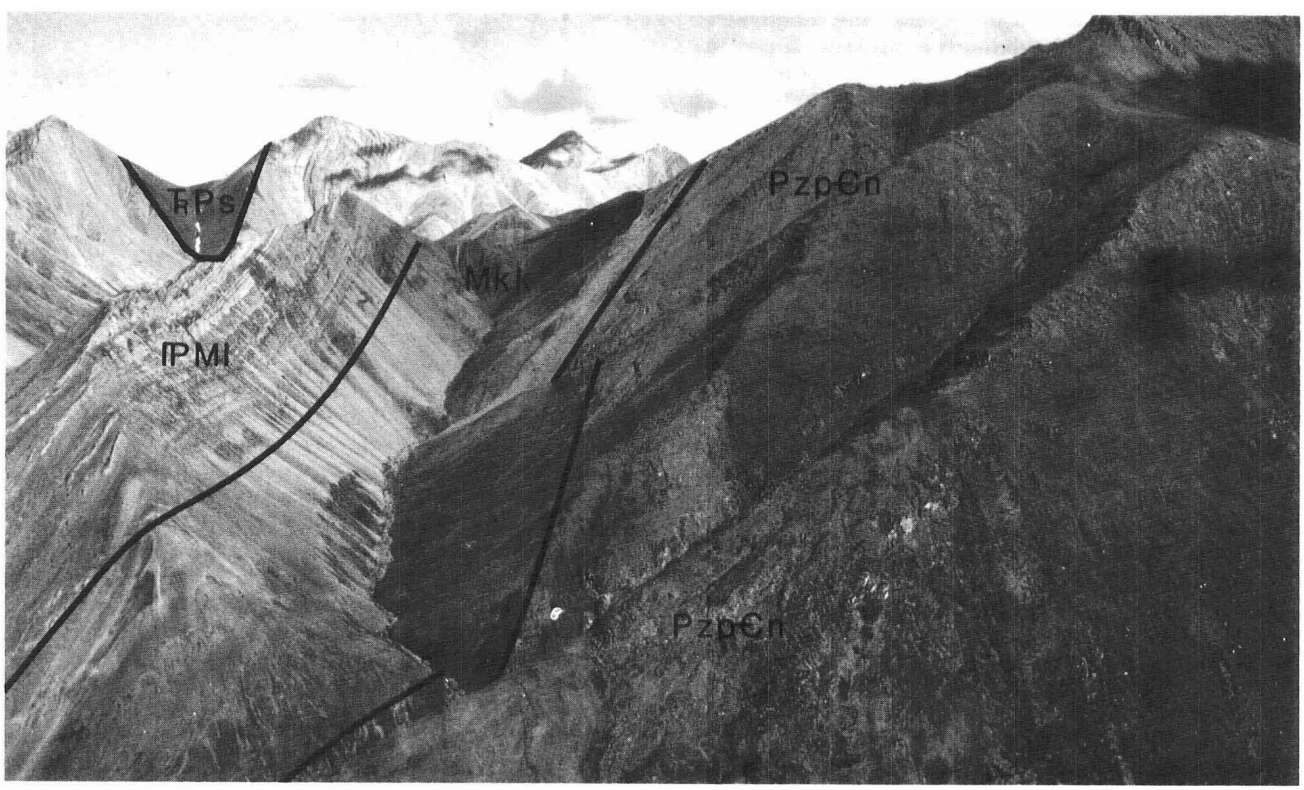


Figure 30. Sadlerochit Group (TRPs), Lisburne Group (IPMl), and Kayak Shale and Kekiktuk Conglomerate (Mkk) of Ellesmerian sequence unconformably overlie lower Paleozoic rocks of Franklinian sequence (PzpЄn) in Franklin Mountains, northeastern Brooks Range. Tight folds in Sadlerochit and Lisburne, in contrast to broad folds in pre-Mississippian rocks, suggest detachment in Kayak Shale.

Sadlerochit Mountains. In a few subsurface areas, however, the Kekiktuk is over 1,000 ft (300 m) thick and may represent deposition in local intermontane basins that were developed during a pre-Mississippian orogenic event. The Kekiktuk is succeeded upward by the Kayak Shale and the Lisburne Group. The Kayak Shale is dominantly black marine shale with abundant ironstone concretions; it is up to 900 ft (275 m) thick and commonly gradational with both the Kekiktuk and the overlying Lisburne, but in some areas the contacts are relatively abrupt. The Kayak is a major detachment horizon, above which the Lisburne Group is folded independently of the underlying beds or detached by thrusting.

The Wachsmuth, Alapah, and Wahoo Limestones of the Lisburnc Group consist of platform carbonates, dominantly massive bioclastic limestone and dolomite with variable amounts of nodular chert and interbedded shale, that average 1,500 to 2,000 ft (450 to 600 m) thick but are greater than 3,000 ft (925 m) thick in some places. The Lisburne represents dominantly northward transgressive deposition on a shallow platform several hundred miles wide. Near the northern limit of the Lisburne and on local topographic highs, red shale, sandstone, and limestone of the Itkilyariak Formation are present in the lower part of the Lisburne Group and, in places, occupy the entire stratigraphic position of the Lisburne. The top of the Lisburne is truncated by a regional unconformity that probably marks a major eustatic sea level drop.

A transgressive-regressive cycle, the Sadlerochit Group, unconformably overlies the Lisburne. It consists of a basal transgressive unit--the Echooka Formation, and a regressive wedge--the Kavik Shale and Ivishak Formation. The Permian Echooka Formation consists of up to 600 ft (185 m) of calcareous sandstone and siltstone that is locally conglomeratic. The overlying Kavik Shale is up to 600 ft (185 m) thick and represents prodelta shale deposited in advance of the marine-to-fluvial deltaic wedge of the Lower Triassic Ivishak Formation, the main reservoir in the Prudhoe Bay oil field. Toward its northern limit, the Ivishak consists of coarse conglomerate and sandstone deposited in braided- and meandering-stream environments and is up to 700 ft (215 m) thick. Southward, it becomes finer grained and predominantly marine. The top of the Ivishak represents the beginning of the overlying Middle Triassic to Lower Cretaceous transgressive interval.

The Middle and Upper Triassic Shublik Formation is composed of thinly interbedded, organic-rich black shale and limestone characterized by phosphate nodules and abundant pelecypods *Halobia* sp. and *Monotis* sp. Average thickness of the formation is 300 ft (90 m). Generally, the Shublik unconformably overlies the Sadlerochit Group, but in northern Yukon Territory and near Point Barrow, it oversteps the northern limit of the Sadlerochit Group, Lisburne Group, and Kayak-Kekiktuk units and onlaps the Franklinian sequence.

The Shublik Formation is conformably overlain in the subsurface by the Sag River Sandstone, or its surface equivalent, the Karen Creek Sandstone. These units are composed dominantly of very fine grained glauconitic and intensely bioturbated shallow-marine sandstone. In outcrop, the Karen Creek is up to 100 ft (30 m) thick; it thins rapidly to the south but is present as a 5-ft-thick

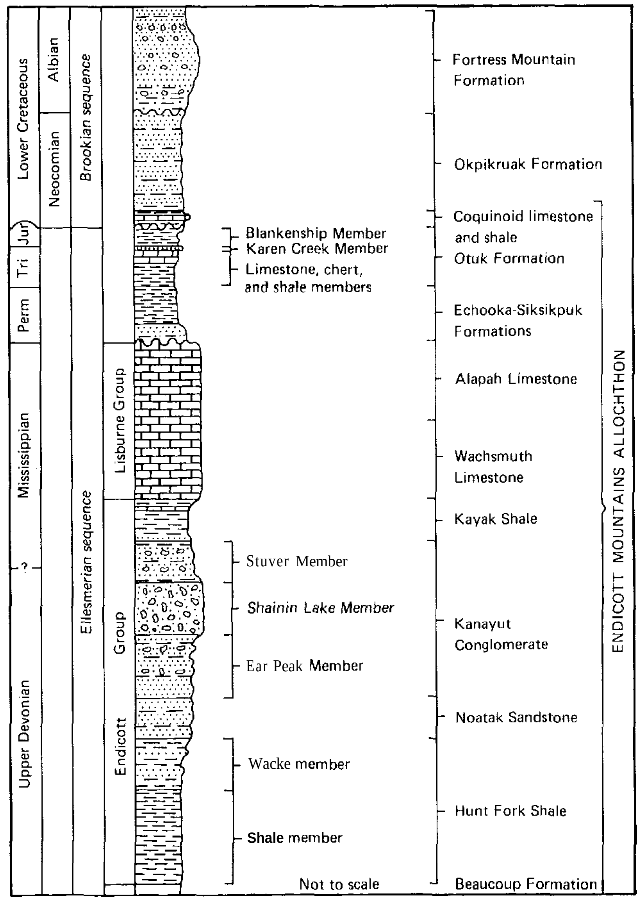


Figure 31. Generalized columnar section of rock units on Endicott Mountains allochthon in northern Endicott Mountains.

(1.5 m) bed in the Doonerak fenster, where it is the top of the Ellesmerian sequence.

The upper part of the autochthonous and parautochthonous Ellesmerian sequence consists of Jurassic and Lower Cretaceous (Neocomian) rocks that are present only in the subsurface and along the mountain front of northeastern Brooks Range. Hubbard and others (1987) have proposed the name Beaufortian sequence for this part of the Ellesmerian sequence, which represents deposition associated with the initiation of rifting of the Arctic Alaska plate.

The upper Ellesmerian (Beaufortian) sequence consists of the Jurassic to Lower Cretaceous (lower Neocomian) Kingak Shale, several relatively thin Lower Cretaceous (upper Neocomian) sandstone intervals, and the Lower Cretaceous (upper Neocomian) pebble shale. The Kingak Shale is characterized by gray to black clay shale and reaches a thickness of more than 3,000 ft (925 m) in some areas. Throughout most of the area, it conformably overlies the Triassic Karen Creek Sandstone or Shublik Formation, but in the northern Yukon Territory and in the subsurface at Barrow, it oversteps the Triassic and rests unconformably on the pre-Mississippian Franklinian sequence.

In the subsurface of the northern Arctic Slope and in the Sadlerochit Mountains area of the northeastern

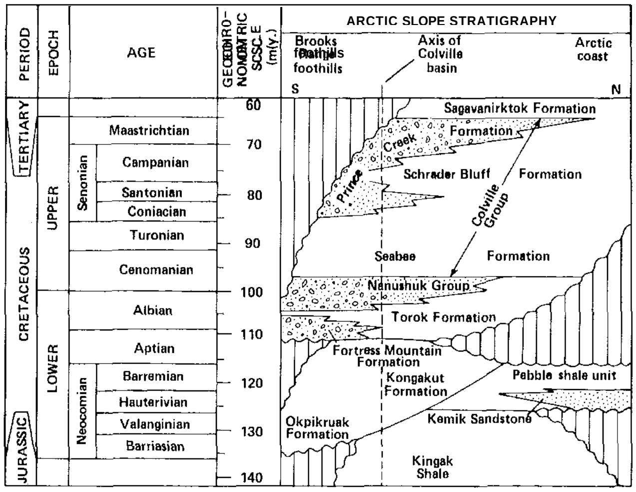


Figure 32. Generalized stratigraphic relationships of Brookian sequence in Colville basin. (Kingak Shale, Kemik Sandstone, and pebble shale unit are part of Ellesmerian sequence.)

Brooks Range, the Kuparuk River Formation, the Kemik Sandstone, and related discontinuous sandstone bodies are the last coarse-grained clastic horizons in the upper Ellesmerian (Beaufortian) sequence derived from northern sources. These units consist of up to 350 ft (110 m) of fine-grained glauconitic and conglomeratic sandstone. The upper Neocomian (Hauterivian) Kemik, upper Kuparuk River, and other sandstone bodies all occupy a stratigraphic position above a regional Neocomian unconformity, which, in the subsurface, truncates the pre-Hauterivian Ellesmerian sequence.

Where the Kemik and related sandstone bodies are not present, the Neocomian unconformity is overlain by a regionally extensive organic-rich, laminated shale that contains abundant matrix-supported sand grains and pebbles. This interval, known informally as the pebble shale unit, is up to about 300 ft (90 m) thick and is present along the Barrow arch (Beaufort sill) (fig. 28) in most of the Arctic Slope subsurface, where it represents the top of the Ellesmerian sequence. The shale is overlain by distal deposits of the Brookian sequence, which are derived from the Brooks Range orogenic belt to the south. Southward into the Colville basin, the Neocomian unconformity dies out and the pebble shale appears to be continuous with the Kingak Shale.

Rocks of the parautochthonous Ellesmerian sequence--Kayak Shale and Lisburne Group limestone--can be seen from the Dalton Highway near Mile 226 at the eastern end of the Doonerak fenster. To the west, near Mount Doonerak, the Sadlerochit Group, the Shublik Formation, and the Karen Creek Sandstone are preserved beneath the basal thrust fault of the Endicott Mountains allochthon.

ALLOCHTHONOUS ROCKS OF THE ELLESMERIAN SEQUENCE

In the northern Brooks Range province, the allochthonous Ellesmerian sequence (fig. 31) consists of the distal equivalents of the autochthonous and parautochthonous Ellesmerian sequence (fig. 29) of the Arctic Slope and northeastern Brooks Range. In addition to the distal sediments, a thick, Upper Devonian to Lower Mississippian clastic wedge conformably underlies the Lisburne Group and Kayak Shale on the lowest allochthon in the province, the Endicott Mountains allochthon. This wedge is absent on the structurally higher allochthons that form the western Endicott and De Long Mountains.

The Upper Devonian to Lower Mississippian clastic wedge is composed of a regressive deltaic sequence as thick as 12,000 ft (3,700 m), derived from the north and northeast, and has been studied in detail by Nilsen (1981), Nilsen and Moore (1984a), and Moore and others (chap. 15). The wedge consists of relatively competent conglomerate and sandstone of the fluvial-deltaic Kanayut Conglomerate and marine Noatak Sandstone; the relatively incompetent prodelta Hunt Fork Shale; and the Beaucoup Formation, which is transitional between the Middle Devonian and older carbonate units and the Upper Devonian deltaic complex. These rocks form the main spine of the Brooks Range and are visible adjacent to the Dalton Highway for over 30 mi (50 km) from about Mile 237 to Mile 268 (figs. 83, 86, and 88). Throughout the area, the relatively incompetent Hunt Fork Shale and Beaucoup Formation have acted as major detachment horizons and commonly contain isoclinal folds and complex internal deformation; in some areas, rocks mapped as Beaucoup may be a tectonic assemblage.

Some of the most complete sections of the Kanayut in the entire Brooks Range are present in the Atigun River area near the Dalton Highway; these are discussed in detail by Moore and others (chap. 15), who have recognized two facies belts of the Kanayut separated by a regional thrust fault, the Toyuk thrust. The Kanayut in the southern belt forms the Continental Divide at Atigun Pass (figs. 85 and 88) and is a thinner and finer grained equivalent of the Kanayut section to the north. In the northern belt, three members of the Kanayut are recognized: two meandering-stream complexes separated by a braided-stream complex (fig. 92). Pebble- to cobble-conglomerate beds are abundant within the Kanayut and are particularly thick and coarse within the braided-stream complex.

The Kanayut Conglomerate is conformably overlain by nearly 900 ft (275 m) of transgressive marine black clay shale of the Mississippian Kayak Shale and the Mississippian to Lower Pennsylvanian Lisburne Group (fig. 91). The Lisburne, composed mostly of platform carbonate rocks, is up to 3,400 ft (1,050 m) thick (Armstrong and Mamet, chap. 16) and consists dominantly of massive bioclastic limestone and dolomite with variable amounts of chert replacement nodules and disseminated masses. Although not readily distinguishable by lithologic criteria on a regional basis, two formations have been delineated within the Lisburne in the eastern Endicott Mountains: 1) Lower and Upper Mississippian Wachsmuth Limestone, and 2) Upper Mississippian Alapah Limestone (Bowsher and Dutro, 1957; Brosgé and others, 1962). The limestones and dolomites of the Lisburne Group form massive light-gray cliffs that dominate most of the central and northeastern Brooks Range mountain front and are visible from the Dalton Highway between Mile 268 and Mile 271 (figs. 33 and 100); the Lisburne is also present in regional synclines south of the mountain front (figs. 41, 43, 91, and 93). The Lisburne in the central and eastern Brooks Range has been studied and described in detail by Armstrong (1970a, 1976), Armstrong and others (1970, 1976) and Armstrong and Mamet (1974, 1975, 1978, chap. 16). Regional correlations of the Lisburne are based largely on formaminifera zonation and conodont studies.

In the northern Endicott Mountains near the Dalton Highway, the Lisburne Group is disconformably overlain by a sequence that consists of the Permian Echooka Formation, laterally transitional with the Siksikpuk Formation (Adams and Siok, chap. 17), and the Triassic to Middle Jurassic Otuk Formation (Bodnar, chap. 18). The Echooka Formation, about 300 ft (90 m) thick, consists of a distinctive yellow-brown-weathering calcareous siltstone and overlying black phyllitic shale; the Otuk Formation, also about 300 ft (90 m) thick, consists of black shale and thinly interbedded black, organic limestone that contains an abundant megafauna of the pelecypods *Halobia* and Monotis. The Echooka Formation is visible at the mountain front, where an overturned section is exposed beneath an overturned Lisburne section east of the Dalton Highway at Mile 271 (fig. 33). Although not visible from the highway, the Otuk Formation is well exposed in Atigun Gorge about 2.5 mi (4 km) downstream (east) from the Atigun River bridge at Mile 271 (fig. 34).

The top of the Ellesmerian sequence on the Endicott Mountains allochthon consists of a thin (<150 ft; 50 m) section of unnamed black clay shale, and a distinctive 3- to 6-ft-thick (1 to 2 m) horizon of red-brown-weathering coquinoid limestone (fig. 31) that consists entirely of the pelecypod *Buchia sublaevis* of early Neocomian (Valanginian) age (Jones and Grantz, 1964). Although very thin, this conspicuous limestone interval is present at a number of localities along the north front of the Brooks Range. In Atigun Gorge, tectonically disrupted beds of the coquinoid limestone closely associated with the top of the Otuk Formation (fig. 34) are present at several localities (Bodnar, chap. 18). The coquinoid limestone seems to be a marker horizon for the Endicott Mountains allochthon; it has not been observed on any of the higher allochthons in the Brooks Range.

In the De Long Mountains, the coquinoid limestone overlies Jurassic black shale and forms the top of the Jurassic to Lower Cretaceous Ipewik Formation (Mayfield and others, 1983). However, along the Endicott Mountains front, the coquinoid limestone unconformably overlies about 20 ft (6 m) of lower Middle Jurassic beds at the top of the Otuk Formation (Mull and others, 1982). The unconformity at the base of the coquinoid limestone seems to be of regional tectonic significance, because the top of the autochthonous Ellesmerian sequence in the Colville basin consists of more than 3,000 ft (90 m) of Jurassic black shale that is not present on the Endicott Mountains allochthon.

BROOKIAN SEQUENCE

Rocks of the Brookian sequence in the northern Brooks Range and Arctic Slope were derived from a source in the Brooks Range orogenic belt and indicate an abrupt reversal in the direction of sediment derivation from that of the underlying sedimentary sequences. Brookian sediments occur in two separate settings: 1) a relatively thin section of allochthonous rocks that overlie the Ellesmerian rocks on the allochthons of the northern thrust belt; and 2) a very thick section of dominantly autochthonous rocks that fill the Colville basin north of the Brooks Range.

ALLOCHTHONOUS ROCKS OF THE BROOKIAN SEQUENCE

The allochthonous Ellesmerian sequence in the central Brooks Range is overlain by the Lower Cretaceous (Neocomian) Okpikruak Formation (Brosgé and others, 1979a), which records the onset of Brooks Range orogeny. At some localities, Okpikruak of Valanginian age appears to conformably overlie the coquinoid limestone at the top of the Ellesmerian sequence (Mull, 1985; Mull and others, 1989); but at other localities, Okpikruak of Berriasian age is in thrust contact with the underlying Valanginian coquinoid limestone (Jones and Grantz, 1964). On the structurally higher allochthons in the western Endicott and De Long Mountains, Upper Jurassic fossils are reported from the Okpikruak (Mayfield and others, 1983). This progression from older orogenic sediments on the higher allochthons to younger orogenic sediments on the lower allochthons apparently records northward migration of the orogenic front as it involved progressively younger Cretaceous rocks in the more northerly portions of the proto-Colville basin (Snelson and Tailleur, 1968).

Regionally, the Okpikruak is composed mainly of rhythmic sandstone-shale turbidites probably deposited in a middle to outer submarine-fan setting (Siok, chap. 19). Olistostrome deposits are locally abundant in some parts of the Okpikruak in the western and west-central Brooks Range. Modal analyses of the Okpikruak near the Dalton Highway by Siok (chap. 19) suggest a mixed provenance for the Okpikruak; the data are clustered between the undissected magmatic arc and recycled orogen provenance fields of Dickinson and Suczek (1979).

Structurally disrupted beds of Okpikruak overlying coquinoid limestone are present in Atigun Gorge (fig. 34) downstream from the Atigun River bridge at Mile 270.7. However, a thick section of rhythmic siltstone and shale in Atigun Gorge mapped by Brosgé and others (1979a) as Okpikruak is here thought to be part of the Albian Torok or Fortress Mountain Formation.

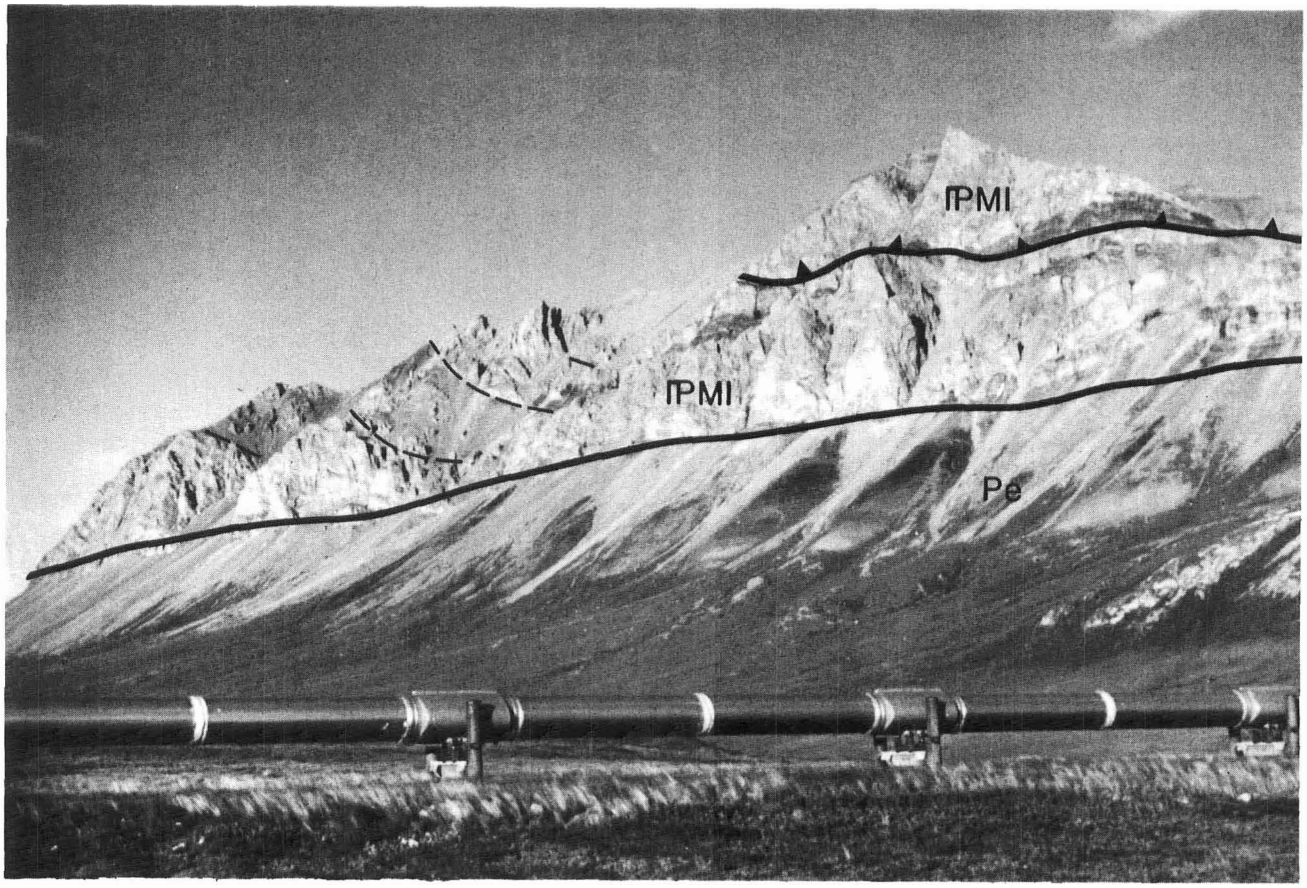


Figure 33. View southeastward near Mile 270 toward Endicott Mountains front on south side of Atigun Gorge. Stratigraphically continuous section of inverted Lisburne Group *(IPMl)* and Echooka Formation (Pe) of Sadlerochit Group forms lower cliffs and underlying dark shaly slopes and is overlain by thrust plate of overturned Lisburne that forms high peak.

AUTOCHTHONOUS ROCKS OF THE BROOKIAN SEQUENCE

On the Arctic Slope, the autochthonous Brookian sequence unconformably overlies the autochthonous Ellesmerian sequence; it fills the asymmetrical Colville basin north of the Brooks Range and progrades onto the gently dipping south flank of the Beaufort sill (fig. 28; sheet 1). The sequence is composed of Cretaceous and Tertiary clastic rocks derived from erosion of the Brooks Range to the south and west. Albian and younger strata are confined to the area north of the mountains, but Neocomian and older strata apparently continue to depths greater than 30,000 ft (10 km) beneath the thrust-faulted mountain front. Near the northern flank of the Brooks Range, the rocks are complexly deformed but do not appear to have undergone major thrusting. The generalized stratigraphic nomenclature and structural framework of the Brookian sequence in the eastern Colville basin is illustrated in figures 28 and 32.

In the northeastern Brooks Range, the base of the Brookian sequence, the Kongakut Formation (Detterman and others, 1975), is a distal equivalent of the Okpikruak Formation present on the allochthons to the south. The upper part of the Kongakut, the siltstone member, is primarily a rhythmic shale-siltstone graywacke section that contains abundant features typical of turbidite deposits, such as tool marks and flute and load casts. Manganese nodules are present in some places. The lower part of the formation, as defined by Detterman and others (1975), consists of a laminated, organic-rich pebble-shale horizon; a quartzose sandstone--the Kemik Sandstone Member; and a basal clay-shale horizon. Detailed studies in the Sadlerochit Mountains of the northeastern Brooks Range (Molenaar and others, 1987; Mull, 1987) indicate that the Kemik was deposited in a shoreface environment with a sediment source from the north. This contrasts with the upper part of the Kongakut Formation, where the sediments were deposited as submarine fans with a source from the south. Because of the contrasting lithology and sediment provenance of the Kemik and upper Kongakut, the Kemik has been elevated to formation status (Molenaar and others, 1987; Mull, 1987). Turbidite deposits of the Kongakut Formation are mapped south of the Dalton Highway between Mile 285 and Mile 300 (Brosgé and others, 1979a), but the shallow-marine deposits of the Kemik Sandstone and associated pebble-shale horizons are not present near the highway.

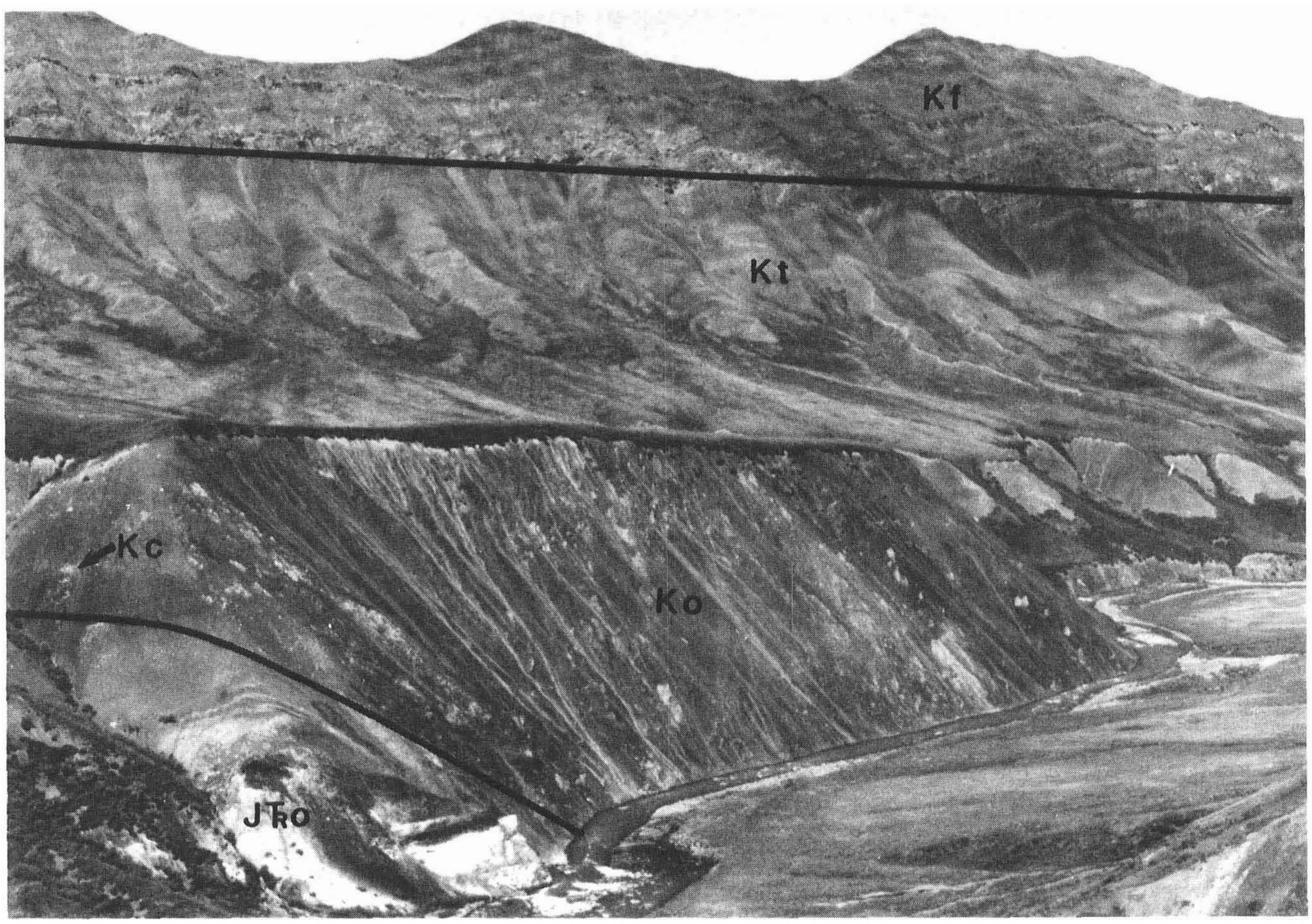


Figure 34. View northward across Atigun River toward south flank of Atigun syncline. Sandstone and conglomerate of Fortress Mountain Formation (Kf) form cliffs below crest of ridge; lower slopes are underlain by probable Torok Formation (Kt). High bluff at river is intensely sheared Okpikruak Formation (Ko); steeply dipping boundary between Otuk Formation (JTRo) and Okpikruah contains exotic chert masses along strike and may be a folded thrust fault. Isolated beds of coquinoid limestone (Kc) overlie Otuk Formation at arrow.

In the deeper part of the Colville basin, deposition was probably continuous from Neocomian into Albian time, but on the flanks of the basin unconformities are present. The Kongakut and Torok section records progressive filling of the Colville basin, and the upper Torok-Nanushuk section documents the upward transition from marine turbidite deposits into nonmarine fluvial deposits.

Near the Brooks Range mountain front, the transition from turbidite (flysch) to nonmarine (molasse) deposition took place during the Albian and is recorded in the proximal Fortress Mountain Formation (figs. 34 and 35; Crowder, chap. 20) and the Torok Formation-Nanushuk Group section (fig. 36). The lower shales of the Torok Formation contain a restricted, pyritized radiolarian fauna in subsurface and surface exposures; the upper shales of the Torok contain an abundant calcareous microfauna, which records filling of the Colville basin to above the carbonate compensation depth (CCD).

The marine shales of the Torok Formation grade upward into the Nanushuk Group (fig. 32), a major deltaic complex. The Nanushuk Group consists of a basal marine sandstone--the Tuktu Formation--which grades upward into a fluvial sequence of sandstone and siltstone with numerous interbedded coals--the Chandler Formation (Huffman, 1985; chap. 21).

In addition to the coals of the Nanushuk Group, large-diameter tree stumps, dinosaur tracks, and skin impressions have been reported on the western Arctic Slope (Roehler and Stricker, 1984), and large dinosaur tracks have been found on the central Arctic Slope (Witte and others, 1987). Further, Spicer (1985) reported plant megafossils indicative of a warm, mildly seasonal climate. These findings present an interesting dilemma. On the basis of paleomagnetic data, Irving (1979) determined that the paleolatitude of northern Alaska during the middle of the Cretaceous was 80° to 85° N. Paleomagnetic data from a study of the Nanushuk Group on the western Arctic Slope (Witte, 1982) suggest that the Nanushuk Group was deposited at a paleolatitude of 74.5° N. ± 7.5°, a somewhat lower latitude than Irving suggested. Conventional paleogeographic reconstructions of Alaska and the Arctic also yield a high paleolatitude for northern Alaska in the Cretaceous. The evidence of dinosaur tracks, skin

Figure 35. View northward toward basal Fortress Mountain Formation on north side of Atigun Gorge. Gritty sandstone beds overlie silty mudstone with numerous zones of calcareous nodules.

imprints, extensive forests, and diverse flora in the Nanushuk Group seems inconsistent with the inferred high-latitude position for northern Alaska during the Cretaceous (Spicer, 1985; Witte and others, 1987).

Across most of the Arctic Slope, the Nanushuk Group extends as a nearly east-west-trending belt underlying the northern foothills. On the eastcentral Arctic Slope, however, the belt converges with the Brooks Range mountain front (sheet 1). Nonmarine deposits of the Nanushuk are not present along the northeasterly trending front of the Philip Smith Mountains east of the Dalton Highway. Correlative rocks are entirely turbidites deposited northeast of the prograding deltaic complex of the Nanushuk. Regional relationships suggest that the development of the northeastern Brooks Range uplifted the eastern end of the Colville basin and postdates deposition of the Nanushuk (Mull, 1985).

The first stage of active hydrocarbon exploration and drilling in Naval Petroleum Reserve 4 (NPR4) by the U.S. Navy in the late 1940s and 1950s focused on rocks of the Nanushuk Group; numerous oil and gas shows were encountered, and a small noncommercial oil field at Umiat was discovered. Industry exploration in the early 1960s initially focused on the Nanushuk Group too, with little success. The results of this exploration have substantially reduced interest in the Nanushuk Group as a hydrocarbon-exploration objective. However, reconnaissance studies and estimates of very large coal reserves in the Nanushuk Group suggest that its coal resources may be of considerable economic interest in the future.

During Cenomanian and Turonian time, a major transgression spread the marine Seabee Formation of the Colville Group southwestward over the Nanushuk Group on the central Arctic Slope (Detterman and others, 1963; Mull, 1985). The overlying marine Schrader Bluff Formation of Senonian and Maestrichtian age interfingers upward with nonmarine tongues of the Prince Creek Formation, which prograded northeastward during Senonian and Maestrichtian time (figs. 32, 37, and 109). The Colville basin in the central Arctic Slope was filled by the end of the Cretaceous and lapped over the Beaufort sill. During the Tertiary, the Sagavanirktok Formation was deposited to the northeast. Paleobotanical studies indicate that by Paleocene time the mild mid-Cretaceous climate had deteriorated to a cool, temperate climate with pronounced seasons (Spicer, 1985).

Detailed discussion of the Upper Cretaceous and Tertiary stratigraphy is beyond the scope of this volume. However, Upper Cretaceous stratigraphy of the Umiat and the Chandler River regions, 80 mi (130 km) to the west, has been described in detail by Detterman and others (1963) and by Brosgé and Whittington (1966).

Figure 36. View of the 'Ice Cut' at Mile 325; north-dipping turbidite deposits at base of Nanushuk Group (Kn) overlie shale of Torolz Formation (Kt). Exposures on east bank of river (at right in background) dip south on south flank of anticline.

Detterman and others (1975) and Molenaar (1983) have described the depositional relations of Cretaceous and lower Tertiary rocks to the east, and Molenaar and others (1987) have diagrammatically illustrated Cretaceous and lower Tertiary correlations in the Umiat area. Molenaar and others (1986) have correlated Tertiary strata present in the subsurface of northeastern Alaska.

BROOKIAN ROCKS NEAR THE DALTON HIGHWAY

Exposures of most of the major Lower Cretaceous rock units of the Brookian sequence are accessible from the Dalton Highway. Several hundred feet of shaly turbidite deposits, and overlying conglomerate, of the Fortress Mountain Formation are extensively exposed on the north side of Atigun Gorge east of Mile 271 (fig. 34). North of Atigun Gorge, Fortress Mountain Formation caps the high hills of Atigun syncline east of the Dalton Highway between Mile 272 and Mile 275. The shaly turbidites are also present in some of the hills south of the highway near Mile 305.

The Nanushuk Group and top of the underlying Torok Formation are particularly well exposed on the southeast flank of Marmot syncline at Slope Mountain near Mile 301 (fig. 105). This section has been studied by Huffman and others (1985) as part of a regional study of the Nanushuk Group (chap. 21).

Near Slope Mountain, the highway turns northward down the Sagavanirktok River valley and crosses a series of anticlines and synclines that are delineated by resistant beds of the Nanushuk and Colville Groups (sheet 1). Outcrops, however, are limited to scattered rubble traces across ridge tops, a few stream-cut banks, and a few road cuts or material quarries opened during construction of the Dalton Highway and the Trans-Alaska Pipeline. A road cut near the top of the 'Ice Cut' at Mile 325 exposes a few tens of feet of turbidite deposits at the top of the Torok Formation and base of the Nanushuk Group (fig. 36). Coarse-grained, friable sandstone of the Upper Cretaceous Prince Creek Formation, or Tertiary Sagavanirktok Formation, caps the hills between Mile 352 and Mile 354 and underlies the Sagavanirktok River bluffs near Sagwon (fig. 109). These bedrock exposures are the youngest and northernmost accessible by foot from the Dalton Highway. Better exposures of the Prince Creek and Sagavanirktok Formations are present in the bluffs on the east side of the Sagavanirktok River, 5 to 6 mi (8 to 10 km) downstream from Sagwon (figs. 37 and 111), and are visible from the Dalton Highway near Mile 357.

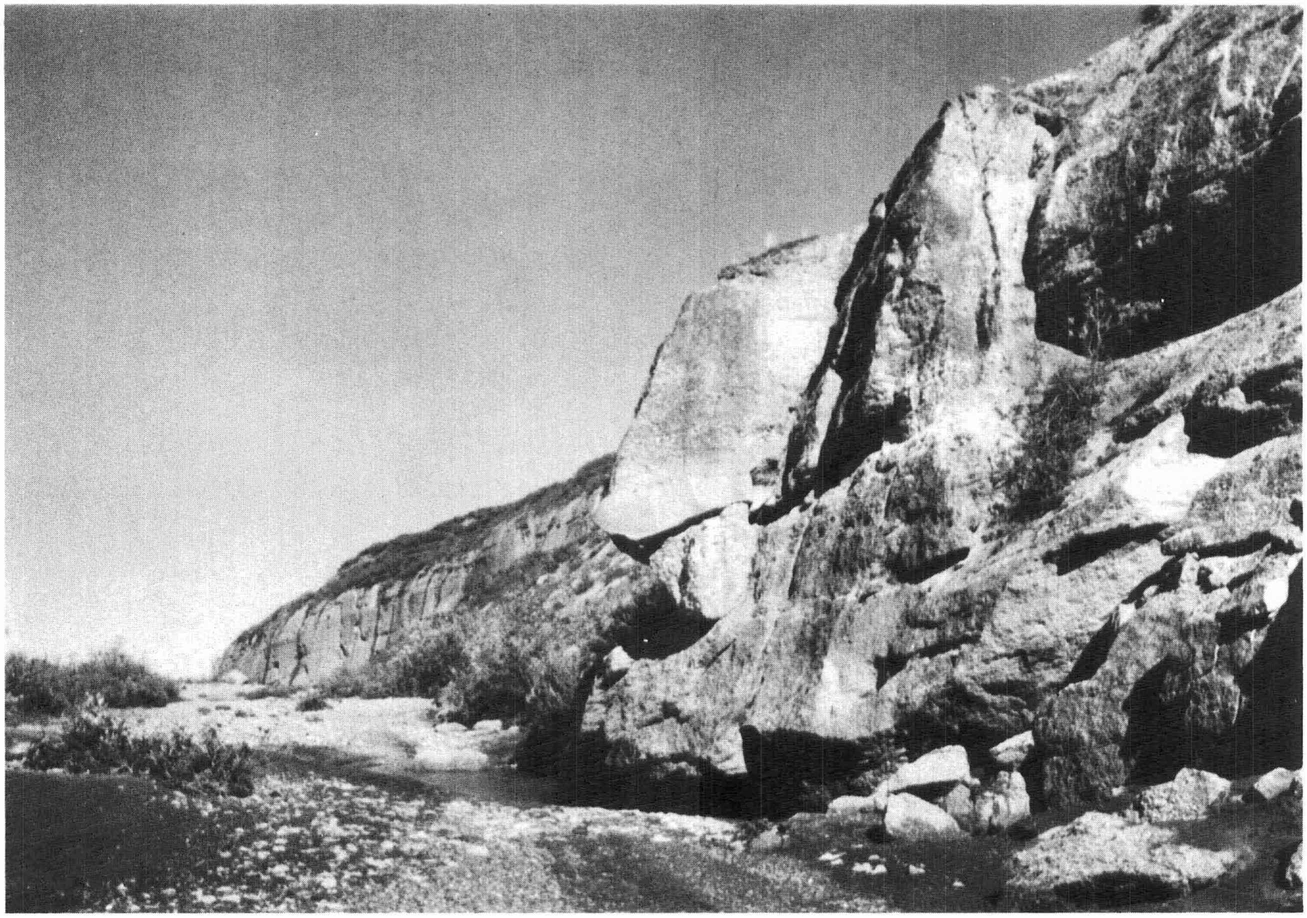


Figure **37.** Massive chert- and quartz-pebble conglomerate *of* Prince Creek Formation or lower *Sagwon* Member of Sagavanirktok Formation on east bank of Sagavanirktok River, north flank of *Ivishak* anticline 6 mi (10 km) northeast *of Sagwon.* Bluff is about 60 ft (18 m) high.

North of Mile 357, the highway descends from the low, rolling foothills onto the Arctic Coastal Plain, which extends northward 60 mi (100 km) to the Beaufort Sea. On the east side of the Sagavanirktok River between Mile 381 and Mile 395, the primarily nonmarine Tertiary Sagavanirktok Formation is well exposed in the Franklin Bluffs (figs. 38 and 113). North of Franklin Bluffs, no lithified sediments are exposed.

Figure 38. View southeastward toward Franklin Bluffs, which are composed of nearly flal-lying Sagavanirktok Formation. Sagavanirktok River is in foreground.

CHAPTER 6.

SUMMARY OF STRUCTURAL STYLE AND HISTORY OF BROOKS RANGE DEFORMATION

By C.G. Mull[1]

INTRODUCTION

Regional reconstructions of northern Alaska suggest that the Broolcian orogeny began as the result of Mesozoic plate movement and convergence between Arctic Alaska (Arctic Alaska terrane) and an oceanic plate (Angayucham terrane) that occupied what is now the Koyukuk basin on the south side of the Brooks Range (figs. 26 and 39; sheet 1). The ophiolitic complex of the Angayucham terrane, probably part of an island arc or oceanic plateau, was obducted northward over the edge of the Arctic Alaska terrane as a result of the plate convergence. A north-vergent thrust belt was formed as allochthonous slices of the Arctic Alaska terrane were successively peeled off beneath the obducting oceanic plate of the Angayucham terrane, these allochthons form the northern part of the central and western Brooks Range and lie north of the internal plutonic and metamorphic belt, which composes the core of the range. Crustal shortening >300 mi (600 km) can be demonstrated in the western Brooks Range, and there is some evidence that shortening decreases to the east (Mull, 1982; Mayfield and others, 1983), although this interpretation is disputed by Oldow and others (1987c). Regional stratigraphic, structural, and radiometric data suggest that the initial phase of major crustal shortening and allochthon development was followed by a later phase of diminished crustal shortening and a strong component of vertical uplift in the internal metamorphic and plutonic belt; this two-stage history is diagrammatically illustrated in figure 39. Isostatic rebound of the continental crust, which was deeply depressed beneath oceanic crust of the Angayucham terrane, may have played an important role in the later uplift of the interior belt.

As a result of the uplift of the internal metamorphic and plutonic belt, the central and western Brooks Range has the form of a regional west-plunging antiform cored by several plutons (sheet 1). The north flank and west plunge of the antiform are bounded by the belt of allochthons that represent the higher structural levels of the orogenic belt. The south flank of the antiform is composed of the schist belt and the overlying obducted Angayucham terrane and may have been modified by a late stage of low-angle normal faulting.

STRUCTURAL STYLE AND TIMING OF CENTRAL AND WESTERN BROOKS RANGE DEFORMATION

The evolution of the central and western Brooks Range apparently began during the Late Jurassic and Early Cretaceous and is recorded in widespread turbidites of the lower Brookian sequence, the Okpilcruak Formation (figs, 31 and 32). The Okpikruak is early Neocomian in age (Mull, 1985), except in the De Long Mountains of the western Brooks Range, where Mayfield and others (1983) found Late Jurassic fossils from graywacke on one of the higher allochthons. In general, the formation consists of thick, rhythmic turbidites of thinly interbedcled mudstone and fine-grained graywacke with minor cobble to boulder conglomerate; in some places, large exotic blocks of chert, limestone, and mafic igneous rock are encased in pebbly mudstone (Mull, 1982, 1985; Crane, 1987). These coarse, chaotic deposits, or olistostromes (wildflysch), indicate orogenesis and high topographic relief that resulted in large blocks of sediment emplaced into the Cretaceous depositional basin by gravitational sliding.

Major crustal shortening continued through Neocomian (about 120 to 135 Ma) and possibly into Aptian time and is indicated by allochthons thrust over Valanginian coquinoid limestone at a number of locali-

[1]DGGS, 3700 Airport Way, Fairbanks, Alaska 99709

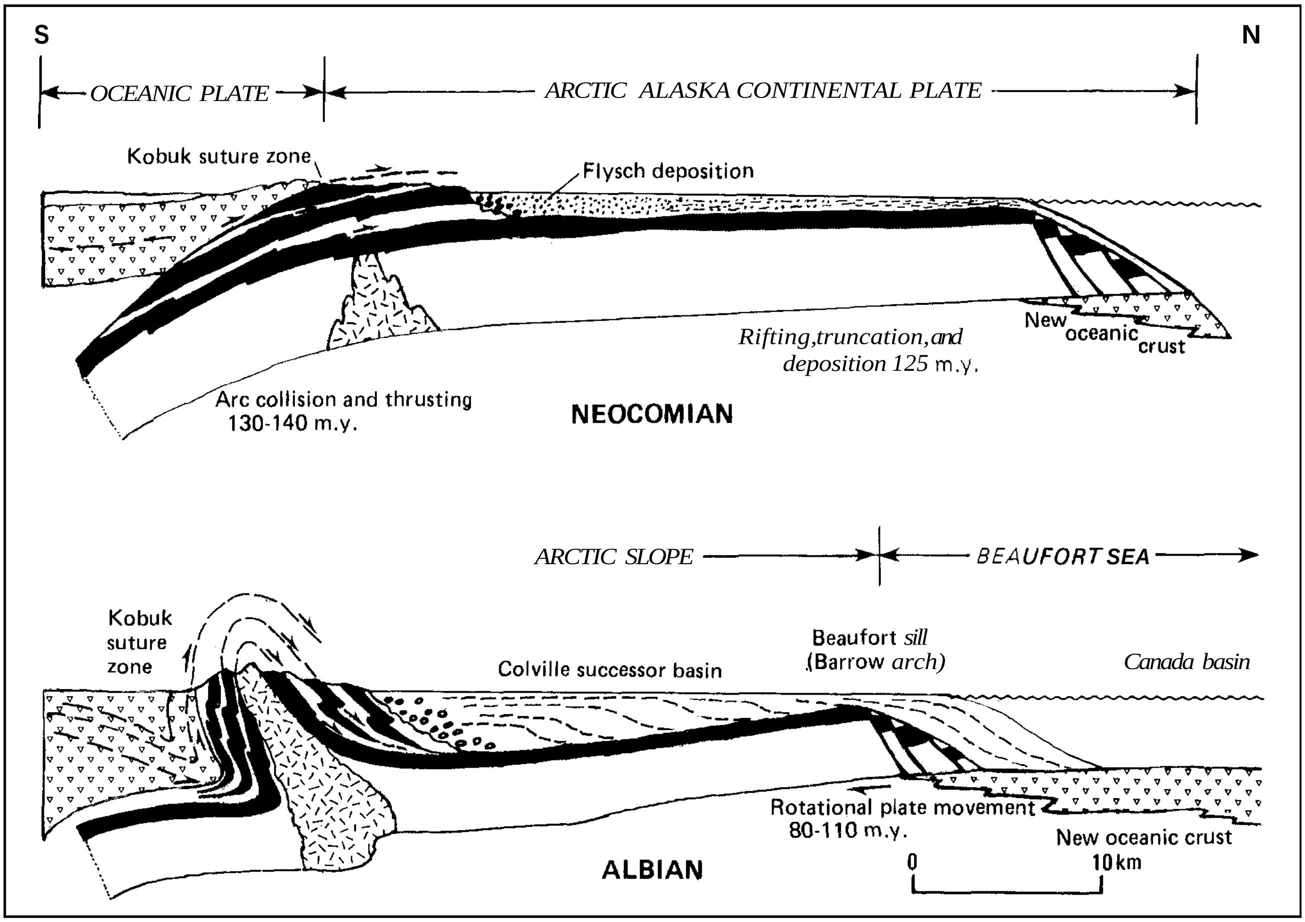


Figure 39. Inferred sequence of tectonic events in evolution of Broolzs Range, Arctic Slope, and continental margin of Beaufort Sea. Granite core is Devonian age (K-Ar date was reset during Cretaceous orogeny).

ties in the central Brooks Range foothills (Mull and others, 1989). At other localities, thick sections of gently deformed autochthonous conglomerate of the Albian Fortress Mountain Formation unconformably overlie tectonically telescoped thrust slivers of several of the allochthons (Mull, 1982; Mayfield and others, 1983; Mull, 1985). These relationships suggest that most crustal shortening and intense deformation in the central Brooks Range had been completed by the Albian, about 100 Ma.

Opposing regional dip off the north and south flanks of all the larger plutons in the internal metamorphic and plutonic belt of the Brooks Range suggests a late-stage, regional doming and a strong component of vertical uplift in the core of the range (Mull, 1982). This structural style is quite different from that of the frontal zone of the Canadian Rockies and the Wyoming-Idaho thrust belt. In those belts, sled-runner thrust faults typically dip westward toward the core of the orogenic belt (Bally and others, 1966; Royse and others, 1975; and Ollerenshaw, 1978). In contrast, in the northern Brooks Range, major folding and refaulting of the allochthons have taken place throughout a large portion of the thrust belt, and, west of the Dalton Highway, extensive remnants of allochthons from the structurally higher levels of the thrust belt are present north of the mountain front.

On the south flank of the Arrigetch Peaks pluton in the Schwatka Mountains, granite is locally thrust southward over metamorphic rocks (Nelson and Grybeck, 1980; Mull, 1982), and apparent north-dipping, overturned rock sequences suggest a component of south vergence associated with regional doming of the core of the range (fig. 39). South-vergent folds and nappes north of the plutons also suggest a component of south-vergent deformation associated with uplift of the core of the range. This deformation seems more extensive than simple back thrusting associated with a dominantly north-vergent structural event.

A large number of K-Ar dates from the internal metamorphic and plutonic belt range from 90 to 110 Ma (Turonian to Aptian) (Turner and others, 1979; Mull, 1982) and postdate maximum crustal shortening and emplacement of the major allochthons during the Neocomian by 10 to 20 m.y. Some of these Cretaceous cooling ages are from plutons that yield a cluster of U-Pb and Rb-Sr dates of about 360 Ma (late Middle Devonian) (Dillon and others, 1980), which would suggest resetting

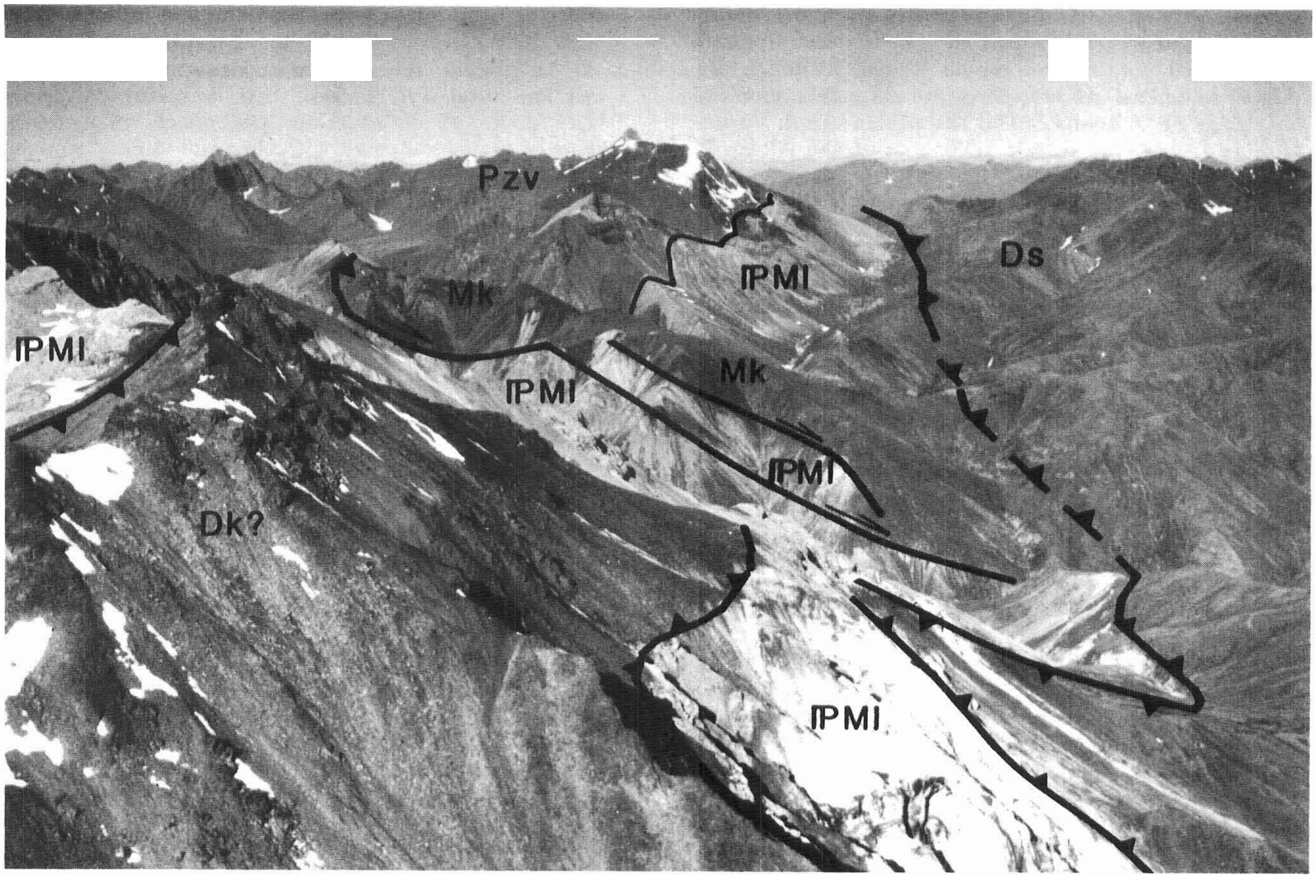


Figure 40. View westward from Falsoola Mountain along north flank of Doonerak fenster toward Mt. Doonerali (center skyline). North-dipping Lisburne Group limestone and Kayak Shale are overlain by Amawh thrust, sole fault of Endicott Mountains allochthon. Base of allochthon consists of Beaucoup Formation, Hunt Fork Shale, and Kanayut Conglomerate(?). Geologic units: Pzv, lower Paleozoic volcanic rocks; Ds, Hunt Fork Shale and Beaucoup Formation, undifferentiated; Dk?, Kanayut Conglomerate(?); Mk, Kayak Shale and Kekiktuk Conglomerate; lPMl, Lisburne Group.

of the K-Ar clock during deep burial and subsequent uplift during the later stages of Brooks Range orogeny (Mull, 1982).

North of the internal metamorphic and plutonic belt, the allochthons that form the frontal ranges dip regionally to the north off the core of the range (sheet 1). Polyphase deformation of the allochthons resulted in a series of regionally north-vergent anticlinoria and synclinoria, which were presumably formed by duplexing as lower structural levels were shortened during later stages of the deformation. Out-of-sequence thrusting is present locally but does not appear to be characteristic of the range as a whole.

In the eastern Endicott Mountains, the sole thrust of the Endicott Mountains allochthon is folded across the Doonerak fenster (figs. 26 and 27; sheet 1) and, south of the fenster, it dips regionally south beneath structurally higher rocks of the internal metamorphic and plutonic belt. In this part of the southern Brooks Range, Dillon (sheet 2) has recognized a number of fault-bounded panels which also dip regionally south, although local anticlinal and synclinal reversals are present. West of the Doonerak fenster on the north side of the plutons in the Schwatka Mountains, regional dips are all to the north, and nowhere do the allochthons dip southward beneath the plutonic belt. In the Schwatka Mountains, the root zone of the allochthons must lie south of the plutons, either in the schist belt or, more likely, at the Kobuk suture zone beneath the Angayucham terrane. The contrast between these two structural styles is illustrated by Mull and others (1987a, cross sections A-A' and B-B'), but no satisfactory explanation has been proposed to explain the difference.

Regional north dip is also characteristic of the northern part of the eastern Endicott Mountains (fig. 40), although reversal in dip across regional anticlinoria and synclinoria is present (fig. 41). With few exceptions, stratigraphic tops at the mountain front are to the north (figs. 41 and 42), even in areas where the rocks are imbricated. The leading edge of the Endicott Mountains allochthon, which forms the northern front of the mountains, is buried north of the front by remnants of some of the higher allochthons or by the postorogenic clastics of the Albian Fortress Mountain Formation.

Deposition of a major clastic sequence of Albian to

Cenomanian age north of the range in the Colville basin (figs. 28 and 32) also seems to coincide with uplift of the internal core of the Brooks Range. Although pre-Albian sediments are present in the basin axis, much of the basin fill is composed of the Albian Torok Formation and overlying deltaic sediments of the Albian to Cenomanian Nanushuk Group. North of the mountain front, seismic and other subsurface data show that the Albian section is over 15,000 ft (5 km) thick. The southern limit of the Albian sequence is composed of thick proximal conglomeratic sections of the Fortress Mountain Formation that overlie the allochthonous rocks of the disturbed belt at a regional angular unconformity (Mull, 1982; Mayfield and others, 1983; Mull, 1985).

In general, the regional stratigraphic relationships and structural style suggest that shortening during the later stages of deformation took place on a greatly reduced scale, compared with the magnitude of shortening that occurred during the Neocomian. Although the incompetent Albian shales in the foothills anticlines are generally complexly folded, the overlying, more competent sandstones and conglomerates are only gently folded, and nowhere are Albian rocks overlain by thrust-faulted older rocks.

STRUCTURAL FEATURES OF THE ENDICOTT MOUNTAINS NEAR DALTON HIGHWAY

The regional structural style of the eastcentral Brooks Range is visible from the Dalton Highway. From the south flank of the range near Mile 168 to the Doonerak fenster at about Mile 225, regional dip is dominantly to the south, although local reversals in dip are present. North of the Doonerak fenster, the regional dip is predominantly north, although numerous folds and south-dipping thrust faults are present. Regional north dip of folded thrusts that bound major allochthons is particularly well demonstrated along the north flank of the Doonerak fenster (fig. 40) in the Endicott Mountains from about Mile 233 to the Continental Divide at Mile 245.

Although not clearly visible from the Dalton Highway, regional folding of the Endicott Mountains allochthon can be seen on maps of the Philip Smith Mountains Quadrangle (fig. 41; Brosgé and others, 1979a). South of the mountain front, regional synclines in the Kanayut Conglomerate contain infolds of Lisburne carbonate and Kayak Shale that depositionally overlie the Kanayut Conglomerate (fig. 43). These infolds highlight a regional structural style that is otherwise less obvious in the Kanayut section.

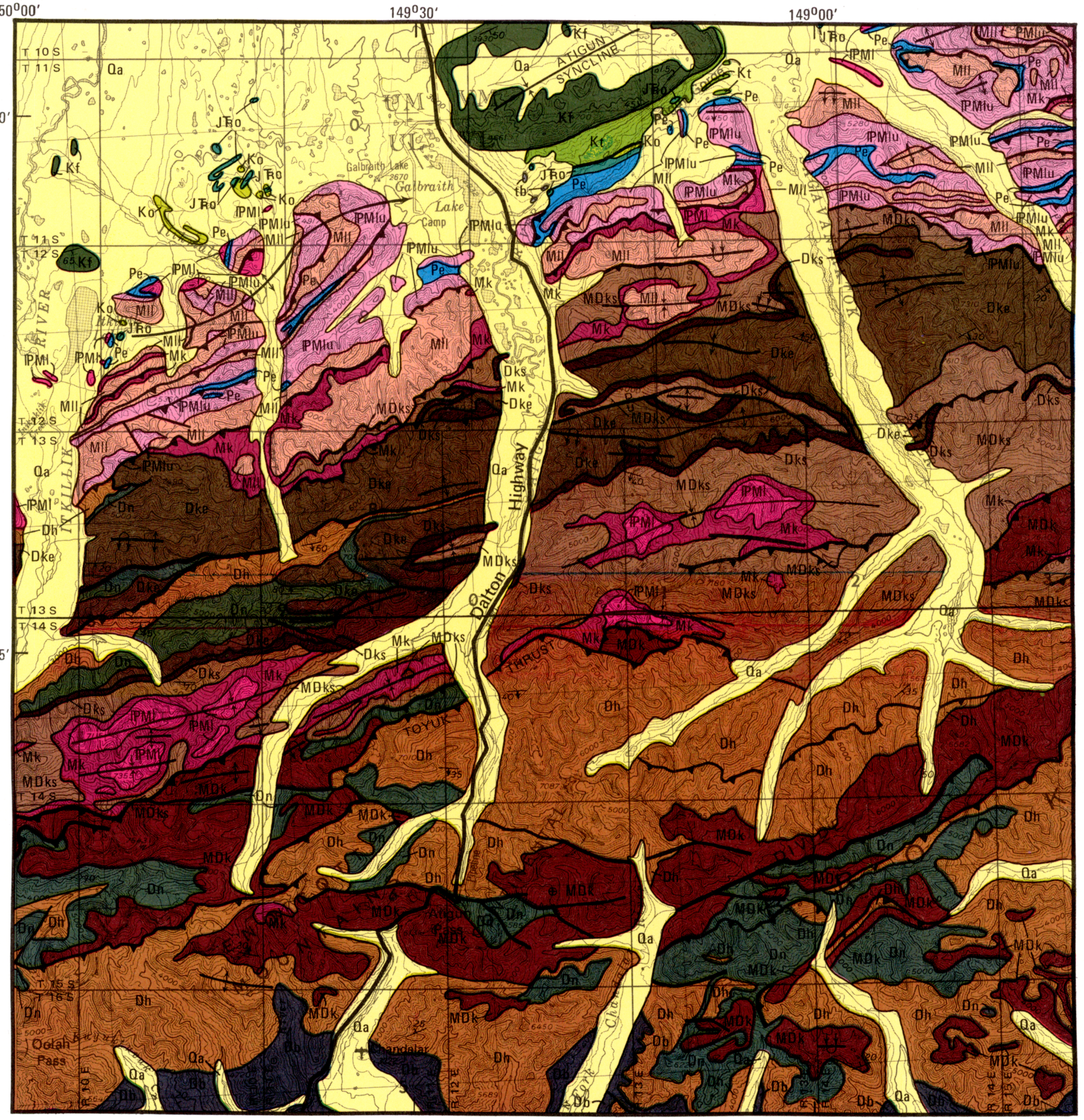
The Kanayut Conglomerate contains north-vergent, asymmetrical to overturned folds (fig. 43) that grade along strike into south-dipping thrust faults. Regional anticlinal and synclinal trends are obscured by smaller scale structures, and obvious marker beds are scarce in the extremely thick sections of clastic rock. Intensity of deformation increases southward. At the headwaters of the Atigun River, the Toyuk thrust--a major regional thrust fault--superimposes thick siltstone and shale of the Hunt Fork Shale over the Kanayut Conglomerate (fig. 41). Farther to the south, near the base of the Endicott Mountains allochthon, the Hunt Forlc Shale is characterized by intense isoclinal folding (fig. 44).

Folded thrust sheets of Lisburne Group carbonates at the mountain front are clearly visible from the Dalton Highway near Mile 271 (fig. 33). East of the highway, overturned south-dipping Lisburne limestone forms high cliffs and is stratigraphically overlain by shale and siltstone of the Permian Echooka Formation, which form the smooth, lower slopes. West of the highway, across Galbraith Lake, at least three imbricated sheets of Lisburne Group limestone are folded into an east-plunging anticline (figs. 41, 99, and 100). Steeply north-dipping Lisburne dip slopes form the mountain front. Similar north dip at the mountain front is evident in the Cobblestone Creek area, 25 mi (40 km) west of the Dalton Highway (fig. 42), and in many other areas along the mountain front.

North of Mile 271 on the north side of Atigun Gorge, uniformly north-dipping Albian conglomerate and shale of the Fortress Mountain and Torok(?) Formations (figs. 32, 34, and 35) depositionally overlie intensely sheared graywacke and shale of the Neocomian Okpikruak Formation. Isolated tectonic blocks of green chert, siltstone, and bioclastic limestone (fig. 99) are closely associated with the Okpikruak Formation (R.A. Glenn, oral commun., 1987) and overlie intensely deformed coquinoid limestone of Valanginian age and the Otuk Formation of Jurassic and Triassic age at the top of the Endicott Mountains allochthon (figs. 31 and 34). The blocks of green chert, siltstone, and limestone are anomalous to this part of the Brooks Range and are probably remnants of a higher allochthon thrust over the Endicott Mountains allochthon before deposition of the Albian sediments. Similar anomalous rocks are far more widespread north of the mountain front west of Atigun Gorge and form the disturbed belt of allochthons of the central and western Brooks Range.

STRUCTURAL STYLE AND TIMING OF NORTHEASTERN BROOKS RANGE DEFORMATION

Mountains of the northeastern Brooks Range arc characterized by broad anticlinoria and synclinoria developed in autochthonous or parautochthonous rocks of the Mississippian to Jurassic Ellesmerian sequence (fig. 29) and are cored by duplexes developed in the underlying pre-Mississippian Franlclinian sequence



DESCRIPTION OF MAP UNITS

Qa ALLUVIAL DEPOSITS, UNDIFFERENTIATED (QUATERNARY)

Kt TOROK FORMATION (LOWER CRETACEOUS-ALBIAN)—Prodelta deposits composed of laminated, black clay shale and silty shale. Possibly exposed on north side of Atigun Gorge

Kf FORTRESS MOUNTAIN FORMATION (LOWER CRETACEOUS-ALBIAN)—Dominantly thick turbidite deposits composed of dark-gray sandstone, conglomerate, siltstone, and interbedded mudstone. Forms Atigun syncline. Small, local exposures north of Atigun syncline consist mostly of dark-gray, partly conglomeratic sandstone

Ko OKPIKRUAK FORMATION (LOWER CRETACEOUS-NEOCOMIAN)—Turbidite deposit composed of rhythmically interbedded dark-gray to black siltstone, graywacke, and shale with minor conglomeratic beds. Lithologically similar to parts of Torok (Kt) and Fortress Mountain (Kf) Formations. Locally contains thin coquinoid limestone at base

J℞o OTUK FORMATION (LOWER JURASSIC TO TRIASSIC)—Thinly interbedded gray to black limestone, calcareous shale, and organic shale. Forms extensive crumpled exposures in Atigun Gorge and limited exposures elsewhere

Pe ECHOOKA FORMATION OF SADLEROCHIT GROUP (PERMIAN)—Upper part is black, phyllitic shale, with minor maroon and pale-green shale and scattered lenses, seams, and nodules of barite. Lower part is yellow-brown-weathering calcareous siltstone and silty limestone discontinuously exposed overlying Lisburne Group along northern mountain front

IPMl LISBURNE GROUP (LOWER PENNSYLVANIAN AND MISSISSIPPIAN)—Gray limestone, shaley in part, and dolomite; contains abundant nodular chert in some areas. Forms massive, light- to medium-gray-weathering cliffs and rubble-covered mountains. In places, differentiated into an upper, light-gray-weathering unit and a lower, darker gray-weathering horizon

IPMlu UPPER LISBURNE GROUP (LOWER PENNSYLVANIAN AND MISSISSIPPIAN)—Light-gray-weathering, fine- to medium-grained limestone with chert. Forms massive cliffs

Mll LOWER LISBURNE GROUP (MISSISSIPPIAN)—Medium-gray-weathering limestone, shaley in part, and dolomite, with black, nodular chert

Mk KAYAK SHALE (MISSISSIPPIAN)—Fissile, black clay shale and silty shale, with thin yellow-brown-weathering silty limestone beds in upper part; contains abundant red-brown-weathering nodules in some areas

MDk KANAYUT CONGLOMERATE (LOWER MISSISSIPPIAN AND UPPER DEVONIAN)—Deltaic complex composed of dark-gray-weathering, fine- to medium-grained sandstone and conglomerate with interbedded siltstone and shale. In southern part of outcrop belt, forms crest of Endicott Mountains along Continental Divide

MDks STUVER MEMBER OF KANAYUT CONGLOMERATE (LOWER MISSISSIPPIAN AND UPPER DEVONIAN)—Meandering-stream deposits composed of shale, shaley siltstone, thinly bedded sandstone and quartzite, and minor conglomerate. Weathers to brown and red-brown slopes

Dks SHAININ LAKE MEMBER OF KANAYUT CONGLOMERATE (UPPER DEVONIAN)—Meandering-stream deposits composed of conglomerate, sandstone, and shale in thinning-upward cycles. Forms massive, resistant, dark-gray-weathering ledges on ridge tops and spurs on valley walls

Dke EAR PEAK MEMBER OF KANAYUT CONGLOMERATE (UPPER DEVONIAN)—Meandering-stream deposits of conglomerate, sandstone, and shale in thinning- and fining-upward cycles. Weathers brown to red-brown on hillsides and forms resistant ledges

Dn NOATAK SANDSTONE (UPPER DEVONIAN)—Channel-mouth bar deposit composed of dark-brown-weathering calcareous sandstone and black shale; locally conglomeratic

Dh HUNT FORK SHALE (UPPER DEVONIAN)—Prodelta deposits composed of gray-weathering shale and shaley siltstone interbedded upward with fine- to medium-grained sandstone. Forms high mountains north of Continental Divide near Atigun Pass

Db BEAUCOUP FORMATION (UPPER DEVONIAN)—Dark-gray to green-gray shale, phyllitic in part. Forms light-brown to orange-brown-weathering slopes south of Continental Divide near Atigun Pass

tb TECTONIC(?) BLOCKS—Small, isolated exposures in Atigun Gorge composed of green-gray chert, green siltstone, and altered crinoidal limestone. Range from ten to several hundred feet diameter. Age and unit unknown. In places, closely associated with small, discontinuous outcrops of Otuk Formation (J℞o) and coquinoid limestone of Endicott Mountains allochthon. Some blocks encased in groundmass of Permian and Triassic black, phyllitic shale; others associated with sheared graywacke and shale of Okpikruak Formation (Ko). Blocks are probably a broken formation formed at the base of an overlying allochthon during Early Cretaceous time but before deposition of the Albian Fortress Mountain Formation

MAP SYMBOLS

Contact

High-angle fault—U, upthrown side; D, downthrown side

Thrust fault—Sawteeth on upper plate

Anticline, showing plunge of axis

Overturned anticline, showing direction of dip of limbs

Syncline

Overturned syncline, showing direction of dip of limbs

Strike and dip of beds—Arrow indicates estimated measurement

15 Inclined

⊕ Horizontal

1: 250,000

0 5 10 mi

0 5 10 km

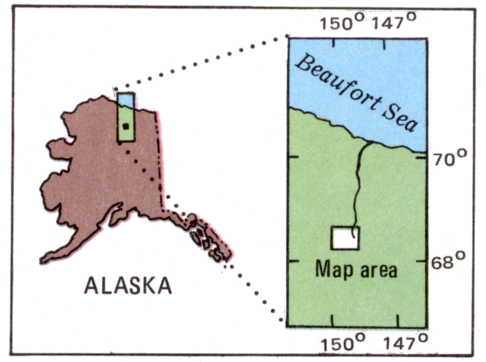


Figure 41. Geologic map of southwestern Philip Smith Mountains Quadrangle. Modified from Brosgé and others (1979a).

Figure 42. View eastward *toward* north-dipping limestone of Lisburne Group ot mountain front. Cobblestone Creek, eastern Endicott Mountains. *Permian* and Triassic *strata* are exposed in stream-cut *banks* just downstream (north) from hills of Lisburne Group.

(fig. 30), (Reiser and others, 1971, 1980; Leiggi and Russell, 1985; Leiggi, 1987). The Sadlerochit and Shublik Mountains, the northernmost ranges in the northeastern Brooks Range, are long, doubly plunging anticlines broken along their crests by high-angle reverse faults. Both faults have as much as 10,000 ft of throw that displaces south-dipping sections of over 7,000 ft of Proterozoic to Middle Devonian dolomite and limestone on the south against Cretaceous rocks on the north. In both ranges, the faults die out to the east and west, where Mississippian to Triassic rocks are draped over the buried extensions of the faults and show no evidence of major shortening. These basement-involved faults are interpreted to flatten at depth and sole out into a regional décollement; shortening at the Sadlerochit Mountains front is about 16 percent and increases southward (Leiggi and Russell, 1985; Leiggi, 1987).

The Kekiktuk Conglomerate and Kayak Shale, which form the base of the Ellesmerian sequence, are very thin or absent in the Sadlerochit Mountains, and the Lisburne is pinned to the underlying pre-Mississippian rocks at a well-exposed angular unconformity along which no horizontal movement has occurred. To the south, in the Shublik Mountains, Third Range, and Romanzof Mountains, where the Kayak Shale is present, the Lisburne Group and overlying rocks of the Ellesmerian sequence are detached from the underlying rocks and deformed into tight folds that have wavelengths markedly less than the wavelengths of the regional anticlinoria. The detachment horizon is the incompetent Kayak Shale. Leiggi (1987) estimates that the Ellesmerian section has been shortened 41 percent at the front of the Franklin Mountains (fig. 30), about 25 mi south of the Sadlerochit Mountains front.

Detachment zones are also present in the Jurassic to Lower Cretaceous Kingak Shale. The Lower Cretaceous Kemik Sandstone has been thrust northward at least 10 mi (16 km) above a detachment in the underlying Kingak Shale in the eastern Sadlerochit Mountains area (Mull, 1987). In addition, detachment and northward translation of Albian and younger strata are interpreted from field relationships and seismic data from the foothills and coastal plain north of the mountains (Bruns and others, 1987; Kelley and Foland, 1987; Decker and others, 1988).

East of the Sadlerochit and Shublik Mountains, detailed mapping in the British Mountains shows that the Ellesmerian sequence is extensively thrust duplicated (Hanks and Wallace, 1987; Wallace and Hanks, 1988). To the south in the southern British Mountains, where bedding plane faults within the Ellesmerian sequence are more evident than along the northern mountain front,

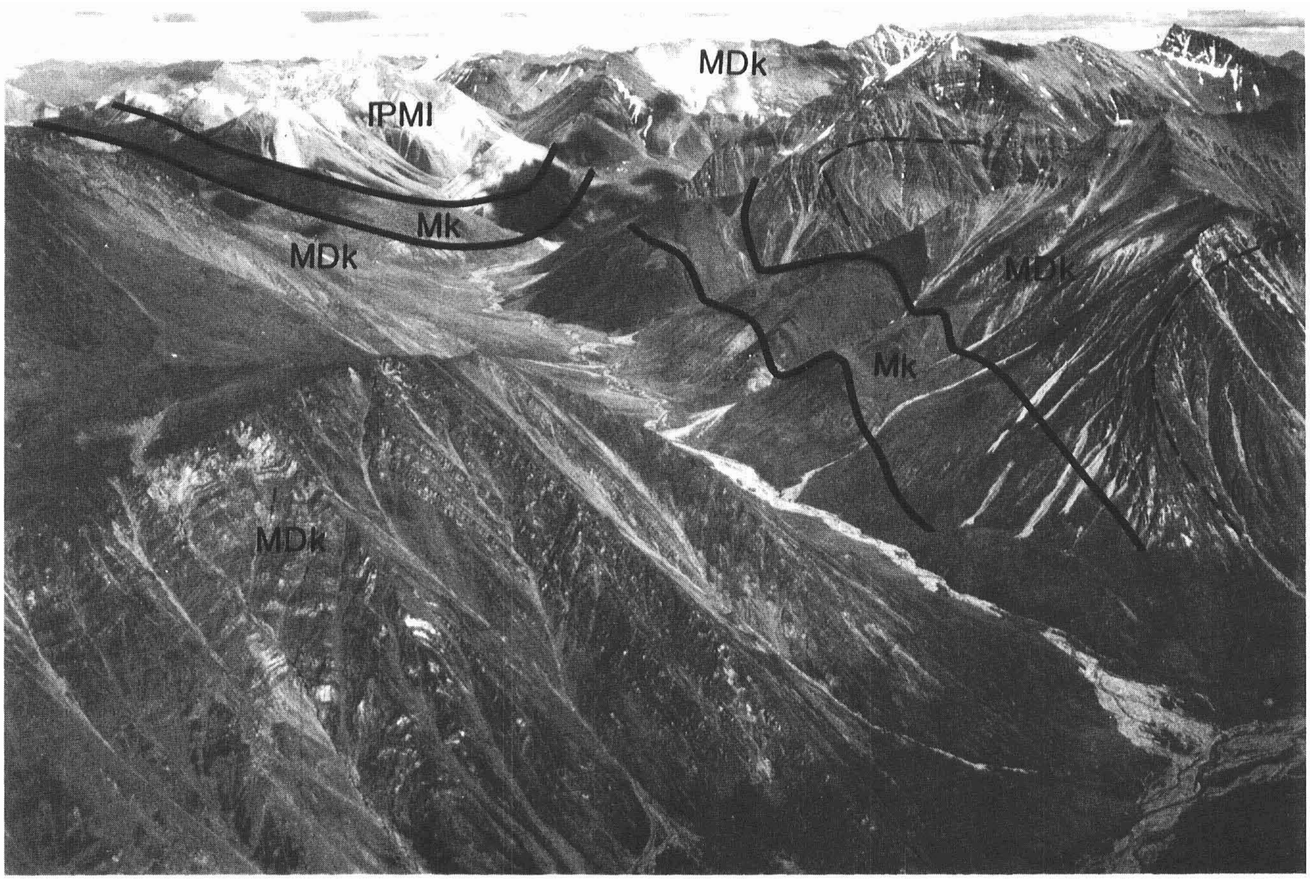


Figure 43. View eastward up tributary of Itkillik River to synclinal rnfold of Lisburne Group on divide between Itkillik and Atigun Rivers. Note overturned anticline in Kanayut Conglomerate at right. Geologic units: MDk, Kanayut Conglomerale; Mk, Kayak Shale; lPMl, Lisburne Group.

the intensity of shortening seems to increase (Mull and Camber, 1987). No estimates of the amount of shortening have been made in the British Mountains.

With a few exceptions, rocks of the Franklinian sequence beneath the pre-Mississippian unconformity dip regionally south. Most workers believe that duplexing of this sequence formed the regional anticlinoria that are expressed in the unconformably overlying Ellesmerian rocks (Leiggi, 1987; Wallace and Hanks, 1988). The Franklinian sequence is composed of several distinctively different sedimentary and mafic-igneous rock packages that were juxtaposed during a pre-Mississippian orogenic event and subsequently truncated by the base of the Ellesmerian sequence (Moore, 1986). The relatively uniform, regional south dip of these rocks beneath the unconformity suggests to most workers that the pre-Mississippian deformation was north vergent. On the basis of local detailed studies, Oldow and others (1987c) believe that the pre-Mississippian deformation in the northeastern Brooks Range was south vergent and that the present regional south dip of the pre-Mississippian rocks in the northeastern Brooks Range is entirely the result of north-vergent Mesozoic and Tertiary duplexing of the Franklinian rocks beneath the unconformity. This interpretation is controversial, and its acceptance awaits more regional data.

