GUIDEBOOK 5

GUIDEBOOK TO PERMAFROST AND RELATED FEATURES, PRUDHOE BAY, ALASKA

Edited by

S.E. Rawlinson
Alaska Division of Geological and Geophysical Surveys

Fourth International Conference on Permafrost
July 18-22, 1983
University of Alaska
Fairbanks, Alaska, U.S.A.

STATE OF ALASKA

Bill Sheffield, *Governor*

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Ross G. Schaff, *State Geologist*

Cover photo: *Airphoto of Prudhoe Bay oil field near Big Lake (lower right corner). Network of roads and pipelines connect well pads with gathering centers amid ubiquitous elongated and oriented thaw lakes. Sohio Base Operations Center along right side of Big Lake, which is 4,000 m (13,124 ft) long with long axis trending 347° azimuth. (NASA Ames photo 9807, Accession 3101, July, 1982.)*

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GUIDEBOOK TO PERMAFROST AND RELATED FEATURES AT PRUDHOE BAY, ALASKA

Edited by S.E. Rawlinson[1]

INTRODUCTION

General Statement

Although this guidebook was prepared for participants of the Fourth International Conference on Permafrost held in Fairbanks, Alaska, July 18 through 22, 1983, it will also be of interest to a less technically oriented audience. The guidebook introduction is followed by Section A, which includes a discussion of unique features and points of interest along major roads at Prudhoe Bay. Section B includes vegetation, landforms, and soils maps of major road corridors at Prudhoe Bay. More common features of the area are discussed in Section C (Selected Topics). Sections B and C are cross referenced to Section A.

Acknowledgments

This guidebook is the product of efforts by many people, but for preparation of the manuscript, the staff of the Alaska Division of Geological and Geophysical Surveys (DGGS) deserves special recognition. Steven Hardy and Terry Owen researched and wrote short sections on several special topics and, with Duncan Hickmott and Karen Pearson, drew most line figures. Hickmott and Dave Vogel drafted the preliminary and final route maps. Pearson designed the cover, and Ann Schell conceived, edited, and reviewed the color artwork for the maps. Richard Reger and Cheri Daniels reviewed the manuscript.

The following individuals contributed specific sections or provided information for specific sections of the guidebook.

Peter Barnes	U.S. Geological Survey, Menlo Park, California
Kaye Everett	Ohio State University, Columbus, Ohio
Frank Fisher	Alyeska Pipeline Service Company, Anchorage, Alaska
Steven Hardy	Formerly Alaska Division of Geological and Geophysical Surveys, Fairbanks, Alaska
John Harper[2]	Woodward-Clyde Consultants, Walnut Creek, California
Peter Hellstrom	ARCO Alaska, Inc., Anchorage, Alaska
Duncan Hickmott	Alaska Division of Geological and Geophysical Surveys, Fairbanks, Alaska
Terry Owen	Alaska Division of Geological and Geophysical Surveys, Fairbanks, Alaska
Richard Shafer	Sohio Alaska Petroleum Company, Anchorage, Alaska
John Staffeld	Exxon Petroleum Company, Anchorage, Alaska
Dave Vogel	Alaska Division of Geological and Geophysical Surveys, Fairbanks, Alaska
Pat Webber	University of Colorado, Boulder, Colorado

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[1] DGGS, 794 University Avenue, Basement, Fairbanks, Alaska 99701.
[2] Presently with Dobrocky Seatech Ltd., Sidney, British Columbia, Canada.

Many others deserve recognition for logistical support, contributions, or assistance in organizing the field trip to Prudhoe Bay for the Fourth International Conference on Permafrost. ARCO Alaska, Inc., and Sohio Alaska Petroleum Company arranged logistics and ground transportation, and representatives from these companies accompanied the field trip. Alyeska Pipeline Service Company arranged tours of Pump Station 1. Shell Oil Company was enthusiastic and helpful with a proposed visit to an artificial-island drill site. Kodiak-Nabors, a subsidiary of Anglo-Energy, provided accommodations at their facility at Prudhoe Bay. The North Slope Borough is recognized for their assistance with field-trip activities at Barrow, Alaska.

John Harper, formerly of Woodward-Clyde Consultants and presently with Dobrocky Seatech Ltd., Skip Walker of the University of Colorado, and Beth Knol of Shell Oil Company provided evening discussions during the field trip. Harper and David Hopkins of the U.S. Geological Survey accompanied the field trip as field specialists. Jess Walker of Louisiana State University conceived and conducted the Colville River float trip (Walker, 1983). Duncan Hickmott and Terry Owen (DGGS) assisted with field-trip logistics.

Physical Setting

Prudhoe Bay is located within the Arctic Coastal Plain physiographic province (Wahrhaftig, 1965) on the coast of the Beaufort Sea near lat 70°15' N, long 148°30' W (fig. 1). Relief is generally 1 to 2 m (3.2 to 6.4 ft); river terraces and pingos provide the few areas of greater relief [up to about 10 m (33 ft)]. Surface elevation rises from sea level at the coast to about 30 m (98 ft) approximately 25 km (16 mi) inland.

Shallow thaw lakes cover about 25 to 30 percent of the marshy tundra in the Prudhoe Bay (Everett, 1980a) area. Most lakes are strikingly elongated and consistently oriented north-northwest. Other notable features of the Arctic Coastal Plain in the Prudhoe Bay area include beaded drainage, patterned ground, thaw gullies and depressions, pingos, and frost boils.

Climate

The Prudhoe Bay area has a modified arctic coastal maritime climate (Brown, 1975) and is within the arctic climatic zone as defined by Koppen (1936). Mean monthly temperatures (1970-79) at the Atlantic Richfield airfield range from 7°C (45°F) in July to -30°C (-22°F) in February. The mean annual temperature is -13°C (9°F). The lowest recorded temperature was -49°C (-56°F) in February 1971 and January 1976, and the highest temperature was 28°C (82°F) in July 1975. Soil temperatures are up to 10°C (18°F) higher than air temperatures 1 m (3.3 ft) above the ground surface (Conover, 1960; Kelley and Weaver, 1969; Weller and Holmgren, 1974). Bunnel and others (1975) showed variations up to 4°C (7.2°F) among temperatures of the rims, troughs, and basins of low-center ice-wedge polygons. Temperatures on the coast are cooler during spring and summer and warmer during fall than temperatures farther inland (Walker, 1980). Haugen (1979) recorded total precipitation of 223 mm (8.8 in.) and 183 mm (7.2 in.), about 35 percent as rain, during 1977 and 1978, respectively.

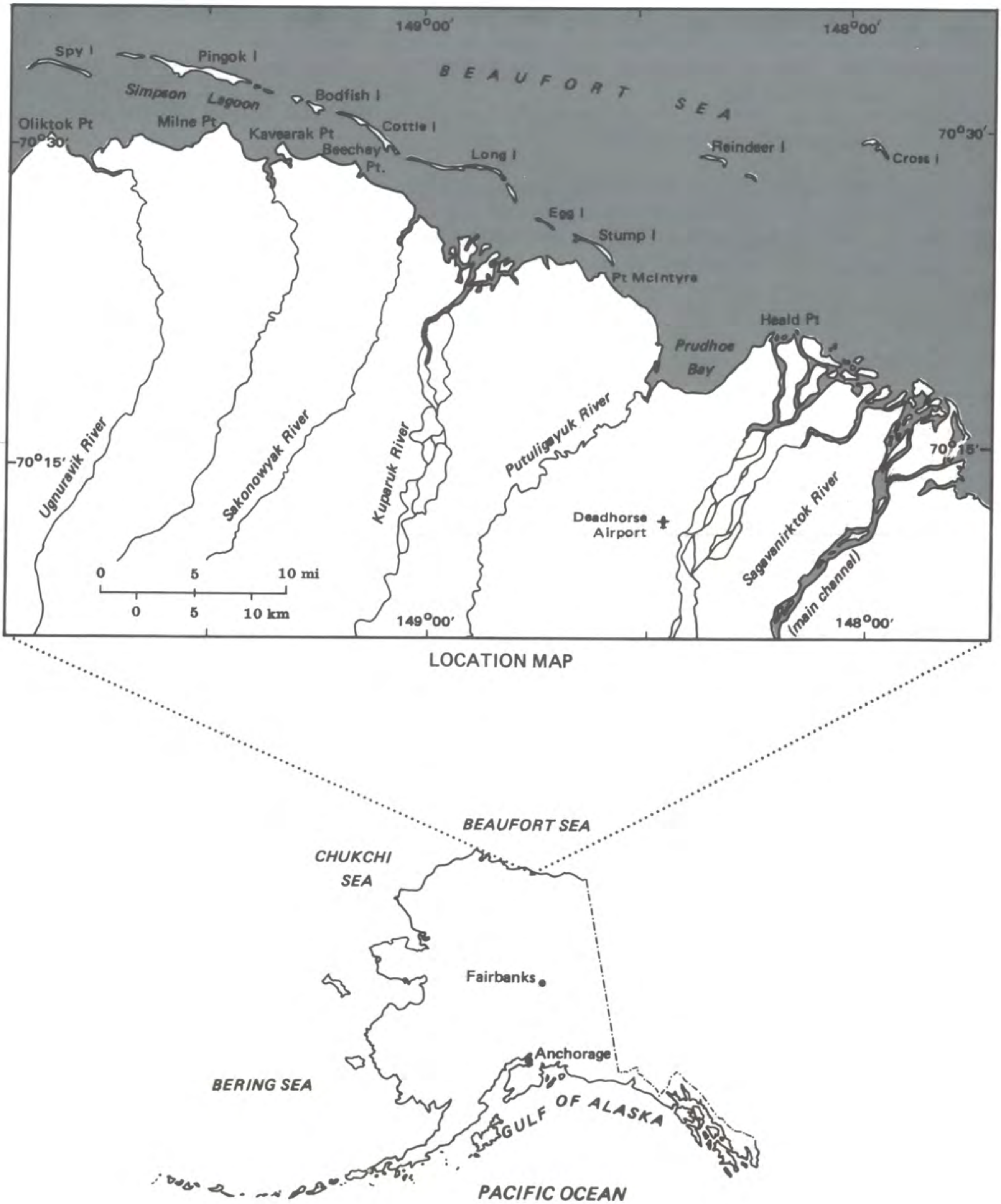

Figure 1. Map showing the location of Prudhoe Bay, Alaska.

Winds in the Prudhoe Bay area are east and northeast in summer and west and west-northwest in winter. A high-pressure center to the north and a low-pressure center over the Gulf of Alaska dictate wind directions in the area. The mean annual wind velocity is 22 km per hr (14 mi per hr), with the highest means in spring, early summer, and fall, and the lowest means in late winter (Gamara and Nunes, 1976).

The climatic regime (with its seasonal variations and subsequent freezing and thawing of near-surface sediments) maintains permafrost conditions and directly, and often catastrophically, affects geologic processes. Storms may cause rapid and dramatic modifications of the landscape. Severe storms generally include westerly winds accompanied by increases in sea level and the shoreward movement of ice (Short, 1973).

Geology

About 1 km^2 (0.39 mi^2) of the Sadlerochit Formation about 3,550 m (11,648 ft) beneath Prudhoe Bay constitutes the main zone of oil production (fig. 2). The Sadlerochit Formation consists of sandstone and gravel conglomerate deposited by braided streams about 220 m.y. B.P. during the Permian and Triassic Periods. This formation is part of 3,750 m (12,304 ft) of post-Devonian deposits that overlie uplifted lower Paleozoic rocks of the Barrow Arch (fig. 2).

A Lower Cretaceous marine shale unconformably overlies Jurassic and older sediments. This shale is probably the source of the hydrocarbons and caps the hydrocarbon reservoir. Overlying the Lower Cretaceous shale are nearly 2,500 m (8,203 ft) of marine and nonmarine Cretaceous and Tertiary siltstone, sandstone, and conglomerate from the Brooks Range to the south. Unconsolidated Quaternary sand and gravel of the Gubik Formation unconformably overlie the Tertiary deposits.

Permafrost

Onshore permafrost

The Prudhoe Bay area is in the continuous-permafrost zone (Ferrians, 1965), where unfrozen ground occurs only below river channels and lakes deeper than 2 m (6.6 ft). Most of the 660 m (2,165 ft) of permafrost beneath the Arctic Coastal Plain formed during the Pleistocene Epoch (Gold and Lachenbruch, 1973). The temperature of permafrost at Prudhoe Bay is colder than elsewhere on the coastal plain and varies between -9°C (16°F) at 50-m (164 ft) depth and about 0°C (32°F) at 600-m (1,969 ft) depth. An implication of this condition is that gas hydrates, if present at Prudhoe Bay, are stable to great depths (Lachenbruch and others, 1982). The depth of seasonal thaw, which is locally variable depending largely on soil texture, is generally about 0.5 m (1.6 ft) and rarely exceeds 1.0 m (3.3 ft).

Offshore permafrost

Prior to development of the Prudhoe Bay oil field, permafrost was undocumented beneath the Beaufort Sea. MacKay (1972) first documented ice in sediments beneath the Beaufort Sea off the MacKenzie Delta. The ice was 9 m

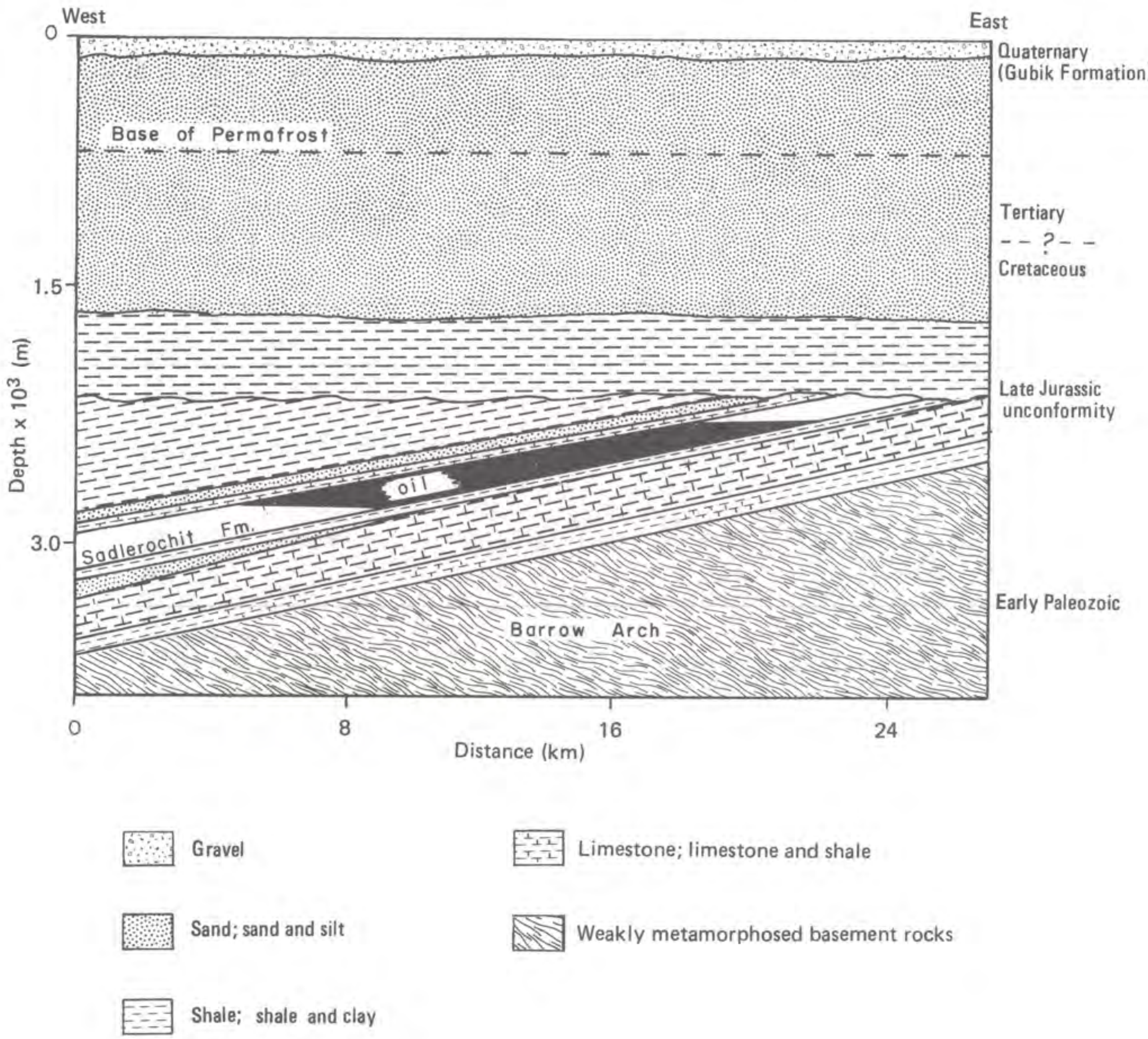

Figure 2. West-to-east cross-sectional drawing of the subsurface geology at Prudhoe Bay. Modified from Sohio Alaska Petroleum Company, 1982.

(30 ft) below the sea floor under 12 m (39 ft) of water. Permafrost began to form beneath the Beaufort Sea about 18,000 yr B.P. during the Wisconsinan continental glaciation, when the continental shelf was exposed to about the -90-m (-295 ft) isobath in the Prudhoe Bay area (Hopkins, 1979a). Sediments to several hundred meters depth froze up to 22 km (13.7 mi) seaward from the present shore. These frozen sediments have been inundated by seawater, creating unique chemical and thermal systems.

Although the freezing point of normal seawater is -1.8°C (28.8°F), the mean annual temperature of the sea floor in the Beaufort Sea is -1.3°C (29.7°F) (Lewellen, 1974), which indicates the presence of permafrost, as thermally defined by Muller (1943). However, bottom sediments are commonly unbonded due to the salinity of the surrounding water (Osterkamp and Harrison, 1976). Deeper sediments commonly do not contain ice because dissolved salts, confining pressure, and capillary forces depress the freezing point of pore water below the ambient temperature (Lachenbruch and others, 1982).

Offshore boreholes near Prudhoe Bay (fig. 3) indicate that the boundary between bonded and unbonded permafrost is highly irregular (fig. 4). It is as shallow as 10 m (33 ft) in 2 m (6.6 ft) of water (Sellman and Chamberlain,

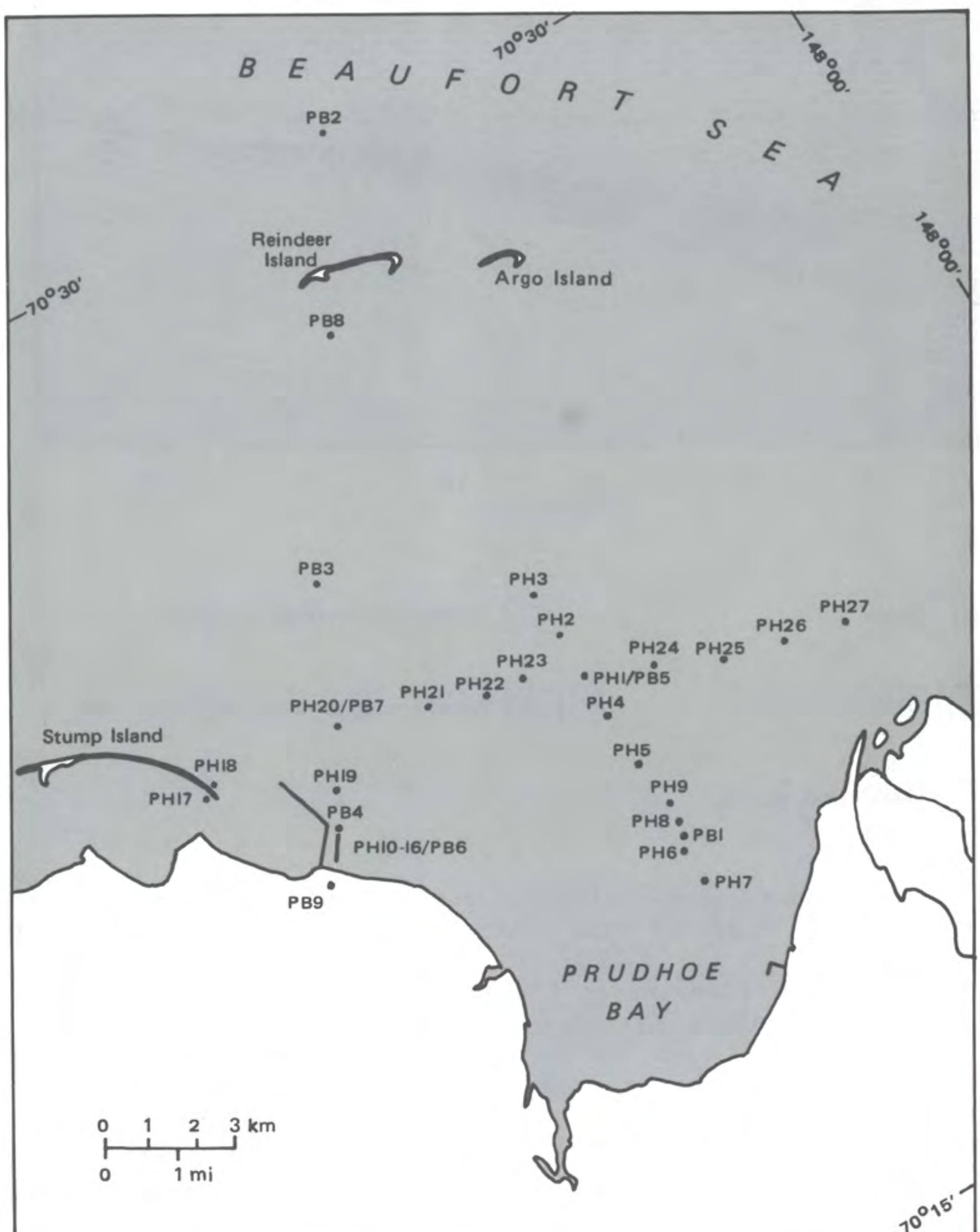

Figure 3. Map showing the location of offshore boreholes near Prudhoe Bay. From Sellmann and others, 1977.

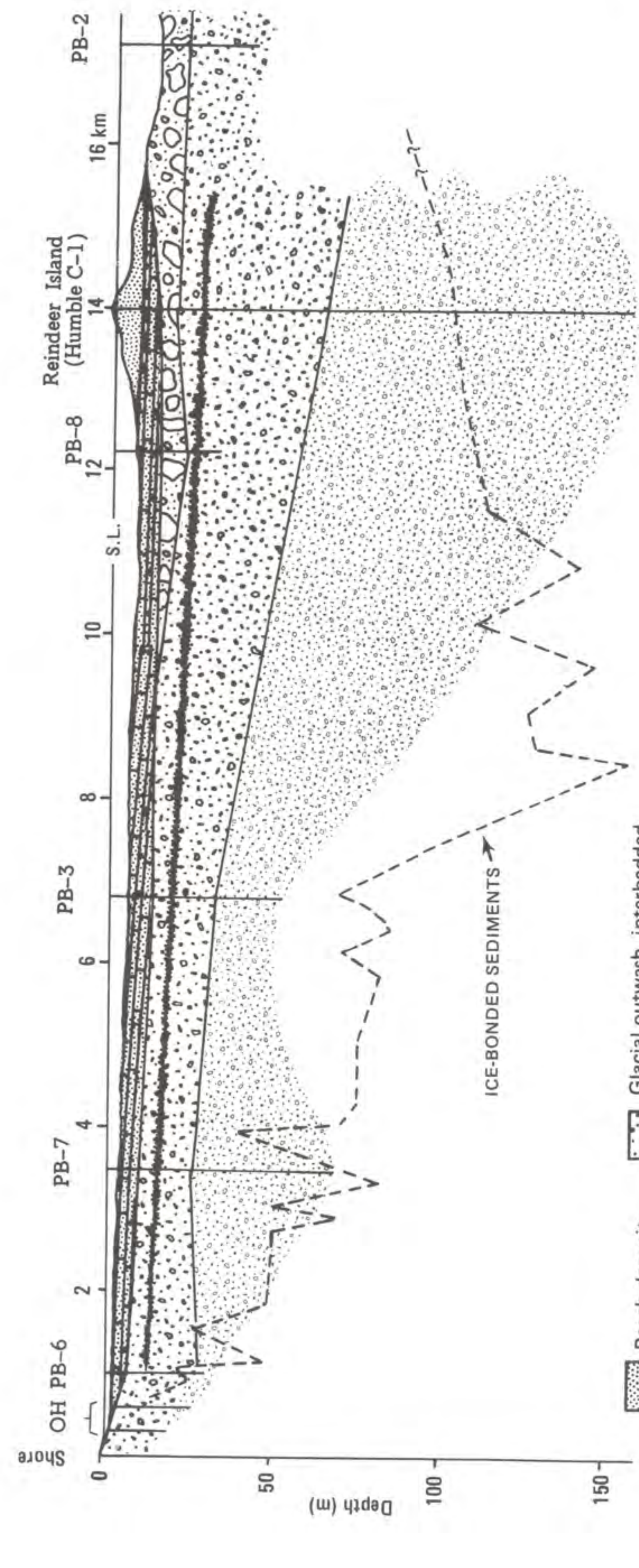

Figure 4. South-to-north cross-sectional drawing of the offshore subsurface geology and permafrost at Prudhoe Bay. Boreholes are shown in figure 3. Modified from Hopkins and Hartz, 1978b.

1978). Although the boundary generally dips seaward, it rises off Reindeer Island (Rogers and Morack, 1978). Large depressions in the bonded-permafrost surface that are evident on many cross sections may represent paleovalleys of rivers that drained the area during emergence (Hopkins and Hartz, 1979). These areas were stripped of the overconsolidated clays that cover most of the sea floor and have remained relatively unfrozen. The absolute thickness of bonded permafrost beneath the Beaufort Sea has not been determined because of drilling limitations, but the deepest borehole penetrated 90 m (295 ft) of bonded permafrost (Harding-Lawson Associates, 1979).

Island permafrost

Most islands in the Beaufort Sea near Prudhoe Bay are underlain by permafrost. These islands are either emergent remnants of the inundated coastal plain or constructional features. Permafrost is more pervasive in remnant islands than in constructional islands.

Discontinuously bonded permafrost was encountered in five boreholes on Reindeer Island, which is constructional. A borehole on Cottle Island, which is a remnant, showed bonded permafrost to 6 m (20 ft), which was the extent of drilling beneath the active layer. Two boreholes on Stump Island, which was initially a remnant but has since eroded leaving accumulations of sand and gravel, showed bonded permafrost to 11 m (36 ft), which was the extent of drilling (Harrison and Osterkamp, 1979).

Seismic data from offshore islands agree with drill data and support the thesis that shallow, bonded permafrost underlies remnant islands, but is generally absent under constructional islands (Rogers and Morack, 1978; Morack and Rogers, 1981). However, permafrost is indicated by thermal-contraction cracks on older parts of some constructional islands, where repeated freezing and thawing reduce salt brines in the sediments and allow them to freeze. Generally, permafrost forms in 40 to 50 yr on these islands (Hopkins and Hartz, 1978a).

Vegetation and Landforms

Studies of the Prudhoe Bay area indicate a strong correlation between vegetation, soils, and landforms (Everett, 1975; Webber and Walker, 1975; Everett and others, 1978, 1980; Walker and others, 1980). Webber and Walker (1975) recognized 13 vegetation types and their characteristic microsites along the existing road system at Prudhoe Bay (fig. 5; table 1). With techniques used by Webber and Walker (1975), Walker and Webber (1980) distinguished four vegetation groups at Prudhoe Bay on the basis of the site moisture regime:

- B Vegetation on dry, barren, or exposed sites
- U Vegetation on moist, well-drained upland sites or well-drained microsites
- M Vegetation on wet or lowland sites
- E Vegetation on sites where water is present during the entire growing season

An open-water group (W) was also distinguished, but no vegetation grows in the lakes and sands (W1) and streams and rivers (W2) communities.

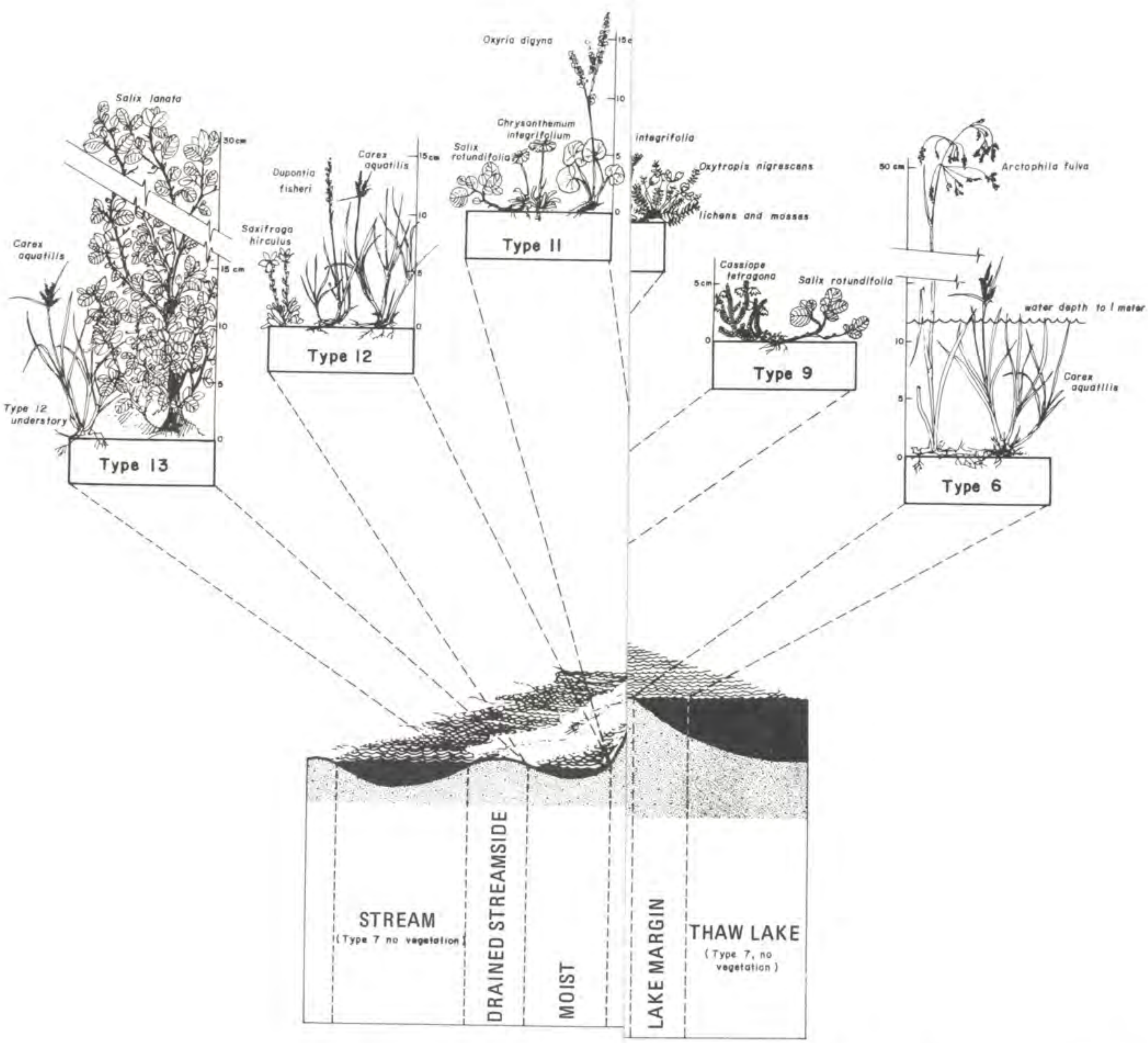

Figure 5. Relationships between 13 vegetation types and their associated microsites at Prudhoe Bay.

Table 1. Vegetation types and characteristic taxa and microsites in the Prudhoe Bay area (Webber and Walker, 1975).

Vegetation type	Characteristic species	Characteristic microsite
1.	*Dryas integrifolia* and crust lichens	Ridge crests of high-center polygons, small ridges, and high creek bluffs
2.	*Dryas integrifolia* and *Cetraria* spp.	Dry polygon rims and well-drained areas
3.	*Carex aquatilis* or *Eriophorum angustifolium* (or both) and *Dryas integrifolia*	Polygon rims and flat areas that are not continually wet
4.	*Carex aquatilis* or *Eriophorum angustifolium* (or both) *Drepanocladus* spp., usually with *Pedicularis sudetica*	Centers of many low-center polygons and troughs and poorly drained areas such as pond margins
5.	*Carex aquatilis* and *Scorpidium scorpioides*	Wet polygon troughs, pond margins, and very wet areas where there is shallow standing water throughout the summer
6.	*Carex aquatilis* or *Arctophila fulva* (or both)	Standing water of moderate depth [30 to 100 cm (12 to 39 in.)], lake margins, and thermokarst pits
7.	No vegetation	Deep water [>100 cm (39 in.)]
8.	*Saxifraga oppositifolia* and *Salix reticulata*, often with *Juncus biglumis* and several lichens	Frost boils
9.	*Cassiope tetragona* and *Salix rotundifolia*	Snowbanks
10.	Diverse vegetation with *Dryas integrifolia*, *Oxytropis nigrescens*, and *Carex rupestris*	Pingos
11.	Diverse vegetation with *Salix rotundifolia*, *Chrysanthemum integrifolium*, and *Oxyria digyna*	Slumping river bluffs and areas of erosion or solifluction (or both)

12.	Carex aquatilis and Dupontia fisheri with Saxifraga hirculus and other dicotyledons	Stream banks
13.	Salix lanata and Carex aquatilis	Stream and lake banks

Of the 42 vegetation types recognized within the four groups, 22 are common and have distinctive taxa (table 2). Table 3 correlates vegetation types of Webber and Walker (1975) with vegetation types of Walker and Webber (1980).

Table 2. Common vegetation types and characteristic taxa in the Prudhoe Bay area, as defined by the site-moisture regime (Walker and Webber, 1980).

Vegetation type	Common taxa
B1	Dryas integrifolia, Oxytropis nigrescens
B2	Dryas integrifolia, Saxifraga oppositifolia
B3	Saxifraga oppositifolia, Juncus biglumis
B4	Epilobium latifolium, Artemisia arctica
B5	Dryas integrifolia, Kobresia myosuroides
B6	Dryas integrifolia, Astragalus alpinus
B7	Braya purpurascens, Anemone parviflora
B9	Elymus arenarius var. mollis, Dupontia fisheri
B13	Salix ovalifolia, Artemisia borealis
U1	Carex aquatilis, Ochrolechia frigida
U2	Eriophorum vaginatum, Dryas integrifolia
U3	Eriophorum angustifolium, Dryas integrifolia
U4	Carex aquatilis, Dryas integrifolia
U8	Salix lanata, Carex aquatilis
U9	Dryas integrifolia, Eriophorum angustifolium
M1	Carex aquatilis, Carex rariflora
M2	Carex aquatilis, Drepanocladus brevifolius
M4	Carex aquatilis, Scorpidium scorpioides
M5	Carex aquatilis, Salix rotundifolia
E1	Carex aquatilis
E2	Arctophila fulva
E3	Scorpidium scorpioides

Table 3. Correlation between vegetation types of Webber and Walker (1975) and vegetation types of Walker and Webber (1980).

Webber and Walker (1975)	Walker and Webber (1980)
1	B2
2	U1, U2
3	U4
4	M2
5	M4

Table 3. (con.)

Webber and Walker (1975)	Walker and Webber (1980)
6	E1, E2
7	W1, W2
8	B3
9	U6, U7
10	B1
11	B7
12	M5
13	U8

Everett (1980a) mapped 12 landforms common in the Prudhoe Bay area and discussed the Sagavanirktok River sand dunes and their associated vegetation types (table 4).

Table 4. Common landforms (Everett, 1980a) and associated vegetation types (Walker and Webber, 1980) in the Prudhoe Bay area.

Landform	Vegetation stand type
High-center polygons [center-trough relief >0.5 m (1.6 ft)]	B1, B2, U3
High-center polygons [center-trough relief ≤0.5 m (1.6 ft)]	B1, B2, U2, U3
Low-center polygons [rim-center relief >0.5 m (1.6 ft)]	U3, U4, M2, M4
Low-center polygons [rim-center relief ≤0.5 m (1.6 ft)]	U3, U4, M2, M4
Mixed high- and low-center polygons	B1, B2, U3, U4, M2, M4
Frost-boil tundra	B3
Strangmoor or disjunct polygon rims, or both	U4, M3, M4, U1, U2, M1
Hummocky terrain	B1
Reticulate patterned ground	U2, U3
Nonpatterned ground	M1, M2, M4
Alluvial flood plain	B4, U8, M5, B6, B7, U9
Pingo	B1
Sand dunes	B9, B13, B5

Soils

Four soil orders in the Prudhoe Bay area are Entisols, Inceptisols, Mollisols, and Histosols. Entisols (including Psamments and Orthents) are poorly developed soils. Inceptisols (including Aquepts) are mineral soils that have horizons with distinctive chemical and physical characteristics. Mollisols (including Borolls and Aquolls) are dark, base-saturated soils. In Histosols (including Fibrists and Saprists), organic material composes the top 40 cm (16 in.) of the soil profile.

Suborders of these soil orders (in parentheses) reflect a soil-forming factor. As part of the soil classification, these suborders are prefixed by the great-groups designator that describes aspects of the center soil profile. A prefix of 'Cry' indicates a soil with a mean annual temperature between 0° and 8°C (32° and 46°F). Subordinate soil-forming processes that modify characteristics of the dominant process are emphasized by the subgroup. In the nomenclature, the subgroup precedes other descriptions. The terms 'pergelic,' 'ruptic,' and 'histic' apply to soils in the Prudhoe Bay area. Pergelic denotes permanent frost, ruptic denotes soil interruption, and histic denotes organic material (Everett, 1980c). Everett (1980c) mapped eight soils as distinct morphologic entities in the Prudhoe Bay area and described a ninth for the Sagavanirktok River dunes. These soils are associated with specific landforms (table 5).

Table 5. Common soils and associated landforms in the Prudhoe Bay area (Everett, 1980c).

Soil unit	Associated landforms
Pergelic cryoboroll	Pingos, high-center polygons
Pergelic cryaquoll	Steam banks, slightly convex interfluves
Pergelic ruptic aqueptic cryaquoll	Frost boils
Histic pergelic cryaquept	Low-center polygons, disjunct polygon rims and strangmoor
Pergelic cryofibrists	Nonpatterned ground, disjunct polygon rims and strangmoor, low-center polygons
Pergelic cryohemists	Low-center polygons (center)
Pergelic cryosaprists	Low-center polygons (rim), high-center polygons
Pergelic cryorthent	River flood plains and terraces
Pergelic cryopsamments	Active or partially stabilized sand dunes

Wildlife

A surprisingly diverse fauna inhabits the Prudhoe Bay area, and since the inception of development, continual studies and monitoring have assessed its impact on wildlife. Simplistically, those animals most directly affected by development, and hence those most studied, are fish, birds, and mammals.