In the northeastern Brooks Range, allochthons representing the structurally higher levels of the orogenic belt are present in only two areas: 1) a regional syncline near Porcupine Lake, 40 mi south of the mountain front in the eastern Philip Smith Mountains; and 2) the Chandalar River drainage about 60 mi south of the mountain front (sheet 1). In the Porcupine Lake area, reconnaissance mapping has revealed a klippe of sedimentary rocks of the Endicott Mountains and higher allochthons capped by mafic igneous rocks of the Angayucham terrane. In the Chandalar River area, an extensive thrust sheet of Upper Devonian clastic rocks of the Endicott Mountains allochthon overlies parautochthonous, imbricated Lisburne Group limestone of the North Slope stratigraphic sequence (fig. 29).

Although substantial amounts of shortening have occurred within the Franklinian and Ellesmerian sequences in the northeastern Brooks Range, the absence of allochthonous rocks of the structurally higher levels in most of the northeastern Brooks Range precludes a direct comparison between the amounts of crustal shortening in the eastern, central, and western Brooks

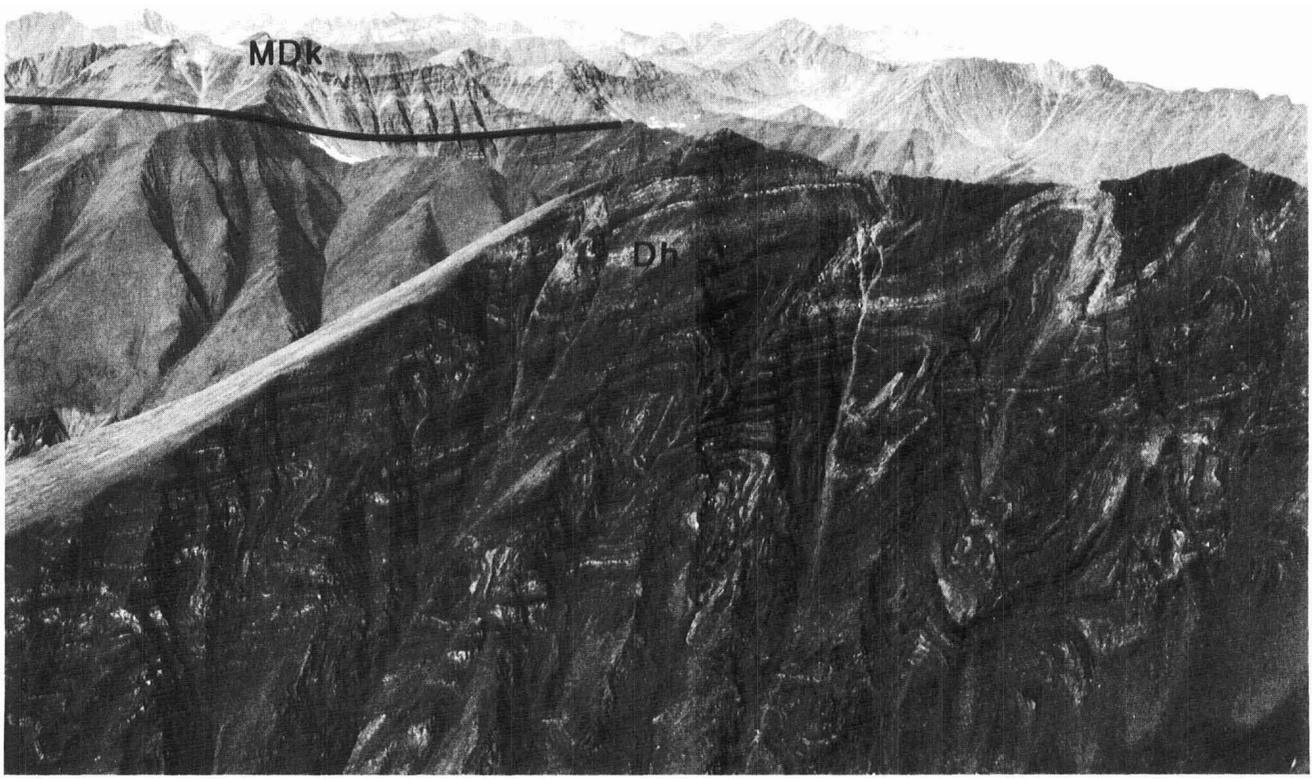


Figure 44. Isoclinal folding in Hunt Fork Shale north of Mount Doonerak in Inclined Mountain syncline. Geologic units: Dh, Hunt *Fork* Shale; *MDk*, *Kanayut* Conglomerate.

Range. Available data are not sufficient to support the contentions of Oldow and others (1987c) and Rattey (1987), who suggest that total shortening in the eastern end of the Brooks Range is comparable to that in the central and western parts of the range.

Uplift began much later in the northeastern Brooks Range than in the central and western Brooks Range (Mull, 1982, 1985). Bruns and others (1987) suggest that deformation of rocks beneath the coastal plain began in the Eocene and continues to the present day. Geomorphic evidence suggests that the Sadlerochit Mountains have also been affected by very recent uplift.

STRUCTURAL STYLE AND TIMING OF ARCTIC FOOTHILLS DEFORMATION

The southern part of the central Brooks Range foothills is a belt of complex structure known informally as the disturbed belt (Tailleur and Brosgé, 1970). The belt is composed of complexly faulted slivers of allochthonous rock from the higher structural levels of the thrust belt (Mull and others, 1987a, cross section A-A'). These are mainly sedimentary rocks that are the southern facies of rocks on the structurally lower Endicott Mountains allochthon, which forms the Endicott Mountains front. The slivers were isolated and preserved north of the mountain front by the Albian and Late Cretaceous deformation that uplifted the internal metamorphic and plutonic belt and resulted in folding of the northern Brooks Range belt of allochthons. North of the disturbed belt is a belt of complexly folded Lower Cretaceous shale that probably overlies imbricated slivers of the allochthonous rocks at depth. East of the Itkillik River, the disturbed belt narrows and converges with the Endicott Mountains front at Atigun Gorge (sheet 1); it is not readily discernible where the Dalton Highway crosses the foothills.

At a number of localities in the southern part of the foothills, distinctive basin-like, doubly plunging synclines are mapped in the Fortress Mountain Formation and Nanushuk Group. These 'thumbprintstyle' synclines were probably formed by intersection of north-trending, high-angle faults with older, regional, east-west-trending décollement synclines. These north-trending faults are

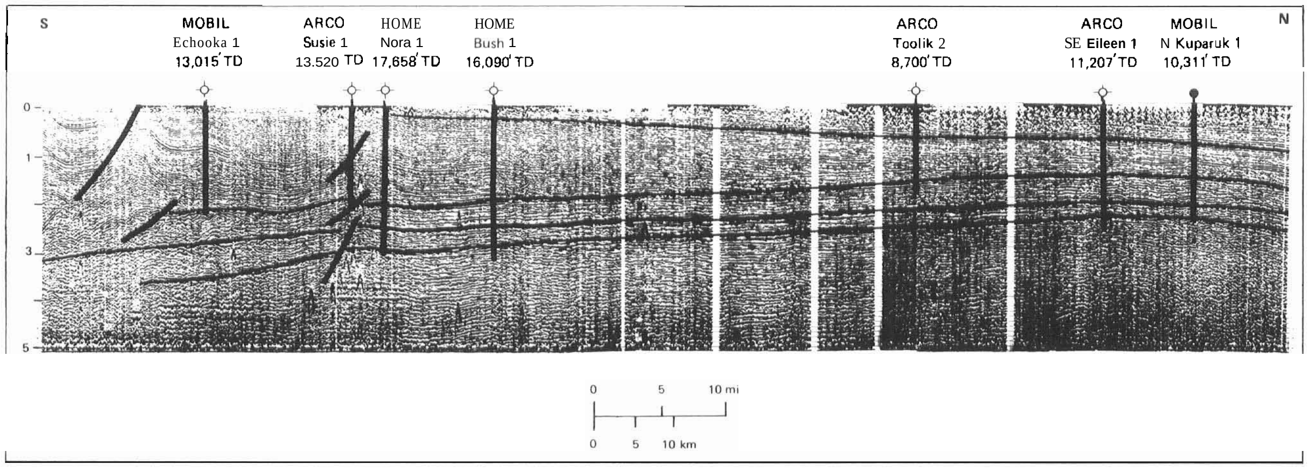


Figure 45. Regional seismic line across northern foothills to Prudhoe Bay. Because of velocity contrast along length of line, vertical exaggeration grades from 2½ times at southern end to 4 times at northern end. Seismic line courtesy of Atlantic Richfield Company, 1965.

not readily discernible across the lowlands underlain by Torok Formation; however, in some places they are inferred by a marked change in structural style or by apparent offsets of the Lisburne Group carbonates at the mountain front.

The Dalton Highway passes near two of the thumbprint synclines: 1) Atigun syncline (figs. 41 and 104), developed in the Fortress Mountain Formation on the north side of Atigun Gorge near Mile 271; and 2) Marmot syncline (fig. 104), of which Slope Mountain near Mile 301 forms the southeast flank. Itigaknit and Imnavait Mountains, visible north of the highway between Miles 286 and 298, are also thumbprint synclines (fig. 104).

The southern edge of the northern part of the foothills is delineated by the Tuktu escarpment,, a regional feature formed by resistant north-dipping beds of the Nanushuk Group (fig. 28). In a comparable physiographic position in the foothills of the Canadian Rockies, a back thrust underlies resistant Cretaceous clastics (Bally and others, 1966; Ollerenshaw, 1978) and forms part of a triangle zone (Jones, 1982). It is possible that north-dipping back thrusts similar to those in the Canadian Rockies foothills may underlie the Brooks Range foothills; however, such faults have not been documented from surface evidence.

North of the Tuktu escarpment in the northern part of the foothills belt is a series of long, east-west trending folds in the relatively competent sandstone beds of the Nanushuk Group and overlying Upper Cretaceous (Cenomanian to Maastrichtian) Colville Group (sheet 1). The synclines generally have a smooth, gentle profile, whereas the anticlines are sharp and marked by steep dips near their axes. Exposures in the cores of breached anticlines generally consist of contorted shale. Northward, the folds decrease in amplitude and finally flatten out under the Arctic Coastal Plain.

Seismic data (fig. 45) show that competent beds of the foothills belt were deformed independently and decoupled from the underlying south-dipping pre-Cretaceous section. This décollement resulted from relatively minor Late Cretaceous to Tertiary compression. In the foothills of the central and western Brooks Range, the decoupling zone is the thick shale of the Torok Formation; in the foothills of the northeastern Brooks Range, decoupling apparently occurs in Upper Cretaceous or Tertiary horizons.

North of Mile 355, the Dalton Highway descends onto the Arctic Coastal Plain, and, except for a low-amplitude anticline near Mile 381, structure is visible only on seismic records (fig. 45).

CHAPTER 7.

DALTON HIGHWAY ROAD LOG

INTRODUCTION

Three groups of geologists, working during the summer and fall of 1984, were the primary compilers of the Dalton Highway road log:

1. W.W. Patton, Jr., T.P. Miller, and S.E. Box (U.S. Geological Survey) logged the area between the Yukon River (Mile 56) and the South Fork of the Koyukuk River (Mile 166.2).
2. J.T. Dillon, D.N. Solie, J.E. Decker, J.M. Murphy, A.A. Bakke, and J.A. Huber (DGGS) logged the area between the South Fork of the Koyukuk River and the Chanclalar Shelf near the crest of the Brooks Range (Mile 237.1).
3. C.G. Mull and E.E. Harris (DGGS) logged the area between the Chandalar Shelf and Pruclhoe Bay (Mile 414).

During the summers of 1986-88 C.G. Mull and K.E. Adams updated the log. The description of the outcrop at Mile 68.3 was provided by J.M. Murphy and T.E. Moore (U.S. Geological Survey); the Prospect Creek area (Mile 130 lo 135), by T.E. Smith (DGGS); the Jim River area (Mile 148), by J.D. Blum (DGGS);and Sulcakpak Mountain (Mile 202), by J.A. Huber (University of Alaska). Glacial geology discussions were provided by T.D. Hamilton (U.S. Geological Survey). Other entries are modified from DGGS 'Guideboolc 4' (Brown and Kreig, 1983) and 'The Milepost' (Alaska Northwest Publishing Company, 1988). The base for the geologic strip maps was taken from U.S. Geological Survey 1:63,360- and 1:250,000-scale topographic maps (fig. 46).

Road-log mileages in this guideboolt are referenced lo lhe small green mileposts along the cast side of the Dalton Highway. These mileposts were put up after Guideboolc 4 was published, so mileages in this guidebook may differ slightly from those in Guidebook 4. Although the Dalton Highway begins officially at the intersection with the Elliott Highway near Livengood, the road log begins at the Yukon River crossing at Mile 56. As a point of interest, distances to the Dalton Highway terminus at Prudhoe Bay are sometimes given, in parentheses, after milepost numbers in this guidebook; for example, (PB 205) means the milepost is 206 mi from Prudhoe Bay. Large orange mileposls, seen at some places along the Trans-Alaska Pipeline and near the Dalton Highway, mark the mileages on the Trans-Alaska Pipeline System, beginning at Pump Station 1 at Prudhoe Bay, and a small-diameter buried gasline north of the Brooks Range. 'These mileages do not correspond to the highway mileages.

The Dalton Highway is open to the public as far north as a checkpoint on Chandalar Shelf (Mile 237.1). North of the checkpoint, the road is open only to holders of DOTPF (Alaska Department of Transportation and Public Facilities) permits. These are issued in Fairbanks for valid business or scientific reasons and to the area's residenls. Permits cannot be obtained at the checkpoint or by telephone.

Travelers on the Dalton Highway should carry spare tires, standard tools, and emergency gear. Unleaded gasoline, meals, lodging, and towing services are available only at the Yukon River crossing (Mile 56), 140 mi (225 km) north of Fairbanks; at Coldfoot (Mile 175), 260 mi (416 km) north of Fairbanks; and at Deadhorse (Prudhoe Bay) at the end of the Dalton Highway (Mile 414). DOTPF maintenance stations along the highway are not open to the public for gas or repair services.

Drive the Dalton Highway with extreme caution. Keep well to the right and drive with headlights on at all times, for much of the traffic consists of heavy trucks that sometimes take more than half the road. Flying rocks arc a continual hazard, particularly on curves. The road is maintained regularly, but after long periods of rain it may be very slick or rough; when the road is dry, visibility is frequently limited by dust. When stopping, park as far off the road as possible; parking areas arc located along numerous access roads to the pipeline righl-of-way or to abandoned quarries and gravel pits. Do not block these roads, as they are used from time to time by the Alyeska Pipeline Service Company. Sightseers are warned to slay off the pipeline and righl-of-way; the route is palrolled regularly by Alyeska personnel in helicopters and road vehicles. Crossing lhe pipeline right-of-way, however, is permitted. Pump stations and air strips along the highway are not open to the public.

Wildlife is often seen along the route. Between Fairbanks and the upper Dietrich River valley (about Mile 230) moose and black bear may be encountered. Dall sheep are often visible on the north side of Atigun Pass between Mile 245 and 250. Between the Brooks Range mountain front at Mile 270 and Prudhoe Bay at Mile 414, caribou are seen frequently, and barren-ground grizzly bears are occasionally sighted. Do *not* feed either the black or grizzly bears. Both are dangerous, and even leaving food behind for them has the long-term effect of turning them into 'garbage bears,' encouraging them to become a nuisance, and ultimately resulting in their having to be destroyed.

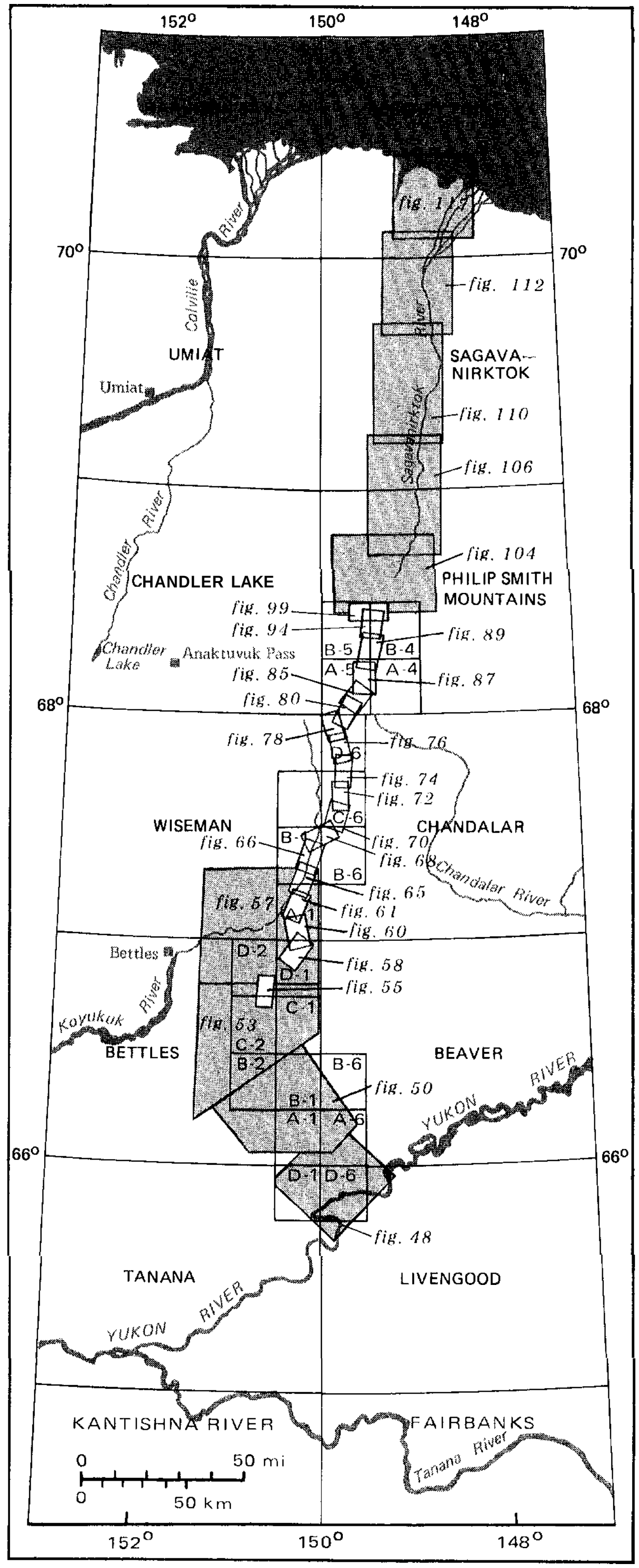


Figure 46. Index to 1:63,360- and 1:250,000-scale U.S. Geological Survey topographic maps along guidebook route. Open areas designate road-log maps that have 1:63,360-scale base; shaded areas designate maps that have 1:250,000-scale base.

In the area of the Yulcon River bridge, the Yulcon River has cut into mafic rocks (TRMt) of the Tozitna terrane (Jones and others, 1984a), as shown by representative lithologies in beach cobbles. The terrane consists of a structurally complex assemblage of Mississippian to Triassic basalt and radiolarian chert, Permian limestone, and rare Jurassic ultramafic rocks that were intruded by thick, sill-like gabbroic bodies. The terrane is probably thrust over pelitic schists of the Proterozoic(?) and Paleozoic Ruby terrane (PzPr). Direction of thrusting has not yet been determined; however, both southeastward and northwestward vergence have been suggested.

North of the Yukon River, the Dalton Highway winds through the heavily forested Fort Hamlin Hills on the south flank of the Ruby geanticline (fig. 49).

MILE 60.7 (fig. 48). The road crosses an insulated, elevated segment of the pipeline laid in a large culvert beneath the road embankment. The crossing was specifically designed for the underlying thaw-unstable soils. Parallel to the road is a 3,600-St-long (1,200 m) airstrip, so beware of low-flying aircraft. (See Brown and Kreig, 1983, p. 89).

MILE 61.8 (fig. 48). Turn east into the DOTPF maintenance camp; then turn north onto the first road, which leads to a small quarry. In the face of the quarry is an exposure of deeply weatheretl plagioclase-clinopyroxene gabbro of the Tozitna terrane (TRMt). The gabbro is typically altered to a low-grade greenschist-facies assemblage (albite + epidote + chlorite + actinolite ± hornblende). Red chert, in uncertain relationship to the gabbro, is exposed in the drainage ditch near the turnoff to the quarry. Clear, spherical radiolarians within the chert are visible with a hand lens. Jones and others (1984b) have recovered radiolarians of Mississippian, Pennsylvanian, Permian, and Late Triassic age from other localities within the Tozitna terrane.

MILE 66.3 (fig. 48). Road cuts on both sides of the road expose gabbro and diabase of the Tozitna terrane (TRMt).

MILE 67.2 (fig. 48). Road cuts expose phyllitic quartzofeldspathic mctagraywacke of the Ruby terrane (PzEr), which lies structurally beneath the Tozitna terrane.

MILE 68.3 (fig. 48).[3] Road crosses pipeline. Road cuts on the north and east sides of the Dalton Highway and in the east wall of the pipeline trench north of the road expose the contact between the Narvak and Slate Creek thrust panels (see entry for Mile 165.7). Diabase of the Narvak panel (TRMt) is separatctl from metagraywaclce turbidites of the unclerlying Slate Creek panel (part of PzPr) by a tectonically mixed zone of blocks and fragments of diabase and metagraywaclce in a matrix of scaly argillite. The matrix foliation and subparallel-aligned blocks strike generally northeast and dip gently south.

The mixed zone grades downward into attenuated beds of graywacke, and scaly to pencil-cleaved argillite with detached fold limbs. In turn, the argillite and graywacke grade downward into planar phyllite that overlies fine-grained, thin-bedded turbidites. The turbidite beds are graded, overturned, and contain flutes, grooves, ripples, and Bouma sequences. These features suggest north-vergent overturning and could indicate northward thrusting of the Tozitna terrane (TRMt) over the Ruby terrane (PzPr). Detailed structural studies, however, are needed to support these interpretations.

MILE 69.8 (fig. 48). Turn east onto the pipeline access road and clrive to the locked gate. A 13-ft-high (4 m) road cut along the access road exposes a phyllitic, thin-bedded graywacke-shale sequence of the Slate Creek panel (PzEr), which structurally underlies the Tozitna terrane. The sequence has been metamorphosed to a lower grade greenschist-facies assemblage (quartz + albite + muscovite + rutile + pyrite + retrograde chlorite). Metamorphism probably occurred in Early Cretaceous time, on the basis of K-Ar ages (about 135 Ma) of the structurally underlying schists.

The graywacke-shale sequence has been isoclinally folded and is associated with axial-planar cleavage, local mullion structure, and a finely streaked mineral lineation that plunges to the southeast. Orientation of the fold axes is variable and probably indicates rotation of the folds during deformation. Although the kinematics of this deformation are uncertain, they are critical to modeling the direction of emplacement of the Tozitna terrane.

MILE 73.5. SAND HILL (fig. 48).

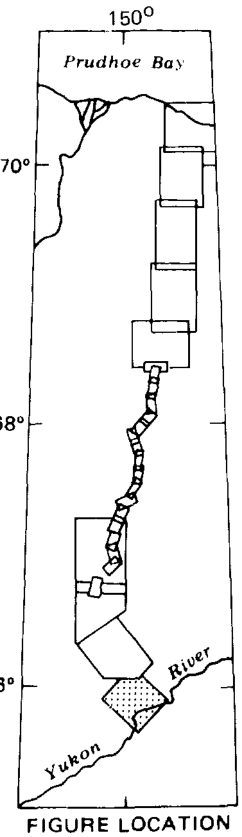


Figure 48. Geologic map of Dalton Highway area *from* Mile 56 to Mile 76. Map modified from Chapman and *others* (*1971*), *Brosgé* and *others (1973)*, *Patton* and *Miller* (*1973*), and Chapman and others (1982).

[3]Prepared by J.M. Murphy and T.E. Moore, U.S. Geological Survey. 1988.

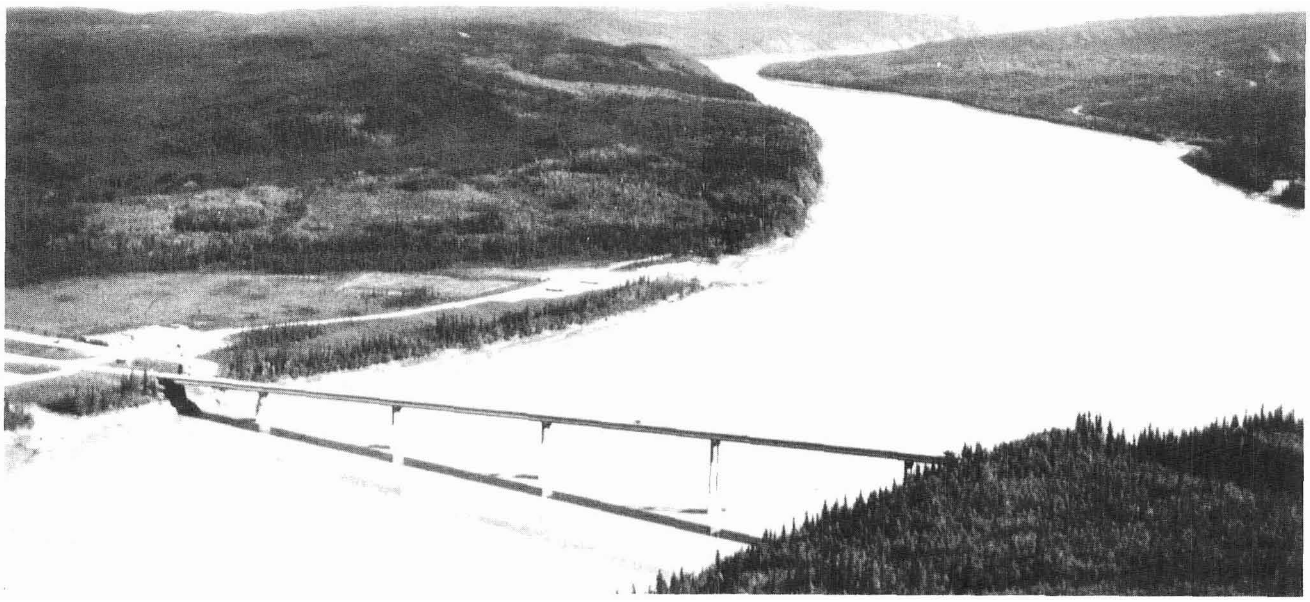


Figure 47. View northeastward along Yukon River from Yukon River bridge near Mile 56. Photograph by C.G. Mull, August 1976.

ROAD LOG FROM YUKON CROSSING (MILE 56) TO SOUTH FORK KOYUKUK RIVER (MILE 156.2)

By W.W. Patton, Jr.,[1] T.P. Miller,[2]
and S.E. Box[1]

MILE 56. YUKON RIVER CROSSING (figs. 47 and 48). The Yukon is the largest river in Alaska, the fifth largest in North America, and the 20th largest in the world. It heads in Atlin, Bennett, and Tagish Lakes near the border between British Columbia and the Yukon Territory in Canada and flows west and northwest 1,985 mi (3,170 km) to the Bering Sea. The Yukon is navigable for 1,782 mi (2,850 km) from Whitehorse, Yukon Territory, to the sea during the period between breakup in mid-May and freezeup in October. During summer, the river carries suspended glacial sediment from the White River and other glacier-fed rivers in the Yukon Territory.

From Whitehorse, the Yukon flows through a generally narrow valley to Circle, Alaska, where it enters the Yukon Flats basin, a 70-mi-wide (110 km) lowland of Cenozoic age that extends about 200 mi (320 km) along the river from Circle to Fort I-Iamlin, 15 mi (25 km) upstream from the Yukon River crossing. At Fort Hamlin, the river enters the Ramparts and flows about 100 mi (160 km) to Tanana in entrenched meanders as deep as 2,175 ft (670 m). The uplands above Tanana are underlain by resistant pre-Tertiary deposits and small, downfaulted basins of soft Tertiary sedimentary rock. Downstream from Tanana, the Yukon flows through broad lowlands, now and again impinging on the bordering hills before reaching the Bering Sea.

The river drains an area of about 334,000 mi^2 (835,000 km^2). The flow from the drainage area (206,000 mi^2; 517,000 km^2) above Rampart (50 mi [85 km] downstream from the Dalton Highway crossing) ranges from about 96,000 ft^3/s (2,800 m^3/s) in early spring to about 686,000 ft^3/s (20,000 m^3/s) in late spring. The maximum probable flood at Rampart was estimated at 34,000,000 ft^3/s (1,000,000 m^3/s). Breakup of river ice in May is a spectacular event, accompanied by a sudden rise in river level and ice jams in narrows such as beiow Fort Hamlin.

A major obstacle to pipeline builders was the Yukon River crossing. During bridge construction in 1974-75, hovercraft were used in summer and an ice bridge during winter to transport supply trucks. The 2,170-ft (700 m) steel box-girder bridge was completed in October 1975. Alyeska Pipeline Service Company funded additional work to accommodate the pipeline, which now runs along the upstream side of the bridge. (See Brown and Kreig, 1983, p. 80-81.)

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[2]U.S. Geological Survey, 4200 University Drive. Anchorage, Alaska 99508.

In the area of the Yukon River bridge, the Yukon River has cut into mafic rocks (TRMt) of the Tozitna terrane (Jones and others, 1984a), as shown by representative lithologies in beach cobbles. The terrane consists of a structurally complex assemblage of Mississippian to Triassic basalt and radiolarian chert, Permian limestone, and rare Jurassic ultramafic rocks that were intruded by thick, sill-like gabbroic bodies. The terrane is probably thrust over pelitic schists of the Proterozoic(?) and Paleozoic Ruby terrane (PzPr). Direction of thrusting has not yet been determined; however, both southeastward and northwestward vergence have been suggested.

North of the Yukon River, the Dalton Highway winds through the heavily forested Fort Hamlin Hills on the south flank of the Ruby geanticline (fig. 49).

MILE 60.7 (fig. 48). The road crosses an insulated, elevated segment of the pipeline laid in a large culvert beneath the road embankment. The crossing was specifically designed for the underlying thaw-unstable soils. Parallel to the road is a 3,600-ft-long (1,200 m) airstrip, so beware of low-flying aircraft. (See Brown and Kreig, 1983, p. 89).

MILE 61.8 (fig. 48). Turn east into the DOTPF maintenance camp; then turn north onto the first road, which leads to a small quarry. In the face of the quarry is an exposure of deeply weathered plagioclase-clinopyroxene gabbro of the Tozitna terrane (TRMt). The gabbro is typically altered to a low-grade greenschist-facies assemblage (albite + epidote + chlorite + actinolite ± hornblende). Red chert, in uncertain relationship to the gabbro, is exposed in the drainage ditch near the turnoff to the quarry. Clear, spherical radiolarians within the chert are visible with a hand lens. Jones and others (1984b) have recovered radiolarians of Mississippian, Pennsylvanian, Permian, and Late Triassic age from other localities within the Tozitna terrane.

MILE 66.3 (fig. 48). Road cuts on both sides of the road expose gabbro and diabase of the Tozitna terrane (TRMt).

MILE 67.2 (fig. 48). Road cuts expose phyllitic quartzofeldspathic metagraywacke of the Ruby terrane (PzEr), which lies structurally beneath the Tozitna terrane.

MILE 68.3 (fig. 48).[3] Road crosses pipeline. Road cuts on the north and east sides of the Dalton Highway and in the east wall of the pipeline trench north of the road expose the contact between the Narvak and Slate Creek thrust panels (see entry for Mile 165.7). Diabase of the Narvak panel (TRMt) is separated from metagraywacke turbidites of the underlying Slate Creek panel (part of PzPr) by a tectonically mixed zone of blocks and fragments of diabase and metagraywacke in a matrix of scaly argillite. The matrix foliation and subparallel-aligned blocks strike generally northeast and dip gently south.

The mixed zone grades downward into attenuated beds of graywacke, and scaly to pencil-cleaved argillite with detached fold limbs. In turn, the argillite and graywacke grade downward into planar phyllite that overlies fine-grained, thin-bedded turbidites. The turbidite beds are graded, overturned, and contain flutes, grooves, ripples, and Bouma sequences. These features suggest north-vergent overturning and could indicate northward thrusting of the Tozitna terrane (TRMt) over the Ruby terrane (PzPr). Detailed structural studies, however, are needed to support these interpretations.

MILE 69.8 (fig. 48). Turn east onto the pipeline access road and drive to the locked gate. A 13-ft-high (4 m) road cut along the access road exposes a phyllitic, thin-bedded graywacke-shale sequence of the Slate Creek panel (PzEr), which structurally underlies the Tozitna terrane. The sequence has been metamorphosed to a lower grade greenschist-facies assemblage (quartz + albite + muscovite + rutile + pyrite + retrograde chlorite). Metamorphism probably occurred in Early Cretaceous time, on the basis of K-Ar ages (about 135 Ma) of the structurally underlying schists.

The graywacke-shale sequence has been isoclinally folded and is associated with axial-planar cleavage, local mullion structure, and a finely streaked mineral lineation that plunges to the southeast. Orientation of the fold axes is variable and probably indicates rotation of the folds during deformation. Although the kinematics of this deformation are uncertain, they are critical to modeling the direction of emplacement of the Tozitna terrane.

MILE 73.5. SAND HILL (fig. 48).

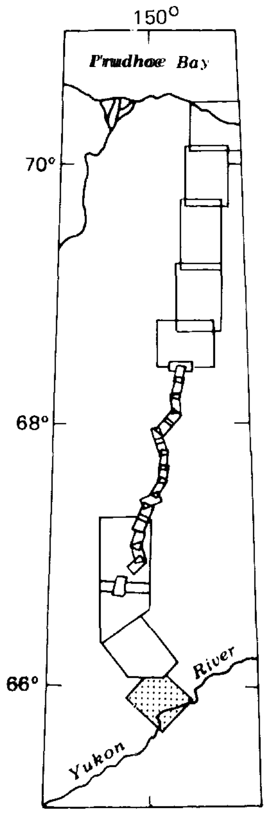


Figure 48. Geologic map of *Dalton* Highway area from Mile 56 to Mile *76*. Map modified from Chapman and others *(1971)*, *Brosgé* and others *(1973)*, *Patton* and Miller *(1973)*, and Chapman and others *(1982)*.

[3]Prepared by J.M. Murphy and T.E. Moore, U.S. Geological Survey, 1988.

EXPLANATION

[To be used with figures 48,50,53, and 57]

- Q — Surficial deposits (Quaternary)
- QTb — Basalt (Quaternary-upper Tertiary)
- Tv — Volcanic rocks (lower Tertiary)
- Kc — Conglomerate, graywacke, mudstone (Cretaceous)
- Kg — Granitic rocks (Cretaceous)
- Ja — Angayucham terrane: ultramafic rocks (Jurassic)
- Jt — Tozitna terrane: ultramafic rocks (Jurassic)
- ŦMa — Angayucham terrane: basalt, chert, gabbro, and limestone (Triassic to Mississippian)
- ŦMt — Tozitna terrane: basalt, gabbro, chert, and limestone (Triassic to Mississippian)
- PzPr — Ruby-Arctic Alaska terranes: pelitic schist, phyllite, greenstone, quartzite, and carbonate rocks (lower Paleozoic and Proterozoic?)

1 : 250,000

0 — 5 mi

0 — 8 km

MAP SYMBOLS

- Contact
- Fault, inferred
- Thrust fault, inferred
- 92 — Designated point of interest in road log; number indicates mileage from beginning of Dalton Highway

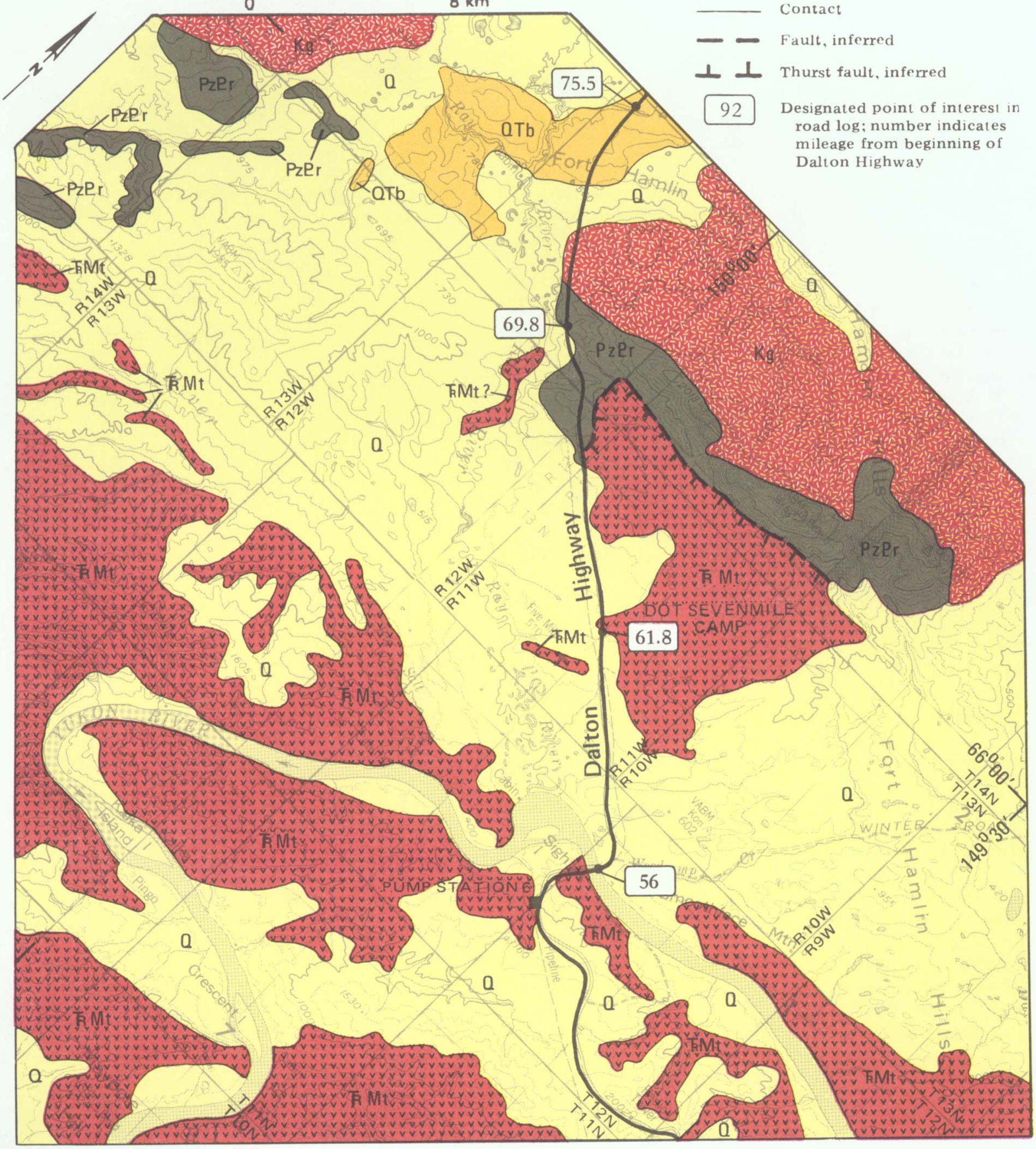


Figure 49. View southward from Fort Hamlin Hills toward Yukon River. Heavily forested, rolling hills are characteristic of south flank of Ruby geanticline. Photograph by C.G. Mull, August 1985.

MILE 74.8. ROLLER COASTER (fig. 48).

MILE 75.5 (fig. 48). Low cuts on both sides of the road expose upper Cenozoic olivine-basalt flows (QTb) depositionally overlain by unconsolidated quartzose sand and gravel (Q). Similar undated basalts are present along the east side of the Yukon Flats, which is underlain by a thick(?) sedimentary basin, as shown by a 50 mGal gravity low within the flats. Downfaulting associated with formation of the basin may be related to the undated basalts.

MILE 78.2 (fig. 50). The road reaches a high point that provides a good view of Caribou Mountain (3,179 ft; 970 m) and the valley to the south.

MILE 79. NO NAME CREEK BRIDGE (North Fork Ray River) (fig. 50).

MILE 82 (fig. 50). To the west lies a group of hills composed of mafic rocks of the Tozitna terrane (ƦMt). These rocks structurally overlie subhorizontally foliated micaceous schist of the Ruby terrane (PzEr). To the east lie tors of horizontally foliated quartzitic schist of the Ruby terrane (PzPr) above cryoplanation terraces.

MILE 85 (fig. 50). Hills along skyline to the north are underlain by an unnamed Cretaceous granitic pluton (Kg).

MILE 86.3 (fig. 50). Access road on the left leads to a quartzite quarry in the Ruby terrane (PzEr). (See Brown and Kreig, 1983, p. 97-99).

MILE 87. MACKEY HILL (fig. 50).

MILE 90.2 (fig. 50). Bordering a wide spot in the road, 16-ft-high (5 m) road cuts expose quartz-mica schist (greenschist facies) of the Ruby terrane (PzEr); the schist structurally underlies the phyllitic graywacke-shale sequence (see entry for Mile 69.8). Mica trains and quartz rods in the schist define a southeast-plunging lineation; numerous quartz segregation bands parallel schistosity. Foliation dips gently to the south and is locally cut by small, southeast-vergent thrust faults that

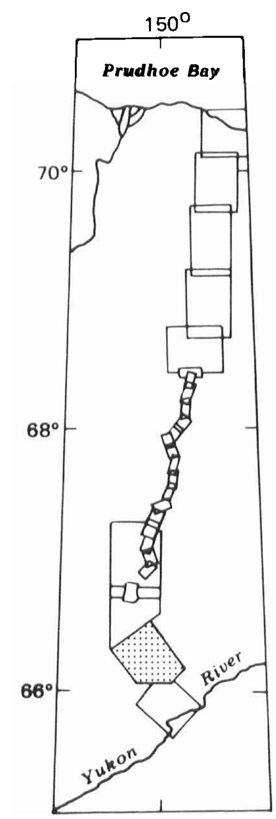
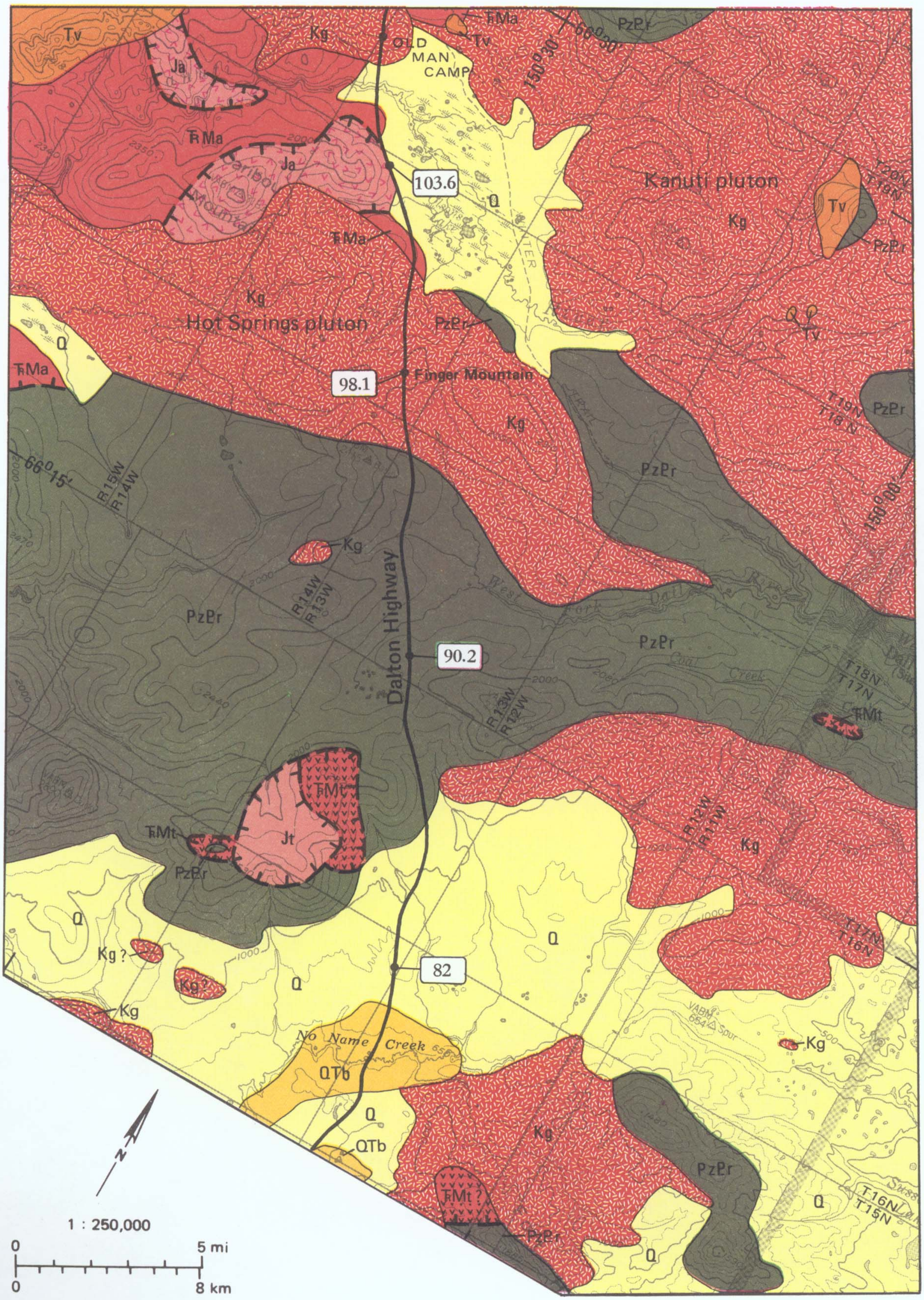


Figure 50. Geologic map of Dalton Highway area from Mile 76 to Mile 108. Map modified from Chapman and others (1971), Brosgé and others (1973), Patton and Miller (1973), and Chapman and others (1982). See figure 48 for map explanantion.



Tv
Kg
OLD MAN CAMP
Ja
TRMa
Tv
PzPr
150°30'
66°30'
103.6
Q
Kanuti pluton
Caribou Mountain
Kg
Hot Springs pluton
PzPr
98.1
Finger Mountain
T19N
T18N
66°15'
R15W
R14W
R14W
R13W
Dalton Highway
90.2
Coal Creek
T18N
T17N
TRMt
R13W
R12W
R12W
R11W
Jt
T17N
T16N
82
Kg ?
No Name Creek
QTb
VABM 664 Spur
TRMt ?
T16N
T15N
150°00'
T20N
T19N
1 : 250,000
0
5 mi
0
8 km
N

Sold the schistosity into small, asymmetric folds. The fabric of the schist probably developed during overthrusting of the Tozitna terrane. Thin sections cut parallel to the lineation reveal two planar elements that intersect at a low angle. These are S C fabrics (Berthé and others, 1979; Lister, 1984), whose geometry suggests southeastward motion of the upper plate. More detailed fabric studies are needed to adequately constrain the kinematic parameters of the schist deformation.

MILE 93.9 (fig. 50). A steep access road on the west leads to a quarry in quartz-mica schist of the Ruby terrane (PzPr). Subhorizontal isoclinal folds and well-developed quartz augen within the schist indicate noncoaxial shear during foliation clevelopment. Large andalusite ancl biotite crystals crosscut the foliation, indicating that the schist was thermally altered by the adjacent Hot Springs pluton.

In the tundra-covered uplands near the quarry are good examples of solifluction features ancl sortecl circles and polygons. The small sorted circles appear to be active. (See Brown and Kreig, 1983, p. 99.)

MILE 95.6 (fig. 50). At the bottom of the slope is the approximate contact between metamorphic bedrock of the Ruby terrane (PzPr) to the south ancl younger granitic rocks (Kg) to the north. (See Brown and Kreig, 1983, p. 99.)

MILE 98.1 FINGER MOUNTAIN (PB 305.9) (figs.50 and 51). Finger Mountain is one of the more interesting summits on the roacl. The name is derived from 'Finger Rock,' one of the tors on the east side of the highway that protrudes upward at an angle and resembles a pointing finger. The mountain was a landmark for early aviators who used the tors, particularly Finger Rock, for navigation. The tors are products of weathering over a long period of time; their shapes were influenced by spacing of north-south ancl east-west joint sets in the rock. (See Brown ancl Kreig, 1983, p. 99-103.)

The tors are composed of biotite granite of the Hot Springs pluton (Kg) and display large potassium-feldspar megacrysts typical of the Ruby geanticline. The Finger Mountain granite has characteristics of S-type granites-. low in sodium, high in potassium, and compositionally restricted to biotite and two-mica leucogranite (Miller, 1984). Relatively high isotopic ratios (initial $^{87}Sr/^{86}Sr$, $^{207}Pb/^{204}Pb$, and O^{18}) probably indicate that significant amounts of continental crust of Paleozoic and older(?) age were incorporated into the parent magma (Arth and others, 1984). Mica from the granites yields an Early Cretaceous K-Ar age (about 110 Ma).

From Finger Mountain, the road descends toward Little Kanuti Flats (fig. 25), a broad valley of small lakes and swampy areas bounded on the north by the Kanuti pluton.

MILE 100.3 (fig. 50). An access road to the west leads to a granite quarry in the Hot Springs pluton (Kg). At this locality, the rock is much finer grained than on Finger Mountain and lacks large feldspar phenocrysts, even though surfaces near the quarry are almost totally covered with large feldspar crystals. (See Brown and Kreig, 1983, p. 103.)

Figure 61. Granite tor of Early Cretaceous (100 Ma) Hot Springs pluton on north side of Finger Mountain (Mile 98.1) View northward across Little Kanuti Flats lo Kanuti pluton. Photograph by C.G. Mull, November 1984.

MILE 103.6 to 103.9 (figs. 50 and 52). Road crosses shoulder of Caribou Mountain. Outcrop rubble on the west side of the road consists of contact-metamorphosed, serpentinized harzburgite and gahbro of the allochthonous Angayucham terrane (Ja). The harzburgite is highly strained and partially altered to serpentine and contains abundant finegrained, euhedral olivine. The relatively fresh gabbro contains andesine, and late-stage brown hornblende which replaced the original clinopyroxene.

MILE 105.7. KANUTI RIVERCROSSING (fig. 50). Metagabbro of the Angayucham terrane (Ja) crops out in the stream bottom at the pipeline crossing, and mafic igneous rock of the Angayucham terrane (TRMa) is exposed in the quarry on the west side of the roacl south of the bridge. About 2,000 ft (600 m) north of the river on the pipeline right-of-way is the contact between mafic igneous rock (TRMa) to the south and granite (Kg) to the north. (See Brown and Kreig, 1983, p. 105.)

MILE 105.9. OLD MAN AIRFIELD (fig. 50).

MILE 107. OLD MAN CAMP (figs. 50 and 52). The quarry on the west side of the road is in weathered, pink granite of the Kanuti pluton (Kg). The granite contains large feldspar crystals.

MILE 109.3 (fig. 53). Twenty-ft-high (6 m) road cuts along both sides of the road expose grus over granite of the Kanuti pluton (Kg). To the east are numerous outcrops of the weathered granite; to the west on the hilltops are numerous outcrops of weathered porphyritic granite. An access road at the crest of the hill exposes the contact between granitic bedrock to the southwest and mafic bedrock of the Angayucham terrane (TRMa) to the northeast. (See Brown and Kreig, 1983, p. 107.)

MILE 110 (fig. 53). The long, steep hill descending to the north is known locally as the 'Beaver Slide,' because it is extremely slippery when wet. On a clear clay, the peaks of the southern Brooks Range about 50 mi (80 km) to the north are first visible from this point. A closer range of hills, the Jack White Range, is about 30 mi to the north.

MILE 113.9 (fig. 53). The Hickel Highway, a winter ice road to the Brooks Range and Arctic Slope, crosses the Dalton Highway immediately south of the Fish Creek bridge. The highway was constructed by the State of Alaska during the winter of 1969-70 and was used for two winters by trucks that hauled equipment to northern Alaska. It was named for former Governor Walter J. Hickel, who, at the time, was Secretary of the Interior.

MILE 114. FISH CREEK BRIDGE (fig. 53). Fish Creek is the southernmost stream along the Dalton Highway north of the Yukon River to have been mined for gold. (See Brown and Kreig, 1983, p. 108.)

MILE 115.3. ARCTIC CIRCLE (lat 66°33'24.9" N.) (PB 298.7) (fig. 53). The Yukon-Koyukuk basin and the Kanuti Flats lie to the west of the highway. Mafic (TRMa) and ultramafic rocks of the Angayucham terrane overlie schistose rocks of the Ruby geanticline (PzPr) and dip beneath the north, east, and southeast flanks of the basin. The extent to which the schistose rocks along the Ruhy geanticline margin project beneath the basin is uncertain. A thick sequence of mid-Cretaceous (Albian to Cenomanian) clastic rocks fills the northeastern end of the basin. The clastic detritus is derived primarily from the metamorphic rocks and overlying mafic allochthonous rocks of the basin's margins. Hills in the far distance to the west are composed of Lower Cretaceous andesitic volcanic rocks that also underlie much of the basin. These rocks are considered to be remains of an intraoceanic volcanic arc that collided with North America. The collision resulted in overthrusting of the older Angayucham rocks (TRMa) over

Figure 52. View norlhweslward from Mile 102 across shoulder of Caribou Mountain (left center), which contains harzburgite and gabbro of Angayucham terrane. Road and pipeline cross Kanuti River (upper center) and climb to Old Man Camp (upper right) at Mile 107 on flank of Kanuti pluton. Photograph by C.G. Mull, August 1976.

the continental margin at the present margins of the Yukon-Koyukuk basin. Low initial $^{87}Sr/^{86}Sr$ ratios from crosscutting Upper Cretaceous (~85 Ma) plutons (Arth and others, 1984) indicate that no Paleozoic or older continental crust underlies the Lower Cretaceous volcanic rocks.

A road cut just south of the Arctic Circle exposes phyllite of the Slate Creek panel (part of PzPr) that appears to structurally overlie schist of the Ruby geanticline (PzPr) and to underlie rocks of the Angayucham terrane (TRMa). Beyond the Arctic Circle sign is a campground. Several tors, among them a prominent greenstone spire in the Ruby terrane (PzPr), are present along the access road beyond the campground.

MILE 119.8 (figs. 53 and 54). To the west is the Koyukuk basin. The basin was glaciated, probably during late Tertiary and early Quaternary time. The oldest recognizable glacial advance is correlated with the Gunsight Mountain glacial phase of the northcentral Brooks Range. The advance is marked by low, broad, featureless drift and by streams deflected into ice-marginal courses. A younger glacial advance, correlated with the Anaktuvuk River Glaciaticn of the northern Brooks Range, extended southeast across the Koyukuk basin to Hulgothen Bluffs. An ice-dammed proglacial lake filled the valley of Bonanza Creek (fig. 54) to about 820 to 900 ft (250 to 275 m) in elevation. The lake was fed by drainage systems of Fish and Bonanza Creeks and by meltwater streams that issued from the ice front. (See Brown and Kreig, 1983, p. 111.)

MILE 124.6. SOUTH FORK OF BONANZA CREEK (fig. 53). At the river crossing is the approximate contact between Proterozoic(?) and lower Paleozoic phyllitic and schistose rocks of the Ruby terrane (PzPr) and granitic rocks of the Bonanza pluton (Kg). The large knob west of the river is biotite granite. On the south side of Bonanza Creek east of the low ridge is a zone of mineralized soil underlain by phyllite.

MILE 126 to 127 (fig. 53). Granite tors of the Bonanza pluton (Kg) are visible northeast and southwest of the road.

MILE 128 (fig. 53). The road crosses a tributary of Bonanza Creek and begins to climb the south flank of Gobblers Knob.

MILE 129 (fig. 53). On the west side of the road, a low cut exposes weathered biotite-granite grus of the Bonanza pluton (Kg), which contains resistant aplite dikes.

MILE 130.3 (figs. 53 and 55).[4] Just west of a sharp bend in the road, a 10-ft-high (3 m) road cut exposes andalusite-bearing quartz-muscovite-biotite schist. This belt of schist is about 1 mi wide and grades northward into the zoned Prospect Creek metamorphic belt that includes lineated phyllite, spotted phyllite, phyllite, slate, argillite, and siltstone. The metamorphic sequence was developed from dominantly pelitic protoliths and has most characteristics of regional dynamothermal metamorphic belts. Thus, the Bonanza pluton was probably emplaced late in the metamorphic episode, crosscutting the metamorphic-mineral isograds on a regional scale. Similar granitic bodies in the area have yielded K-Ar ages between 100 and 115 Ma.

The zoned metamorphic sequence is bordered on the north, perhaps across a thrust fault, by weakly recrystallized tan and gray shales, with minor chert, and the Angayucham basalt (TRMa)--a wide band of mafic metavolcanic rocks that locally includes horizons of gray marble and red chert.

MILE 131.2. GOBBLERS KNOB (elevation 1,700 ft; 550 m) (PB 282.8) (figs. 53 and 55). Gobblers Knob is a high hill just above treeline and provides a good view westward and southward toward the east end of the Koyukuk basin. Mean annual temperature at this treeline elevation is about 27 °F (-3 °C). (See Brown and Kreig, 1983, p. 113.)

MILE 132 (figs. 53, 55, and 56).[4] A broad turnout (with restroom) to the left on the north side of Gobblers Knob provides a good view northward toward Prospect Creek, Jim River, Pump Station 5, and closer hills of the Jack White Range; peaks in the distance are part of the southern Brooks Range. A road to the right leads to a quarry that exposes phyllitic, thin-bedded quartzose graywacke and shale of low greenschist facies in the Prospect Creek metamorphic belt. Postkinematic biotite grows across the synkinematic greenschist-facies assemblage. Cleavage is at a low angle to the bedding and has an associated finely streaked mineral lineation that plunges to the south-southeast. Abundant quartz veins are folded and boudinaged. A narrow dike of biotite lamprophyre cuts the foliation and is presumably related to the adjacent 110 Ma biotite granite (Kg).

MILE 135.[4] PROSPECT CREEK (figs. 53 and 55). Prospect Creek is well known for its recently discovered placer-gold deposits. The lower part of the creek is a side-glacial channel developed in Pleistocene time beside the Jim River ice sheet. Apparently, the channel acted as a natural sluice box to concentrate gold and other heavy minerals that were released from mineralized veins in phyllite and slate-siltstone metamorphic zones.

MILE 135.5 (figs. 53 and 55). Low road cuts expose basalt rubble of the allochthonous Angayucham terrane (TRMa).

MILE 135.7. PROSPECT CREEK CAMP (figs. 53 and 55). The lowest temperature ever recorded in the United States, -79 °F (-62 °C), was recorded at Prospect Camp on January 24, 1971. This point is the eastern terminus of the winter road from Bettles and the proposed starting point of a transportation corridor that would connect the Ambler mining district and Nome to railheads in interior Alaska.

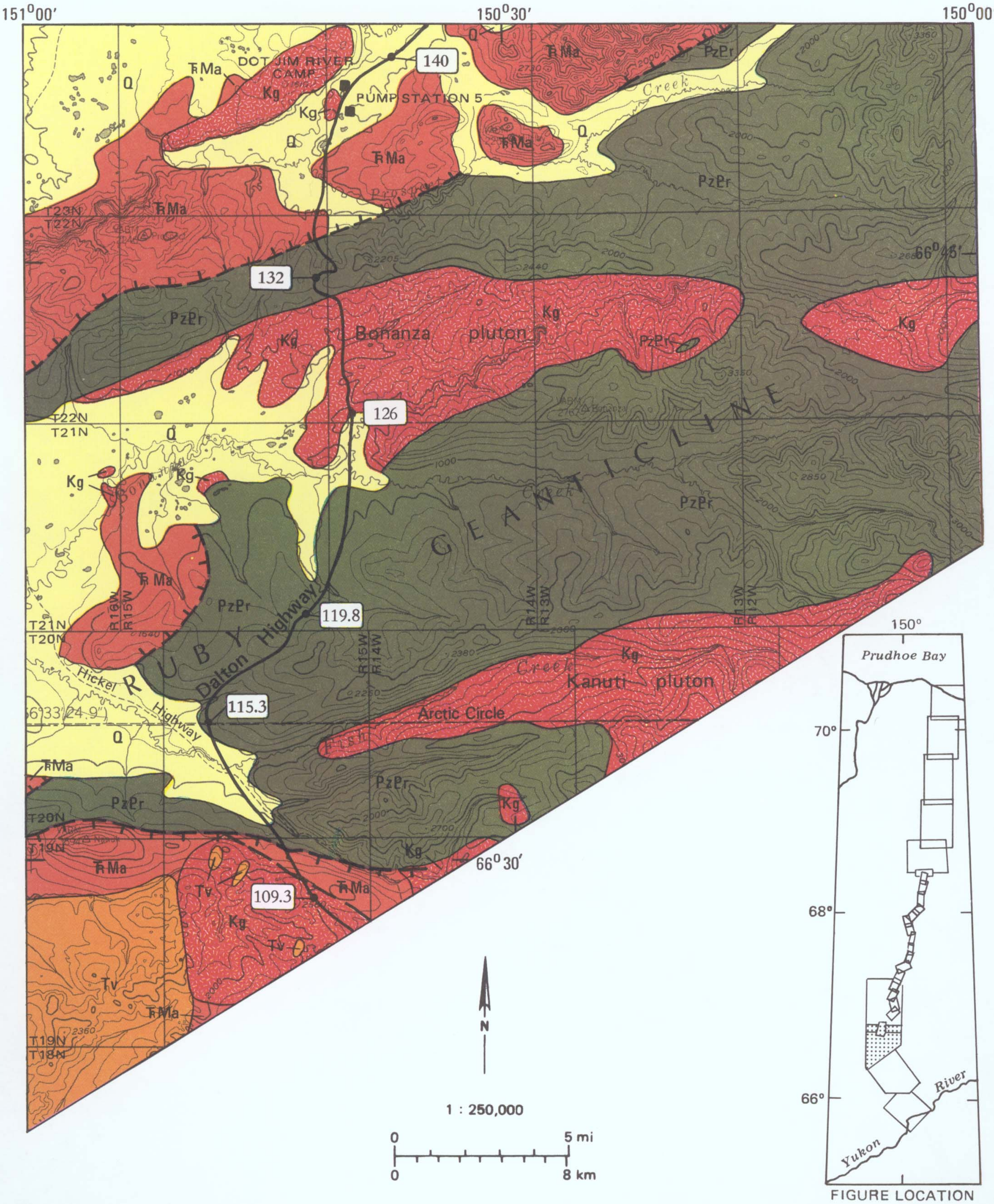
Mile 137.1. PUMP STATION 5 AND AIRPORT (figs. 53 and 55). The state-operated airport is located east of the pump station. The pump station has a refrigerated foundation that is constructed on a ridge of cemented gravel flanked by ice-rich organic silt. (See Brown and Kreig, 1983, p. 113-115.)

MILE 138.1 (figs. 53 and 55). A side road on the left leads to Jim River DOTPF road-maintenance camp. These facilities are not for public use.

MILE 140 (figs. 53, 54, and 55).[5] The highway crosses a channel of the Jim River. This point is the approximate location of the end moraine of the Jim River glacier and the drift limit that correlates with the

*Figure **53.** Geologic map of Dalton Highway area from Mile 108 to Mile 141. Map modified from Chapman and others (1971), Brosgé and others (1973), Patton and Miller (1973), and Chapman and others (1982). See figure 48 for map explanation.*

[4]Prepared by T.E. Smith, DGGS. 1985.
[5]Prepared by T.D. Hamilton, U.S. Geological Survey, 1983.


151°00′
150°30′
150°00′
DOT JIM RIVER CAMP
PUMP STATION 5
140
132
126
119.8
115.3
109.3
Bonanza pluton
Kanuti pluton
Arctic Circle
RUBY GEANTICLINE
Dalton Highway
Hickel Highway
66°45′
66°30′
66°33′24.9″
Kg
PzPr
Q
Tv
T23N
T22N
T21N
T20N
T19N
T18N
R16W
R15W
R14W
R13W
R12W
N
1 : 250,000
0
5 mi
0
8 km
150°
Prudhoe Bay
70°
68°
66°
Yukon
River
FIGURE LOCATION

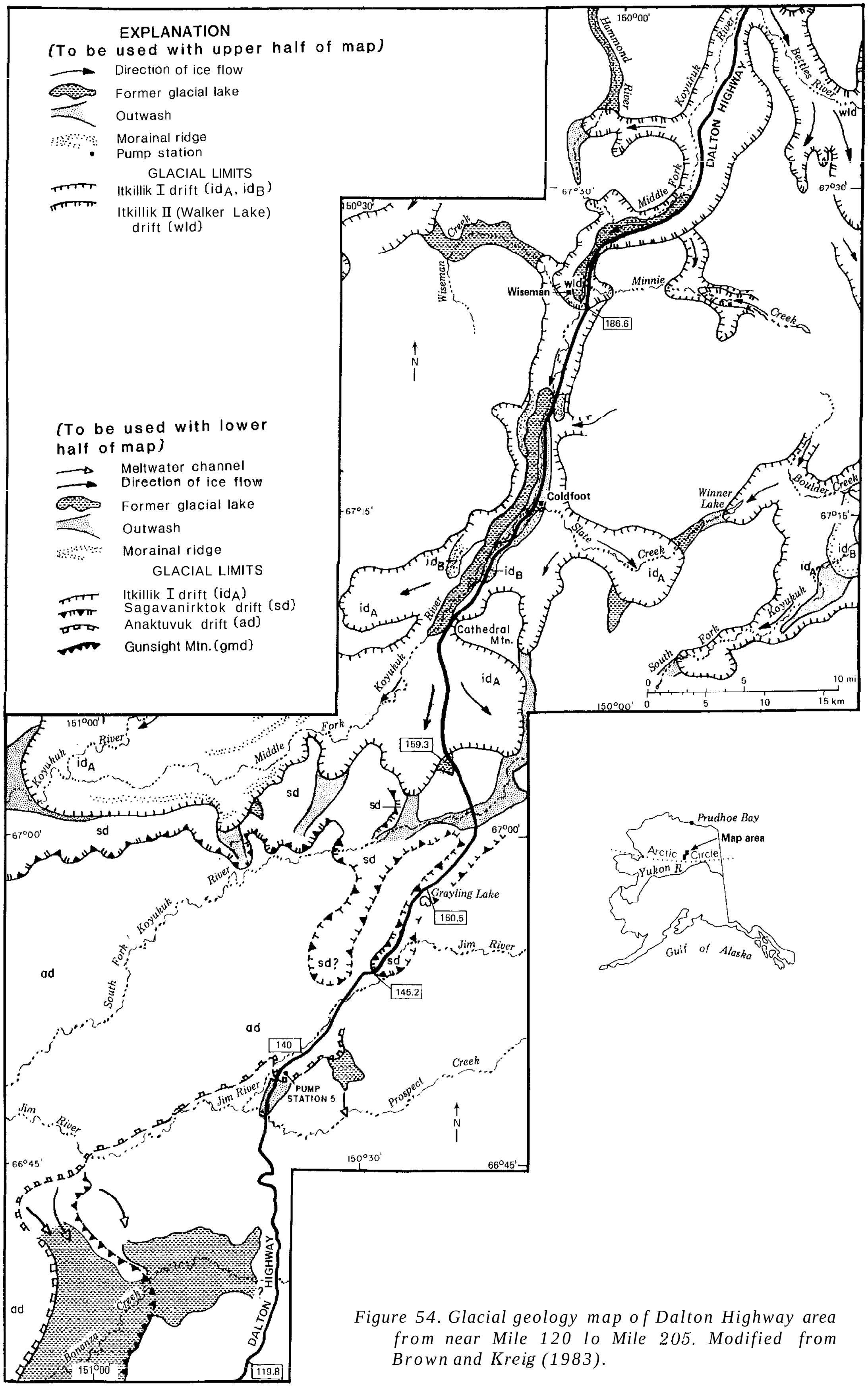


Figure 54. Glacial geology map of Dalton Highway area from near Mile 120 lo Mile 205. Modified from Brown and Kreig (1983).

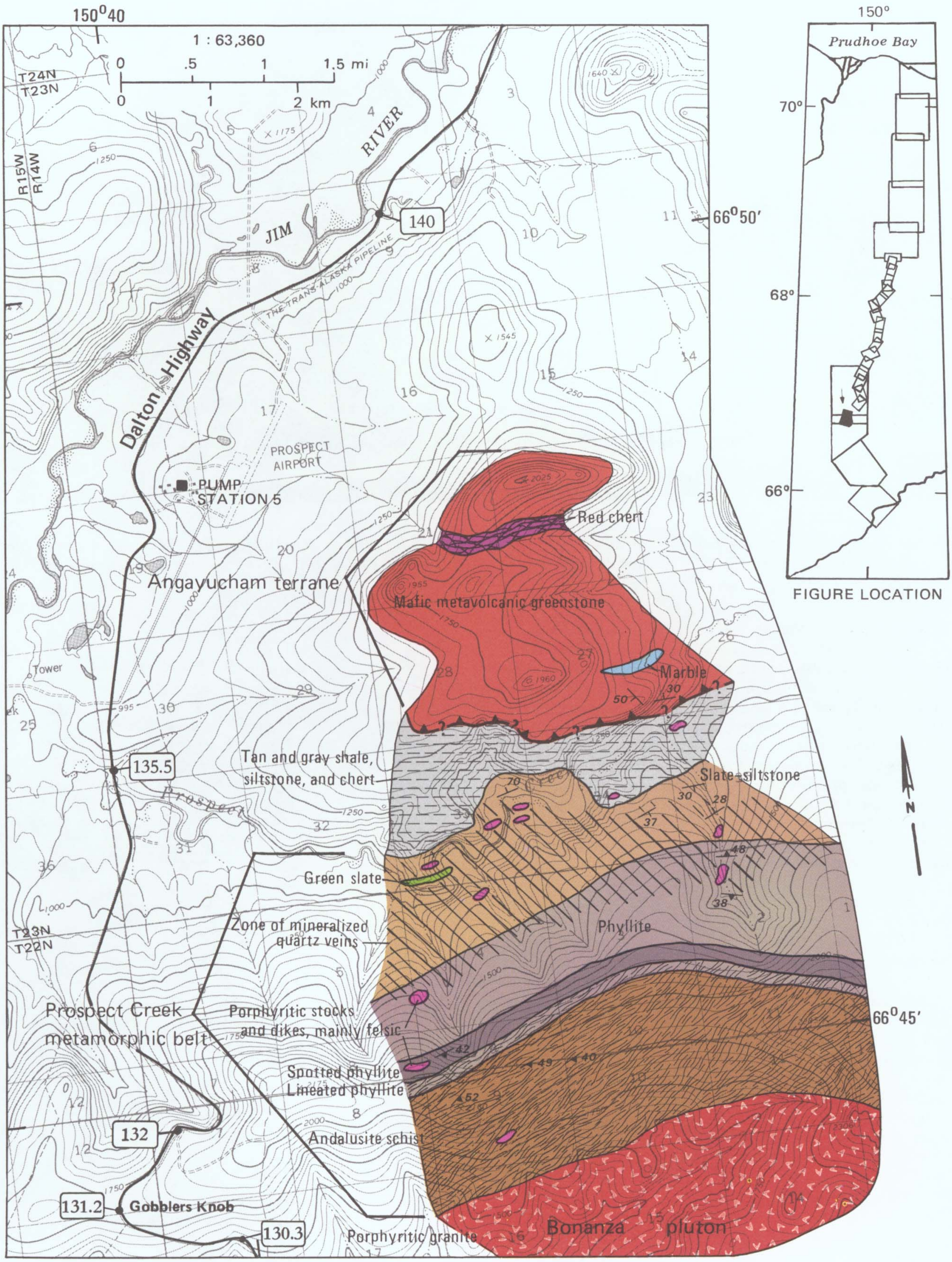


Figure 55. Geologic map of Dalton Highway area near Gobblers Knob, Mile 130 to Mile 141. Map by T.E. Smith and M.S. Robinson, DGGS, 1985.

Figure 56. View northward from north side of Gobblers Knob (Mile 132) to Jim River valley (Mile 137). Pump Station 5 at right center; peaks of Jack *White* Range (elevation 2,900 ft; 9,000 m) in distance. Photograph by C.G. Mull, May 1985.

Anaktuvuk River glacial advance (fig. 54). A remnant of a glacial outwash train, presumably the Anaktuvuk River Glaciation, extends south toward Prospect Creek. The drift has been deeply eroded by the Jim River; thus its former limits are not known. A few miles northeast, a remnant of an end moraine correlative with that of the Jim River glacier dams a proglacial lake south of Douglas Creek. An outlet stream from the proglacial lake crossed the present drainage divide and flowed south into Prospect Creek. Farther downstream, Jim River was deflected into what was probably an ice-marginal course along the north flank of a bedrock ridge, where it eroded its present deep and narrow canyon.

MILE 141.7. DOUGLAS CREEK (fig. 57).

MILE 144.1. JIM RIVER BRIDGE (third crossing) (fig. 57).

MILE 145.2 (figs. 54 and 57). The road ascends a probable moraine front (fig. 54) covered by black spruce. The drift limit is continuous with end moraines of Sagavanirktok River age (middle Quaternary) mapped farther to the north and northeast in both the Koyukuk and Chandalar river valleys (Hamilton, 1978b,c). The drifts of Sagavanirktok River age have steeper flanks, more primary relief, and are morphologically much fresher than deposits of the Anaktuvuk River ice advance. In addition, the drifts typically occupy valley-floor positions, in contrast to the Anaktuvuk River deposits, which have almost always been eroded from the centers of modern valleys (Hamilton, 1979a). (See Brown and Kreig, 1983, p. 115.)

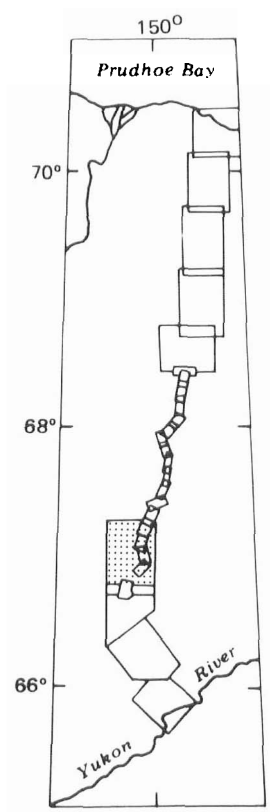


FIGURE LOCATION

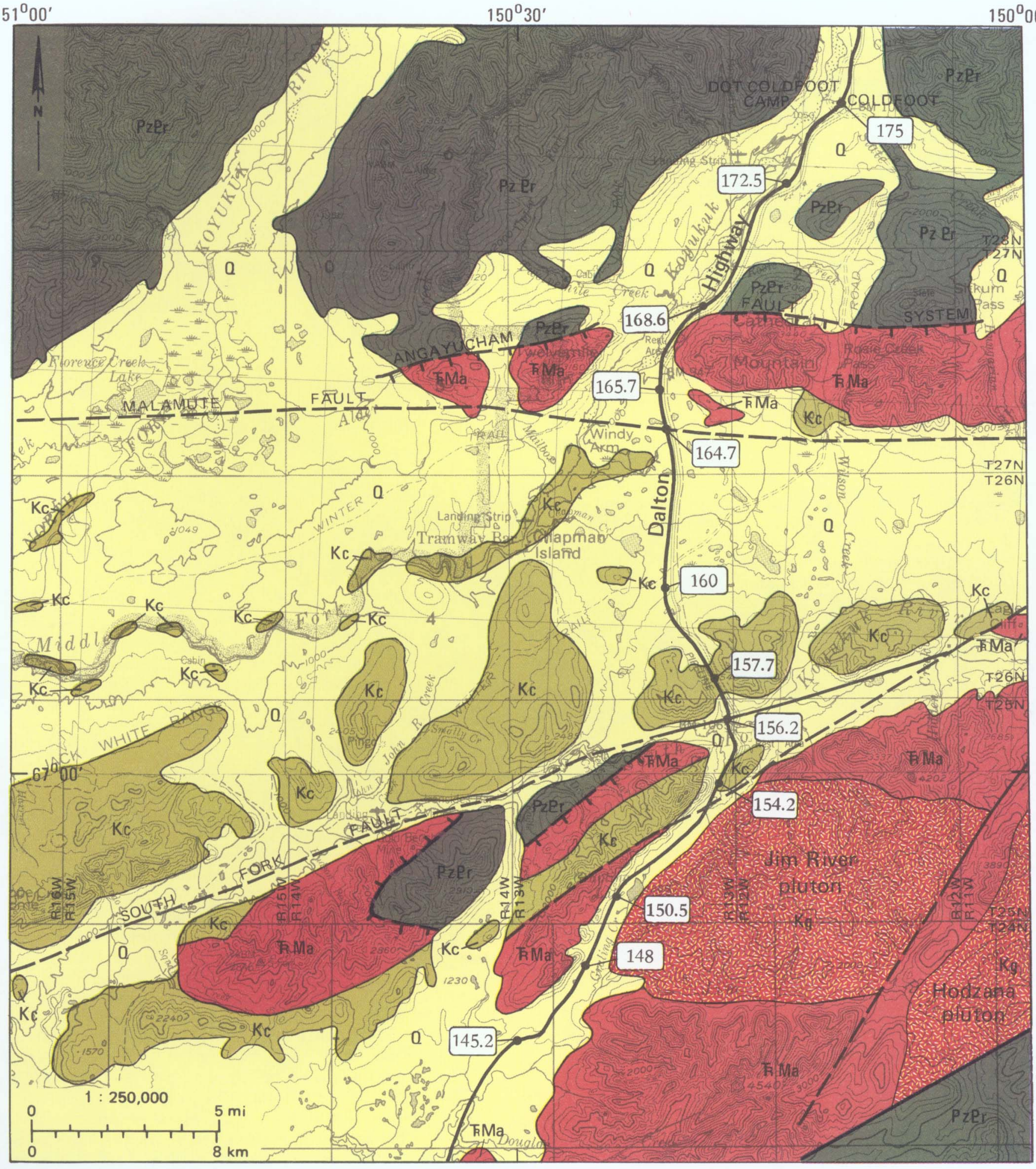


Figure 57. Geologic map of Dalton Highway area from Mile 141 to Mile 177. Map modified from Chapman and others (1971), Brosgé and others (1973), Patton and Miller (1973), and Chapman and others (1982). See figure 48 for map explanation.

MILE 145.6 (fig. 57). The road crosses the pipeline. From this point, the foothills of the Brooks Range are visible for the first time. (See Brown and Kreig, 1983, p. 117.)

MILE 146.8 (fig. 57). Brooks Range foothills are visible to the northeast through a gap in the hills. This gap is cut along the Grayling Lake fault, which separates the Jim River pluton (Kg) to the southeast from the Angayucham volcanics (TRMa) to the northwest.

MILE 148 (figs. 57 and 58).[6] The Jim River valley is visible to the east and follows the contact between the mafic volcanic rocks (fig. 57, TRMa; fig. 58, MzPzv) of the Angayucham terrane to the south, and the Jim River pluton (fig. 57, Kg; fig. 58, Kg, Kmz, Ksy) to the north. The steep talus slopes east of the highway from Mile 148 to Mile 152.5 consist of several igneous phases of the pluton.

The Jim River pluton is composed of texturally varied biotite-hornblende ± pyroxene syenites and monzonites and a core of hiotite-hornblende granite. K-Ar ages from this pluton, and the Hodzana pluton to the east, average 106 ± 6 Ma; a three-point Rb-Sr whole-rock isochron yields an age of 111 Ma. These plutons are two of many Lower Cretaceous plutons that intrude the Ruby geanticline. The Jim River pluton is unique because it also intrudes the narrow band of mafic volcanic rocks of the Angayucham terrane (fig. 57, TRMa; fig. 58, MzPzd, MzPzv) that separates the meta-sedimentary rocks of the Ruby geanticline from the Yukon-Koyultuk basin. Preliminary results of petrologic and isotopic studies of the Jim River pluton, and a comparison of this pluton with other plutons in the Ruby geanticline and Yukon-Koyukuk basin, are presented in chapter 11.

MILE 150.5. GRAYLING LAKE (figs. 54, 57, and 58). The U-shaped trough in which Grayling Lake lies was scoured by a glacier of Sagavanirktok River age (middle Pleistocene) and is much older than glacial valleys formed by the Late Pleistocene ice advances in the Brooks Range. The area has been greatly modified by postglacial weathering and erosion, but traces of lateral moraines or kame terraces are still evident near the base of the eastern valley wall. Along the bases of nearby valley walls, a rock glacier, talus aprons, and most of the alluvial fans are inactive, as shown by their weathered and vegetated surfaces (T.D. Hamilton, oral commun., 1983). Grayling Lake is not a primary kettle; rather, it is a shallow water body that probably formed as a thaw lake in older lacustrine sediments that filled the valley floor. (See Brown and Kreig, 1983, p. 117.)

MILE 154.2 (fig. 57 and 58). The right fork of the side road to the east leads to a quarry in Lower Cretaceous (Albian) monzonite and syenite of the Jim River pluton (fig. 57, Kg; fig. 58, Kg, Kmz, Ksy). Biotite and hornblende from the pluton yielded an average K-Ar age of 107 ± 6 Ma; a Rb-Sr whole-rock isochron yielded an age of 112 ± 4 Ma (Blum and others, 1987).