Marine, anadromous, and freshwater fish winter in deeper pools or springs that do not freeze and return to coastal areas to feed in the spring. Common anadromous fish in the area are arctic char (Salvelinus alpinus), chum salmon (Oncorhynchus keta), and pink salmon (O. gorbuscha). Freshwater fish include grayling (Thymallus arcticus), longnose sucker (Catostomus catostomus), round whitefish (Prosopium cylindraceum), broad whitefish (Coregonus nasus), humpback whitefish (C. clupeaformis), burbot (Lota lota), and sculpin (family Cottidae)(ARCO Alaska, Inc., 1983).

Northern latitudes are a critical nesting habitat for waterfowl, and a number of species nest in the Prudhoe Bay area. Common species of geese and ducks in the area include black brant goose (Branta nigricans), white-fronted goose (Anser albifrons frontalis), lesser Canada goose (Branta canadensis minima), snow goose (Chen caerulescens caerulescens), old-squaw duck (Clangula hyemalis), common eider duck (Somateria mollissima), king eider duck (S. spectabilis), spectacled eider duck (S. fischeri), Steller's eider duck (Polystieta stelleri), pintail duck (Anas acuta), and harlequin duck (Histrionicus histrionicus pacificus)(Gavin, 1980).

Swans, loons, and mergansers in the Prudhoe Bay area include the whistling swan (Cygnus columbianus), arctic loon (Gavia arctica pacifica), red-throated loon (G. stellata), yellow-billed loon (G. adamsii), and red-breasted merganser (Mergus serrator). Birds of prey that generally nest in higher country, but are observed in the area, include the golden eagle (Aquila chrysaetos), peregrine falcon (Falco peregrinus), gyrfalcon (F. rusticolus), rough-legged hawk (Buteo lagopus), snowy owl (Nyctea scandiaca), and short-eared owl (Asio flammeus). Other species that inhabit the Arctic Coastal Plain include several gulls (family Laridae), sandpipers (family Scolopacidae), plovers (family Charadriidae), phalaropes (family Phalaropodidae), ptarmigan (family Tetraonidae), ravens (family Corvidae), and buntings and longspurs (family Fringillidae)(Gavin, 1980).

Mammals that inhabit the Prudhoe Bay area, but generally live in the foothills of the Brooks Range to the south and are infrequently seen, include moose (Alces alces), grizzly bear (Ursus horribilis), wolf (Canis lupus), and red fox (Vulpes fulva). Mammals that inhabit the coastal plain and are seemingly oblivious to or even benefit from development include arctic fox (Alopex lagopus), lemming (Dicrostonyx groenlandicus and Lemmus alascens), least weasel (Mustela rixosa), and caribou (Rangifer tarandus arcticus). Polar bear (Thalarctos maritimus) are infrequently seen on the coast, preferring the sea ice and occasionally the offshore islands. Musk ox (Ovibos moschatus), once found in northern Alaska, were reintroduced in the 1960s and inhabit the Canning River area (Gavin, 1980). The Beaufort Sea supports large populations of marine mammals, including bowhead whales (Balaena mysticetus), beluga whales (Dolphinapterus leucas), ringed seals (Phoca hispida), harbor seals (P. vitulina), and bearded seals (Erignathus baroctus) (ARCO Alaska, Inc., 1983).

SECTION A
ROUTES AND STOPS

The Kuparuk, Putuligayuk River, West Dock, and East Dock field-trip routes provide access to the Prudhoe Bay and Kuparuk oil fields (fig. 6). Aerial photographs taken in 1980 cover most of the four routes and provide an excellent perspective of spatial relationships. This section describes the routes from the aerial photographs and discusses unique features or type examples of features or facilities. The reader is urged to refer to Sections B and C (as suggested in figure captions) while reading Section A.

Kuparuk Route

The Kuparuk route extends from Deadhorse Airport to the ARCO Operations Center at the Kuparuk field (fig. 7).

Deadhorse Airport is the primary terminus for private and commercial aircraft serving the Prudhoe Bay area. The runway was extended and paved in the late 1970s to accommodate increasing air traffic. Presently two commercial air carriers with terminals at Deadhorse Airport offer daily flights between Anchorage and Fairbanks. Several charter services that provide helicopter and fixed-wing aircraft are also based at Deadhorse and offer scheduled and chartered flights. Accommodations are available for people not employed by the petroleum industry or service companies.

The braided west channel of the Sagavanirktok River provided sand and gravel during construction of the Dalton Highway, which trends roughly parallel to the river (fig. 8). West of the Dalton Highway, terrace deposits extend to a low scarp visible as a dark-to-light change in gray tone that trends from the bottom-left corner of figure 8 toward the top-right corner. These Sagavanirktok River deposits are among the oldest in this area (Updike and Howland, 1979). Their relative age is indicated by the presence of permafrost-related features that developed after abandonment of the channel, including a pingo that is cut by the west- to east-trending road off the east end of the runway and numerous low-center ice-wedge polygons, nonsorted circles rimmed by vegetation, and thaw lakes. A drained thaw-lake basin just below the intersection of the Dalton Highway and an abandoned west-trending road were cut by the active river channel. Here, the Sagavanirktok River apparently migrated eastward and cut deeper into unconsolidated coastal-plain deposits; it is now migrating westward.

West of the terrace deposits, thaw ponds and lakes dot the tundra surface and ice-wedge polygons are ubiquitous. In the top-left corner of figure 8, the abandoned road crosses a thaw channel that drains a partially drained lake basin and another lake. Thaw along both sides of the abandoned road has formed water-filled trenches. Water in these trenches sometimes initiates preferential thaw along ice wedges and forms thaw channels that may connect with and drain a thaw lake. A photograph taken before this road was built, however, shows that the road was not responsible for this thaw channel and lake drainage.

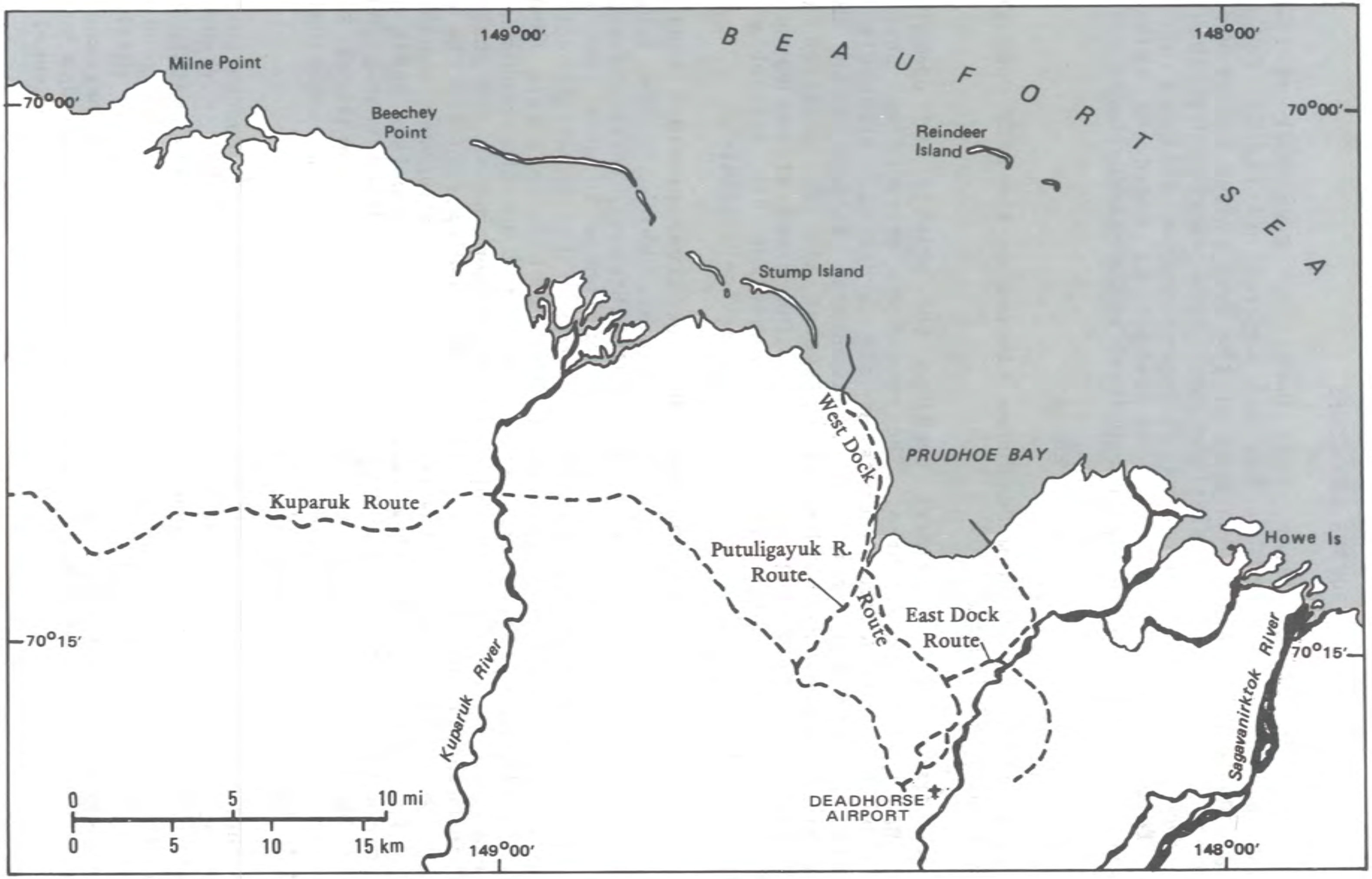

Figure 6. Map showing the Kuparuk, Putuligayuk River, West Dock, and East Dock field-trip routes.

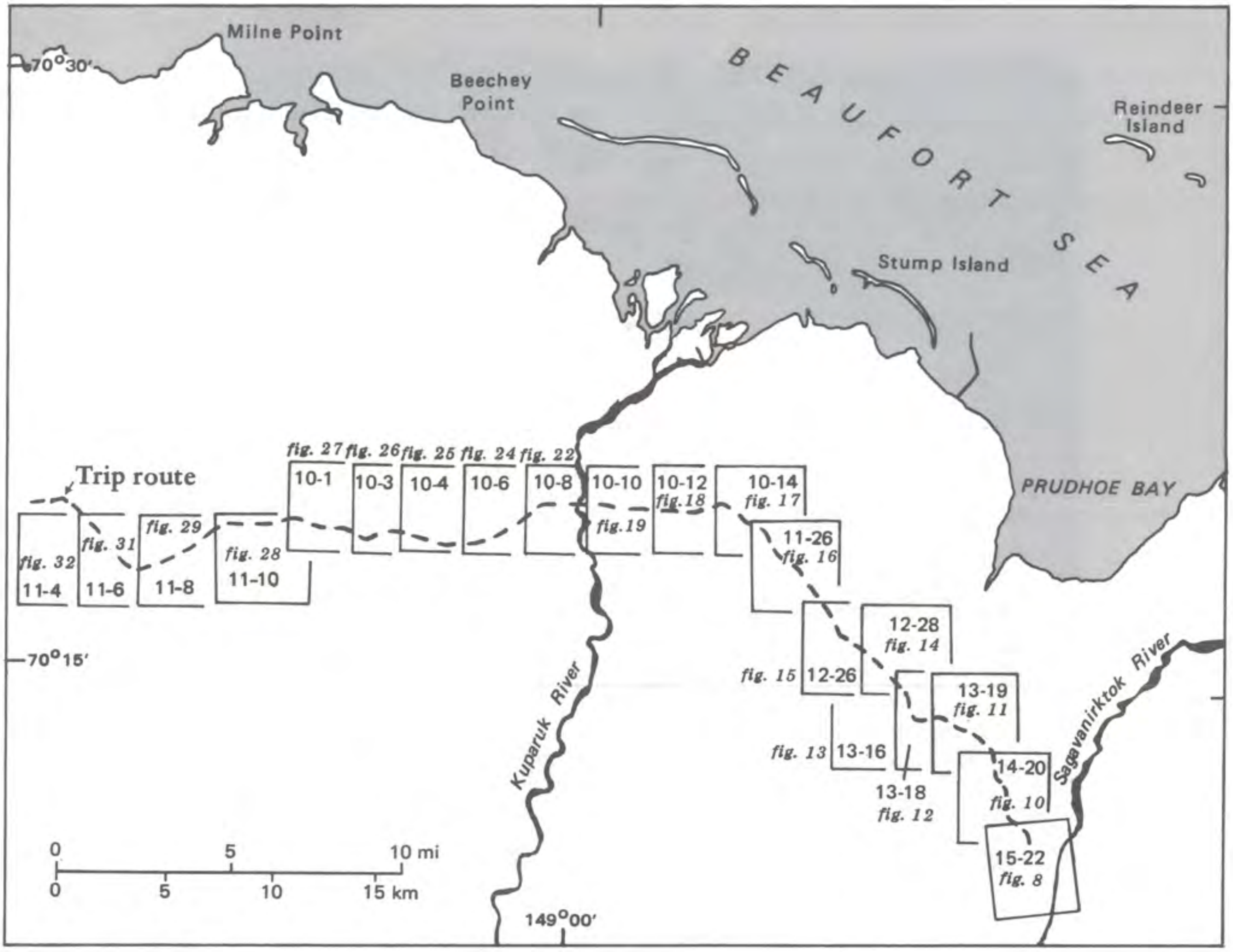

Figure 7. Index map of aerial photographs of the Kuparuk route, Prudhoe Bay, Alaska.

Stop 1.

An abandoned road north of Deadhorse Airport has thaw depressions along ice-wedge polygons (fig. 9). These depressions begin to form during the first summer after road maintenance is halted.

North along the road from Deadhorse Airport is the intersection of roads leading to the western (Kuparuk route) and eastern (East Dock route) parts of the Prudhoe Bay oil field (fig. 10). These roads skirt Colleen Lake, which provides a year-round water supply for nearby facilities. Preferential erosion along ice wedges has produced the scalloped shoreline of Colleen Lake; scallops are best developed along the northern shore. Beyond the intersection with the Kuparuk route, an access road to a storage pad precedes a drained thaw-lake basin that has been cut by Colleen Lake. This lake basin drained more recently than most others in the figure, as shown by the lack of reestablished ice-wedge polygons. Drill Site 13 occupies a partially drained lake basin near the northwest corner of Colleen Lake. An oil pipeline from Drill Site 13 to Drill Site 6 trends parallel to the road. Orthogonal bends in the pipeline are spaced at regular intervals to accommodate pipeline movement.

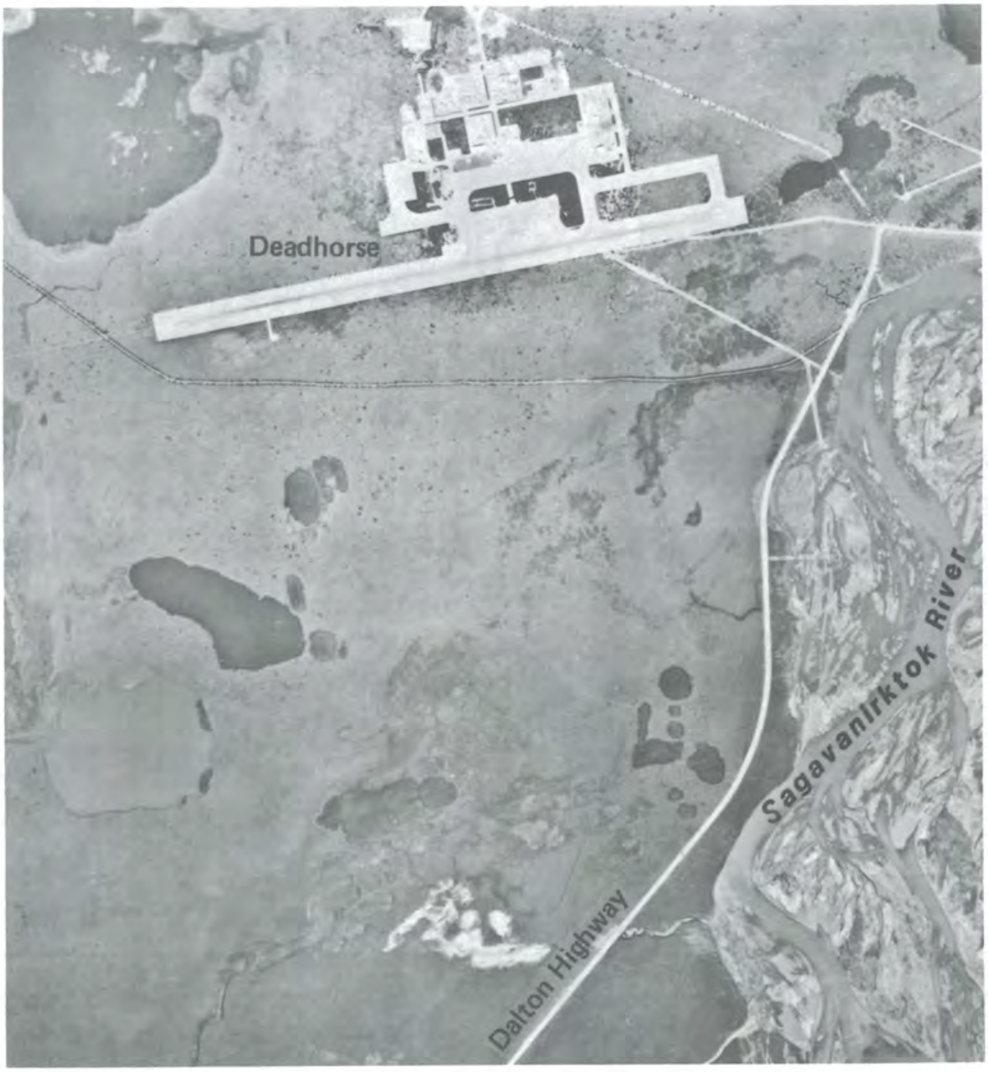

Figure 8. Kuparuk route [North Pacific Aerial Surveys (NPAS) Prudhoe Bay photograph 15-22, 1980.] See also Section C (gravel removal, pingos, ice-wedge polygons, nonsorted circles, thaw lakes, taliks, and linear and polygonal depressions).

The intersection of the road along the north end of Colleen Lake that connects the Kuparuk and East Dock routes is visible near the bottom of figure 11.

The Kuparuk route continues along an area of indistinct, large-diameter ice-wedge polygons between numerous thaw ponds and two partially drained thaw lakes. A small pingo is visible in the western thaw lake, which apparently drained through the thaw channel in the northeast corner of the lake basin. The route crosses the pipeline from Drill Site 13 just south of the road to Drill Site 6. Blockage of suprapermafrost ground water has flooded the triangular area formed by the Kuparuk route, the pipeline, and the road to Drill Site 6.

Figure 9. Thaw depressions along ice-wedge polygons in an abandoned road near Deadhorse Airport, Prudhoe Bay, Alaska. Photograph by S.E. Rawlinson, 1982.

The Kuparuk route crosses an area of low-center ice-wedge polygons between the road to Drill Site 6 and the Little Putuligayuk River. The eastern boundary of the U.S. Tundra Biome Program (1970-1974) study area is east of the Little Putuligayuk River, about 3 km west of the road to Drill Site 6. The study area included a corridor along parts of the Kuparuk route and the Putuligayuk River route. Biotic and abiotic studies were designed to validate and be comparative with comprehensive studies at Barrow and to provide basic ecological data. Biotic studies included determinations of flora, fauna, and nutrient cycles. Abiotic studies of air and soil temperatures, snow-cover thicknesses, soil and landform associations, and soil and water chemistry were also conducted. Project reports are shown in Brown (1975).

The Little Putuligayuk River originates on the coastal plain in a thaw lake about 7 km southwest of Deadhorse Airport. The river drains between several thaw lakes, the last of which is visible at the left edge of figure 11 south of the Kuparuk route, and meanders northward where it merges with the Putuligayuk River just south of Prudhoe Bay.

Stop 2.

High-center ice-wedge polygons and reticulate patterned ground are well developed on the north side of the Kuparuk route along the Little Putuligayuk River.

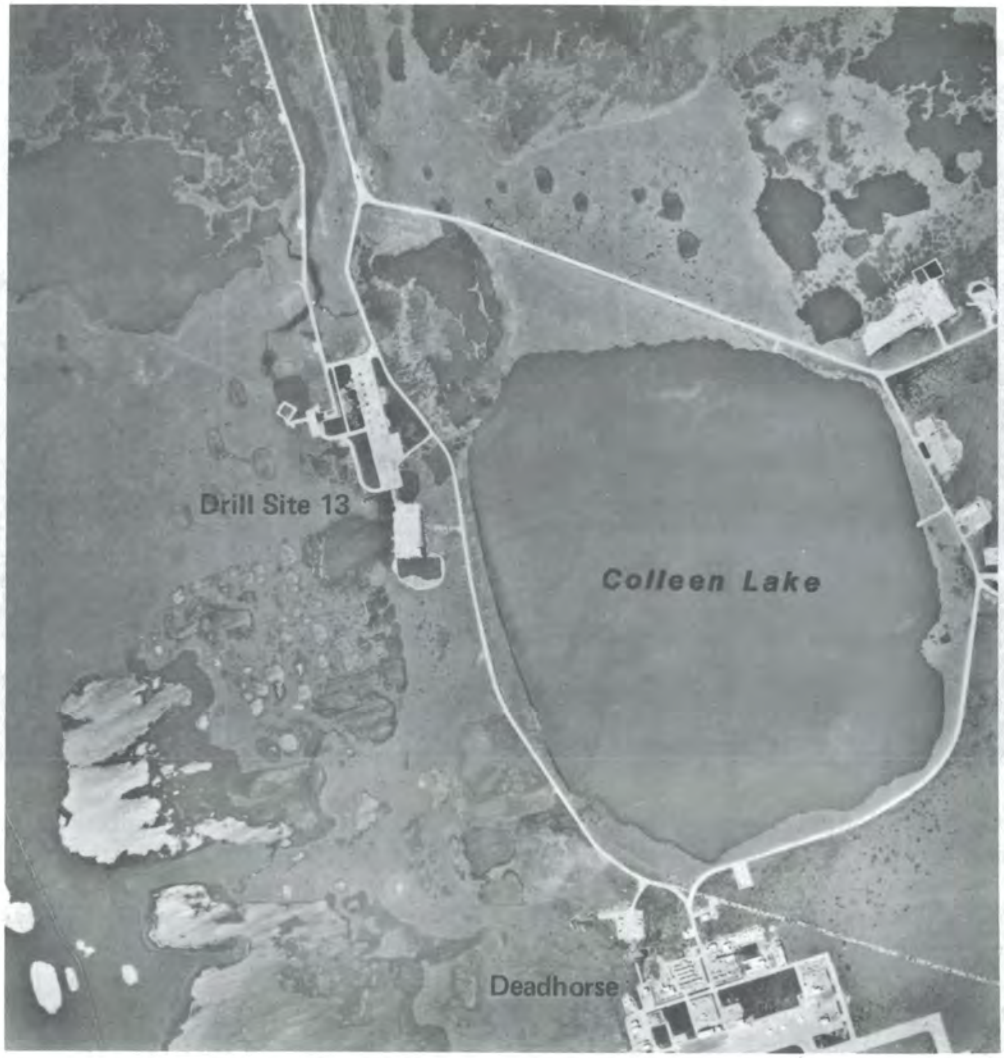

Figure 10. Kuparuk route (NPAS Prudhoe Bay photograph 14-20, 1980). See also Section B (fig. 61) and Section C (thaw lakes, ice wedges, and ice-wedge polygons).

The Kuparuk route continues westward from where it crosses the Little Putuligayuk River across an area of chiefly low-center ice-wedge polygons. South of the route, the Little Putuligayuk River meanders from a thaw lake in the bottom-left corner of figure 12, past Drill Site 14, and into another thaw lake. From this lake, it flows across a drained lake basin to the route crossing. North of the route, a thaw channel has recently drained the lake adjacent to the road, as shown by the virtual absence of patterned ground. Because of the relatively small size of this lake, the preexisting ice-wedge polygons probably were not completely destroyed by thaw. Eventually the permafrost table will rise, and the ice-wedge polygons will be reestablished. During the Tundra Biome Program, this lake basin was the site of a study of the effect of soil types on the nutrient level in small streams (Douglas and Bilgin, 1975). The concentration of nutrients in small watersheds was determined to be proportional to their size and the amount of organic soil present.

Figure 11. Kuparuk route (NPAS Prudhoe Bay photograph 13-19, 1980). See also Section B (fig. 62) and Section C (ice-wedge polygons, thaw lakes, pingos, reticulate patterned ground, and linear and polygonal depressions).

The road to Drill Site 14 turns south from the Kuparuk route just east of where the Kuparuk route turns sharply northward. An oil pipeline heads north from Drill Site 14, crosses the route, and trends northwest across the previously described drained lake basin to Flow Station 3. The route skirts the western shore of the drained thaw lake across an area of low-center polygons to the intersection of the Kuparuk and Putuligayuk River routes near the left edge of figure 12.

Stop 3.

A small turnout on the west side of the Kuparuk route, just before the intersection with the Putuligayuk River route, features the Prudhoe Bay Commemorative Monument, which is wedge shaped and oriented with the long dimension parallel to the prevailing northeast wind to minimize snow accumulation. Viewed from the southeast, Pump Station 1 of the Trans-Alaska Pipeline System is visible in the background.

The Kuparuk Route continues northward from its intersection with the Putuligayuk River route to the road to Pump Station 1.

Stop 4.

Alyeska Pump Station 1 is the first of 10 operational pump stations along the Trans-Alaska Pipeline System. Here, facilities that are not present at other pump stations meter incoming oil, control hydrocarbon emissions, and accommodate differences between flow rates from producers and the pipeline pumping rate. The station also has launching and receiving facilities for scrapers that periodically clean and monitor the pipe. Three mainline pumps, powered by 17,500 hp gas turbines, are each capable of pumping 87,088 l of oil

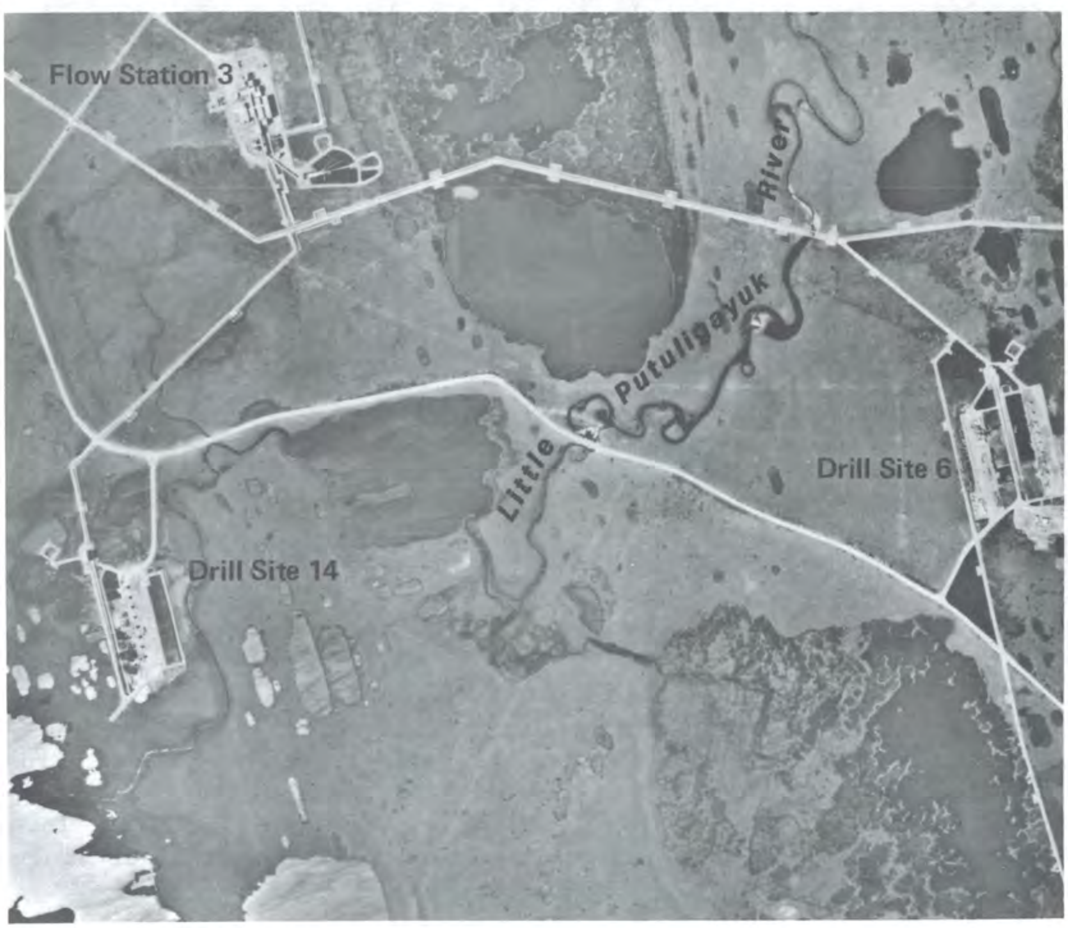

Figure 12. Kuparuk route (NPAS photograph 13-18, 1980). See also Section B (fig. 62; fig. 63) and Section C (ice-wedge polygons, thaw lakes, and aufeis).

per min (23,000 gal per min) or about 828,000 bbl[3] per d. Two pumps operate together and the third is a standby (Alyeska Pipeline Service Company, 1982a).

Pump Station 1 is located in the basin of a large, shallow lake that was intentionally drained in 1974 via a ditch to the Putuligayuk River. The extent of the lake basin is evident by the light-gray area surrounding the pump station (fig. 13). Soils beneath the pump station originally consisted of two major strata: an organic-rich alluvial and eolian silt and underlying alluvial and outwash sand and gravel with varying amounts of silt. The silt stratum varied between 1 and 4 m (3.3 and 13.1 ft) thick and had a mean moisture content of 15 percent and a density of about 480 kg per m^3 (30 lb per ft^3). This stratum was removed from beneath the sites of buildings and other on-grade structures. The sand and gravel stratum is free of massive ice but

Figure 13. Kuparuk route (NPAS Prudhoe Bay photograph 13-16, 1980). See also Section B (fig. 63) and Section C (thaw lakes).

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[3] bbl = 151.4 l (40 gal).

does contain ice-rich zones. Originally, zones within the gravel were thawed. The moisture content of the sand and gravel ranges between 10 and 45 percent (Frank Fisher, written commun., 1982).

The Trans-Alaska Pipeline originates at the southern end of Pump Station 1 and trends southwestward toward the bottom-left corner of figure 13. In the figure, the 1.2-m (3.9 ft)-diameter pipe is above ground except for a small section below the two lakes adjacent to Drill Pad X, where the pipe is buried to allow caribou migration. Elsewhere, the 1,290-km (800 mi)-long pipeline is buried where soil conditions permit; almost half of the pipeline is above ground. Elevated sections have a zigzag design so that longitudinal expansion or contraction of the pipe is translated into sideways movement (Alyeska Pipeline Service Company, 1982b).

The road to Drill Pad X roughly parallels the route of the Trans-Alaska Pipeline. West and east of this road, terrace deposits of the Putuligayuk River are visible in the top-left section of figure 13. The boundary between these deposits and adjacent coastal-plain deposits is very indistinct, but trends approximately from Drill Pad X to the thaw lake east of Pump Station 1. An oil pipeline from Drill Pad X crosses these deposits. The active Putuligayuk River channel is visible in the top-left corner of figure 13.

The Kuparuk Route continues northwest from the road to Pump Station 1 across Putuligayuk River terrace deposits to the road to Drill Pad X (fig. 14). The ditch that drained the lake in which Pump Station 1 is located trends roughly parallel to the Kuparuk route and connects the northwest corner of the lake basin with the large, southwest-bending meander of the Putuligayuk River. West of the Putuligayuk River, the route continues across terrace deposits toward the road to the Central Power Station.

The approximate boundary of Putuligayuk River terrace deposits trends from the bottom-left corner of figure 15, past the southern end of Drill Pad B, to the thaw lake adjacent to this drill pad. The boundary then trends from the north shore of the thaw lake, to the right side of the figure south of the thaw lakes. The boundary is often a lighter gray tone than adjacent coastal plain deposits, and the terrace deposits have an indistinct mottled appearance. Dark areas within the thaw lake adjacent to Drill Pad B are disseminated peat eroded from the shoreline bluff.

The Kuparuk route continues northwest from the power station across an area of high-center ice-wedge polygons toward Sohio Gathering Center 3. This center, which is one of six such facilities in the Prudhoe Bay field, is similar to the flow stations operated by ARCO Alaska, Inc. on the eastern side of the field. Each gathering center can process about 300,000 bbl of oil per d. Crude oil is piped from the drill pads to the gathering centers where water and gas are removed by dehydration and pressure reduction and the oil is cooled from its emergent temperature of about 82°C (180°F) to 60°C (140°F). From the gathering centers, the oil is piped to Pump Station 1 (Sohio Alaska Petroleum Company, 1982).

Through 1981, the water at each gathering center was injected into a sandstone formation about 1,500 m (4,922 ft) below the surface. To aid oil recovery, water is now injected into the base of the Sadlerochit Formation about 3,700 m (12,140 ft) below the surface. In 1985, sea water will also be

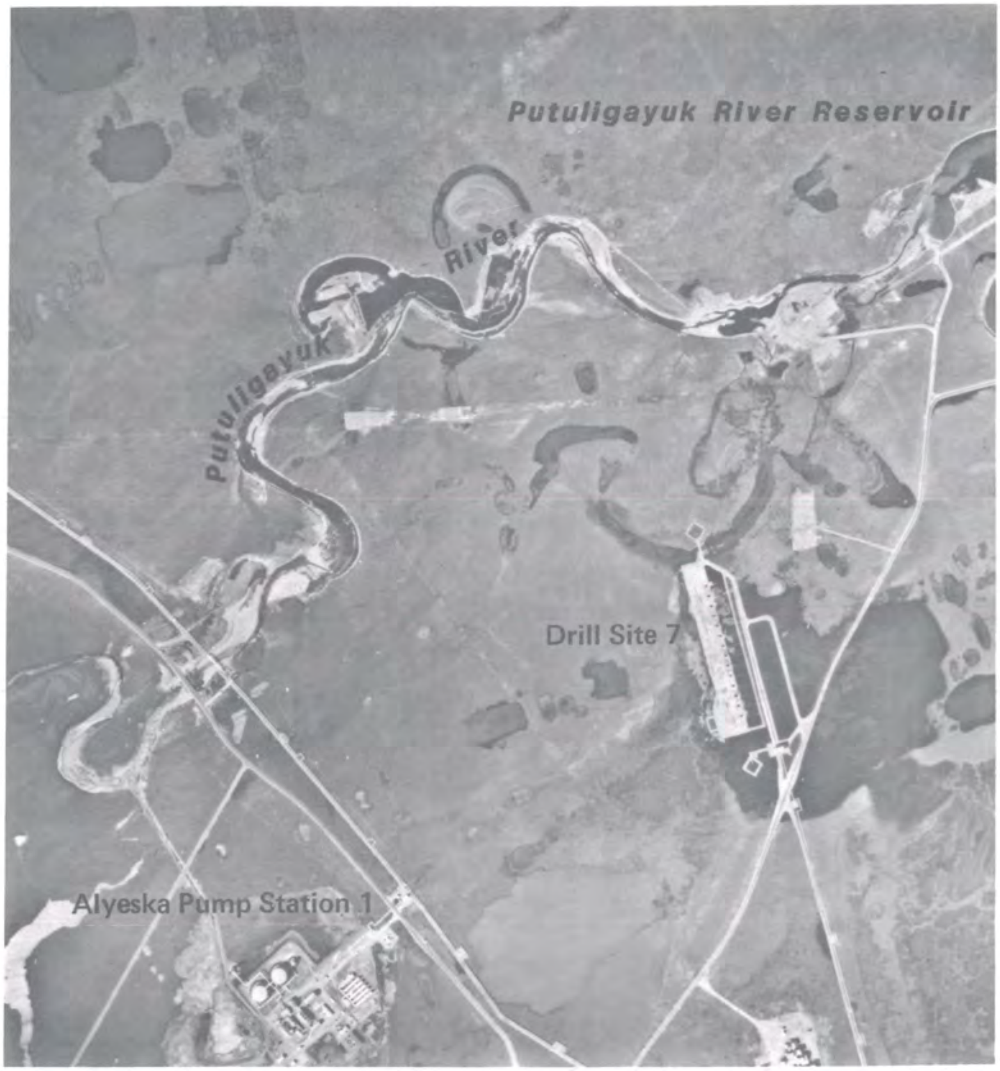


Figure 14. Kuparuk route (NPAS Prudhoe Bay photograph 12-28, 1980). See also Section B (fig. 64; fig. 65) and Section C (thaw lakes and ice-wedge polygons).

injected. Gas is piped from the gathering centers to the Central Compression Plant for reinjection into the field's gas cap (Sohio Alaska Petroleum Company, 1982).

Each gathering center has gas-, fire-, and trouble-detection systems, equipment for fire suppression, and emergency gas-flaring facilities (Sohio Alaska Petroleum Company, 1982). The flaring facilities are circular or fan shaped on the aerial photographs (fig. 15).

Almost the entire top-left quarter of figure 15 is covered by superimposed thaw-lake basins of varying age . The route enters a lake basin east of where it crosses pipelines leading to Sohio Gathering Center 3 from Drill Pads A and B. Superimposed on this lake basin is a younger lake basin, the shoreline of which skirts the Kuparuk route between the pipeline overpass and Gathering Center 3.

Figure 15. Kuparuk route (NPAS Prudhoe Bay photograph 12-26, 1980). See also Section B (fig. 65; fig. 66) and Section C (thaw lakes, pingos, ice-wedge polygons, Waterflood Project, strangmoor, and linear and polygonal depressions).

A closed-system pingo (named 'Mount Prudhoe' by oil-field employees) is visible at the northern end of this younger lake basin, directly west of Gathering Center 3. A similar, less well defined, hydrolaccolith is located at the southern end of the lake basin.

Stop 5.