The left fork of the side road leads to a quarry in an Albian(?) cobble conglomerate (fig. 57, Kc; fig. 58, Kic) that is adjacent to the Jim River pluton at the margin of the Yukon-Koyukuk basin. The conglomerate, however, is separated from the pluton by a northeast-trending fault that is probably part of the South Fork fault zone.

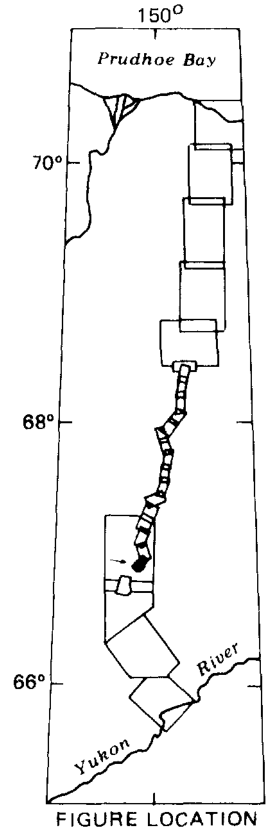


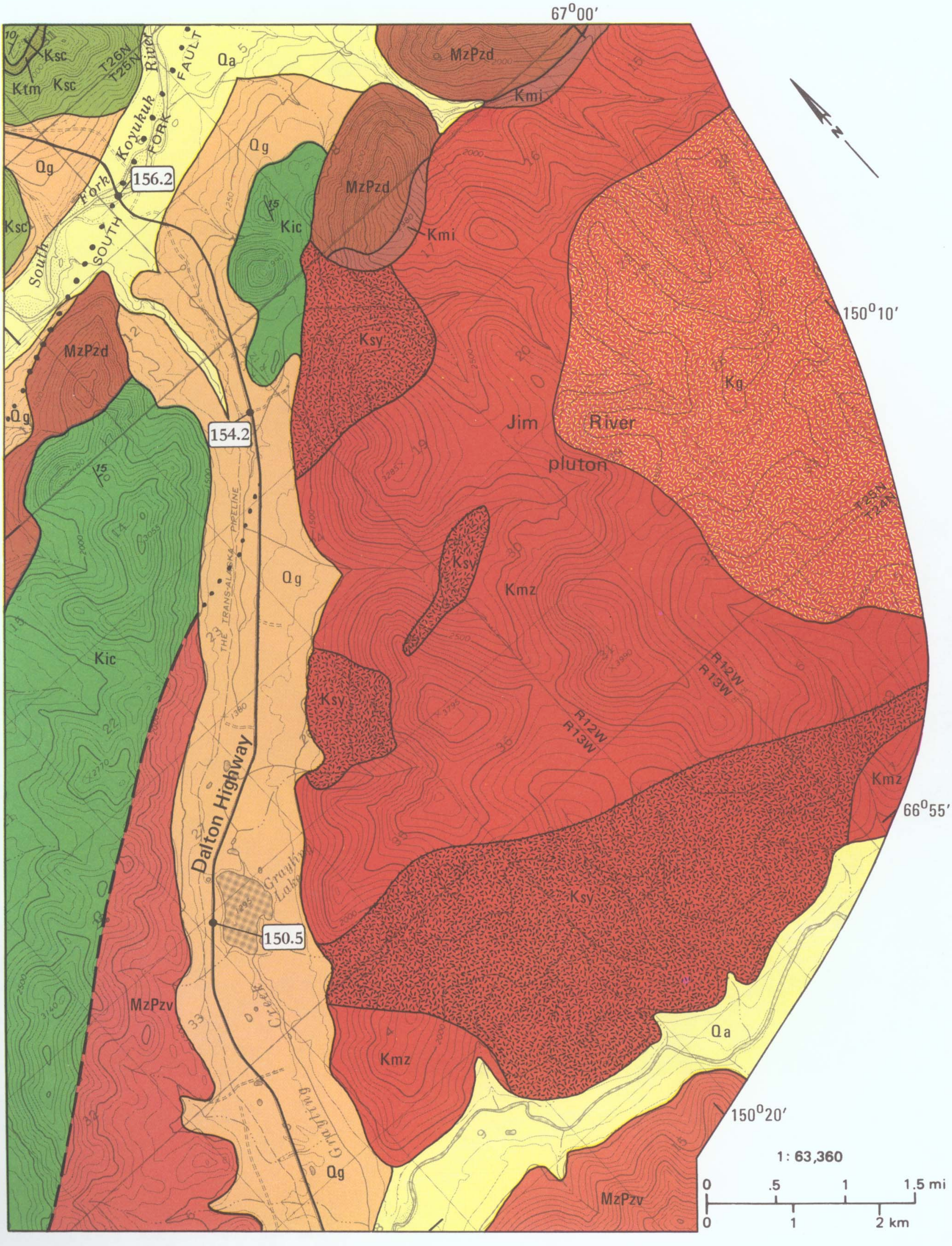
Figure 58. Geologic map of Dalton Highway area near Grayling Lake and South *Fork* Koyukuk *River*, Mile 148 to Mile 157. Map by J.D. Blum, DGGS, 1985. See figure 82 for map explanation.

Other northeast-trending, high-angle faults with sub-horizontal slickensides cut the conglomerate. Bedding in the conglomerate is poorly expressed, but where delineated, it dips steeply to the east toward the pluton.

Clast types in the conglomerate are mostly phyllitic metagraywacke, with lesser amounts of diabase and greenstone, chert, felsic volcanic rock, and white vein quartz. The clasts are matrix supported and generally well rounded. Channels and cross-bedding are locally visible. The conglomerate is mostly disorganized and probably deposited from debris flows, but whether the flows were subaerial or submarine is uncertain.

The source of felsic hypabyssal volcanic clasts and abundant potassium feldspar in the conglomerate matrix is uncertain. They may be derived from the granite plutons of the Ruby geanticline and their volcanic equivalents. Radiometric dating of the Jim River pluton and regional paleontologic data, however, indicate that the conglomerate and pluton are about the same age. J.M. Murphy (written commun., 1988) suggested that the conglomerate may have been thermally metamorphosed by the Jim River pluton, and, if so, the conglomerate would be older than the pluton, and the felsic clasts would be from a source other than the Ruby geanticline.

[6]Prepared by J.D. Blum. DGGS, 1985.


67°00′
150°10′
66°55′
150°20′
Ksc
Ktm
Qa
Qg
MzPzd
Kmi
Kic
Ksy
Kg
Kmz
MzPzv
Jim River pluton
156.2
154.2
150.5
South Fork Koyukuk River
SOUTH FORK FAULT
T26N
T25N
T24N
R12W
R13W
Dalton Highway
THE TRANS-ALASKA PIPELINE
Grayling Lake
Grayling Creek
1: 63,360
0 .5 1 1.5 mi
0 1 2 km

ROAD LOG FROM SOUTH FORK KOYUKUK RIVER (MILE 156.2) TO CHANDALAR SHELF (MILE 237.1)

By J.T. Dillon,[7] D.N. Solie, J.E. Decker, J.M. Murphy, A.A. Bakke, and J.A. Huber[8]

MILE 156.2. SOUTH FORK KOYUKUK RIVER (PB 257.7) (figs. 57, 58, 59, and 60). At this point, the final link of the haul road was made on September 7, 1974. This large river is a tributary of the Koyukuk River, which flows past the villages of Bettles, Allakaket, Alatna, Hughes, and Huslia and then drains into the Yukon River near the village of Koyukuk. On the south side of the South Fork Koyukuk River bridge is a parking area and room for camping. (See Brown and Kreig, 1983, p. 119.)

The South Fork fault trends east-northeast along the river valley. The fault is one of several Late Cretaceous to early Tertiary east-west-trending, high-angle fault zones that have many miles of right slip. It is characterized by gouge that separates equivalent portions of the Angayucham terrane and marks the northern limit of Cretaceous granites in Alaska. The South Fork fault and the Malamute fault to the north may be part of the Tintina fault system.

MILE 157.7 (figs. 57 and 60). A side road to the east provides easy access lo 300 ft (100 m) of excellent quarry-face exposures of marginal conglomerate (fig. 60, Ksc) of the Yukon-Koyukuk basin on the north side of the South Fork fault.

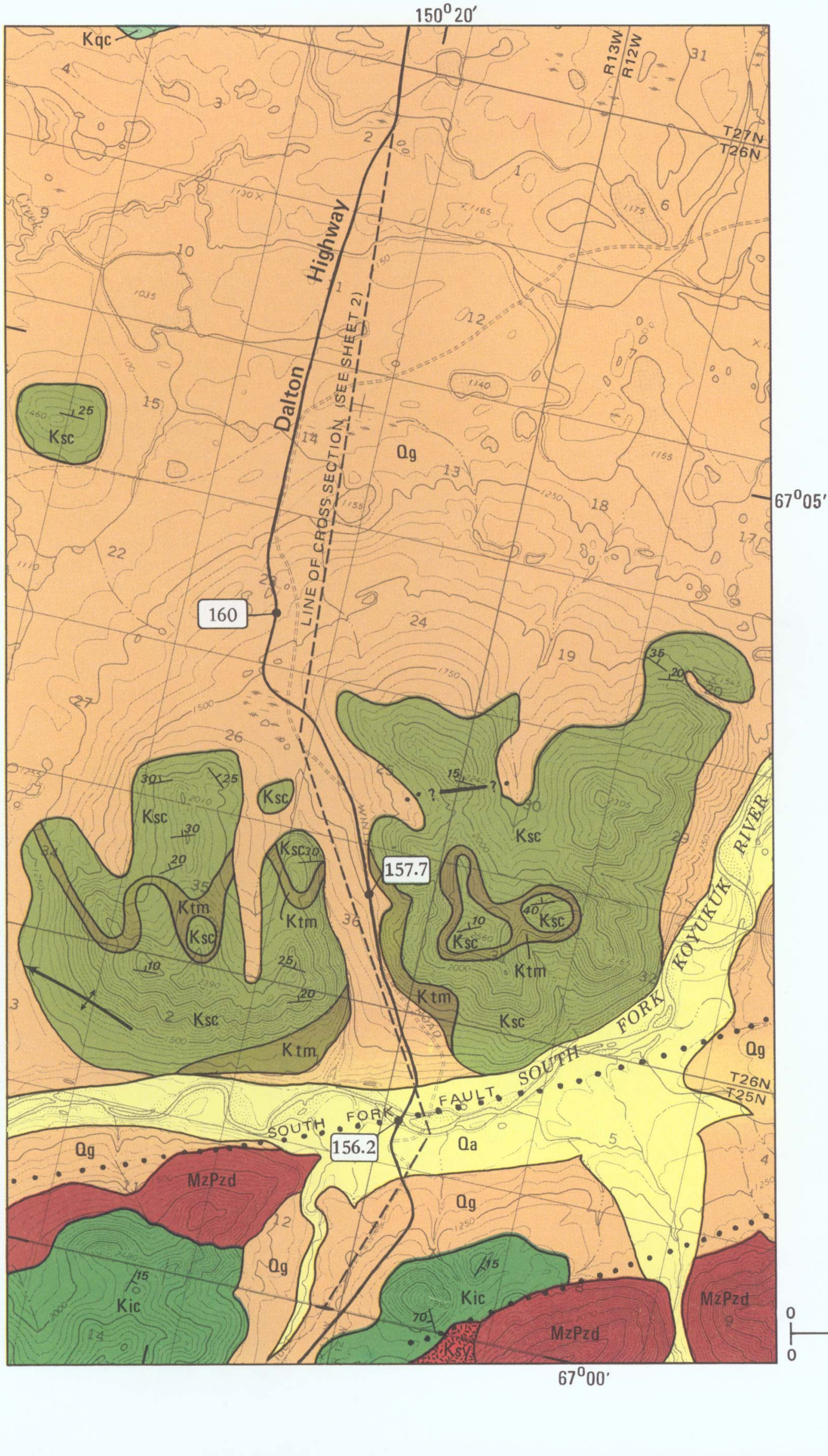
Matrix-supported, bimodal clasts in the conglomerate are composed of quartzose metagraywacke, mafic volcanic rock fragments, chert, diabase, minor white vein quartz, and a few granitic clasts. The conglomerate is horizontally stratified and locally channeled into interbedded coarse sandstone and mudstone; in some places, the conglomerate contains features that show it was injected into the mudstone. A few beds of imbricated

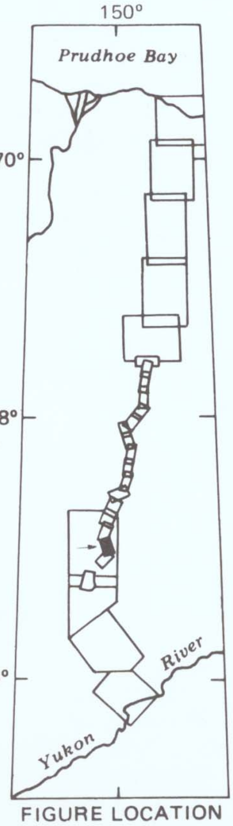
Figure 59 View northward across South Fork Koyukuk River near Mile 156. Final linkup of Dalton Highway was made here on September 27, 1974. Hills in distance are composed of mid-Cretaceous (Albian) conglomerate. Photograph by C.G. Mull, August 1976.

[7]Deceased; formerly of DGGS, 3700 Airport Way, Fairbanks, Alaska 99709.

[8]DGGS, 3700 Airport Way, Fairbanks, Alaska 99709.

Figure 60. Geologic map of Dalton Highway area from Mile 155 to Mile 164. See figure 82 for map explanation


150°20′
67°05′
67°00′
Dalton Highway
LINE OF CROSS SECTION (SEE SHEET 2)
R13W
R12W
T27N
T26N
T25N
160
157.7
156.2
Kqc
Ksc
Ktm
Qg
Qa
MzPzd
Kic
SOUTH FORK KOYUKUK RIVER
SOUTH FORK FAULT
N
1: 63,360
0 .5 1 1.5 mi
0 1 2 km


150°
Prudhoe Bay
70°
68°
66°
Yukon River
FIGURE LOCATION

clasts indicate southwesterly directed paleocurrents. Deposition probably occurred by mass flow because 1) clasts are matrix supported and bimodal; 2) some clasts are suspended in the matrix in gravitationally unstable orientations; 3) the unit generally lacks crossed, graded, or imbricated bedforms; and 4) intraformational shale rip-up clasts and poorly developed reverse grading and erosional channels are present at the base of thick conglomerate beds.

Along the southern flank of the Brooks Range, Cretaceous conglomerates (fig. 57, Kc) unconformably overlie obducted oceanic rocks (fig. 57, TrMa) of the Angayucham terrane. To the south, across the South Fork fault, apparently coeval conglomerate at Mile 154.2 unconformably overlies rocks of the Angayucham terrane. The conglomerate at Mile 154.2, however, contains clasts of Cretaceous felsic volcanic rock that are absent at Mile 157.7.

A change in clast composition of successively younger conglomerates that fringe the southern Brooks Range records the progressive unroofing of the range. The clasts change from fine-grained mafic and ultramafic rocks, including gabbro, at the base of the conglomerate sequence to chert, metagraywacke, and vein quartz at the top. In the Dalton Highway area, conglomerate as young as Cenomanian age contains no clasts of schist from the schist belt of the Brooks Range (J.M. Murphy and Suzanne Saward, written commun., 1988); however, clasts derived from the schist belt are present in Albian conglomerate farther west (Dillon and others, 1984, 1987). This suggests that uplift and erosion down to the core of the southern Brooks Range occurred earlier in the west than in the east (J.M. Murphy, written commun., 1988).

MILE 159 (figs. 57 and 60). The road crosses the pipeline.

MILE 159.3 to 159.6 (figs. 54, 57, and 60).[9] The road crosses bog deposits that contain ice-wedge polygon features and thermokarst ponds developed in a former small proglacial lake. The road then crosses end moraines of the Itkillik Glaciation (at the gravel pits) and enters the drift complex of Itkillik age. The Itkillik Glaciation, the last major series of ice advances in the Brooks Range, is represented by three principal drifts in the valley systems of the south, middle, and north forks of the Koyukuk River. The outermost drift was deposited by large piedmont lobes that formed when valley glaciers receded and is older than the maximum range of radiocarbon dating. A set of younger moraines has sharper relief than the outermost Itkillik drift but is also too old to date by radiocarbon methods. Ice tongues in both the north and middle forks of the Koyukuk River terminated in moraine-dammed lakes that formed during the first Itkillik advance. A drift sheet along the South Fork Koyukuk River that is correlative(?) with the ice tongues is marked by a conspicuous outwash train and an extensive moraine-dammed lake. The youngest substage of the Itkillik is termed the Walker Lake advance and is well dated by radiocarbon between 11,800 and 24,500 yr B.P. (fig. 23). Glaciers of Walker Lake age flowed sluggishly as underfit ice streams through broad troughs carved by much larger glaciers of the older Itkillik substages; the glaciers of Walker Lake age generally terminated 10 to 20 mi (16 to 32 km) inside the range. Moraine-dammed lakes of Walker Lake age are still present in some valleys, but elsewhere glacial lakes either did not form or were drained early and have been filled by later alluviation on the valley floors.

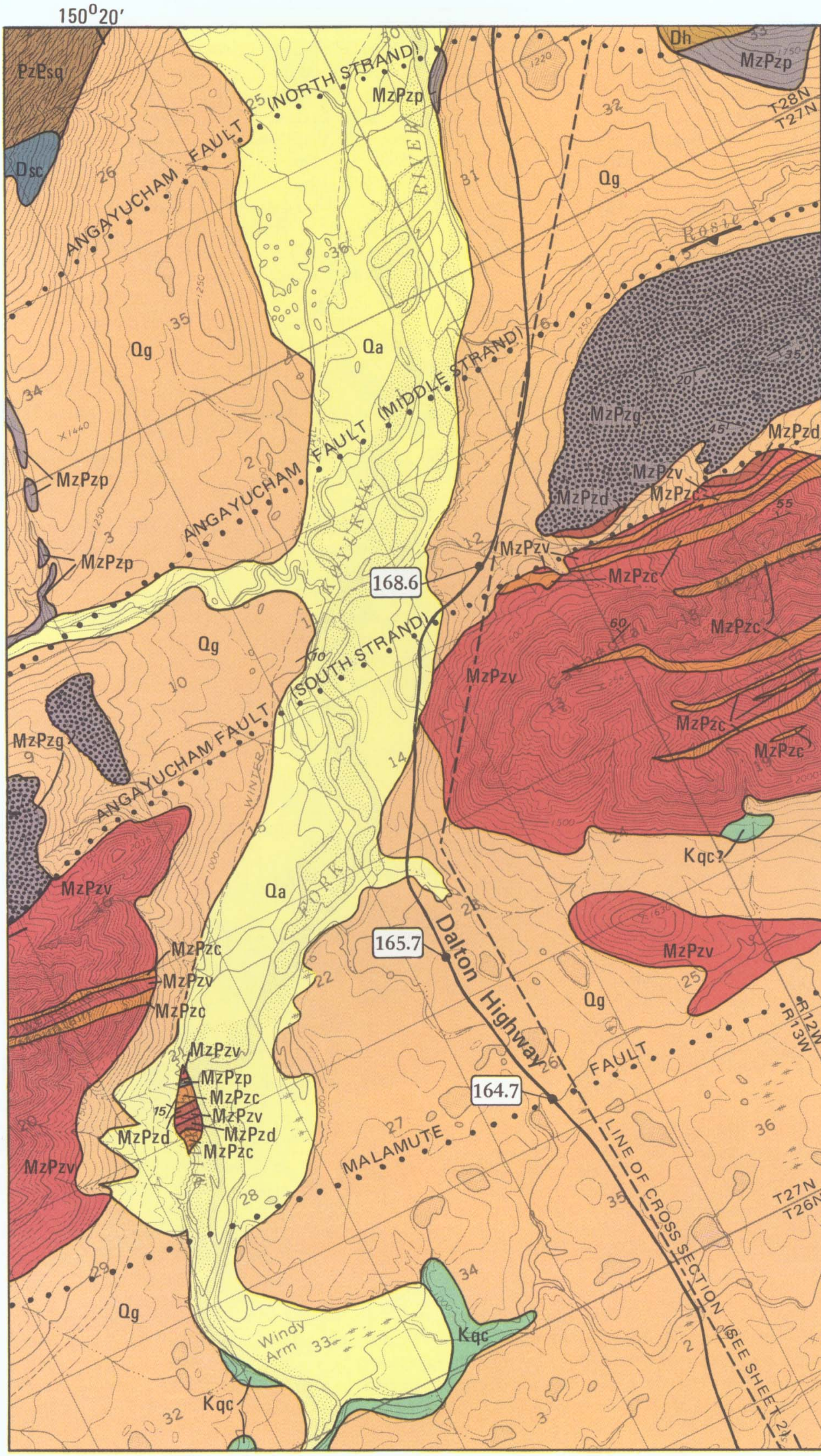
MILE 160 (figs. 57 and 60).[10] The road crosses a recessional moraine(?) and descends onto an outwash plain. From the crest of the moraine is a good view of the Brooks Range to the north. The southernmost row of peaks within the range is underlain by mafic rocks (fig. 57, TrMa) of the Angayucham terrane. The relatively low area north of these peaks is underlain by phyllite and metagraywacke of the Slate Creek panel (fig. 139, fault panel 10). The high peaks farther north are underlain by the schist belt of the Arctic Alaska terrane; these schists are similar to the country-rock schists of the Ambler mining district, 175 mi (280 km) to the, west.

MILE 164.7 (figs. 57 and 61). The road crosses the approximate trace of the mid-Cretaceous Malamute fault. This is one of the northern strands of the Malamute-South Fork and Kobuk systems of right-lateral, high-angle faults present along the northern edge of the Koyukuk basin. The Malamute fault displaces Devonian to Cretaceous rocks at the triangular junction of the Ruby geanticline, Koyukuk basin, and the southern Brooks Range (fig. 143). It is marked by broken formation and fault gouge and strikes subparallel to the Angayucham fault system along the south flank of the Brooks Range. The Malamute fault has undergone about 25 mi (40 km) of right separation and a few thousand feet of normal displacement. A similar fault, the South Fork fault (Mile 156.2), locally separates the Angayucham terrane from the Ruby terrane and is the other main strand of the Malamute-South Fork fault system.

MILE 165.7 (figs. 57 and 61). A turnout to the left provides a good view of the valley. At this point, the road enters the central Brooks Range. Twelvemile Mountain (3,190 ft; 980 m) to the west and Cathedral Mountain (3,000 ft; 920 m) to the northeast are composed of mafic igneous rocks (MzPzv) and chert (MzPzc) of the Narvak fault panel (fig. 139, fault panel 11) of the Angayucham terrane. Along the south flank of the Brooks Range, the volcanic rocks (MzPzv) of the Angayucham terrane, interpreted as oceanic crust, dip to the south and structurally overlie south-dipping phyllite and metagraywacke (MzPzg, MzPzp) of the Slate Creek fault panel (fig. 139, fault panel 10). The Slate Creek panel is of controversial affinity: some workers consider it part of the Angayucham terrane, whereas others consider it part of the Arctic Alaska terrane. The phyllite and graywacke unit, in turn, structurally overlies polymetamorphic rocks of the southern Brooks Range schist belt, part of the Arctic Alaska terrane. The major tectonic boundary between the Angayucham and Arctic Alaska terranes is called the Kobuk suture (sheet 1) and

Figure 61. Geologic map of Dalton Highway area near Twelvemile and Cathedral Mountains, Mile 163 to Mile 172. See figure 82 for map explanation.

[9]Prepared by T.D. Hamilton, U.S. Geological Survey, 1983
[10]Prepared by W.W. Patton, U.S. Geological Survey. 1985.



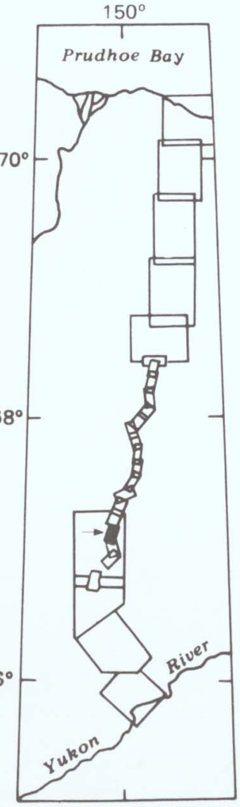
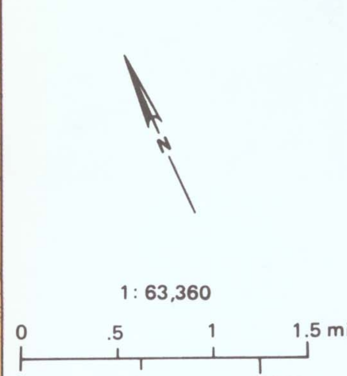


FIGURE LOCATION



consists of as many as three strands of the Late Jurassic to Early Cretaceous Angayucham fault system. Recent studies (Miller, 1987; Oldow and others, 1987b) suggest that the compressional margin represented by the Angayucham fault system has been modified by a later stage of extensional, low-angle normal faulting.

MILE 168.2 (figs. 57 and 61). Cathedral Mountain is visible to the east. The ragged, brown pinnacles consist of pillow basalt (MzPzv) and interlayered chert (MzPzc).

MILE 168.6 (figs. 57 and 61). Turn left into the storage yard. To the west lies Twelvemile Mountain; to the east, Cathedral Mountain. The south strand of the Angayucham fault system (Kobuk suture) is exposed on the north side of Twelvemile Mountain and crosses the highway near Mile 168.6. The thrust is marked by mylonite and broken formations in a phyllitic matrix. Volcanic rocks (MzPzv) of the Narvak fault panel (fig. 139, fault panel 11) were displaced northward by the thrust onto metagraywacke and phyllite (turbidite deposits; MzPzg) of the Slate Creek fault panel (fig. 139, fault panel 10), which underlies the lowlands to the north (fig. 62).

Regionally, the Angayucham volcanics (MzPzv) have yielded fossils of mixed age and provenance. Permian foraminifera and megafossils have been recovered from limestone interbeds at one locality. Limestone interbeds at other localities, however, have yielded Mississippian to Permian foraminifera and megafossils, and chert interbeds have yielded Triassic radiolarians. The phyllite and graywaclre unit (MzPzp) of the Slate Creek panel has yielded palynomorphs of Early Devonian(?)age.

MILE 170.1. ROSIE CREEK (figs. 57 and 61). A splay of the Angayucham fault system crosses the valley and trends eastward up Rosie Creek.

MILE 172 (figs. 57, 61, 63, and 65). The highway crosses the approximate trace of the north strand of the Angayucham fault system. This strand separates the monometamorphic phyllite and metagraywacke unit (MzPzg, MzPzp) of the Slate Creek panel from the polymetamorphic rocks of the southern Brooks Range schist belt of the Arctic Alaska terrane. The schist belt, also called the Coldfoot subterrane by Jones and others (1987), is separated from the Devonian metamorphic rocks to the north by a major thrust fault.

MILE 172.5 (figs. 57 and 65). A bumpy, but passable, access road on the right leads to a quarry in pyrite-hornblende gabbro. Locally, the gabbro contains pyrite cubes to 1 in. (2 cm) across. Two types of cubes are present: those with biotite and quartz and those without. The matrix minerals are now recrystallized and veined by calcite.

MILE 172.7 (figs. 57 and 65). The road descends from the hill crest onto the flood plain of the Middle Fork Koyukuk River.

MILE 173.5 (figs. 57 and 65). To the east (over the pond) is a good view of uniform, south-dipping graphitic schist (PzPsq, PzPqs) on the north side of Slate Creek. The schist makes up the southernmost rocks of the Brooks Range schist belt and is probably equivalent to the Upper Devonian Hunt Fork Shale of the Arctic Alaska terrane in the central Brooks Range.

MILE 174 (figs. 57 and 65). Cathedral and Twelvemile Mountains are visible to the south.

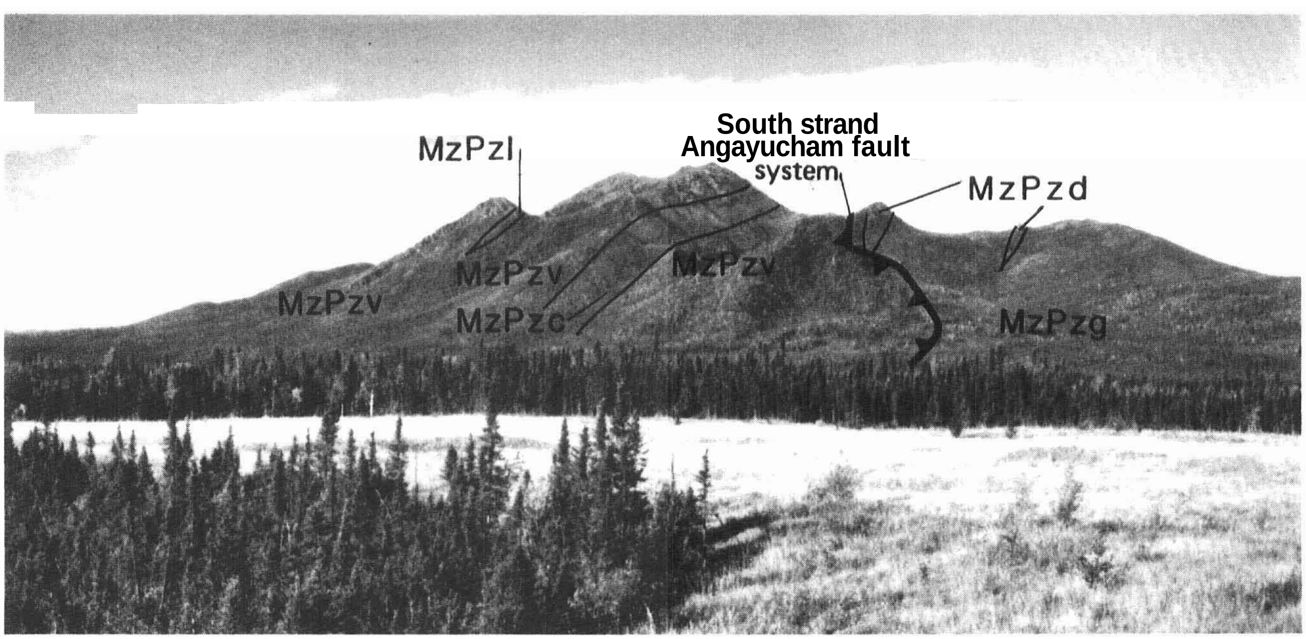


Figure 62. View weslward toward south strand of Angayucham fault system (Kobuk suture) on Twelvemile Mountain near Mile 167. The strand crosses saddle on right and thrusts south-dippirig pillow basalt (MzPzv) and chert (MzPzc) of Angayucham volcanics northward over phyllite and metagraywacke (MzPzg). Metagraywacke contains bodies of diabase and gabbro (MzPzd), which have been interpreted as dikes and sills but could be tectonic slivers. Carboniferous foraminifera1 grainstone (MzPzl) forms base of south peak. Photograph by J.M. Murphy, August 1984.

MILE 174.3 (figs. 57 and 65). The Brooks Range schist belt is visihle to the northeast in upper Clara Creek. Foliations clip to the southeast on the south flank of Emma Dome antiform.

MILE 175. COLDFOOT (PB 238.8) (figs. 57, 64, and 65). A side road to the right leads to Coldfoot. The town was founded in 1899 at the mouth of Slate Creek when prospectors first discovered placer gold on Slate, Myrtle, Clara, Emma, Gold, Porcupine, and other nearby creeks. In 1898, over 1,000 people had taken steamers up the Koyukuk River to search for gold in the upper Koyukuk drainage. Most people were soon discouraged by the absence of bonanzas and the remote, inhospitable country. Accorcling to Marshall (1933), only 200 people wintered in the upper Koyukuk drainage that year in the instant towns of Arctic City, Bergman, and Peavy and in camps along the South Fork Koyukuk River. In the spring of 1899, more left the Koyukuk mining district. Those who stayed were the seasoned prospectors, and their persistence quickly paid off when new strikes were made later that year on Slate and Myrtle Creeks, tributaries of the Middle Fork Koyukuk River. Two new towns were founded: Slate Creek at that creek's confluence with the Middle Fork, and Bettles, downstream on the Koyukuk River at the confluence with the John River.

In 1900, Bettles largely replaced the downstream town of Bergman as the major supply point for upriver placer mines. The town of Slate Creek became known as Coldfoot, named after a 'cheechako,' or newcomer, who reached the Slate Creek diggings, got cold feet, and turned back. In the early 1900s, Pickarts, Bettles, and Pickarts, distributors for the Alaska Commercial Company, established a store in Coldfoot. The new mining town was also the office of the U.S. Commissioner, probate judge, coroner, and recorder. By 1904, the settlement consisted of about 80 well-built cabins. The place was practically deserted during the summer, but about 60 prospectors, trappers, and Natives lived there during the winter. In 1902, the Alaska Commercial Company abandoned its store, which was soon replaced by another owned by Stevens and Plummer. The community received its supplies from Bettles by boat and sled. In winter, mail was delivered to the town once a month by dog team from Fort Yukon. About 1908, the town was eclipsed by Wiseman, and the Coldfoot post office, established in 1900, was closed by 1912. The old Coldfoot cemetery is visible in the forest west of the turnoff to Coldfoot. Creeks north of the town are still sites of placer-gold mining. (See Brown and Kreig, 1983, p. 129-131.)

On January 26, 1989, with a recorded temperature below -82 °F (-63 °C) (the lowest temperature the available thermometers could measure), Coldfoot achieved the dubious distinction of unofficially breaking the long-standing United States low temperature record of -79 °F (-62 °C) set at Prospect Creek (Mile 135.7) on January 24, 1971, ancl the North American low temperaturc record of -81 °F (-63 °C) set at Snag, Yukon Territory. From January 14 to January 31, 1989, the temperature at Coldfoot did not rise above -60 °F (-51 °C).

MILE 176 (figs. 57 and 65). To the northeast is an eclogite(?) locality (fig. 144) (Gottschalk and others, 1984) on an isolated knob low on the hillside. Eclogite has not been previously reported in the Brooks Range. Metabasite dikes, however, are common in the banded-and-knotty schists of the schist belt, and some of these dikes may have been metamorphosed to eclogite under high pressure. Many of the banded-and-knotty schists

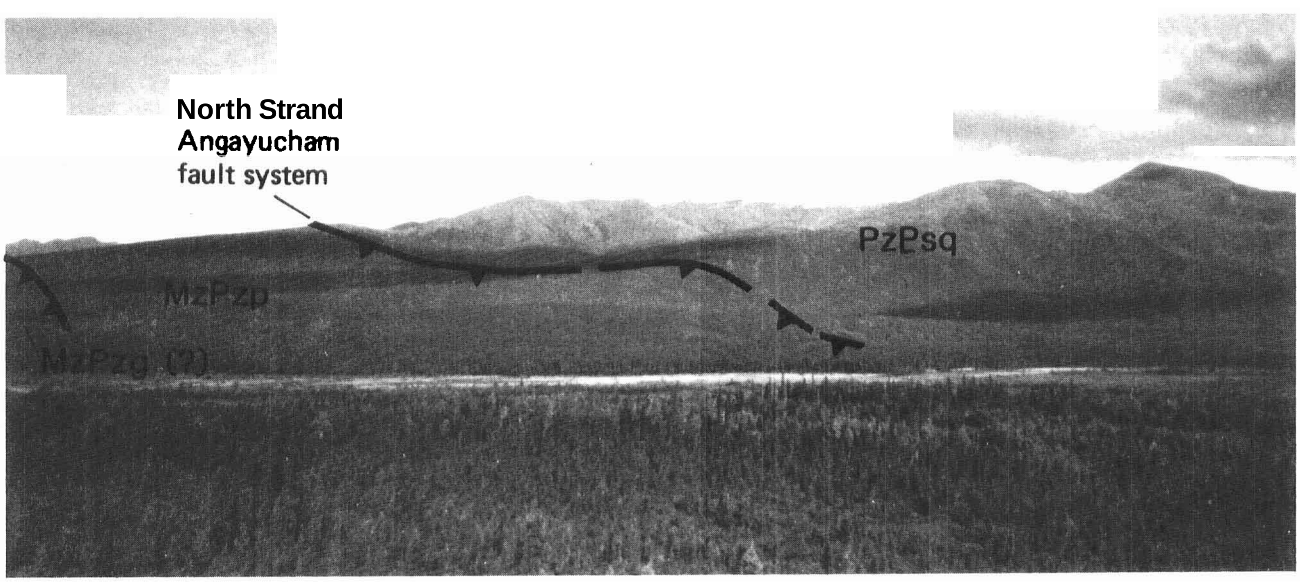


Figure 63. View westward across Middle Fork Koyukuk River near Mile 172. Phyllite and metagraywacke (MzPzg, MzPzp) of Angayucham terrane underlie lowlands to left and are thrust over graphilic schist (PzPsq) of Arctic Alaska terrane, which form highlands on right. North strand of Angayucham fault system crosses low saddle at left center. Photography by A.A. Bakke, August 1984.

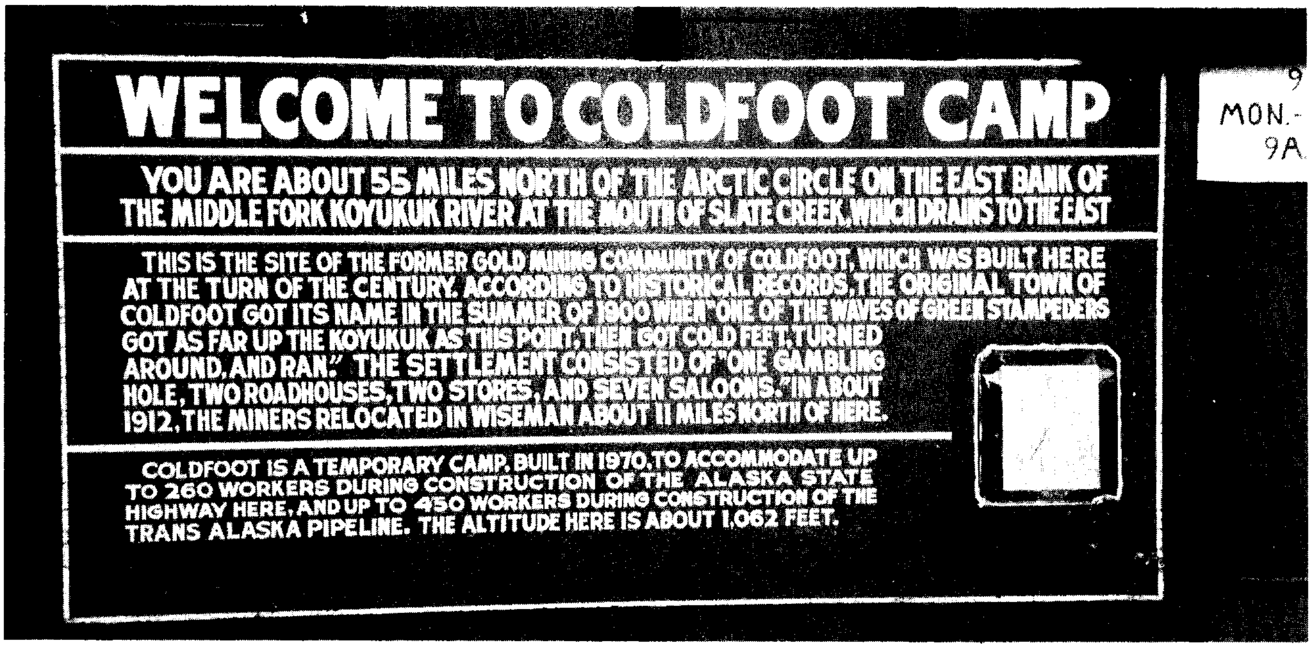


Figure 64. Sign summarizing history of Coldfoot Camp (Mile 175). Photograph by A.A. Bakke, August 1984.

contain blue amphibole and lawsonite that have been partially replaced by actinolite and epidote, respectively. Two ages of blueschist-facies metamorphism, Proterozoic and Jurassic, have been proposed for southern Brooks Range rocks (Dusel-Bacon and others, 1989).

MILE 177.2 (figs. 65 and 144). Emma Dome is visible to the northwest. The dome is composed of banded-and-knotty schist (PzPqs) intruded by rhyodacite and gabbro dikes that may be hypabyssal intrusive rocks correlative with the bimodal Devonian Ambler volcanics (Hitzman and others, 1982; Dillon, chap. 10). The dome lies at the crest of an antiform that trends east-northeast across the Dalton Highway near Marion Creek and parallels a synform to the north. The axis of the antiform plunges west on the west side of the Middle Fork Koyukuk River valley and east on the east side of the valley. Calcareous schist (PzEcs) and marble (PzPm) are exposed in the core of the antiform on Emma Creek below the knotty-mica schist (PzPqs). Because the lower units (PzPcs, PzPm) in the core of the antiform are not present on the east side of the valley at Marion Creek, a fault may trend up the Koyukuk River valley. The axial plane of the antiform is not appreciably displaced laterally; therefore, the east side of the valley must have been downdropped by a dip-slip fault. On the west side of the valley, a garnet-biotite-muscovite granite gneiss (Dgr) is exposed in the core of the antiform, where it intrudes the marble and calcareous schist. All metamorphic structures predate the antiform.

MILE 179.8. MARION CREEK (fig. 65).

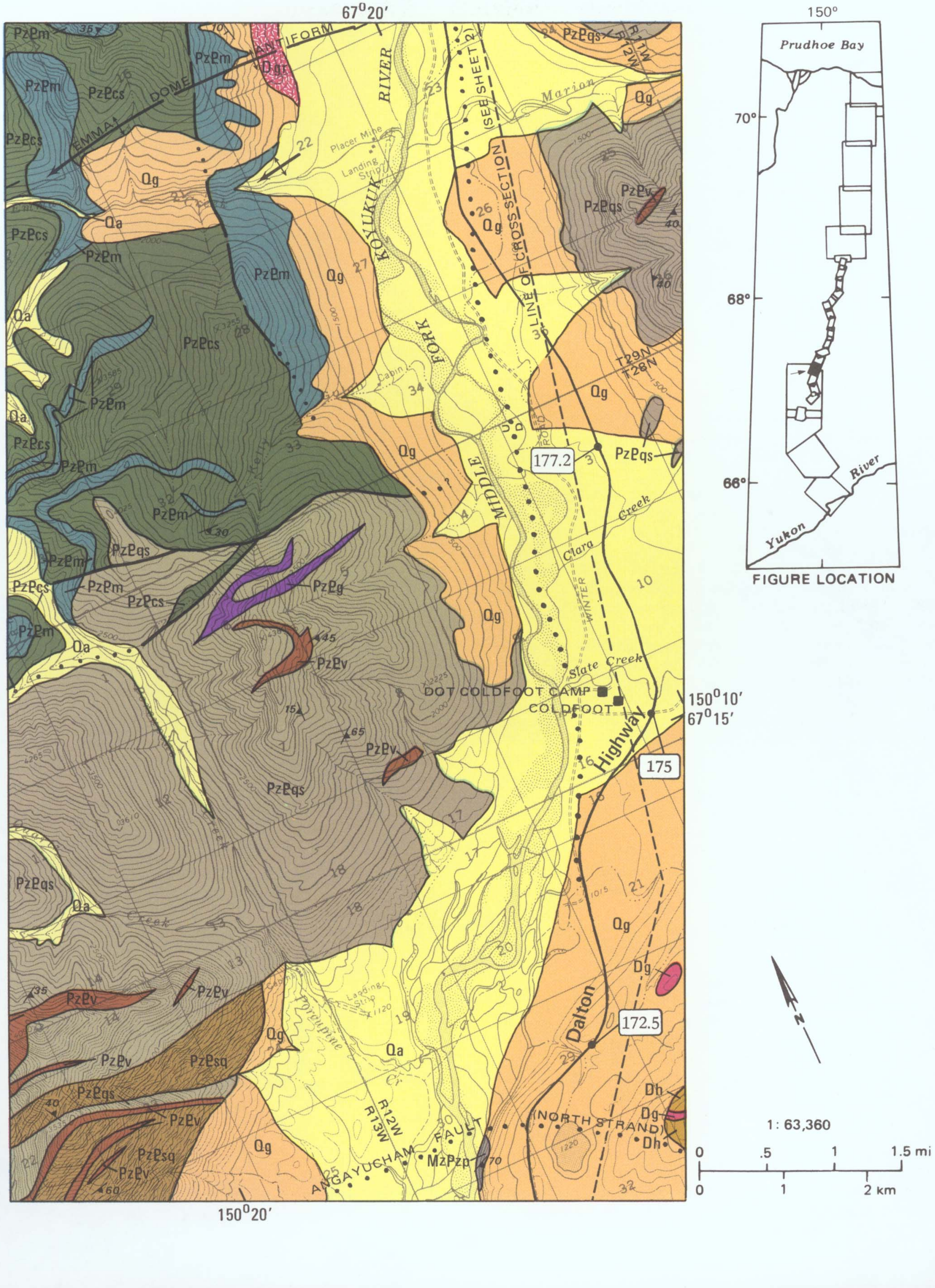
MILE 180.5 (fig. 66). A road on the right leads to Marion Creek campground, a large clearing with a lot of flat ground but no facilities. A narrow, rough track leads through the trees from the south edge of the clearing to Marion Creek.

MILE 181.3 (fig. 66). To the west down the pipeline access road is a good view of garnet-biotite-muscovite granite gneiss (Dgr) on the west side of the Middle Fork Koyukuk River. The gneiss may be Devonian in age, based on lithologic correlation with dated granites nearby, but it could also be as old as Precambrian. Where the granite has intruded marble and calcareous schist, it has formed skarn.

MILE 185.9 (PB 228.1) (fig. 66). An access road to the east leads to a quarry on a protruding ridge of Precambrian or lower Paleozoic polymetamorphosed mica schist (PzPqs). From the quarry, the historic mining community of Wiseman is visible to the west across the Middle Fork Koyukuk River. Also visible from this ridge are the schist belt to the south and, across the Wiseman thrust, Devonian metamorphic rocks to the northwest. The Wiseman thrust separates the mica schist from underlying Middle to Upper Devonian calcareous, chloritic sandstone and associated metamorphic rocks (Dc, Dbs, Dbcp) of the interior metamorphic and plutonic belt of the Brooks Range.

The quarry is in the banded-and-knotty polymetamorphic country rock of the Brooks Range schist belt. Structural relationships are well displayed in the riprap and on the quarry wall. At least two, and possibly three, foliations can be identified. Intersection of the foliations and flow textures in the schist resulted in the bands, rods, and lens structures. The lenses, called knots (fig. 140) because of their refolded shapes, were most likely formed by displacement of the oldest penetrative cleavage. Evidence for the oldest metamorphic event is regional, for the oldest metamorphic structures and textures in the schist belt are not preserved at this locality. The oldest schistosity (S_1) found

Figure 65. Geologic map of Dalton Highway area near Coldfoot, Mile 171 to Mile 180. See figure 82 for map explanation.


67°20′
150°20′
150°10′
67°15′
EMMA DOME ANTIFORM
KOYUKUK RIVER
MIDDLE FORK
LINE OF CROSS SECTION
(SEE SHEET 2)
Marion
Placer Mine
Landing Strip
Cabin
Clara Creek
Slate Creek
WINTER ROAD
DOT COLDFOOT CAMP
COLDFOOT
Dalton Highway
177.2
175
172.5
T29N
T28N
R12W
R13W
R11W
R12W
Porcupine Cr.
Landing Strip
ANGAYUCHAM FAULT
(NORTH STRAND)
PzPm
PzPcs
PzPqs
PzPg
PzPv
PzPsq
Dgr
Qg
Qa
Dg
Dh
MzPzp
150°
Prudhoe Bay
70°
68°
66°
Yukon River
FIGURE LOCATION
N
1: 63,360
0 .5 1 1.5 mi
0 1 2 km

at the quarry, however, affects relatively dry rock that may have been metamorphosed previously at a higher grade. The grade of subsequent events is that of blueschist-greenschist and albite-epidote-amphibolite facies.

Wiseman (fig. 67), originally called Nolan, was established about 1908 as a supply point for mining operations on the Hammond River and on Wiseman, Mascot, and Nolan Creeks. The town was located at the head of navigation for shallow-draft scows and poling boats. A post office was established in 1909, but Wiseman's heyday came about 1910, after gold prospectors abandoned Coldfoot, 11 mi (18 km) to the south. An airfield was built during 1926-27 and served as the major stopover between Fairbanks and Barrow. In 1930, about 100 people lived nearby and were served largely by airplane. Wiseman reportedly has never had a church, but during the gold rush, it had as many as three brothels at one time. Pioneering ecologist and writer Robert Marshall (1933) showed a direct correlation between the number of miners and the number of prostitutes in Wiseman. The post office was closed in 1956, but, despite the inconvenience, a few year-round residents still live in the town. About 5 mi (8 km) northwest of Wiseman is another early mining community, now called Nolan, located on Nolan Creek. The Wiseman mining district is the most productive gold district in the Brooks Range; over 300,000 oz of gold have been recovered. Gold grades range to several oz/yd^3 and fineness is about 920.

The Wiseman area is typical of the central and southern Brooks Range. Glacier-scoured valleys contain alluvial and glacial deposits and are walled by high ridges of limestone, shale, sandstone, phyllite, and schist. Alluvial fans and colluvial aprons extend from the lower valley walls toward the flood plain of the Middle Fork Koyukuk River. (See Brown and Kreig, 1983, p. 131-134.)

MILE 186.6 (figs. 54 and 66). A road cut, about 12 to 15 ft (4 to 5 m) high, extends along the west side of the road, where it crosses an end moraine of Walker Lake age. (See Brown and Kreig, 1983, p. 134.)

MILE 187.2. MINNIE CREEK (fig. 66). The highway crosses the trace of the Wiseman thrust, a regional fault at the northern boundary of the schist belt.

MILE 188.5. MIDDLE FORK KOYUKUK RIVER (first crossing) (figs. 66 and 68). The road crosses the Middle Fork Koyukuk River; the pipeline crosses under the river downstream from the road. The road on the left leads to the Hammond River and the communities of Wiseman and Nolan and is usually passable when dry.

This point is a good place to start float trips down the Koyukuk River. The river can be negotiated easily in rafts, canoes, or kayaks. It takes about five 8-hr days of floating to reach Bettles. Along the river are good exposures of the Angayucham volcanics, the overlying Cretaceous conglomerate, and rocks of the schist belt.

MILE 190.6. HAMMOND RIVER (fig. 68).

MILE 190.8. MIDDLE FORK KOYUKUK RIVER (second crossing) (fig. 68). From this point, Devonian metasediments (Dhcp) are visible to the west up the Hammond River. The lower Hammond River and its north-flowing tributaries contain high-grade placer-gold deposits, which may be derived from sources similar to those in the Nolan-Wiseman area.

MILE 192.7 (fig. 68). At this point is a sign commemorating the linkup of the Dietrich and Coldfoot segments of the haul road.

MILE 194 (figs. 68 and 69). The sharp spire of Sukakpak Mountain (4,159 ft; 1,360 m), 10 mi (16 km) to the north, comes into view for the first time. The pyramid of Wiehl Mountain, 4 mi (6.5 km) east of Sukakpak, is also visible. Massive, white marble of the Devonian Skajit Limestone (Dsk) composes the two mountains, both of which are synclinal and bounded on the south by high-angle faults.

MILE 196 (fig. 68). Poss Mountain is visible to the southeast (3 mi [5 km] east of the map border). The top of the mountain is composed of Proterozoic to lower Paleozoic(?) knotty-mica schist, which has been thrust on Proterozoic to lower Paleozoic(?) marble at the base of the mountain.

MILE 195.2 to 197.5 (figs. 68 and 70). Nugget, Sheep, Gold, and Linda Creeks on the east side of the road have produced placer gold. These creeks form the northeastern part of the upper Koyukuk (Wiseman) mining district. West of the road on the north side of Gold Creek is an abandoned, sod-roofed miner's cabin.

MILE 196 (figs. 54 and 68). A remote-operated pipeline valve and control building are visible west of the highway. Propane fuel tanks used to power the facility are buried in the frozen ground.

The road follows the U-shaped trough that was scoured and deepened by successive Late Pleistocene glaciers that flowed south from source areas near the Continental Divide.

MILE 197.5 (fig. 70). Pull off the road to view the Wiehl Mountain syncline to the northeast (2 mi [3 km] east of the map border). The Skajit Limestone (Dsk) on Wiehl Mountain is intruded by the westernmost granitic plutons of the Chandalar area. Mafic and felsic intrusive and volcanic rocks near Wiehl Mountain indicate bimodal magmatism.

MILE 197.8. LINDA CREEK (fig. 70). Stream-washed, gold-bearing gravel was discovered on Linda Creek in 1901 at a depth of about 15 ft (5 m) and is currently being mined.

MILE 199 (fig. 70). To the south is a good view of the northern edge of the schist belt, where knotty-mica schist and calc-schist and marble on the hanging wall of the Wiseman thrust overlie the southern edge of Devonian and lower Paleozoic(?) metasediments (Dbcp, Dhs). The upper Koyukuk mining district is visible to the southwest.

MILE 200.3 (fig. 70). Deeply eroded Devonian and lower Paleozoic(?) metasediments (Dbcp, Dbs) are visible to the southwest.

MILE 201.8 (PB 212.2) (figs. 7, 69, 70, and 72). An access road to the west leads to the pipeline. To the northeast is a good view of the south side of Sukakpak Mountain (4,459 ft; 1,359 m). The mountain is composed of marble of the Devonian Skajit Limestone (Dsk), which was probably deposited in an intertidal environment. The gross structure of Sukakpak Mountain is a synform that is overturned to the northwest and

Figure 66. Geologic map of Dalton Highway area near Wiseman, Mile 179 to Mile 189. See figure 82 for map explanation.

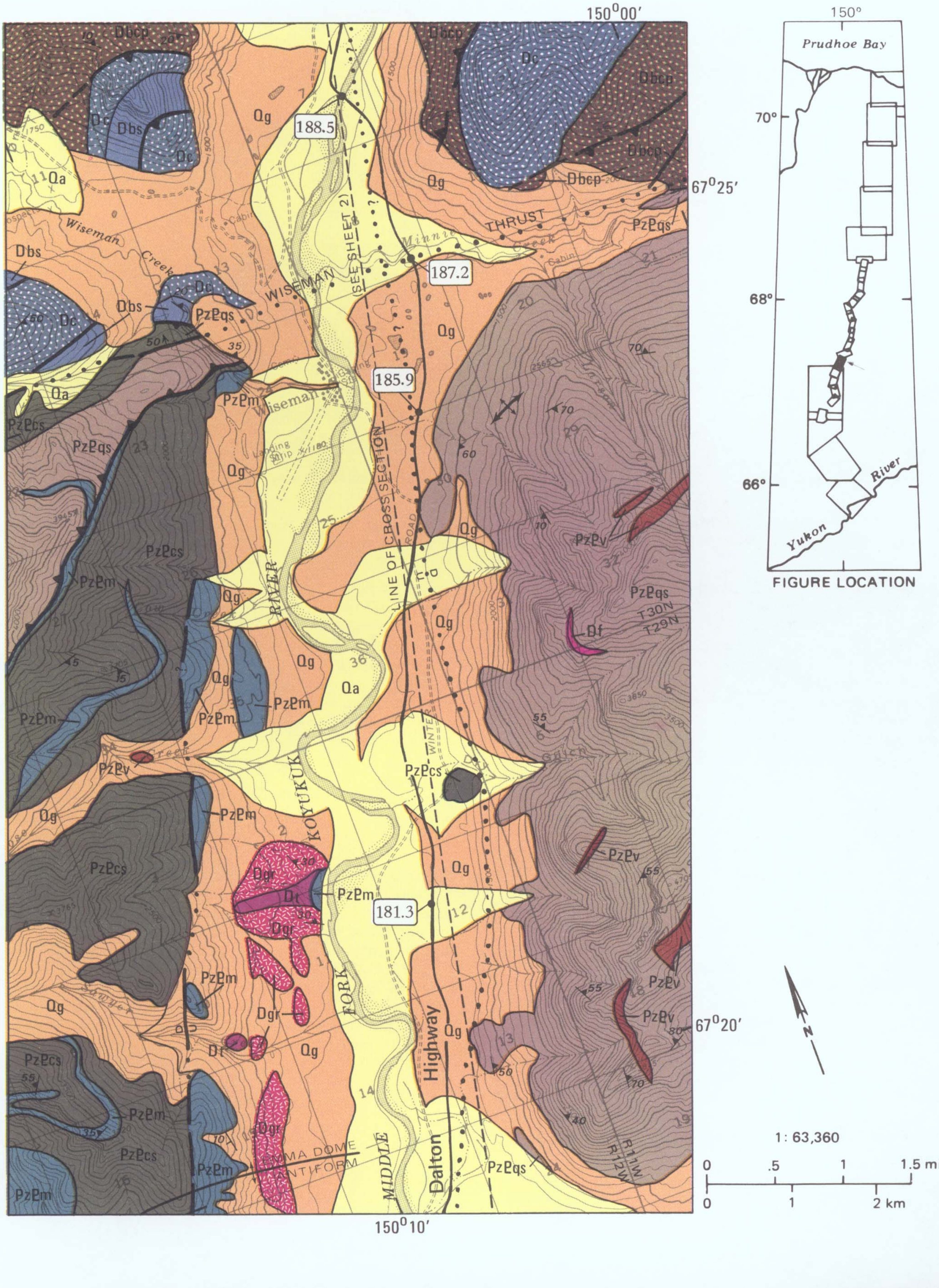

150°00′
150°10′
67°25′
67°20′
Dbcp
Dc
Dbs
Qg
Qa
188.5
187.2
185.9
181.3
WISEMAN
THRUST
(SEE SHEET 2)
LINE OF CROSS SECTION
Wiseman Creek
Minnie Creek
PzPqs
PzPm
PzPcs
PzPv
Df
Dgr
T30N
T29N
R11W
R12W
KOYUKUK
RIVER
MIDDLE FORK
Dalton Highway
WINTER ROAD
EMMA DOME ANTIFORM
150°
Prudhoe Bay
70°
68°
66°
Yukon River
FIGURE LOCATION
N
1: 63,360
0 .5 1 1.5 mi
0 1 2 km

Figure 67. View southward toward historic mining community of *Wiseman* along Middle Fork Koyukuk River. Note Trans-Alaska Pipeline and Dalton Highway in distance. Photograph by C.G. Mull, July 1982.

plunges about 15° NE. At the southern end of the mountain, the marble is in fault contact with a chlorite-mica-quartz schist (Ɛcq). The fault strikes N. 82° E. and dips 45° SE. and can be traced for over 20 mi (32 km) to the east. The fault apparently truncates the southwest-trending belt of Skajit Limestone at Sukakpak Mountain because the massive marble is not present on the west side of the Middle Fork Koyukuk River. A quartz-stibnite-gold vein, which contains gold values to 1.5 oz/ton, intrudes the fault zone at the southern end of Sukakpak Mountain. A notch at the northern end of the mountain marks a vertical fault that strikes N. 70° W. and has minor displacement.

MILE 203.4 (figs. 70 and 72). A turnout on the west side of the road, directly across from Sukakpak Mountain, is a good vantage point to view the dramatic 2,000-ft-high (600 m) cliff face of Skajit Limestone (Dsk). The carbonate has been subjected to two periods of metamorphism that have totally destroyed original bedding; the apparent layering in the mountain is a combination of S_2 and S_3 mineral foliation. The Skajit consists dominantly of three types of massive, medium-grained marble: 1) crystalline marble; 2) white calcite marble with black bands of graphitic marble; and 3) black graphitic or dolomitic marble.

Schist layers within the marble consist of 1) mica-quartz schist that is probably of pelitic origin; 2) quartz-mica schist that contains relict phenocrysts of plagioclase (An_{27}) and is therefore thought to be a metamorphosed felsic volcanic rock; and 3) mafic schist that contains relict igneous textures and is probably a hypabyssal intrusive correlative with other mafic plutons in the Chandalar Quadrangle.

MILE 204.3. MIDDLE FORK KOYUKUK RIVER (third crossing) (figs. 70 and 72). On the right side of the highway north of the Middle Fork Koyukuk River is a wide turnout with litter barrels and a restroom. From this point is a good view of north-vergent isoclines on the northwestern face of Sukakpak Mountain; S_2 foliation is folded, and S3 foliation is axial-planar to the isoclines.

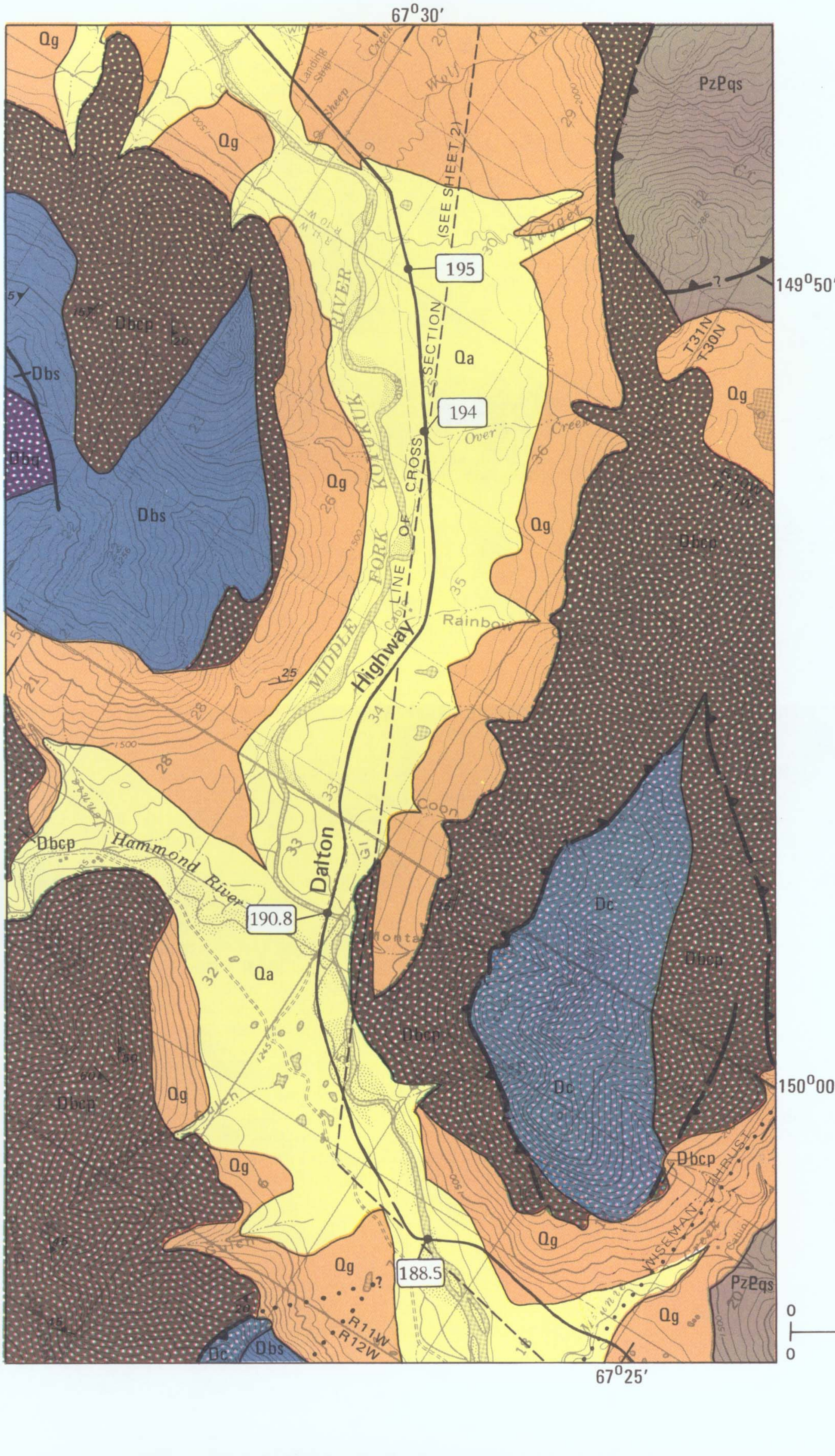
MILE 205 (figs. 70 and 72). On the left side of the highway is a turnout and litter barrel. To the southeast at the northern end of Sukakpak Mountain is the contact between the Skajit Limestone (Dsk) and the underlying Ordovician graphitic phyllite (Obpm). Ahead and to the right is the imposing pyramid of Dillon Mountain.[11] Like Sukakpak Mountain, Dillon Mountain is composed of Skajit Limestone that has been folded into a tight syncline and overturned to the northwest.

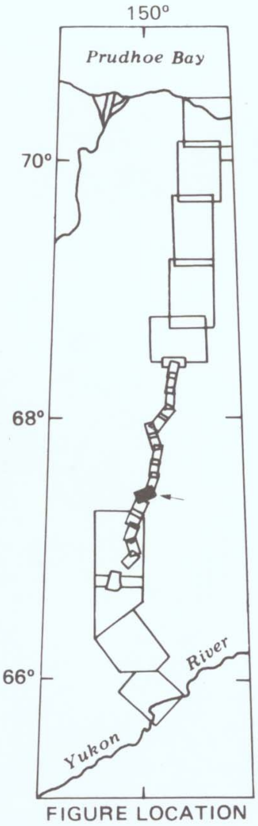
MILE 205.2 (fig. 72). To the southwest is a good view of orange marble and calcareous schist (Ɛcs) of Cambrian(?) age on the west side of the Dietrich River. Cambrian and Ordovician fossils have been recovered from lithologically similar rocks near Snowden Mountain (Mile 216.6).

MILE 206 (fig. 72). To the southeast lies Wiehl Mountain (2 mi [3 km] east of the map border).

[11]Name does not appear on current topographic map but has recently been proposed lo U.S. Board on Geographic Names (C.G. Mull and K.E. hdams. written commun.. 1989).

Figure 68. Geologic map of Dalton Highway area in Middle Fork Koyukuk River valley, Mile 187 to Mile 197. See figure 82 for map explanation.


67°30′
149°50′
150°00′
67°25′
Qg
Qa
Dbcp
Dbs
Dbq
Dc
PzPqs
MIDDLE FORK KOYUKUK RIVER
Dalton Highway
LINE OF CROSS SECTION
(SEE SHEET 2)
195
194
190.8
188.5
Hammond River
Wolf
Nugget
Over Creek
Rainbow
Coon
WISEMAN THRUST
Wiseman Creek
T31N
T30N
R11W
R12W
1:63,360
0 .5 1 1.5 mi
0 1 2 km


150°
Prudhoe Bay
70°
68°
66°
Yukon
River
FIGURE LOCATION

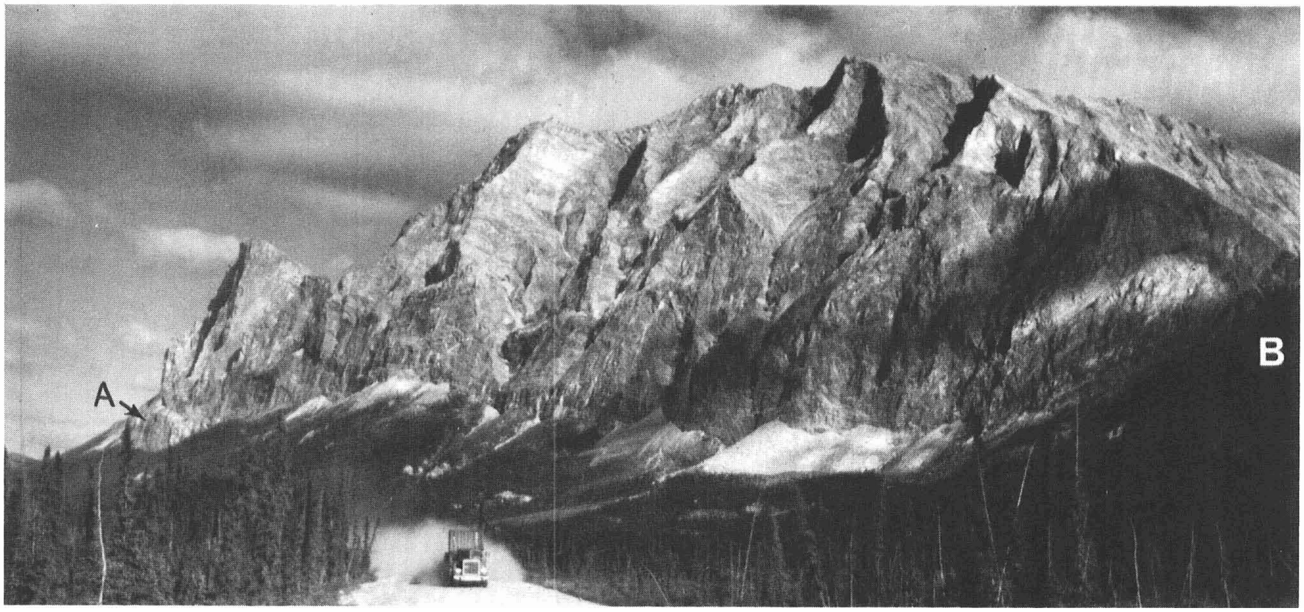


Figure 69. View northwestward from near Mile 202 of west wall of Sukakpak Mountain. Mountain is composed of marble of Devonian Skajit Limestone, which has been folded into a recumbent syncline, and underlying lower Paleozoic(?) graphitic phyllite. From a distance, several small isoclinal folds can be seen on lower part of cliff face at 'A.' At right, marble is faulted against chlorite-mica-quarlz schist. Within fault zone at 'B' are auriferous quartz-stibnite veins. Photograph by J.M. Murphy, August 1984.

MILE 206.9. DIETRICH RIVER BRIDGE (fig. 72). The road crosses the Dietrich River, just upstream from where the Dietrich River joins the Bettles River. The Bettles flows from the southeast between Dillon and Sukakpak Mountains to form the Middle Fork Koyukuk River.

Each winter, much of the Dietrich River valley north of Sukakpak Mountain is buried by aufeis (overflow ice), which forms when water from alluvial-fan deposits or stream underflow is forced to discharge at the surface of a river where freezing has blocked the channel. Successive overflows often build up as thick sheets of ice that persist throughout much of summer.

MILE 207.5 to 208 (fig. 72). To the north lies Snowden Mountain, which is also composed of Skajit Limestone (Dsk) folded into a tight syncline. East of the highway on Dillon Mountain, a section that consists of Cambrian quartz schist (Ccq) and Ordovician marble and graphitic phyllite (Obpm) is unconformably overlain by Skajit Limestone. On the west side of the valley, Cambrian quartz schist (Ccq) and calc-schist (Ccs) are unconformably overlain by calcareous quartz sandstone, wacke, and conglomerate (Dbcp) of the Middle and Upper Devonian Beaucoup Formation, and the Skajit is not present.

MILE 208.5 (figs. 71 and 72). To the south is a good view of the southeast dip of the base of the Skajit marble (Dsk) at Sukakpak Mountain.

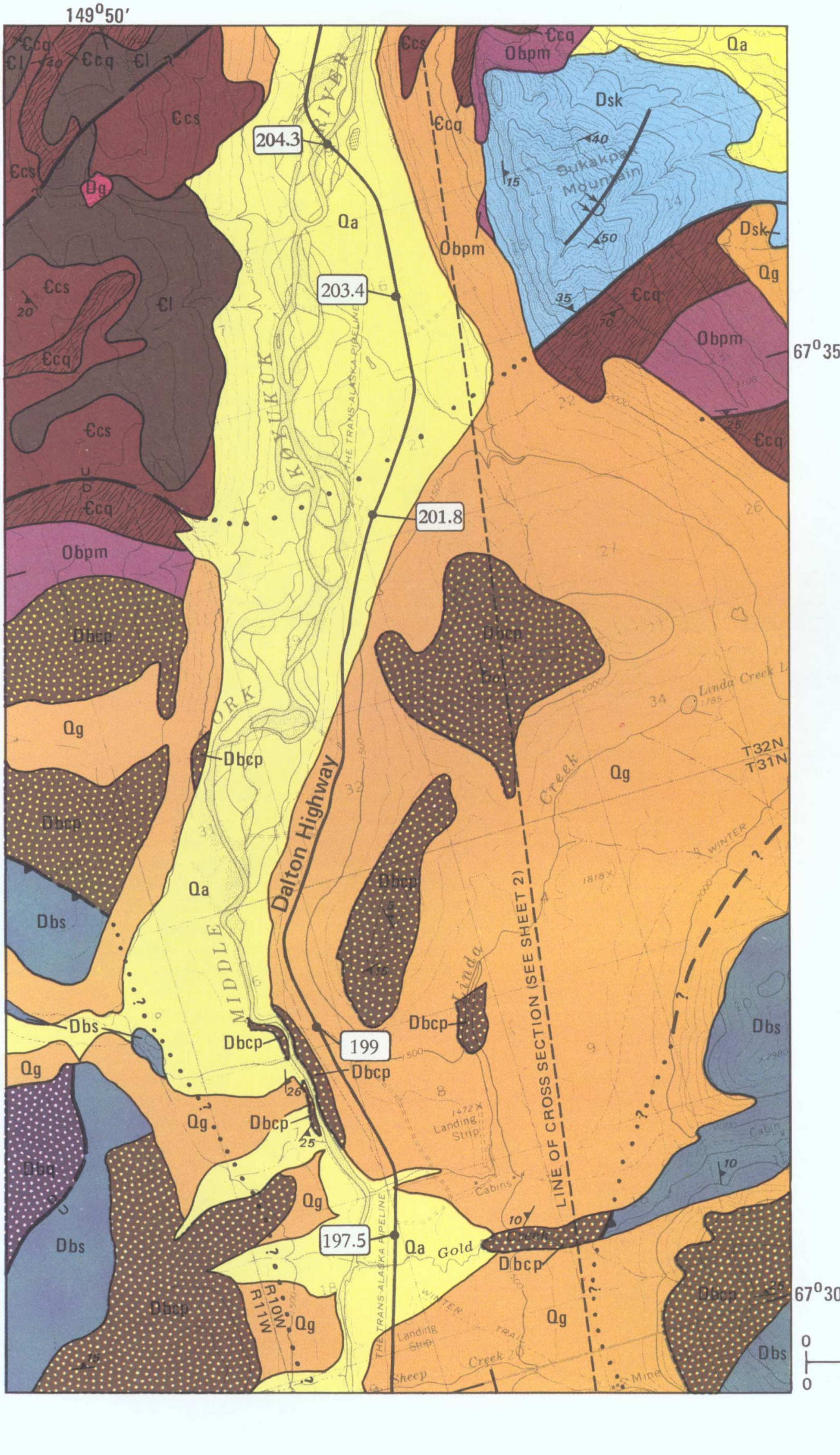
MILE 209.3. DIETRICH CAMP (figs. 72 and 73). Dietrich was one of the major pipeline-construction camps. Just north of Dietrich is the northern limit of paper birch along the road corridor.

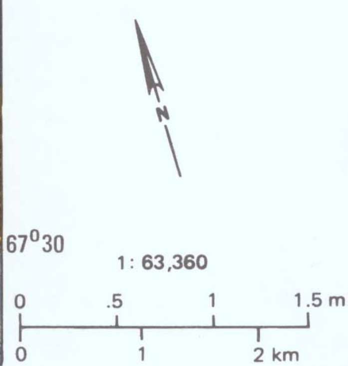
MILE 210.7. DISASTER CREEK (PB 203) (figs. 72 and 74). Between Disaster Creek and Snowden Mountain, 6 mi (10 km) to the north, the Middle and Upper Devonian Beaucoup Formation (Dbs, Dbl, Dbcp) crops out on both sides of the Dietrich River valley and in places unconformably overlies Ordovician graphitic phyllite (Obpm). The regional relationship between the stratigraphic sequence in which the Beaucoup unconformably overlies Ordovician rocks, and the sequence in which the Skajit overlies Ordovician rocks, as at Sukakpak and Dillon Mountain, is unknown. It is possible that the Beaucoup regionally truncates the Skajit, as well as the Ordovician rocks, but it is also possible that the two sequences are juxtaposed by a regional thrust fault (W.P. Brosgé, oral commun., 1989).

MILE 211.2 (figs. 72 and 74). Fossiliferous limestone of the Beaucoup Formation (Dbl) is visible on the ridge southeast of Snowden Mountain. High, dark-colored peaks on the ridge are remnants of a gabbro dike (Dg) that intruded and metamorphosed Ordovician graphitic phyllite (Obpm).

MILE 211.5 (figs. 72 and 74). The road crosses a segment of the pipeline that was rerouted up the hillside in 1986. The original line, buried under the Dietrich River, had undergone substantial settling, but no leakage occurred.

Figure 70. Geologic map of Dalton Highway area in Middle Fork Koyukuk River valley, Mile 197 to Mile 205. See figure 82 for map explanation.





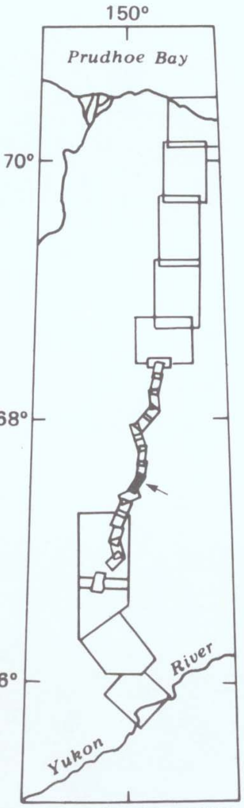


FIGURE LOCATION

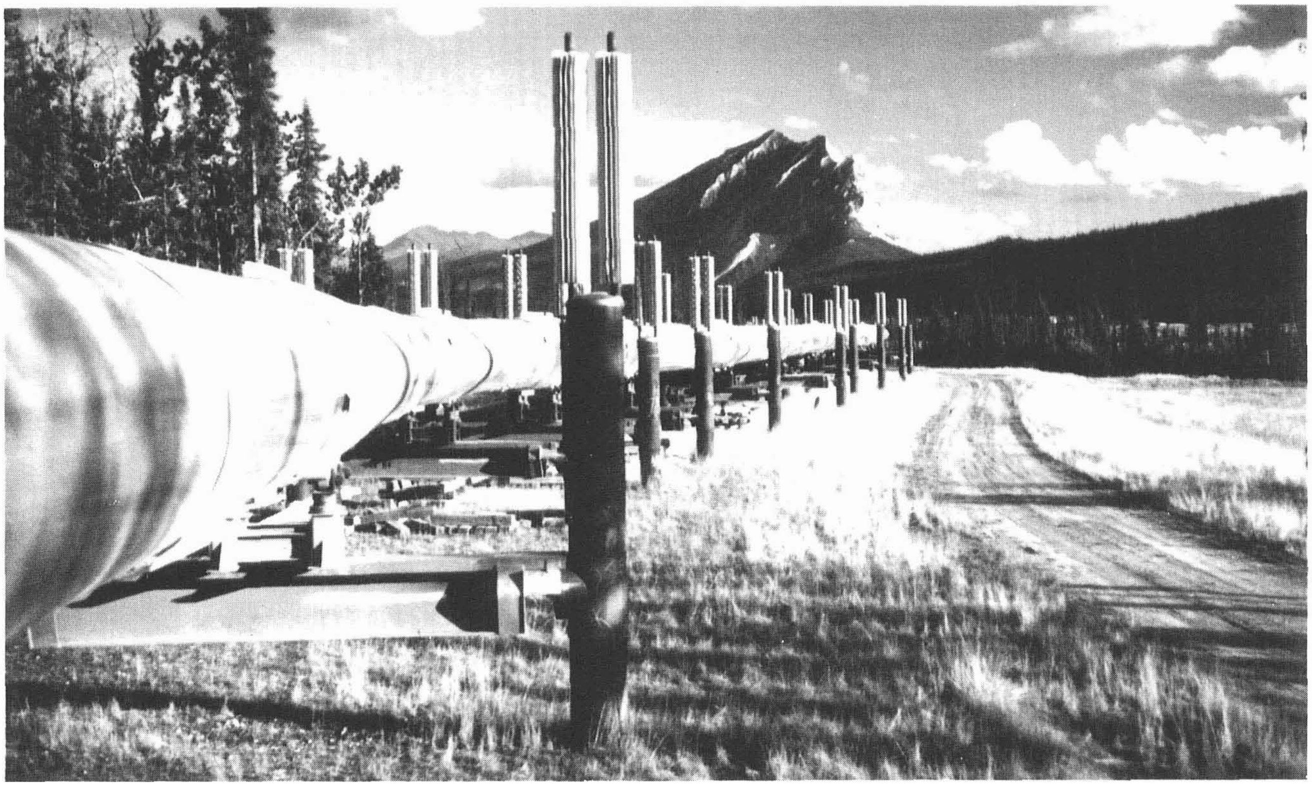


Figure 71. View southward toward Sukakpak Mountain from near Dietrich Camp (Mile 209). Photograph by C.G. Mull, July 1982.

MILE 211.9 (fig. 74). The road crosses the rebuilt segment of pipeline (see entry for Mile 211.5) again as the pipeline trends down the valley to join the original alignment. To the north, long sections of the pipeline are buried beneath the bed of the Dietrich River.

MILE 212 (figs. 74 and 75). To the south is a good view of Skajit Limestone (Dsk) on Sukakpak and Dillon Mountains.

MILE 213 (figs. 74 and 141). A fault is visible to the northeast in a canyon on the south side of Snowden Mountain. The fault, marked with horizontal slickenslides, truncates marble of the Skajit Limestone (Dsk), so that the marble is not present on the west side of the Dietrich River valley. On the south side of the fault, Ordovician conodonts (Anita Harris, written commun., 1985) have been recovered from thin, black to dark-gray marble (Om) interlayered with calcareous graphitic phyllite (Obpm). Devonian megafossils are present in the massive, gray marble and orange dolomite of the Skajit several miles east of the Dalton Highway (J.T. Dutro, Jr., written commun., 1983). At the north base of the Snowden Mountain massif, Cambrian trilobites have been found in thin, brown, sandy dolomite and calcareous schist (Ꞓl) that unconformably underlie the Skajit. Several miles to the northeast, the Skajit unconformably overlies the Ordovician rocks (Obpm) (Palmer and others, 1984).

MILE 213.4. SNOWDEN CREEK (fig. 74).

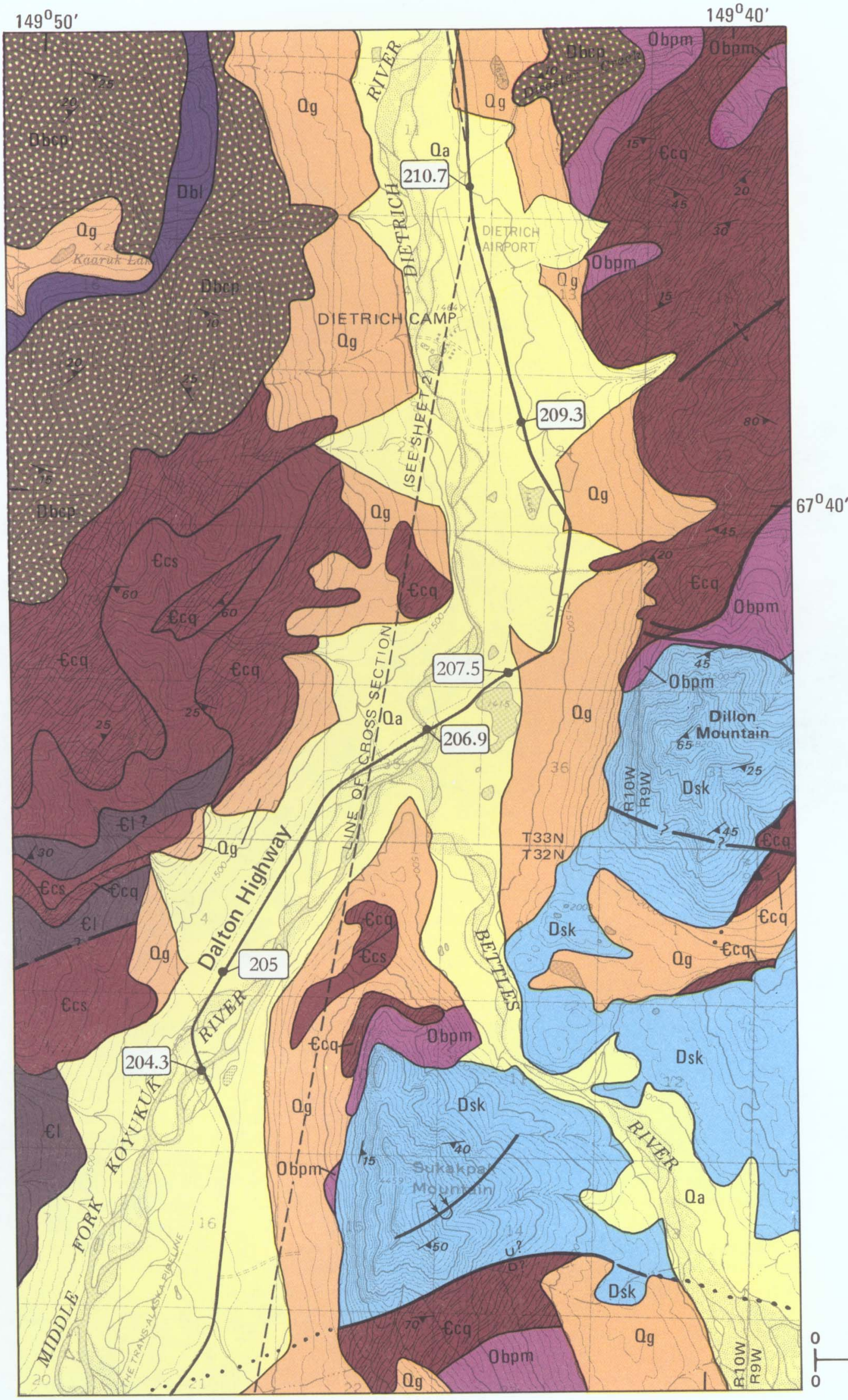
MILE 214 (fig. 74). A gabbro dike (Dg) that intrudes Ordovician phyllite (Obpm) is visible to the northeast on the south side of Snowden Mountain. On the west side of the Dietrich River valley, siltstone, slate, phyllite, and limestone of the Upper Devonian Beaucoup Formation (Dbl, Dbs, Dbcp) dip regionally south.

MILE 216 (fig. 74). Pinnacles of Skajit Limestone (Dsk) are visible to the northeast on Snowden Mountain.

MILE 216.6 (figs. 74 and 141). Snowden Mountain lies to the east. Between Snowclen Mountain and the south edge of the Doonerak fenster, about 8 mi to the north, most of the Devonian formations are repeated two or three times in a southeast-dipping homocline. The repeated sections provide evidence for two or three layer-parallel thrust faults.

Conglomerate Mountain, on the west side of the valley (2 mi [3 km] off the map), and on strike with Snowden Mountain, is composed of conglomerate (OꞒvc) of Cambrian or Ordovician age. Many of the clasts are volcanic rock; however, the conglomerate contains several other types of clasts, including abundant carbonate and vein quartz. The conglomerate is interlayered with schistose shale-chip sandstone and siltstone and grades into gray, purple, and green siliceous phyllite (OꞒvp) to the north. The conglomerate and associated

Figure 72. Geologic map of Dalton Highway area near Sukakpak Mountain, Mile202 to Mile 212. See figure 82 for map explanation



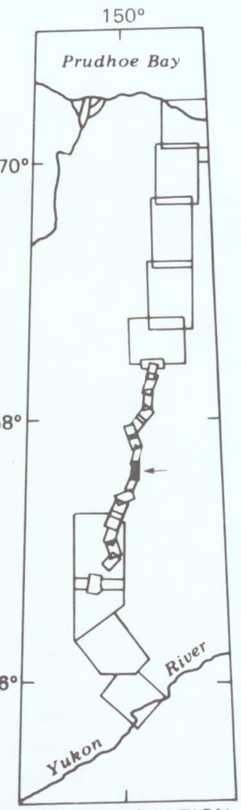
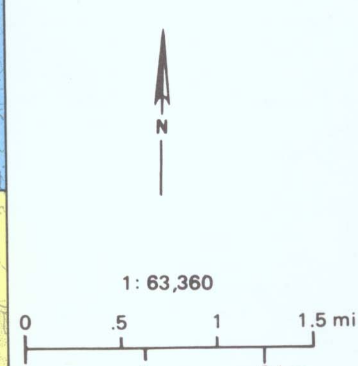


FIGURE LOCATION



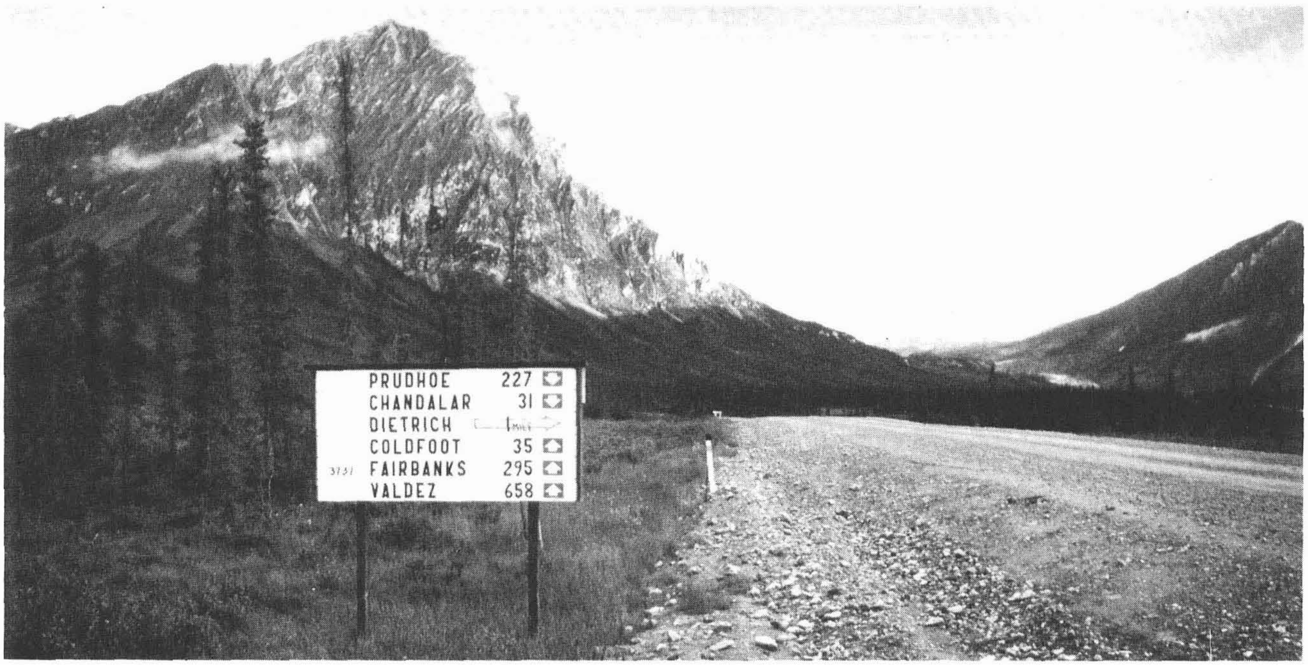


Figure *73.* Road sign at turnoff to *Dietrich* Camp (Mile 209.3). *Dillon* Mountain in background is composed *of* Skajit Limestone. Photograph by C.G. Mull, July 1982.

rocks are not present east of the Dietrich River but are correlated lithologically with lower Paleozoic rocks (O€vp) on the north side of Snowden Mountain and with Cambrian and Ordovician volcanic and volcaniclastic rocks in the Doonerak fenster.

MILE 217 (fig. 74). To the southwest are outcrops of the Beaucoup Formation and other Devonian rocks on the north flank of a syncline. This is the eastern end of a regional syncline that can be traced for over 25 mi (40 km) to the southwest.

MILE 217.7 (figs. 74 and 76). To the northeast at the head of a canyon on the northwest side of Snowden Mountain are prominent spires of Ordovician and Cambrian marble, calc-schist, and calcareous phyllite (Ccs) that have been thrust northward onto Devonian Whiteface Mountain volcanics (Dwg). Note the isoclinal folds near the top of the peaks.

MILE 219.9 (fig. 76). An access road on the left leads to material site 106-1A. Within a short walk down the access road, campsites can be found in the trees adjacent to the gravel pit, and water can be taken from a creek that flows past the northern end of the pit.

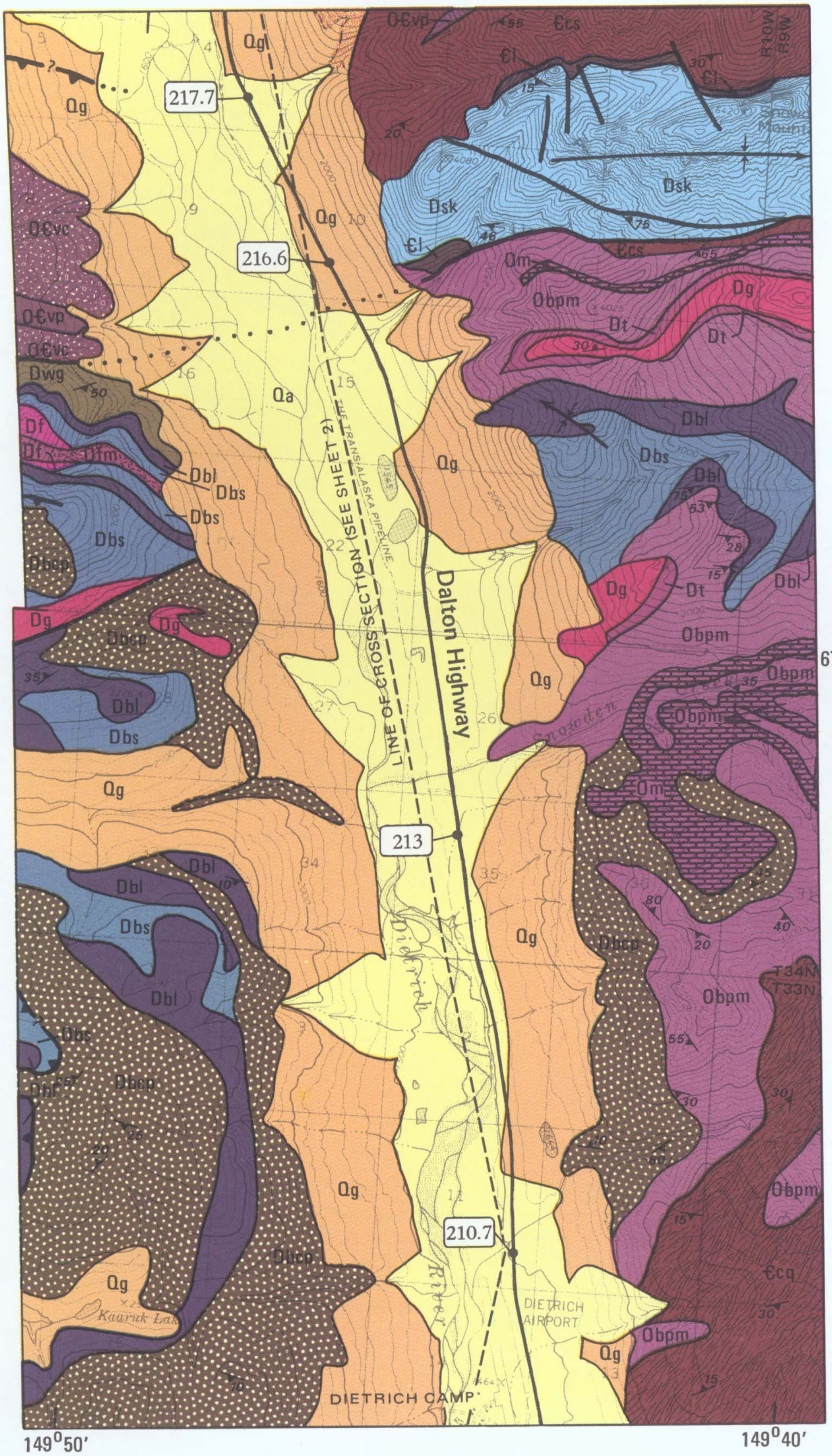
MILE 221 (fig. 76). To the southeast is a view of brown-weathering, trilobite-bearing marble (€l) on the north side of Snowden Mountain. These rocks are stratigraphically overlain by gray marble of the Skajit Limestone (Dsk).

MILE 221.7 (fig. 76). A rock quarry in the Skajit Limestone (Dsk) on the east side of the road contains coarse, black, locally pyritic marble with abundant, rectilinear calcite veins. The veins are both parallel and perpendicular to S_1 foliation. Veins that crosscut S_1 foliation fill extension fractures.

In the cliffs to the northeast (fig. 77), the Skajit is 1,000 to 2,000 ft (300 to 600 m) thick and dips regionally southeast, as do all the rocks between this point and Snowden Mountain to the south. A major thrust fault separates the section of Skajit on Snowden Mountain from the same section at this locality. The Skajit thins rapidly to the west, averaging <100 ft (30 m) thick, and becomes interlayered with siliceous clastic and volcaniclastic rocks of the Whiteface Mountain volcanics (Dwpg). This apparently abrupt facies change may have resulted from encroachment of a clastic depositional regime on the carbonate banks during Devonian time. The lateral variation could also be the result of thrust juxtaposition of a thick section of Skajit, as on the east side of the valley, with a sequence containing a thin section of Skajit, and Whiteface Mountain volcanics, as on the west side of the valley.

About 7 mi (11 km) up the valley to the north at the east plunge of the Doonerak anticlinorium are dark-gray and brown hills with smooth slopes that are composed of Upper Devonian Hunt Fork Shale and Beaucoup Formation. Regionally, the Hunt Fork Shale grades downward into the Beaucoup Formation and grades upward into the Upper Devonian Noatak Sandstone and Upper Devonian to Lower Mississippian Kanayut Conglomerate. The Hunt Fork consists of prodelta siliciclastic sediments deposited seaward of a major deltaic system. Regionally, the Beaucoup consists of a wide variety of interbedded carbonate and clastic sediments, including conglomerate, that represent a transition from the clastic depositional environment of the Kanayut-Noatak-Hunt Fork system to the older carbonate environments of the Skajit Limestone and the volcanic environments of the Whiteface Mountain

Figure 74. Geologic map of Dalton Highway area near *Snowden* Mountain, Mile 210 to Mile 218. See figure 82 for map explanation.



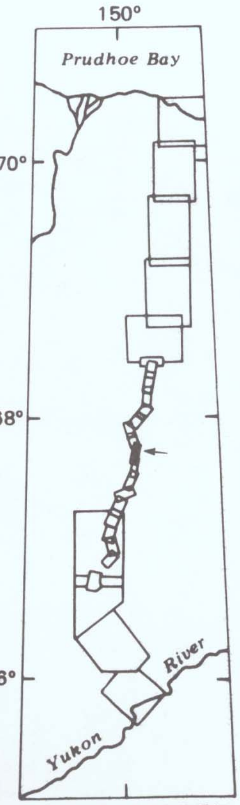


FIGURE LOCATION

Figure 75. Aerial view of Dietrieh River valley to south. Bettles River flows northwest between Dillon Mountain on left and Sukakpak Mountain on right and joins Dietrich River to form Middle Fork Koyukulz River. Rugged white peaks are Skajit Limestone. Dietrich Camp and airstrip are in center. Photograph by C.G. Mull, July 1982.

volcanics. However, because the relatively incompetent Hunt Fork and Beaucoup formations have acted as a detachment horizon during thrusting, in some places the heterogeneous assemblage of the Beaucoup may be tectonic rather than sedimentary.

MILE 222 (fig. 76). Isoclinally folded marble of the Skajit Limestone (Dsk) is visible to the east near the top of the cliffs.

MILE 224.1 (figs. 76 and 78). A road to the right (east) leads to a gravel pit. To the southeast is a thrust fault at the base of an unnamed mountain peak (1 mi [1.6 km] east of the map border) of Ordovician or Silurian dolomite. The dolomite has been folded into a recumbent syncline that overlies Middle Ordovician marble and graphitic phyllite (J.T. Dutro, Jr., oral commun., 1985). The Middle Ordovician rocks, in turn, structurally overlie the Devonian Whiteface Mountain volcanics (Dwpg, Dwg). An east-west-trending, high-angle fault with about a mile of right-lateral separalion trends up the canyon to the east. Devonian Hunt Fork Shale (Dhf), Whiteface Mountain volcanics (Dwpg, Dwg), and Skajit Limestone (Dsk) are exposed on the canyon walls and in the creek bed.

MILE 224.2 (figs. 76 and 78). To the northwest, across the Dietrich River, are exposures of Hunt Fork Shale (Dhf), Beaucoup Formation (Dbl, Dbcp), and Whiteface Mountain volcanics (Dwc) on the south and east flanks of the Doonerak antiform. East of the highway, thick marble of the Skajit Limestone (Dsk) forms spectacular cliffs. The marble is underlain (Dwb) and overlain (Dwpg) by the Devonian Whiteface Mountain volcanics. The volcanic rocks form black, orange, and green layers at the base of the cliffs and are thrust onto brown Hunt Fork Shale, which forms the low, rounded hills to the north near the road.

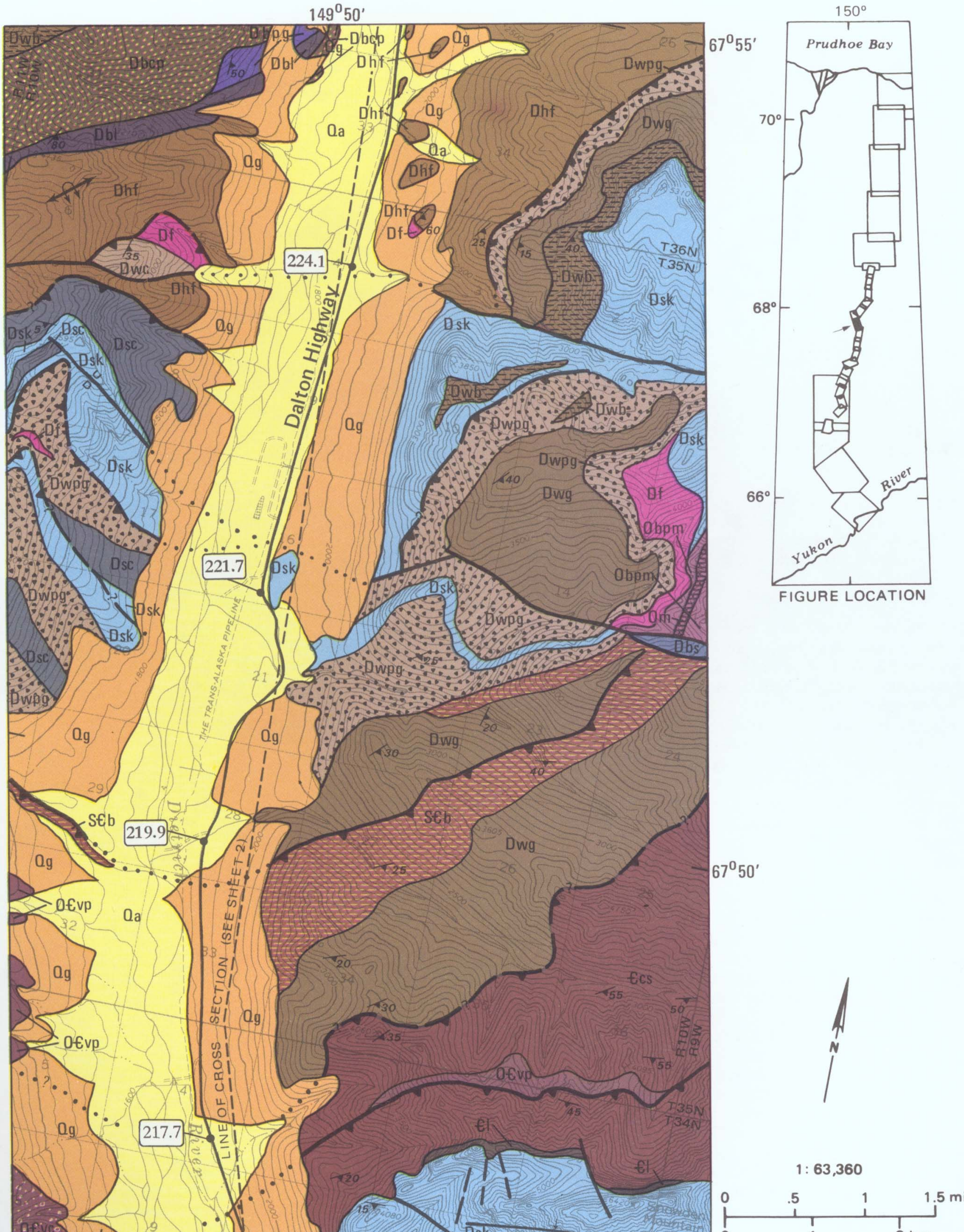
MILE 225 (figs. 76 and 78). The Skajit Limestone (Dsk) is visible to the southwest, where it crosses the Dietrich River valley.

MILE 225.5 (figs. 76 and 78). Along the east side of the road are outcrops of Hunt Fork Shale (Dhf) that consist of black, pyritic phyllite with quartz segregation layering. Three types of foliation developed in the outcrops: 1) S_1 foliation is parallel to the quartz veins; 2) S_2 foliation is vertical and trends N. 30° E.; and 3) S_3 foliation is a semipenetrative crenulation cleavage defined by the mineral sericite.

MILE 225.8 (PB 188.2) (figs. 27, 78, and 79).[12] On the west side of the road is a turnout at a pipeline gate valve. To the northwest up Kuyuktuvuk Creek lies the eastern end of the Doonerak fenster, the most important feature for understanding the structural evolution of the central Brooks Range (sheets 1 and 2; Mull and others, chap. 14). The fenster can be traced for over 50 mi (80 km) to the southwest along the axis of the Doonerak antiform. Rocks of the parautochthonous North Slope stratigraphic sequence (fig. 29) are exposed in the fenster and contrast markedly with the stratigraphic sequence on the overlying Endicott Mountains allochthon (fig. 31) north of the fenster and other allochthonous rocks south of the fenster. The parautochthonous North Slope stratigraphic sequence exposed on the high ridges west of Kuyuktuvuk Creek and in the canyon of Trembley Creek can be reached by day hikes from this point; this is the only part of the fenster that can be reached conveniently without light aircraft or helicopter. East of Kuyuktuvuk Creek, the Doonerak antiform plunges eastward toward the Dietrich River and the Dalton Highway, where the

Figure 76. Geologic map of Dalton Highway area in Dietrich River valley, Mile 217 to Mile 226. See figure 82 for map explanation.

[12] Prepared by C.G. Mull, DGGS, 1985


149°50′
67°55′
67°50′
Dalton Highway
THE TRANS-ALASKA PIPELINE
LINE OF CROSS SECTION (SEE SHEET 2)
224.1
221.7
219.9
217.7
Dietrich River
Snowden Mountain
T36N
T35N
T34N
R10W
R9W
150°
Prudhoe Bay
70°
68°
66°
Yukon River
FIGURE LOCATION
N
1: 63,360
0 .5 1 1.5 mi
0 1 2 km

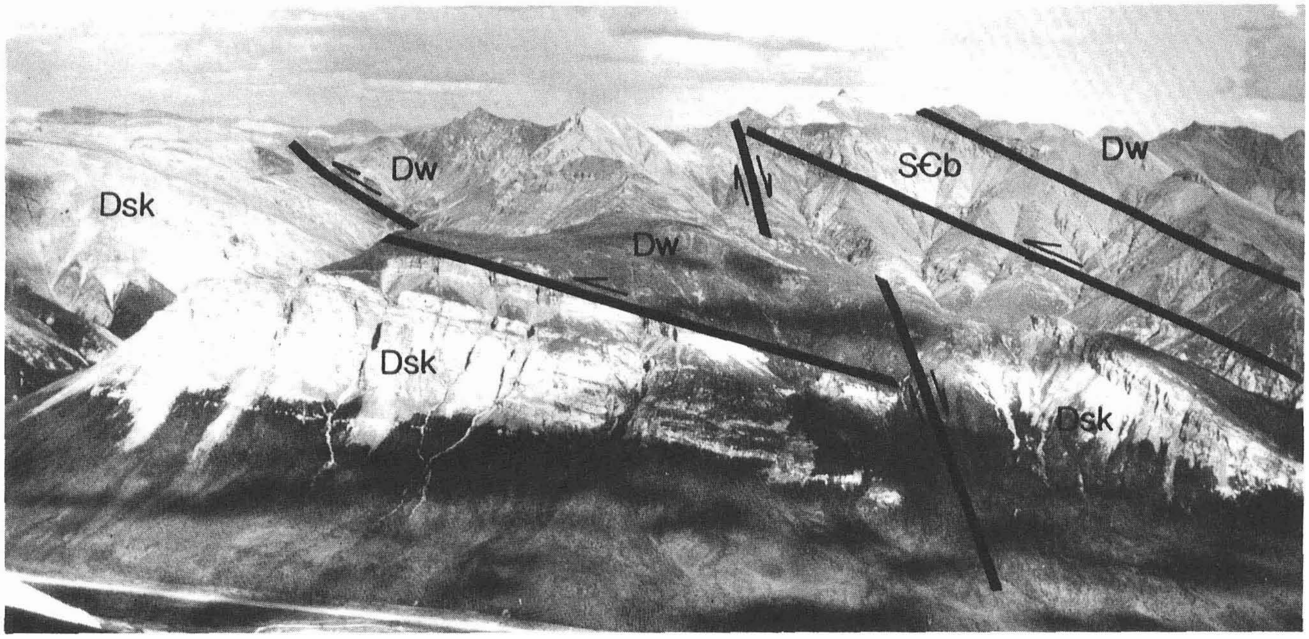


Figure 77. View eastward toward cliffs of *Skajit* Limestone (Dsk) north of *Snowden* Mountain from Mile 222 to Mile 223. *Skajit* is overlain by thrust sheet of phyllite, graywacke, and limestone of Whiteface Mountain uolcanics (Dw). High mountains in distance to soulh are formed by higher thrust sheet of Cambrian to *Silurian phyllite* and siltstone *(SЄb)* and overlying graywacke of Whiteface Mountain *volcanics* (Dw). Photograph by C.G. Mull, August 1985.

parautochthonous North Slope stratigraphic sequence is buried beneath overlying allochthonous rocks. Rocks as young as Triassic in the fenster and on the Endicott Mountains allochthon are all folded, as are the related metamorphic structures. The folding probably occurred during Early (Albian) or Late Cretaceous time.

The parautochthonous North Slope sequence at the eastern end of the Doonerak fenster consists of Mississippian to Lower Pennsylvanian Lisburne Group limestone and Mississippian Kayak Shale and Kekiktuk Conglomerate unconformably underlain by lower Paleozoic argillite. The sequence is broken by several normal faults, and, in some places, is a broken formation that consists of large blocks of Lisburne encased in a sheared matrix of Kayak Shale. Twenty miles (32 km) to the west on the north side of Mount Doonerak, the parautochthonous sequence consists of Cambrian to Ordovician metavolcanic rocks unconformably overlain by a relatively unbroken section of Mississippian through Upper Triassic deposits: Kekiktuk Conglomerate, Kayak Shale, Lisburne Group, Sadlerochit Group, Shublik Formation, and Karen Creek Sandstone.

The parautochthonous rocks in the fenster are overlain by Upper Devonian Hunt Fork Shale and related rocks of the Middle and Upper Devonian Beaucoup Formation at the base of the Endicott Mountains allochthon. (The Hunt Fork Shale and Beaucoup Formation are also part of other allochthonous sequences in the southern Brooks Range.) Around the eastern plunge of the Doonerak antiform, the Amawk thrust--the sole fault of the Endicott Mountains allochthon--trends approximately east-west along Trembley Creek, turns north up Kuyuktuvuk Creek, and then loops westward up a tributary of Kuyuktuvuk Creek. Klippen composed

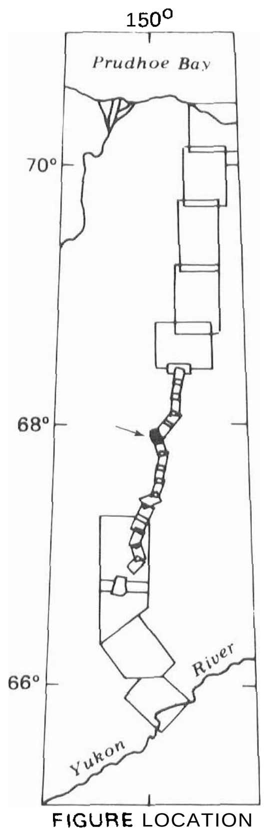
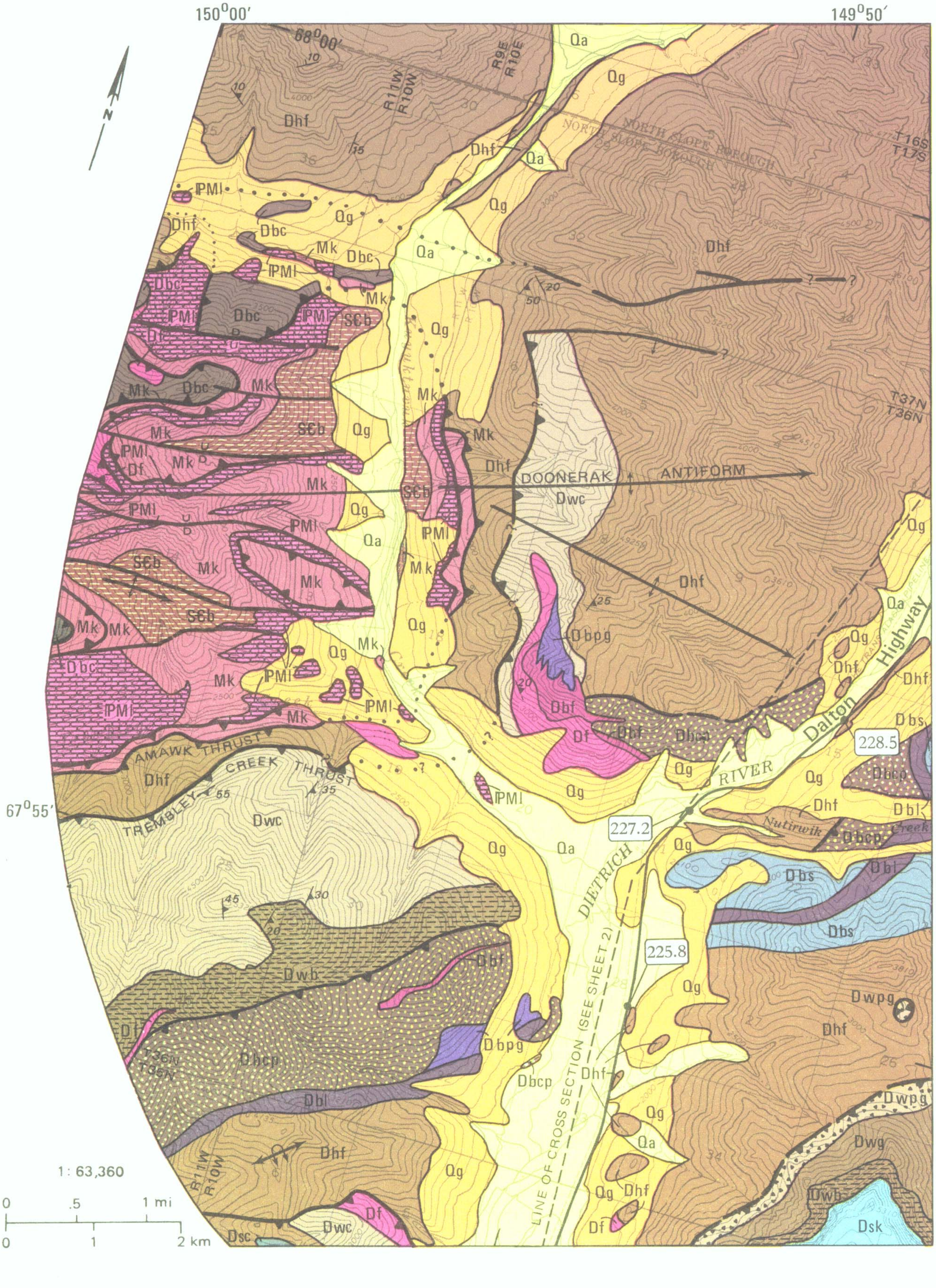


Figure 78. Geologic map of Dalton Highway area at eastern end of Doonerak antiform, Mile 224 to Mile 229. See figure 82 for map explanation.


150°00′
149°50′
68°00′
67°55′
R9E
R10E
R11W
R10W
T16S
T17S
T37N
T36N
NORTH SLOPE BOROUGH
DOONERAK ANTIFORM
AMAWK THRUST
TREMBLEY CREEK THRUST
DIETRICH RIVER
Dalton Highway
Nutirwik Creek
LINE OF CROSS SECTION (SEE SHEET 2)
228.5
227.2
225.8
Dhf
Qa
Qg
Dbc
Mk
SЄb
Dwc
Dbpg
Dbf
Df
Dbcp
Dbs
Dbl
Dwb
Dwpg
Dwg
Dsk
Dsc
1: 63,360
0 .5 1 mi
0 1 2 km

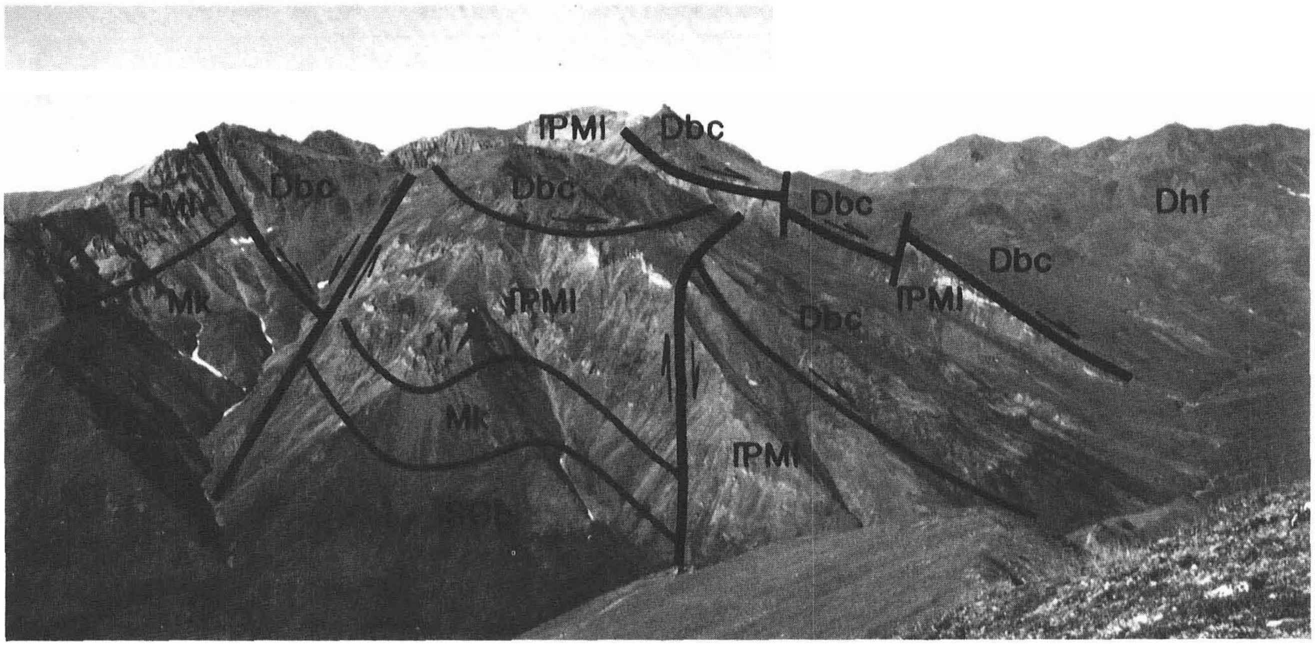


Figure 79. View westward toward eastern end of Doonerak fenster. North-dipping Upper Devonian Hunt Fork Shale (Dhf) and *Beaucoup* Formation (Dbc) on Endicott Mountains allochthon are thrust over parautochthonous North Slope stratigraphic sequence, which consists of Cambrian lo Silurian phyllite *(S€b)*, Mississippian Kayak Shale (Mk), and Mississippian to Pennsylvanian Lisburne Group limestone *(lPMl)*. The folded Amawk thrust has been cut by younger high-angle faults probably formed during formation of the Doonerak antiform. Photograph by C.G. Mull, July 1985.

of thick sections of interbedded pebble conglomerate and quartzitic sandstone similar to the Upper Devonian to Lower Mississippian Kanayut Conglomerate, but mapped as Beaucoup Formation, structurally overlie the parautochthonous Lisburne along the crest of the high ridge west of Kuyuktuvuk Creek. The Endicott Mountains allochthon is composed of a stratigraphic sequence over 15,000 ft (4,600 m) thick that consists dominantly of Upper Devonian Hunt Fork Shale, Upper Devonian to Lower Mississippian Kanayut Conglomerate, Mississippian to Lower Pennsylvanian Lisburne Group, Permian Siksikpuk Formation, and Triassic to Jurassic Otuk Formation.

Along the southern side of Trembley Creek canyon and down the eastern plunge of the Doonerak antiform east of Kuyuktuvuk Creek, a thin Hunt Fork Shale (Dhf) section on the Endicott Mountains allochthon is overlain by the Trembley Creek thrust. This thin sliver of Hunt Fork expands northward to form most of the base of the Endicott Mountains allochthon. The allochthon roots to the south beneath thrust plates of older Devonian and lower Paleozoic rocks. The base of the thrust sheet above the Trembley Creek thrust is composed of interfingered Whiteface Mountain volcanics (Dwc) and Beaucoup Formation (Dbcp), which form high points at the southern end of the ridge between Kuyuktuvuk Creek and the Dietrich River and are overlain by Hunt Fork Shale, which forms the smooth slopes to the east.

To the northeast on Table Mountain, farther down the eastern plunge of the antiform and east of the Dietrich River, massive, gray Skajit marble and the Whiteface Mountains volcanics overlie the Table Mountain thrust. This thrust and the Trembley Creek thrust may merge to define a horse in a duplex system; however, the fault geometry cannot be mapped in the mass of incompetent Hunt Fork Shale between Kuyuktuvuk Creek and the Dietrich River.

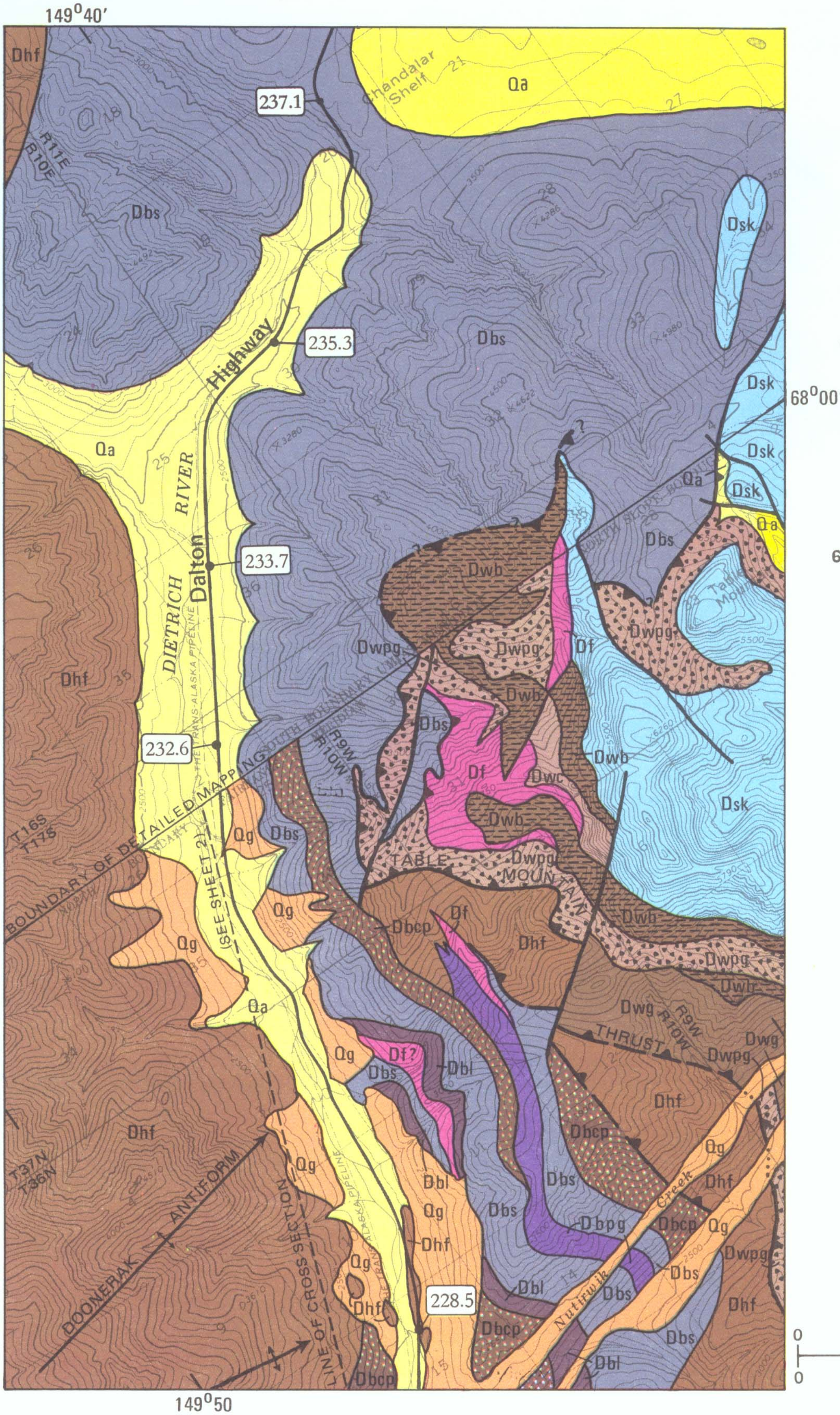
MILE 226.5 (fig. 78). To the east in the Nutirwik Creek drainage are cliffs of Skajit Limestone (Dsk) that overlie the Whiteface Mountain volcanics (Dwg, Dwb, Dwpg). The volcanics, in turn, structurally overlie the Hunt Fork Shale (Dhf).

MILE 227.2. NUTIRWIK CREEK (fig. 78). Parking is available on the dike south of the creek. To the west up lower Kuyuktuvuk Creek and Trembley Creek is a view of the south side of the Doonerak fenster.

A 1-day hike to the east up Nutirwik Creek leads to a beautiful canyon with excellent exposures of Skajit Limestone (Dsk) and underlying lower Paleozoic rocks; the walking is good except at high water after heavy rains. **A** high pass to the Chandalar Shelf, 6 mi (9 km) due east, can be reached by a more arduous hike that follows a sheep trail along the cliffs on the north side of a gorge of the east fork of Nutirwik Creek and then crosses to the south side of the gorge several hundred feet below the pass. Large volcanic and plutonic complexes of the Whiteface Mountain volcanics underlie the Skajit marble near the pass.

MILE 228.5 (figs. 78 and 80). For the next 2 to 3 mi (**3** to **5** km), the road trends almost parallel with structural strike--roughly north-south--of the eastern

Figure 80. Geologic map of Dalton Highway area from Nutirwik Creek to Chandalar Shelf, Mile 228 to Mile 238. Map modified from *Brosgé* and others *(1979a)*. See figure 82 for map explanation.



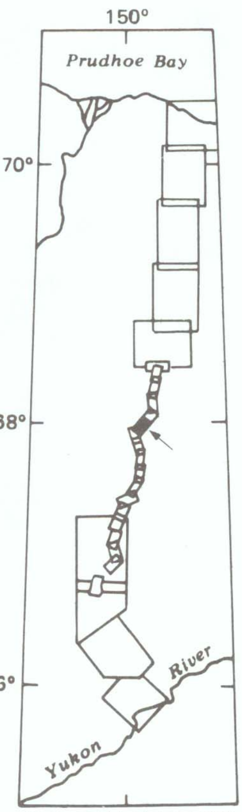


FIGURE LOCATION

1: 63,360

0 .5 1 1.5 mi

0 1 2 km

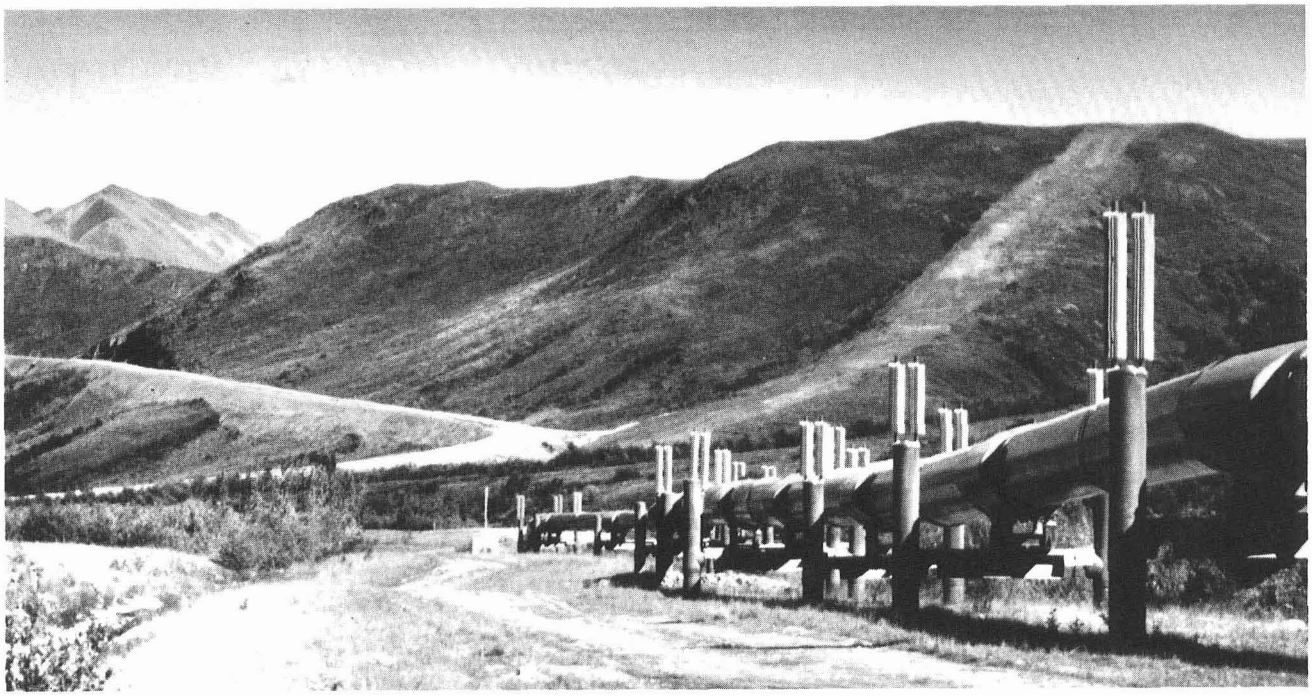


Figure 81. View northeastward toward base of Chandalar Shelf near Mile 236. Highway climbs from valley of upper *Dietrich* River to headwaters of a tributary of North Fork Chandalar River; buried pipeline runs up slope to right. Road cuts are in Upper Deuonian *Beaucoup* Formation. Photograph by *C.G.* Mull, July 1984.

plunge of the Doonerak antiform. The mountains to the west are Hunt Fork Shale (Dhf), overlying the Trembley Creek thrust. Graphitic phyllite and metasandstone in the Hunt Fork are exposed along the east side of the road in a series of road cuts up to 30 ft (10 m) high. S_1 and S_2 foliations are recognized in these exposures; however, S3 foliation is not apparent, possibly due to coarser grain size and more resistant lithologies. Numerous quartz veins are present. Massive Skajit Limestone (Dsk) and other lower Paleozoic rocks in the mountains to the east structurally overlie the Hunt Fork and are part of the unnamed allochthon that overlies the Table Mountain thrust.

MILE 231.8 (fig. 80). Up the canyon to the northwest are outcrops of northeast-dipping Hunt Fork Shale (Dhf).

MILE 232.6 (fig. 80). Up the canyon to the east lies Table Mountain, which is composed of Skajit Limestone (Dsk) above the Table Mountain thrust. Slopes below the thrust consist of Devonian Beaucoup Formation (Dbcp, Dbs) and Hunt Fork Shale (Dhf). The view to the west across the river is of Hunt Fork Shale.

MILE 233.7 (fig. 80). Up the valley to the northwest is a view of Upper Devonian to Lower Mississippian Kanayut Conglomerate. The Kanayut forms the rugged, stratified peaks above the rounded ridges and smooth slopes of the conformably underlying Upper Devonian Hunt Fork Shale (Dhf). Both units are part of the Endicott Mountains allochthon. The relatively incompetent Hunt Fork Shale is often isoclinally folded and commonly acts as a detachment horizon for thrust faults or folds in the Kanayut.

MILE 234.8 (fig. 80). The North Slope Borough sign on the right is about 2.5 mi north of the borough boundary.

MILE 234.9 (fig. 80). At this point, a sign marks the northernmost tree along the pipeline corridor. The tree belongs to a stand of white spruce that is an ecological reserve for the study of vegetation and forest dynamics (Densmore, 1980). The treeline in this area has been relatively stable for several centuries: 30 percent of the trees are over 200 yr old and some are at least 400 yr old. Under present climatic conditions, regeneration by white spruce seedlings will be adequate to replace the stand and even increase stand density. There is some evidence of extension of the treeline on alluvial sites beyond the present line. (See Brown and Kreig, 1983, p. 149.)

MILE 235.3 (figs. 80 and 81). A wide turnout with litter barrels is at the base of the Chandalar Shelf, where the road begins to climb a steep (9^{o}) grade. Nearly continuous outcrops, 30 to 100 ft (10 to 30 m) high, in black phyllite of the Beaucoup Formation (Dbs) are present on the east side of the road as it winds to the top of the shelf.

MILE 236 to 237 (fig. 80). Road-cut exposures of black phyllite of the Beaucoup Formation (Dbs) are present on both sides of the road. Bedding is well preserved locally, although the phyllite is cut by numerous quartz veins and two or three cleavages.

MILE 236.2 (fig. 80).[13] From the wide shoulder on the west side of the road is a good view to the northwest of the upper Dietrich River valley, where the Kanayut Conglomerate has been folded into a regional synclinorium and forms the high mountain peaks. The road cut on the east side of the road is in black phyllite of the Beaucoup Formation (Dbs). From here to the north front of the mountains at Mile 270, the Dalton Highway is on rocks of the Endicott Mountains allochthon.

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[13]Prepared by C.G. Mull, DGGS, 1985.

MAP SYMBOLS

Contact

High-angle fault—Dashed where approximately located; dotted where concealed; queried where inferred. U, upthrown side; D, downthrown side. Arrow indicates dip of fault

Thrust fault—Dashed where approximately located; dotted where concealed; queried where inferred. Sawteeth on upper plate

Anticline, showing plunge of axis

Overturned anticline, showing direction of dip of limbs and plunge of axis

Syncline, showing plunge of axis

Overturned syncline, showing direction of dip of limbs and plunge of axis

49 Strike and dip of beds

50 Strike and dip of foliation

DESCRIPTION OF MAP UNITS

QUATERNARY DEPOSITS

Qa ALLUVIAL DEPOSITS, UNDIFFERENTIATED (QUATERNARY)

Qg GLACIAL DEPOSITS, UNDIFFERENTIATED (QUATERNARY)

CRETACEOUS SEDIMENTARY ROCKS
(fault panel 11)

Kqc SANDSTONE AND CONGLOMERATE (UPPER TO LOWER CRETACEOUS-CENOMANIAN TO ALBIAN)—Predominantly sandstone and conglomerate composed of vein quartz and schist clasts. Nonmarine deposit

Ksc METASEDIMENTARY-CLAST CONGLOMERATE (UPPER TO LOWER CRETACEOUS-CENOMANIAN TO ALBIAN)—Predominantly cobble conglomerate and subordinate sandstone composed mostly of metagraywacke clasts. Nonmarine deposit

Kic IGNEOUS-CLAST CONGLOMERATE (LOWER CRETACEOUS-ALBIAN)—Predominantly cobble conglomerate and subordinate sandstone composed mostly of mafic-igneous clasts. Nonmarine deposit

Ktm SANDSTONE, CONGLOMERATE, AND SHALE (LOWER CRETACEOUS-ALBIAN)—Predominantly sandstone and abundant conglomerate and shale. Transitional marine to nonmarine deposits

CRETACEOUS METAMORPHIC AND INTRUSIVE IGNEOUS ROCKS
(fault panel 12)

Kmi INJECTION MIGMATITES, HORNFELS, AND APLITE DIKES (CRETACEOUS)

Kg GRANITE (CRETACEOUS)—Medium- to coarse-grained, porphyritic biotite-hornblende granite

Kmz MONZONITE (CRETACEOUS)—Fine- to coarse-grained, equigranular to porphyritic monzonite

Ksy SYENITE (CRETACEOUS)—Fine- to coarse-grained, equigranular to porphyritic biotite-hornblende syenite ± pyroxene

MIDDLE PALEOZOIC TO MESOZOIC ROCKS WITH ONE METAMORPHIC FABRIC
(fault panels 10, 11)

MzPzw METAGRAYWACKE (TRIASSIC? TO DEVONIAN)—Brown-weathering, medium-grained metagraywacke with abundant phyllite interlayers and local interlayers of bedded radiolarian chert

MzPzp PHYLLITE (TRIASSIC? TO DEVONIAN)—Platy, black phyllite and dark-gray metagraywacke with minor greenstone

MzPzv VOLCANIC ROCKS (LOWER JURASSIC TO DEVONIAN)—Includes pillow basalt, breccia, tuff, gabbro, and minor argillite

MzPzd MAFIC DIKES AND SILLS (LOWER JURASSIC? TO DEVONIAN?)

MzPzc CHERT (LOWER JURASSIC TO MISSISSIPPIAN)—White, gray, green, red, and black, banded radiolarian chert

UPPER PALEOZOIC SEDIMENTARY ROCKS SLIGHTLY METAMORPHOSED
(fault panels 1, 2)

Units exhibit two regional metamorphic fabrics. Metamorphic grade increases southward from that of lowermost to middle greenschist facies. Sedimentary textures are well preserved.

PMl LISBURNE GROUP (PENNSYLVANIAN TO MISSISSIPPIAN)—Gray, cherty limestone and dolomite

Mk KAYAK SHALE AND KEKIKTUK CONGLOMERATE (LOWER MISSISSIPPIAN)—Kayak consists predominantly of black shale and minor brown limestone; Kekiktuk consists of quartzite and minor conglomerate

DEVONIAN SEDIMENTARY AND VOLCANIC ROCKS WITH TWO METAMORPHIC FABRICS
(fault panels 3, 6-9)

Units grade southward from middle to upper greenschist facies and consist mostly of phyllite and limestone in north and schist and marble in south.

Dhf HUNT FORK SHALE (UPPER DEVONIAN)—Phyllite, wacke, sandstone, conglomerate, and limestone. In some places, grades downward into Beaucoup Formation; in other places, unconformably overlies upper Middle Devonian and older rocks

Dh PELITIC SCHIST (UPPER DEVONIAN?)—Probably correlative with Upper Devonian Hunt Fork Shale

Middle and Upper Devonian Beaucoup Formation

Units grade downward and southwestward into Skajit Limestone and are laterally equivalent to Whiteface Mountain and Ambler volcanic and sedimentary rocks.

Dbs BLACK SILTSTONE, PHYLLITE, AND SLATE (UPPER AND MIDDLE DEVONIAN AND LOWER PALEOZOIC?)—Contains lenses of limestone and dolomite

Dbcp CALCAREOUS, CHLORITIC SANDSTONE AND CONGLOMERATE (UPPER AND MIDDLE DEVONIAN)—Locally contains limestone

Dbc CHLORITE-MUSCOVITE-QUARTZITE CONGLOMERATE AND SANDSTONE (UPPER TO MIDDLE DEVONIAN)

Dbpg PURPLE AND GREEN PHYLLITE (UPPER TO MIDDLE DEVONIAN)—Locally volcaniclastic(?)

Dbl BLACK TO PLATY-GRAY LIMESTONE (LOWER UPPER AND UPPER MIDDLE DEVONIAN)

Dbq BLACK QUARTZITE AND METASILTSTONE (LOWER UPPER AND UPPER MIDDLE DEVONIAN)

Devonian carbonate and clastic rocks

Dsk SKAJIT LIMESTONE (DEVONIAN)—Massive, gray marble, dolomite, and carbonate conglomerate with minor graphitic and calcareous schist and quartzite

Dc CHLORITIC AND CARBONATE ROCKS (UPPER AND MIDDLE DEVONIAN)—Calcareous, chloritic sandstone, siltstone, conglomerate, graphitic phyllite, dolomitic phyllite, and marble

Dsc CHLORITE-QUARTZITE SANDSTONE, CONGLOMERATE, LIMESTONE, AND PHYLLITE (MIDDLE TO LOWER? DEVONIAN)

Middle to Upper Devonian Whiteface Mountain volcanics

Units consist of metavolcanic and metasedimentary rocks stratigraphically and lithologically equivalent to parts of Beaucoup Formation and Ambler metavolcanic rocks. Locally includes middle Paleozoic rocks of units Dwc and Dwb.

Dwc CALCAREOUS, GRAPHITIC PHYLLITE, PLATY LIMESTONE, TUFF, AND FELSIC INTRUSIVE ROCKS (UPPER TO MIDDLE DEVONIAN)

Dwg GRAYWACKE, QUARTZITE, PHYLLITE, AND FOSSILIFEROUS LIMESTONE (UPPER TO MIDDLE DEVONIAN)

Dwb BLACK PHYLLITE (UPPER TO MIDDLE DEVONIAN)—Black, chloritic, carbonaceous phyllite with thin lenses of brown, finely crystalline dolomite

Dwpg PURPLE AND GREEN PHYLLITE AND CHLORITIC QUARTZITE (MIDDLE DEVONIAN?)

DEVONIAN IGNEOUS AND THERMALLY METAMORPHOSED ROCKS WITH TWO METAMORPHIC FABRICS
(fault panels 6, 9)

Df FELSIC VOLCANIC ROCKS (DEVONIAN)—Unit includes flows, tuffs, lahars, and hypabyssal intrusive rocks of Ambler and Whiteface Mountain volcanic rocks and Devonian granitic plutonic rocks

Dfm BIMODAL INTRUSIVE COMPLEXES (DEVONIAN)

Dbf BLASTOPORPHYRITIC FELSIC INTRUSIVE ROCKS (DEVONIAN)—Part of Ambler and Whiteface Mountain volcanic rocks and Devonian granitic plutonic rocks

Dg DIABASE, GABBRO, AND DIORITE DIKES AND SILLS (DEVONIAN)

Dgr MUSCOVITE-BIOTITE GRANITE ORTHOGNEISS (DEVONIAN)

Dt TREMOLITE SKARN, CALC-SILICATE HORNFELS, AND SILICEOUS HORNFELS (DEVONIAN?)—Formed during emplacement of Devonian(?) plutons

LOWER PALEOZOIC ROCKS OF DOONERAK WINDOW AND RELATED EXPOSURES
(fault panels 1, 2, 6)

Metamorphic grade ranges from prehnite-pumpellyite to lower greenschist facies. Black phyllite and metasiltstone (SЄb), volcanic phyllite (OЄvp), and volcanic conglomerate (OЄvc) units unconformably overlain by Mississippian Kekiktuk Conglomerate.

SЄb BLACK PHYLLITE AND METASILTSTONE (SILURIAN TO CAMBRIAN)—Contains minor quartzite, limestone, and red and green phyllite

Obpm BLACK PHYLLITE AND MARBLE (MIDDLE ORDOVICIAN)—Black, graphitic, pelitic phyllite interlayered with thin, black, crinoidal marble

Om MARBLE (MIDDLE ORDOVICIAN)—Gray to black, crinoidal marble. Contains conodonts

OЄvp VOLCANIC PHYLLITE (ORDOVICIAN OR CAMBRIAN)—Gray, purple, and green laminated phyllite and interlayered volcanic rocks

OЄvc VOLCANIC CONGLOMERATE (ORDOVICIAN? TO CAMBRIAN?)—Polymictic conglomerate with abundant clasts of intermediate volcanic rocks

Єl SANDY MARBLE (LOWER MIDDLE CAMBRIAN)—Locally contains trilobites

Єcq MUSCOVITE-ALBITE-CHLORITE QUARTZ SCHIST (CAMBRIAN?)

Єcs CHLORITIC QUARTZ CALC-SCHIST, DOLOMITIC PHYLLITE, AND MARBLE (CAMBRIAN?)

PROTEROZOIC TO PALEOZOIC ROCKS WITH THREE METAMORPHIC FABRICS
(fault panels 3, 8, 9)

Units consist mostly of upper greenschist-facies rocks but include amphibolite-facies paragneiss and local relict blueschist- and eclogite-facies metabasite.

PzPv GREENSCHIST AND AMPHIBOLITE (LOWER PALEOZOIC? TO PROTEROZOIC)—Present as interlayers in quartzite (PzPqs) and calcareous schist (PzPcs) units

PzPg DIABASE AND GABBRO DIKES, SILLS, AND INTRUSIVE COMPLEXES (LOWER PALEOZOIC? TO PROTEROZOIC)

PzPsq SCHIST AND QUARTZITE (LOWER PALEOZOIC? OR PROTEROZOIC)—Graphitic schist with layers and lenses of quartzite

PzPqs QUARTZITE AND SCHIST (LOWER PALEOZOIC? OR PROTEROZOIC)—Quartzite with 1- to 10-cm-thick lenses of graphitic schist

PzPcs CALCAREOUS SCHIST (LOWER PALEOZOIC? OR PROTEROZOIC)—Graphitic, quartzose calcareous schist and thin marble interlayers

PzPm MARBLE (LOWER PALEOZOIC? TO PROTEROZOIC)—Thick, gray marble layers in calcareous schist (PzPcs) unit

Figure 82. Explanation for geologic maps from South Fork Koyukuk River to Chandalar Shelf (figs. 58, 60, 61, 65, 66, 68, 70, 72, 74, 76, 78, and 80).

Figure 83. View northward from Table Mountain to Chandalar Shelf and crest of Endicott Mountains. Chandalar River tributaries flow across broad, alluviated valleys on Chandalar Shelf; at left, incised head of *Dietrich* River is graded to lower base level and has pirated part of Chandalar drainage. Photograph by J.T. *Dillon*, July 1984.

ROAD LOG FROM CHANDALAR SHELF (MILE 237.1) TO PRUDHOE BAY (MILE 414)

By C.G. Mull and E.E. Harris[14]

MILE 237.1. CHANDALAR SHELF (PB 176.9) (figs. 80, 83, and 85). On the east side of the road is the highway checkpoint. To the north lies the crest of the Endicott Mountains; to the east, a tributary of the North Fork Chandalar River; to the south, Table Mountain; and to the southwest, the upper Dietrich River valley. Upper Devonian to Lower Mississippian Kanayut Conglomerate (MDk), folded in a regional synclinorium, forms rocks of the Continental Divide along the crest of the Endicott Mountains. From Chandalar Shelf northward, the rocks lose most of their metamorphic fabric.

The road levels out to the northeast on the drift-covered floor of the broad, glaciated valley of a western tributary to the North Fork Chandalar River. The tributary is at a higher base level than that of the Dietrich River and its tributaries on the Koyukuk drainage system to the south; consequently, streams in mountain valleys of the Koyukuk drainage system are developed at generally lower altitudes and have captured the adjoining drainages of the North Fork Chandalar River.

To the northeast, across the Chandalar Shelf, a large morainal ridge trends west-southwest. The ridge was deposited by the latest valley glaciation as a medial(?) or eastern lateral moraine of a glacier tongue that flowed southwestward over the Chandalar Shelf and into the Dietrich River valley.

MILE 239.5. CHANDALAR CAMP (figs. 84 and 85). Chandalar Camp was formerly a pipeline-construction camp and is now the site of DOTPF and Alyeska Pipeline Service Company maintenance camps. These facilities are not for public use.

MILE 242.2 (fig. 85). The highway crosses the west fork of the North Fork Chandalar River. On the south side of the fork about 200 yd (180 m) upstream, poorly preserved brachiopods and solitary horn corals have been recovered from silty limestone beds in Hunt Fork Shale (Dh).

MILE 242.3 (fig. 85). The highway begins to climb toward Atigun Pass. To the south is a good view down the west fork of the North Fork Chandalar River; to the north, north-dipping Kanayut Conglomerate (MDk) caps the Continental Divide. Conspicuous red, orange, and yellow oxidized zones are common in the Kanayut and contain abundant pyrite but no other significant mineralization.

MILE 243.8 (fig. 85). A section of Kanayut Conglomerate (MDk) is well exposed near a waterfall up a small gully to the northwest; parking is available in a broad turnout to the left. The section is part of a southern belt of Kanayut that is distinctly thinner and finer grained than a northern belt recognized north of the range crest (Moore and others, chap. 15).

[14]DGGS, 3700 Airport Way, Fairbanks. Alaska 99709.

Figure 84. View southward toward Chandalar Camp (Mile **239)** *and Table Mountain. Dalton Highway and pipeline descend from Chandalar Shelf into upper Dietrich River valley at right. Skajit Limestone, which forms top of Table Mountain, is thrust northward onto Hunt Fork Shale, which underlies lower slopes of mountain.*

MILE 244.7. ATIGUN PASS (PB 169.9) (figs. 85, 86, 87, and 88). At this point, the road crosses the summit of Atigun Pass (elevation 4,643 ft; 1,447 m) on the Continental Divide. On the east side of the road is a broad turnout with parking; on the west are good exposures of Kanayut Conglomerate (MDk).

The pipeline is buried through Atigun Pass to minimize potential avalanche, slushflow, and rockfall hazards and to avoid impact on wildlife. A detailed drilling program during pipeline construction revealed that in certain sections on each side of the summit there are no thaw-stable soils or competent bedrock in which to bury pipe. Along these sections, a 12-in.-thick (28 cm) concrete slab was poured in the bottom of a trench and pipe was then placed in a box made of thick, specially fabricated, high-strength Styrofoam insulation. The box was enclosed in plywood, and the trench was backfilled with permeable gravel that would allow heat to dissipate upward. Since the pipeline went into service in 1978, differential settling has required expensive maintenance and repair work--including grouting, drainage modification, and artificial ground freezing--at least twice, once in 1980 and again in 1988. Heat pipes over the insulated pipe are designed to maintain frozen-ground conditions. (See Brown and Kreig, 1983, p. 153-162.)

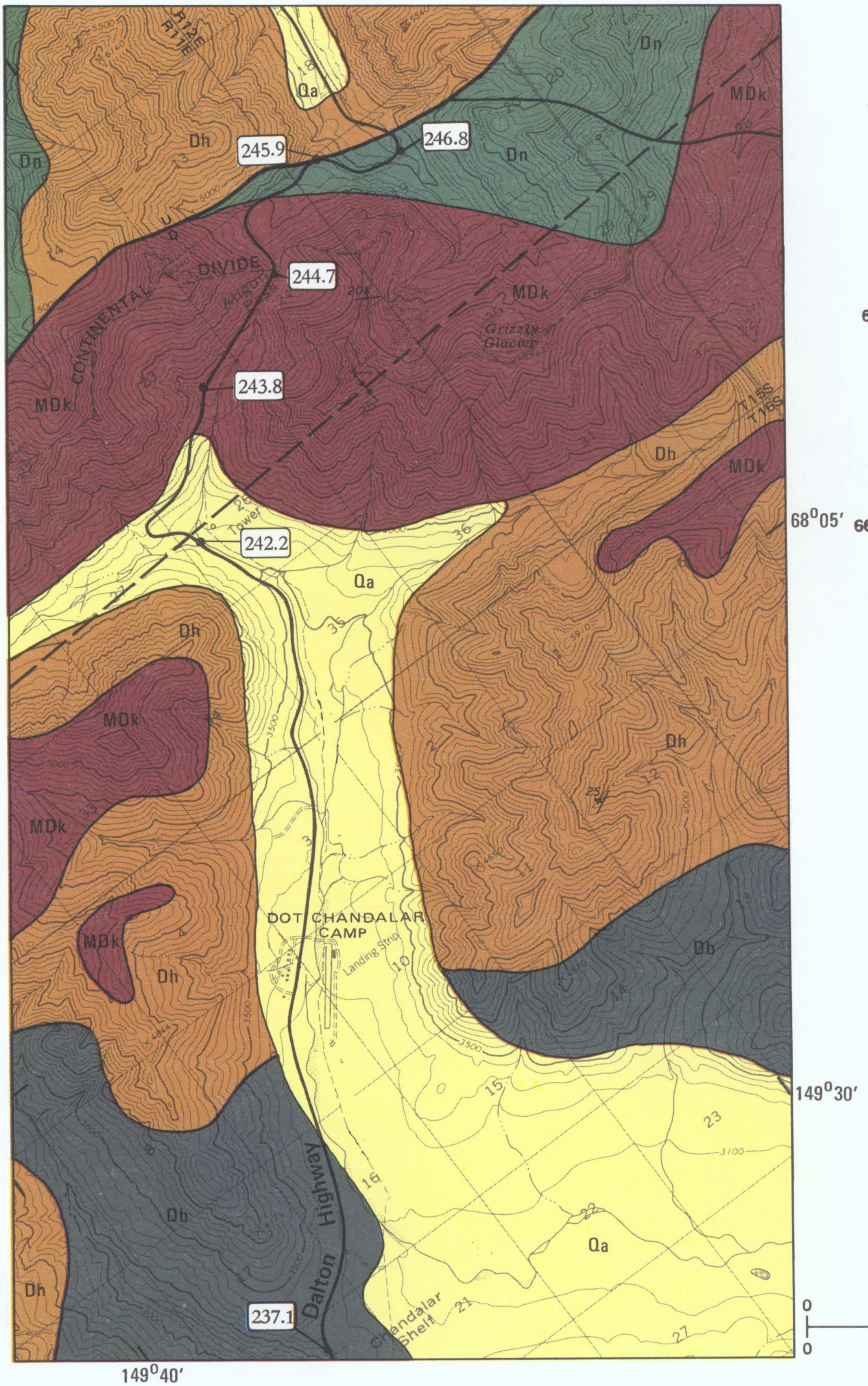
A cirque glacier and two ice-cored rock glaciers are present southeast of the pass at the headwaters of the Atigun River. The region was just high enough to support cirque glaciation the past 4,500 yr. More than 95 percent of the Neoglacial ice masses in the Brooks Range are north of the Continental Divide (Ellis and Calkin, 1979). South of the divide, higher summer temperatures associated with the continental climate of Alaska's interior prevented Holocene glaciers from forming in cirques at these altitudes.[15]

MILE 245.3 (figs. 85 and 87). To the left are good exposures of Kanayut Conglomerate (MDk).

MILE 245.9 (figs. 85, 86, and 87). Northeast of Atigun Pass, the highway crosses a buried segment of the pipeline. A scenic turnout on the left, where Dall sheep can often be seen, provides a good view to the north down Atigun River valley. Past the turnout, the road begins a steep descent into the valley along the east fork of the upper Atigun River. The valley is typical of many of the larger, north-trending valleys in the central and eastern Brooks Range and displays the classic

[15]Prepared by J.M. Ellis and P.E. Calkin, State University of New York at Buffalo. 1983.

Figure 85. Geologic map of Dalton Highway area from Chandalar Shelf to Atigun Pass, Mile **237** *to Mile 248. Map modified from Brosgé and others (1979a). See figure 118 for map explanation.*


Dn
Dh
Qa
MDk
Db
245.9
246.8
244.7
243.8
242.2
237.1
CONTINENTAL DIVIDE
Grizzly Glacier
DOT CHANDALAR CAMP
Landing Strip
Dalton Highway
Chandalar Shelf
Tower
T15S
T16S
R11E
R12E
68°05′
149°30′
149°40′
N
1: 63,360
0 .5 1 1.5 mi
0 1 2 km

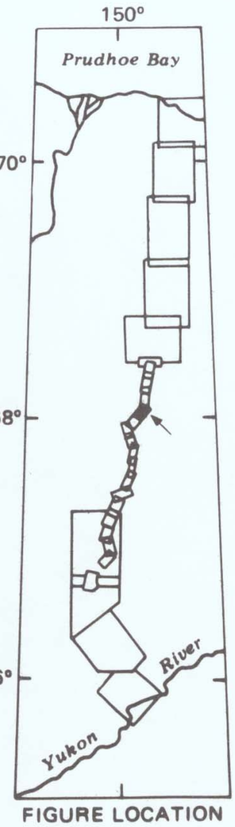

150°
Prudhoe Bay
70°
68°
66°
Yukon River
FIGURE LOCATION

Figure 86. View northeastward from summit of Atigun Pass. Note folding in Hunt Fork Shale in mountains across valley. Pipeline is buried at right.

U-shape of glaciated mountain valleys. Throughout most of its length, the valley is cut into rocks of the non-marine Kanayut Conglomerate (MDk), marine Noatak Sandstone (Dn), and marine Hunt Fork Shale (Dh).

MILE 246.8 (figs. 85 and 87). To the left is a turnout at the northern base of Atigun Pass. Good exposures of the marine Noatak Sandstone (Dn) are visible on a ridge southeast of the road. The beds consist of cross-bedded, medium- to coarse-grained sandstone and interbedded conglomerate.

For the much of the next 7 mi (11 km) to the north, the Atigun River valley is cut in Hunt Fork Shale (Dh). Sedimentary features in the Hunt Fork suggest a wide range of depositional environments, from sub-marine fan to shallow-marine shelf. The relative incompetence of the unit has resulted in spectacular isoclinal folding in some areas.

Mass-wasting deposits are conspicuous along the valley walls and seem to be better developed in areas underlain by the Hunt Fork. These deposits include steep alluvial fans; talus cones, some of which terminate in bouldery ramparts or lobate rock glaciers; and mud-flow or debris cones with prominent natural levees.

MILE 247 to 248 (figs. 86 and 87). Isoclinal folding in the wacke member of the Hunt Fork Shale (Dh) is visible on the valley walls east of the road.

MILE 247 to 255 (fig. 87). Along this stretch of the highway, the pipeline is buried under the Atigun River.

MILE 249.4. SPIKE CAMP CREEK (fig. 87). A fault on the east side of the valley juxtaposes the wacke member of the Hunt Fork Shale (Dh) on the south against the shale member of the Hunt Fork on the north; the shale member has regional south dip. The high ridge to the west is composed of south-dipping Noatak Sandstone (Dn) and overlying Kanayut Conglomerate (MDk).

MILE 250. ATIGUN CAMP (fig. 87). The site of Atigun Camp, a former pipeline-construction camp, lies to the right of the road.

MILE 250 to 252 (fig. 87). To the south are good views of Atigun Pass, the Continental Divide, and Grizzly Glacier.

MILE 252.5 (figs. 87 and 90). Isoclinal folds in the shale member of the Hunt Fork (Dh) are visible up-valley to the east.

MILE 253. ATIGUN RIVER (fig. 87). A recumbent fold in the shale member of the Hunt Fork (Dh) is visible on the east side of the valley; tightly folded Hunt Fork is also visible on the west.

MILE 253.5 (fig. 87). Sharply folded Hunt Fork Shale (Dh) is visible on the west side of the valley.

MILE 254.5 (figs. 87 and 89). The highway crosses the trace of a major folded thrust fault that juxtaposes the southern belt of Kanayut Conglomerate (MDk) and Hunt Fork (Dh) with the northern coarser and thicker belt of Kanayut. On the east side of the Atigun River valley, the steeply dipping fault trends through a small gully and juxtaposes brown-black-weathering Hunt Fork Shale on the south against red-brown-weathering Kanayut Conglomerate on the north. On the west side of the valley, the fault bifurcates and juxtaposes Hunt Fork

Figure 87. Geologic map of Dalton Highway area in Atigun River valley, Mile *244* to Mile *255.* Map modified from Brosge and others *(1979a)*. See figure 118 for map explanation.

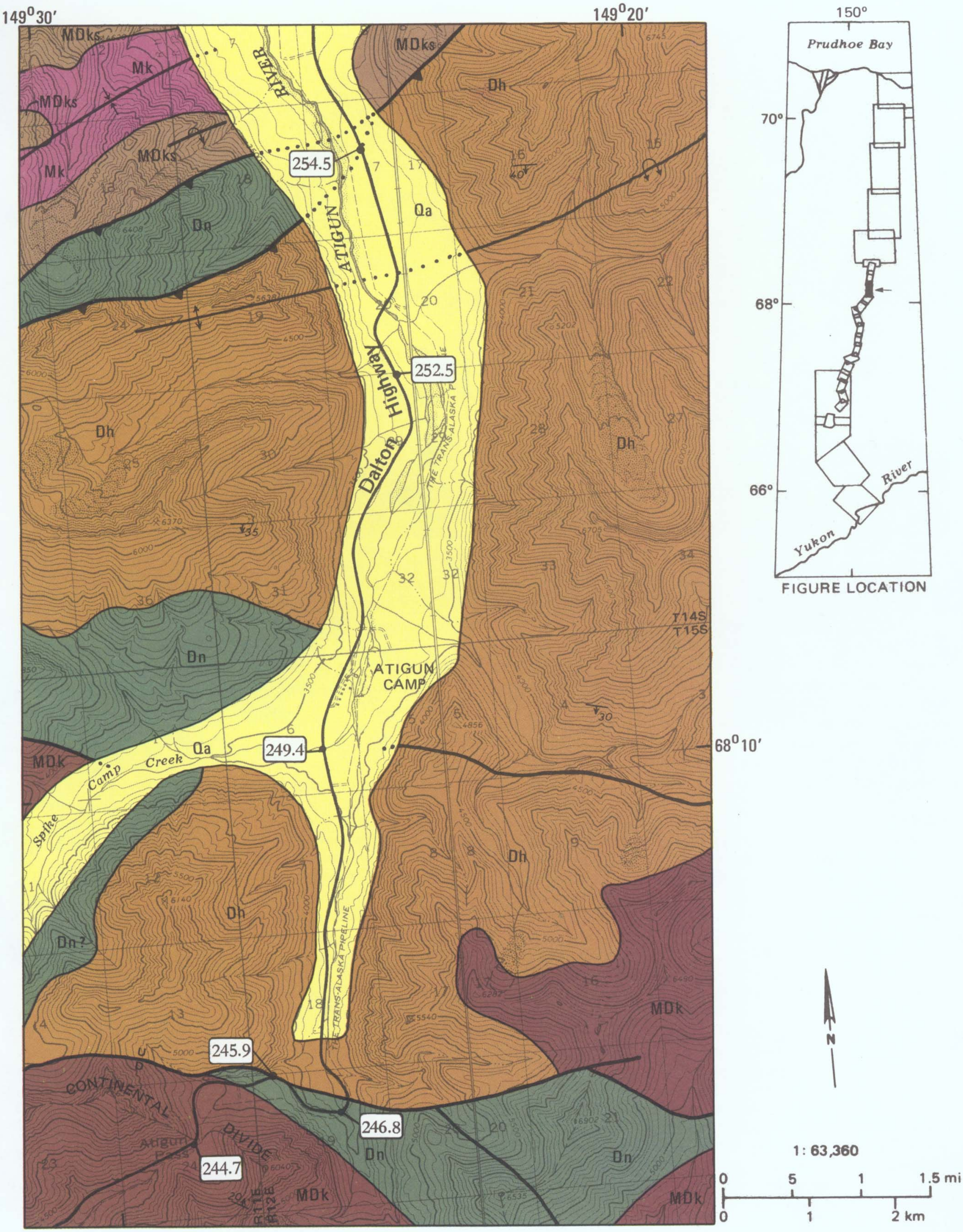

149°30′
149°20′
MDks
Mk
MDk
Dn
Dh
Qa
Dn?
ATIGUN
RIVER
Dalton Highway
THE TRANS ALASKA PIPELINE
ATIGUN CAMP
Spike Camp Creek
CONTINENTAL DIVIDE
Atigun Pass
254.5
252.5
249.4
245.9
246.8
244.7
T14S
T15S
R11E
R12E
68°10′
150°
Prudhoe Bay
70°
68°
66°
Yukon River
FIGURE LOCATION
N
1: 63,360
0 .5 1 1.5 mi
0 1 2 km

Figure 88. View southward toward Continental Divide at Atigun Pass in Endicott Mountains. Peaks in foreground, composed of Kanayut Conglomerate, are up to 6,500 ft (1,950 m) high; sharp peak on skyline (center) is Mount Doonerak, 7,457 ft (2,237 m) high.