The west side of 'Mount Prudhoe' and the lake basin in which it is located are cut by a younger lake basin that has been cut by Big Lake. From the top of 'Mount Prudhoe,' an orthogonal system of large-diameter ice-wedge polygons is evident in the youngest lake basin. Like most lakes in the Prudhoe Bay area, Big Lake is elongated and oriented (347° azimuth); it is about 4,000 m (13,124 ft) long and 1,450 m (4,757 ft) wide. Twenty-one test borings in Big Lake in February 1970 showed surface-ice thicknesses between 0.5 m and 1.7 m (1.6 and 5.6 ft) and a small amount of water below the ice. The lake substrata consist of 0.9 to 3.9 m (3.0 to 12.8 ft) of silt, the upper part of which is seasonally frozen, and underlying sediments that are thawed to depths of 1.4 to 6.1 m (4.6 to 20.0 ft) (Updike and Howland, 1979). A 13.6-million-l (3 million gal) reservoir was built in Big Lake across from the Sohio Base Operations Center (BOC) to supplement their water supply. During winter, foam panels are floated on the reservoir and warm water is circulated in it to prevent freezing (Sohio Alaska Petroleum Company, 1982).

The Kuparuk route continues northwest from Gathering Center 3 toward the Sohio BOC across a thaw-lake basin with small thaw lakes and ponds separated by areas of strangmoor and large-diameter ice-wedge polygons. Ponding caused by blockage of suprapermafrost ground water is evident between the Kuparuk route and several small access roads to the Sohio BOC pad near the top-left corner of figure 15.

Stop 6.

Sohio BOC was built in 1972 to accommodate 476 oil-field workers. Three main buildings, each with three stories, serve as a self-contained city. In addition to kitchen and dining facilities, a dispensary, library, commissary, and snack bars, the BOC has saunas, game rooms, basketball and volleyball courts, a track, a theater, and a swimming pool. A field maintenance facility, a firehouse, and the main Operations Control Center adjoin the BOC. The Operations Control Center includes a computer system and other equipment that regulate oil processing and monitor the flow of oil from the Sohio-operated side of the oil-field to Pump Station 1 and the flow of gas piped to the Central Compression Plant (Sohio Alaska Petroleum Company, 1982).

The Kuparuk route continues from the Sohio BOC along the eastern shore of Big Lake toward Gathering Center 1 (fig. 16). Surface features in this section are chiefly strangmoor and indistinct, large-diameter ice-wedge polygons, some mixed high- and low-center ice-wedge polygons, and nonpatterned ground within the lake basin east of the northern end of Big Lake. Various pipelines and service roads converge at Gathering Center 1. The pipeline, which trends roughly parallel to the Kuparuk route and bounds the east side of the Sohio BOC, leads to Gathering Center 3 and on to Pump Station 1.

Drainage in the two dark-gray-toned basins north of the road from Gathering Center 1 to Drill Pad D and east of Gathering Center 1 was especially impaired by transecting roads (fig. 16). Recently, large culverts were installed in the roads around Gathering Center 1 to increase drainage of the lake basins. However, impaired drainage is still evident in the large lake basin east of Gathering Center 1. North of the road transecting this basin, large-diameter orthogonal ice-wedge polygons are beginning to reform; south of the road, these polygons are absent because of more wetness and, hence, a depressed permafrost table.

The Kuparuk route crosses an area of reticulate patterned ground across from the northern extension of the gravel pad of Gathering Center 1. Where the road turns northward, it crosses a small thaw stream that meanders from the large lake basin north of Big Lake into the large lake in the bottom-left corner of figure 16. The ground surface within these lake basins is marked by strangmoor or indistinct large-diameter ice-wedge polygons. From the thaw stream, the route continues past a storage pad to the east to the road to Drill Pad F and on to Frontier Camp in the top-left corner of figure 16. Reticulate patterned ground is common along this stretch of the Kuparuk route.

The Kuparuk route turns sharply westward at Frontier Camp and continues across a uniform area of frost-boil tundra. Two adjacent pingos are north of the route at the northern end of the thaw lake just northwest of Frontier Camp. The almost equal size and the similarity of terrain suggest the pingos are roughly the same age. The eastern side of the pingo nearer the route has been truncated by a small lake, which indicates that it either predates the

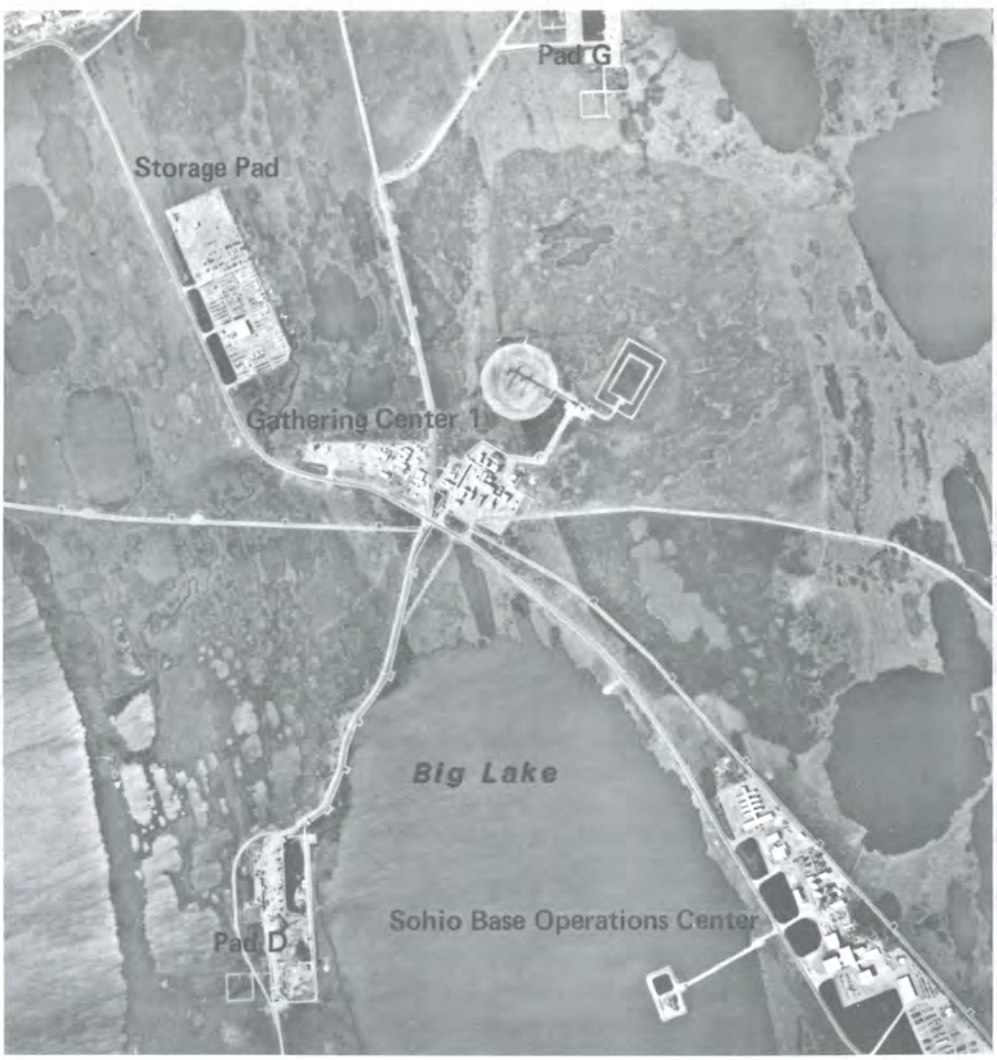


Figure 16. Kuparuk route (NPAS Prudhoe Bay photograph 11-26, 1980). See also Section B (fig. 66; fig. 67; fig. 68) and Section C (ice-wedge polygons, linear and polygonal depressions, reticulate patterned ground, and strangemoor).

lake or is the same age as the lake, is still growing, and has consequently been modified by the lake.

The route continues past the southern tip of Africa Lake across an area of strangmoor and indistinct ice-wedge polygons, then turns northward along the western shore of Africa Lake across an area of indistinctly patterned ground before turning westward around the northern end of a partially drained lake basin (fig. 17). The eastern margin of this lake basin is bounded by a slightly elevated ridge that trends from the northern end of the thaw lake in the lower left corner of figure 17 to the Kuparuk route. Reticulate patterned ground covers the ridge. Surface features within the thaw-lake basin are strangmoor and indistinct, large-diameter ice-wedge polygons.

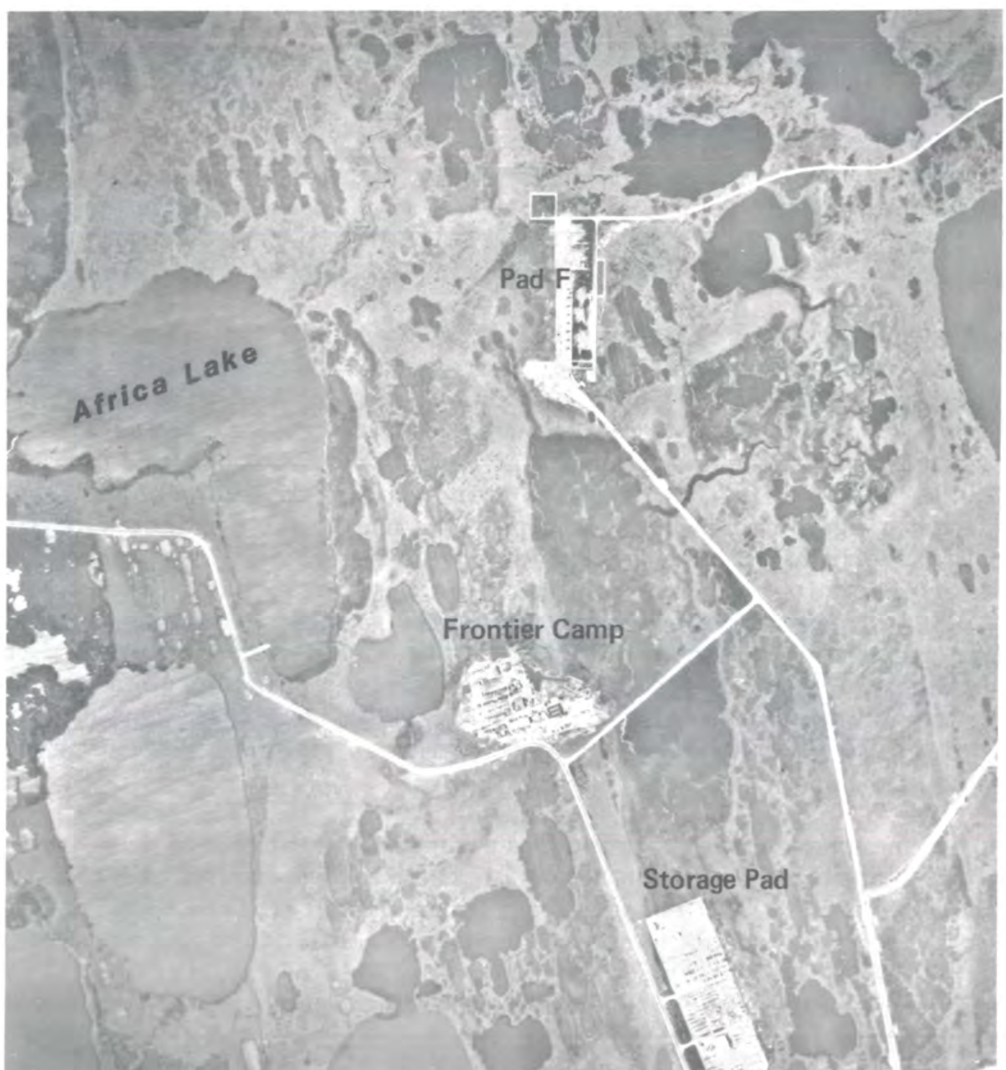


Figure 17. Kuparuk route (NPAS Prudhoe Bay photograph 10-14, 1980). See also Section B (fig. 68) and Section C (nonsorted circles, pingos, thaw lakes, ice-wedge polygons, reticulate patterned ground, and strangemoor).

The Kuparuk route leaves the partially drained lake basin at the road to Drill Pad Q just east of the road to Drill Pad J (fig. 18). The ground surface is characterized by strangmoor and indistinct, large-diameter ice-wedge polygons. A pipeline from Drill Pad R (top-left corner, fig. 18) merges with the Kuparuk route between the road to Drill Pad Q and the pipeline service road from the Kuparuk route to Gathering Center 2. The latter road trends south from the Kuparuk route just west of the intersection of the pipeline service road from Drill Pad R with the Kuparuk route.

The northern extension of the lake basin south of the route near the center of figure 18 is superimposed on the southern end of an older lake basin whose northern end is crosscut by a basin of intermediate age. These lake basins illustrate progressive redevelopment of permafrost-related features following drainage. The northern extension of the southernmost---and youngest---lake basin is wet, with very indistinct ice-wedge polygons and frost-boils. The northernmost---and intermediate-aged---lake-basin surface is covered by strangmoor and large-diameter ice-wedge polygons. The central---and oldest---lake-basin surface is covered by large-diameter ice-wedge polygons and small thaw ponds.

Sohio Construction Camp 2 is south of the Kuparuk route on the western boundary of the youngest of the three lake basins. From Construction Camp 2, the Kuparuk route trends westward toward the Kuparuk River.

The Kuparuk route between the elongate lake at the right side of figure 19 and the road to Drill Pad N crosses a diverse assemblage of landforms. The small lake basin north of the elongate lake contains numerous thaw ponds surrounded by nonpatterned ground; its very wet surface is shown by dark-gray tones on the photograph. A large, well-defined pingo is located north of this lake basin, and similar pingos are common west of the Kuparuk River. These pingos probably originated in thaw-lake basins, but sufficient time has passed since their inception for obliteration of strandlines. The route crosses a strip of reticulate patterned ground that borders the eastern boundary of a large drained lake that is visible east of Drill Pad N. High-center ice-wedge polygons dominate the northeast corner of this lake basin. Strangmoor and large-diameter ice-wedge polygons occur within the northern part of the basin east of a thaw stream and just west of the access road to Drill Pad N. A thaw stream originates near Drill Pad N and flows northward to the Kuparuk River.

West of the thaw stream, frost-boil tundra, strangmoor and large-diameter ice-wedge polygons are common. North of the Kuparuk route and the large lake basin east of Drill Pad N, strangmoor, large-diameter ice-wedge polygons, and reticulate patterned ground surround numerous small thaw ponds. West of the road to Drill Pad N and to the Kuparuk River flood plain, reticulate patterned ground and frost-boil tundra occur north and south of the Kuparuk route, respectively.

Stop 7.

The Kuparuk route enters the Kuparuk River flood plain near the upper right edge of figure 20. Reticulate patterned ground merges with hummocky terrain on the flood-plain scarp next to the oxbow lake north of the route.

Frost-boil terrain is dominant south of the route along the top of the flood-plain scarp. Figure 21 shows representative stratigraphic sections in some of these deposits. Kuparuk (KUP) sections 1 and 2 are in inactive flood-plain deposits, sections 4 and 5 are in abandoned flood-plain deposits, and section 3 is in terrace deposits. Two criteria for differentiating these units are their relative elevation and relative frequency and thickness of peat layers in the sections. Except for Fct and Fpt deposits, fluvial deposits (prefixed by F) are listed from lowest elevation with the thinnest and least number of peat layers to highest elevation with the thickest and greatest number of peat layers. Stratigraphic sections in figure 21 show repeated channel deposition of sand and gravel or sand and subsequent flood-plain deposition of sand and silty sand. Deposits of peat that separate clastic deposits indicate periods of limited flooding or nonflooding. Relatively thick peat deposits at or near the tops of stratigraphic sections 4 and 5 indicate abandonment.

The Kuparuk route crosses abandoned flood-plain deposits from the eastern boundary of the Kuparuk River flood plain to the junction of the road to the Kuparuk water reservoirs and Drill Pad M north of the route. West of this junction (to the crossing of the pipeline from Drill Pad M and the adjacent junction of the road to Service City), the route crosses inactive flood-plain deposits. A morphologic difference between these deposits and the abandoned flood-plain deposits is the absence of low-center ice-wedge polygons in the inactive deposits. West of the junction to Service City, the route crosses sand and gravel channel deposits. Unvegetated deposits such as these have been used to construct many nearby roads and drill pads. Gravel-removal activities are apparent in figure 19 in the channel north of the three water reservoirs and in the channel west of Service City.

West of the channel deposits, the Kuparuk route again crosses inactive flood-plain deposits. Eolian dunes composed of sand from adjacent channel deposits are present north and south of the route along the eastern edge of inactive flood-plain deposits. The dunes are vegetated and thus obscured south of the route, but are nonvegetated and well defined to the north. The route continues to the left edge of figure 19 across abandoned flood-plain deposits with well-defined low-center ice-wedge polygons.

Near the center of figure 22, the route leaves abandoned flood-plain deposits and again crosses sand and gravel channel deposits to the Kuparuk River bridge. Remains of a bridge that was destroyed by river ice in June 1980 are in the channel just south of the new bridge.

Stop 8.

The Kuparuk River bridge was constructed in 1981 at a cost of about $8 million. Under contract to ARCO Alaska, Inc., Peratrovich & Nottingham, Inc., of Anchorage designed this bridge, which was built by Morrison-Knudsen Company, Inc. When the Kuparuk River was channeled through the 90-m (300 ft) wide area, unique engineering and design features were necessary to prevent thaw around foundation piles set in permafrost that underlies the active flood plain (fig. 23).

Figure 18. Kuparuk route (NPAS Prudhoe Bay photograph 10-12, 1980). See also Section B (fig. 69; fig. 70) and Section C (ice-wedge polygons, nonsorted circles, thaw lakes, and strangmoor).

Refrigeration and heat-pipe systems in each foundation pile maintain ground temperatures to avert thawing of the surrounding soil and subsequent settlement problems. During the two-week period of breakup, when the river can reach a width of 2,750 m (9,000 ft), flow is diverted over a 300-m (1,000 ft) section of the east embankment that is below flood stage. This design feature makes the crossing inaccessible during this time, but it significantly reduced the cost of bridge construction.