Shale against Noatak Sandstone (Dn), which, in turn, is faulted against steeply overturned, massive beds of conglomerate, sandstone, and red shale of the northern belt of the Kanayut. To the northwest, high on the west valley wall, the Kanayut is overlain by black Kayak Shale (Mk) in the axis of a tight syncline. To the west near Anaktuvuk Pass, the fault that juxtaposes the southern and northern belts is known as the Toyuk thrust (Brosgé and others, 1979b).

MILE 257.5 (figs. 89 and 91). To the southwest lies the West Fork Atigun River valley. West of the valley, the Kanayut Conglomerate dips south into a northeast-southwest-trending regional syncline, which can be traced for over 30 mi (48 km) (see fig. 43). Limestone cliffs of the Mississippian to Lower Pennsylvanian Lisburne Group form the high point in the axis of the syncline and are underlain by Mississippian Kayak Shale (10 mi [16 km] west of the map border). On the south side of the valley (6 mi [10 km] west of the map border), an anticline is visible in the Kanayut. Note the contrast between the open folding in the Lisburne and the tight folding in the Kanayut.

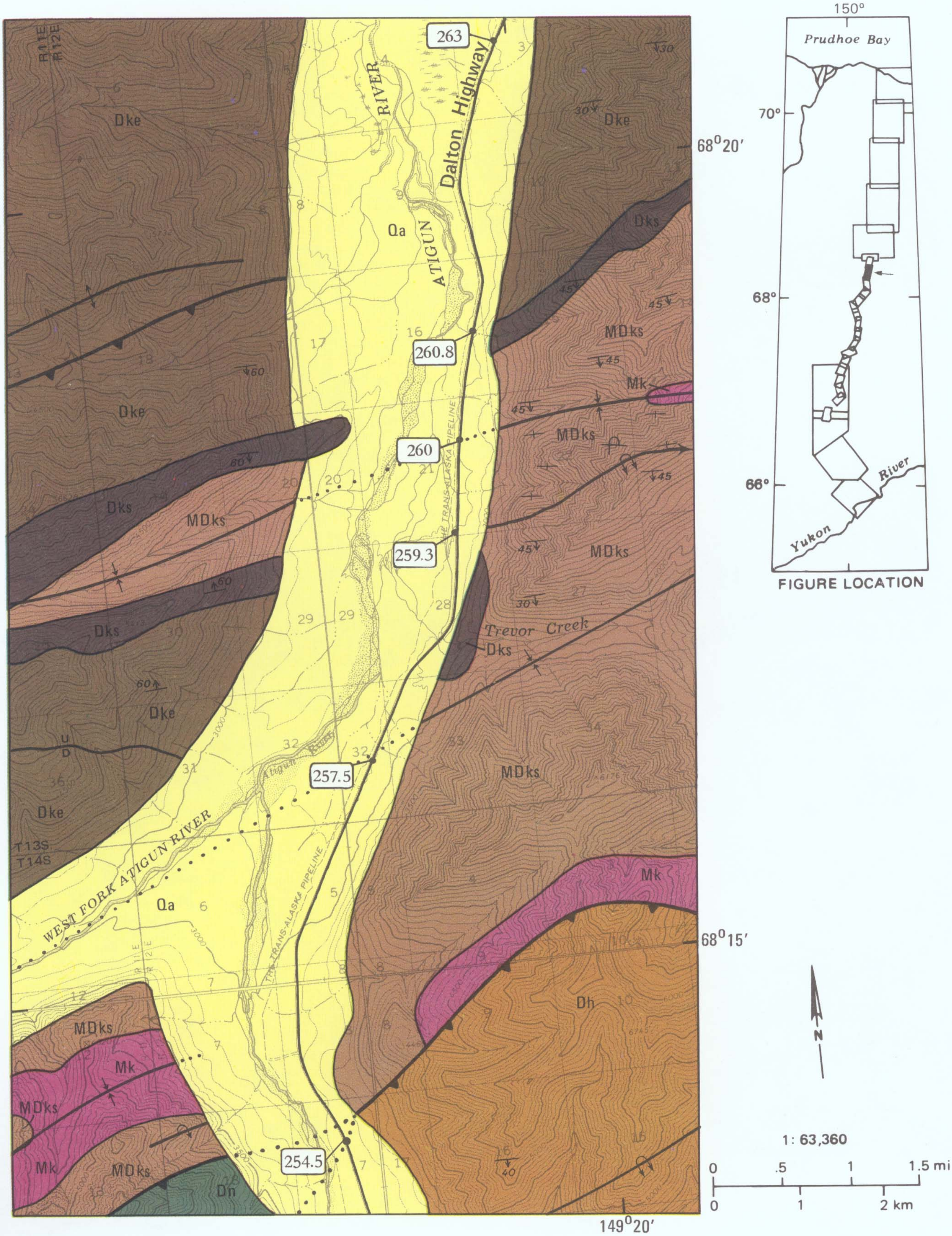
MILE 257.5 to 268 (figs. 89, 91, 92, 93, and 94). The lower Atigun River valley traverses the northern belt of Kanayut Conglomerate. In this belt, the Kanayut is up to 8,300 ft (2,550 m) thick and consists of three members, in ascending order: the Ear Peak Member (Dke), a meandering-stream deposit; the Shainin Lake Member (Dks), a braided-stream deposit; and the Stuver Member (MDks), a meandering-stream deposit (Moore and others, chap. 15). The Kanayut overlies shallow-marine sandstone and conglomerate of the Noatak Sandstone (Dn), which, in turn, overlies the prodelta Hunt Fork Shale (Dh).

In the northern facies belt, the Kanayut is a relatively competent unit that is commonly detached from the underlying incompetent Hunt Fork Shale and is characterized by spectacular open folds and subsidiary thrust faults. The overlying competent Lisburne Group (lPMl) is commonly folded independently of the Kanayut by detachment within the intervening Kayak Shale (Mk). The limbs of a number of the Kanayut folds are visible from the highway, but the Kayak Shale and Lisburne, high on the valley walls, are not visible until the highway approaches the northern mountain front. Structures are dominantly north vergent.

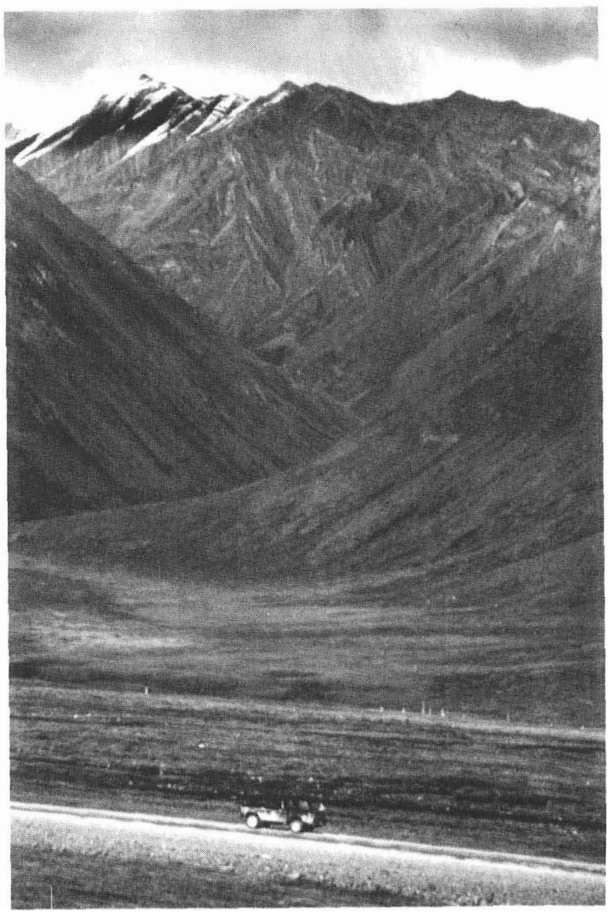
MILE 258.5. TREVOR CREEK (fig. 89). Shainin Lake (Dks) and Ear Peak Members (Dke) of the Kanayut Conglomerate are well exposed on the west side of the valley.

MILE 259.3 (figs. 89 and 92). An access road leads to a gravel pit on the east side of the valley. South of the pit on the east valley wall is an overturned anticline in the Stuver Member (MDks) of the Kanayut Conglomerate.

Figure 89. Geologic map of Dalton Highway area in Atigun River valley, Mile254 to Mile 263. See figure 118 for map explanation.



263
260.8
260
259.3
257.5
254.5
Dalton Highway
ATIGUN RIVER
WEST FORK ATIGUN RIVER
Trevor Creek
THE TRANS-ALASKA PIPELINE
Dke
Dks
MDks
Mk
Qa
Dh
Dn
R11E
R12E
T13S
T14S
68°20′
68°15′
149°20′
150°
Prudhoe Bay
70°
68°
66°
Yukon
River
FIGURE LOCATION
N
1: 63,360
0 .5 1 1.5 mi
0 1 2 km



MILE 260 (figs. 89 and 92). The axis of a tight syncline trends northeast-southwest across the upper Atigun River valley. On the high cliffs to the west, the Ear Peak Member (Dke) and massive Shainin Lake Member (Dks) of the Kanayut Conglomerate form prominent cockscomb features.

MILE 260.8 (PB 152) (figs. 89 and 92). A short road to the east leads to a rock quarry--which Dall sheep sometimes visit--on a spur of a ridge formed by braided-stream deposits of the massive Shainin Lake Member (Dks) of the Kanayut Conglomerate. Resistant, thick conglomerate of the Shainin Lake can be traced down the ridge to the west side of the valley. The conglomerate consists dominantly of matrix-supported pebbles and cobbles of quartz and gray, black, and dark-red chert in a light green-gray litharenite matrix. In addition to chert, lithic clasts include less common volcanic, metamorphic, and granitic rock fragments. Radiolarians are present in the chert and chert-argillite clasts.

MILE 263 (figs. 89 and 94). The axis of an anticline in the Ear Peak Member (Dke) of the Kanayut is visible in the east valley wall.

From this point northward, the Atigun River changes from a braided channel in gravel deposits to a meandering channel in finer grained sediments (fig. 95). The valley was dammed by a large, compound end moraine north of Galbraith Lake that formed a lake that may have extended south as much as 18 mi (30 km). This part of the valley is a broad, poorly drained, sandy plain with abundant ice-wedge polygons, string bogs, and thaw lakes. Test borings and bluff exposures show a

Figure 90. View northeastward from near Mile 252.5 up side cnnyon to isoclinal folds in Hunt Fork Shale. Topographic relief is about 3,500 ft (1,050 m).

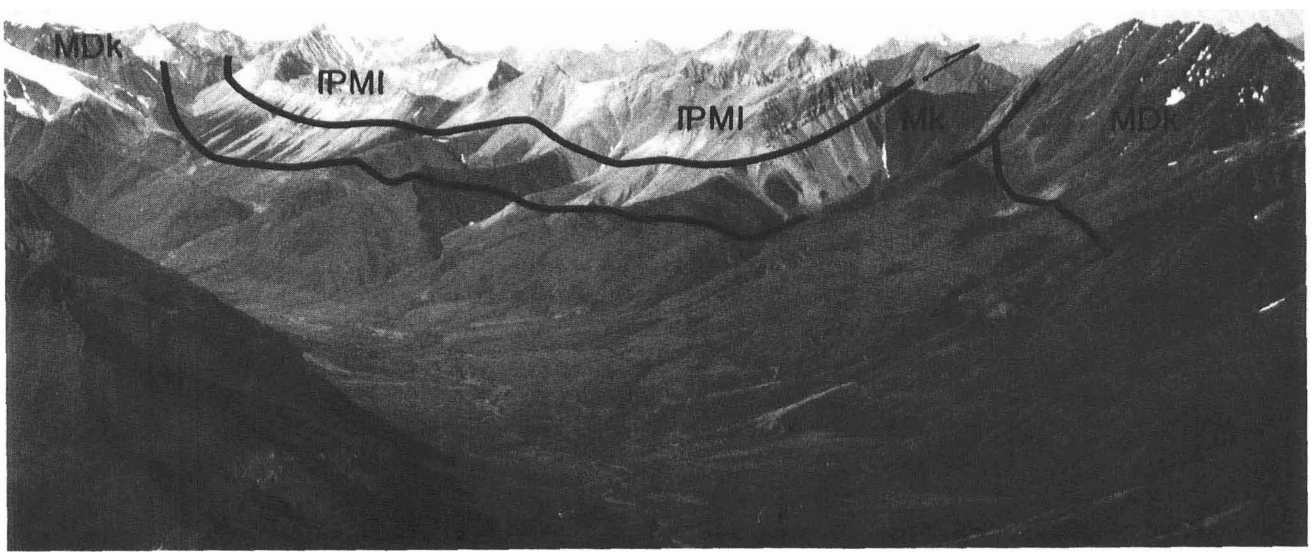


Figure *91. View* westward up West Fork Atigun River. Synclinal infold *of* Lisburne Group carbonates *(lPMl)* and Kayak Shale (Mk) overlies Kanayut Conglomerate *(MDk)* on Endicott Mountains allochthon.

deep fill of lacustrine silt and clay that grades southward into predominantly deltaic sand with some fine gravel. (See Brown and Kreig, 1983, p. 173-175.)

MILE 264 (fig. 94). On the east valley wall, a gently south-dipping thrust fault in the axis of an overturned syncline places the nearly vertical Shainin Lake Member (Dks) of the Kanayut Conglomerate over the gently south-dipping Stuver (MDks) and Shainin Lake Members of the Kanayut.

MILE 265.1. ROCHE MOUTONNÉE CREEK (fig. 94). The axis of a tight anticline in the Ear Peak Member (Dke) of the Kanayut Conglomerate trends westward across the valley and into a zone of complex faults.

MILE 265.2 (fig. 94). To the southeast is a view up Roche Moutonnée Creek to a high peak capped by the Shainin Lake Member (Dks) of the Kanayut Conglomerate.

MILE 266 (figs. 93 and 94). On the east valley wall, the massive marker horizon of the Shainin Lake Member (Dks) of the Kanayut Conglomerate is overturned and dips about 70°S. on the north flank of an overturned anticline. A tight, asymmetric syncline in the Kanayut trends through the low saddle to the northeast. Kayak Shale (Mk) and broadly folded Lisburne Group carbonates (IPMl) (not visible from the road) overlie the tightly folded Kanayut in the axis of the syncline.

MILE 267 (figs. 93 and 94). From the east side of the road, a symmetrical anticline in the Stuver Member (MDks) of the Kanayut Conglomerate can be traced southwestward across the valley, where it is cut along its northern flank by a thrust fault.

MILE 267.5. HOLDEN CREEK (figs. 93, 94, and 95). At this point, the trace of a thrust fault at the northern edge of the northern belt of the Kanayut trends southwestward across the valley. To the east, south-dipping sandstone and conglomerate in the Stuver Member (MDks) of the Kanayut are thrust over a south-dipping thrust plate of Lisburne Group limestone (Mll, IPMlu) and Kayak Shale (Mk). On the west, the northern edge of the Kanayut belt is a zone of tight folds and imbricate thrust slices in both the hanging and footwalls of the thrust fault. From the crest of the low hill just north of Holden Creek is a good view of Pump Station 4.

MILE 268 to 271 (figs. 94 and 99). The highway crosses the belt of Lisburne Group carbonate rocks that characterizes the mountain front of most of the central and northeastern Brooks Range (Armstrong and Mamet, chap. 16). In general, the upper part of the Lisburne (IPMlu) is a thick, massive, cliff-forming, light-gray-

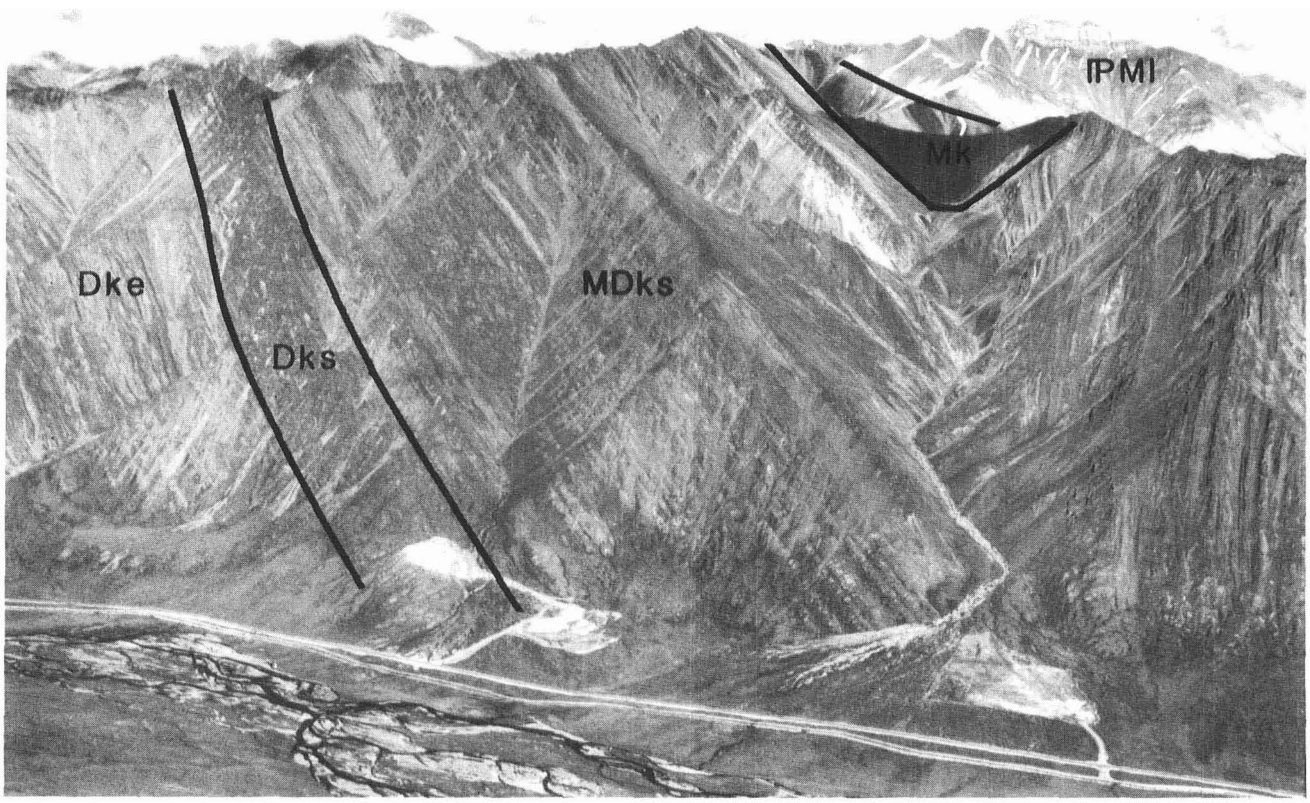


Figure 92. View northeastward across Atigun River valley near Mile 260 toward south flank of syncline, where longest and most complete section of Kanayut Conglomerate in Brooks Range is exposed. Note contrast in deformation between Kanayut, which is tightly folded, and Lisburne, which is folded into a broad syncline. Height of valley wall is about 3,500 ft (1,075 m). Geologic units: Dke, Ear Peak Member of Kanayut Conglomerate; Dks, Shainin Lake Member of Kanayut Conglomerate; MDks, Stuver Member of Kanayut Conglomerate; Mk, Kayak Shale; IPMl, Lisburne Group.

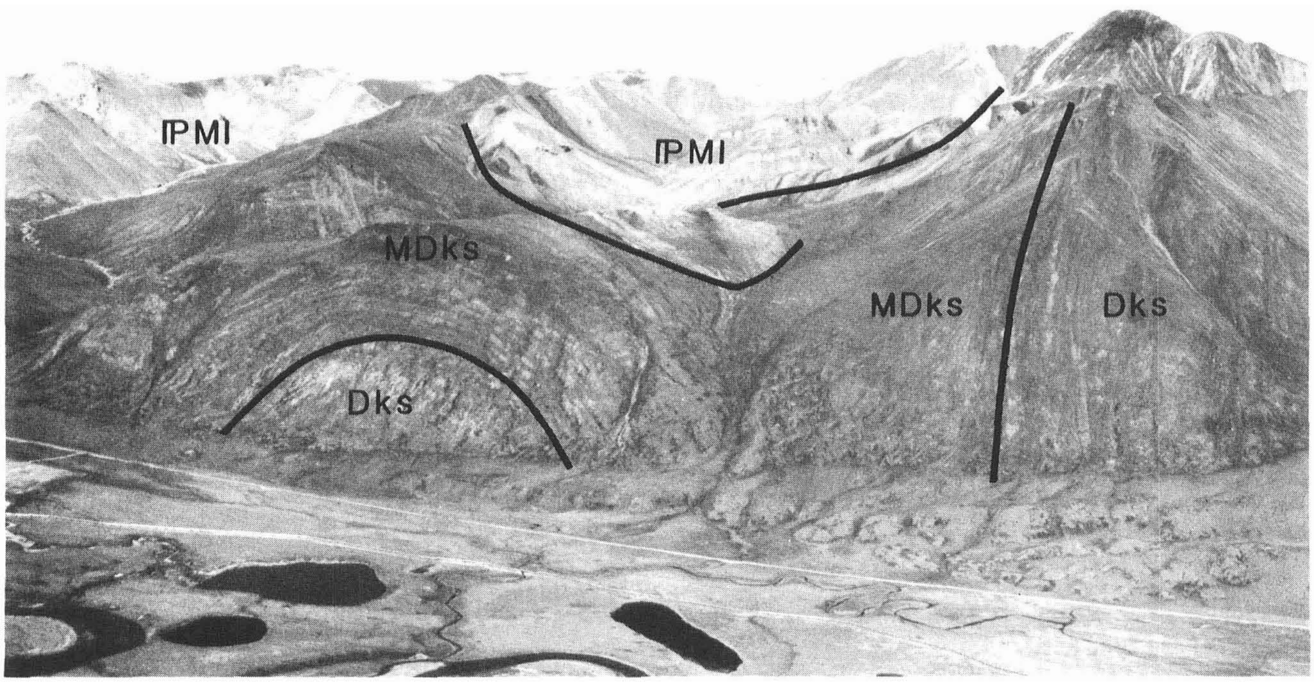


Figure 93. View of *syncline in* Lisburne Group and Kanayut Conglomerate on east side of Atigun River valley near Mile 266. Lisburne is detached from Kanayut by movement in incompetent Kayak Shale, which is discontinuously exposed in the syncline. Geologic units: Dks, *Shainin* Lake Member of *Kanayut* Conglomerate; *MDks*, *Stuver* Member of Kanayut Conglomerate; *lPMl*, Lisburne Group.

weathering unit that consists of limestone and dolomite and contains zones of abundant nodular and disseminated chert. The lower part of the Lisburne (Mll) consists of less resistant, medium-gray-weathering limestone. In the eastern Endicott Mountains of the central Brooks Range, the mountain front consists dominantly of polydeformed sheets of Lisburne. Some areas to the west consist of broadly folded imbricate sheets that were probably deformed by duplexing of an underlying sheet of Lisburne. Other areas, such as the mountain front at Atigun Gorge, display recumbent to overturned sheets of Lisburne that resulted from multiple stages of folding and thrusting, which may have included out-of-sequence thrusting of underlying sheets of Lisburne (fig. 97).

MILE 269.3 (figs. 94 and 99). A road to the left leads to Pump Station 4 (fig. 96). A broad, glaciated valley extends north from Pump Station 4 to just south of Galbraith Lake (fig. 95).

Lacustrine, fluvial, and eolian deposits form the valley floor and are underlain by glacial and glaciofluvial sediments. Blowout troughs (50 to 65 ft [15 to 20 m] deep), separated by sharp-crested sand ridges (yardangs), are conspicuous along the margins of the Atigun River flood plain, where they parallel the dominant down-valley wind direction. Sand blown from the troughs is deposited downwind as longitudinal dunes and sand blankets 2 to 25 ft (0.6 to 8 m) thick.

Pump Station 4 is built on an unrefrigerated foundation on limestone of the Lisburne Group. Water wells drilled in bedrock to 800 ft (245 m) were unsuccessful and did not reach the bottom of the permafrost. This pump station and the three to the north are powered by natural gas, which flows from Prudhoe Bay in an 8 to 10 in. (20 to 25 cm) diam buried gasline. (See Brown and Kreig, 1983, p. 175.)

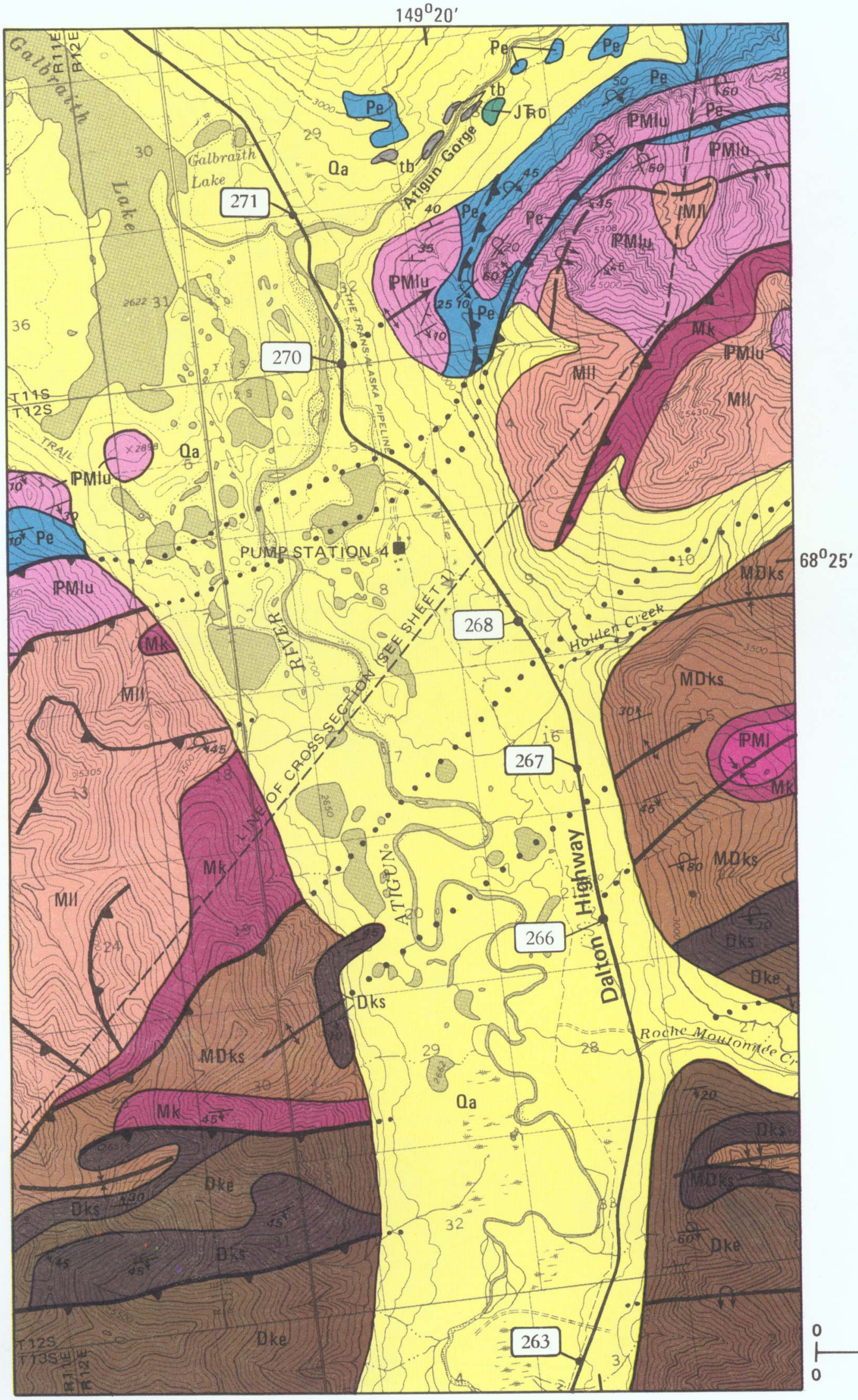
MILE 269.4 (figs. 94 and 99). The road crosses the pipeline.

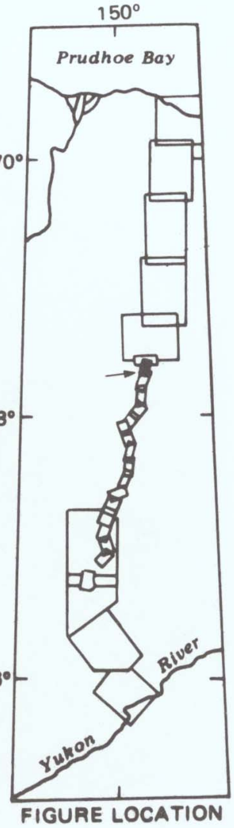
MILE 270 (figs. 94, 97, and 99). The axis of a broad anticline in the Lisburne Group (lPMlu) is visible on the lower slopes to the east.

MILE 270.7. ATIGUN RIVER (figs. 94 and 99). At this point, the Atigun River, after flowing generally northward in a braided and meandering course, turns abruptly to the northeast and flows parallel to the mountain front through Atigun Gorge. The gorge--a narrow, incised canyon--extends downstream 8 mi (13 km) from the bridge.

MILE 271 (figs. 94 and 99). **A** pipeline access road on the right, at the crest of a hill overlooking the Atigun River, provides off-road parking. From this overlook is a good view of the Atigun River valley and mountains to

Figure 94. Geologic map of Dalton Highway in Atigun River valley,, Mile 263 to Mile 273. Map modified from *Brosgé* and others (*1979a*). See figure 118 for map explanation.


149°20'
68°25'
Galbraith Lake
Atigun Gorge
PUMP STATION 4
ATIGUN RIVER
THE TRANS-ALASKA PIPELINE
LINE OF CROSS-SECTION (SEE SHEET 1)
Holden Creek
Roche Moutonnée Cr.
Dalton Highway
TRAIL
271
270
268
267
266
263
T11S
T12S
T13S
R11E
R12E
Qa
Pe
tb
JTRo
PMlu
Mll
Mk
MDks
PMl
Dks
Dke


150°
Prudhoe Bay
70°
68°
66°
Yukon River
FIGURE LOCATION

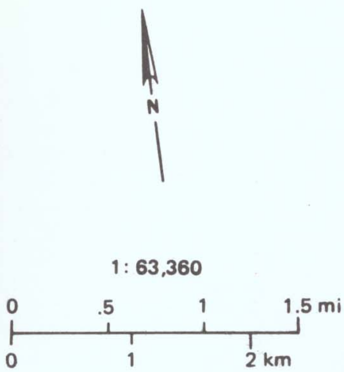

N
1: 63,360
0 .5 1 1.5 mi
0 1 2 km

Figure **95.** View of Atigun River valley to the north. River meanders through fine-grained lacustrine sediments deposited in a glacially dammed lake. Carboniferous *Lis*burne Group limestone is on left, and Cretaceous Fortress Mountain *Formation* is at upper right. Arctic Slope and southern foothills are in distance; Galbraith Lake is in center. Pump Station 4 is small cluster of buildings at right center.

the south, the mountain front to the east, and Atigun Gorge to the northeast.

Lisburne Group carbonates (lPMlu) (Armstrong and Mamet, chap. 16) form the high, light-gray-weathering cliffs to the east (fig. 33). The smooth yellow-orange- and black-weathering slopes below the Lisburne are composed of gray, phyllitic Permian shale and calcareous siltstone (Pe) that are transitional between the Echooka Formation (Sadlerochit Group) of the northeastern Brooks Range and the Siksikpuk Formation (Etivluk Group) of the central and western Brooks Range (Adams and Siok, chap. 17). The Lisburne and Echooka, in normal stratigraphic succession, are overturned at the leading edge of a thrust plate that overlies a gently folded sheet of Lisburne on the lower slopes at the western end of the ridge (figs. 33 and 97). The Lisburne that forms the highest point on the ridge and the upper two-thirds of the cliff face (lPMlu) is part of an overturned sequence at the leading edge of a lower thrust sheet. This sheet has further inverted the underlying Lisburne and Echooka at the western end of the high cliffs so that, at one place, the contact has been folded through a 240° arc (figs. 97 and 98). This extreme overturning probably resulted from duplex formation or out-of-sequence thrusting that occurred during a phase of deformation following the initial emplacement of the Endicott Mountains allochthon.

Structurally disrupted Jurassic to Triassic Otuk Formation (J₮o), Valanginian coquinoid limestone, and Neocomian Okpikruak Formation (Ko) (Bodnar, chap. 18) are present in Atigun Gorge and are depositionally(?) overlain by moderately folded siltstone and mudstone of the Albian Torok and Fortress Mountain Formations (Kt, Kf). Several isolated blocks (tb; tectonic slivers?) of green-gray chert occur near the faulted(?) contact between the Otuk and Okpikruak Formations; other exotic blocks, composed of various lithologies, can also be found in the gorge (R.A. Glenn, oral commun., 1988). Lithologies that compose the blocks are anomalous to the Endicott Mountains allochthon and suggest that the higher allochthons of the westcentral and western Brooks Range extended to the northern front of the eastern Endicott Mountains before deposition of the Albian rocks.

To the north, the brown ridges and high cliffs of Atigun syncline (fig. 104) consist of conglomerate and graywacke of the Fortress Mountain Formation (Crowder, chap. 20). The lower slopes are underlain by thick, silty mudstone of either the Torok Formation or Okpikruak Formation (Siok, chap. 19) (figs. **32** and **34).**

To the west across Galbraith Lake, the mountain front is formed by three imbricate sheets of the Lisburne Group (Mll, lPMlu) folded into an east-plunging anticlinal nose (fig. 100).

At this point, the Dalton Highway leaves the Brooks Range and heads north into the Arctic (North) Slope province, which extends about 150 mi (240 km) from the north side of the Brooks Range to the Arctic Ocean.

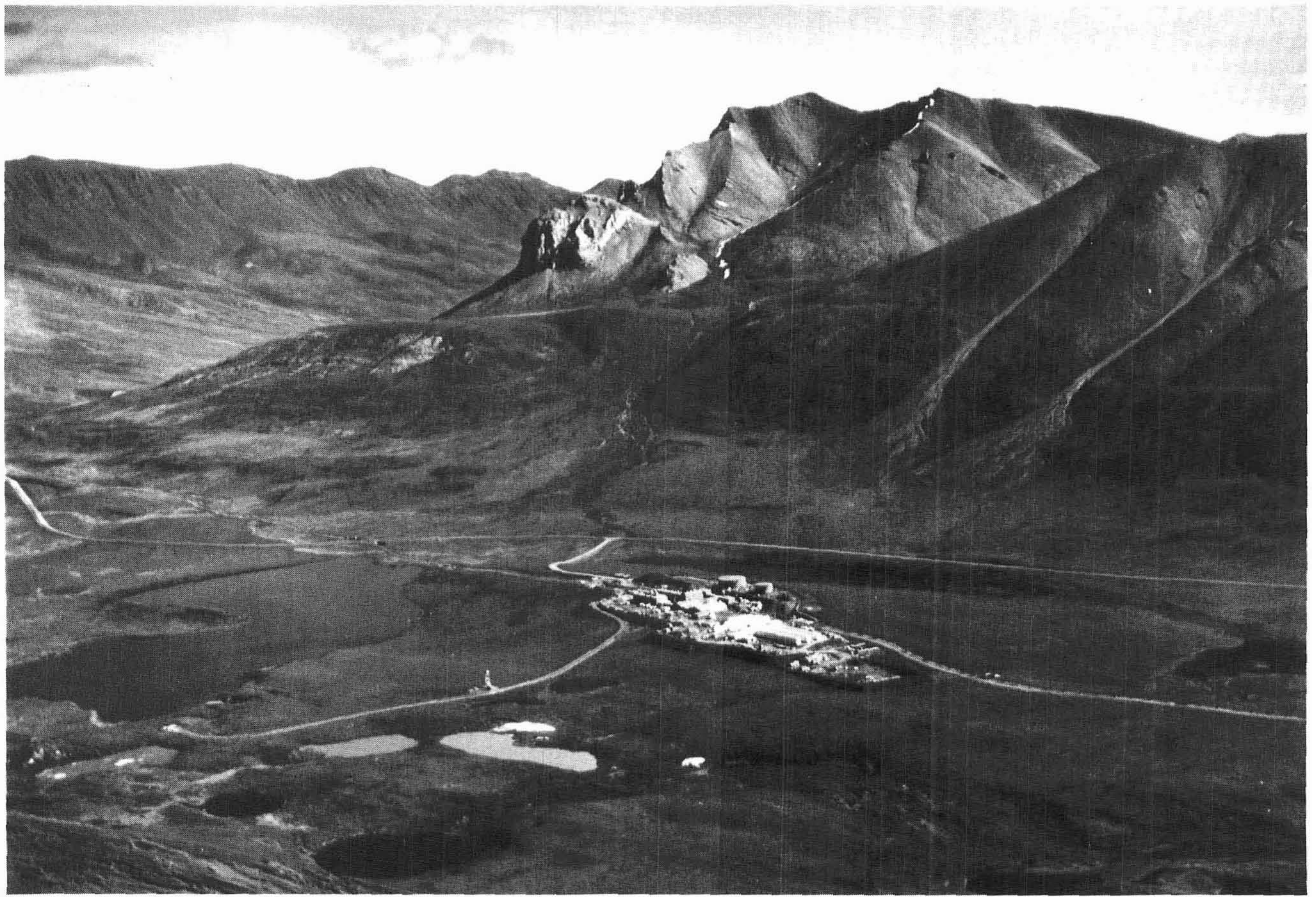


Figure 96. View northeastward toward Pump Station 4 at Mile **269.3.** Low hills on left are composed of conglomerate *of* Albian Fortress Mountain Formation; high hills on right are formed by carbonates of Carboniferous Lisburne Group. Note linear blowout troughs (foreground) formed in eolian sediments by dominant down-valley winds.

MILE 274.7. GALBRAITH LAKE CAMP (figs. 99 and 104). A side road to the left leads to the Galbraith pipeline-construction camp (now dismantled) and the Galbraith Lake airstrip. At the end of the road (4 mi; 6 km) is a campsite next to a clear stream and away from highway traffic. To the east from the turnoff is a good view of massive beds of conglomerate and sandstone of the Fortress Mountain Formation (Kf) at the western end of Atigun syncline (fig. 101) (Crowder, chap. 20).

MILE 275.8 (fig. 104). The road crests a low hill that provides a good view to the southwest of the Brooks Range mountain front.

MILE 276 (figs. 103 and 104). The road crosses a series of recessional moraines of the Itkillik II Glaciation. Boulders and kamelike sand-and-gravel deposits are abundant on the drift surface. (See Brown and Kreig, 1983, p. 179.)

MILE 284.3. TOOLIK LAKE (figs. 103 and 104). The side road to the west leads to Toolik Lake (fig. 102), the site of a former small pipeline-construction camp. Since 1975, Toolik Lake has been a scientific base camp operated during the summer by the University of Alaska Institute of Arctic Biology. A wide variety of university- and government-supported biological, botanical, and limnological studies are carried out from the camp.

Toolik Lake is a large, compound kettle of Itkillik II age, formed by glacier ice from the Itkillik valley to the west. Sediments in Toolik Lake span a time from about 13,000 yr B.P. to the present. The hillside to the east is covered with mass-movement features. Itkillik II moraines associated with Toolik Lake contain many sorted-boulder features. East of the Toolik Lake turnoff, the road ascends the outer moraines of Itkillik I age. Swales between the moraines show slight thermokarst formation along the road. (See Brown and Kreig, 1983, p. 179 and 182.)

Resistant sandstone beds of the Albian to Cenomanian Nanushuk Group (Kn) compose Arc Mountain to the west (12 mi [20 km] from the map border) and Itigaknit Mountain to the northwest.

MILE 285 (figs. 103 and 104). The road crosses the outer limit of a lateral moraine of Itkillik age. Generally, the margin of the Itkillik drift sheet is sharply defined by abrupt changes in soil, vegetation, drainage, and relief. To the east, the broad, rolling, tussock-covered ridges deposited by the older Sagavanirktok Glaciation contrast sharply with the steeper, drier, more irregular, bouldery moraines of the Itkillik ice limit. From this stop, the front of the double moraine of Itkillik II age that encloses Galbraith Lake is visible (Hamilton, 1978c). (See Brown and Kreig, 1983, p. 182.)

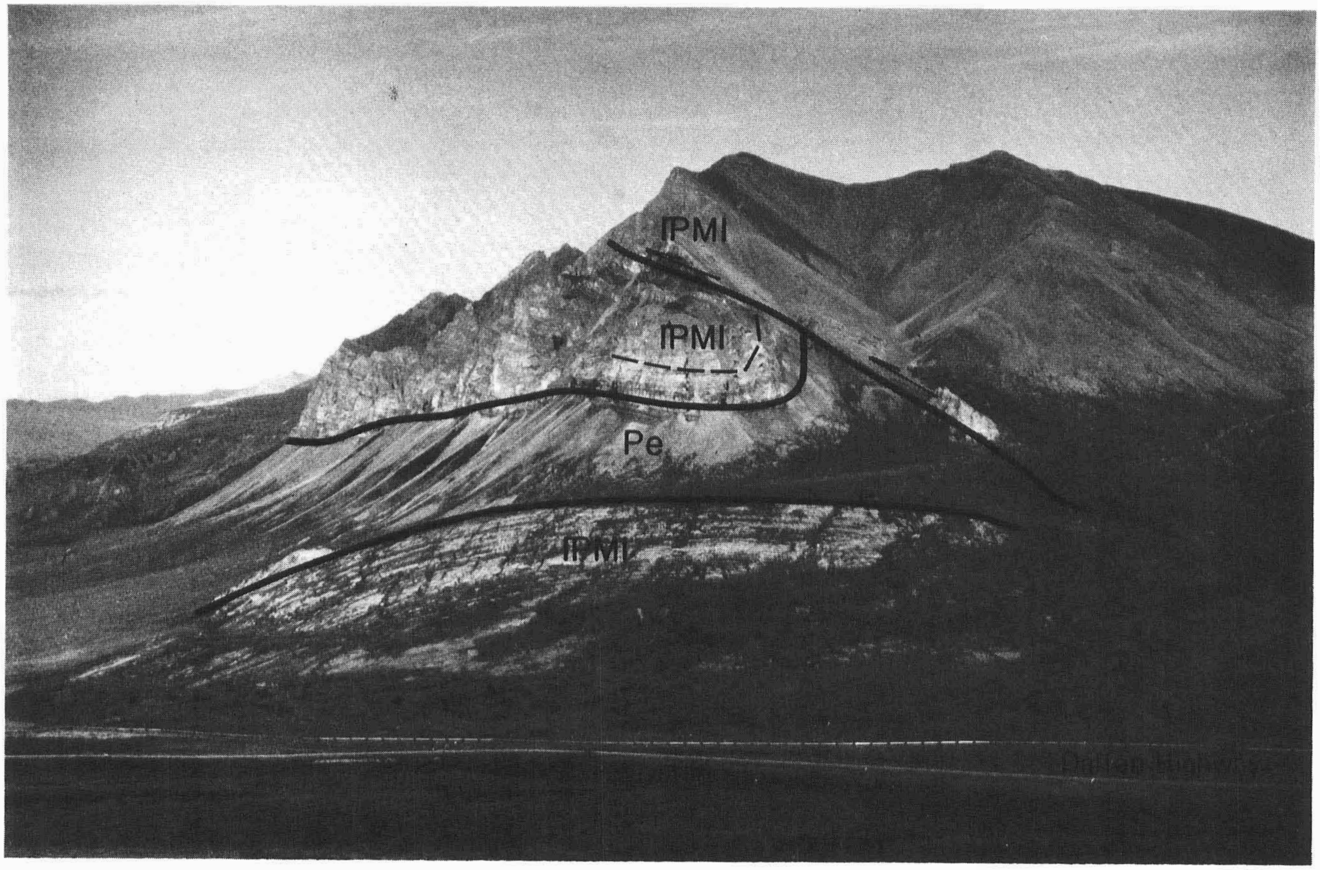


Figure 97. View eastward toward Carboniferous Lisburne Group (lPMl) at mountain front on south side of Atigun Gorge. Three sheets of Lisburne limestone are visible: 1) lower north-dipping sheet is upright; 2) middle cliff-forming sheet is inverted and unconformably overlies Permian Echooka Formation (Pe); and 3) upper sheet above thrust fault is also inverted Contact between inverted Lisburne and Echooka is well exposed and unfaulted.

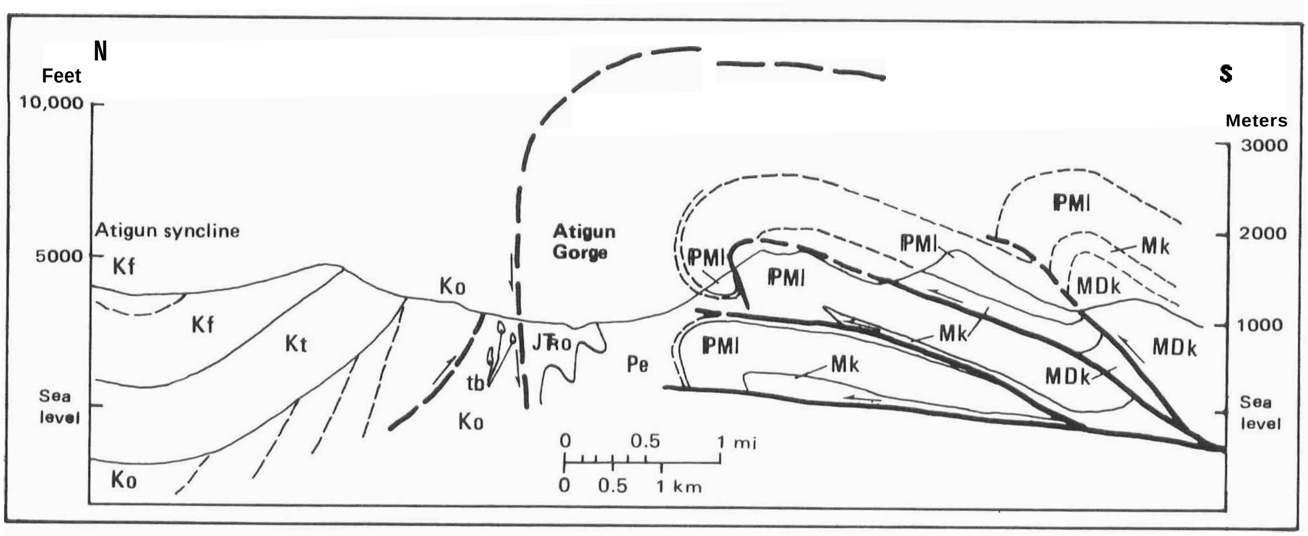


Figure 98. Generalized north-south cross section of Atigun Gorge area. Mile 271. Modified from R.A. Glenn, University of Alaska, 1988. Geologic units: MDk, Kanayut Conglomerate; Mk. Kayak Shale; lPMl, Lisburne Group; Pe, Echooka Formation; JTo, Otuk Formation; Ko, Okpikruak Fornnation; Kt, Torok Formation; Kf, Fortress Mountain Formation; tb, tectonic blocks.

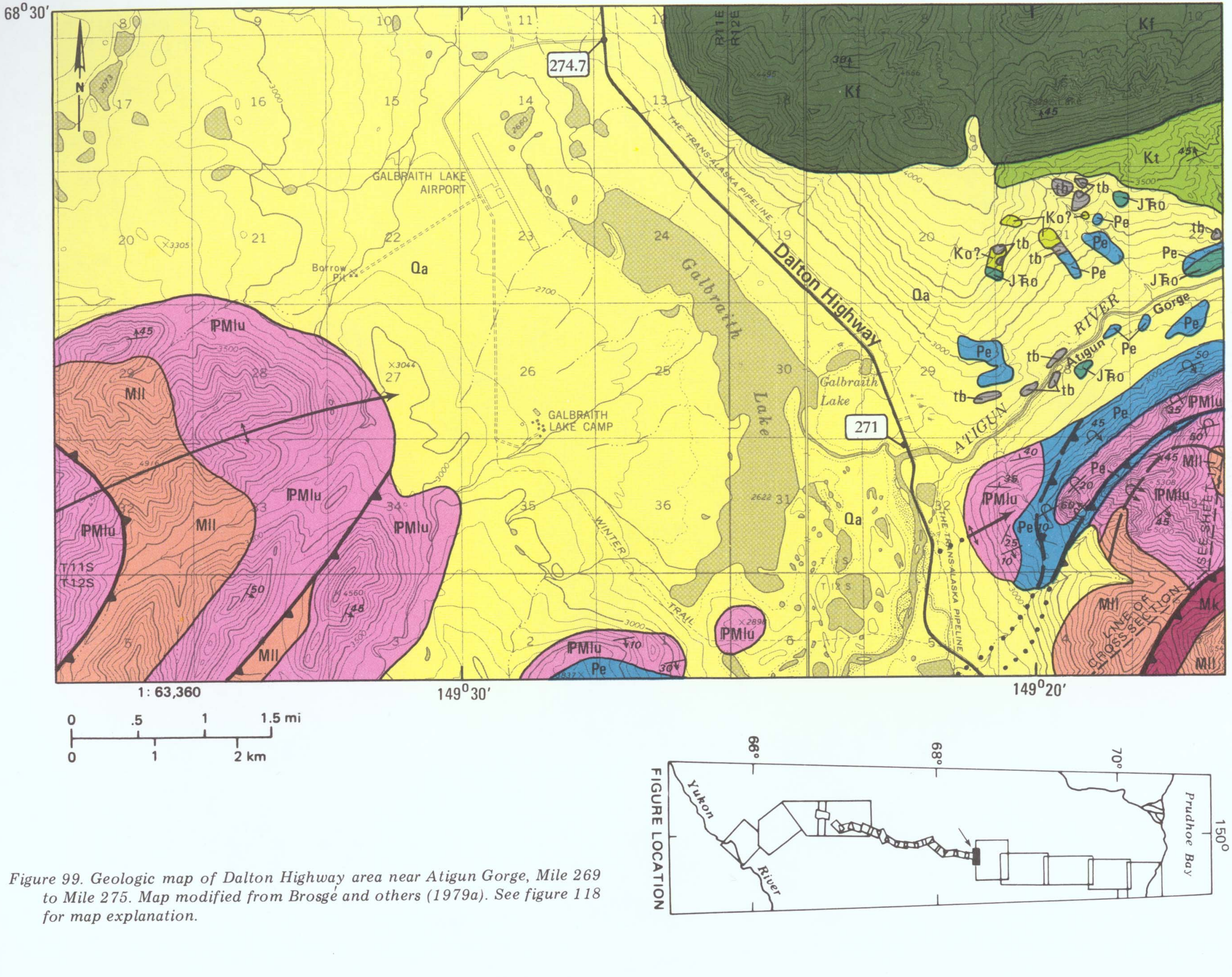


Figure 99. Geologic map of Dalton Highway area near Atigun Gorge, Mile 269 to Mile 275. Map modified from Brosgé and others (1979a). See figure 118 for map explanation.

MILE 286.1 (fig. 104). At the crest of the ridge is a turnout that provides a scenic view of the Brooks Range to the south and east. Imnavait Mountain to the north and Slope Mountain to the northeast are composed of deltaic sandstone of the Nanushuk Group (Kn).

MILE 286.3 to 296.9 (figs. 103 and 104). The road crosses Sagavanirktok-age drift that is appreciably older and morphologically more subdued than Itkillik I drift. (See Brown and Kreig, 1983, p. 182.)

MILE 288.9. KUPARUK RIVER (fig. 104).

MILE 289.2 (PB 126) (fig. 104). The pipeline passes through a large culvert beneath the road. Traces of the buried 8 to 10 in. (20 to 25 cm) diam gasline can be seen next to the road in many places between here and Prudhoe Bay; fenced valves and mileposts mark the route.

MILE 289.4 (fig. 104). The pipeline is buried under the tundra for caribou crossing.

MILE 290.6 (fig. 104). The headwaters of the Toolik River are about 3 mi (5 km) south of the highway. Black, rubble-covered outcrops to the south are mostly Fortress Mountain Formation (Kf).

MILE 297.5 (figs. 103 and 104). The road intersects the outer Itkillik drift limit at the western margin of the Sagavanirktok River valley. Soils are generally granular and firm within the limit, with only minor silty, organic swale fillings. (See Brown and Kreig, 1983, p. 183.)

MILE 298.7 (fig. 104). At the crest of a low ridge is a small turnout that provides a good view of the Sagavanirktok River valley to the east and Slope Mountain to the northeast (fig. 227). Slope Mountain is on the southeastern flank of Marmot syncline, one of the many, large 'thumbprint' synclines in the southern foothills. Itigaknit and Imnavait Mountains to the northwest are also thumbprint synclines, as is Atigun syncline near the mountain front at Mile 270. These synclines are apparently formed by the intersection of north-trending faults

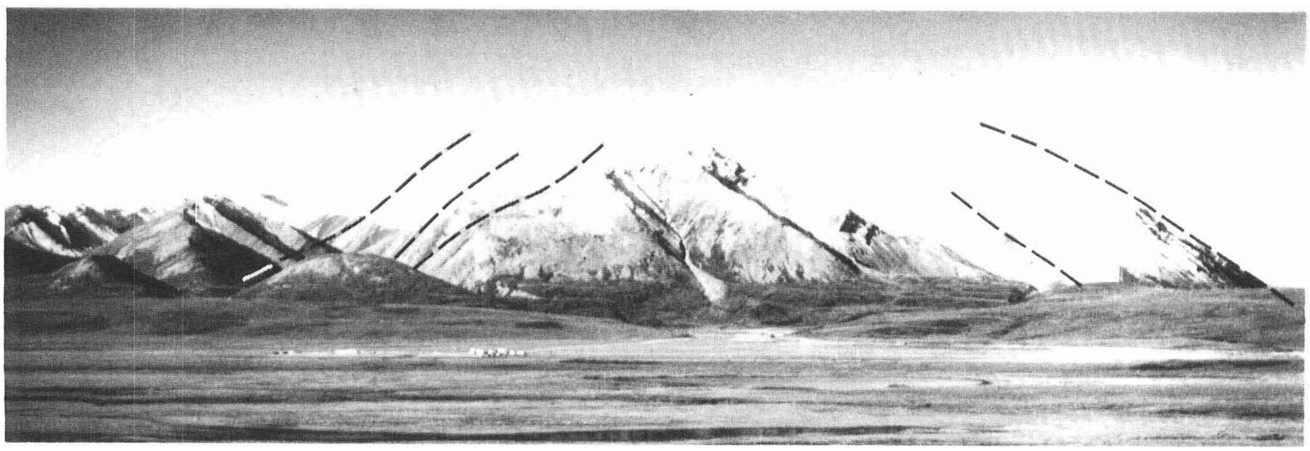


Figure 100. View southwestward toward northeast-plunging nose of Lisburne Group carbonates at mountain front southwest of Galbraith Lake.

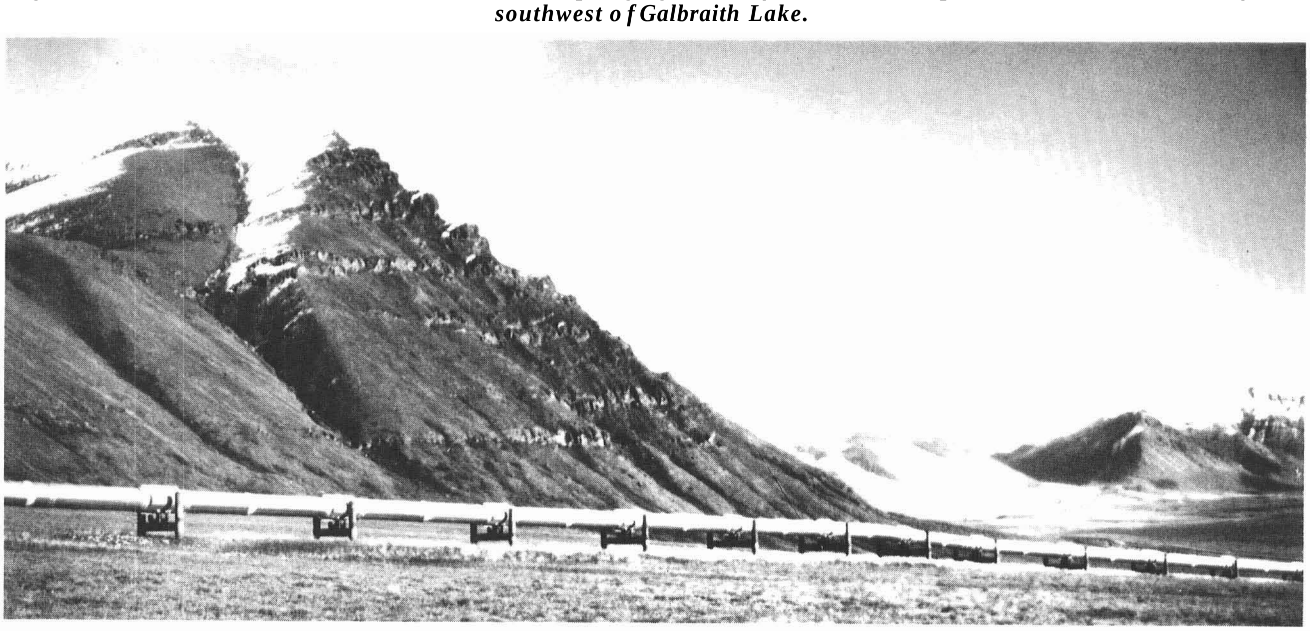


Figure 101. View southeastward toward Fortress Mountain Formation at western end of Atigun syncline near Mile 274.

that crosscut older regional east-west-trending detachment folds that warp the Albian and Upper Cretaceous section of the foothills belt. From this point, the road descends into the Sagavanirktok River valley, along which it runs for the next 120 mi (190 km) to Prudhoe Bay.

MILE 301 (PB 113) (figs. 104, 105, and 106). A pipeline access road to the north (left) leads to a materials site at the base of Slope Mountain that was used during pipeline construction; pull into the road to park, but do not block it.

Slope Mountain is composed of a continuous section of the deltaic clastic wedge of the Nanushuk Group (Kn); this is the most accessible and one of the best exposed sections of the Albian to Cenomanian clastic wedge in northern Alaska. The section grades downward from dominantly fluvial sediments at the top to marine sands at the base, which overlie prodelta shale of the Torok Formation (Kt) (Huffman, chap. 21). In this part of the Arctic Slope, the coal-bearing, nonmarine section at the top of the Nanushuk is called the Killik Tongue of the Chandler Formation, and the dominantly marine sandstone toward the base is known as the Tuktu Formation.

MILE 302.1 (figs.103, 104, 106, and 107). The pipeline is above ground near Slope Mountain and it crosses the end and ground moraines of the Itkillik River Glaciation. Gallagher Flint Station, one of the oldest known archaeological sites in northern Alaska, occupies a large kame north of the road. The site was excavated in 1970-71 (Dixon, 1975). Charcoal in loess found at depths of 8 to 10 in. (20 to 25 cm) was dated at 10,540 ± 150 yr B.P. Several other radiocarbon dates between 2,600 and 3,200 yr B.P. were obtained on charcoal at shallower depths near the base of the surface organic mat. Archaeological remains found at this site suggest the inhabitants may have been bearers of a technological tradition from which both the Inuit and Aleut material cultures were derived. (See Brown and Kreig, 1983, p. 183.)

MILE 305 (figs. 103, 104, and 106). The road crosses the front of a moraine of Itkillik II age and follows an outwash terrace that issues from it. Much of the regional drift sequence is visible from this sector of the valley. The broad, 600- to 800-ft-high (180 to 250 m) ridge that flanks the west side of the Sagavanirktok River valley is a compound lateral moraine built by superimposed drifts of Sagavanirktok and Itkillik age. East of the valley, a corresponding lateral moraine is visible a few miles farther north. A younger readvance of Itkillik II age is widespread throughout this part of the northern Brooks Range. Ice readvanced to a position north of Galbraith Lake and flowed east through Atigun Gorge to block the upper course of the Sagavanirktok River. Radiocarbon dates from the Sagavanirktok and Anaktuvuk River valleys indicate that the readvance culminated between about 12,500 and 13,000 yr B.P. (Hamilton, 1979b). (See Brown and Kreig, 1983, p. 183-185.)

MILE 305.6 (figs. 104 and 106). A side road to the right leads to the Slope Mountain (Sag River) DOTPF maintenance camp. These facilities are not for public use. The nearby hills to the southeast are mostly a fine-grained sandstone-siltstone facies of the Fortress Mountain Formation (Kf); the prominent cone-shaped hill to the northeast is underlain by shale-siltstone distal turbidites of the Neocomian Kongakut Formation (Kk). Parautochthonous Lisburne Group carbonates (lPMlu) compose the mountain front to the east. About 10 mi (16 km) southeast of the mountain front up the Ribdon River lies the northern edge of the Endicott Mountains allochthon.

The first geologic exploration of the Sagavanirktok River valley was made in the summer of 1946 by George Gryc and E.H. Lathram of the U.S. Geological Survey Navy Oil Unit. In late May, they were flown into a small lake about a mile south of the present Slope Mountain (Sag River) DOTPF camp. From the lake, they backpacked up the Sagavanirktok valley to the mountain front and then made a reconnaissance survey of the

Figure 102. View northwestward toward Toolik Lake research camp, Mile 284.3.

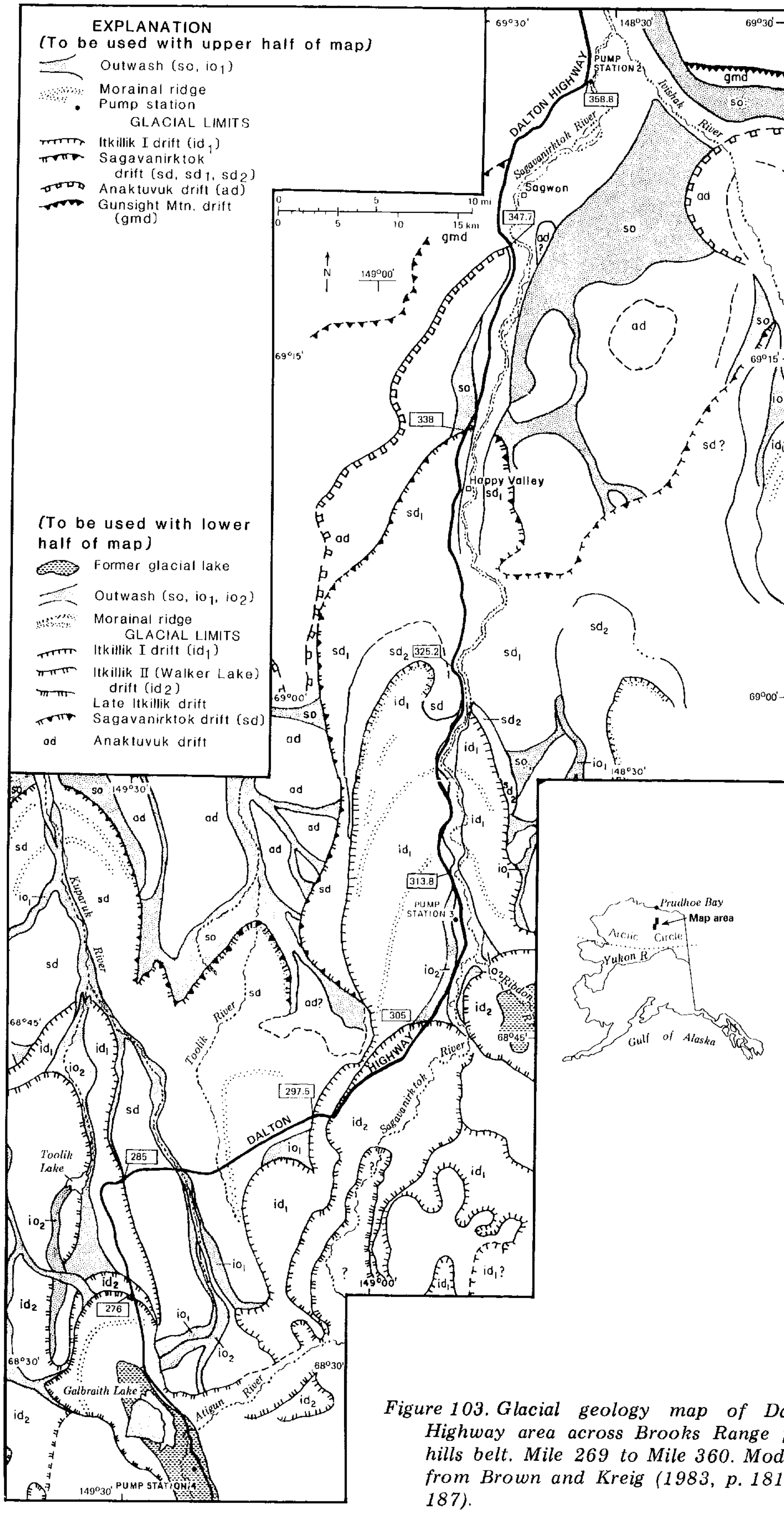
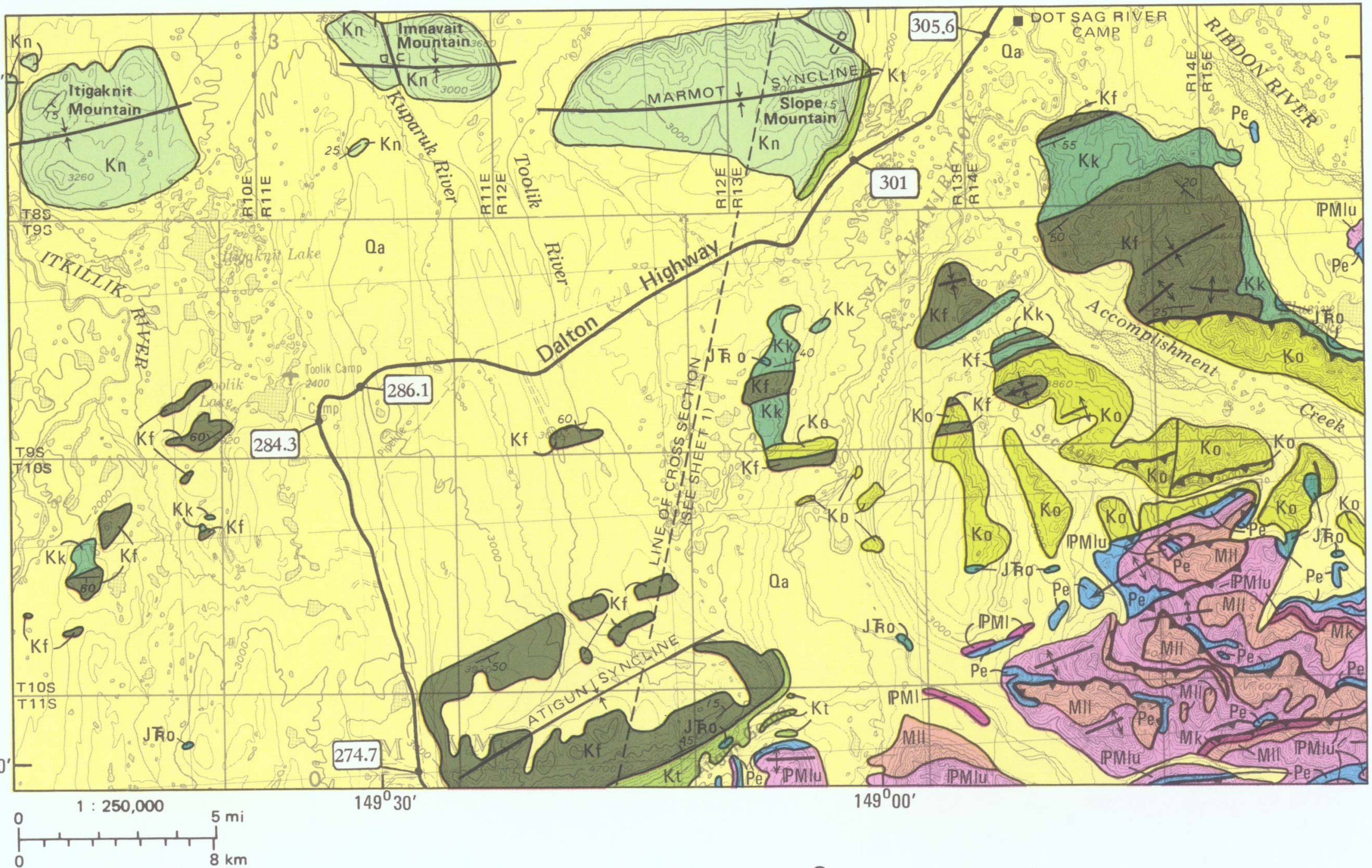


Figure 103. Glacial geology map of Dalton Highway area across Brooks Range foothills belt. Mile 269 to Mile 360. Modified from Brown and Kreig (1983, p. 181 and 187).



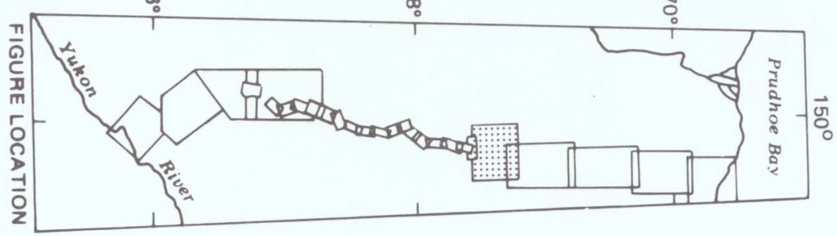


Figure 104. Geologic map of Dalton Highway area from Atigun syncline to Slope Mountain, Mile 275 to Mile 306. Map modified from Brosgé and others (1979a). See figure 118 for map explanation.

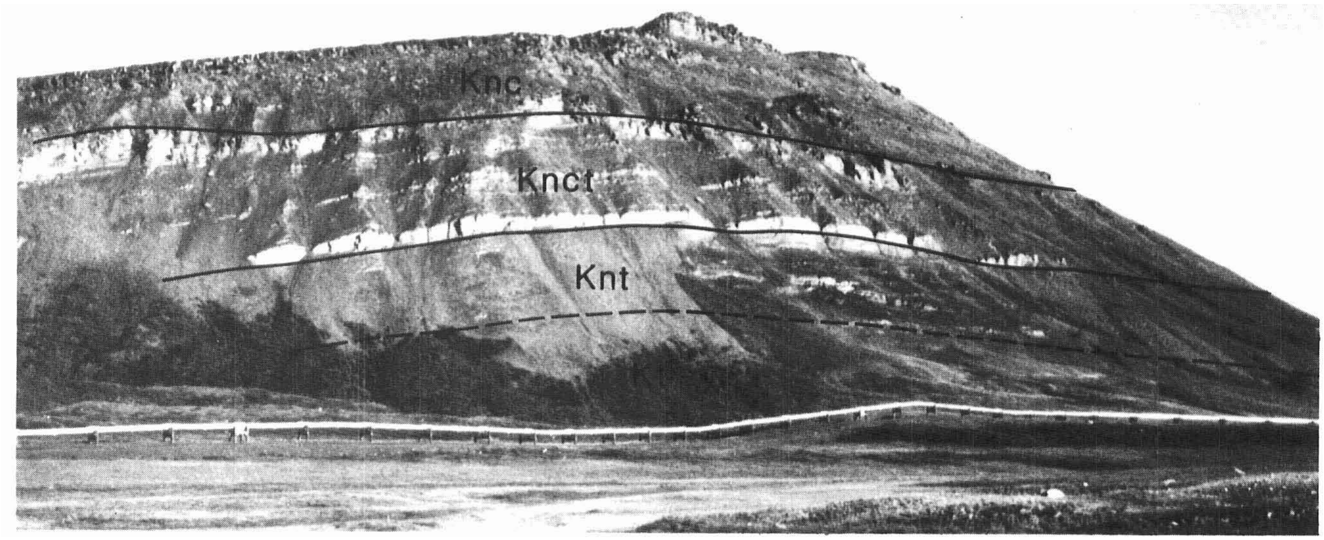


Figure 105. View northwestward toward Slope Mountain near Mile 301. Topographic relief is about 1,400 ft (430 m). Mountain is composed of one of most completely exposed sections of Nanushuk Group on central Arctic Slope. Geologic units: Knc, nonmarine sandstone and conglomerate of Chandler Formation of Nanushuk Group; Knct, transitional nonmarine to marine deposits of Chandler Formation that form resistant cliffs across center of face; Knt, marine sandstone and shale of Tuktu Formation of Nanushuk Group; Kt, prodelta shale of Torok Formation.

valley by boat and backpack traverses downstream 75 mi (120 km) to Franklin Bluffs, completing their trip in late August.

MILE 309.9 (fig. 106). The road begins its descent to the Sagavanirktok River flood plain, on which it runs for the next 4 mi (6 km).

MILE 311.9 (fig. 106). A turnoff to the left leads to Pump Station 3. The pump station is built on a refrigerated foundation to prevent the underlying permafrost from thawing.

MILE 313.8 to 354 (figs. 103, 106, and 110).[16] The road crosses nested end moraines of Itkillik age until just beyond Mile 320. From there, the road continues north past the northern drift limits of the Sagavanirktok River (Mile 340), the Anaktuvuk River (about Mile 350), and the Gunsight Mountain(?) (about Mile 355) ice advances. Drift is seldom present along the highway north of Mile 340 because substantial valley deepening has taken place since Early Pleistocene time.

MILE 320 (fig. 106). Scattered exposures of shale and sandstone of the Nanushuk Group (Kn) are present in the east bank of the river.

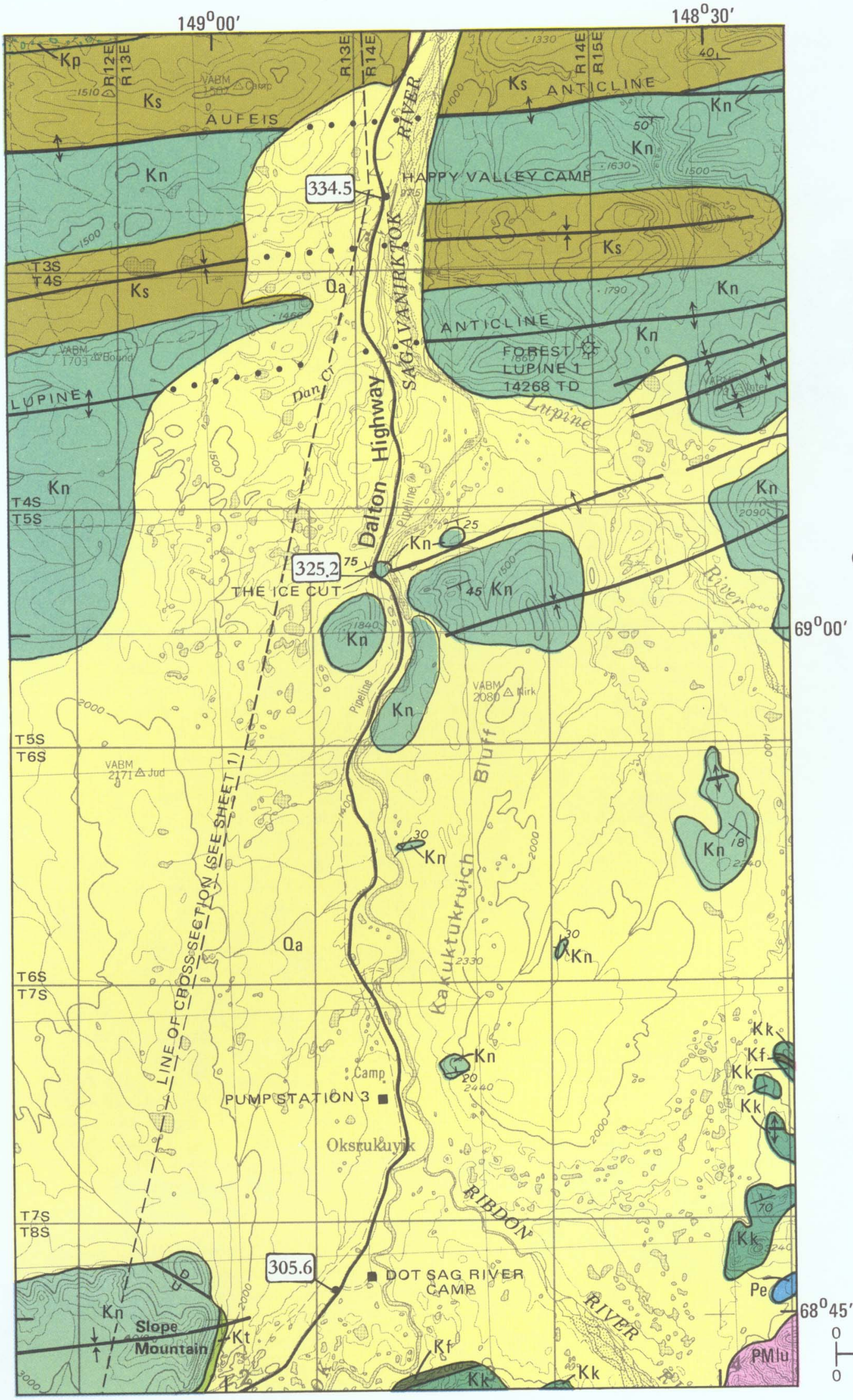
MILE 324.1 (figs. 106 and 108). South-dipping sandstone beds of the Nanushuk Group (Kn) are present on the flank of an unnamed anticline visible in the low bluffs to the east across the river.

MJLE 324.7 (fig. 106). The road begins a steep climb from the Sagavanirktok River flood plain to the uplands on the west side of the valley.

[16]Prepared by T.D. Hamilton, U.S. Geological Survey. 1985.

MILE 325 (fig. 106). The road enters the 'Ice Cut,' a road cut named for massive ground ice uncovered where the road was built. On either side of the Ice Cut, sandstone beds of the basal Nanushuk Group (Kn) overlie soft clay and shale of the Torok Formation (Kt) (fig. 36). The sandstone is micaceous, dark gray, very fine grained, and forms beds 6 in. to 3 ft (15 cm to 1 m) thick that contain well-developed tool marks, groove casts, small load casts, and a few flute casts. These structures suggest that the sandstone was deposited as a turbidite and that current flow was to the east. The sandstone beds dip 70° N. to 70° S., overturned, on the north flank of an unnamed east-northeast-trending anticline (fig. 108). The anticline is one of a series of detachment structures in the foothills belt (sheet 1). Although these detachment structures are readily mapped in other parts of the belt and are visible on aerial photographs, most of the structures are not obvious in the Sagavanirktok River valley because of limited exposures. Across this part of the foothills belt, the synclines typically have a smooth, broad profile, whereas the anticlines have sharp crests and are cored by contorted shale of the Torok Formation; many are faulted along the axes. The folds generally decrease in

Figure 106. Geologic map of Dalton Highway area in Sagavanirktok River valley from Slope Mountain to Happy Valley, Mile 301 to Mile 339. Map south of lat 69° N. modified from Brosgé and others (1979a); map north of lat 69° N. by C.G. Mull, DGGS, 1985. See figure 118 for map explanation.