The Kuparuk River bridge consists of four 90-m (300 ft)-wide box girders placed on 120-cm (48 in.)-diameter foundation piles. For the bridge approach embankments, 34,000 m^3 (45,000 yd^3) of gravel fill were deposited. To reduce erosion, the embankments and the section of road flooded during breakup were covered by 11,000 m^2 (100,000 ft^2) of concrete block tied together with 1.25-cm (0.5 in.)-diameter wire and assembled in 2.4 by 12 m (8 by 40 ft)

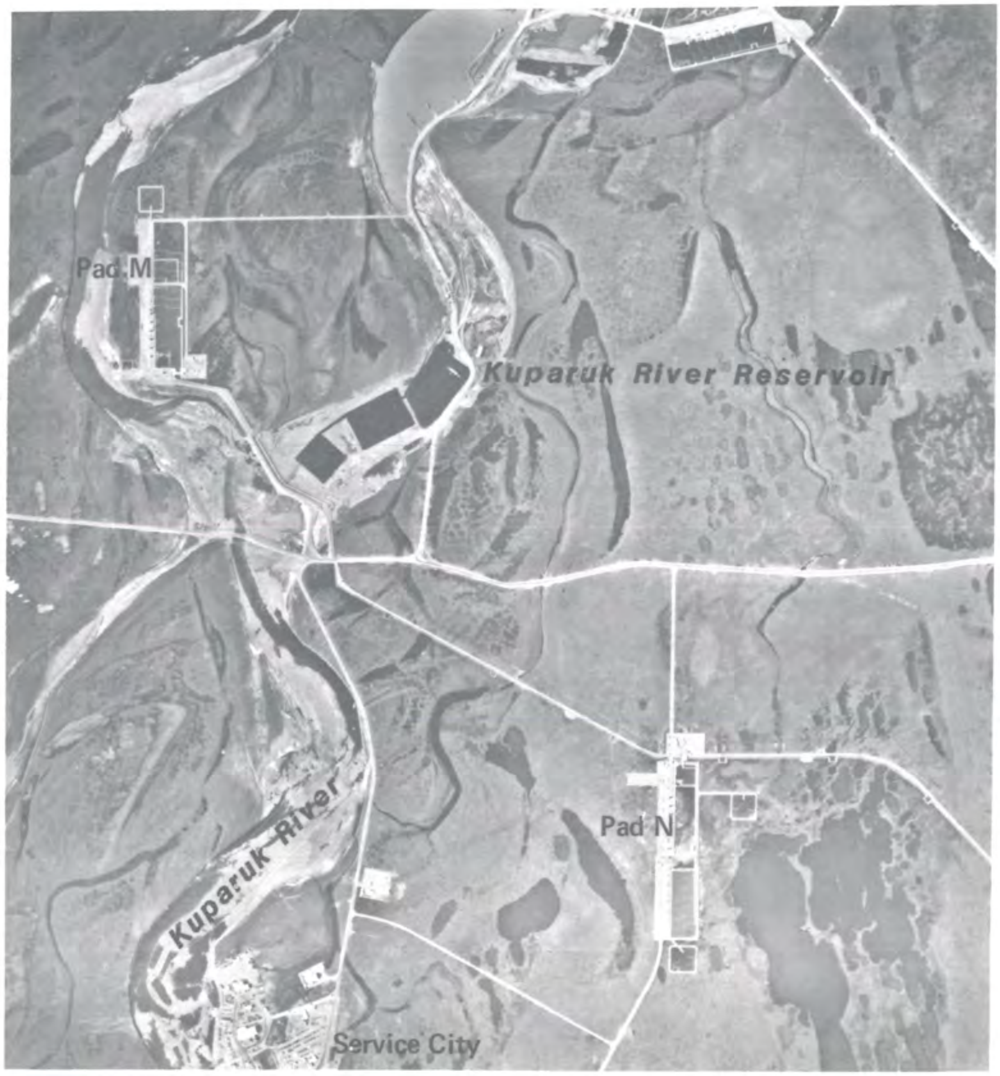


Figure 19. Kuparuk route (NPAS Prudhoe Bay photograph 10-10, 1980). See also Section B (fig. 69; fig. 70) and Section C (thaw lakes, pingos, reticulate patterned ground, ice-wedge polygons, hummocks, river flooding, gravel removal, eolian forms and processes, strangemoor and taliks).

mats. The structure can accommodate loads up to 2,086 metric tons (2,300 tons) (Alaska Construction and Oil, 1982).

From the Kuparuk River bridge to the western scarp of the flood plain, the route crosses flood-plain and channel deposits. Coastal plain deposits---generally peat overlying sand and sandy gravel---are exposed in the 5-m (16 ft)-high scarp. Eolian dunes are visible north and south of the route along the top of the scarp.

Terrain west of the Kuparuk River is more topographically variable than terrain in the Prudhoe Bay area. Large, broad pingos outside of defined lake basins are very common, and many have been deeply cut by thaw lakes (or their shapes have been modified during growth by thaw lakes).

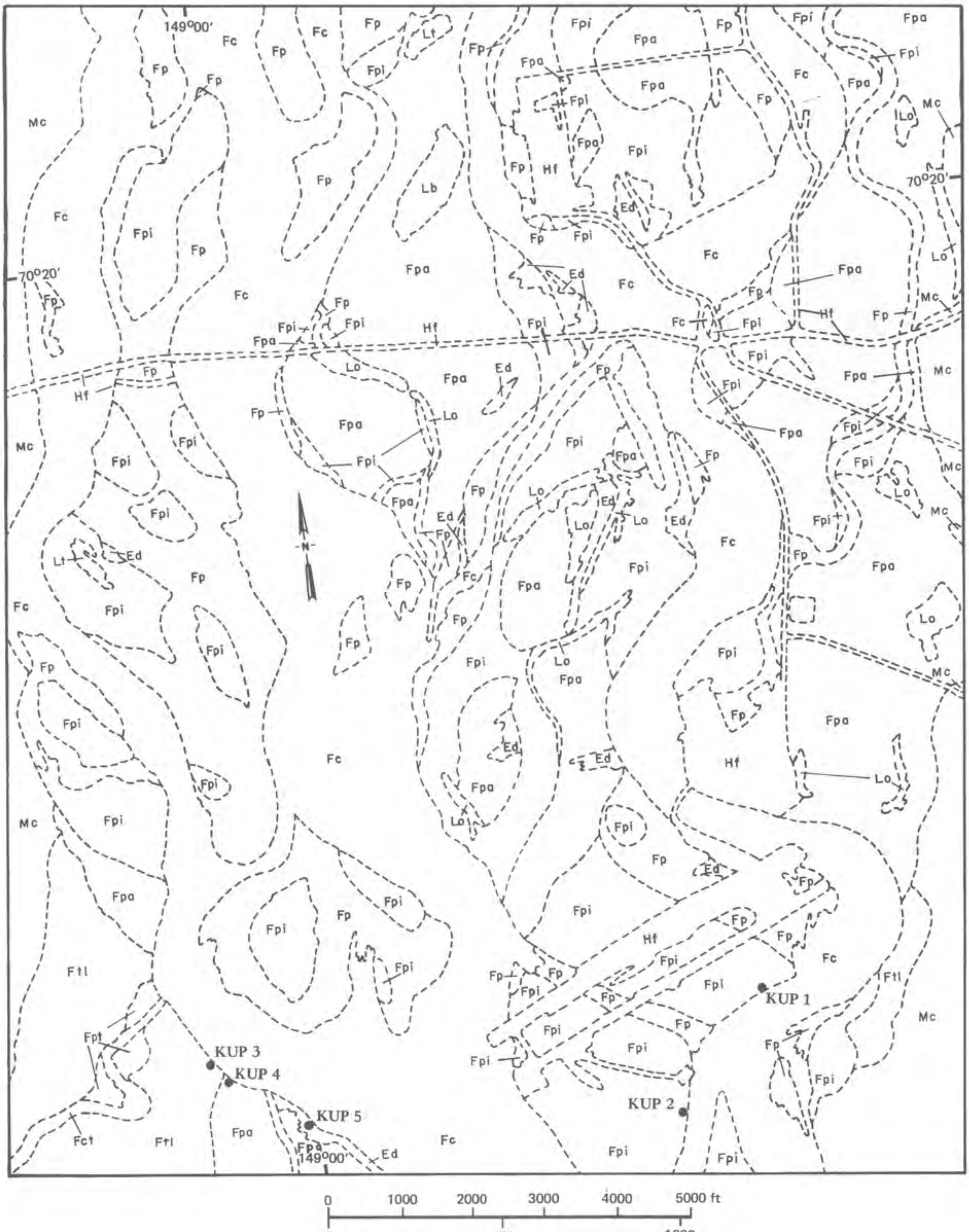


Figure 20. Surficial-geology map of part of the Kuparuk River flood plain.

MAP EXPLANATION
(modified from Cannon and Rawlinson, 1981)

Fc CHANNEL DEPOSITS—Well-sorted sand and gravel within active channels; perennially unfrozen.

Fp ACTIVE FLOOD-PLAIN DEPOSITS—Well-sorted sand and gravel, may contain small amounts of silt and organic matter; little or no vegetation; subject to frequent inundation and icing; perennially unfrozen.

Fpi INACTIVE FLOOD-PLAIN DEPOSITS—Well-sorted sand and gravel with some silt and organic matter; with silt and fine sand cover generally less than 1 m (3.3 ft) thick; moss, grass, and low-bush vegetation; surface may have meander scars or oxbow lakes and indistinct polygonal ground; subject to frequent inundation; continuously frozen, active layer to 0.6 m (2 ft) thick; low ice content.

Fpa ABANDONED FLOOD-PLAIN DEPOSITS—Bedded peat, silt, and fine sand 1 to 1.5 m (3.3 to 4.9 ft) thick over sand and gravel with some silt and organic matter; tundra vegetation; surface has meander scars, oxbow lakes, and polygonal ground; thaw lakes are rare; surfaces are generally bounded by clearly defined scarps; surface is to 2 m (3.3 to 6.6 ft) above inactive flood-plain surface; eolian sand dune and cover deposits may be present; subject to infrequent inundation, continuously frozen, active layer to 0.6 m (2 ft) thick; moderate ice content.

Ftl LOW-TERRACE DEPOSITS—Bedded peat, silt, and fine sand 1 to 1.5 m (3.3 to 4.9 ft) thick over sand and gravel with some silt and organic matter; tundra vegetation; surface has meander scars, oxbow lakes, and distinct low-center ice-wedge polygons, thaw lakes and pingos may be present; bounded by scarps that are often poorly defined; terrace tread is 2 to 4 m (6.6 to 13 ft) above inactive floodplain surface; active and stabilized eolian sand-dune and cover deposits may be present; not subject to inundation; continuously frozen, active layer to 0.6 m (2 ft) thick; moderate to high ice content.

Fct THAW-CHANNEL DEPOSITS—Well-sorted sand and gravel in thaw channels; silt and fine sand in small channels; may contain a small amount of organic matter; no vegetation; deposits are derived locally from erosion of coastal-plain deposits; subject to frequent inundation; perennially unfrozen.

Fpt THAW FLOOD-PLAIN DEPOSITS—Chiefly silt and fine sand with a small amount of gravel and organic matter, grass and moss vegetation; meander scars may be present on higher levels; subject to frequent inundation; continuously frozen, active layer to 0.6 m (2 ft) thick.

Lt THAW-LAKE DEPOSITS—Bedded silt, fine sand, and organic matter; organic matter dominant near surface; thaw bulb below filled lakes, depth of thaw depends on lake size; drained lakes are continuously frozen, active layer to 1 m (3.3 ft) thick; little or no ground ice depending on the size of the basin - small basins may have ice wedges, polygons, large basins have no ice.

Lo OXBOW-LAKE DEPOSITS—Bedded silt, fine sand, and organic matter over flood-plain deposits; thaw bulb below lake, depth of thaw depends on the lake size.

Ed DUNE DEPOSITS—Fine and medium sand; little or no vegetation, grass and low brush when present; dry frozen; sand derived chiefly from flood-plain deposits.

Hf FILL DEPOSITS—Sand and gravel artifically deposited.

Mc COASTAL-PLAIN DEPOSITS—Chiefly peat, silt and fine sand with a small amount of gravel over sand and gravel; tundra vegetation; continuously frozen, active layer to 0.6 m (2 ft) thick; moderate to high ice content.

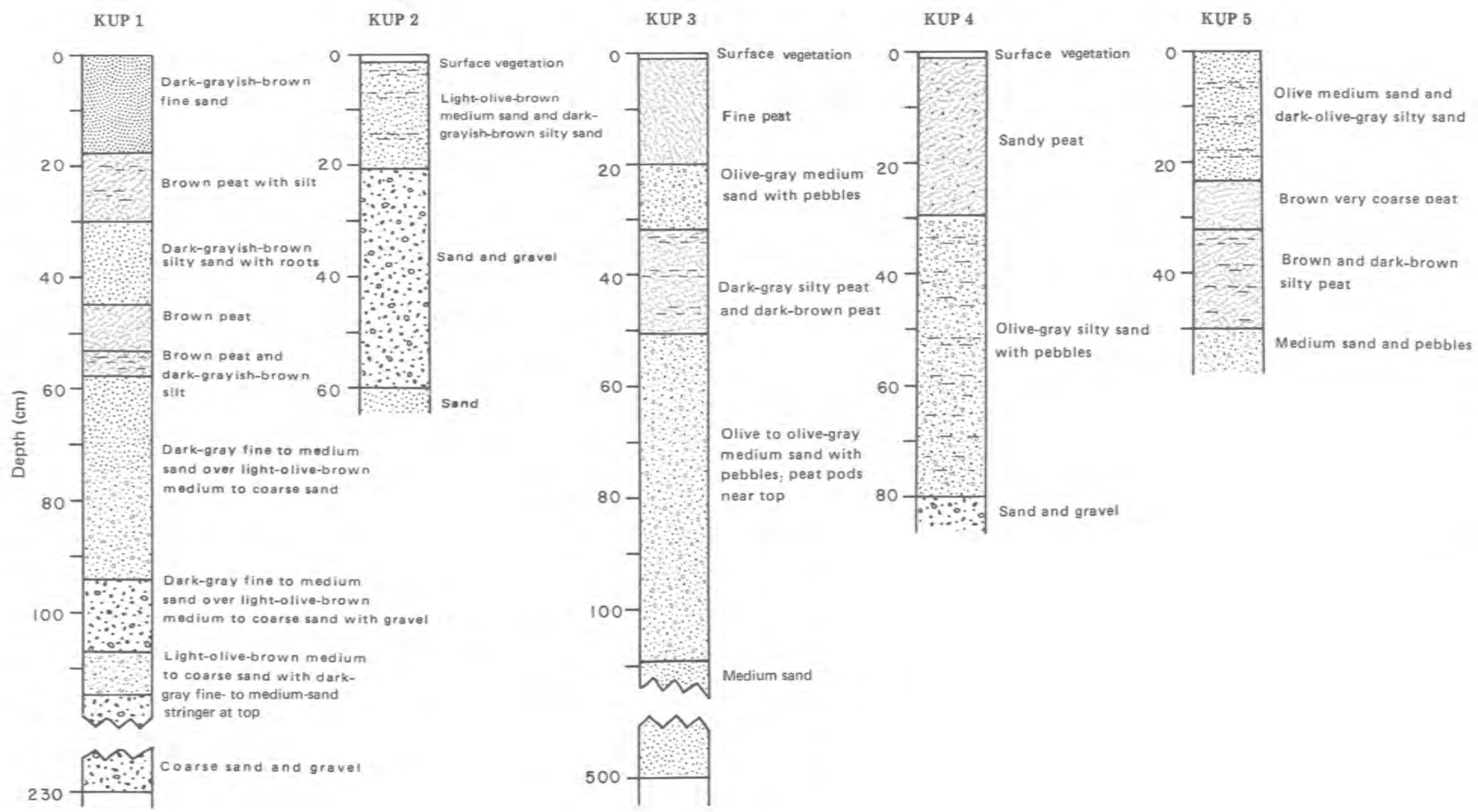


Figure 21. Stratigraphic sections of Kuparuk River inactive flood-plain deposits (KUP 1 and 2), abandoned flood-plain deposits (KUP 4 and 5), and low-terrace deposits (KUP 3) near the Kuparuk route.

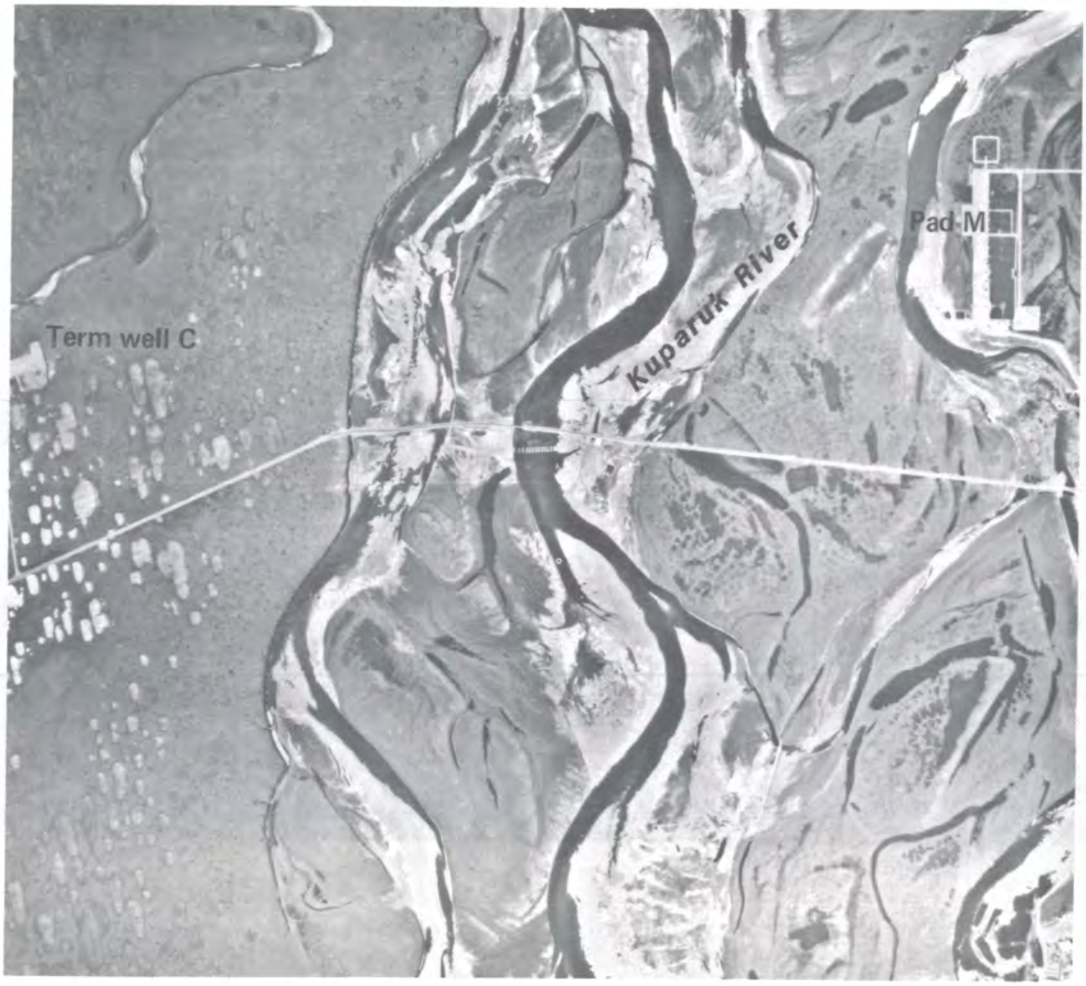


Figure 22. Kuparuk route (NPAS Prudhoe Bay photograph 10-8, 1980). See also Section C (eolian forms and processes, thaw lakes, pingos, and aufeis).

The large pingos suggest that the coastal-plain surface west of the Kuparuk River is older than the surface in the Prudhoe Bay area, which generally has small pingos that are within well-defined lake basins. Much of the Prudhoe Bay area has been modified by river migration and may be younger than adjacent areas. Radiocarbon dates reported by Smith and others (1980) indicate that Putuligayuk River terrace sand and gravel were deposited as late as 5,500 yr B.P., and that the new Putuligayuk River was established by 2,150 or possibly 3,900 yr B.P. The onset of peat accumulation elsewhere on the coastal plain was dated at 8,500 years B.P.

Rapid development for production of the Kuparuk field and other wells west of the Kuparuk River has occurred since 1979. Today a pipeline that carries oil from the Kuparuk field to Pump Station 1 parallels the Kuparuk route west of the Kuparuk River and diverges and crosses the river about 2 km (1.3 mi) south of the Kuparuk River bridge. Another pipeline that connects wells north of the Kuparuk route (west of the Kuparuk River) with Gathering Center 2 crosses the river about 2 km (1.3 mi) north of the Kuparuk River

Figure 23. The Kuparuk River bridge. Photograph by S.E. Rawlinson, 1982.

bridge. New roads from the Kuparuk route are also evident.

The Kuparuk route turns southwest at the western boundary of the Kuparuk River flood plain and crosses an area dotted by thaw ponds to a road that leads northward to Term Well C drill pad. Test pits in this area and elsewhere suggest that areas with numerous closely spaced thaw ponds have a very high ground-ice content.

The Kuparuk route crosses an unnamed tributary of the Kuparuk River west of the road that leads to Term Well C near the right side of figure 24. In a zone along both sides of this stream and in similar streams, there is often a notable paucity of thaw lakes, and the terrain is dry and slightly elevated. Good drainage within this zone promotes an aerobic condition that accounts for thinner organic accumulations, which make these soils very susceptible to frost heaving and massive-ice buildup (Walker and others, 1980).

Small thaw streams---such as the unnamed tributary---result from thaw and drainage along connected ice wedges. Initially, water may drain along the melting ice wedges on top of a depressed tundra mat. Eventually, this mat is broken, and sand and gravel that are derived locally from erosion of coastal-plain deposits accumulate in the channel. Sand and gravel deposits are light-gray patches within the channel in figure 24. As the stream increases

Figure 24. Kuparuk route (NPAS Prudhoe Bay photograph 10-6, 1980). See also Section C (ice wedges, ice-wedge polygons, thaw lakes, and pingos).

in size, the initial ice-wedge control becomes progressively less evident. As the stream meanders, inactive flood-plain and point-bar deposits remain. Such deposits are visible near the bottom of figure 24.

From the unnamed tributary, the Kuparuk route continues southwest across an area of low-center ice-wedge polygons and thaw ponds. The route crosses a distinct lake-basin boundary at the intersection of a road that leads northward to MPC 13-15-11-12 drill pad. This lake boundary indicates the former size of the large, elongate lake along the left edge of figure 24. A well-developed system of orthogonal ice-wedge polygons is evident on the drained portion of the lake. The route continues past the southern end of the lake and crosses another small drained lake basin before the intersection of an abandoned road and the road to an airstrip just visible at the bottom-left corner of figure 24.

The abandoned road trends northward from the Kuparuk route along the eastern shore of a large drained lake basin, crosses the Sakonowyak River, and then trends parallel to the river to the top-right corner of figure 25. Water-filled thaw depressions bound the road on both sides. West of the abandoned road, the Kuparuk route enters the drained lake basin. Ice-wedge polygons have been reestablished in the lake basin since it drained through the small thaw channel at its northern end. The route leaves the lake basin near the bottom-right center of figure 25 and crosses an area of numerous thaw ponds and ice-wedge polygons.

As with the Kuparuk River tributary previously described, the Sakonowyak River at the bottom-left center of figure 25 is bounded by lake-free zones. Sand and gravel exposed during installation of culverts in the road at the Sakonowyak River appear white in figure 25. The flood plain extends to the edges of the graded area. West of the Sakonowyak River (left edge of figure 25), the Kuparuk route crosses an area of numerous thaw ponds and ice-wedge polygons. Two large pingos within this area are visible in the bottom-left corner of figure 25. The low, broad pingo nearest the road and adjacent to

Figure 25. Kuparuk route (NPAS Prudhoe Bay photograph 10-4, 1980). See also Section C (thaw lakes, linear and polygonal depressions, ice-wedge polygons, and pingos).

Chevron Tract Well 23-18-11-12 is typical of pingos west of the Kuparuk River.

The Kuparuk route skirts the top margin of a partially drained lake basin west of Chevron Tract Well 23-18-11-12 at the bottom-left center of figure 26. Water remains in the deeper central part of this basin, although a thaw channel connects it with a thaw lake north of the route. Many elongate lakes on the coastal plain have a deep central trough bounded along the long sides by distinct shelves. Commonly a shelf encircles the trough, as is the case with the basin along this route. The mechanism that forms these shelves is uncertain. Perhaps near shore, where water annually freezes to the lake bottom, permafrost is maintained and thus not quickly eroded; near the center of the basin, where water may not freeze to the lake bottom, permafrost is thawed and thus rapidly eroded. Preferential deposition of sediment along the long sides of the lake is another possible explanation for the shelves.

North of the route, the thaw lake connected via a thaw channel to the partially drained lake has incised the eastern flank of a large pingo that is

Figure 26. Kuparuk route (NPAS Prudhoe Bay photograph 10-3, 1980). See also Section C (thaw lakes, pingos, and taliks).

not within obvious strandlines. The pingo is thus relatively old and predates the lake, although absolute ages are unknown. Southwest from the pingo and adjacent to the Kuparuk route on the south, another thaw lake with an encircling shelf is visible in the bottom-left corner of figure 26. The shelf on this lake is flooded and supports various aquatic vegetation.

The Kuparuk route continues westward along the bottom of figure 27 and discontinuously along the top of figure 28 amid thaw lakes and thaw-lake basins. These lakes and lake basins have incised many large pingos and broad elevated areas. Near the top-left corner of figure 28, the route crosses a lake basin that has cut deeply into the adjacent elevated terrain; relief is up to 3 m (10 ft) and is especially apparent on the western scarp. A small water reservoir is partially visible in the top-left corner of figure 28.

Figure 27. Kuparuk route (NPAS Prudhoe Bay photograph 10-1, 1980). See also Section C (thaw lakes and pingos).

The reservoir in the top-right corner of figure 29 is adjacent to an unnamed stream that meanders across the coastal plain from nearby uplands and enters Simpson Lagoon near Kavearak Point. A new road turns north from the Kuparuk route west of the unnamed stream and terminates at several drill pads near Milne Point, which is also along Simpson Lagoon. From the reservoir, the Kuparuk route follows the stream southwestward. Two new roads have been added along this stretch of the route. The first road leads westward directly to the main facilities of the Kuparuk field, and the second road leads southward to a new drill pad.

Stop 9.

Beaded drainage along the unnamed stream is visible from the Kuparuk route at several places where it parallels the stream. Beaded drainage con-

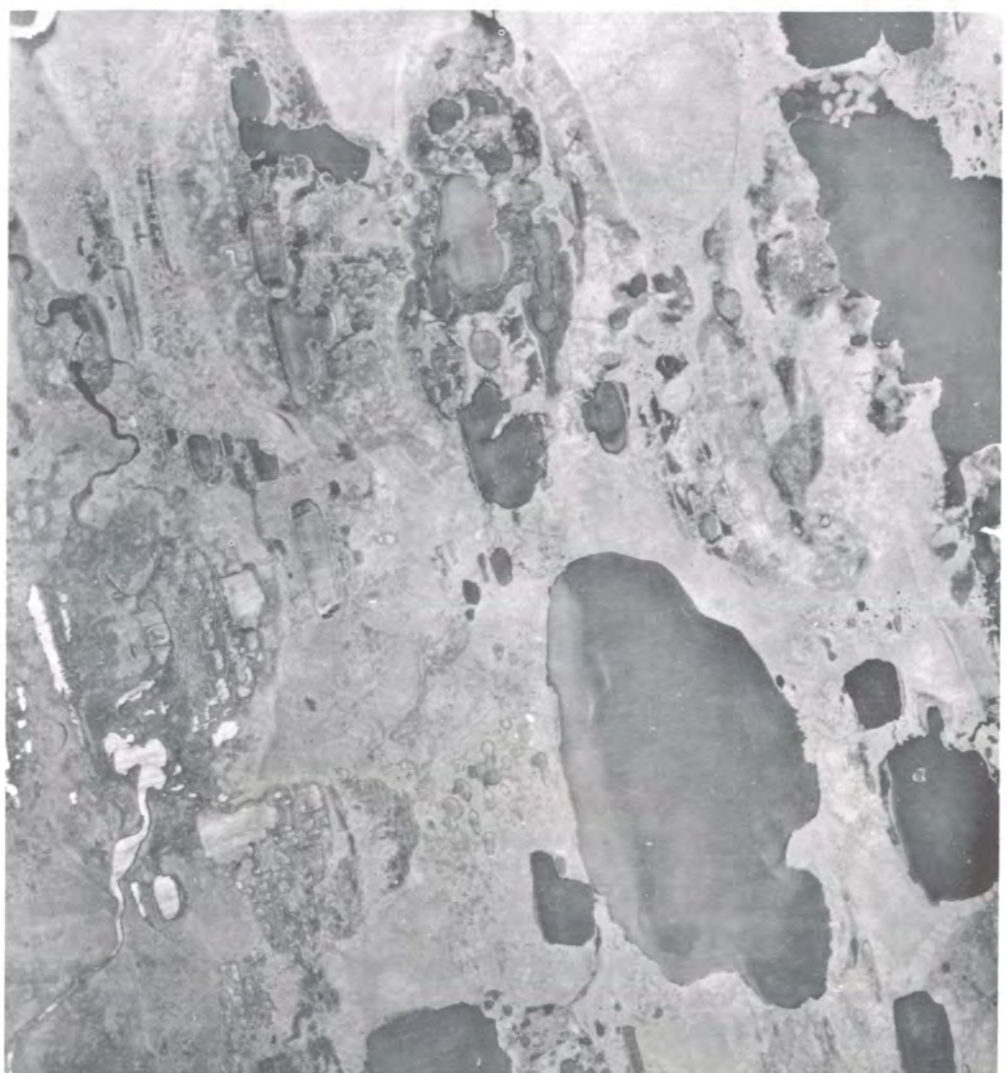


Figure 28. Kuparuk route (NPAS Prudhoe Bay photograph 11-10, 1980). See also Section C (thaw lakes and pingos).

Figure 29. Kuparuk route (NPAS Prudhoe Bay photograph 11-8, 1980). See also Section C (gravel removal, ice wedges, ice-wedge polygons, and pingos).

sists of a series of small pools (at ice-wedge intersections) connected by short channels (fig. 30) (Hopkins and others, 1955; Lawson and Brown, 1978; Washburn, 1980). The pools are 1 to 3 m (3.3 to 9.8 ft) deep, up to 20 m (66 ft) in diameter, and have steep banks that result from thawing and collapse of large ice masses (Hopkins and others, 1955). The straight or angular pattern of the connecting channels results from warm surface waters that flow along polygonal ice wedges (Hopkins and others, 1955; Lewellen, 1972; Washburn, 1980). Rex (1953) noted that beaded streams are the smallest permanent streams flowing on the tundra; their flow and gradient are inadequate to extensively erode the channel.

Near the top-center of figure 29, the unnamed stream turns southward, and the Kuparuk route continues southwestward across an area characterized by low-center ice-wedge polygons. In the left center of figure 29 just north of the large thaw lake, the route crosses the southern flank of C-60 Pingo.

Figure 30. Beaded drainage of a thaw stream in the Prudhoe Bay vicinity. Photograph by S.E. Rawlinson, 1982.

Stop 10.

C-60 Pingo was drilled and logged by Cold Regions Research and Engineering Laboratory (CRREL) personnel in May 1982; the complete borehole stratigraphy is given in Section C under the discussion of pingos (p. 111). Generally, about 7 m (23 ft) of ice-rich coarse alluvial and outwash sediments overlie at least 22 m (72 ft) of massive ice with chips of gravel (Brockett, 1982). This ice thickness corroborates the old age of both this pingo and presumably of other large, broad pingos in the area. From the top of C-60 Pingo, the number of lakes and the variety of natural features can be viewed. The main facilities of the Kuparuk field are visible to the west.

From C-60 Pingo, the Kuparuk route continues southwestward across elevated terrain and drained lake basins to Kuparuk D pad (fig. 31). Beyond Kuparuk D pad, the route turns northwestward along the boundary of a partially drained thaw-lake basin that contains numerous thaw ponds and orthogonal ice-wedge polygons. The route leaves the lake basin near the left center of the figure and crosses an area characterized by low-center ice-wedge polygons to a meandering thaw stream in the top-left corner of figure 31.

Figure 32 extends the coverage of the coastal plain westward from figure 31. The main facilities of the Kuparuk field are just beyond these figures. The Kuparuk field [67 km (40 mi) west of Prudhoe Bay] was discovered in May 1969 in a joint venture between Sinclair Oil Company and British Petroleum.

Figure 31. Kuparuk route (NPAS Prudhoe Bay photograph 11-6, 1980). See also Section C (pingos, thaw lakes, and ice-wedge polygons).

The oil reservoir in the Kuparuk field is the Kuparuk Formation of Early Cretaceous age. The oil is extracted from a 15-m (49 ft)-thick sandstone layer that is 1,920 m (6,300 ft) below sea level; no gas cap is present. In the late 1970s, after the world price of oil increased sufficiently to make the field economically viable, ARCO Alaska, Inc., initiated development. To avoid duplication of production facilities, the field was later unitized. ARCO now owns about 58 percent of the Kuparuk unit; Sohio and British Petroleum are the other principal leaseholders (Arco Alaska, Inc., 1982).

The Kuparuk Operations Center (constructed in 1980) houses 96 employees and a construction camp houses 360 workers. In 1983-84, a second construction camp for 650 workers will be built. Currently, eight drill sites with a total of 90 producing and water-injection wells supply crude oil to the Central Production Facility (CPF) adjacent to the operations center. This facility, which was delivered in 21 modules by the 1981 sealift, separates gas and water

Figure 32. Kuparuk route (NPAS Prudhoe Bay photograph 11-4, 1980). See also Section C (gravel removal, thaw lakes, cryoturbation features, and nonsorted circles).

from the oil and compresses the gas for reinjection. The current daily production capacities are 120,000 bbl of oil, 8,000 bbl of water, and 3.7 million m^3 (130 million ft^3) of gas; 3.1 million m^3 (110 million ft^3) of gas are reinjected. Since December 1981, the CPF has supplied more than 100,000 bbl of oil per d to Pump Station 1 via a 42-km (26 mi)-long, 41-cm (16 in.)-diameter elevated pipeline that will later be replaced by a 61-cm (24 in.)-diameter pipeline (ARCO Alaska, Inc., 1982).

Stop 11:

Gravel has been mined in an open pit adjacent to the main Kuparuk facilities since the late 1970s (fig. 33). This pit has been enlarged in the past few years and another pit has been excavated west of the main Kuparuk facilities to satisfy the demand for gravel for westward expansion of the oil-field facilities. An excellent section of coastal-plain sediments is exposed

Figure 33. Oblique aerial photograph of the Kuparuk gravel pit. The Ugnuravik River west of the pit flows northward toward the Beaufort Sea. Photograph by S.E. Rawlinson, 1982.

in the Kuparuk pit to a depth of about 10 m (33 ft). Organic-rich silt and sand of probable eolian and lacustrine origins overlie about 5 m (16 ft) of alluvial sand that gradationally overlies at least 4 m (13 ft) of outwash gravel.

A thaw gully that drained a lake along the eastern side of the pit (fig. 34), facilitated a detailed description of the stratigraphy of a lake basin, the lake edge, and the surrounding tundra (fig. 35). The tundra section adjacent to the lake basin consists chiefly of peat layers over medium sand, typical of the materials underlying most tundra in the Prudhoe Bay area. A sequence of material similar to the tundra section is evident at the lake-basin margin, but these deposits overlie depressed deposits of the tundra section. Peat pods within the basal sand, indicative of cutting and mixing, are present in the depressed deposits. The pods diminish toward the center of the basin. The section in the basin interior reveals similar materials to the other sections, but includes undecomposed organic material and exhibits more thorough intermixing with the underlying deposits. Except for the uppermost peats, sand is intermixed in the peat layers and peat pods are intermixed with sand near the base. This intermixing indicates lake deepening as a result of thawing of underlying sediments and subsequent cutting of previously depressed deposits.

Figure 34. Oblique aerial photograph of a small, drained thaw lake and thaw gully adjacent to the Kuparuk gravel pit. Vegetation-rimmed nonsorted circles (peat rings) surround the thaw lake. Photograph by S.E. Rawlinson, 1982.

Vegetation-rimmed, nonsorted circles (peat rings) are also present near the drained thaw pond (fig. 34).

Putuligayuk River Route

The Putuligayuk River route extends from the Kuparuk route near Pump Station 1 to the West Dock route near the mouth of the Putuligayuk River (fig. 36).

Near the top-right corner of figure 37, the Putuligayuk River route trends northeastward from the Kuparuk route to the road that leads to Flow Station 3. Between the intersection of the two routes and this road, the route crosses the pipeline that connects Flow Station 3 with Pump Station 1. Low-center ice-wedge polygons are the primary surface features along this stretch of the route, but strangmoor and discontinuous, large ice-wedge polygons are present near the road to Flow Station 3.

The Putuligayuk River route north of the road to Flow Station 3 crosses hummocky reticulate patterned ground to the lake that partially surrounds Drill Site 7 west of the route. Blockage of suprapermafrost ground water by the nearby road network has refilled this preexisting lake basin.

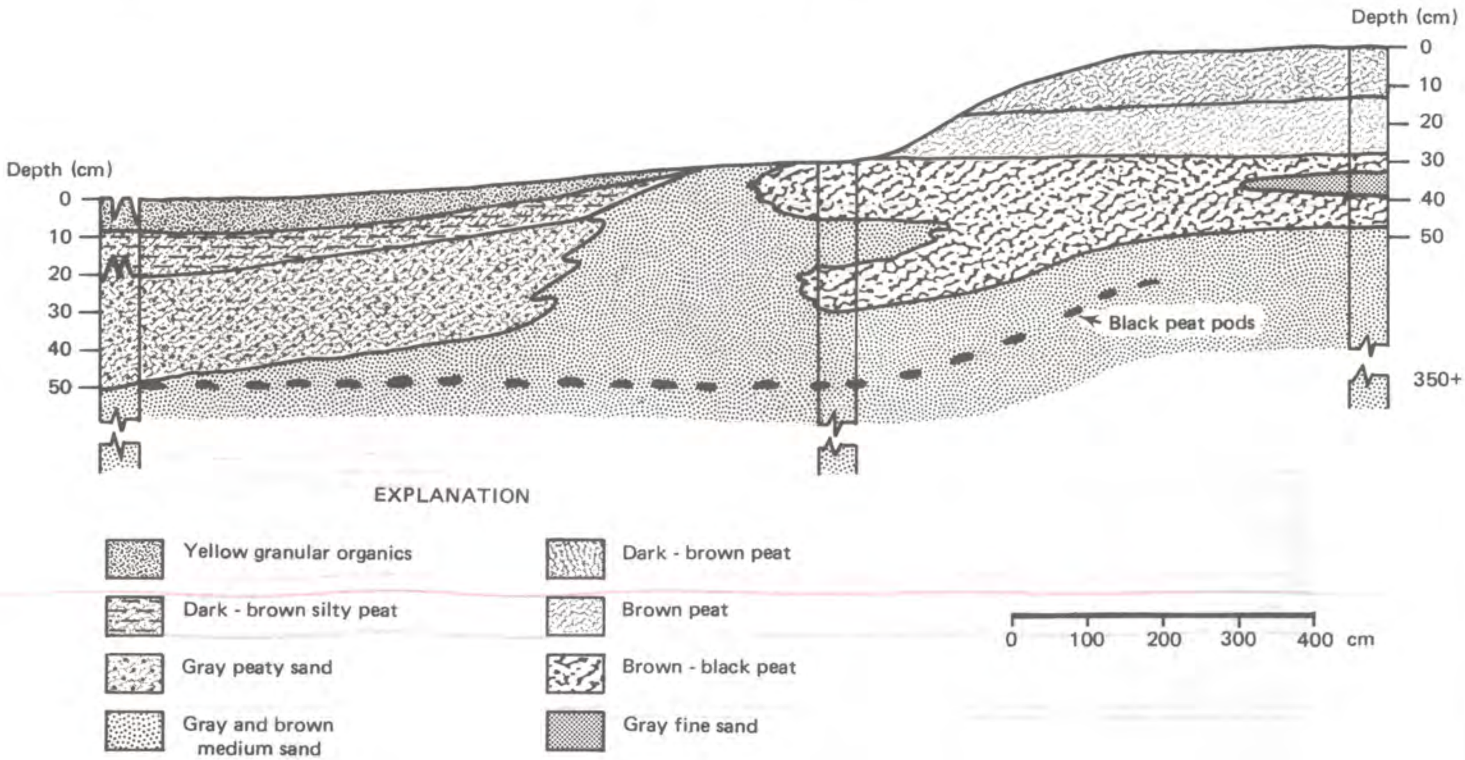


Figure 35. Diagram of the stratigraphy of the lake basin and surrounding tundra exposed in the thaw gully in figure 34.