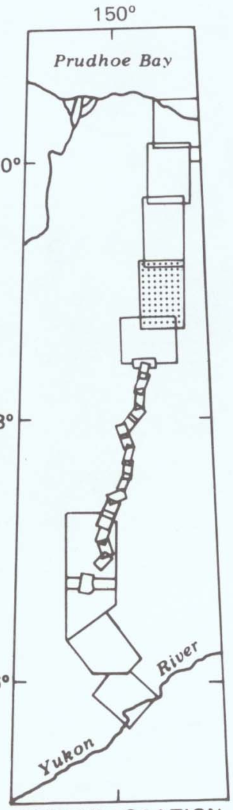


FIGURE LOCATION

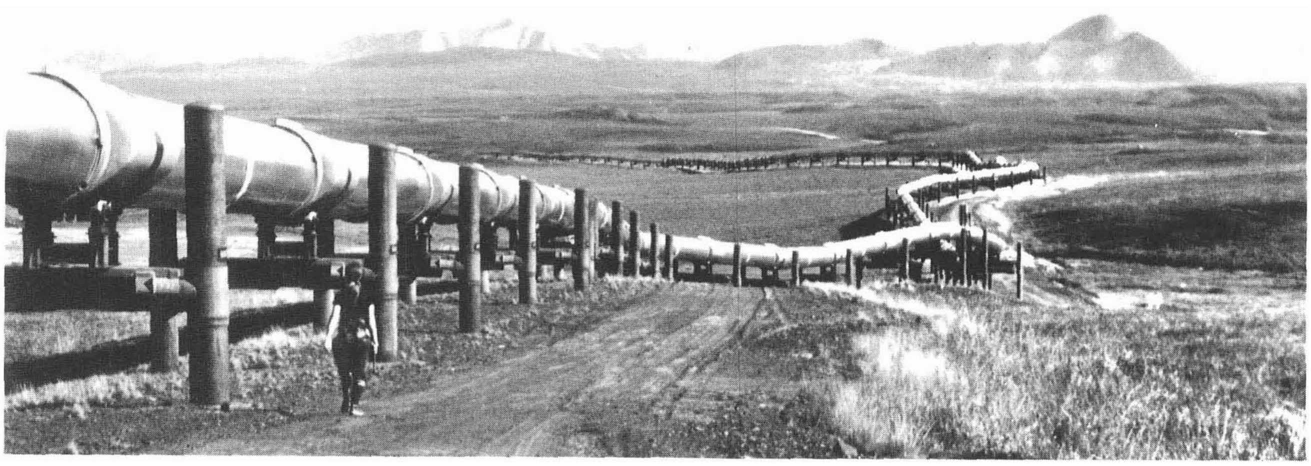


Figure 107. View eastward along Trans-Alaska Pipeline from Mile 302 toward Sagavanirktok River valley and northeastern Brooks Range. Valley is filled with glacial drift from early *Wisconsin Itkillik* Glaciation.

amplitude to the north, so that the northernmost anticlines have smooth, gentle crests. Seismic data show that these structures were deformed independently of structure at depth (fig. 45); detachment occurred in the thick shale section of the Torok.

MILE 325.2 (PB 88.8) (fig. 106). At the top of the Ice Cut is a turnout. The Ice Cut is well known to truckers, who find the steep grade a challenge when the road is icy.

MILE 325.2 to 338 (figs. 103, 106, and 110). The road crosses ground and end moraines of the Sagavanirktok River Glaciation. This terrain is typical of the northern foothills of the Brooks Range. (See Brown and Kreig, 1983, p. 191-192.)

MILE 329.5 (fig. 106). On the east side of the river, steeply south-dipping beds of the Nanushuk Group (Kn) are visible on the south flank of the Lupine anticline.

MILE 330.8. DAN CREEK (fig. 106).

MILE 334.5. HAPPY VALLEY CAMP (fig. 106). The road to the right leads to the Happy Valley pipeline-construction camp and airstrip. This is a convenient campsite--close to the Sagavanirktok River and away from road traffic--but is often plagued by mosquitoes during the middle of summer. The State of Alaska and U.S. Bureau of Land Management maintain small cabins here for field personnel; an Alaska State Trooper or Fish and Game Protection Officer is sometimes based here during the hunting season in August and September. A number of semipermanent hunting camps are located near the airstrip, and a few tent-camp sites are present along the small stream west of the Happy Valley turnoff.

MILE 338.5 to 342.3 (figs. 103 and 110). River-cut exposures of a 100-ft-thick (30 m) outwash terrace of Sagavanirktok River age are visible along the east side of the flood plain. This oxidized outwash gravel overlies till of Anaktuvuk River age, which is underlain by bedrock in some places. In a few exposures, the outwash directly overlies bedrock and scattered glacial erratics.

MILE 339.7 (fig. 110). Faint rubble traces on the hillside east of the river consist of gently north-dipping Seabee Formation or Schrader Bluff Formation of the Upper Cretaceous Colville Group (Ks) on the north flank of Aufeis anticline.

MILE 343.5 (fig. 110). On the south flank of the Kuparuk anticline, resistant, gently south-dipping beds underlie the tundra east of the river.

MILE 343.7 (fig. 110). The axis of the Kuparuk anticline crosses the road near here. To the south, up the Sagavanirktok River valley, lies the Brooks Range.

MILE 344 (fig. 110). The massive, arched concrete blocks to the east along the river are unused collars that were made to weight the pipeline when it was to be buried under the river.

MILE 344 to 346 (fig. 110). Scattered exposures of bentonitic shale of the Upper Cretaceous Schrader Bluff Formation (Ks) are visible in the east bank of the river.

MILE 347.7 (figs, 103 and 110). To the north, on the northwest side of the river, are bluffs of the north flank of the Ivishak anticline (fig. 109). These are composed of gently north-dipping Upper Cretaceous Prince Creek Formation (Kp) and lower Tertiary Sagwon Member of the Sagavanirktok Formation (Ts). The Tertiary-Cretaceous boundary is located part way down the river bluff to the left (R.N. Detterman, oral commun., 1985). Both the Prince Creek and Sagavanirktok at this locality are nonmarine and consist of poorly consolidated sandstone, conglomerate, and coal (Detterman and others, 1975). They are differentiated primarily on the basis of age, rather than lithologic

Figure 108. View eastward from Mile *325* across *Sagavanirktok* River toward axis of unnamed anticline. Northeastern Brooks Range in distunce.

criteria. The Ivishak anticline plunges gently west and, in contrast to the Kuparuk, Aufeis, and Lupine anticlines to the south, has *a* gentle, smooth, unfaulted axis.

Sagwon, an airstrip and abandoned camp on the east side of the river, was a major staging area for geological field parties, wintertime seismic crews, and drilling activities in the 1960s. Constructed during the winter of 1963-64, the airstrip became known as the Sag I strip (later Sagwon) when a second, temporary airstrip was built downstream.

The road climbs out of the Sagavanirktok River valley onto the uplands west of Sagwon. This point marks the northernmost advance of the Anaktuvuk River Glaciation; it also marks the northern limit of alder along the road corridor. The rolling uplands to the north may have been covered by glacier ice during the Gunsight Mountain Glaciation.

MILE 352.3 (fig. 110). An outcrop of coarse-grained fluvial sandstone of the Prince Creek Formation (Kp), or possibly Sagavanirktok Formation (Ts), is exposed along a small stream that drains west from the crest of the uplands west of Sagwon. Similar low, ledge-forming sandstone beds (Kp or Ts) are exposed east of the road as the road climbs the crest of a low, rolling hill to the north. Dips are gentle on the north flank of the Ivishak anticline.

MILE 353.3 (fig. 110). A side road to the west leads to a gravel quarry in poorly consolidated conglomerate, probably of the Sagwon Member of the Sagavanirktok Formation (Ts). Clasts, up to 4 in. (10 cm) diam, consist mostly of black to gray chert (probably from the Lisburne Group) and white quartz (probably from the Hunt Fork Shale), with lesser amounts of dark-gray, fine-grained quartzite (probably from the Kanayut Conglomerate) and light-gray to white, silicified pyroclastic(?) rock (probably from the Upper Cretaceous Seabee Formation).

MILE 354 (fig. 110). Poorly consolidated sandstone and conglomerate of the Sagwon Member of the Sagavanirktok Formation (Ts) form the scattered, bare hills to the left.

MILE 355.1 (PB 58.9) (fig. 110). From the turnout at the crest of the hill is a good view of the Arctic Coastal Plain to the north and the Franklin Bluffs (25 mi [40 km] north) and White Hills (15 mi [24 km] northwest) (both composed of Tertiary Sagavanirktok Formation [Ts]) to the north and northwest.

MILE 357 (figs. 37, 110, and 111). To the east on the east side of the Sagavanirktok River are excellent bluff exposures of sandstone, conglomerate, and coal of the Sagavanirktok Formation (Ts) or the Prince Creek Formation (Kp). These beds are probably coeval with the Ugnu sands, which contain an estimated 11 to 19 billion barrels of heavy oil and tar in the Kuparuk area west of Prudhoe Bay. A short distance upstream, an oil-saturated, coarse-grained sandstone is exposed along the east bank of the river at low-water stage. The bluffs are a nesting site for the endangered peregrine falcon and thus are closed to helicopter access.

MILE 358.8. PUMP STATION 2 (fig. 110). The road begins a gentle descent onto the Arctic Coastal Plain and the terraces of the Sagavanirktok River, which extend to the Arctic Ocean, some 60 mi (100 km) north; at this point, the elevation of the Arctic Coastal

Figure *109.* View northeastward from Mile *347.7* across Sagavanirktok River. Distant bluffs of Upper Cretaceous Prince Creek Formation and Tertiary Sagavanirktok Formation dip gently north on south flank of Ivishak anticline. Tertiary-Cretaceous boundary is in middle of bluffs at left (R.N. Detterman, oral commun., *1985).* Abandoned *Sagwon* Camp and airstrip in center.

Plain is 545 ft (170 m). The pipeline is elevated in this area because the overburden of ice-rich silt was too thick (15 ft; 5 m) to trench. The northern limit of dwarf birch along the road corridor is at the base of a slope opposite Pump Station 2. This point marks the northern boundary of federal lands controlled by the Bureau of Land Management; land north of this point is owned by the State of Alaska. (See Brown and Krieg, 1983, p. 193-194.)

MILE 361 (fig. 110). East of the road, the Ivishak River empties into the Sagavanirktok River. The pipeline is buried in frozen, thaw-stable soil under fine-grained, thaw-unstable soils. The line of bluffs that borders the low hills to the north is the Franklin Bluffs (fig. 112). The Brooks Range is visible to the southeast, and the White Hills are visible to the west. (See Brown and Kreig, 1983, p. 197.)

Mile 375 (fig. 112). The small hill about 5 mi (8 km) west of the road is one of many pingos in the Toolik River pingo field, an area which may have the greatest concentration of pingos on the North Slope. The field occupies a region of the lake-dotted Arctic Coastal Plain between the White Hills and Franklin Bluffs. This portion of the coastal plain serves as a corridor for the Sagavanirktok, Putuligayuk, and Toolik Rivers. Regional elevation ranges from 190 to 240 ft (60 to 75 m); relative relief, excluding the pingos, ranges from 10 to 20 ft (3 to 6 m).

In plan view, most pingos in the area are ovoid (fig. 11); their long axes range from 160 ft (50 m) to over 400 ft (130 m). They range in height from a few feet to nearly 65 ft (20 m). Pingos generally represent localized bulges of frozen near-surface sediment uplifted by hydrostatic forces associated with the formation of an ice core. They may form in recently drained thaw lakes that were deep enough to have had thaw windows or deep thaw bulbs beneath them and where the unfrozen sediments had suitable permeability (fig. 17). There are numerous examples of the association between pingos and thaw-lake basins on the Arctic Coastal Plain.

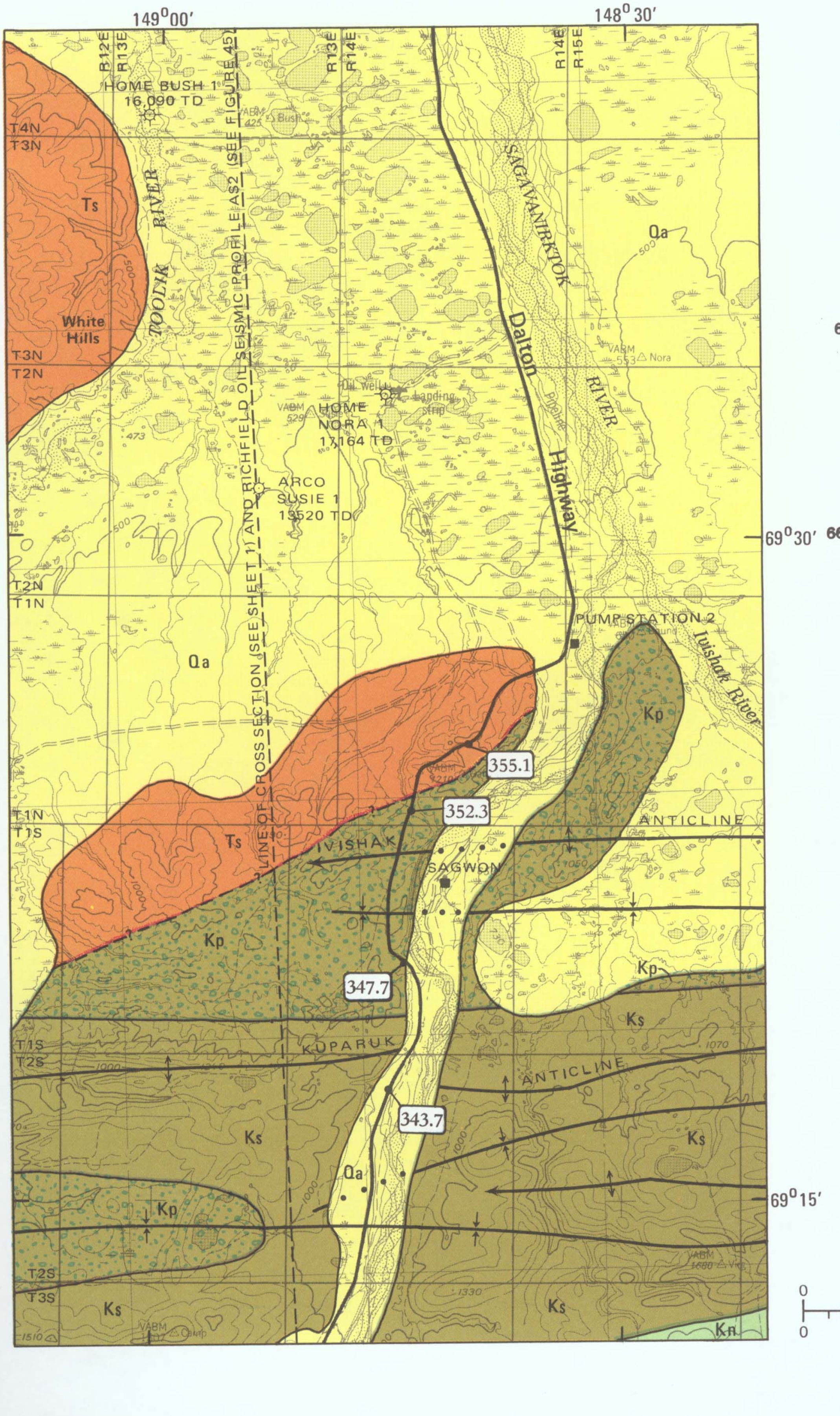
MILE 377.4. FRANKLIN BLUFFS CAMP (PB 36.6) (fig. 112). A road to the right leads to the Franklin Bluffs pipeline-construction camp. Equipment from a number of inactive seismic camps is in storage here, A pingo (VABM Beny) is visible 11 mi (18 km) to the northwest; rocks of the Sagavanirktok Formation (Ts) are visible in the White Hills, 9 mi (14 km) to the southwest.

MILE 381 (figs. 38, 112, and 113). Brown-weathering claystone of the lower Franklin Bluffs Member of the Sagavanirktok Formation (Ts) is exposed on the east side of the Sagavanirktok River at the south end of Franklin Bluffs. This claystone contains Eocene pollen (R.N. Detterman, oral commun., 1985) and is part of a coarsening-upward sequence deposited in either a deltaic or lacustrine environment (L.D. Carter, oral commun., 1986). A low-amplitude anticline is also visible.

MILE 381 to 395 (figs. 38, 112, and 113). On the flat coastal plain, the road parallels the Sagavanirktok River and Franklin Bluffs (figs. 10 and 114). Along the road, small groups of caribou are often seen.

The east branch of the Sagavanirktok River is actively eroding the bluffs over most of their length. The lower, orange-colored part of the Franklin Bluffs is

Figure *110.* Geologic map of Dalton Highway area in Sagavanirktok River valley, Mile *337* to Mile *375.* See figure *118* for map explanation.


149°00'
148°30'
R12E
R13E
R13E
R14E
R14E
R15E
HOME BUSH 1
16,090 TD
T4N
T3N
Ts
TOOLIK RIVER
White Hills
T3N
T2N
LINE OF CROSS SECTION (SEE SHEET 1) AND RICHFIELD OIL SEISMIC PROFILE AS2 (SEE FIGURE 45)
HOME NORA 1
17,164 TD
Oil well
Landing strip
ARCO SUSIE 1
13520 TD
SAGAVANIRKTOK RIVER
Dalton Highway
Pipeline
Qa
Nora
69°30'
T2N
T1N
PUMP STATION 2
Ivishak River
Qa
Kp
355.1
352.3
T1N
T1S
ANTICLINE
IVISHAK
Ts
SAGWON
Kp
Kp
347.7
Ks
T1S
T2S
KUPARUK
ANTICLINE
343.7
Ks
Ks
Qa
Kp
69°15'
T2S
T3S
Ks
Ks
Kn
N
1: 250,000
0
5 mi
0
8 km

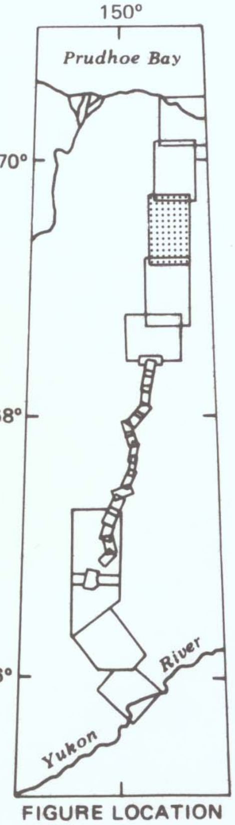

150°
Prudhoe Bay
70°
68°
66°
Yukon River
FIGURE LOCATION

Figure 111. View eastward from near Mile 357. Resistant cliffs on east side of Sagavanirktok River are composed of clean, massive sandstone, conglomerate, and interbedded coal of lower Tertiary Sagwon Member of Sagavanirktok Formation. These beds are probably coeval with Ugnu sands of Kuparuk area west of Prudhoe Bay, which contain an estimated 11 to 19 billion barrels of heavy oil and tar.

composed of ferruginous, weakly indurated siltstone interbedded with relatively thin, well-indurated, gritty sandstone and pebble conglomerate. The cementing material is intensely colored by oxidizing iron. These beds are undergoing badlands erosion. The upper part of the bluffs is a very bright, white quartz pebble-to-boulder conglomerate. This lithology is also exposed at other locations on the bluffs and on the upland part of the foothills east of the Toolik River. The white color lends the name to the White Hills.

It is common during summer for a cloud mass or fog bank to form between Franklin Bluffs and Prudhoe Bay, particularly in the morning. The low clouds develop from a cool Arctic air mass that regularly moves southward from the Beaufort Sea. (See Brown and Kreig, 1983, p. 199-200.)

MILE 397 (fig. 112). A pingo (VABM Percy) is visible 2 mi (3 km) west of the road (fig. 115).

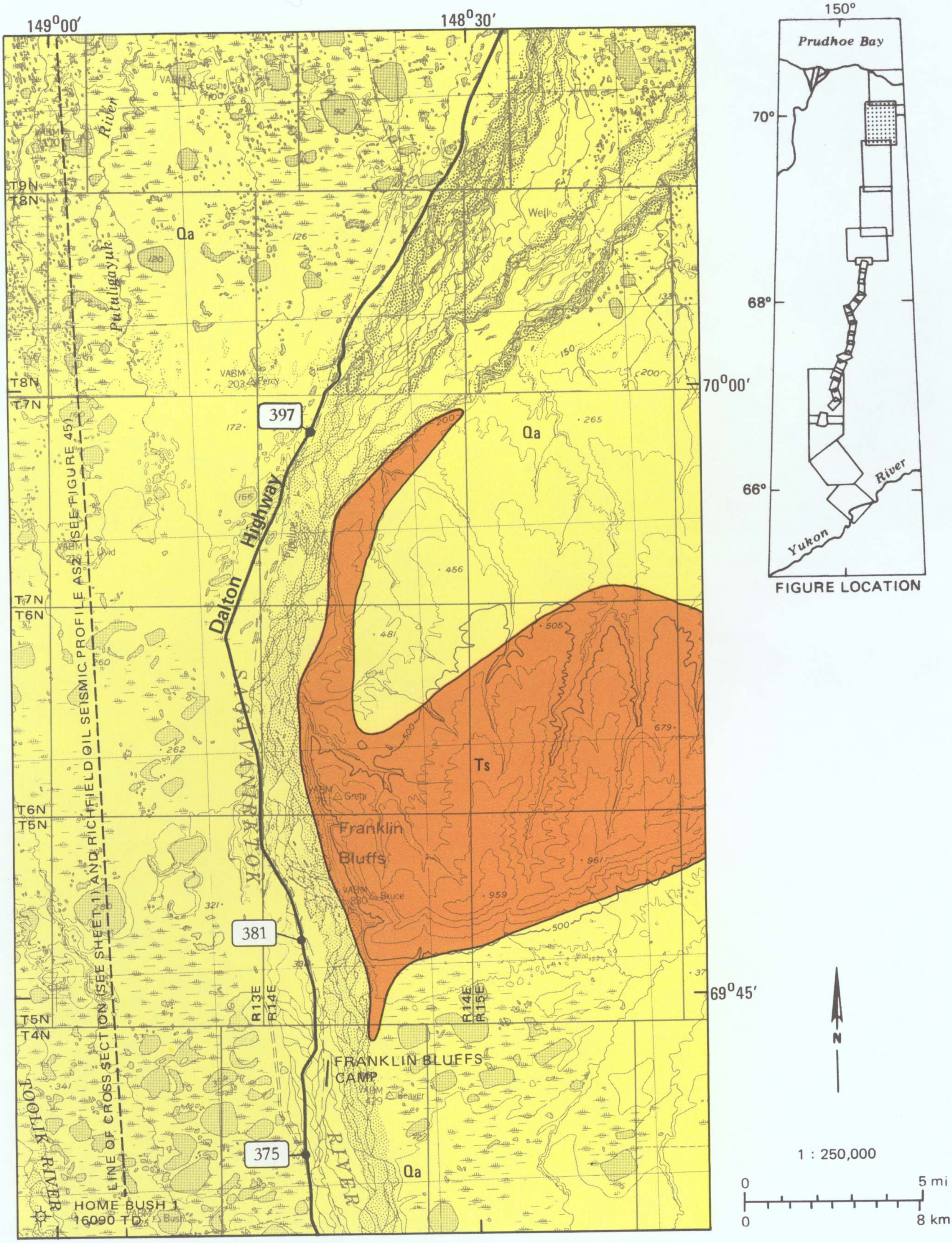
Several small pingos in the Prudhoe Bay region (fig. 117) have been cored by the Cold Regions Research and Engineering Laboratory (CRREL). 'Weather Pingo' contains 40 ft (12 m) of ice under 3.5 ft (1.1 m) of sandy soil. 'Prudhoe Mound' contains 30 ft (9 m) of ice under 7 ft (2.2 m) of overburden. A third large pingo west of the Kuparuk River contains more than 80 ft (25 m) of ice. (See Brown and Kreig, 1983, p. 212.)

MILE 398.6 (fig. 112). At this point, the road crosses the buried pipeline for the last time. Well-developed, low-centered ice-wedge polygons (fig. 15) are visible beside the road.

MILE 409 (fig. 117). The Prudhoe Bay oil field is visible along the horizon to the north.

MILE 414. PRUDHOE BAY (Deadhorse) (figs. 116 and 117). Prudhoe Bay marks the end of the Dalton Highway. The fork to the left leads to Deadhorse Airport, the main concentration of service-company facilities, and the beginning of the spine road to the west end of the Prudhoe Bay field and to the Kuparuk field. Prudhoe Bay field drill sites 12 and 13 are in the immediate Deadhorse area; however, most field facilities are located to the north or northwest. Security checkpoints are located on the road to the main Atlantic Richfield Company (ARCO) base camp and field facilities and on the road west to the Standard Alaska Production Company camp and facilities. Passes are required beyond these checkpoints but are not issued to the general public. Lodging and meals are available at several camps, or hotels, in Deadhorse. A small store with limited stock and a post office are also located in the area.

Figure 112. Geologic map of Dalton Highway area near Franklin Bluffs, Mile 373 to Mile 409. See figure 118 for map explanation.


149°00′
148°30′
70°00′
69°45′
T9N
T8N
T7N
T6N
T5N
T4N
R13E
R14E
R15E
Putuligayuk River
Qa
Ts
Dalton Highway
397
381
375
Franklin Bluffs
FRANKLIN BLUFFS CAMP
SAGAVANIRKTOK RIVER
TOOLIK RIVER
HOME BUSH 1
16090 TD
LINE OF CROSS SECTION (SEE SHEET 1) AND RICHFIELD OIL SEISMIC PROFILE AS2 (SEE FIGURE 45)
Well
150°
Prudhoe Bay
70°
68°
66°
Yukon River
FIGURE LOCATION
N
1 : 250,000
0
5 mi
0
8 km

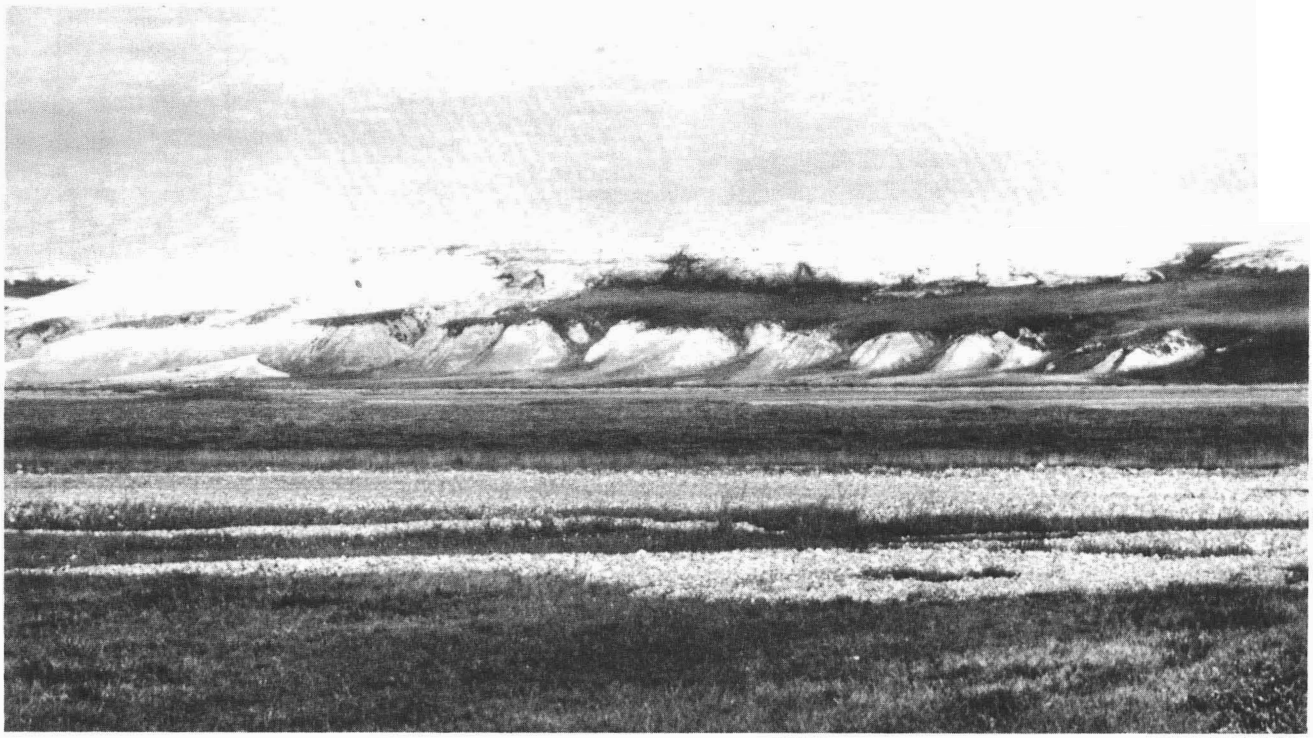


Figure 113. View eastward toward Franklin Bluffs along Sagavanirktok River Bluffs composed of nearly flat-lying Tertiary Sagavanirktok Formation.

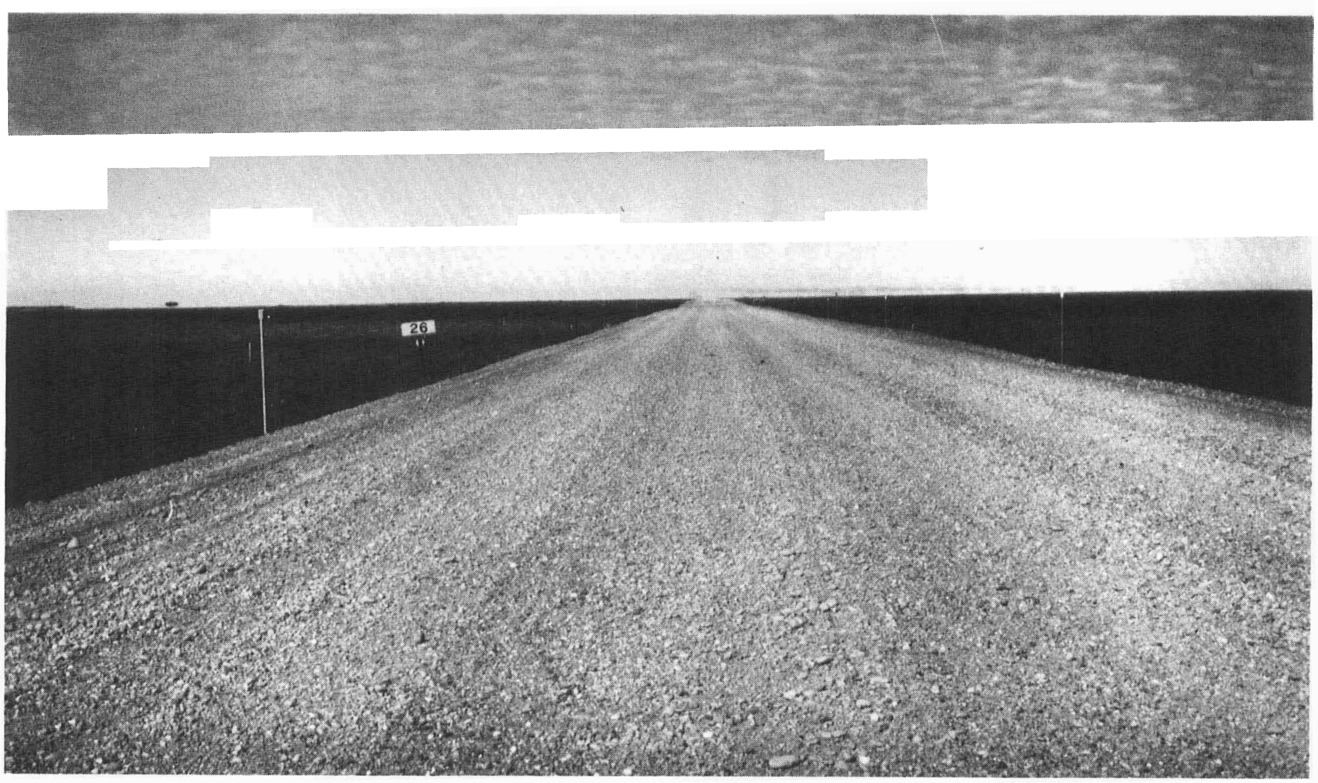
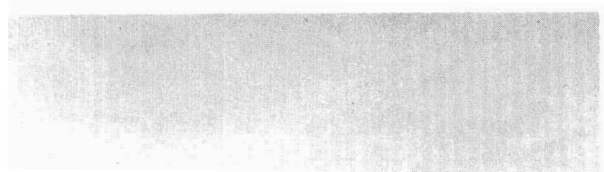


Figure 114. Dalton Highway on Arctic Coastal Plain, heading for Prudhoe Bay. Milepost 26 (left) is for 10-in.-diam (25 cm) gasline to Pump Stations 2, 3, and 4.



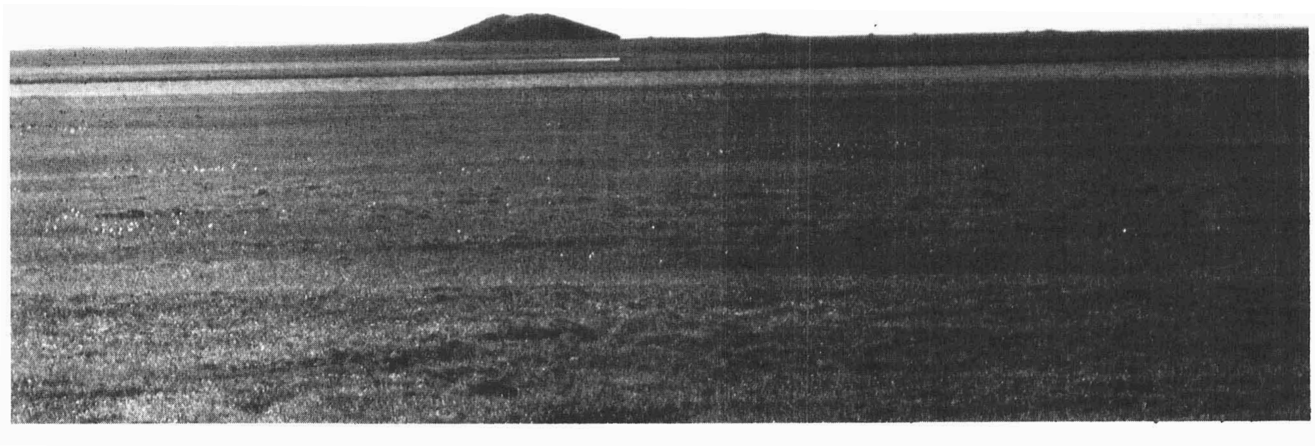
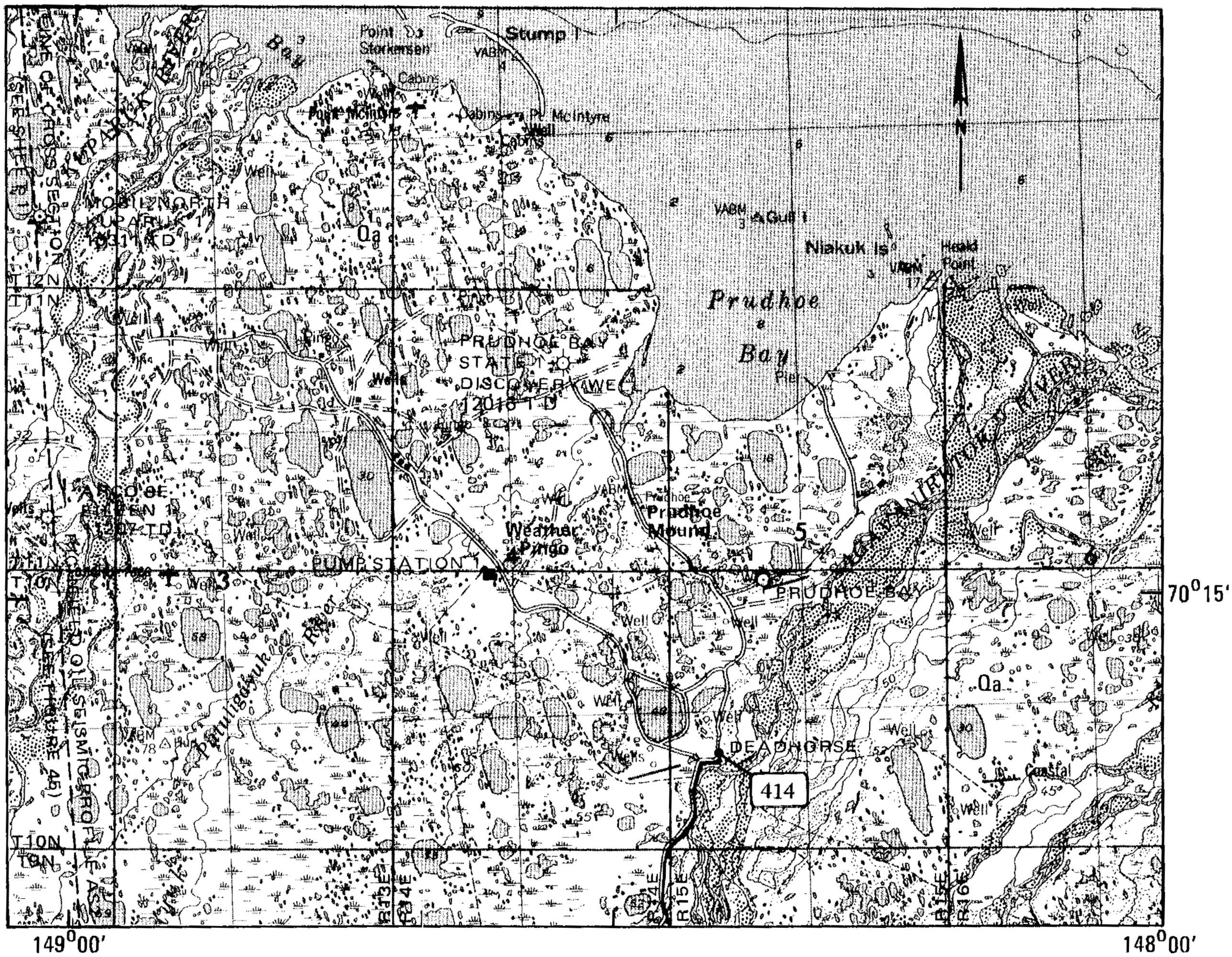
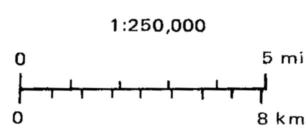


Figure 115. View westward from Mile 397 toward pingo (VABM Percy) in Toolik River pingo field, Arctic Coastal Plain.

Figure 116. Prudhoe Bay oil field. View eastward toward ARCO Flow Station 1 (left center) and Drill Site 1 (upper right) and gathering lines from other drill pads. Sagauanirktok River in background.





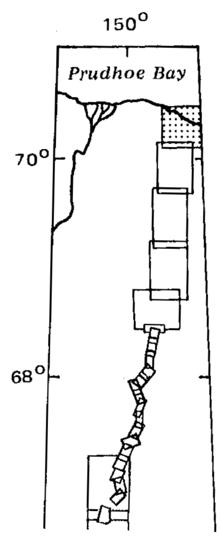
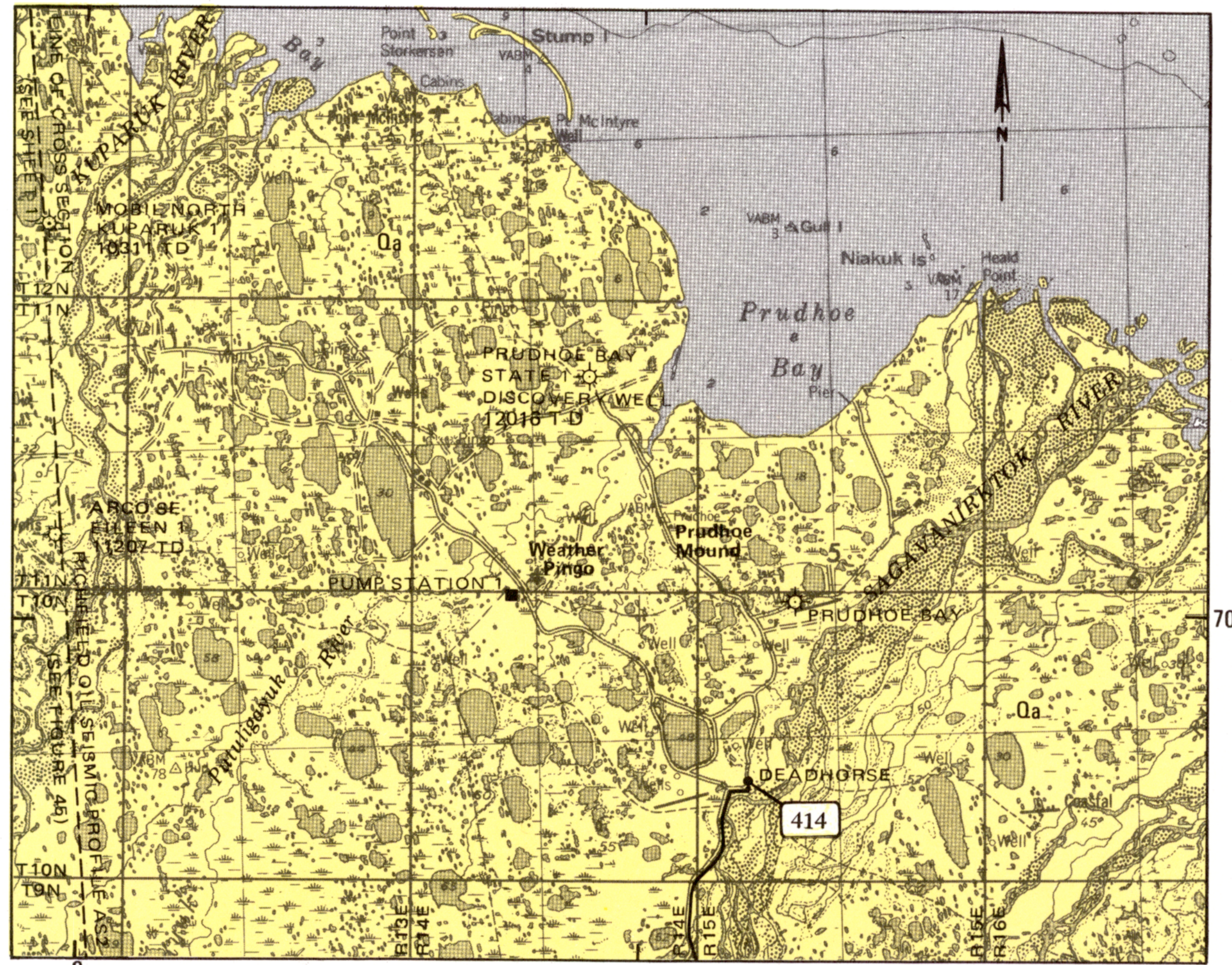


FIGURE LOCATION

Figure 117. Topographic map of Prudhoe Bay area at end of Dalton Highway, Mile 414. See figure 118 for map explanation.



1:250,000

0 — 5 mi

0 — 8 km

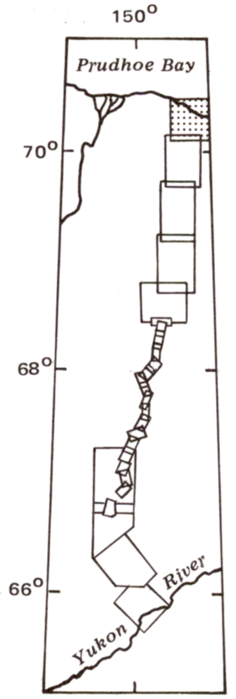


FIGURE LOCATION

Figure 117. Topographic map of Prudhoe Bay area at end of Dalton Highway, Mile 414. See figure 118 for map explanation.

MAP SYMBOLS

—?— Contact—Dashed where approximately located; queried where inferred

U/D High-angle fault—Dashed where approximately located; dotted where concealed. U, upthrown side; D, downthrown side

Thrust fault—Dashed where approximately located; dotted where concealed. Sawteeth on upper plate

Fold—Dashed where approximately located; dotted where concealed

- Anticline, showing plunge of axis
- Overturned anticline, showing direction of dip of limbs and plunge of axis
- Syncline, showing plunge of axis
- Overturned syncline, showing direction of dip of limbs and plunge of axis

Strike and dip of beds—Arrow indicates estimated measurement

- 33 Inclined
- Horizontal
- 62 Overturned
- 49 Overturned >180°

DESCRIPTION OF MAP UNITS

Qa ALLUVIAL DEPOSITS, UNDIFFERENTIATED (QUATERNARY)

Ts SAGAVANIRKTOK FORMATION (TERTIARY)—Upper part consists of nonmarine deposits of unconsolidated to poorly consolidated sandstone, conglomerate, and brown claystone; forms White Hills and Franklin Bluffs. Lower part is massive sandstone and conglomerate interbedded with coal and medium- to coarse-grained quartz-black chert sandstone; forms river bluffs in Sagwon area. Not easily differentiated on lithologic criteria from Prince Creek Formation (Kp) in Sagwon area

Kp PRINCE CREEK FORMATION OF COLVILLE GROUP (UPPER CRETACEOUS)—Nonmarine deposits composed of sandstone, conglomerate, siltstone, carbonaceous shale, and coal. Forms bluffs along Sagavanirktok River near Sagwon. Not easily distinguished on lithologic criteria from Sagavanirktok Formation (Ts) in Sagwon area

Ks SCHRADER BLUFF AND SEABEE FORMATIONS OF COLVILLE GROUP (UPPER CRETACEOUS)—Marine deposits composed of bentonitic clay shale, tuffaceous siltstone, and tuffaceous, fine-grained, light-gray sandstone. Exposed in low, scattered cutbanks and occasionally on rubble ridges; generally poorly exposed in Sagavanirktok River valley

Kn NANUSHUK GROUP (UPPER AND LOWER CRETACEOUS-CENOMANIAN AND ALBIAN)—Light-gray sandstone, conglomerate, siltstone, and minor coal deposited in a deltaic complex up to 3,500-ft thick. Upper part of sequence consists of fluvial sandstone, conglomerate, and conglomeratic sandstone deposited on delta plain; lower part of sequence consists of shallow-marine sandstone and siltstone. Sandstone is dominantly quartz and chert; conglomerate pebbles are black chert and white quartz. Sequence forms high, mesa-like hills in southern foothills north of Brooks Range. To north, sequence grades rapidly to turbidite deposits of fine-grained sandstone and shale that form scattered rubble-ridge exposures; sequence grades downward to prodelta marine deposits

Kt TOROK FORMATION (LOWER CRETACEOUS-ALBIAN)—Prodelta deposits composed of laminated, black clay shale and silty shale. Exposed at base of Slope Mountain and possibly north side of Atigun Gorge; probably underlies most of lowland area north of Slope Mountain

Kf FORTRESS MOUNTAIN FORMATION (LOWER CRETACEOUS-ALBIAN)—Dominantly thick turbidite deposits composed of dark-gray sandstone, conglomerate, siltstone, and interbedded mudstone. Forms Atigun syncline. Small, local exposures north of Atigun syncline consist mostly of dark-gray, partly conglomeratic sandstone

Kk KONGAKUT FORMATION (LOWER CRETACEOUS-NEOCOMIAN)—Turbidite deposit composed of dark-gray to black, manganiferous shale, siltstone, and graywacke; pebbly in part. Forms isolated exposures north of mountain front. Distal equivalent to Okpikruak Formation (Ko). In small outcrops and in absence of fossils, difficult to differentiate from parts of Torok Formation (Kt)

Ko OKPIKRUAK FORMATION (LOWER CRETACEOUS-NEOCOMIAN)—Turbidite deposit composed of rhythmically interbedded dark-gray to black siltstone, graywacke, and shale with minor conglomerate beds. Lithologically similar to parts of Torok (Kt), Kongakut (Kk), and Fortress Mountain (Kf) Formations. Locally contains thin coquinoid limestone at base

JTRo OTUK FORMATION (LOWER JURASSIC TO TRIASSIC)—Thinly interbedded gray to black limestone, calcareous shale, and organic shale. Forms extensive crumpled exposures in Atigun Gorge and limited exposures elsewhere

Pe ECHOOKA FORMATION OF SADLEROCHIT GROUP (PERMIAN)—Upper part is black, phyllitic shale, with minor maroon and pale-green shale and scattered lenses, seams, and nodules of barite. Lower part is yellow-brown-weathering calcareous siltstone and silty limestone discontinuously exposed overlying Lisburne Group along northern mountain front

IPMl LISBURNE GROUP (LOWER PENNSYLVANIAN AND MISSISSIPPIAN)—Gray limestone, shaley in part, and dolomite; contains abundant nodular chert in some areas. Forms massive, light- to medium-gray-weathering cliffs and rubble-covered mountains. In places, differentiated into an upper, light-gray-weathering unit and a lower, darker gray-weathering horizon

IPMlu UPPER LISBURNE GROUP (LOWER PENNSYLVANIAN AND MISSISSIPPIAN)—Light-gray-weathering, fine- to medium-grained limestone with chert. Forms massive cliffs

Mll LOWER LISBURNE GROUP (MISSISSIPPIAN)—Medium-gray-weathering limestone, shaley in part, and dolomite, with black, nodular chert

Mk KAYAK SHALE (MISSISSIPPIAN)—Fissile, black clay shale and silty shale, with thin yellow-brown-weathering silty limestone beds in upper part; contains abundant red-brown-weathering nodules in some areas

MDk KANAYUT CONGLOMERATE (LOWER MISSISSIPPIAN AND UPPER DEVONIAN)—Deltaic complex composed of dark-gray-weathering, fine- to medium-grained sandstone and conglomerate with interbedded siltstone and shale. In southern part of outcrop belt, forms crest of Endicott Mountains along Continental Divide

MDks STUVER MEMBER OF KANAYUT CONGLOMERATE (LOWER MISSISSIPPIAN AND UPPER DEVONIAN)—Meandering-stream deposits composed of shale, shaley siltstone, thinly bedded sandstone and quartzite, and minor conglomerate. Weathers to brown and red-brown slopes

Dks SHAININ LAKE MEMBER OF KANAYUT CONGLOMERATE (UPPER DEVONIAN)—Meandering-stream deposits composed of conglomerate, sandstone, and shale in thinning-upward cycles. Forms massive, resistant, dark-gray-weathering ledges on ridge tops and spurs on valley walls

Dke EAR PEAK MEMBER OF KANAYUT CONGLOMERATE (UPPER DEVONIAN)—Meandering-stream deposits of conglomerate, sandstone, and shale in thinning- and fining-upward cycles. Weathers brown to red-brown on hillsides and forms resistant ledges

Dn NOATAK SANDSTONE (UPPER DEVONIAN)—Channel-mouth bar deposit composed of dark-brown-weathering calcareous sandstone and black shale; locally conglomeratic

Dh HUNT FORK SHALE (UPPER DEVONIAN)—Prodelta deposits composed of gray-weathering shale and shaley siltstone interbedded upward with fine- to medium-grained sandstone. Forms high mountains north of Continental Divide near Atigun Pass

Db BEAUCOUP FORMATION (UPPER DEVONIAN)—Dark-gray to green-gray shale, phyllitic in part. Forms light-brown to orange-brown-weathering slopes south of Continental Divide near Atigun Pass

tb TECTONIC(?) BLOCKS—Small, isolated exposures in Atigun Gorge composed of green-gray chert, green siltstone, and altered crinoidal limestone. Range from ten to several hundred feet diameter. Age and unit unknown. In places, closely associated with small, discontinuous outcrops of Otuk Formation (JTRo) and coquinoid limestone of Endicott Mountains allochthon. Some blocks encased in groundmass of Permian and Triassic black, phyllitic shale; others associated with sheared graywacke and shale of Okpikruak Formation (Ko). Blocks are probably a broken formation formed at the base of an overlying allochthon during Early Cretaceous time but before deposition of the Albian Fortress Mountain Formation

Figure 118. Explanation for geologic maps from Chandalar Shelf to Prudhoe Bay (figs. 85, 87, 89, 94, 99, 104, 106, 110, 112, and 117).

CHAPTER 8.

HISTORY OF OIL EXPLORATION ON THE ARCTIC SLOPE[1]

By *C.G.* Mull[2]

INTRODUCTION

Discovery of the giant Prudhoe Bay oil field in 1968 focused worldwide attention on Alaska and thrust Alaska into the forefront of oil and gas production in the United States. As a result of this discovery, the Arctic Slope and the Beaufort Sea continental shelf have become an arena of intense oil and gas exploration that will continue for many years. Revenue from hydrocarbon production at Prudhoe Bay accounts for about 85 percent of Alaska's total revenues and has led to the creation of a permanent fund in which all Alaskans share. Impacts of this discovery affect all Alaskans and have a marked effect on domestic and international policies of the United States.

Although great public attention surrounded construction of the Trans-Alaska Pipeline from Prudhoe Bay to Valdez, little attention has been paid to the history of exploration that led to the discovery of the Prudhoe Bay field. Various historical aspects of geologic exploration in northern Alaska have been discussed by Gryc (1970), Morgridge and Smith (1972), Jamison (1978), Jamison and others (1980), and Dutro (chap. 2). The history reported in this chapter is summarized from these sources and from personal files, and supplemented by conversations with G.H. Pessel, C.H. Selman, and L.F. Fay, all formerly with Richfield Oil Corporation (ARCO), and M.D. Mangus of Atlantic Refining Company and ARCO.

EARLY EXPLORATION

The history of petroleum development in northern Alaska probably began in the 19th century, when Eskimo travelers along the coast discovered natural-oil seeps near Cape Simpson, 50 mi (80 km) southeast of Barrow and 150 mi (240 km) northwest of Prudhoe Bay and at Angun (Ungoon) Point (30 mi [50 km] southeast of the village of Kaktovik on Barter Island). For many years, residents of the areas traveled to these seeps to cut blocks of oil-soaked tundra for use as fuel. These deposits were almost unknown to the outside world when pioneering geologist and explorer Ernest de K. Leffingwell mentioned their presence in his classic report on scientific studies of the Canning River region, which is located more than 60 mi (100 km) southeast of Prudhoe Bay (Leffingwell, 1919). Leffingwell spent from 1906 to 1914 mapping the géology of the area, and although he had not actually visited the seeps, he mentioned them in a general discussion of the economic potential of the area. As a result of his report, mineral claims were staked in the area of the seeps at Cape Simpson in the 1920s.

NAVAL PETROLEUM RESERVE 4 EXPLORATION

In 1923, a large area surrounding the Simpson oil seeps and extending south to the crest of the Brooks Range was withdrawn from oil and gas or mineral leasing to become Naval Petroleum Reserve 4 (NPR-4). During this era, the U.S. Navy had become increasingly aware of its dependence on oil to fuel its fleet and was concerned about future supplies. Leffingwell's report of oil seeps, combined with geologic data from U.S. Geological Survey (USGS) geologist F.C. Schrader, suggested to the Navy that this area might contain its future supplies of oil. In a pioneering exploration in 1901, Schrader crossed the Brooks Range (not yet named) through

[1]The original version of this paper appears in the volume (Alaska's Oil/Gas & Minerals Industry' (Alaska Geographic, 1982).
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Anaktuvuk Pass, traversed down the Anaktuvuk and Colville Rivers to the coast, and then traveled west to Barrow and Cape Lisburne (Schrader, 1904). Although Schrader neither saw nor heard about the oil seeps, his geologic data suggested the presence of a major sedimentary basin. Leffingwell's report proved that at least some sediments in the basin could contain hydrocarbons. Leffingwell also named the Sadlerochit Formation for a distinctive series of Permian and Triassic rocks exposed in the Sadlerochit Mountains.

Following the establishment of NPR-4, a flurry of geologic exploration brought USGS geologists P.S. Smith, J.B. Mertie, Jr., Sidney Paige, James Gilluly, W.T. Foran, and others to the Brooks Range and Arctic Slope. Many of these early, unheralded geologic expeditions that began with Schrader and Leffingwell were conducted on foot, by boat, or by dog team, with hardships that far exceeded the trials of the builders of the pipeline more than 50 yr later. Most of these geologists were out of contact with civilization for months; they lived off the land and felt their way across a terrain that, in an era prior to airplanes in Alaska, was still virtually unmapped. Some of the names that were left on features at the time--No Luck Lake, Disappointment Creek, Desperation Lake--reflect in a small way the rigors of their explorations.

During the 1930s and the early years of World War II, little attention was paid to northern Alaska, but during the war, the Navy again realized its need for dependable fuel supplies and embarked on an aggressive program of oil exploration. Preliminary field parties were sent out in 1944, but by the time geophysical crews and drilling rigs were moved to this remote area, the war had ended. Exploration nevertheless continued until 1953. Surface geologic mapping was conducted by the USGS Navy Oil Unit throughout the Brooks Range and Arctic Slope by boat, weasel (tracked vehicle), and foot traverse. This work resulted in the drilling of a number of exploratory wells on NPR-4. The first stage of active oil exploration focused on rocks of Cretaceous age, particularly on the Nanushuk Group. Most wells were drilled on anticlines and many had at least small oil and gas shows. But in all of NPR-4, only three small discoveries were made. One small noncommerical oil field was discovered at Umiat and provided high-quality crude oil for local use during the exploration of NPR-4. A small gas field was also discovered in Upper Cretaceous rocks at Gubik, just east of Umiat. The most important discovery was near Barrow, where the small south Barrow gas field produces from thin Jurassic sandstone. This field, with original reserves estimated at 18 billion ft^3 of natural gas, provides fuel for Barrow (Carter and others, 1977). The most important result of the NPR-4 exploration, however, was the addition of a significant amount of technical data to existing knowledge about northern Alaska geology. A number of USGS geologists still active in the profession began their careers in this second generation of exploration on the Arctic Slope.

OIL INDUSTRY EXPLORATION

A lull followed the cessation of the Navy exploration program in 1953, until Richfield Oil Corporation discovered oil in 1957 at Swanson River on the Kenai Peninsula, and again the attention of the oil industry was focused on Alaska. The discovery of this significant oil field (more than 250 million barrels), the first in Alaska, proved that Alaska had the potential for producing major quantities of oil and gas. By the summer of 1958, oil industry geologists, working out of tent camps, had fanned out across most of Alaska, and in 1959 they began studying the Arctic Slope. This third generation of geologists had the advantage of helicopter transportation

Figure 119. Richfield Oil geologic field camp at Cache One Lake, supported by Bell G2 helicopter and Cessna 180 float plane, August *1963.*

(fig. 119) and could build on the foundation established by USGS research. Interest in northern Alaska was also stimulated by the availability of lands leased from the U.S. Bureau of Land Management. These newly released lands lay to the east and south of NPR-4, in the low, rolling northern foothills of the Brooks Range, and covered a number of surface anticlines. Seismic exploration in this area began in 1962. The following 2 yr saw the beginning of industry drilling in the Umiat area. Six shallow exploratory holes were drilled on surface anticlines; all were dry holes except for a small gas well east of Umiat.

During this period, two other significant events occurred. In 1960, the U.S. Government established the Arctic National Wildlife Range (now the Arctic National Wildlife Refuge), which covered the entire eastern end of the Arctic Slope and Brooks Range from the Canning River to the Alaska-Yukon border. Second, Alaska, as part of its land entitlement under the Statehood Act, selected more than 1,800,000 acres of the Arctic Coastal Plain that borders the Beaufort Sea between NPR-4 and the wildlife range. This swampy, lake-covered area contains no surface rock exposures, but was recommended for selection by the State's only geologist, Tom Marshall, who recognized geologic similarities of the Arctic Slope to petroleum-bearing areas in the Rocky Mountains of the western United States. Selection of the coastal-plain area was also advantageous because it eliminated potential disputes between state and federal governments over the definition of navigable streams in upland areas. If the surrounding lands were state lands, it would be unnecessary to define the limit of navigability of streams that flow into the Arctic Ocean. The land thus selected included Prudhoe Bay, an obscure geographic feature named more than 130 yr earlier by Arctic explorer Sir John Franklin--the first white man to explore the coast west of the Mackenzie River in Canada.

In late 1964, Alaska received tentative approval for its land selections from the U.S. Government and, in December of that year, held a competitive sale for leases in the area of the Colville River delta. British Petroleum (BP) and Sinclair Oil and Gas Company acquired a large block of land (on which two wells were drilled in 1966 and 1967). In July 1965, a second sale of Arctic Slope leases was held by the State; this sale included lands in the Prudhoe Bay area. In this sale, Richfield (now part of ARCO) and Humble Oil Company (now Exxon Company, USA.)--as partners--acquired more than 71,500 acres of land that covered the crest of a subsurface structure next to Prudhoe Bay. BP, with lower bids, acquired nearly 82,000 acres located down the southern and western flank of the structure. Other companies, including Mobil Oil Corporation, Phillips Petroleum Company, Union Oil Company, Chevron U.S.A. Inc., and Atlantic Refining Company, acquired flank acreage and land to the west near the Kuparuk River. At the time of the 1965 sale, the only information available was seismic data combined with projections of subsurface stratigraphy from Brooks Range outcrops 80 to 130 mi (130 to 200 km) to the south and east. The nearest exploratory well was in NPR-4, 75 mi (120 km) west of Prudhoe Bay.

Also during 1965, Richfield, to solve the logistical problem of moving giant drilling rigs to remote areas of the Arctic, pioneered the use of the Lockheed C-130 Hercules cargo plane for hauling heavy equipment to the Arctic Slope (fig. 120). Richfield arranged for Alaska

Figure 120. First construction equipment unloaded from initial flight of *Lockheed C-130* Hercules cargo plane for Richfield Oil in support of oil exploration, *Sagwon* airstrip, March 1965.

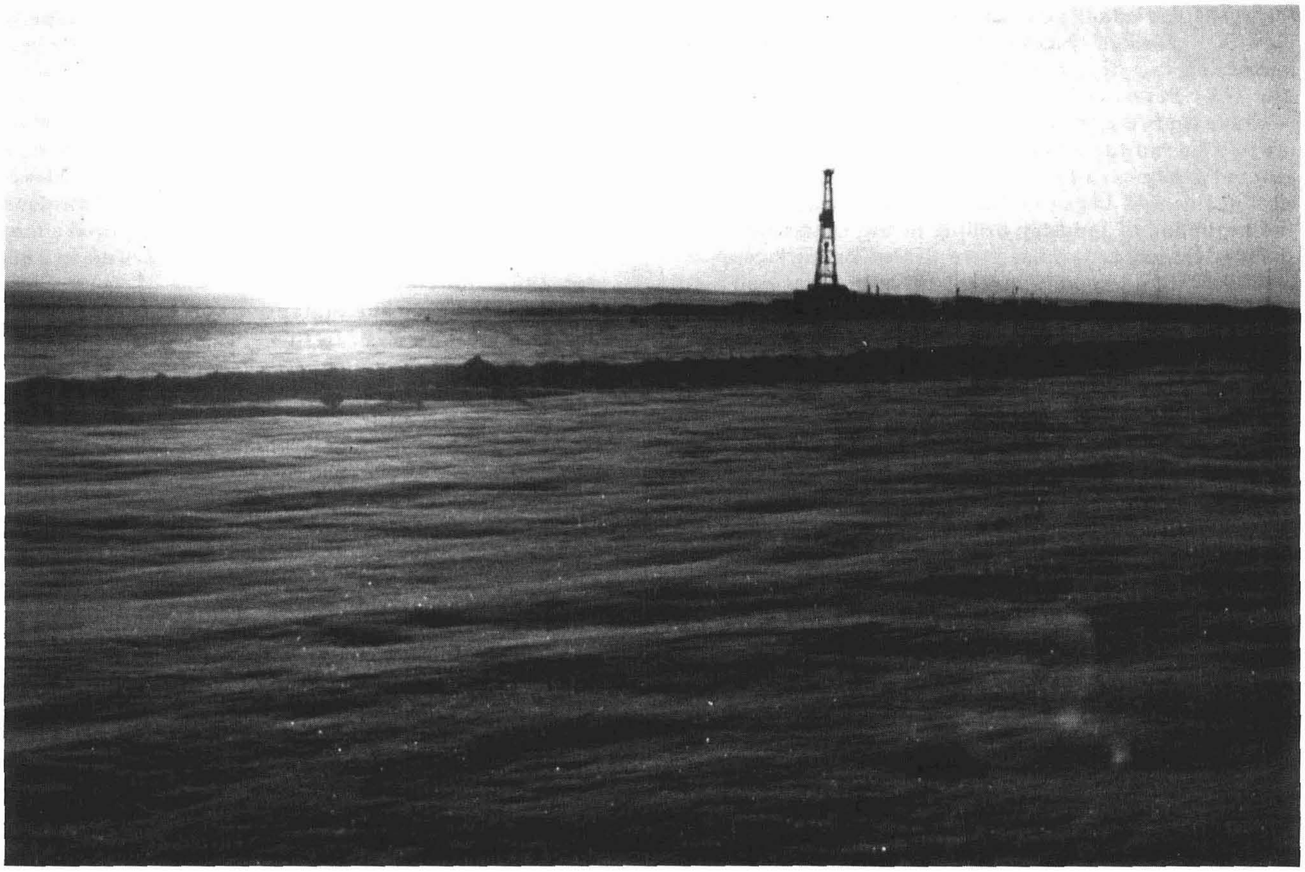

Figure 121. Midnight view on June 1, 1966, of ARCO-Humble (Exxon) exploratory well, Susie 1, drilled to 13,500 ft--the deepest well drilled on the Arctic Slope at that time.

Airlines to lease a C-130 for its first use as a commercial aircraft; the first equipment was flown in from Fairbanks in March 1965. In January 1966, a snow and ice airstrip was built on tundra at a location called Susie 1, about 80 mi (130 km) east of Umiat and 8 mi (13 km) west of the present Pump Station 2 on the Trans-Alaska Pipeline. During a 2-wk period of operating nearly around the clock (as weather permitted), more than 80 plane loads of equipment were flown from Fairbanks to the Susie 1 ice strip. This airlift included an entire drill rig disassembled into plane-sized components, drill pipe and supplies, and modular units to construct a camp for the drilling crew and support personnel. With Humble Oil Company (Humble) as a partner, Richfield (ARCO) drilled the exploratory well at Susie 1 (fig. 121) to 13,500 ft (4,115 m) in the Jurassic Kingak Shale--the deepest well drilled on the Arctic Slope at that time. The hole was dry, but good shows were seen in Upper Cretaceous sandstones.

PRUDHOE BAY DISCOVERY

In 1966, Richfield merged with the Atlantic Refining Company, and the new firm--the Atlantic Richfield Company (ARCO)--inherited the operations and lands acquired by Richfield, including the acreage held jointly with Humble at Prudhoe Bay. Following the dry hole at Susie 1, the drill rig was moved overland 60 mi (100 km) north to a new drill site at Prudhoe Bay. This well, Prudhoe Bay State 1, the second well drilled on the Arctic Slope by ARCO and Humble, was spudded in April 1967. With the coming of the summer, a snow and ice airstrip built across two small lakes thawed, and drilling was suspended until after freezeup in the fall.

In November 1967, drilling was resumed at Prudhoe Bay State 1 (figs. 122 and 123). Good oil shows were found in the Cretaceous, and an open hole drill-stem test (DST) of the interval from 6,876 to 6,998 ft (2,096 to 2,133 m) recovered 1,500 ft (457 m) of high quality (28 $^{\circ}$API) oil and some gas. In December, at 8,202 ft (2,500 m), sandstone and conglomerate of the Triassic Ivishak Formation of the Sadlerochit Group were encountered, along with strong gas shows. On December 26, 1968, a DST of the Sadlerochit from 8,410 to 8,953 ft (2,563 to 2,729 m) had a very strong immediate flow of gas to the surface. The interval flowed an estimated 1.5 million ft^3 per day with a surface pressure of 3,075 psi. Following a successful fishing job for stuck

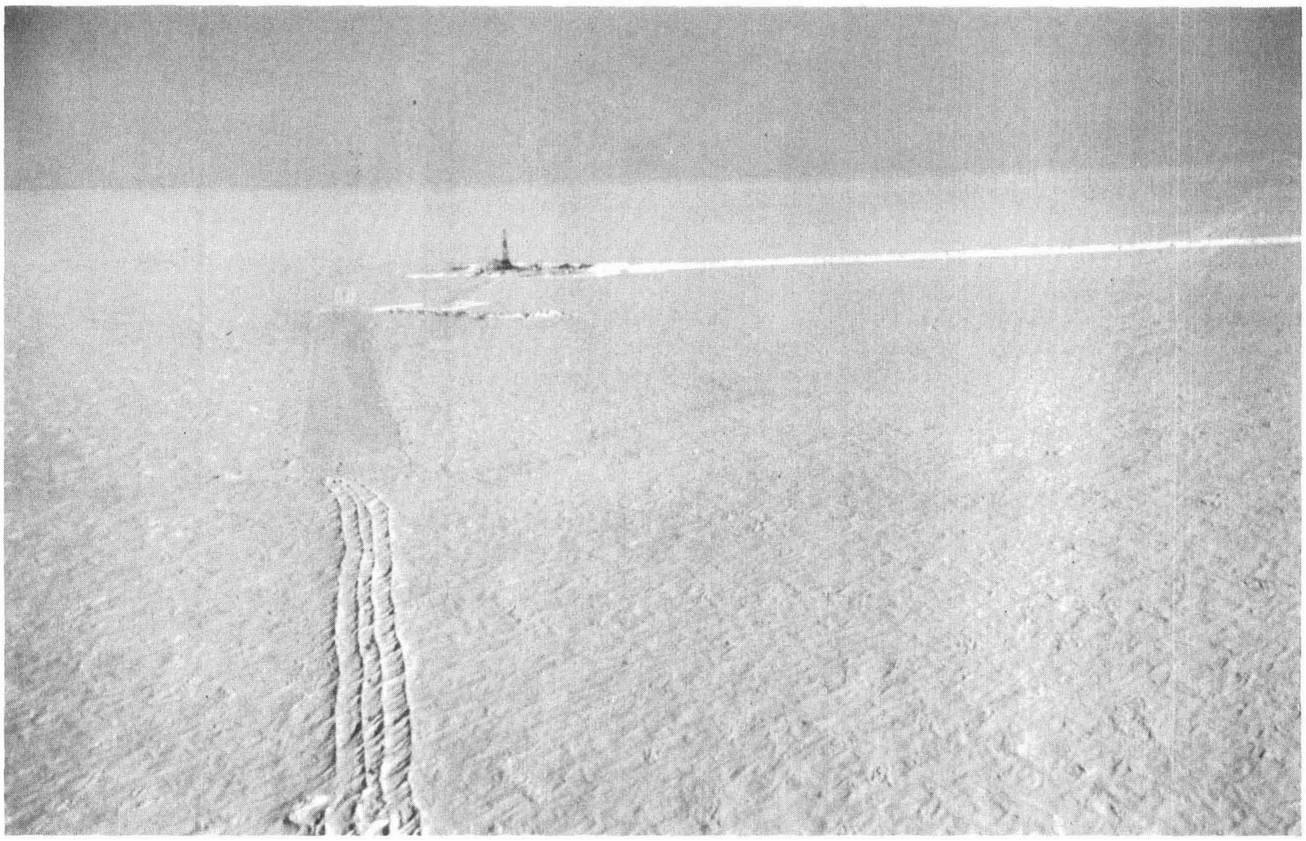

Figure *122.* View northeastward toward ARCO-Humble (Exxon) discovery well, Prudhoe Bay State 1, February 1968. Snow and ice airstrip shown at left; road to water supply *at* right; ice-covered Prudhoe Bay on horizon.

testing tools, drilling continued through the sandstone and conglomerate of the Ivishak, and casing was set to 8,745 ft (2,665 m). The gas-oil contact encountered at 8,630 ft (2,630 m) resulted in 378 ft (115 m) of net gas sand and 17 ft (5 m) of net oil sand in the Sadlerochit.

Accompanied by some minor press coverage, drilling continued into limestone and dolomite of the Mississippian and Pennsylvanian Lisburne Group. In March, a DST in the Lisburne flowed *22* million ft^3 per day dry gas and 1,152 barrels per day of 27 °API oil. A subsequent test of 16 ft (5 m) of sand at the base of the Sadlerochit flowed over 2,200 barrels of oil per day. This was the first clear indication that a major oil field existed below the gas cap.

In April, drilling began on a second well, Sag River State 1, located about 7 mi (11 km) southeast of the Prudhoe Bay discovery well (fig.124). Here, the Sadlerochit Group was more than 300 ft (100 m) downdip, and more than 400 ft (122 m) of sandstone and conglomerate were oil-saturated. ARCO and Humble then retained the firm of DeGolyer and McNaughton to make an independent evaluation of the results of the first two wells. This firm electrified the world with its report that Prudhoe Bay "could develop into a field with recoverable reserves of some 5 to 10 billion barrels of oil, which would rate it as one of the largest petroleum accumulations known to the world today." With this announcement, the rush to the Arctic was on, and Alaska has not been the same since. Subsequent evaluations have indicated that the reservoir in the Sadlerochit alone contained 9.6 billion barrels of recoverable oil and 26 trillion ft^3 of natural gas. This accumulation is almost twice the size of the next largest oil field in North America (the East Texas field) and contains almost one-third of the known oil reserves and 12 percent of the gas reserves in the United States. Since the Trans-Alaska Pipeline to Valdez was completed in 1977, the field has produced over 6 billion barrels of oil and is currently producing at the rate of about 1.5 million barrels per day. Details of the Prudhoe Bay field are given by Mull and Opstad (chap. 9).

RECENT DISCOVERIES

Subsequent exploration along the Arctic coast and Beaufort Sea has revealed additional oil and gas accumulations, but none as large as the field at Prudhoe Bay. West of the main Prudhoe Bay field, the Kuparuk oil field contains about 1.6 billion barrels of recoverable oil in Lower Cretaceous sandstones and is the tenth largest

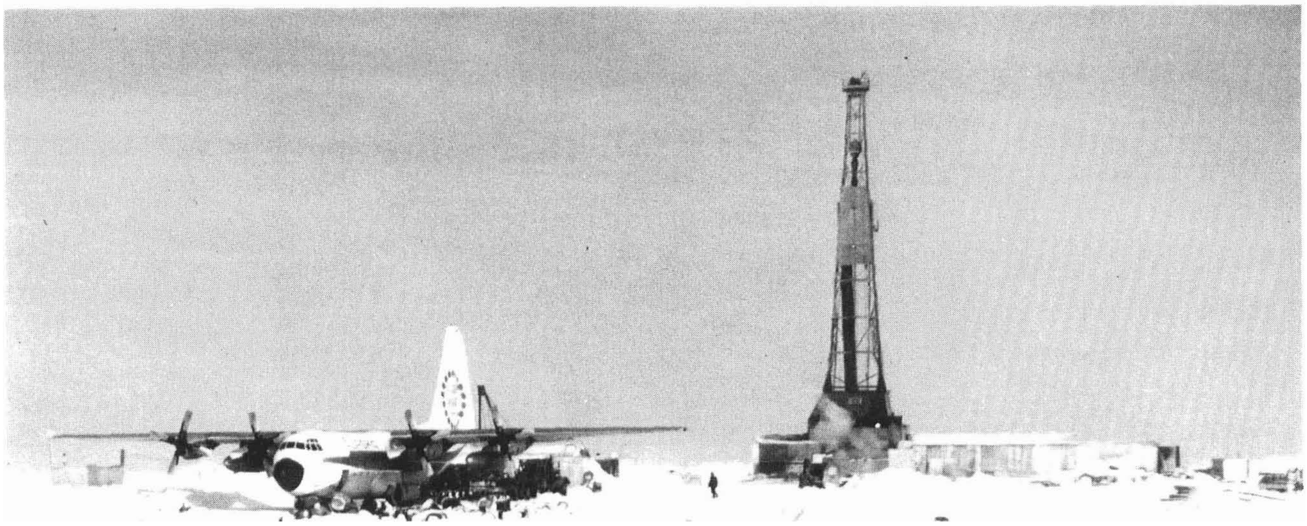

Figure 123. C-130 Hercules supply plane at Prudhoe Bay discovery well, March 1968. Drill rig, camp, and all drilling supplies were flown to northern Alaska in theseplanes.

field discovered in the United States. When it comes into full production at a planned rate of 250,000 barrels per day, Kuparuk will be second only to Prudhoe Bay in daily production of oil in the United States. Details of the Kuparuk River field are given by Masterson and Paris (1987) and Eggert (1987).

Additional smaller discoveries have been made in the Prudhoe Bay area. Of particular significance will be production of an estimated 500 million barrels of recoverable oil from the Lisburne pool at Prudhoe Bay. This pool is currently under active development by ARCO and partners, in a program that may require 180 wells.

Sandstone and conglomerate of the Lower Mississippian Kekiktuk Conglomerate have also yielded discoveries in the Duck Island-Sagavanirktok River delta area northeast of Prudhoe Bay. Standard Alaska Production Company (formerly Sohio) and partners will develop this first offshore field in northern Alaska, the Endicott field; it is estimated to contain 350 million barrels of recoverable oil. The Endicott reservoir is discussed by Woidneck and others (1987) and Melvin (1987). Also offshore, Shell Oil Company has announced a discovery in the Sadlerochit Group (Ivishak Formation) at Seal Island, 5 mi (8 km) north of the coast. This field is estimated to contain 300 million barrels of recoverable oil. Onshore and northwest of Prudhoe Bay, the Gwydyr Bay and Milne Point areas contain 30 and 60 million barrels, respectively, of recoverable oil; Milne Point is currently under development by Conoco, Inc. Other small discoveries are discussed by Weimer (1987).

In addition to reserves that can be developed by conventional techniques, large reserves of heavy oil are present in the shallow Upper Cretaceous to Paleocene West Sak and Ugnu sands that overlie the Kuparuk River Formation in the area of the Kuparuk field. These areas are estimated to contain between 26 and 44 billion barrels of hydrocarbon in place. This heavy oil may be degraded oil that spilled from the original Prudhoe Bay reservoir during Tertiary tilting of that accumulation (Werner, 1987). The West Sak sands are estimated to contain 15 to 25 billion barrels of 16 to 22 °API gravity oil and have been studied by ARCO in a pilot hot-water-flood project. The Ugnu sands contain 11 to 19 billion barrels of 8 to 12 °API gravity hydrocarbon that is classified as bitumen at 60 °F reservoir temperature. Unconventional production techniques will be required to recover any of this hydrocarbon.

In addition to the 26 trillion ft^3 of natural gas in the Prudhoe Bay field, 5 trillion ft^3 and 350 million barrels of condensate have also been delineated by Exxon in the Point Thompson area, 50 mi (80 km) east of Prudhoe Bay. These reserves will not be developed until market prices justify the expense.

Still further to the east, the untested potential of the Arctic National Wildlife Refuge (ANWR) is currently the subject of intense debate; its future as an exploratory objective will be determined by Congress.

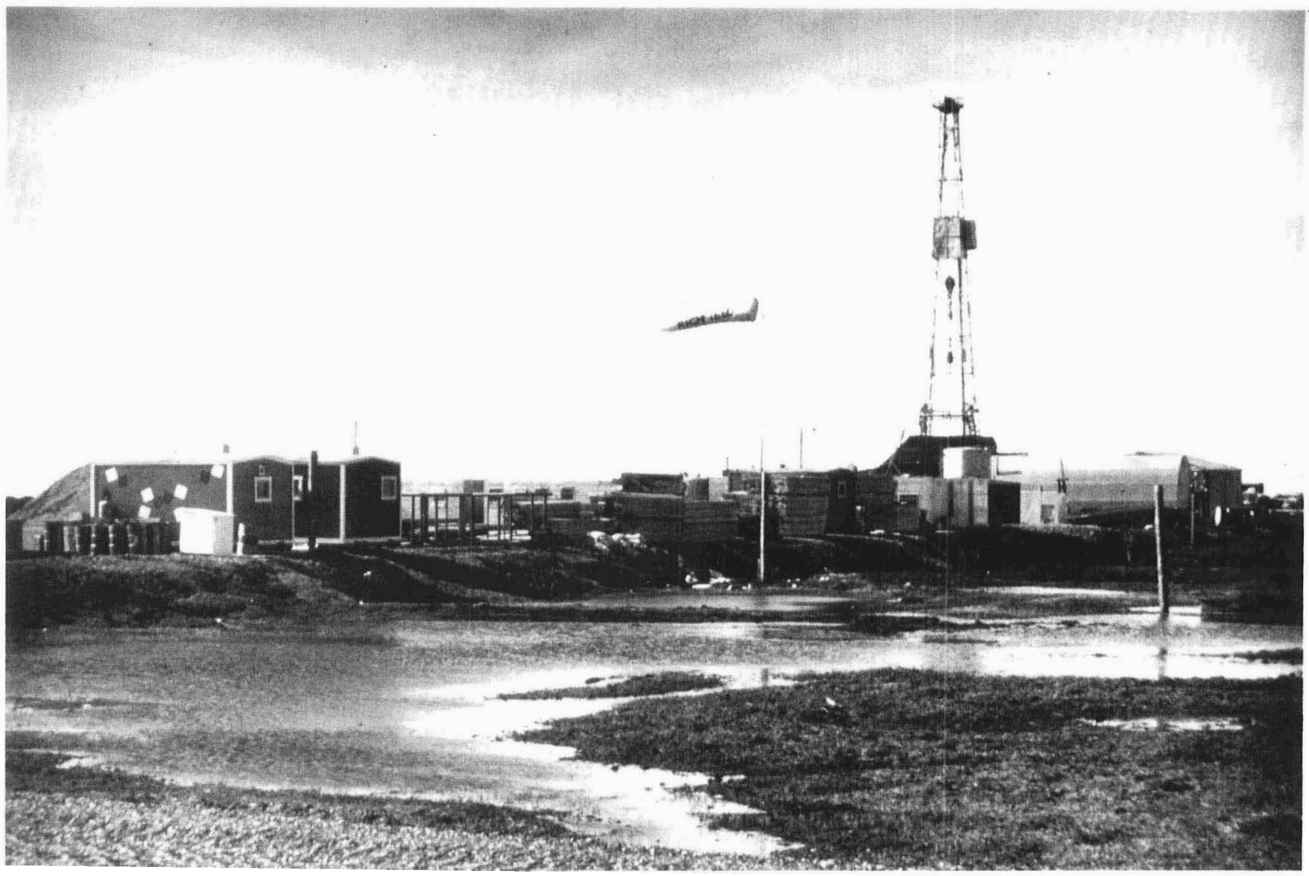

Figure 124. ARCO-Humble (Exxon) Sag River State 1, the Prudhoe Bay field confirmation well, 7 mi (11 km) southeast of Prudhoe Bay State 1, June 1968.

CHAPTER 9.

THE PRUDHOE BAY OIL FIELD

By C.G. Mull[1] and E.A. Opstad[2]

INTRODUCTION

The geology of the Prudhoe Bay oil field and nearby areas is discussed in detail by Rickwood (1970), Morgridge and Smith (1972), Jones and Speers (1976), Jamison and others (1980), Carman and Hardwick (1983), and Alwin and others (1989). The generalized discussion that follows includes data from these sources and from personal files.

REGIONAL STRUCTURAL AND STRATIGRAPHIC SETTING

The Prudhoe Bay field is located on the crest of the Barrow arch, a broad, linear stable area of shallow pre-Mississippian basement that underlies the northern Arctic Slope and coastal waters of the Beaufort Sea (figs. 26 and 28; sheet 1). The arch plunges gently southeastward from a depth of about 2,500 ft (775 m) subsea at Barrow to 12,000 ft (3,700 m) subsea in the Prudhoe Bay area. Regional subsurface and seismic data show that upper Paleozoic and lower Mesozoic strata onlap the arch from the south. The north flank of the arch is formed by a zone of half grabens and normal faults downdropped on the north toward the Canada basin. These structural relations suggest that the term 'arch' is misleading. A more descriptive term, 'Beaufort ill has been suggested (Mull, 1985) to describe the linear feature that separates the Colville basin to the south from the Canada basin to the north.

The stratigraphic section at Prudhoe Bay and elsewhere in northern Alaska was originally subdivided into three unconformity-bounded tectonic sequences by Lerand (1973). This scheme has been widely embraced by many workers and is summarized below (fig. 125):

1. Brookian sequence--Lower Cretaceous to Quaternary sediments derived from the south in the Brooks Range. Includes organic shales that many North Slope workers believe were probably the source for most of the area's hydrocarbons.
2. Ellesmerian sequence--Mississippian to Lower Cretaceous sediments derived dominantly from the north. Includes all major reservoir horizons in the Prudhoe Bay area, including the Kekiktuk Conglomerate, Lisburne Group, Sadlerochit Group, and Kuparuk River Formation.
3. Franklinian sequence--Pre-Mississippian rocks. Consists dominantly of argillite, representing economic basement at Prudhoe Bay and much of North Slope.

In addition to these classically recognized subdivisions, Hubbard and others (1987) have suggested a fourth sequence called the Beaufortian. Clastic deposits in this sequence are thought to be related to an episode of incipient rifting that began during the Jurassic (about 200 Ma) and culminated in successful rifting during the Early Cretaceous (about 125 to 130 Ma).

PRUDHOE BAY STRUCTURE AND HYDROCARBON DISTRIBUTION

The Prudhoe Bay field is a combination structural and stratigraphic trap. Eastern closure is provided by a regional Lower Cretaceous unconformity (commonly referred to as the LCU) that truncates gently southwest-dipping (1^{o} to 2^{o}) rocks of the Triassic Ivishak Formation of the Sadlerochit Group (figs. 126 and 127). The northern limit of the field is formed by east-west-trending faults that have throws to 1,000 ft (300 m) and are downdropped to the north. In the west, northwest-southeast trending faults, downdropped as much as

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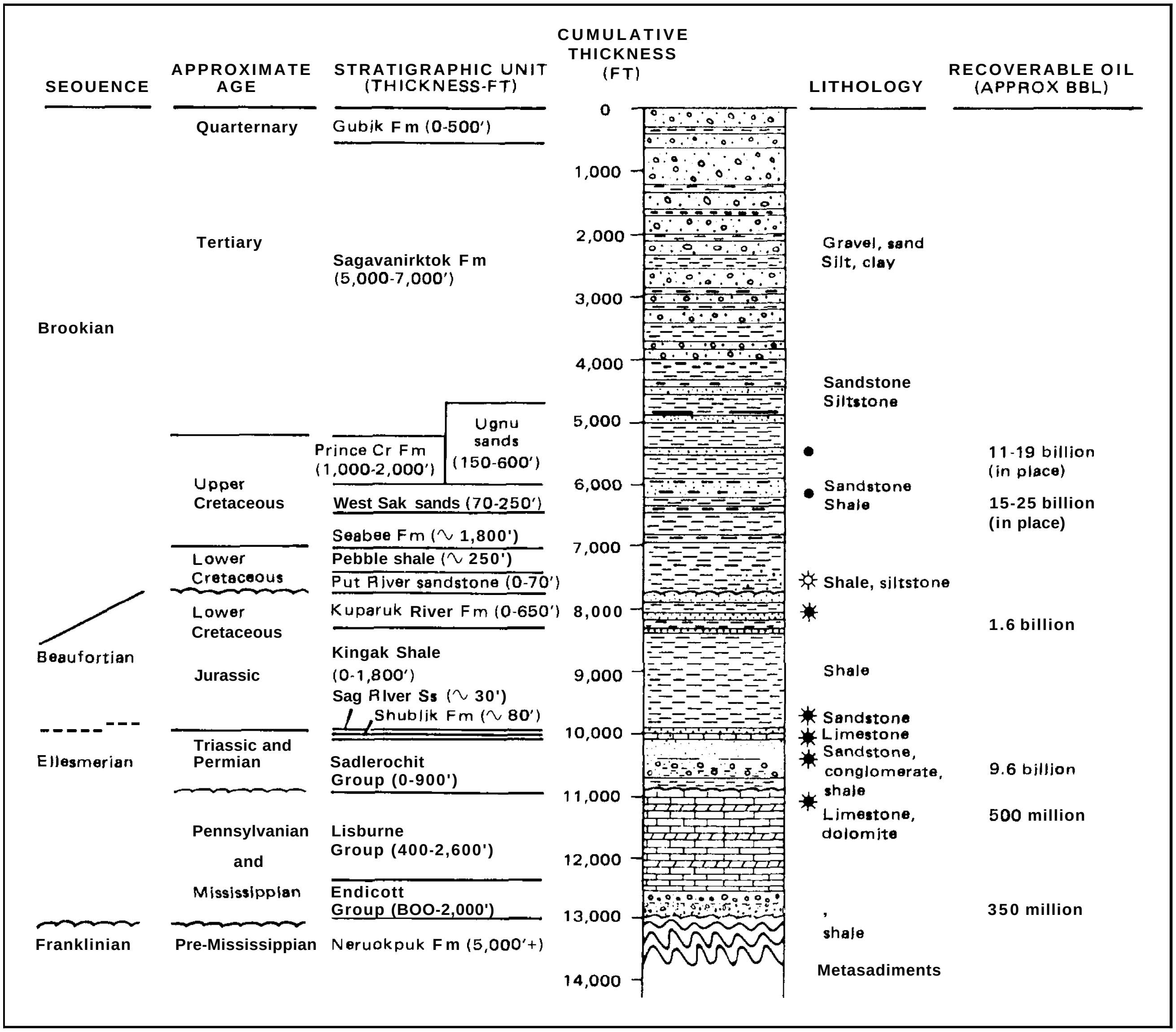

Figure 125. Generalized columnar section of rock units in Prudhoe Bay area. Symbols: Closed circle, oil reseruoir; open well symbol, gas reservoir; closed well symbol, oil and gas reseruoir. Modified from Jamison and others (1980).

300 ft (90 m) to the southwest, limit the field and divide the 'West End' from the 'Main Area' (fig. 127). At its maximum dimensions, the field is about 32 mi (50 km) long by 12 mi (20 km) wide; the total productive area is about 255 mi^2 (1,000 km^2). At the time of discovery, the field contained about 50 billion barrels of hydrocarbons.

The high point of the reservoir is 7,950 ft (2,465 m). In the Main Area of the Prudhoe field, gas is found to 8,575 ft (2,658 m) subsea; originally, the gas column in this area was 625 ft (194 m) thick. In the West End, the gas-oil contact is at 8,769 ft (2,718 m) subsea (fig. 127). The base of the light oil column in the Main Area is at the top of a heavy-oil and tar zone; however, in the West End the light oil column overlies water. The oil column reaches a maximum thickness of 465 ft (144 m) in the Ivishak Formation. Although variations exist throughout the field, Alwin and others (1989) report the following analysis for a typical Prudhoe Bay crude oil:

Type.	Napthenic to aromatic
API gravity.	27.9° (mean)
Initial gas-oil ratio (GOR).	7.45 ft^3/bbl
Sulfur	0.99 wt pct
Viscosity	37.4 centipoise (mean @ 60 °F)
Pour point	7.9 °F
Distillate	10 to 15 pct
Reservoir temperature . .	About 200 °F

The heavy-oil and tar zone, which averages 50 ft (15 m) thick, contains a mixture of black, very heavy oils and tar high in asphaltenes. This mixture is, for the

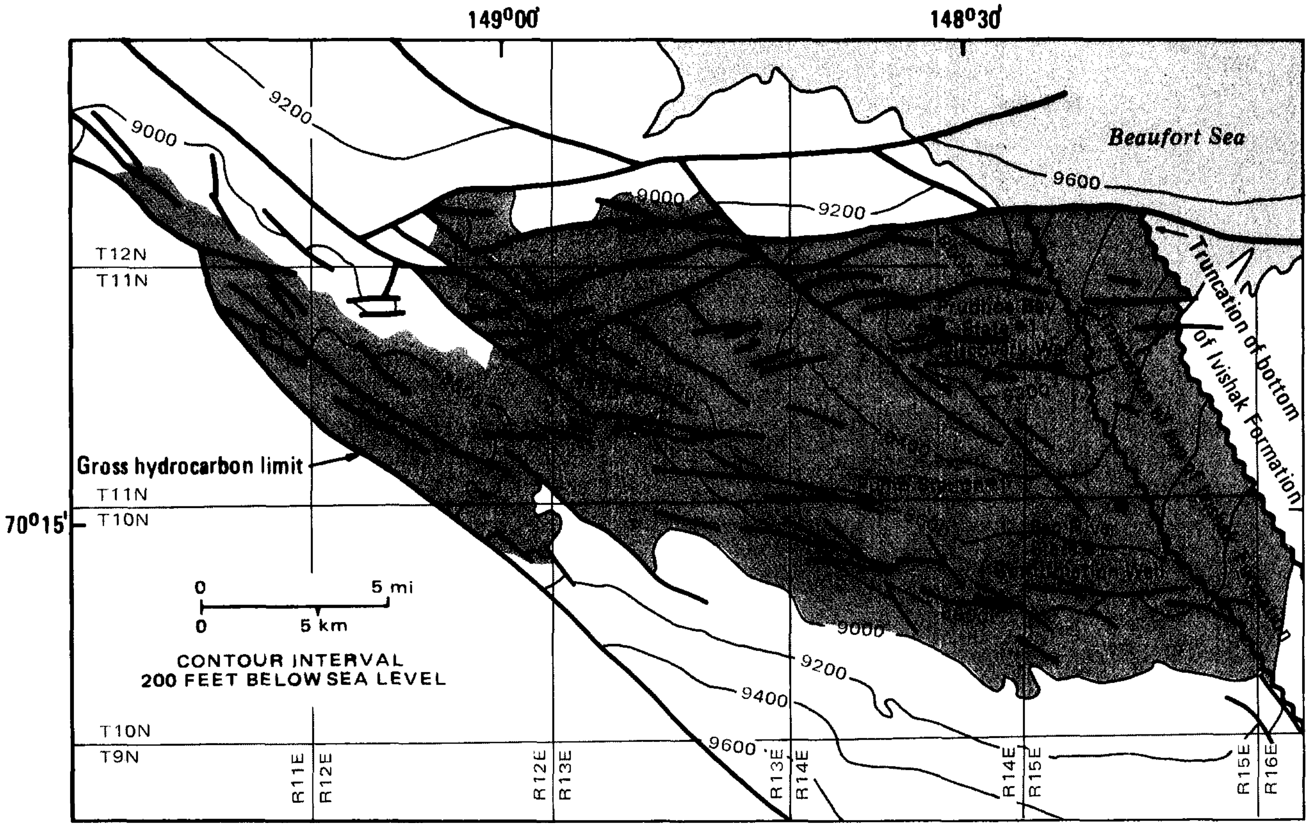

Figure 126. Structural contour map of top of Ivishak Formation in Prudhoe Bay oil field. Dark-gray area represents *limit* of oil field; heavy lines designate normal faults.

most part, immobile and nonrecoverable. Numerous theories have been proposed to account for the formation of the heavy oil and tar, but most workers favor gas deasphalting, in which methane percolates through the aquifer and light oil column causing the heavy asphaltenes to precipitate. The asphaltenes then gravitated to the lower reaches of the reservoir. This theory is supported by the relatively high carbon dioxide and methane content of the reservoir connate water (Alwin and others, 1989).

Below the heavy-oil and tar zone in the Main Area is a wedge of residual oil, which thickens to the east. Oil saturation in the residual-oil zone ranges from 0 to 10 percent, and the zone holds about 3 billion barrels of unrecoverable oil (Alwin and others, 1989). The base of the residual oil zone is interpreted as the ancient oil-water contact. The contact now dips sharply to the east, which is taken as evidence for tilting of the Prudhoe Bay structure since the time it was first filled.

SOURCE ROCKS

North Slope investigators have suggested several units as sources of hydrocarbons in the Prudhoe Bay field: the Triassic Shublik Formation, the Jurassic and Lower Cretaceous Kingak Shale, the Cretaceous pebble shale. and other Lower Cretaceous marine shales. Morgridge and Smith (1972) and Jones and Speers (1976) felt that the Cretaceous shales above the LCU not only provided a cap rock for the reservoir but also provided the major source of hydrocarbons for the Prudhoe Bay accumulation. This contention is supported by the relatively low source-rock potential of strata below the LCU, compared with source-rock potential above the LCU (fig. 128). Morgridge and Smith (1972) also pointed out that only the Cretaceous shales have direct contact with all major reservoirs in the area. Objections have been raised to the concept of downsection oil migration from younger source beds to older reservoir horizons. Mapping by Tailleur and Engwicht (1978), however, shows that the LCU can be traced to progressively greater depths for at least 50 mi (80 km) to the southeast from Prudhoe Bay. Since this surface ranges from 7,900 ft (2;400 m) subsea at Prudhoe Bay to >12,000 ft (3,700 m) subsea to the southeast, oil could have migrated laterally and updip from a very large drainage area in the Cretaceous shales.

Although total organic content and stratigraphic relations point strongly to the Cretaceous section as the hydrocarbon source for much of the oil in the Prudhoe Bay area, geochemical typing of Prudhoe Bay oil has not matched any single proposed source (Bird, 1985; Magoon and Bird, 1987). This work, however, has clearly established a close genetic relation between crude oil found in the Ivishak Formation, Kuparuk River Formation, and Upper Cretaceous West Sak and Ugnu

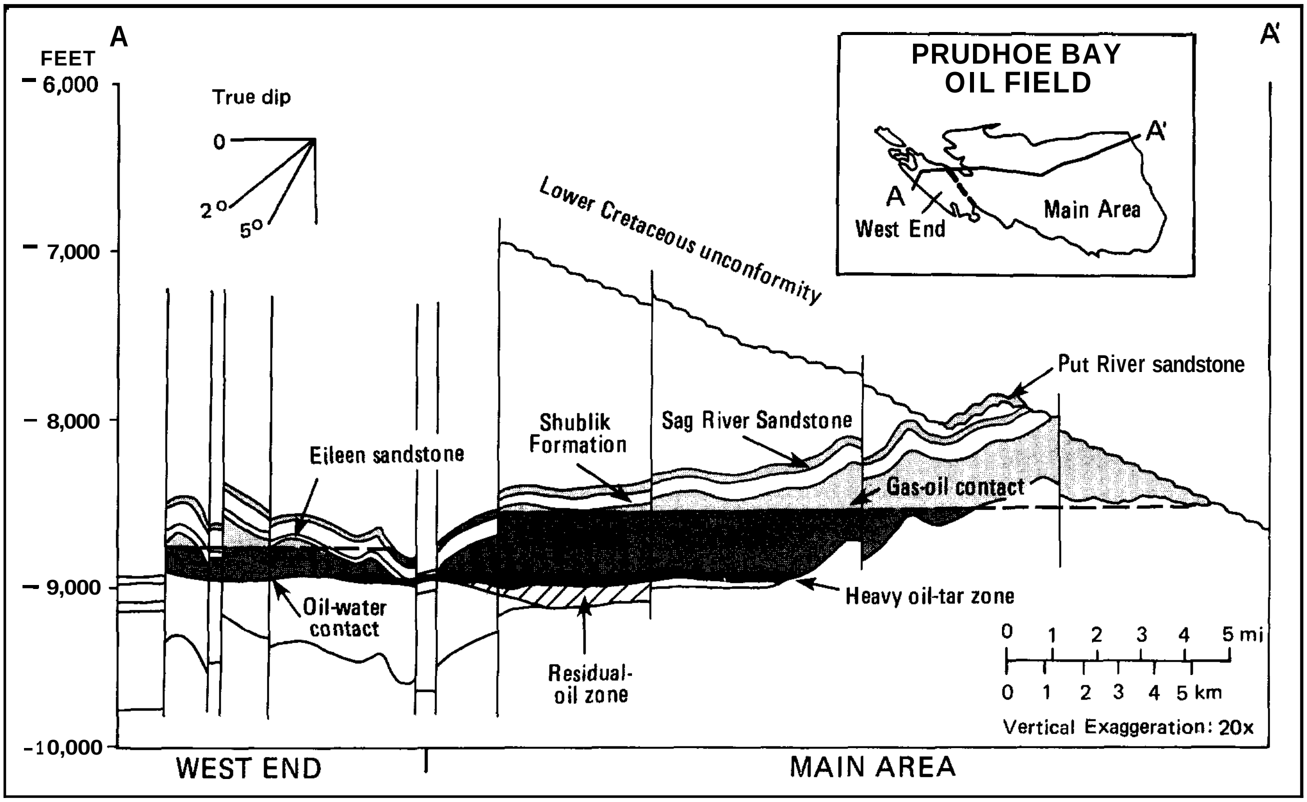

Figure 127. Generalized east-west cross section of Triassic lo Lower Cretaceous horizons in Prudhoe Bay oil field, showing distribution of hydrocarbons. Light-gray area *indicates* gas-bearing strata; dark-gray area, oil-bearing strata.

sandstones. An alternative source has been proposed by Claypool and Magoon (1985), who reported that of nine oil samples and 15 rock samples evaluated by 26 geochemical laboratories in a blind test, 17 of the laboratories chose the Triassic Shublik Formation as the source of the Prudhoe Bay oil. Moreover, the Shublik is sandwiched between the Sag River Sandstone and the Ivishak Formation, and they would provide an excellent pathway for updip migration of hydrocarbons. Even so, a Triassic source does not fit the regional geologic picture in the Prudhoe Bay area as well as a Cretaceous source does. Seifert and others (1979) have also suggested that older beds were the source for many of the hydrocarbons found in the Prudhoe area. Faced with somewhat conflicting information, most geologists feel that several sources contributed to hydrocarbon accumulations in the Prudhoe Bay field.

BURIAL HISTORY

Deposition of the Ivishak Formation--the major reservoir in the Prudhoe Bay field--ended in Early Triassic time, about 240 Ma. Continued sedimentation during the Jurassic eventually buried the Ivishak to a depth of 2,200 ft (700 m) subsea. The quiescent burial process was terminated with the abrupt onset of differential uplifting and faulting, which ended during Hauterivian (Early Cretaceous) time, about 125 Ma. During the tectonic event, the Ivishak was uplifted, tilted to the southwest, and later truncated by the LCU (Jones and Speers, 1976), in what is now the eastern part of the Prudhoe Bay field. While the Ivishak was exposed, its porosity was enhanced by meteoric water and associated matrix dissolution, which is evident in thin section (Melvin and Knight, 1984).

From about 90 to 110 Ma (Albian to Turonian time), the Ivishak again underwent uniform burial. During the Late Cretaceous and Early Tertiary (55 to 85 Ma), this process accelerated, burying the Ivishak to 3,700 ft (1,100 m) under the eastern part of the field and to 6,000 ft (1,800 m) under the western part of the field. Alwin and others (1989) suggested that tilting of the Ivishak to the southwest may have been accentuated by thick accumulations of Upper Cretaceous Colville Group sediments to the southwest of the field. The loading increased the structural relief created by prior differential uplift of the Ivishak. Burial continued during the Eocene, from 40 to 55 Ma, while hydrocarbons, generated from organic-rich sediments to the southeast, began migrating into the Prudhoe area. At this time, the crest of the structure was at 4,750 ft (1,475 m) subsea and dipped 2° to 3° to the southwest. By the Late Eocene, 40 Ma, the original oil-water contact was at 6,950 ft (2,150 m) and the maximum height of the hydrocarbon column was 2,200 ft (680 m). The original gas-oil contact has yet to be identified. The original oil accumulation covered about 276 mi^2 (720 km^2) and may have contained as much as 90 billion barrels

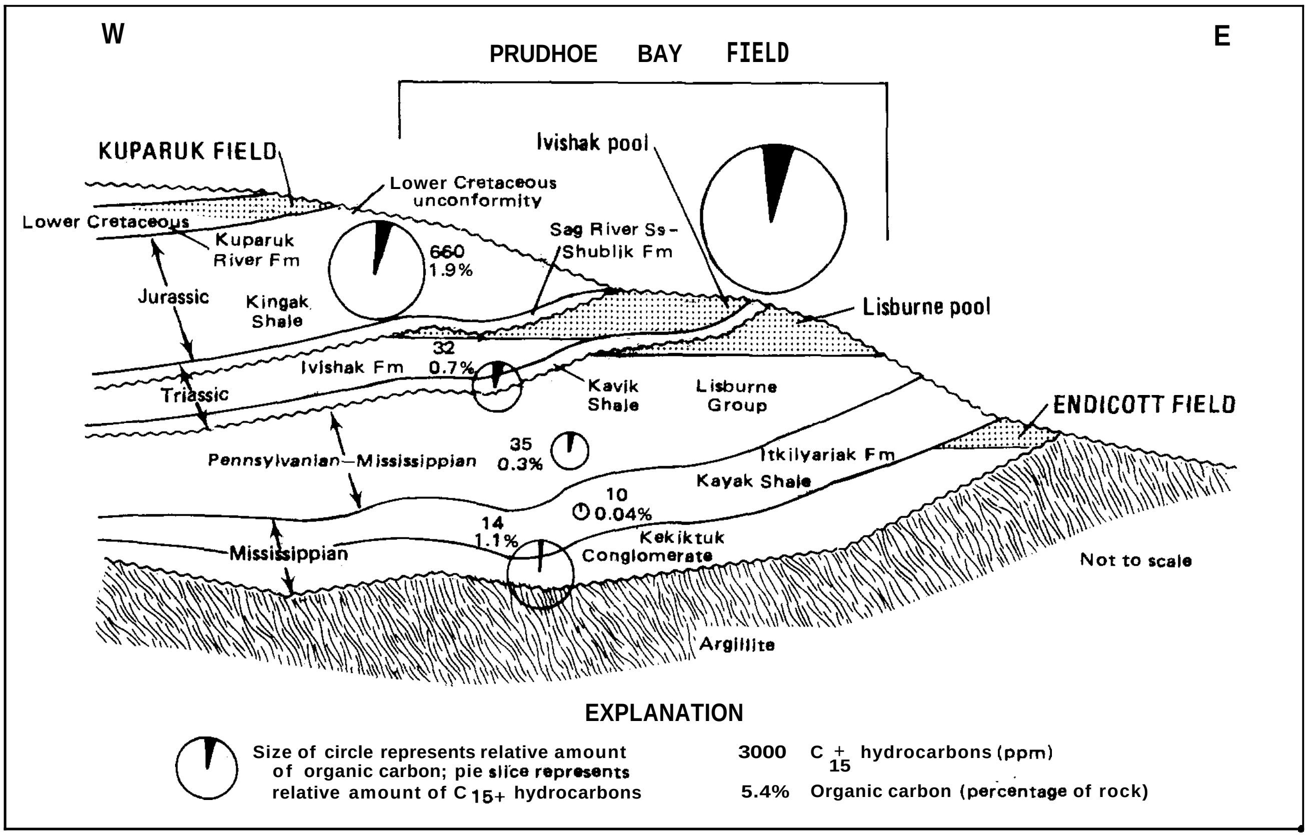

Figure 128. Generalized east-west cross section of reservoir horizon-source rock relations in Prudhoe Bay area. Shaded areas indicate oil reservoirs. Modified from Morgridge and Smith (1972).

of in-place hydrocarbons (Alwin and others, 1989) (fig. 129).

Between Late Eocene time and the present, burial continued as the Prudhoe Bay structure was tilted to the northeast. Tilting may have been the result of a north-easterly progradation of Tertiary sediment (Alwin and others, 1989). As closure of the original Prudhoe Bay structure slowly decreased, hydrocarbons spilled to the northwest into the West End of the field and beyond. This northwesterly migration may also be the source for hydrocarbons in the Kuparuk, West Sak, and Ugnu reservoirs (Carman and Hardwick, 1983).

Structural changes and spillage significantly reduced the hydrocarbon volume to that of the present Prudhoe Bay field. As much as 1,200 ft (370 m) of structural relief above the original oil-water contact was lost in the northeastern portion of the field; however, in the western portion some 355 ft (110 m) was gained (fig. 129).

RESERVOIR HORIZONS

IVISHAK FORMATION

The Ivishak Formation is the largest of several Triassic reservoirs in the Prudhoe Bay field (table 2). Since the beginning of field development, 95 wells have been drilled through various intervals of the reservoirs and over 37,000 ft (11,470 m) of core have been taken. From core analyses, the lithologic characteristics of the reservoirs have been well established.

Numerous workers have interpreted the Ivishak Formation and the underlying Kavik Shale as a prograding deltaic complex that grades from prodelta shale of the Kavik to a braided-stream complex of the Ivishak (Morgridge and Smith, 1972; Eckelmann and others, 1975; Jones and Speers, 1976; Lawton and others, 1987). The braided-stream complex was deposited by a number of southward-flowing and overlapping fluvial systems. Alternatively, Atkinson and others (1988) have suggested that the Ivishak was deposited on an outwash plain.

Lawton and others (1987) and Atkinson and others (1988) described two large-scale depositional cycles in the Ivishak. The lower progradational megacycle coarsens upward and is overlain by an upper megacycle that fines upward (fig. 130). The basal sandstones of the formation were deposited in a shallow-marine environment and interfinger with prodelta shales and siltstones of the Kavik Formation. Within the field area, the Ivishak thins from over 650 ft (200 m) in the south to about 350 ft (110 m) in the north; this is due largely to erosion along a pre-Shublik unconformity at the top of the Ivishak Formation.

For reservoir development in much of the field, the Ivishak has been divided into eight vertical zones, described below in descending order:

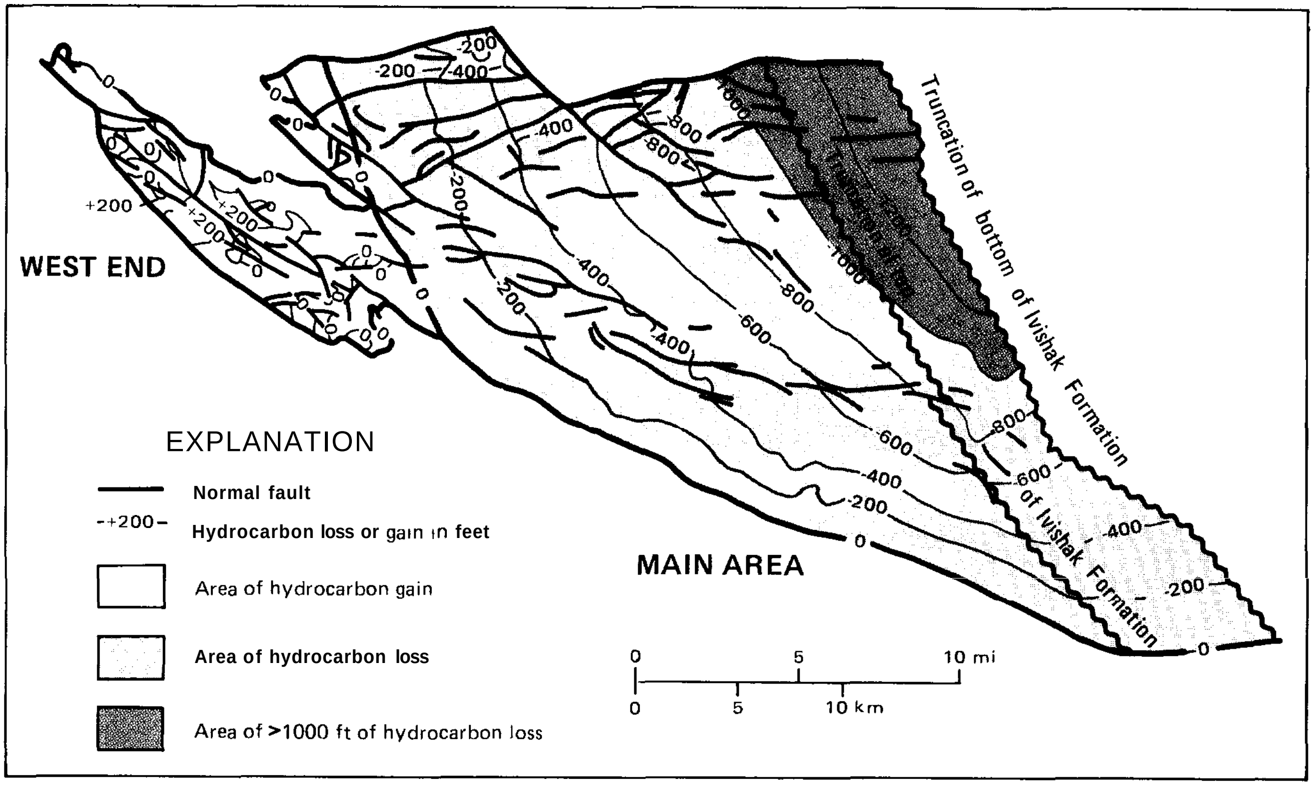

Figure 129. Subsurface map of Prudhoe Bay field showing areas of hydrocarbon loss and gain in Ivishak Formation. Migration resulted from regional tilling between Late Cretaceous time and present.

1. Zones 4A and 4B, at the top of the Ivishak, together average 170 ft (50 m) thick and consist of cross-bedded sandstone deposited from a southward-flowing braided fluvial complex (Lawton and others, 1987). Zone 4A contains a shale interval, ranging from 10 to 80 ft (3 to 25 m) thick, that acts as a barrier to fluid movement in the southeastern part of the field.
2. Zone 3 averages 64 ft (20 m) thick, is characterized by an abrupt increase in grain size from sandstone to pebbly sandstone and conglomerate, and is capped by clast-supported pebble to cobble conglomerate. Some of the lowest porosities--but highest permeabilities (>3,000 md)--in the field are found in this interval.
3. Zones 2A, 2B, and 2C together average 240 ft (75 m) thick and are high-energy fluvial sequences dominated by coarse-grained and pebbly sandstone beds. Zone 2B contains a 20-ft-thick (6 m) shale, deposited on a flood plain, that acts as a barrier to fluid movement. Alwin and others (1989) noted a transition from a dominantly marine to a dominantly fluvial environment in Zone 2B; the top of Zone 2B may be an intraformational unconformity.
4. Zones 1A and 1B overlie the Kavik Shale and together average 108 ft (33 m) thick. The zones are composed of siltstone and very fine grained sandstone and were deposited in distributary mouth bars and channels (Lawton and others, 1987).

MINOR RESERVOIR HORIZONS

Minor reservoir horizons in the Prudhoe Bay field are the Put River, Eileen, Sag River, and Shublik D sandstones (fig. 127; table 2). None of these units represent a major hydrocarbon play, and only the Sag River is currently being produced.

Put River sandstone

The Put River is a Lower Cretaceous sandstone that locally unconformably overlies the Triassic Sag River Sandstone. It is composed of poorly cemented interbedded conglomerate and conglomeratic sandstone and contains clasts that represent most of the Ellesmerian units exposed along the Lower Cretaceous unconformity. Maximum thickness of the unit is about 66 ft (20 m). Core porosity and permeability average 12.5 percent and 170 md, respectively. The formation probably was deposited in a submarine channel from a relatively near source. The unit trends northwest-southeast and is largely restricted to the gas-cap area, although some downdip wells to the southeast have encountered correlative glauconitic sands unconformably overlying the Kingak Shale in the oil column.

Eileen and Shublik D sandstones

The Eileen and Shublik D sandstones are closely related. Both units are transgressive-marine deposits

Table 2. Characteristics of Cretaceous and Triassic reservoirs in Prudhoe Bay oil field

Rock unit	Thickness (approx ft)	Lithology	Depositional environment	Age
Put River sandstone	0-65	Sandstone, conglomeratic sandstone	Submarine channel	Early Cretaceous
Sag River Sandstone	10-65	Sandstone, siltstone	Marine--shallow shelf	Early Triassic
Shublik Formation	30-150	Limestone, shale, phosphatic rock; minor sandstone, siltstone	Marine--offshore	Early Triassic
Eileen sandstone	0-50	Sandtone, siltstone, shale	Marine--shallow shelf	Early Triassic
Ivishak Formation	350-650	Sandstone, conglomerate; minor siltstone, shale	Nonmarine--moderate- to high-energy braided and meandering streams to Marine--low-energy delta to shallow shelf	Early Triassic

wedged between the fluvial sequence of the upper Ivishak Formation and the overlying marine carbonates of the Shublik Formation. The Eileen rests unconformably on the Ivishak and is composed of Ivishak sands reworked into beach and shallow-marine deposits. The sandstone is restricted to the West End of the field and extreme western part of the Main Area. It is a very poor reservoir rock, having an average porosity and permeability of only 6.7 percent and 0.3 md, respectively, largely reduced by silica and ankerite cementation. The phosphatic Shublik D sandstone was deposited as a series of thin, coalescing fans and small submarine channels at a minor unconformity at the top of the Eileen sandstone. With the exception of several isolated occurrences in the Main Area of the field, the Shublik D is confined to the West End.

Sag River Sandstone

The Sag River Sandstone is the only minor Prudhoe Bay reservoir of significance, with approximately 740 million barrels of oil in place and production of roughly 127 million barrels of oil as of April 1988 (Alwin and others, 1989). The unit consists of homogeneous, well-sorted, bioturbated, fine- to very fine grained glauconitic sandstone that was derived from a source to the north-northeast. It varies from nearly 60 ft (18 m) thick in the northern part of the field to <20 ft (6 m) thick in the southern part. Porosity averages about 22 percent and permeability is about 32 md. The sandstone was deposited during a marine regression in an offshore environment below wave base. Phosphate nodules, which are characteristic of slow deposition, are commonly present at the top and base of the sand. Reservoir quality is significantly reduced to the southwest in response to increased postdepositional compaction and increased authigenic ankerite, both of which reduce primary porosity and permeability.

PETROGRAPHY AND FIELD TRENDS

Important trends in reservoir characteristics are the result of original sedimentation and a number of postdepositional chemical and physical processes. In the field, total porosity, macroporosity, and permeability all increase toward the northeast, partly because of decreased compaction and partly because of leaching near the LCU. Microporosity and intergranular cements increase to the southwest as the effects of dissolution lessen. Finally, grain size, which influences all of the above factors, increases to the northeast, in the direction of the source of the Ivishak Formation.

Grain constituents of the Ivishak consist principally of quartz (55 to 85 percent), microporous chert (10 to 35 percent), dense chert (5 to 30 percent), and minor rock fragments (<1 percenl); the chert fraction becomes markedly more abundant as grain size increases. In the southwestern part of the field, 25 percent of the bulk rock volume is composed of authigenic cements. These include quartz, siderite, and pyrite-marcasite, along with kaolinite-dickite, calcite (in some areas), chlorite, barite, and iron oxides (Melvin and Knight, 1984). Distribution of the authigenic cements is not uniform throughout the field. Quartz cementation increases to the southwest, as does siderite; in contrast, pyrite-marcasite increases to the northeast. This somewhat mutually exclusive distribution has been attributed to a very late stage of siderite dissolution in the upstructure area of the field by carbonic acid produced during hydrocarbon generation (Payne, 1987).

Microporous chert has a large impact on reservoir-development strategies. Dissolution of biogenic debris (Payne, 1987) within the chert created intragranular porosities as high as 60 percent (Alwin and others, 1989). The presence of microporosity results in a complex dual-porosity system in the Ivishak Formation that significantly controls the distribution of fluids within the reservoir. Because the capillary displacement pressure for the micropore system is substantially greater than for the intergranular macropore system, Ivishak microporosity tends to remain 100 percent water-saturated far above the oil-water contact. This relationship leads to several interesting phenomena. In areas of the field such as the West End, where microporosity often dominates pore structure, and total height of the hydrocarbon column above the oil-water contact is low, over 20 percent of the early cores cut above the oil-water contact were interpreted to be 100 percent water-saturated. In these areas, because of the very small pore throats of the micropore system (<5 microns), pressures required for hydrocarbons to displace water initially trapped in the micropores is high. As a consequence, these rocks must be well above the oil-water contact before pressures are sufficient to displace connate water from the micropore system. Near the oil-water contact, these rocks are devoid of hydrocarbons and appear in hand specimen as bright white siltstone and fine- to very fine grained sandstone ('white rock'). This phenomena has also been observed in the residual oil zone, where foot-by-foot core analysis reveals intervals of zero oil saturation in predominantly microporous rock.

On the other hand, some West End wells have flowed oil, with no water cut, even though apparent water-saturations ranged to 70 percent. In this case, microporosity composes 60 percent of the total pore system and is essentially 100 percent water-saturated, whereas the macroporosity ranges between 20 and 30 percent water-saturated, typical irreducible levels. Because the micropore water is tightly bound, West End wells with pore geometries of this type have initial production characteristics similar to western Main Area wells.

The extent to which this phenomena will affect development of the West End is unknown, since development has only recently begun. Standard Alaska Production Company has recognized the potential impact on West End development strategies and is actively investigating the variability of pore geometry and capillarity. These issues will be resolved as more wells are drilled away from the central part of the Eileen structure into downflank areas, where height above the oil-water contact is reduced and overall reservoir rock quality is expected to decrease.

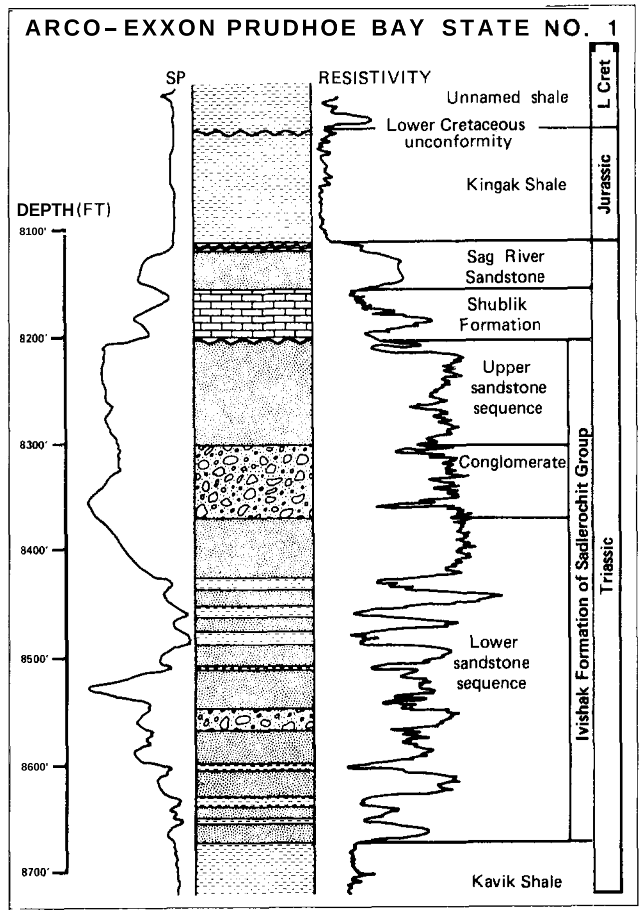

Figure 130. Log of *Ivishak* Formation reservoir from discovery well in Prudhoe Bay field. Modified from *Jamison* and others (1980).

FIELD OPERATIONS

The Prudhoe Bay field has been unitized and is being jointly developed by Atlantic Richfield Company (ARCO) and Standard Alaska Production Company (Standard), a division of BP America. Table 3 lists percentages of ownership.

The field is divided along a north-south line; Standard operates the western part, and ARCO operates the eastern part (fig. 131). Because of the low, swampy nature of the tundra in the Prudhoe Bay area, directional drilling is conducted from 6-ft-thick (2 m) gravel pads (fig. 132). About 925 wells have been drilled thus far, and the 5-yr drilling plan calls for an additional 1,346 wells to be drilled by January 1, 1993. Oil from the wells on each pad passes through pipelines built on gravel pads, or elevated on piles, into six gathering centers (Standard) or flow stations (ARCO) (fig. 133). In these facilities, solution gas and water are separated from the oil, which is cooled. The gas is then piped to a central compressor plant on the ARCO side, compressed, and then reinjected into the gas cap to maintain reservoir pressure. (To further maintain reservoir pressure, a major water-flood operation is underway.) The oil is piped to Alyeska Pipeline Service Company Pump Station 1 at the beginning of the Trans-Alaska Pipeline (fig. 134).

A small crude-oil topping plant, operated by ARCO (fig. 135), refines about 15,000 barrels of oil per day

Table 3. Owners of Prudhoe Bay oil field
[Percentages may be adjusted due to pending litigation]

Company	Oil rim (pct)	Gas cap (pct)
Standard Alaska Production Company	50.68	13.84
ARCO Alaska, Inc.	21.78	42.46
Exxon Company, U.S.A.	21.78	42.46
Mobil Oil Corporation	1.89	0.28
Phillips Petroleum Company	1.88	0.26
Chevron U.S.A. Inc.	0.67	0.48
Others	1.32	0.22

into naptha, diesel fuel, and jet fuel to support North Slope field operations. Standard operates a central power station that supplies electrical power for all field facilities.

Two major housing facilities and a number of smaller camps provide room and board for field personnel. The ARCO complex (fig. 136) was the first to be built (1968); it housed about 500 permanent staff. Later, temporary camps were built to house an additional 2,600 construction workers. BP-Alaska began construction of its base-operations camp in 1972 to house 250 in permanent facilities and 1,250 in temporary quarters (fig. 137). This facility is now operated by Standard. In addition to these major facilities, many construction and service companies operate smaller camps on state-managed land near the Sagavanirktok River (fig. 138). Deadhorse is the site of the state-operated airfield; docking facilities are located at the east and west docks on the shore of Prudhoe Bay.

The Trans-Alaska Pipeline System (TAPS), operated by Alyeska Pipeline Service Company, is owned by eight companies with approximately the following percentages of ownership:

Sohio Pipeline Company.	33.3
BP Pipelines, Inc..	15.7
ARCO Pipeline Company	21
Exxon Pipeline Company	20
Mobil Alaska Pipeline Company.	5
Union Alaska Pipeline Company, Phillips Petroleum Company, and Amerada Hess Corporation	5

The pipeline is 48 in. (118 cm) diam and 800 mi (1,280 km) long, of which 420 mi (670 km) are elevated and 375 mi (600 km) are buried. It has 10 pump stations, operates at a pressure of up to 1,180 psi, and is currently delivering 2 million barrels of oil per day to the tanker terminal at Valdez: 1.5 million barrels per day are produced from the Prudhoe Bay field and 500,000 barrels per day are provided by the Kuparuk and Endicott fields.

ORIGIN AND PRONUNCIATION OF THE NAME PRUDHOE BAY

Until the discovery of oil in 1968, Prudhoe Bay was an insignificant, 9-mi-wide (14 km) bay on the shore of the Arctic Ocean. Until it came into worldwide notice, the only known fact about the origin of its name was recorded by Donald J. Orth (1967), who noted that the bay had been named by Sir John Franklin on August 16, 1826. Franklin, an officer in the British Royal Navy, was one of the early explorers who searched for the Northwest Passage.

In the course of Franklin's career, he commanded major Arctic expeditions in 1818, 1819-22, 1825-27, and 1845-47. On the third expedition, in 1825, he traveled north down the Mackenzie River in Canada to the Arctic Ocean, and then west along the Arctic coast to rendezvous with Captain Frederick W. Beechey, who was to sail eastward along the north coast of Alaska.

By mid-August 1826, Beechey had reached and named Point Barrow but was forced to turn back because of heavy pack ice. Franklin was hindered by dense fog amid the shoals east of the mouth of the Sagavanirktok River and was forced to camp several days on a 'dreary' and 'detestable' island he named Foggy Island. On the morning of August 16, 1826, the fog cleared briefly and Franklin set off with his crew to the west. After he passed the unseen mouth of the Sagavanirktok, however, the fog returned and the wind increased. With drift ice closing in, Franklin (1828) wrote, "We could no longer proceed with safety and therefore endeavored to find a landing place. An attempt was made at Point Heald, and another on the western point of Prudhoe Bay, but both were frustrated by the shoalness of the water and the height of the surf." Failing in these attempts, he then headed seaward, intending to tie his boat to a large ice floe, when he found one of the several low offshore gravel islands that lie north of Prudhoe Bay. He named the island Return Reef, now part of the Return Islands. The following day, the fog cleared again and he could see westward; from Return Reef, he named Gwydyr Bay and Beechey Point. On the morning of August 18, Franklin concluded that the summer was too far advanced for the expedition to succeed, and he turned back to retrace his steps to civilization. Return Reef, northwest of the mouth of Prudhoe Bay, thus became the westernmost point of Franklin's exploration. Many place names used today were given by Beechey and Franklin.

With the passage of time, the significance of many names faded into obscurity, and so it was with Prudhoe Bay--until James W. Phillips, a writer and historian, researched the origin of Alaska and Yukon place names. Reading British archives, he found that Franklin almost certainly named Prudhoe Bay for a fellow naval officer and explorer-scientist, Captain Algernon Percy, Baron of Prudhoe (Phillips, 1974). Percy later became Fourth Duke of Northumberland, and his lesser title, Baron of Prudhoe, passed into oblivion. Twelfth century Prudhoe Castle, overlooking the River Tyne from high on a hill in Northumberland County, exemplifies the old Saxon meaning of Prudhoe: 'proud height.'

Since discovery of oil at Prudhoe Bay, debate has

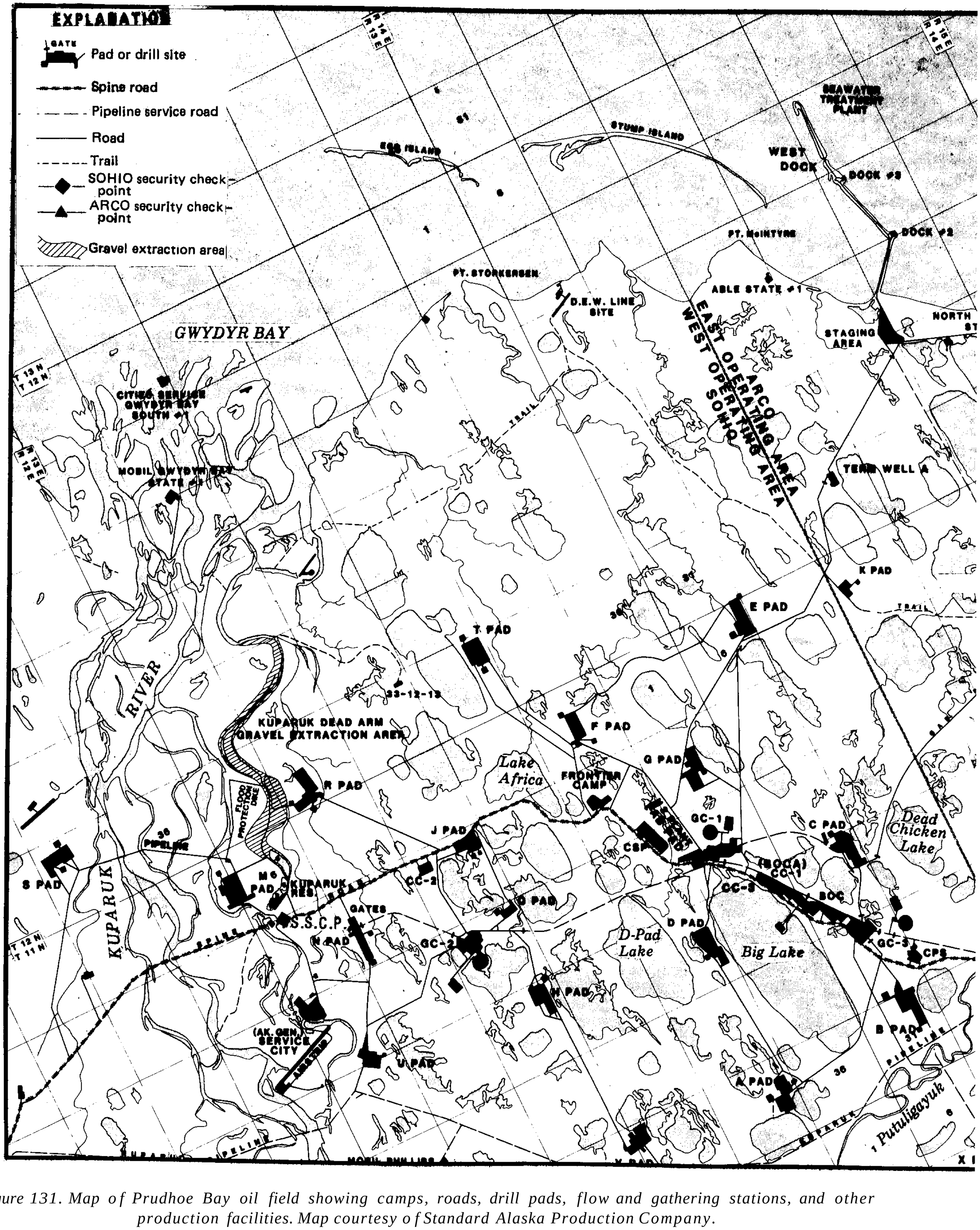

Figure 131. Map of Prudhoe Bay oil field showing camps, roads, drill pads, flow and gathering stations, and other production facilities. Map courtesy of Standard Alaska Production Company.

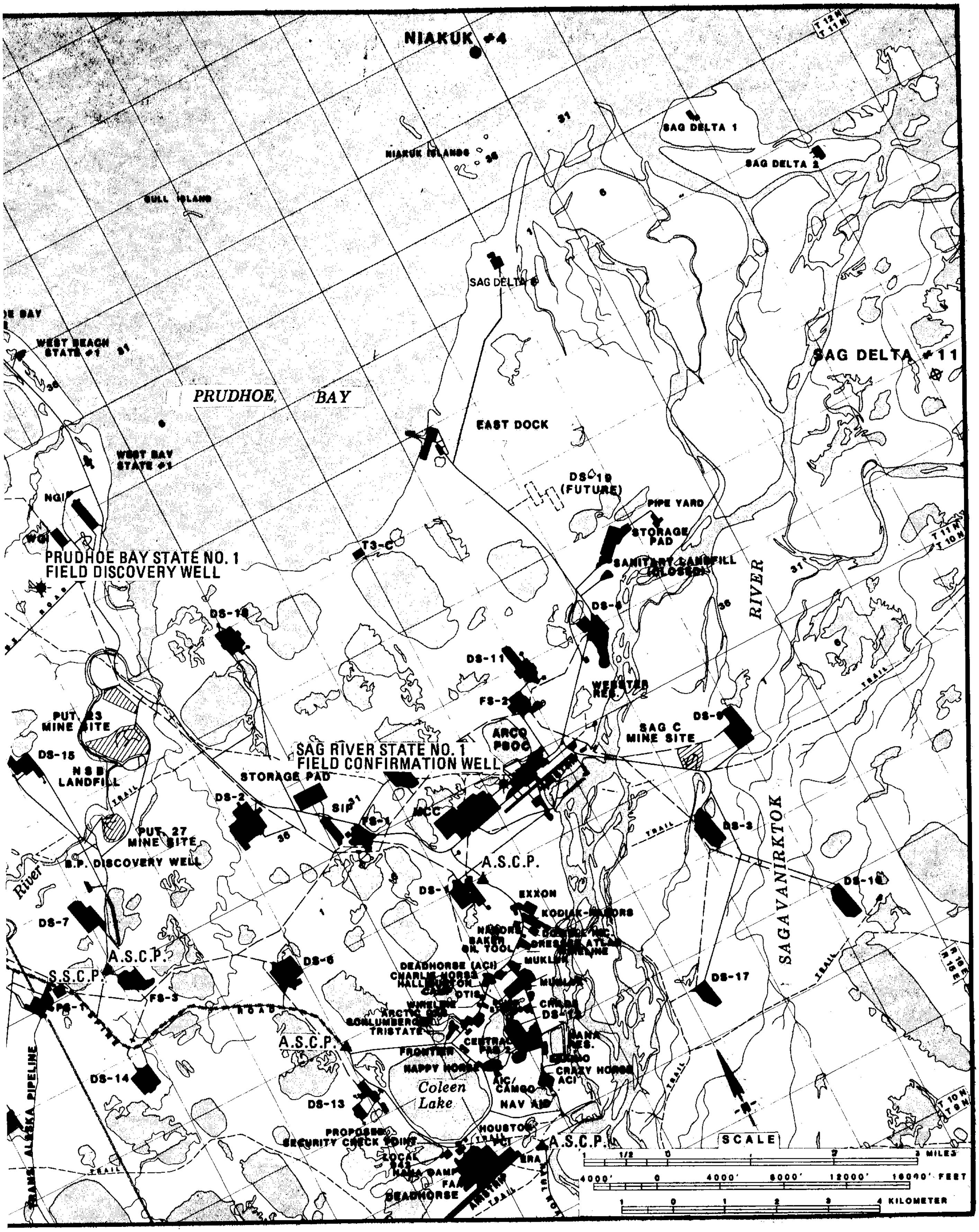
NIAKUK #4
SAG DELTA 1
SAG DELTA 2
NIAKUK ISLANDS
GULL ISLAND
SAG DELTA 8
WEST BEACH STATE #1
SAG DELTA #11
PRUDHOE BAY
EAST DOCK
WEST BAY STATE #1
DS-19 (FUTURE)
PIPE YARD
STORAGE PAD
T3-C
PRUDHOE BAY STATE NO. 1
FIELD DISCOVERY WELL
SANITARY LANDFILL (CLOSED)
DS-4
RIVER
DS-12
DS-11
WEBSTER RES.
FS-2
DS-9
SAG C MINE SITE
ARCO PBOC
PUT 23 MINE SITE
DS-15
SAG RIVER STATE NO. 1
FIELD CONFIRMATION WELL
NSB LANDFILL
STORAGE PAD
DS-2
SIP
FS-1
MCC
DS-3
PUT 27 MINE SITE
B.P. DISCOVERY WELL
A.S.C.P.
River
DS-16
SAGAVANIRKTOK
DS-1
EXXON
DS-7
KODIAK-NABORS
NABORS
BAKER OIL TOOL
DS-6
DEADHORSE (ACI)
MUKLUK
A.S.C.P.
S.S.C.P.
FS-3
DS-17
ROAD
OTIS
ARCTIC
TRISTATE
FRONTIER
A.S.C.P.
CENTRAL
HAPPY HORSE
DS-14
CRAZY HORSE
ACI
Coleen Lake
DS-13
NAV AID
TRANS ALASKA PIPELINE
PROPOSED SECURITY CHECK POINT
HOUSTON
A.S.C.P.
SCALE
DEADHORSE
TRAIL
3 MILES
FEET
4 KILOMETER

Figure 132. View eastward toward Standard X-pad drill site. Each square box on pad houses wellhead of directionally drilled well. Trans-Alaska Pipeline in center of photograph.

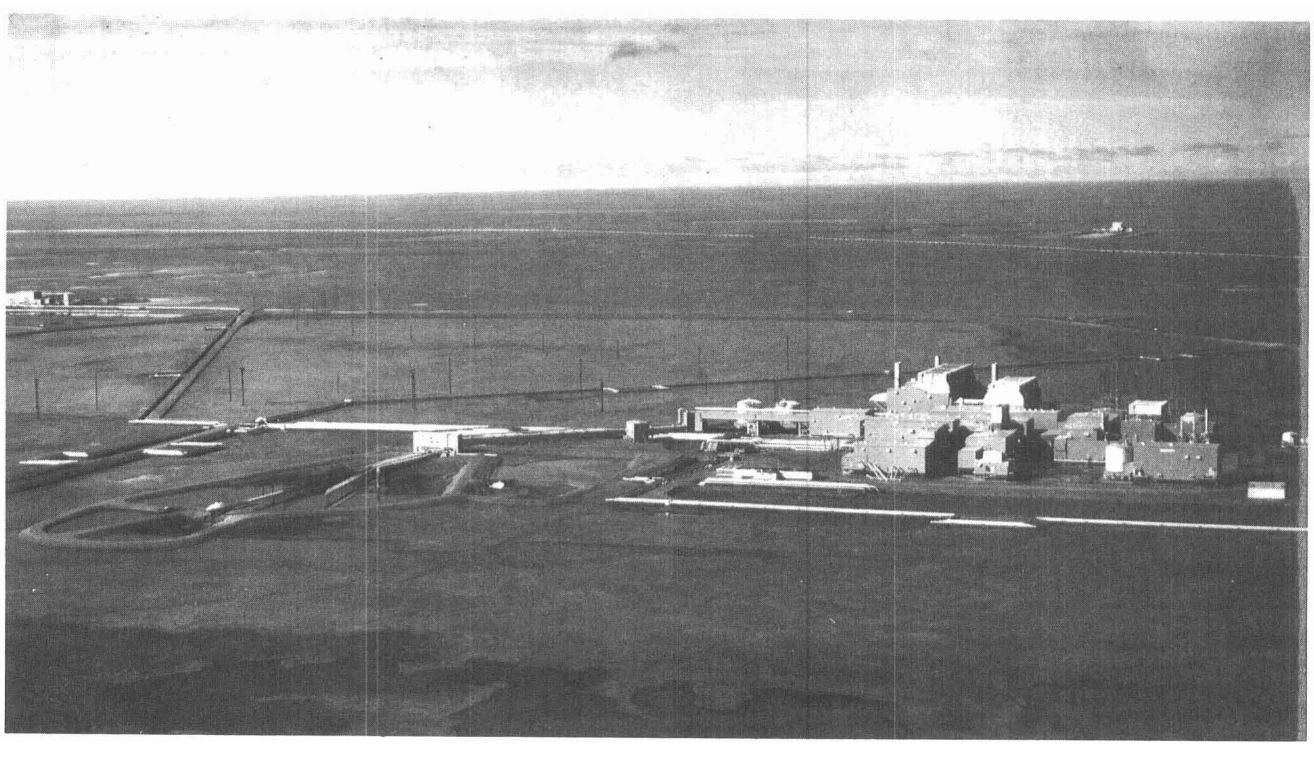

Figure 133. View southwestward toward ARCO Flow Station 3. Trans-Alaska Pipeline in distance; Standard X-pad drill site at upper right.

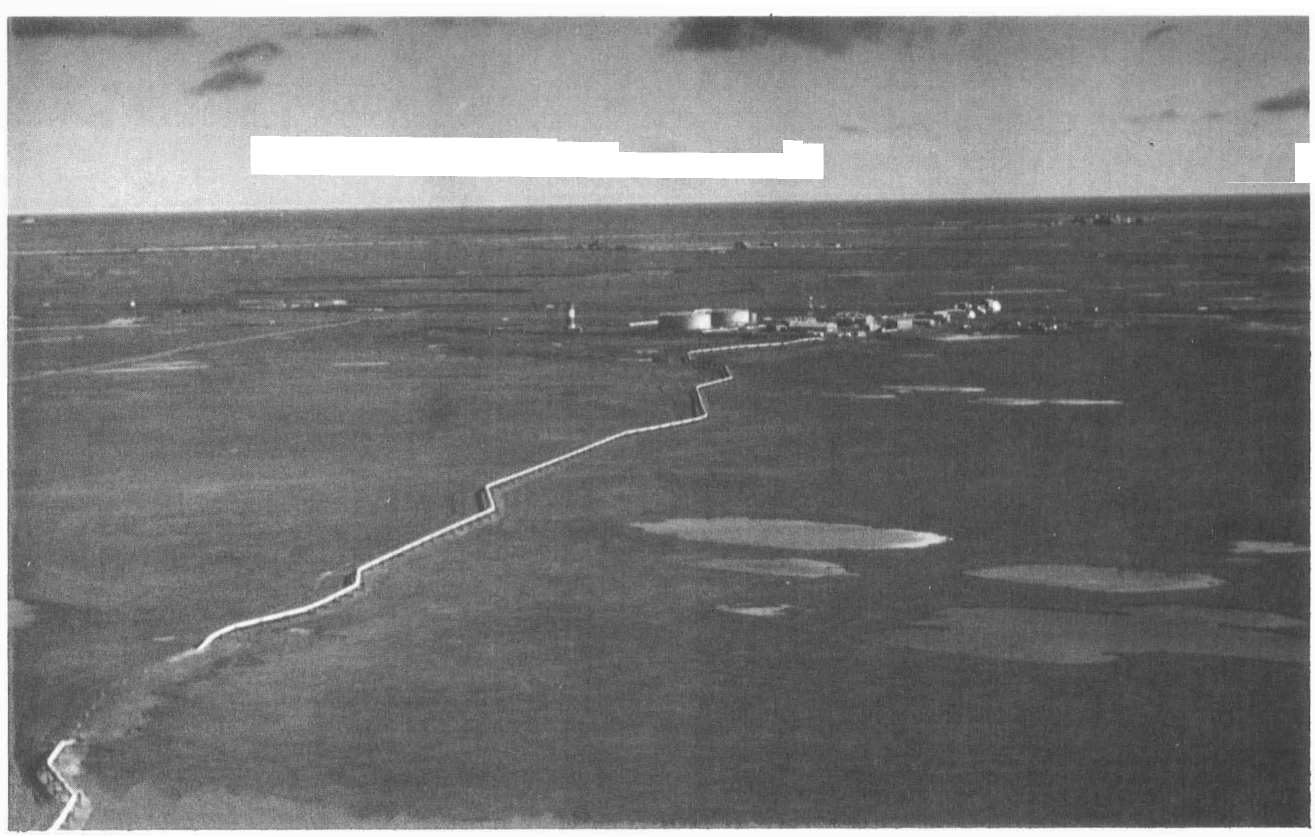

Figure 134. View northward along Trans-Alaska Pipeline to Pump Station 1. Pipeline is elevated because of ice-rich permafrost; burled segment (lower left) is for caribou crossing.

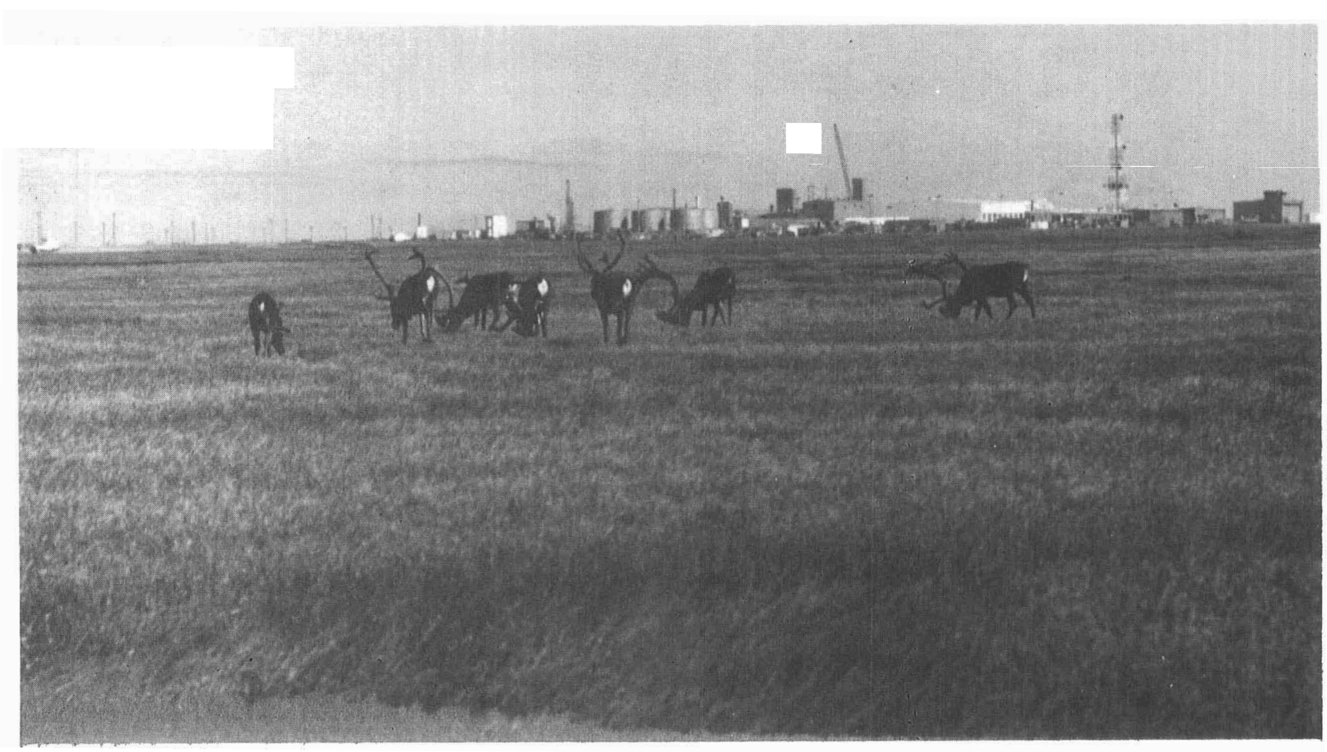

Figure 135. Caribou grazing in Prudhoe Bay oil field near crude-oil topping plant.

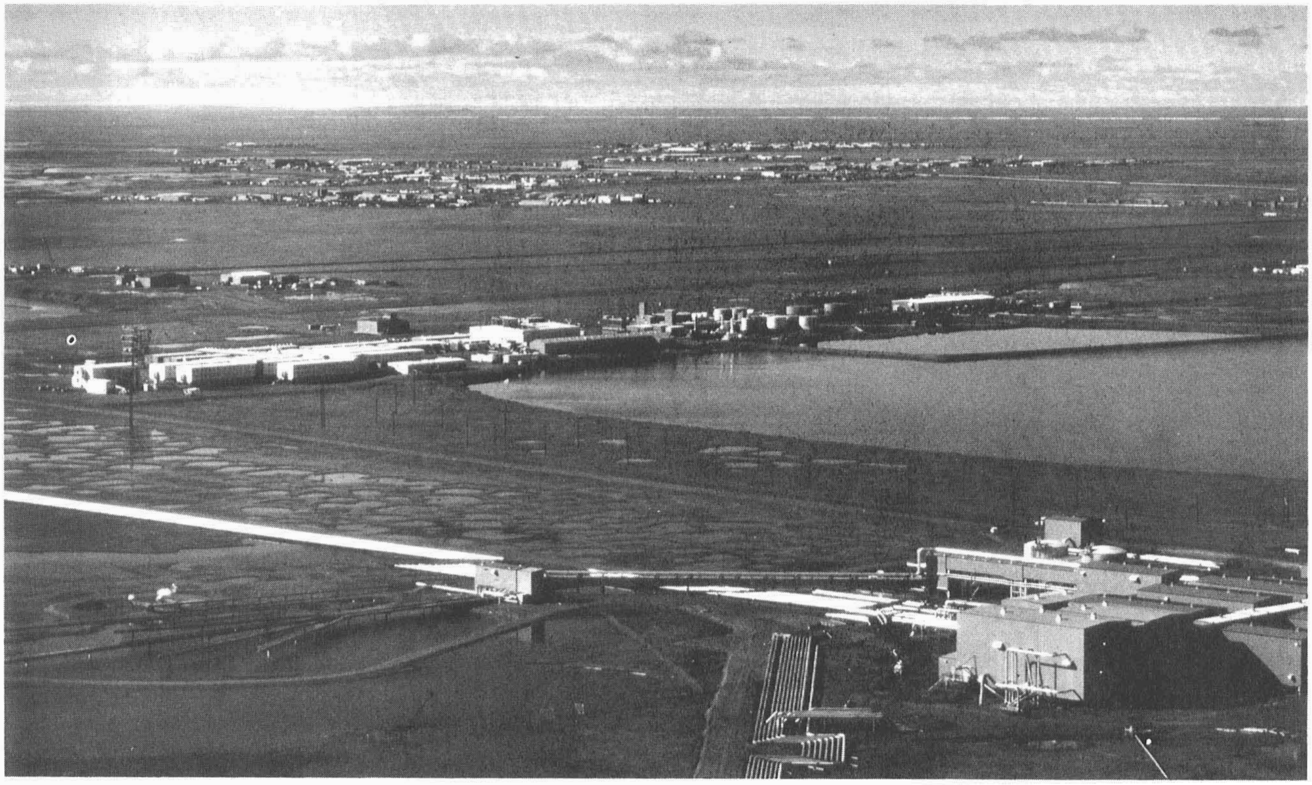

*Figure 136. View southwestward toward ARCO base camp (left center), topping plant (center), service-company camps and support facilities near Deadhorse Airport (center distance), Trans-Alaska Pipeline (far distance), and Flow Station **2** (lower right).*

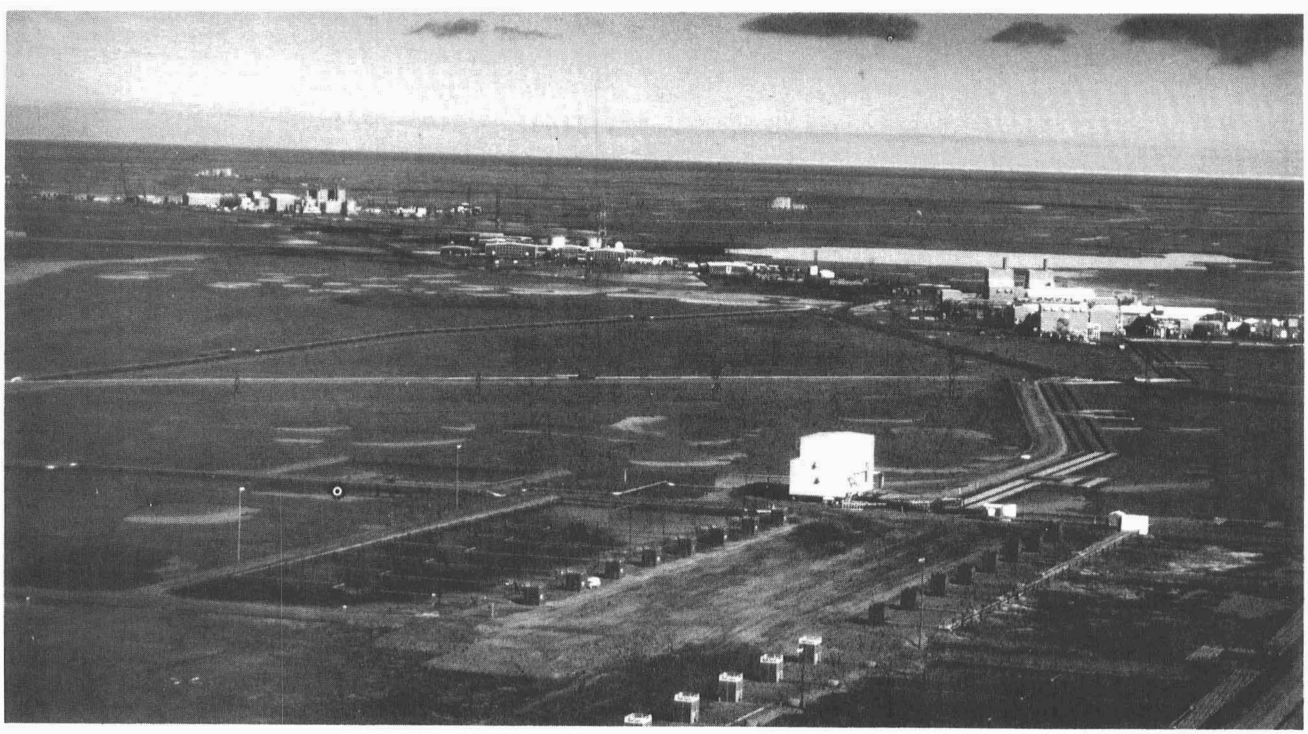

*Figure 137. View northwestward toward Standard B-pad drill site (bottom right). Gathering Center **3** (center right), Standard base camp (center), and Gathering Center 1 (upper left).*

Figure 138. View northward toward Deadhorse Airport and service-company camps and offices, Prudhoe Bay. Field-production facilities are in distance.

developed over proper pronunciation of the name. Early geologists and geophysicists (prior to oil discovery) used the purist pronunciation: Prudd-oh (first syllable accented). After oil discovery, the pronunciation Prewd-oh was adopted through popular usage. But by English grammar rules, this pronunciation is incorrect. In 1982, a visit to Prudhoe, England, furnished an interesting resolution to the question. In Northumberland outside of Prudhoe, proper English is indeed observed in the pronunciation of Prudhoe (Prudd-oh). But in Prudhoe itself, the local residents say Prewd-oh, and some use a third, perhaps colloquial, pronunciation: Prew-dah (rhymes with 'doo-dah'). Regardless of its pronunciation, Prudhoe Bay will remain in the annals of petroleum history as one of the most remarkable development projects of the 20th century.

ACKNOWLEDGMENTS

The foregoing summary of Prudhoe Bay is based on the work of numerous North Slope researchers, representing diverse organizations. We are particularly indebted to B.W. Alwin, M.C. Davidson, and W. Zeck, authors of 'Prudhoe Bay Field - USA Alaska, North Slope.' Their paper will be published in the 'Atlas of Oil and Gas Fields' in 1989. The document provides an excellent overview of the Prudhoe Bay field and served as a source for many of the details presented here.

SELECTED BIBLIOGRAPHY

Adams, D.D., and Dillon, J.T., 1989, Geochemical investigation of the Chandalar C-5 and C-6 Quadrangles, Alaska: Alaska Division of Geological and Geophysical Surveys Report of Investigations 88-15, 140 p., scale 1:63,360, 3 sheets.

Adams, K.E., 1989, Facies comparison of Permian and Triassic strata in the Doonerak fenster with coeval strata on the Endicott Mountains allochthon, northcentral Brooks Range, Alaska: Fairbanks, University of Alaska, unpublished M.S. thesis [in prep.].

Adams, K.E., and Mull, C.G., 1985, Facies comparison of autochthonous and allochthonous Permian and Triassic units, north-central Brooks Range, Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 69, no. 4, p. 655.

Ahlbrandt, T.S., ed., 1979, Preliminary geologic, petrologic, and paleontologic results of the study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, 163 p.

Ahlbrandt, T.S., and Huffman, A.C., 1978, Cretaceous Nanushuk Group, North Slope, Alaska, *in* Johnson, K.M., ed., The United States Geological Survey in Alaska: Accomplishments during 1977: U.S. Geological Survey Circular 772-B, p. B13-B15.

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 Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 14-31.

Alaska Northwest Publishing Company, 1988, The Milepost: Anchorage, p. 521-526.

Allen, H.T., 1887, Report on an expedition to the Copper, Tanana, and Koyukuk Rivers in 1885: Washington, U.S. Government Printing Office, 172 p.

Alwin, B.W., Davidson, M.C., and Zeck, W., 1989, Prudhoe Bay field, U.S.A. Alaska, North Slope, *in* Beaumont, E.A., and Foster, N.H., eds., Atlas of oil and gas fields: American Association of Petroleum Geologists Treatise of Petroleum Geology [in press].

Anderson, Warren, and Associates, 1980, Alaskan North Slope generalized subsurface biostratigraphic correlation chart: San Diego, 1 sheet.

Armstrong, A.K., 1970a, Mississippian dolomites from Lisburne Group, Killik River, Mount Bupto region, Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v.54, no.2, p. 251-264.

_______ 1970b, Carbonate facies and lithostrotionoid coral fauna, Mississippian Kogruk Formation, De Long Mountains, Brooks Range, northwestern Alaska: U.S. Geological Survey Professional Paper 664, 38 p.

_______ 1972, Biostratigraphy of Mississippian lithostrotionoid corals, Lisburne Group, arctic Alaska: U.S. Geological Survey Professional Paper 743-A, P. 28.

_______ 1973, Pennsylvanian carbonates, paleoecology and colonial corals, north flank, eastern Brooks Range, Alaska: U.S. Geological Survey Professional Paper 747, 19 p.

_______ 1976, Carboniferous environments of deposition and facies, Arctic Alaska, *in* Miller, T.P., ed., Symposium on recent and ancient sedimentary environments in Alaska, Anchorage, 1971, Proceedings: Anchorage, Alaska Geological Society, p. A1-A16.

Armstrong, A.K., and Mamet, B.L., 1970, Biostratigraphy and dolomite porosity trends of the Lisburne Group, *in* Adkison, W.L., and Brosgé, M.M., eds., Geological seminar on the North Slope of Alaska, San Francisco, 1970, Proceedings: Los Angeles, American Association of Petroleum Geologists, Pacific Section, p. N1-N16.

_______ 1974, Carboniferous biostratigraphy, Prudhoe Bay State I: American Association of Petroleum Geologists Bulletin, v. 58, no. 4, p. 646-660.

_______ 1975, Carboniferous biostratigraphy, northeastern Brooks Range, arctic Alaska: U.S. Geological Survey Professional Paper 884, 25 p.

_______ 1977, Carboniferous microfacies, microfossils, and corals, Lisburne Group, arctic Alaska: U.S. Geological Survey Professional Paper 849, 129 p.

_______ 1978, Microfacies of the Carboniferous Lisburne Group, Endicott Mountains, arctic Alaska, *in* Stelck, C.R., and Chatterton, B.D.E., eds., Western and arctic Canadian 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, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 60, no. 6, p. 962-972.

Armstrong, A.K., Mamet, B.L., and Dutro, J.T., Jr., 1970, Foraminifera1 zonation and carbonate facies of the Mississippian and Pennsylvanian Lisburne Group, central and eastern Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 54, p. 687-698.

_______ 1971, Mississippian Lisburne Group, Cape Lewis-Niak Creek, northwestern Alaska: U.S. Geological Survey Professional Paper 750-B, p. B23-B24.

Arth, J.G., Carlson, J.L., Foley, N.K., Friedman, I., Patton, W.W., Jr., and Miller, T.P., 1984, Crustal composition beneath the Yukon-Koyukuk basin and Ruby geanticline as reflected in the isotopic composition of Cretaceous plutons [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Programs, v. 16, no. 5, p. 267.

Ashworth, K.K., 1983, Genesis of gold deposits at the Little Squaw Mines, Chandalar mining district, Brooks Range, Alaska: Bellingham, Western Washington University, unpublished M.S. thesis, 98 p.

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., compilers, Giant oil and gas fields: A core workshop: Society of Economic Paleontologists and Mineralogists Core Workshop 2, p. 561-613.

Avé Lallemant, H.G., Oldow, J.S., Russell, B., and Dillon, J.T., 1983, Structural evolution of the central Brooks Range near the Doonerak window, Alaska [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Programs, v. 15, no. 5, p. 274.

Balkwill, H.R., Cook, D.G., Detterman, R.L., Embry, A.F., Hakannson, E., Miall, A.D., Poulton, T.P., and Young, F.G., 1983, Arctic North America and northern Greenland, *in* Moullade, M., and Nairn, A.E.M., eds., The Phanerozoic geology of the world II: The Mesozoic: Amsterdam, Elsevier, 387 p.

Bally, A.W., Gordy, P.L., and Stewart, G.A., 1966, Structure, seismic data, and orogenic evolution of southern Canadian Rocky Mountains: Bulletin of Canadian Petroleum Geology, v. 14, no. 3, p. 337-381.

Bamber, E.W., and Waterhouse, J.B., 1971, Carboniferous and Permian stratigraphy and paleontology, northern Yukon Territory, Canada: Alberta Society of Petroleum Geologists Bulletin, v. 19, no. 1, p. 29-250.

Barnes, D.A., 1987, Reservoir quality of the Sag River Formation, Prudhoe Bay field, Alaska: Depositional environment and diagenesis, in Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, p. 84-74.

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.

_______ 1985, Petrography of sandstones of the Nanushuk Group from four measured sections, in Huffman, A.C., ed., Geology of the Nanushuk Group and related rocks, central North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 75-95.

Bartsch-Winkler, Susan, and Huffman, A.C., 1981a, Compositional variation in Nanushuk Group sandstones, Arctic North Slope, 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. B6-B8.

_______ 1981b, Petrography of the Nanushuk Group and Torok Formation: U.S. Geological Survey Open-file Report OF-81-1222, 62 p.

Bates, R.L., and Jackson, J.A., eds., 1987, Glossary of geology: Alexandria, Virginia, American Geological Institute, 788 p.

Beck, M.E., Cox, A.V., and Jones, D.L., 1980, Penrose conference report: Mesozoic and Cenozoic microplate tectonics of western North America: Geology, v. 8, no. 9, p. 454-456.

Beikman, H.M., 1978, Geologic map of Alaska: U.S. Geological Survey, scale 1:2,500,000, 2 sheets.

Beikman, H.M., and Lathram, E.H., 1976, Preliminary geologic map of northern Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-789, scale 1:2,000,000, 2 sheets.

Benson, C.S., 1982, Reassessment of winter precipitation on Alaska's Arctic Slope and measurements on the flux of windblown snow: University of Alaska Geophysical Institute Report UAG-R-288, 26 p.

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

Berthé, D., Choukraune, P., and Jegouzo, P., 1979, Orthogneiss, mylonite, and noncoaxial deformation of granites: The example of the South American shear zone: Journal of Structural Geology, v. 1, p. 31-42.

Bilello, M.A., 1974, Air masses, fronts, and winter precipitation in central Alaska: U.S. Army Cold Regions Research and Engineering Laboratory Special Report 319, 58 p.

Bird, K.J., 1977, Late Paleozoic carbonates from the 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. B19-B20.

_______ 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., Alaska North Slope oil-rock correlation study: American Association of Petroleum Geologists Studies in Geology #20, p. 3-29.

Bird, K.J., and Andrews, Jack, 1979, Subsurface studies of the Nanushuk Group, 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. 32-41.

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 Geologist Bulletin, v. 61, no. 9, p. 1493-1512.

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

Blake, M.C., Jr., Irwin, W.P., and Coleman, K.G., 1967, Upside-down metamorphic zonation, blueschist facies, along a regional thrust fault in California and Oregon: U.S. Geological Survey Professional Paper 575-C, p. C1-C9.

Blum, J.D., Blum, A.E., Davis, T.E., and Dillon, J.T., 1987, Petrology of cogenetic silica-saturated and -oversaturated plutonic rocks in the Ruby geanticline of north-central Alaska: Canadian Journal of Earth Sciences, v. 24, no. 1, p. 159-169.

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

Bouma, A.H., 1962, Sedimentology of some flysch deposits: Amsterdam, Elsevier, 168 p.

Bowsher, A.L., and Dutro, J.T., Jr., 1957, The Paleozoic section in the Shainin Lake area, central Brooks Range, Alaska: U.S. Geological Survey Professional Paper 303-A, 39 p.

Box, S.E., 1984, Implications of a possibly continuous 4,000-km-long late Early Cretaceous arc-continent collisional belt in northeast U.S.S.R. and northwest Alaska for the tectonic development of Alaska, *in* Howell, D.G., Jones, D.L., Cox, Allan, and Nur, Amos, eds., Circum-Pacific Terrane Conference, Palo Alto, 1983, Proceedings: Palo Alto, Stanford University Publications in the Geological Sciences, v. 18, p. 33-35.

_______ 1985, Early Cretaceous orogenic belt in northwestern 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 Earth Science Series 1, p. 137-145.

Box, S.E., Carlson, Christine, and Patton, W.W., Jr., 1984, Cretaceous evolution of the northeastern Yukon-Koyukuk basin, west-central Alaska [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Progams, v. 16, no. 5, p. 272.

Box, S.E., Patton, W.W., Jr., and Carlson, Christine, 1985, Early Cretaceous evolution of the northeastern Yukon-Koyukuk basin, west-central Alaska, *in* Bartsch-Winkler, Susan, ed., U.S. Geological Survey in Alaska: Accomplishments during 1984: U.S. Geological Survey Circular 967, p. 21-24.

Boyle, R.W., 1955, The geochemistry and origin of gold-bearing quartz veins and lenses of the Yellowknife Greenstone belt: Economic Geology, v. 50, p. 51-66.

_______ 1959, The geochemistry, origin, and role of carbon dioxide, water, sulfur, and boron in the Yellowknife gold deposits, Northwest Territories, Canada: Economic Geology, v. 54, p. 1506-1524.

Brosgé, W.P. and Dutro, J.T., Jr., 1973, Paleozoic rocks of northern and central Alaska, in Pitcher, M.G., ed., Arctic Geology: Proceedings of the Second International Symposium on Arctic Geology: American Association of Petroleum Geologist 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 of Petroleum Geologists Bulletin, v. 46, no. 12, p. 2174-2198.

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

Brosgé, W.P., and Pessel, G.H., 1977, Preliminary reconnaissance geologic map of Survey Pass Quadrangle: U.S. Geological Survey Open-file Report 07-77-27, scale 1:250,000, 1 sheet.

Brosge, W.P., and Reiser, H.N., 1960, Progress map of the geology of the Wiseman Quadrangle, Alaska: U.S. Geological Survey Open-file Map OF-200, scale 1:250,000, 2 sheets.

_______ 1962, Preliminary geologic map of the Christian Quadrangle, Alaska: U.S. Geological Survey Open-file Map OF-62-15, scale 1:250,000, 2 sheets.

_______ 1964, Geologic map and section of the Chandalar Quadrangle, Alaska: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-375, scale 1:250,000, 1 sheet.

_______ 1965, Preliminary geologic map of the Arctic Quadrangle, Alaska: U.S. Geological Survey Open-file Map OF-65-22, scale 1:250,000, 1 sheet.

_______ 1969, Preliminary geologic map of Coleen Quadrangle, Alaska: U.S. Geological Survey Open-file Map OF-69-25, scale 1:250,000, 2 sheets.

_______ 1970, Chemical analyses of stream-sediment samples from the Chandalar and eastern Wiseman Quadrangles, Alaska: U.S. Geological Survey Open-file Report OF-70-402, 9 p.

_______ 1971, Preliminary bedrock geologic map, Wiseman and eastern Survey Pass Quadrangles, Alaska: U.S. Geological Survey Open-file Map OF-71-56, scale 1:250,000, 2 sheets.

_______ 1972, Geochemical reconnaissance in the Wiseman and Chandalar districts and adjacent region, southern Brooks Range, Alaska: U.S. Geological Survey Professional Paper 709, 21 p.

Brosgé, W.P., Reiser, H.N., Dutro, J.T., Jr., and Detterman, R.L., 1976, Reconnaissance geologic map of the Table Mountain Quadrangle, Alaska: U.S. Geological Survey Open-file Map OF-76-546, scale 1:200,000, 2 sheets.

_______ 1979a, Bedrock geologic map of the Philip Smith Mountains Quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-879B, scale 1:250,000, 2 sheets.

Brosgé, W.P., Reiser, H.N., Dutro, J.T., Jr., and Nilsen, T.H., 1979b, Geologic map of Devonian rocks in parts of the Chandler Lake and Killik River Quadrangles, Alaska: U.S. Geological Survey Open-file Map OF-79-1224, scale 1:200,000, 2 sheets.

Brosgé, W.P., Reiser, H.N., Patton, W.W., Jr., and Mangus, M.D., 1960, Geologic map of the Killik-Anaktuvuk Rivers region, Brooks Range, Alaska: U.S. Geological Survey Open-file Report OF-60-21, scale 1:96,000, 2 sheets.

Brosgé, W.P., Reiser, H.N., and Yeend, Warren, 1973, Reconnaissance geologic map of the Beaver Quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-525, scale 1:250,000, 1 sheet.

Brosgé, W.P., and Tailleur, I.L., 1969, Isopach maps of upper Paleozoic and Mesozoic rocks, northern Alaska: U.S. Geological Survey Open-file report, 10 p.

_______ 1970, Depositional history of northern Alaska, *in* Adkison, W.L., and Brosgé, M.M., eds., Geological seminar on the North Slope of Alaska, San Francisco, 1970, Proceedings: Los Angeles, American Association of Petroleum Geologists, Pacific Section, p. D1-D18.

Brosgé, W.P., and Whittington, C.L., 1966, Geology of the Umiat-Maybe Creek region, Alaska: U.S. Geological Survey Professional Paper 303-H, p. 501-638.

Brown, Jerry, and Berg, R.L., 1980, Environmental engineering and ecological baseline investigations along the Yukon River-Prudhoe Bay haul road: U.S. Army Cold Regions Research and Engineering Laboratory Report 80-19, 203 p.

Brown, Jerry, and Kreig, R.A., eds., 1983, Guidebook to permafrost and related features along the Elliott and Dalton Highways, Fox to Prudhoe Bay, Alaska: International Conference on Permafrost, 4th, Fairbanks, 1983, Publications: Alaska Division of Geological and Geophysical Surveys Guidebook 4, 230 p.

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

Cady, J.W., 1978, Aeromagnetic map and interpretation, Chandalar Quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-878-C, scale 1:250,000, 1 sheet.

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

Carey, S.W., 1958, A tectonic approach to continental drift, *in* Continental drift--a symposium: Hobart, Tasmania, University of Tasmania Geology Department, p. 177-355.

Carman, G.J., and Hardwick, Peter, 1983, Geology and regional setting of Kuparuk oil field, Alaska: American Association of Petroleum Geologists Bulletin, v. 67, no. 6, p. 1014-1031.

Carter, R.D., Mull, C.G., Bird, K.J., and Powers, R.B., 1977, The petroleum geology and hydrocarbon potential of Naval Petroleum Reserve No. 4, North Slope, Alaska: U.S. Geological Survey Open-file Report OF-77-475, 61 p.

Cathrall, J.B., Dillon, J.T., and Chazin, B., 1984, Map of anomalous trace metals in rock; and stream sediment pebbles of the Wiseman 10 x 30′ Quadrangle, Brooks Range, Alaska: U.S. Geological Survey Open-file Report OF-84-16143, scale 1:250,000, 1 sheet.

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. 47-174.

Chapman, R.M., Weber, F.R., and Taber, Bond, 1971, Preliminary geologic map of the Livengood Quadrangle, Alaska: U.S. Geological Survey Open-file Report OF-71-66, scale 1:250,000, 2 sheets.

Chapman, R.M., Yeend, Warren, Brosgé, W.P., and Reiser, H.N., 1982, Reconnaissance geologic map of the Tanana Quadrangle, Alaska: U.S. Geological Survey Open-file Report OF-82-734, 18 p., scale 1:250,000, 1 sheet.

Chappell, B.W., and White, A.R.J., 1974, Two contrasting granitic types: Pacific Geology, no. 8, p. 173-174.

Childers, J.M., Sloan, C.E., Meckel, J.P., and Nauman, J.W., 1977, Hydrologic reconnaissance of the eastern North Slope, Alaska, 1975: U.S. Geological Survey Open-file Report OF-77-492, 65 p.

Churkin, Michael, Jr., and Carter, Claire, 1979, Collision-deformed Paleozoic continental margin in Alaska--a foundation for microplate accretion [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Programs, v. 11, no. 3, p. 72.

Churkin, Michael, Jr., Nokleberg, W.J., and Huie, Carl, 1979, Collision-deformed Paleozoic continental margin, western Brooks Range, Alaska: Geology, v. 7, no. 8, 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.

Claypool, G.E., and Magoon, L.B., 1985, Comparison of oil-source rock correlation data for the Alaskan North Slope: Techniques, results, and conclusions, *in* Magoon, L.B., and Claypool, G.E., eds., Alaska North Slope oil-rock correlation study: American Association of Petroleum Geologists Studies in Geology #20, p. 49-81.

Cobb, E.H., 1981, Summaries of data on lists of references to metallic and selected nonmetallic mineral occurrences in the Wiseman Quadrangle, Alaska: Supplement to Open-file Report 76-340: U.S. Geological Survey Open-file Reports OF-81-732-A,-B, 21 p. each.

Collins, F.R., 1958a, Test wells, Umiat area, Alaska, *with* Micropaleontologic study of the Umiat field, northern Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-B, p. 71-206.

_______ 1958b, Test wells, Topagoruk area, Alaska, *with* Micropaleontologic study of the Topagoruk test wells, northern Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-D, p. 265-316.

_______ 1958c, Test wells, Meade and Kaolak areas, Alaska, *with* Micropaleontologic study of Meade test well 1 and Kaolak test well 1, northern Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-F, p. 341-376.

_______ 1959, Test wells, Square Lake and Wolf Creek areas, Alaska, *with* Micropaleontologic study of Square Lake test well 1 and the Wolf Creek test wells, northern Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-H, p. 423-484.

Coney, P.J., 1984, Structural and tectonic aspects of accretion in Alaska, *in* Howell, D.G., Jones, D.L., Cox, Allan, and Nur, Amos, eds., Circum-Pacific Terrane Conference, Palo Alto, 1983, Proceedings: Palo Alto, Stanford University Publications in the Geological Sciences, v. 18, p. 68-70.

Coney, P.J., Jones, D.L., and Monger, J.W.H., 1980, Cordilleran suspect terranes: Nature, v. 288, p. 329-333.

Crane, R.C., 1980, Comment *on* Collision-deformed Paleozoic continental margin, western Brooks Range, Alaska by Michael Churkin, Jr., W.J. Nokleberg, and Carl Huie, 1979 (*in* Geology, v. 7, no. 8, p. 379-383): Geology, v. 8, no. 8, p. 354.

_______ 1987, Cretaceous olistostrome model, Brooks Range, Alaska, *in* Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, p. 433-440.

Crawford, M.L., 1981, Fluid inclusions in low to medium grade metamorphic rocks, *in* Hollister, L.S., and Crawford, M.L., eds., Short course in fluid inclusions: Application to petrology: Mineralogical Association of Canada, p. 44-62.

Crimes, T.P., 1975, The stratigraphical significance of trace fossils, *in* Frey, R.W., ed., The study of trace fossils: New York, Springer-Verlag, p. 109-130.

Crowder, R.K., 1987, Cretaceous basin to shelf transition in northern Alaska: Deposition of the Fortress Mountain Formation, *in* Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, p. 449-458.

Crowell, J.C., 1974, Origin of late Cenozoic basins in southern California, *in* Dickinson, W.R., ed., Tectonics and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication No. 22, p. 190-204.

Daly, R.A., Manger, G.E., and Clark, S.P., Jr., 1966, Density of rocks, *in* Clark, S.P., ed., Handbook of physical constants: Geological Society of America Memoir 97, p. 19-26.

Decker, J.E., 1985, Sandstone modal analysis procedure: Alaska Division of Geological and Geophysical Surveys Public Data-file Report 85-3, 34 p.

Decker, J.E., Camber, W.R., Vandergon, M.A., and Crowder, R.K., 1988, Arctic Creek facies, Arctic National Wildlife Refuge, northeastern Alaska [abs.]: America Association of Petroleum Geologists Bulletin, v. 72, no. 2, p. 176.

Decker, J.E., and Dillon, J.T., 1982, Aeromagnetic map of the Wiseman Quadrangle: Alaska Division of Geological and Geophysical Surveys Open-file Report 176, scale 1:250,000, 1 sheet.

_______ 1984, Interpretation of regional aeromagnetic signatures along the southern margin of the Brooks Range, Alaska [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Programs, v. 16, no. 5, p. 278.

Densmore, David, 1980, Vegetation and forest dynamics of the upper Dietrich River valley, Alaska: Raleigh, North Carolina State University, unpublished M.S. thesis, 183 p.

Detterman, R.L., 1953, Sagavanirktok-Anaktuvuk region, northern Alaska, *in* Péwé, T.L., and others, eds., Multiple glaciation in Alaska, a progress report: U.S. Geological Survey Circular 289, p. 11-12.

_______ 1970, Sedimentary history of Sadlerochit and Shuhlik Formations in northeastern Alaska, *in* Adkinson, W.L., and Brosgé, M.M., eds., Geological seminar on the North Slope of Alaska, San Francisco, 1970, Proceedings: Los Angeles, American Association of Petroleum Geologists, Pacific Section, p. 01-013.

_______ 1973, Mesozoic sequence in Arctic Alaska, in Arctic Geology: American Association of Petroleum Geologists Memoir 19, p. 376-387.

_______ 1974, Fence diagram showing lithologic facies of the Sadlerochit Formation (Permian and Lower Triassic), northeastern Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-584, scale 1:500,000, 1 sheet.

_______ 1976a, Lithofacies fence diagram of Sadlerochit Group for Philip Smith Mountains Quadrangle and adjacent areas, northeastern Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-744, scale 1:375,000, 1 sheet.

_______ 1976b, Biostratigraphy of the Permian and Lower Triassic rocks in the Philip Smith Mountains Quadrangle, *in* Cobb, E.H., ed., The United States Geological Survey in Alaska: Accomplishments during 1975: U.S. Geological Survey Circular 733, p. 32-33.

_______ 1984a, Measured sections of upper Paleozoic to early Tertiary rocks, Demarcation Point Quadrangle, Alaska: U.S. Geological Survey Open-file Report OF-84-370, 1 sheet.

_______ 1984b, Measured sections of late Paleozoic and Mesozoic rocks, Mount Michelson Quadrangle, Alaska: U.S. Geological Survey Open-file Report OF-84-331, 2 sheets.

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., Bowsher, A.L., and Dutro, J.T., Jr., 1958, Glaciation of the Arctic Slope of the Brooks Range, northern Alaska: Arctic, v. 11, no. 1, p. 43-61.

Detterman, R.L., and Dutro, J.T., Jr., 1977, Depositional environment and fauna for a section of the Sadlerochit Group, northeastern Alaska, in Blean, K.M., ed., The United States Geological Survey in Alaska: Accomplishments during 1976: U.S. Geological Survey Circular 751-B, p. B10-B12.

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.

DeYoung, J.H., Jr., 1978, Mineral resources map of the Chandalar Quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-878-18, scale 1:250,000.

Dickinson, W.R., and Suczek, C.A., 1979, Plate tectonics and sandstone composition: American Association of Petroleum Geologists Bulletin, v. 63, no. 12, p. 2164-2182.

Dillon, J.T., 1982, Source of lode- and placer-gold deposits of the Chandalar and upper Koyukuk districts: Alaska Division of Geological and Geophysical Surveys Open-file Report 158, 22 p., scale 1:250,000, 1 sheet.

_______ 1985, Lower Paleozoic and Proterozoic rocks of southern Brooks Range, Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 69, no. 4, p. 661.

Dillon, J.T., Brosgé, W.R., 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, 1 sheet.

Dillon, J.T., Dutro, J.T., Jr., and Brosgé, w.P., 1983, Interim geologic map of the Wiseman Quadrangle, central Brooks Range, Alaska: Alaska Geological Society Symposium Programs with Abstracts.

Dillon, J.T., Hamilton, W.B., and Lueck, L.L., 1981a, Geologic map of the Wiseman A-3 Quadrangle: Alaska Division of Geological and Geophysical Surveys Open-file Report 119, scale 1:63,360, 1 sheet.

Dillon, J.T., Moorman, M.A., and Cathrall, J.B., 1981c, Geochemical reconnaissance of the southwest Wiseman Quadrangle; summary of data on pan-concentrate and stream-sediment samples: Alaska Division of Geological and Geophysical Surveys Open-file Report 133A, 176 p., 1 plate.

Dillon, J.T., Moorman, M.A., and Lueck, L., 1981d, Geochemical reconnaissance of the southwest Wiseman Quadrangle; summary of data on rock samples: Alaska Division of Geological and Geophysical Surveys Open-file Report 133B, 164 p., 1 plate.

Dillon, J.T., Pessel, G.H., Chen, J.A., and Veach, N.C., 1980, Middle Paleozoic magmatism and orogenesis in the Brooks Range, Alaska: Geology, v. 8, no. 7, p. 338-343.

Dillon, J.T., Pessel, G.H., Lueck, L.L., and Hamilton, W.B., 1981b, Geologic map of the Wiseman A-4 Quadrangle: Alaska Division of Geological and Geophysical Surveys Open-file Report 124, scale 1:63,360, 1 sheet.

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

Dillon, J.T., and Tilton, G.R., 1985, Devonian magmatism in Brooks Range, Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 69, no. 4, p. 662.

Dillon, J.T., Tilton, G.R., Decker, J.E., and Kelly, M.J., 1987, Resource implications of magmatic and metamorphic ages for Devonian igneous rocks in the Brooks Range, *in* Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geologic Society, p. 713-723.

Dixon, E.J., Jr., 1975, The Gallagher Flint Station, an early-man site on the North Slope, arctic Alaska, and its role in relation to the Bering Land Bridge: Arctic Anthropology, v. 12, p. 68-75.

Donovan, T.J., and Tailleur, I.L., 1975, Map showing paleocurrent and clast-size data from the Devonian-Mississippian Endicott Group, northern Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-692, scale 1:7,500,000, 1 sheet.

Dusel-Bacon, Cynthia, Brosgé, W.P., Till, A.B., Fitch, M.R., Mayfield, C.F., Reiser, H.N., and Miller, T.P., 1989, Metamorphic facies map of northern Alaska: U.S. Geological Survey Miscellaneous Geological Investigations Map [in press].

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

_______ 1953a, Stratigraphy and paleontology of the Noatak and associated formations, Brooks Range, Alaska [abs.]: Geological Society of America Bulletin, v. 64, no. 12, pt. 2, p. 14-15.

_______ 1953b, Stratigraphy and paleontology of the Noatak and associated formations, Brooks Range, Alaska: New Haven, Connecticut, Yale University, unpublished Ph.D. dissertation, 154 p.

_______ 1980, Comment *on* Collision-deformed Paleozoic continental margin, western Brooks Range, Alaska, by Michael Churkin, Jr., W.J. Nokleberg, and Carl Huie, 1979, (*in* Geology, v. 7, no. 8, p. 379-383): Geology, v. 8, no. 8, p. 355-356.

_______ 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, volume 5: The Arctic Ocean: New York, Plenum Press, p. 21-34.

_______ 1987a, Revised megafossil biostratigraphic zonation for the Carboniferous of northern Alaska, *in* Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, p. 359-364.

_______ 1987b, A brief history of eighty years of geological exploration in the central Brooks Range, northern Alaska, *in* Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, p. 7-12.

Dutro, J.T., Jr., Brosgé, W.P., Detterman, R.L., and Reiser, H.N., 1979, Beaucoup Formation, a new Upper Devonian stratigraphic unit in the central Brooks Range, northern Alaska, *in* Sohl, N.F., and Wright, W.B., Changes in stratigraphic nomenclature by the U.S. Geological Survey, 1978: 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, no. 6, p. 952-961.

Dutro, J.T., Jr., Brosgé, W.P., and Reiser, H.N., 1977, Upper Devonian depositional history, central Brooks Range, Alaska, *in* Blean, K.M., ed., The United States Geological Survey in Alaska: Accomplishments during 1976: U.S. Geological Survey Circular 751-B, p. B15-B18.

Dutro, J.T., Jr., Palmer, A.R., and Repetski, J.E., 1984a, Middle Cambrian fossils from the Doonerak anticlinorium, central Brooks Range, Alaska: Journal of Paleontology, v. 58, no. 6, p. 1364-1371.

Dutro, J.T., Jr., Palmer, A.R., Repetski, J.E., Jr., and Brosgé, W.P., 1984b, The Doonerak anticlinorium revisited, *in* Coonrad, W.L., and Elliott, R.L., eds., The United States Geological Survey in Alaska: Accomplishments during 1981: U.S. Geological Survey Circular 868, p. 17-19.

Dziewonski, A.M., Hales, A.L., and Lapwood, E.R., 1975, Parametrically simple earth models consistent with geophysical data: Physics of the Earth and Planetary Interiors, v. 10, p. 12-17.

Eckelmann, W.R., Fisher, W.L., and Dewitt, R.J., 1975, Prediction of fluvial-deltaic reservoir geometry, Prudhoe Bay field, Alaska, *in* Miller, T.P., ed., Recent and ancient sedimentary environments in Alaska: Anchorage, Alaska Geological Society, p. B1-B7.

Eggert, J.T., 1987, Sandstone petrology, diagenesis, and reservoir quality, Lower Cretaceous Kuparuk River Formation, Kuparuk River field, North Slope, Alaska, [abs.], *in* Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, p. 108.

Ellis, J.M., and Calkin, P.E., 1979, Nature and distribution of glaciers, neoglacial moraines and rock glaciers, east-central Brooks Range, Alaska: Arctic and Alpine Research, v. 11, no. 4, p. 403-420.

_______ 1984, Chronology of Holocene glaciation, central Brooks Range, Alaska: Geological Society of America Bulletin, v. 95, p. 897-912.

Ernst, W.G., 1984, California blueschists, subduction, and the significance of tectonostratigraphic terranes: Geology, v. 12, p. 436-440.

Estabrook, Charles, 1985, Seismotectonics of northern Alaska: Fairbanks, University of Alaska, unpublished M.S. thesis.

Ferrians, O.J., Jr., 1965, Permafrost map of Alaska: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-445, scale 1:2,500,000, 1 sheet.

_______ 1971, Preliminary engineering geologic maps of the proposed Trans-Alaska Pipelirie route, Philip Smith Mountains Quadrangle: U.S. Geological Survey Open-file Report OF-71-103, scale 1:125,000, 2 sheets.

Ferrians, O.J., Jr., Kachadoorian, R., and Greene, G.W., 1969, Permafrost and related engineering problems in Alaska: U.S. Geological Survey Professional Paper 678, 37 p.

Fox, J.E., 1979, A summary of reservoir characteristics of the Nanushuk Group, Umiat test well 11, National Petroleum Reserve in 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. 42-53.

Fox, J.E., Lambert, P.W., Pitman, J.K., and Wu, C.H., 1979, A study of reservoir characteristics of the Nanushuk and Colville Groups, Umiat test well 11, National Petroleum Reserve in Alaska: U.S. Geological Survey Circular 820, 47 p.

Franklin, John, 1828, Narrative of a second expedition to the shores of the Polar Sea in the years 1825, 1826, and 1827: London, John Murray, 320 p.

Fritts, C.E., 1970, Geology and geochemistry of the Cosmos Hills, Ambler River and Shungnak Quadrangles, Alaska: Alaska Division of Mines and Geology Geologic Report 39, 69 p.

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.

Gabrielse, H,, 1985, Major dextral transcurrent displacements along the northern Rocky Mountain trench and related lineaments in north-central British Columbia: Geological Society of America Bulletin, v. 96, no. 1, p. 1-14.

Galloway, J.P., and Carter, K.D., 1978, Preliminary map of pingos in National Petroleum Reserve in Alaska: U.S. Geological Survey Open-file Report OF-78-795, scale 1:500,000, 1 sheet.

Gemuts, I., Steefel, C.I., and Puchner, C.C., 1983, Regional geology and tectonic history of western Alaska, *in* Mull, C.G., and Reed, K.L., eds.. Symposium on Western Alaska Geology and Resource Potential, Anchorage, 1982, Proceedings: Anchorage, Journal of the Alaska Geological Society, v. 3, p. 67-85.

Ghosh, G.B., Sashy, B.B.K., Rao, A.J., and Rahim, A.A., 1970, Ore environment and ore genesis in Ramagiri gold field, Andhra Pradesh, India: Economic Geology, v. 65, p. 801-814.

Gilbert, W.G., Wiltse, M.A., Carden, J.R., Forbes, R.B., and Hackett, S.W., 1977, Geology of the Ruby Ridge, southwestern Brooks Range, Alaska: Alaska Division of Geological and Geophysical Surveys Geologic Report 58, 16 p., scale 1:31,680, 1 sheet.

Gill, J.B., 1981, Orogenic andesites and plate tectonics: New York, Springer-Verlag, 390 p.

Gold, L.W., and Lachenbruch, A.H., 1973, Thermal conditions in permafrost: Review of North American literature, in Permafrost--The North American Contribution to the Second International Conference, Yakutsk, Siberia, U.S.S.R.: Washington, D.C., National Academy of Sciences, p. 3-25.

Gordon, Mackenzie, Jr., 1957, Mississippian cephalopods of northern and eastern Alaska: U.S. Geological Survey Professional Paper 283, 61 p.

Gottschalk, R.R., Jr,, 1987, Structural and petrographic evolution of the southern Brooks Range near Wiseman, Alaska: Houston, Rice University, unpublished Ph.D. dissertation, 263 p.

Gottschalk, R.R., Avé Lallemant, H.G., and Oldow J.S., 1984, Structural and petrologic evolution of the southern Brooks Range near Coldfoot Alaska [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Programs, v. 16, no. 5, p. 287.

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, no. 5, p. 395-399.

Graham, C.M., and England, P.C., 1976, Thermal regimes and regional metamorphism in the vicinity of overthrust faults: An example of sheer heating and inverted metamorphic zonation from southern California: Earth and Planetary Science Letters, v. 31, no. 1, p. 142-152.

Grantz, Arthur, 1966, Strike-slip faults in Alaska: U.S. Geological Survey Open-file Report 03-66-53, 82 p.

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.

Grybeck, D.A., 1977a, Known mineral deposits of the Brooks Range, Alaska: U.S. Geological Survey Open-file Report OF-77-166-C, 45 p.

_______ 1977b, Map showing geochemical anomalies in the Brooks Range, Alaska: U.S. Geological Survey Open-file Report OF-77-166-D, scale 1:1,000,000, 1 sheet.

Gryc, George, 1970, History of petroleum exploration in northern Alaska, *in* Adkinson, W.L., and Brosgé, M.M., eds., Geological seminar on the North Slope of Alaska, San Francisco, 1970, Proceedings: Los Angeles, American Association of Petroleum Geologists, Pacific Section, p. N1-N16.

_______ 1985, The National Petroleum Reserve in Alaska: U.S. Geological Survey Professional Paper 1240-C, 94 p.

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

Gryc, George, and others, 1956, Mesozoic sequence in Colville River region, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 40, p. 209-254.

Gryc, George, Patton, W.W., Jr., and Payne, T.G., 1951, Present Cretaceous stratigraphic nomenclature of northern Alaska: Washington Academy of Sciences Journal, v. 41, no. 5, p. 159-167.

Hackett, S.W., and Dillon, J.T., 1982, Physical rock-property values for selected rock types, southwestern corner, Wiseman Quadrangle, Alaska: Alaska Division of Geological and Geophysical Surveys Open-file Report 143, scale 1:63,360, 1 sheet.

Hall, D.K., and Roswell, C., 1981, The origin of water feeding icings on the eastern North Slope of Alaska: Polar Record, v. 128, p. 433-438.

Hamilton, T.D., 1978a, Late Cenozoic stratigraphy of the south-central 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. B36-B38.

_______ 1978b, Surficial map of the Chandalar Quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-878A, scale 1:250,000, 1 sheet.

_______ 1978c, Surficial geologic map of the Philip Smith Mountains Quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-879A, scale 1:250,000, 1 sheet.

_______ 1979a, Late Cenozoic glaciations and erosion intervals, north-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. B27-B29.

_______ 1979b, Radiocarbon dates and Quaternary stratigraphic sections, Philip Smith Mountains Quadrangle, Alaska: U.S. Geological Survey Open-file Report OF-79-866, 43 p.

_______ 1979c, Surficial geologic map of the Wiseman Quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1122, scale 1:250,000, 1 sheet.

_______ 1982, A Late Pleistocene glacial chronology for the southern Brooks Range: Stratigraphic record and regional significance: Geological Society of America Bulletin, v. 93, no. 8, p. 700-716.

_______ 1983, Glacial geology of the Brooks Range, *in* Brown, Jerry, and Kreig, R.A., eds., Guidebook to permafrost and related features along the Elliott and Dalton Highways, Fox to Prudhoe Bay, Alaska: International Conference of Permafrost, 4th, Fairbanks, 1983, Publications: Alaska Division of Geological and Geophysical Surveys Guidebook 4, p. 22-25.

_______ 1986, Late Cenozoic glaciation of the central Brooks Range, *in* Hamilton, T.D., Reed, K.M., and Thorson, R.M., eds., Glaciation in Alaska--The geologic record: Anchorage, Alaska Geological Society, p. 9-49.

Hamilton, T.D., and Hopkins, D.M., 1982, Correlation of northern Alaskan glacial deposits--a provisional stratigraphic framework, *in* Coonrad, W.L., ed., The United States Geological Survey: Accomplishments during 1980: U.S. Geological Survey Circular 844, p. 15-18.

Hamilton, T.D., and Obi, C.M., 1982, Pingos in the Brooks Range, northern Alaska, U.S.A.: Arctic and Alpine Research, v. 14, no. 1, p. 13-20.

Hamilton, T.D., and Porter, S.C., 1975, Itkillik Glaciation in the Brooks Range, northern Alaska: Quaternary Research, v. 5, no. 4, p. 471-497.

Hanks, C.L., and Wallace, W.K., 1987, The structural geology of Leffingwell Ridge: Implications for the deformational style of the northeastern Arctic National Wildlife Refuge (ANWR), Brooks Range, Alaska [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Programs, v. 19, no. 6, p. 386.

Hansen, Kenneth, Berg, Eduard, and Gedney, Larry, 1968, A seismic refraction profile and crustal structure in central interior Alaska: Bulletin of the Seismological Society of America, v. 58, p. 1657-1665.

Haugen, R.K., 1982, Climate of remote areas in north-central Alaska: 1975-1979 summary: U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) Report 82-35, 114 p.

Haugen, R.K., and Brown, Jerry, 1978, Climatic and dendroclimatic indices in the discontinuous permafrost zone of the central Alaskan uplands, *in* International Conference on Permafrost, 3rd, Edmonton, Canada, 1978, Proceedings: Ottawa, National Research Council of Canada, v. 1, p. 392-399.

_______ 1980, Coastal-inland distributions of summer air temperature and precipitation in northern Alaska: Arctic and Alpine Research, v. 12, no. 4, p. 403-413.

Hawley, C.C., and Associates, 1982, Mineral terranes of Alaska: Fairbanks, Arctic Environmental Information and Data Center, University of Alaska, scale 1:1,000,000, 5 sheets.

Hedberg, Hollis D., ed., 1976, International stratigraphic guide--a guide to stratigraphic classification, terminology, and procedure: New York, John Wiley, 200 p.

Henley, R.W., Norris, R.J., and Paterson, C.J., 1976, Multistage ore genesis in the New Zealand geosyncline: A history of post-metamorphic lode emplacement: Mineral Deposita, v. 11, p. 180-196.

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

Hitzman, M.W., Smith, T.E., and Proffett, J.M., 1982, Bedrock geology of the Ambler district, southwestern Brooks Range, Alaska: Alaska Division of Geological and Geophysical Surveys Geologic Report 75, scale 1:250,000, 2 plates.

Holmes, G.W., Hopkins, D.M., and Foster, H.L., 1968, Pingos in central Alaska: U.S. Geological Survey Bulletin 1241-H, 40 p.

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

Huffman, A.C., 1979, Stratigraphy and petrography of a measured section on the south limb of Barabara syncline, 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. 77-88.

_______ ed., 1985, Geology of the Nanushuk Group and related rocks, central North Slope, Alaska: U.S. Geological Survey Bulletin 1614, 129 p.

Huffman, A.C., and Ahlbrandt, T.S., 1979, The Cretaceous Nanushuk Group of the western and central North Slope, 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. B46-B50.

Huffman, A.C., Ahlbrandt, T.S., Pasternack, Ira, Fox, J.E., Bartsch-Winkler, Susan, May, F.E., Scott, R.A., and Materna, W.L., 1981a, Measured sections of the Cretaceous Nanushuk Group undivided, western North Slope, Alaska: U.S. Geological Survey Open-file Report OF-81-176.

Huffman, A.C., Ahlbrandt, T.S., Pasternack, Ira, Stricker, G.D., Bartsch-Winkler, Susan, Fox, J.E., May, F.E., Scott, R.A., and Materna, W.H., 1981b, Measured sections in the Cretaceous Nanushuk and Colville Groups undivided, central North Slope, Alaska: U.S. Geological Survey Open-file Report OF-81-177.

Huffman, A.C., Ahlbrandt, T.S., Pasternack, 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., ed., Geology of the Nanushuk Group and related rocks, central North Slope, Alaska: U.S. Geological Survey Bulletin 1614, 129 p.

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.

Imlay, R.W., 1961, Characteristic Lower Cretaceous megafossils of northern Alaska: U.S. Geological Survey Professional Paper 335, 74 p.

Irving, E., 1979, Paleopoles and paleolatitude of North America and speculations about displaced terranes: Canadian Journal of Earth Science, v. 16, p. 669-694.

Jamison, H.C., 1978, Exploration chronology leading to the discovery of the Prudhoe Bay field, *in* Tailleur, I.L., Pessel, G.H., and Engwicht, S.E., Maps showing land status and well locations, and tables of well data, eastern North Slope petroleum province, Alaska: U.S. Geological Survey Miscellaneous Field Study Map MF-928-A, 8 p., scale 1:500,000, 5 sheets.

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

Jones, D.L., and Grantz, Arthur, 1964, Stratigraphic and structural significance of Cretaceous fossils from Tiglukpuk Formation, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 48, no. 9, p. 1462-1474.

Jones, D.L., Silberling, N.J., Berg, H.C., and Plafker, George, 1981, Map showing tectonostratigraphic terranes of Alaska, columnar sections, and summary description of terranes: U.S. Geological Survey Open-file Report OF-81-792, 20 p., scale 1:2,500,000, 2 sheets.

Jones, D.L., Silberling, N.J., Chapman, R.M., and Coney, Peter, 1984b, New ages of radiolarian chert from the Rampart district, east-central Alaska, *in* Coonrad, W.L., and Elliott, R.L., eds., The United States Geological Survey in Alaska: Accomplishments during 1981: U.S. Geological Survey Circular 868, p. 39-43.

Jones, D.L., Silberling, N.J., Coney, P.J., and Plafker, George, 1984a, Lithotectonic terrane map of Alaska (west of the 41st meridian), *in* Silberling, N.J., and Jones, D.L., eds., 1984, Lithotectonic terrane maps of the North American Cordillera: U.S. Geological Survey Open-file Report OF-84-523, 12 p., scale 1:2,500,000, 4 sheets.

_______ 1987, Lithotectonic terrane map of Alaska (west of the 141st meridian): U.S. Geological Survey Miscellaneous Field Studies Map MF-1874-A, scale 1:2,500,000, 1 sheet.

Jones, H.P., and Speers, R.G., 1976, Permo-Triassic reservoirs in Prudhoe Bay field, North Slope, Alaska, *in* Braustein, Jules, ed., North American oil and gas fields: American Association of Petroleum Geologist Memoir 24, p. 23-50.

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

Julian, F.E., 1986, Stratigraphy and tectonic provenance of lower Paleozoic rocks, Doonerak structural high, Brooks Range, Alaska [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Programs, v. 18, no. 2, p. 123.

Julian, F.E., Phelps, J.S., Seidensticker, C.M., Oldow, J.S., and Avé Lallemant, H.G., 1984, Structural history of the Doonerak window, central Brooks Range, Alaska [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Programs, v. 16, no. 5, p. 291.

Keller, A.S., Morris, R.H., and Detterman, R.L., 1961, Geology of the Shaviovik and Sagavanirktok Rivers region, Alaska: U.S. Geological Survey Professional Paper 303-D, p. 169-222.

Kelley, J.S., and Foland, R.L., 1987, Structural style and framework geology of the coastal plain and adjacent Brooks Range, *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 [abs.], in Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, p. 757.

Kreig, R.A., and Reger, R.D., 1982, Air photo analysis and summary of landform soil properties along the route of the Trans-Alaska Pipeline System: Alaska Division of Geological and Geophysical Surveys Geological Report 66, 149 p.

Lachenbruch, A.H., 1962, Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost: Geological Society of America Special Report 70, 69 p.

Lachenbruch, A.H., Sass, J.H., Marshall, B.V., and Moses, T.H., Jr., 1982, Permafrost, heat flow, and the geothermal regime at Prudhoe Bay, Alaska: Journal of Geophysical Research, v. 87, no. B11, p. 9301-9316.

Lawton, T.F., Geehan, G.W., and Voorhees, B.J., 1987, Lithofacies and depositional environments of the Ivishak Formation, Prudhoe Bay field, *in* Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, p. 61-76.

Laycock, G., 1979, Main drag to Prudhoe Bay: Audubon, March 1979, p. 36-43.

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

Leiggi, P.A., 1987, Style and age of tectonism of the Sadlerochit Mountains to Franklin Mountains, Arctic National Wildlife Refuge (ANWR), Alaska in Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, 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 Geologist Bulletin, v. 69, no. 4, p. 668.

Lerand, Monti, 1973, Beaufort Sea, *in* McCrossan, R.G., ed., Future petroleum provinces of Canada--their geology and potential: Canadian Society of Petroleum Geologist Memoir 1, p. 315-386.

Liguori, A., Maple, J.A., and Heuer, C.E., 1979, The design and construction of the Alyeska pipeline, in International Conference on Permafrost, 3rd, Edmonton, Canada, 1978, Proceedings: Ottawa, National Research Council of Canada, v. 2, p. 151-157.

Lindsley, D.H., Andreasen, G.E., and Balsley, J.R., 1966, Magnetic properties of rocks and minerals, *in* Clark, S.P., ed., Handbook of physical constants: Geological Society of America Memoir 97, p. 543-552.

Lister, G.S., and Snoke, A.W., 1984, S-C mylonites: Journal of Structural Geology, v. 6, p. 617-638.

Luscher, U., 1981, Geotechnical aspects of Trans-Alaska Pipeline System, *in* International Conference on Soil Mechanics and Foundation Engineering, 9th, Tokyo, Japan, 1981, Proceedings (case history volume): Japanese Society of Soil Mechanics and Foundation Engineering, p. 83-106.

Mackay, J.R., 1979, Pingos in the Tuktoyaktuk Peninsula area, Northwest Territories: Géographie Physique et Quaternaire, v. 33, no. 1, p. 3-61.

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

Magoon, L.B., and Bird, K.J., 1987, Alaskan North Slope petroleum geochemistry for the Shublik Formation, Kingak Shale, pebble shale unit, and Torok Formation in Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontology and Mineralogy, Pacific Section, and Alaska Geologic Society, p. 145-60.

Magoon, L.B., and Claypool, G.E., 1981, Two oil types on the North Slope of Alaska--implications for exploration: American Association of Petroleum Geologists Bulletin, v. 65, no. 4, p. 644-652.

Mamet, B.L., 1962, Remarques sur la microfauna de Foraminiféres du Dinantien: Soc. Géol. Belgique Bulletin, v. 70, no. 2, p. 166-173.

_______ 1968a, Foraminifera, Etherington Formation (Carboniferous), Alberta, Canada: Canadian Petroleum Geologist Bulletin, v. 16, p. 167-179.

_______ 1968b, Sur une microfaune du Viséen Superieur de Terre-Neuve: Naturaliste Canadian, v. 95, no. 6, p. 1375-1382.

Mamet, B.L., and Armstrong, A.K., 1972, Lisburne Group, Franklin and Romanzof Mountains, northeastern Alaska: U.S. Geological Survey Professional Paper 800-C, p. C127-C144.

Mamet, B.L., and Belford, D., 1968, carboniferous foraminifera, Bonapart Gulf Basin, northwestern Australia: Micropaleontology, v. 14, no. 3, p. 339-347.

Mamet, B.L., and Mason, D., 1968, Foraminifera1 zonation of the lower Carboniferous Connor Lakes section, British Columbia: Canadian Association of Petroleum Geologist Bulletin, v. 16, no. 2, p. 147-166.

Mamet, B.L., and Skipp, B., 1970, Preliminary foraminiferal correlations of early Carboniferous strata in the North American Cordillera, *in* Colloque sur la stratigraphie du Carbonifére: Liége Univ. Cong. et Colloques, v. 55, p. 327-348.

Marsh, S.P., Detra, D.E., and Smith, S.C., 1978a, Geochemical and generalized geologic map showing distribution and abundance of molybdenum, copper, and lead in stream sediments in the Chandalar Quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-878-D, scale 1:250,000, 1 sheet.

_______ 1978b, Geochemical and generalized geologic map showing distribution and abundance of barium, arsenic, boron, and vanadium in stream sediments, Chandalar Quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-878-G, scale 1:250,000, 1 sheet.

_______ 1979, Geochemical and generalized geologic map showing distribution and abundance of antimony and niobium in stream sediments, Chandalar 1′ x 3′ Quadrangle, Alaska: U.S. Geological Surveys Miscellaneous Field Studies Map MF-878-H, scale 1:250,000, 1 sheet.

Marshall, Robert, 1933, Arctic Village: New York, Smith and Haas, 399 p.

_______ 1934, Reconnaissance of the northern Koyukuk valley, Alaska: U.S. Geological Survey Bulletin 844-E, p. 247-256.

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.

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, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, p. 95-107.

May, F.E., 1979, Dinoflagellate and acritarch assemblages from the Nanushuk Group (Albian-Cenomanian) and the Torok Formation (Albian), Umiat test well 11, National Petroleum Reserve in Alaska, northern Alaska, in Ahlbrandt, Thomas 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. 113-127.

May, F.E., and Shane, J.D., 1985, An analysis of the Umiat delta complex using palynologic and other data, in Huffman, A.C., ed., Geology of the Nanushuk Group and related rocks, central North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 97-120.

Mayfield, C.F., 1980, Comment on Collision-deformed Paleozoic continental margin, western Brooks Range, Alaska, by Michael Churkin, Jr., W.J. Nokleberg, and Carl Huie, 1979, (in Geology, v. 7, no. 8, p. 379-383): Geology, v. 8, no. 8, p. 357-359.

Mayfield, C.F., Tailleur, I.L., and Ellersieck, Inyo, 1983, Stratigraphy, structure, and palinspastic synthesis of the western Brooks Range, northwestern Alaska: U.S. Geological Survey Open-file Report OF-83-779, 58 p., scale 1:1,000,000, 5 sheets.

Mayfield, C.F., Tailleur, I.L, Mull, C.G., and Sable, E.G., 1978, Bedrock geologic map of the south half of National Petroleum Reserve in Alaska: U.S. Geological Survey Open-file Report OF-78-70-B, scale 1:500,000, 2 sheets.

McPhail, J.F., McMullen, W.B., and Murfitt, A.W., 1976, Yukon River to Prudhoe Bay highway--lessons in Arctic design and construction: Civil Engineering, v. 46, no. 2, p. 78-82.

Melvin, John, 1987, Sedimentological evolution of the Mississippian Kekiktuk Formation, Sagavanirktok delta area, North Slope, Alaska [abs.], in Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, p. 60.

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.

Menzies, R.J., and Imbrie, J., 1958, On the antiquity of the deep sea bottom fauna: Oikos, v. 9, no. 2, p. 192-210.

Mertie, J.B., Jr., 1925, Geology and gold placers of the Chandalar district, Alaska: U.S. Geological Survey Bulletin 773-E, p. 215-263.

Metz, M.C., Krzewinski, T.G., and Clarke, E.S., 1982, The Trans-Alaska Pipeline System workpad--an evaluation of present conditions, in French, H.M., ed., Canadian Permafrost Conference, 4th, Calgary, Canada, 1981, Proceedings (Roger J.E. Brown memorial volume): Ottawa, National Research Council of Canada, p. 523-544.

Metz, P.A., 1980, Comment on Collision-deformed Paleozoic continental margin, western Brooks Range, Alaska, by Michael Churkin, Jr., W.J. Nokleberg, and Carl Huie, 1979, (in Geology, v. 7, no. 8, p. 379-383): Geology, v. 8, no. 8, p. 360.

Metz, P.A., and Robinson, M.S., 1979, Mineral investigation of D-2 lands in the Philip Smith Mountains and Chandler Lake Quadrangles: Juneau, U.S. Bureau of Mines Alaska Field Operations Center unpublished report, 74 p.

Miller, E.L., 1987, Dismemberment of the Brooks Range orogenic belt during middle Cretaceous extension [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Programs, v. 19, no. 6, p. 432.

Miller, T.P., 1984, Plutonic rocks of west-central Alaska: Compositional and petrographic differences related to geologic setting [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Programs, v. 16, no. 5, p. 322.

Miller, T.P., and Lanphere, M.A., 1981, K-Ar age measurements on obsidian from the Little Indian River locality in interior Alaska, 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. B39-B42.

Molenaar, C.M., 1981a, Depositional history of the Nanushuk Group and related strata, 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. B4-B6.

_______ 1981b, Depositional history and seismic stratigraphy of Lower Cretaceous rocks, National Petroleum Reserve in Alaska and adjacent areas: U.S. Geological Survey Open-file Report OF-81-1084, 42 p.

_______ 1983, Depositional relations of Cretaceous and lower Tertiary rocks, northeastern Alaska: American Association of Petroleum Geologists Bulletin, v. 67, no. 7, p. 1066-1080.

_______ 1985, Subsurface correlations and depositional history of the Nanushuk Group and related strata, North Slope, Alaska, in Huffman, A.C., ed., Geology of the Nanushuk Group and related rocks, central North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 37-59.

Molenaar, C.M., Bird, K.J., and Collett, T.S., 1986, Regional correlations sections across the North Slope of Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1907, 1 sheet.

Molenaar, C.M., Bird, K.J., and Kirk, A.R., 1987, Cretaceous and Tertiary stratigraphy of northeastern Alaska, in Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, p. 513-528.

Molenaar, C.M., Egbert, R.M., and Krystinik, L.F., 1981, Depositional facies, petrography, and reservoir potential of the Fortress Mountain Formation (Lower Cretaceous), central North Slope, Alaska: U.S. Geological Survey Open-file Report OF-81-967, 32 p.

Moll, E.J., and Patton, W.W., Jr., 1984, Volcanic history of the southern Yukon-Koyukuk depression: Evidence from the Unalakleet Quadrangle, Alaska [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Programs, v. 16, no. 5, p. 322.

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

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

Moore, T.E., and Nilsen, T.H., 1984, Regional variations in the fluvial Upper Devonian and Lower Mississippian(?) Kanayut Conglomerate, Brooks Range, Alaska, in Nilsen, T.H., ed., Fluvial sedimentation and related tectonic framework, western North America: Sedimentary Geology, v. 38, p. 465-497.

Moore, T.E., Wallace, W.K., Karl, S.K., Mull, C.G., Bird, K.J., Dillon, J.T., in press, Geology of northern Alaska, in Plafker, George, ed., Geology of Alaska: Geological Society of America Geology of North America Series.

Morgridge, D.L., and Smith, W.B., Jr., 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, in Blean, K.M., ed., The United States Geological Survey in Alaska: Accomplishments during 1976: U.S. Geological Survey Circular 751-B, p. B29-B30.

_______ 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 study of Nanushuk Group rocks, North Slope, Alaska: U.S. Geological Survey Circular 794, p. 14-31.

_______ 1980, Comment on Collision-deformed Paleozoic continental margin, western Brooks Range, Alaska, by Michael Churkin, Jr., W.J. Nokleberg, and Carl Huie, 1979, (in Geology, v. 7, no. 8, p. 379-383): Geology, v. 8, no. 8, p. 361-362.

_______ 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, Colorado, Rocky Mountain Association of Geologists, v. 1, p. 45.

_______ 1985, Cretaceous tectonics, depositional cycles, and the Nanushuk Group, Brooks Range and Arctic Slope, Alaska, in Huffman, A.C., ed., Geology of the Nanushuk Group and related rocks, North Slope, Alaska: U.S. Geological Survey Bulletin 1614, p. 7-36.

_______ 1987, Kemik Sandstone, Arctic National Wildlife Refuge, northeastern Alaska, in Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, p. 405-431.

Mull, C.G., and Adams, K.E., 1984, Geologic mapping of the north side of the Doonerak fenster, central Brooks Range, Alaska [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Programs, v. 16, no. 5, p. 324.

Mull, C.G., and Camber, W.R., 1987, Structure of Bathtub Ridge syncline, Arctic National Wildlife Refuge, northeastern Brooks Range, Alaska [abs.]: Geological Society of America, Cordilleran Section, Programs with Abstracts, v. 19, no. 6, p. 435.

Mull, C.G., Crowder, R.K., Adams, K.E., Siok, J.P., Bodnar, D.A., Harris, E.E., Alexander, R.A., and Solie, D.N., 1987c, Stratigraphy and structural setting of the Picnic Creek allochthon, Killik River Quadrangle, central Brooks Range, Alaska, in Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, p. 650-662.

Mull, C.G., Dillon, J.T., and Adams, K.E., 1987b, The Doonerak fenster, central Brooks Range, Alaska, in Hill, M.L., ed., Cordilleran section of the Geological Society of America: Geological Society of America Centennial Field Guide, v. 1, p. 469-472.

Mull, C.G., Harris, E.E., and Tailleur, I.L., 1989, Preliminary geologic map of the Killik River Quadrangle, central Brooks Range, Alaska: U.S. Geological Survey Open-file Map, scale 1:125,000, 1 sheet [in press].

Mull, C.G., and Kososki, B.A., 1977, Hydrocarbon assessment of the Arctic National Wildlife Range, eastern Arctic Slope, Alaska, in Blean, K.M., ed., The United States Geological Survey in Alaska: Accomplishments during 1976: U.S. Geological Survey Circular 751-B, p. B20-B22.

Mull, C.G., and Mangus, M.D., 1972, Itkilyariak Formation: New Mississippian formation of Endicott Group, Arctic Slope of Alaska: American Association of Petroleum Geologits Bulletin, v. 56, no. 8, p. 1364-1369.

Mull, C.G., Roeder, D.H., Tailleur, I.L., Pessel, G.H., Grantz, Arthur, and May, S.D., 1987a, Geologic sections and maps across the Brooks Range and

Arctic Slope to Beaufort Sea, Alaska: Geological Society of America Maps and Charts Series MC-28-S, scale 1:500,000, 1 sheet.

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 Geologic 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., Ellersieck, I.F., and Curtis, S.M., 1982, New upper Paleozoic and lower Mesozoic stratigraphic units, central and western Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 66, no. 3, p. 348-362.

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.

Muller, F., 1959, Beobachten uber pingos [Observations on pingos]: Meddelelser om Gronland, v. 153, no. 3, 127 p. (reprinted as Technical Translation 1073, Ottawa, National Research Council of Canada, 1963).

Muller, S.W., 1947, Permafrost or permanently frozen ground and related engineering problems: Ann Arbor, J.W. Edwards, Inc., 162 p.

Mulligan, J.J., 1974, Mineral resources of the Trans-Alaska Pipeline corridor: U.S. Bureau of Mines Information Circular 8626.

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, American Geophysical Union, v. 66, no. 46, p. 1102.

Murchey, B.L., Swain, P.B., and Curtis, S.M., 1981, Late Mississippian to Pennsylvanian radiolarian assemblages in the Siksikpuk(?) Formation at Nigu Bluff, Howard Pass Quadrangle, Alaska, in Albert, N.R.D., and Hudson, Travis, eds., The U.S. Geological Survey in Alaska: Accomplishments during 1979: U.S. Geological Survey Circular 823-B, p. B17-B19.

Murphy, J.M., and Patton, W.W., Jr., 1988, Geologic setting and petrography of the phyllite and metagraywacke thrust panel, north-central Alaska, 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 1016, p. 104-108.

Mutti, Emiliano, and Ricci Lucchi, Franco, 1972, Le torbiditi dell' Appennino setentrionale: Introduzione all'analisi de facies [Turbidites of the northern Apennines: Introduction to facies analysis]: Societa Geologica Italiana Memorie, v. 11, p. 161-199.

_______ 1975, Turbidite facies and facies associations, in Examples of turbidite facies and facies associations from selected formations of the northern Apennines: International Congress on Sedimentology Field Trip Guidebook A-11, p. 21-36.

_______ 1978, Turbidites of the northern Apennines: Introduction to facies analysis, translated by Tor H. Nilsen: International Geology Review, v. 20, no. 2, p. 125-166.

Nelson, S.W., 1980, Comment on Collision-deformed Paleozoic continental margin, western Brooks Range, Alaska, by Michael Churkin, Jr., W.J. Nokleberg, and Carl Huie, 1979, (in Geology, v. 7, no. 8, p. 379-383): Geology, v. 8, no. 8, p. 364-365.

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-1176-A, scale 1:250,000, 2 sheets.

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, 1 sheet.

Newberry, R.J., Dillon, J.T., and Adams, D.D., 1986, Regionally metamorphosed, calc-silicate hosted deposits of the Brooks Range, northern Alaska: Journal of Economic Geology, v. 81, no. 7, p. 1728-1752.

Newman, G.W., Mull, C.G., and Watkins, N.D., 1979, Northern Alaska paleomagnetism, plate rotation, and tectonics, in Sisson, Alexander, ed., The relationship of plate tectonics to Alaska geology and resources: Alaska Geological Society Symposium, 6th, Anchorage, 1977, Proceedings, 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., Brosge, W.P., Dutro, J.T., Jr., and Moore, T.E., 1981a, Depositional model for the fluvial Upper Devonian Kanayut Conglomerate, Brooks Range, Alaska, 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. B20-B21.

Nilsen, T.H., and Moore, T.E., 1982a, Stratigraphy and sedimentology of the Kanayut Conglomerate, central and western Brooks Range, Alaska: Report of 1981 field season: U.S. Geological Survey Open-file Report OF-81-674, 64 p.

_______ 1982b, Fluvial-facies model for the Upper Devonian and Lower Mississippian(?) Kanayut Conglomerate, Alaska, in Embry, A.F., and Balkwill, H.R., Arctic geology and geophysics: Canadian Society of Petroleum Geologists Memoir 8, p. 1-12.

_______ 1984a, Stratigraphic nomenclature for the Upper Devonian and Lower Mississippian(?) Kanayut Conglomerate, Brooks Range, Alaska: U.S. Geological Survey Bulletin 1529-A, 64 p.

_______ 1984b, The Kanayut Conglomerate in the westernmost Brooks Range, Alaska, in Coonrad, W.L., and Elliott, 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 OF-82-199, 81 p.

Nilsen, T.H., Moore, T.E., and Brosgé, W.P., 1980a, Paleocurrent maps for the Upper Devonian and Lower Mississippian Endicott Group, Brooks Range, Alaska: U.S. Geological Survey Open-file Report OF-80-1066, scale 1:1,000,000, 2 sheets.

Nilsen, T.H., Moore, T.E., Brosgé, W.P., and Dutro, J.T., Jr., 1981b, Sedimentology and stratigraphy of the Kanayut Conglomerate and associated units, Brooks Range, Alaska: Report of 1979 field season: U.S. Geological Survey Open-file Report OF-81-506, 39 p.

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

Nilsen, T.H., and Patton, W.W., Jr., 1984, Fluvial, shallow-marine, and deep-marine Cretaceous facies associations, central Yukon-Koyukuk basin, Alaska [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Programs, v. 16, no. 5, p. 325.

Normark, W.R., Piper, D.J.W., and Hess, G.R., 1979, Distributary channels, sand lobes, and mesotopography of Navy submarine fan, California borderland, with applications to ancient fan sediments: Sedimentology, v. 26, no. 6, p. 749-774.

North American Commission on Stratigraphic Nomenclature, 1983, North American stratigraphic code: American Association of Petroleum Geologists Bulletin, v. 67, no. 5, p. 841-875.

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 Adkinson, W.L., and Brosgé, M.M., eds., Geological seminar on the North Slope of Alaska: Los Angeles, American Association of Petroleum Geologists, Pacific Section, p. P1-P3.

Oldow, J.S., Avé Lallemant, H.G., and Gottschalk, R.R., 1987a, Large-scale extension within a contractional orogen, south-central Brooks Range, Alaska [abs.]: EOS, Transactions, American Geophysical Union, v. 68, no. 44, p. 1457.

Oldow, J.S., Avé Lallemant, H.G., Julian, F.E., Seidensticker, C.M., 1987c, 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, no. 1, p. 37-41.

Oldow, J.S., Avé Lallemant, H.G., Julian, F.E., Seidensticker, C.M., and Phelps, James, 1984, The Doonerak window duplex: Regional implications [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Programs, v. 16, no. 5, p. 326.

Oldow, J.S., Gottschalk, R.R., and Avé Lallemant, H.G., 1987b, Low-angle normal faults: Southern Brooks Range fold and thrust belt, northern Alaska [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Programs, v. 19, no. 6, p. 438.

Oldow, J.S., Seidensticker, C.M., Phelps, J.C., Julian, F.E., Gottschalk, R.R., Boler, K.W., Handschy, J.W., and Avé Lallement, H.G., 1987d, Balanced cross sections through the central Brooks Range and North Slope, Arctic Alaska: Tulsa, American Association of Petroleum Geologists, 19 p., 8 sheets.

Ollerenshaw, N.C., compiler, 1978, Geologic map of Calgary Quadrangle west of 5th meridian, Alberta and British Columbia: Geological Survey of Canada, Map 1457A, and structure section, scales 1:250,000 and 1:125,000, 2 sheets.

Orth, D.J., 1967, Dictionary of Alaska place names: U.S. Geological Survey Professional Paper 567, 1084 p.

Osterkamp, T.E., and Payne, M.W., 1981, Estimates of permafrost thickness from well logs in northern Alaska: Cold Regions Science and Technology, v. 5, p. 13-27.

Pallister, J.S., 1985, Pillow basalts from the Angayucham Range, Alaska: Chemistry and tectonic implications [abs.]: EOS, Transactions, American Geophysical Union, v. 66, no. 46, p. 1102.

Pallister, J.S., and Budahn, J.R., 1989, Pillow basalts of the Angayucham terrane: Oceanic plateau crust accreted to the Brooks Range: Journal of Geophysical Research [in press].

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, Cordilleran section, Abstracts with Programs, v. 16, no. 5, p. 327.

Paris, Chester, 1978, Models of barite deposition with reference to the barite occurrence of Atigun canyon, central Brooks Range, Alaska: University of Alaska Fairbanks Special Topics Paper, 45 p.

Patton, W.W., Jr., 1956, New and redefined formations of Early Cretaceous age, in Gryc, George, and others, Mesozoic sequence in Colville River region, northern Alaska: American Association of Petroleum Geologists Bulletin, v. 40, no. 2, p. 219-223.

_______ 1957, A new upper Paleozoic formation, central Brooks Range, Alaska: U.S. Geological Survey Professional Paper 303-B, p. 41-43.

_______ 1970, Discussion of tectonic history of northern Alaska, in. Adkinson, W.L., and Brosgé, M.M., eds., Geological seminar on the North Slope of Alaska, San Francisco, 1970, Proceedings: Los Angeles, American Association of Petroleum Geologists, Pacific Section, p. E20.

_______ 1973, Reconnaissance geology of the northern Yukon-Koyukuk province, Alaska: U.S. Geological Survey Professional Paper 774-A, p. A1-A7.

_______ 1984, Timing of arc collision and emplacement of oceanic crustal rocks on the margin of the Yukon-Koyukuk basin, western Alaska [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Programs, v. 16, no. 5, p. 328.

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 [in press].

Patton, W.W., Jr., and Hoare, J.M., 1968, The Kaltag fault, westcentral Alaska: U.S. Geological Survey Professional Paper 600-D, p. D147-D153.

Patton, W.W., Jr., and Matzko, J.J., 1959, Phosphate deposits in northern Alaska: U.S. Geological Survey Professional Paper 302-A, 17 p.

Patton, W.W., Jr., and Miller, T.P., 1973, Bedrock geologic map of Bettles and southern part of Wiseman Quadrangles: U.S. Geological Survey Miscellaneous Field Studies Map MF-492, scale 1:250,000, 1 sheet.

Patton, W.W., Jr., Moll, E.J., Lanphere, M.A., and Jones, D.L., 1984, New age data for the Kaiyuh Mountains, westcentral Alaska, in Coonrad, W.L., and Elliott, R.L., eds., The United States Geological Survey in Alaska: Accomplishments during 1981: U.S. Geological Survey Circular 868, p. 30-32.

Patton, W.W., Jr., Stern, T.W., Arth, J.G., and Carlson, Christine, 1987, New U-Pb ages from granite and granite gneiss in the Ruby geanticline and southern Brooks Range, Alaska: Journal of Geology, v. 95, no. 1, p. 118-126.

Patton, W.W., Jr., and Tailleur, I.L., 1964, Geology of the Killik-Itkillik region, Alaska: U.S. Geological Survey Professional Paper 303-G, p. 409-500.

Patton, W.W., Jr., Tailleur, I.L., Brosgé, W.P., and Lanphere, M.A., 1977, Preliminary report on the ophiolites of northern and western Alaska, in Coleman, R.G., and Irwin, W.P., eds., North American ophiolites: Oregon Department of Geology and Mineral Industries Bulletin 95, p. 51-58.

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 (NPRA), in Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geologic Society, p. 77-83.

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

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

Pessel, G.H., Levorsen, J.A., and Tailleur, I.L., 1978, Generalized isopach map of the Shublik Formation, eastern North Slope petroleum province, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-928-N, scale 1:500,000, 1 sheet.

Phelps, J.C., 1986, Occurrence of the Devonian Beaucoup Formation in the northeastern Doonerak window area, central Brooks Range, Alaska [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Programs, v. 18, no. 2, p. 171.

Phelps, J.C., Oldow, J.S., Avé Lallemant, H.G., Julian, F.G., Seidensticker, C.M., Boler, K.W., and Gottschalk, R., 1985, Late-stage high-angle faulting, eastern Doonerak window, central Brooks Range, Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 69, p. 675.

Phillips, J.W., 1974, Name origins: Prudhoe Bay and Duke Island: Alaska Journal, v. 4, no. 3, p. 149-152.

Porsild, A.E., 1938, Earth mounds in unglaciated Arctic northwestern America: Geographical Review, v. 28, p. 46-58.

Porter, S.C., 1964, Late Pleistocene glacial chronology of north-central Brooks Range, Alaska: American Journal of Science, v. 262, p. 446-460.

_______ 1966a, Pleistocene geology of Anaktuvuk Pass, central Brooks Range, Alaska: Arctic Institute of North America Technical Paper 18, 100 p.

_______ 1966b, Stratigraphy and deformation of Paleozoic section at Anaktuvuk Pass, central Brooks Range, Alaska: American Association of Petroleum Geologists Bulletin, v. 50, no. 5, p. 952-980.

Puchner, C.C., 1984, Intrusive geology of the Ray Mountains batholith [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Programs, v. 16, no. 5, p. 329.

Raisz, Edwin, 1966, Landform map of Alaska (2nd ed.): Environmental Protection Section Office of the Quartermaster General, scale 1:3,000,000, 1 sheet.

Rattey, R.P., 1987, Northeastern Brooks Range, Alaska: New evidence for complex thin-skinned thrusting [abs.], *in* Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, p. 757.

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

Reed, I.McK., 1938, Upper Koyukuk region, Alaska: Territory of Alaska Department of Mines unpublished report, 169 p.

Reed, J.C., 1958, Exploration of Naval Petroleum Reserve No. 4 and adjacent areas, northern Alaska, 1944-53: Part 1, history of exploration: U.S. Geological Survey Professional Paper 301, 192 p.

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 OF-71-237, scale 1:250,000, 1 sheet.

_______ 1980, Geologic map of the Demarcation Point Quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations Map I-1133, scale 1:250,000, 1 sheet.

Ricci Lucchi, Franco, 1975, Depositional cycles in two turbidite formations of northern Apennines: Journal of Sedimentary Petrology, v. 45, p. 3-45.

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

Robinson, F.M., 1966, Core tests and test wells, Oumalik area, Alaska, *with* Paleontology of test wells and core tests in the Oumalik area, Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-A, p. 1-70.

_______ 1958a, Test wells, Gubik area, Alaska, *with* Micropaleontologic study of the Gubik test wells, northern Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-C, p. 207-264.

_______ 1958b, Test well, Grandstand area, Alaska, *with* Micropaleontologic study of Grandstand test well 1, northern Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-E, p. 317-339.

_______ 1959a, Test wells, Titaluk and Knifeblade areas, Alaska, *with* Micropaleontologic study of test wells in the Titaluk and Knifeblade areas, northern Alaska, by H.R. Bergquist: U.S. Geological Survey Professional Paper 305-G, p. 377-422.

_______ 1959b, Test wells, Simpson area, Alaska, with a section on Core analyses, by S.T. Yuster: U.S. Geological Survey Professional Paper 305-J, p. 523-568.

_______ 1964, Core tests, Simpson area, Alaska, with a section on Temperature measurement studies, by M.C. Brewer: U.S. Geological Survey Professional Paper 305-L, p. 645-730.

Robinson, F.M., and Collins, F.R., 1959, Core test, Sentinel Hill area and test well, Fish Creek area, Alaska: U.S. Geological Survey Professional Paper 305-I, p. 485-521.

Roeder, D.H., and Mull, C.G., 1978, Tectonics of Brooks Range ophiolites, Alaska: American Association of Petroleum Geologists Bulletin, v. 62, no. 9, p. 1696-1702.

Roehler, H.W., and Stricker, G.D., 1979, Stratigraphy and sedimentation of the Torok, Kukpowruk, and Corwin Formations of Cretaceous age in the Kokolik-Utukok Rivers region, NPRA: U.S. Geological Survey Open-file Report OF-79-995, 80 p.

_______ 1984, Dinosaur and wood fossils from Cretaceous Corwin Formation, National Petroleum Reserve, North Slope of Alaska: Journal of the Alaska Geological Society, v. 4, p. 36-41.

Royse, F., Jr., Warner, M.A., and Reese, D.L., 1975, Thrust belt geometry and related problems, Wyoming-Idaho-northern Utah: Rocky Mountain Association of Geologists Symposium, Denver, 1985, Proceedings, p. 41-54.

Sable, E.G., Dutro, J.T., Jr., and Morris, R.H., 1951, Preliminary report on the stratigraphy and structure of the Driftwood-Noluk area, Alaska: U.S. Geological Survey Investigations Naval Petroleum Reserve No. 4 and adjacent areas Preliminary Report 39, 28 p.

Saltus, R.W., and Blakely, R.J., 1983, Hypermag, an interactive two-dimensional gravity and magnetic modeling program: U.S. Geological Survey Open-file Report OF-83-241.

Sando, W.J., Mamet, B.L., and Dutro, J.T., Jr., 1969, Carboniferous megafaunal and microfaunal zonation in the northern Cordilleran of the United States: U.S. Geological Survey Professional Paper 613-E, 29 p.

Schrader, F.C., 1900, Preliminary report on a reconnaissance along the Chandalar and Koyukuk Rivers, Alaska, in 1899: U.S. Geological Survey 21st Annual Report, pt. 2, p. 441-486.

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

1904, A reconnaissance in northern Alaska across the Rocky Mountains, along Koyukuk, John, Anaktuvuk, and Colville Rivers and the Arctic Coast to Cape Lisburne, in 1901: U.S. Geological Survey Professional Paper 20, 139 p.

Scott, R.A., and Smiley, C.J., 1979, Some Cretaceous plant megafossils and microfossils from the Nanushuk Group, northern Alaska, a preliminary report, 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. 89-111.

Seidensticker, C.M., 1986, Structural development at the northern margin of the Doonerak duplex, Brooks Range, Alaska [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Programs, v. 18, no. 2, p. 182.

Seidensticker, C.M., Julian, F.E., Phelps, J.C., Oldow, J.S., and Ave Lallemant, H.G., 1985, Lateral continuity of the Blarney Creek thrust, Doonerak window, central Brooks Range, Alaska: American Association of Petroleum Geologist Bulletin, v. 69, p. 678.

Seifert, W.K., Moldowan, J.M., and Jones, R.W., 1979, Application of biological marker chemistry to petroleum exploration: 10th World Petroleum Congress, v. 2, p. 425-440.

Selkregg, L.L., 1975a, Alaska regional profiles: Arctic region: Anchorage, University of Alaska Arctic Environmental Information and Data Center, v. 2, 218 p.

_______ 1975b, Alaska regional profiles: Yukon region: Anchorage, University of Alaska Arctic Environmental Information and Data Center, v. 6, 340 p.

Sellars, B.D., 1981, The barite occurrence and stratigraphy of the Siksikpuk Formation in Atigun River Gorge, Brooks Range, Alaska: Fairbanks, University of Alaska, unpublished M.S. thesis, 108 p.

Silberling, N.J., 1970, Biostratigraphy of marine Triassic in northern Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 54, no. 12, p. 2504.

Silberling, N.J., and Jones, D.L., eds., 1984, Lithotectonic terrane maps of the North American Cordilleran: U.S. Geological Survey Open-file Report OF-84-523, 12 p., scale 1:2,500,000, 4 sheets.

Silberling, N.J., and Patton, W.W., Jr., 1964, Triassic rocks of the Brooks Range: U.S. Geological Survey Professional Paper 501-A, p. 116.

Siok, J.P., 1985, Lithostratigraphy, petrology, age, and depositional environments of the Siksikpuk Formation on the Endicott Mountains and Picnic Creek allochthons, north-central Brooks Range, Alaska: Fairbanks, University of Alaska, unpublished M.S. thesis, 235 p.

Sliter, W.V., 1979, Cretaceous foraminifers from the North Slope of 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. 147-157.

Smiley, C.J., 1966, Cretaceous floras from Kuk River area, Alaska--stratigraphic and climatic interpretations: Geological Society of America Bulletin, v. 77, no. 1, p. 1-14.

_______ 1969a, Flora zones and correlations of Cretaceous Kukpowruk and Corwin Formations, northwestern Alaska: American Association of Petroleum Geologists Bulletin, v. 53, p. 2079-2093.

_______ 1969b, Cretaceous floras of Chandler-Colville region, Alaska--stratigraphy and preliminary floristics: American Association of Petroleum Geologists Bulletin, v. 53, p. 482-502.

Smith, D.T., 1986, A gravity investigation of northern Alaska with emphasis on the Wiseman Quadrangle and the adjacent Dalton Highway: Fairbanks, University of Alaska, unpublished M.S. thesis, 116 p.

Smith, D.T., Stone, D.B., and Dillon, J.T., 1987, Bouguer gravity data and north-south gravity and magnetic profile from the Wiseman Quadrangle, Brooks Range, Alaska, *in* Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, p. 725-734.

Smith, P.S., 1939, Areal geology of Alaska: U.S. Geological Survey Professional Paper 192, 100 p.

Smith, P.S., and Mertie, J.B., 1930, Geology and mineral resources of northwestern Alaska: U.S. Geological Survey Bulletin 815, 315 p.

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, no. 3, p. 567.

Spetzman, L.A., 1959, Vegetation of the Arctic Slope of Alaska: U.S. Geological Survey Professional Paper 302-B, p. 19-58.

Spicer, R.A., 1985, Plant megafossil biostratigraphy and the Late Cretaceous environment of northern Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 69, no. 4, p. 679.

_______ 1987, Late Cretaceous floras and terrestrial environment of northern Alaska, *in* Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, p. 497-512.

Stoney, G.M., 1900, Naval explorations in Alaska: Annapolis, U.S. Naval Institute, 105 p.

Swain, P.B., 1981, Upper Triassic radiolarians from the Brooks Range, Alaska: Los Angeles, University of California, unpublished M.S. thesis, 174 p.

Tailleur, I.L., 1980, Rationalization of Koyukuk 'crunch,' northern and central Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 64, no. 5, p. 792.

Tailleur, I.L., and Brosgé, W.P., 1970, Tectonic history of northern Alaska, *in* Adkinson, W.L., and Brosgé, M.M., eds., Geological seminar on the North Slope of Alaska, San Francisco, 1970, Proceedings: Los Angeles, American Association of Petroleum Geologists, Pacific Section, 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, Calgary, Canada, 1967, Publications: Calgary, Canada, Alberta Society of Petroleum Geologists, v. 2, p. 1345-1361.

Tailleur, I.L., and Engwicht, S.E., 1978, Structure maps of top of Sadlerochit Group and cross sections of Sadlerochit reservoir, eastern North Slope petroleum province, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-928-0, scale 1:500,000, 1 sheet.

Tailleur, I.L., and Kent, B.H., 1951, Stratigraphy and structure of the southern foothills section between the Etivluk and Kiligwa Rivers, Alaska: U.S. Geological Survey Investigations, Naval Petroleum Reserve and adjacent areas, Regular Report 43, 26 p.

Tailleur, I.L., Kent, B.H., and Reiser, H.N., 1951, Preliminary report on the stratigraphy and structure of the Kiligwa River area, Alaska: U.S. Geological Survey Investigations, Naval Petroleum Reserve No. 4 and adjacent areas, Preliminary Report 37, 18 p.

_______ 1966, Outcrop geologic maps of the Nuka-Etivluk region, northern Alaska: U.S. Geological Survey Open-file Report OF-66-128, scale 1:63,360, 7 sheets.

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

Tailleur, Irv, and Weimer, Paul, eds., 1987, Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, 874 p.

Talwani, Maanik, Worzik, J.L., and Landisman, Mark, 1959, Rapid gravity computations for two-dimensional bodies with application to the Mendicino submarine fracture zone: Journal of Geophysical Research, v. 64, p. 49-59.

Templeman-Kluit, D.J., 1976, The Yukon crystalline terrane: Enigma in the Canadian Cordillera: Geological Society of America Bulletin, v. 87, p. 1343-1357.

Thomas, H.P., Johnson, E.R., Stanley, J.M., Shuster, J.A., and Pearson, S.W., 1982, Pipeline stabilization project at Atigun Pass: International Symposium on Ground Freezing, 3rd, Hanover, 1982, Proceedings, p. 439-446.

Tissot, B., Durand, B., Espitalie, J., and Combaz, A., 1974, Influence of nature and diagenesis of organic matter in formation of petroleum: American Association of Petroleum Geologist Bulletin, v. 58, no. 3, p. 499-506.

Tourtelot, H.A., and Tailleur, I.L., 1971, The Shublik Formation and adjacent strata in northeastern Alaska; description, minor elements, depositional environments and diagenesis: U.S. Geological Survey Open-file Report OF-462, 62 p.

Turner, D.L., 1984, Tectonic implications of widespread Cretaceous overprinting of K-Ar ages in Alaskan metamorphic terranes [abs]: Geologic Society of America, Cordilleran Section, Abstracts with Programs, v. 16, no. 5, p. 338.

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, no. 9, p. 1789-1804.

Turner, F.J., 1981, Metamorphic petrology--mineralogic, field, and tectonic aspects: New York, McGraw Hill, 524 p.

U.S. Naval Oceanographic Office, 1966, The total intensity of the earth's magnetic field: Map 1703, scale 1:39,000,000, 1 sheet.

Viereck, L.A., 1983, Vegetation, *in* Brown, Jerry, and Kreig, R.A., eds., Guidebook to permafrost and related features along the Elliott and Dalton Highways, Fox to Prudhoe Bay, Alaska: International Conference on Permafrost, 4th, Fairbanks, 1983, Publication: Alaska Division of Geological and Geophysical Surveys Guidebook 4, p. 26-31.

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

Walker, D.A., 1981, The vegetation and environmental gradients of the Prudhoe Bay region, Alaska:

Boulder, University of Colorado, unpublished Ph.D. dissertation, 484 p.

Walker, D.A., Everett, K.R., Webber, P.J., and Brown, J., 1980, Geobotanical atlas of the Prudhoe Bay region, Alaska: U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) Report 80-14, 69 p.

Walker, R.G., and Mutti, Emiliano, 1973, Turbidite facies and facies associations, *in* Middleton, G.V., and Bouma, A.H., eds., Turbidites and deep-water sedimentation: Society of Economic Paleontologists and Mineralogists, Pacific Section, Short Course, p. 119-157.

Wallace, W.K., and Hanks, C.L., 1988, Stratigraphic variations in the structural style of northeastern Brooks Range, Arctic National Wildlife Refuge, Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 72, no. 2, p. 256.

Watson, C.E., 1959, Climate of Alaska, *in* Climatography of the states: Washington, D.C., U.S. Weather Bureau Climatography of the United States 60-49, 24 p.

Weimer, Paul, 1987, Northern Alaska exploration--the past dozen years, *in* Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, p. 31-37.

Werner, M.R., 1987, West Sak and Ugnu sands: Low gravity oil zones of the Kuparuk River area, Alaskan North Slope *in* Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, p. 109-118.

White, A.J.R., Clemens, J.D., Holloway, J.R., Silver, L.T., Chappell, B.W., and Wall, V.J., 1986, S-type granites and their probable absence in southwestern North America: Geology, v. 14, no. 2, p. 115-118.

Wilbur, Steven, Siok, J.P., and Mull, C.G., 1987, A comparison of two petrographic suites of the Okpikruak Formation: A point count analysis, *in* Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, p. 441-447.

Williams, J.R., 1962, Geologic reconnaissance of the Yukon Flats district, Alaska: U.S. Geological Survey Bulletin 1111-H, p. 289-331.

Witte, W.K., 1982, Paleomagnetism and paleogeography of Cretaceous northern Alaska: Fairbanks, University of Alaska, unpublished M.S. thesis, 146 p.

Witte, W.K., Stone, D.B., and Mull, C.G., 1987, Paleomagnetism, paleobotany, and paleogeography of the Arctic Slope, Alaska in Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geologic Society, p. 571-579.

Woidneck, Keith, Behrman, Philip, Soule, Charles, and Wu, Julie, 1987, Reservoir description of the Endicott field, North Slope, Alaska, *in* Tailleur, Irv, and Weimer, Paul, eds., Alaskan North Slope geology: Bakersfield, Society of Economic Paleontologists and Mineralogists, Pacific Section, and Alaska Geological Society, p. 43-59.

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.

Woollard, G.P., Ostenso, N.A., Thiel, E., and Bonini, W.E., 1960, Gravity anomalies, crustal structure, and geology in Alaska: Journal of Geophysical Research, v. 65, p. 1021-1037.

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, p. 1-25.

Wust, S.L., Harms, T.A., and Coney, P.J., 1984, Structural style of the Mosquito terrane, Koyukuk basin, Brooks Range, Alaska [abs.]: Geological Society of America, Cordilleran Section, Abstracts with Programs, v. 16, no. 5, p. 340.

Yochelson, E.L., and Dutro, J.T., Jr., 1960, Late Paleozoic gastropoda from northern Alaska: U.S. Geological Survey Professional Paper 334-D, p. 111-147.

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-B11.