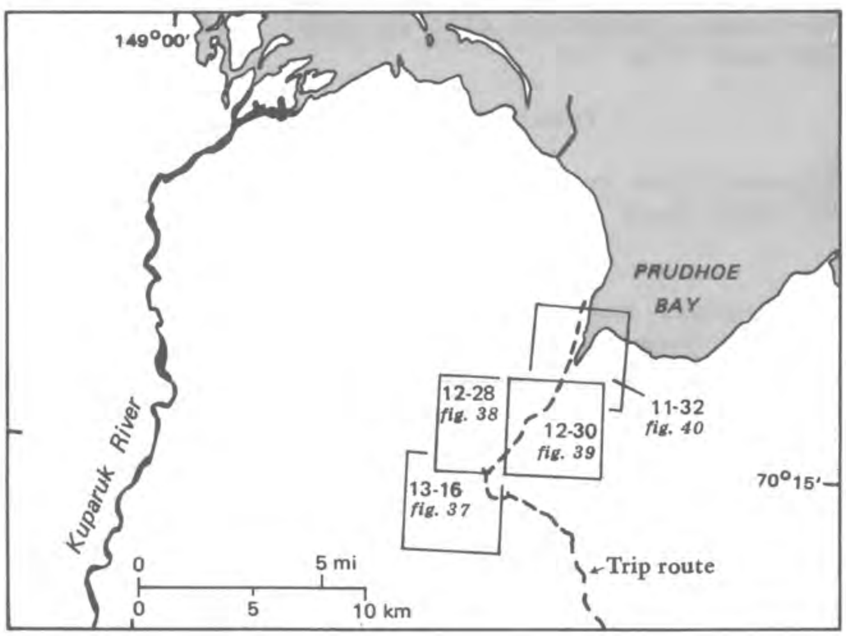


Figure 36. Index map of aerial photographs of the Putuligayuk River route, Prudhoe Bay, Alaska.

Figure 37. Putuligayuk River route (NPAS Prudhoe Bay photograph 13-16, 1980). See also Section B (fig. 72a, b, c) and Section C (ice-wedge polygons and strangmoor).

On figure 38, Weather Pingo is a small white oval at the north end of the lake, east of Drill Site 7. This pingo was cored by CRREL personnel in 1981 (Brockett, 1982). Generally, about 1 m (3.3 ft) of ice-rich, gravelly organic material overlies 12 m (39 ft) of bubble-rich ice that overlies gravel. The borehole was terminated at the gravel contact. This sequence of strata is typical of small, young pingos.

Most of Drill Site 7, the northwestern extension of the surrounding lake, Weather Pingo, and the storage pad north of the lake are on terrace deposits of the Putuligayuk River. The boundary between these deposits and adjacent coastal-plain deposits is very indistinct, but it trends roughly from the bottom-left corner of the photograph to the center-right edge of the photograph. Oxbow lakes occur within this boundary northwest of Drill Site 7 and the storage pad. The Putuligayuk River route enters the terrace deposits

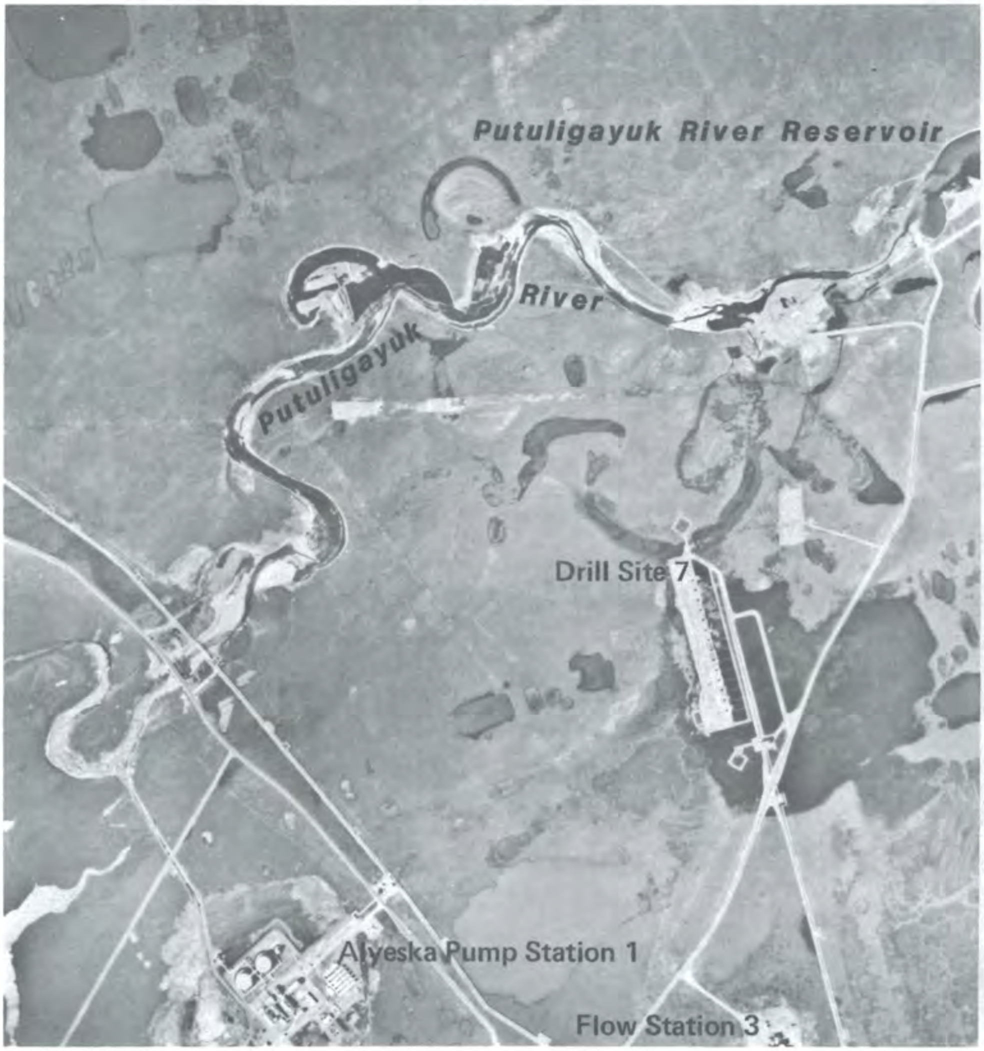


Figure 38. Putuligayuk River route (NPAS Prudhoe Bay photograph 12-28, 1980). See also Section B (fig. 72) and Section C (hummocks, reticulate patterned ground, linear and polygonal depressions, thaw lakes, pingos, ice-wedge polygons, and strangmoor).

between the large lake and the road to the storage pad. Low-center ice-wedge polygons are common from the lake to a point where the oxbow lake is adjacent to the route. At that point, strangmoor and large-diameter ice-wedge polygons are present in a narrow band east of the route. North of the oxbow lake, the route crosses frost-boil terrain that extends to the large river meander at the right edge of figure 38.

The Putuligayuk River turns eastward at the three-way intersection and skirts the southern end of the large meander of the Putuligayuk River.

Stop 12.

The large meander has been excavated for gravel in recent years. A sand

and gravel dam at the northern end now allows the meander to serve as a water reservoir. Permafrost-related terrain features that are encountered on a northeastward traverse along the rim of the meander include frost-boils, low-center polygons, high-center polygons, reticulate patterned ground, and hummocks.

Terraces along the Putuligayuk River were probably deposited by a major branch of the Sagavanirktok River (Cannon and Rawlinson, 1979; Smith and Hopkins, 1979). D.M. Hopkins (Smith and Hopkins, 1979) suggested that a paleovalley offshore from Prudhoe Bay was cut and filled by this large stream and that Prudhoe Bay, now widened by erosion, was the resultant estuary as sea level rose. The pit exposes deposits to about 12 m (39 ft) below the surface; about 1 m (3.3 ft) of bedded, organic-rich silt and sand from deposition in the oxbow lake overlie about 1 m (3.3 ft) of dark-grayish-brown alluvial sand, that coarsens downward and overlies about 10 m (33 ft) of outwash sand and gravel. Most gravel is 2 to 5 cm (0.8 to 2.0 in.) diameter, but some is up to 15 cm (6 in.) diameter. A detrital peat sample (USGS I-10642) (Hopkins and others, 1980) collected 1.8 m (5.9 ft) below the surface in the alluvial sand indicates that the terrace was still being built 5,500 yr B.P. The 'Canning Ash' [3,945 ± 145 yr B.P. (I-10369)] (Hopkins and others, 1980) may be present at the base of the oxbow deposits, and if so, the terrace was abandoned and the Putuligayuk River was incised by 3,900 yr B.P. If the 'Canning Ash' is not present, another sample (USGS I-10643) (Hopkins and others, 1980) indicates abandonment of the terrace and incision of the Putuligayuk River by 2,150 yr B.P. (Hopkins and others, 1980).

From the reservoir, the Putuligayuk River route trends northeastward across the terrace alluvium toward the Putuligayuk River Section 23 gravel mine at the top-center of figure 39. Sand dunes intersect the route between the reservoir and the abandoned road that crosses the route about half the distance to the mine. These dunes appear as light-toned, 'V-shaped' lines that are not discernible on the ground.

The Putuligayuk River route (fig. 40) skirts the Section 23 gravel mine, which is also within a large meander of the Putuligayuk River. Primary access into the pit is on the north side of the meander. Alluvial and outwash sand and gravel occur about 1 m (3.3 ft) below the surface. Oxbow-lake sediments that overlie this sand and gravel consist of three distinct layers: 1) basal gray, fine sand that fines upward to silt and clay; 2) very dark gray sandy silt with pods of fibrous peat near the base; and 3) an organic-rich silt capped by an active layer of vegetation. Near the base of the exposed sand and gravel, two organic horizons within alluvial deposits have been reported (Hopkins and Robinson, 1979; Hopkins and others, 1980). The lower of the two horizons is 9.5 m (31 ft) below the surface. Twigs of Salix and Populus (cottonwood or aspen) yielded a radiocarbon date of 35,600 yr B.P., which is within a postulated mild interstadial that lasted from 45,000 to 25,000 yr B.P. in northern Alaska and was characterized by alluviation and organic accumulation.

From the intersection of the road into the mine, the Putuligayuk River route continues northeastward across terrace deposits for a short distance to a pipeline crossover. This pipeline connects the Central Compression Plant with Flow Station 1. Just beyond this crossover, the Putuligayuk River route intersects the West Dock route.

Figure 39. Putuligayuk River route (NPAS Prudhoe Bay photograph 12-30, 1980). See also Section C (gravel removal, nonsorted circles, ice-wedge polygons, reticulate patterned ground, hummocks, and eolian forms and processes).

West Dock Route

The West Dock route extends from the East Dock route near the ARCO main Construction Camp to West Dock (fig. 41).

Spatial relationships of the West Dock route to the East Dock route and ARCO Operations Center are shown in figure 42. The intersection of the two routes is near the center of the left edge of the figure.

From the intersection of the two routes, the West Dock route trends westward to northwestward across an area characterized primarily by low-center ice-wedge polygons. Reticulate patterned ground occurs adjacent to the north side of the route near the southern end of the large thaw lake. The emergent

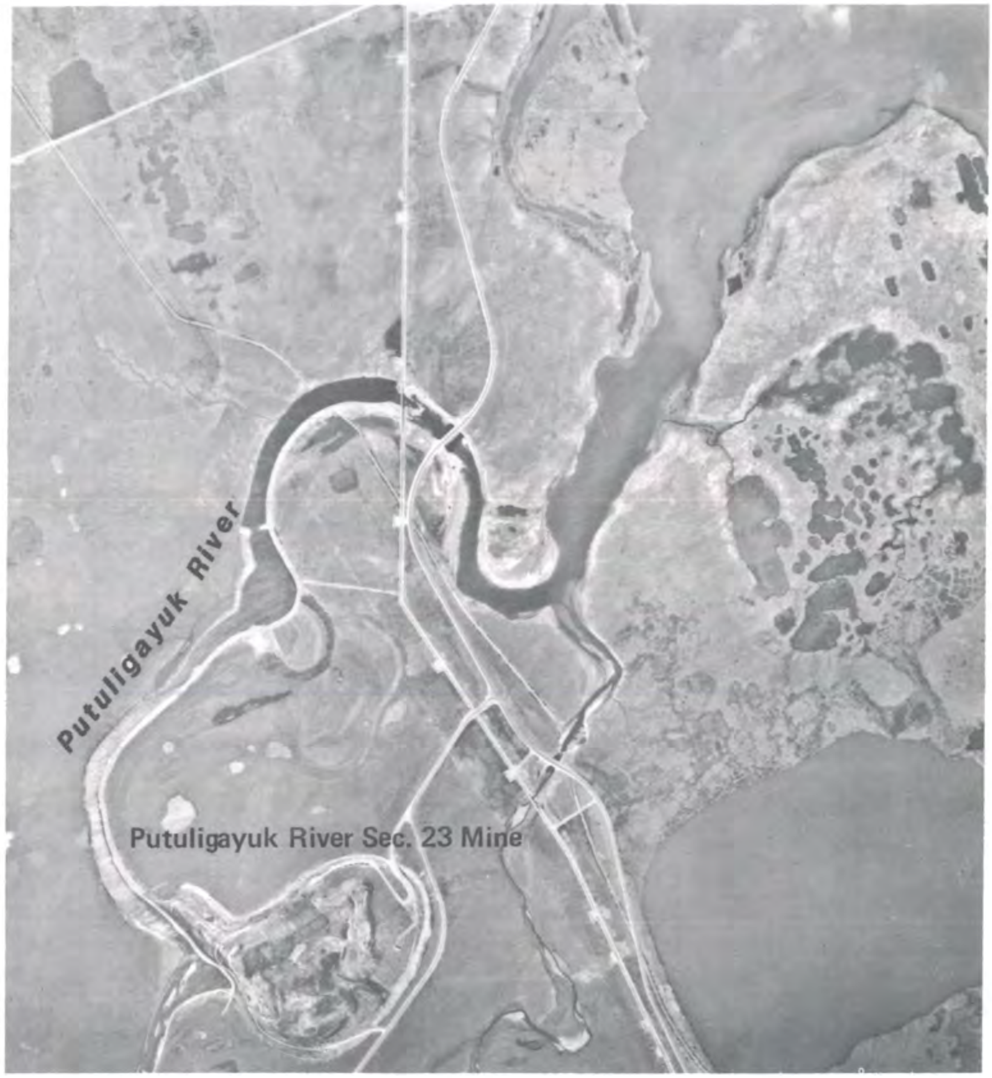


Figure 40. Putuligayuk River route (NPAS Prudhoe Bay photograph 11-32, 1980). See also Section C (gravel removal).

southern end of this lake is characterized by thaw ponds and large-diameter ice-wedge polygons. The route continues along the west side of the thaw lake adjacent to nonpatterned ground and then westward toward Flow Station 1 at the top center of figure 43. Low-center ice-wedge polygons are the dominant terrain feature along the route between the large thaw lake and the pipeline that trends from the top-right corner of figure 43 to Flow Station 1. Reticulate patterned ground is the dominant terrain feature along the route from the pipeline intersection to the flow station. Much of Flow Station 1 and adjacent Drill Site 10 are within two large, drained lake basins. The flow station is approximately on the boundary between these basins on the east shore of the older basin. This older basin is characterized by strangmoor and large-diameter ice-wedge polygons.

The West Dock route trends diagonally across nonpatterned ground in the younger of two basins between Flow Station 1 and Drill Site 10. The route detours around the drill site to minimize traffic. Nonpatterned ground

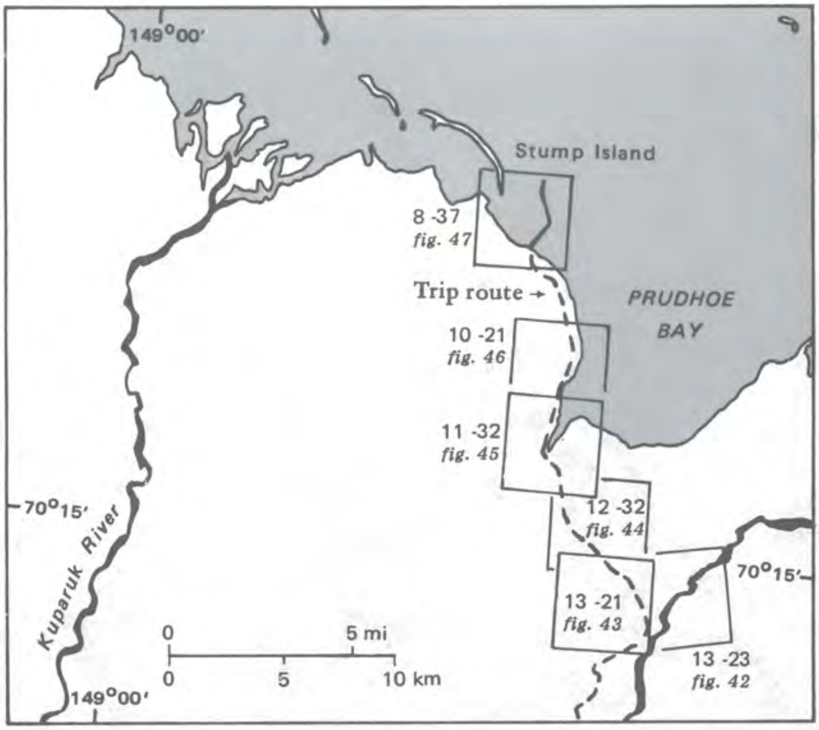


Figure 41. Index map of aerial photographs of the West Dock route, Prudhoe Bay, Alaska.

continues from the drill site to the small thaw pond and stream in the basin. Strangmoor and large-diameter ice-wedge polygons are the dominant terrain features from the stream crossing to where the stream again closely approaches the route. This latter point is also the approximate boundary of the thaw-lake basin. Between the basin boundary and Drill Site 2, the route crosses an area generally characterized by low-center ice-wedge polygons with a small area of high-center ice-wedge polygons near its center. Adjacent to Drill Site 2, the route turns northward. Pipelines west of the route connect the Central Compression Plant to Flow Station 1. The route crosses a narrow strip of reticulate patterned ground just north of the road to Drill Site 10 and again enters a drained lake basin. Strangmoor and large-diameter ice-wedge polygons within this basin are most evident on the east side of the road. A more recently drained lake basin is superimposed on the former basin. Drainage into the Little Putuligayuk River was recent enough that the basin floor is nonpatterned. 'Prudhoe Mound,' a small, well-formed pingo, is within this basin on the east side of the road.

Stop 13.

'Prudhoe Mound' has served as a scientific platform on several occasions, and meterological and other equipment are common at its summit. The pingo was cored by CRREL personnel in 1981 (Brockett, 1982). The stratigraphy is very similar to that of Weather Pingo, consisting of about 2 m (6.6 ft) of sand and gravel underlain by 9 m (29 ft) of ice that is underlain by gravel.

The West Dock route continues northwestward across the recently drained lake basin and leaves the basin near the southwest corner of the large thaw

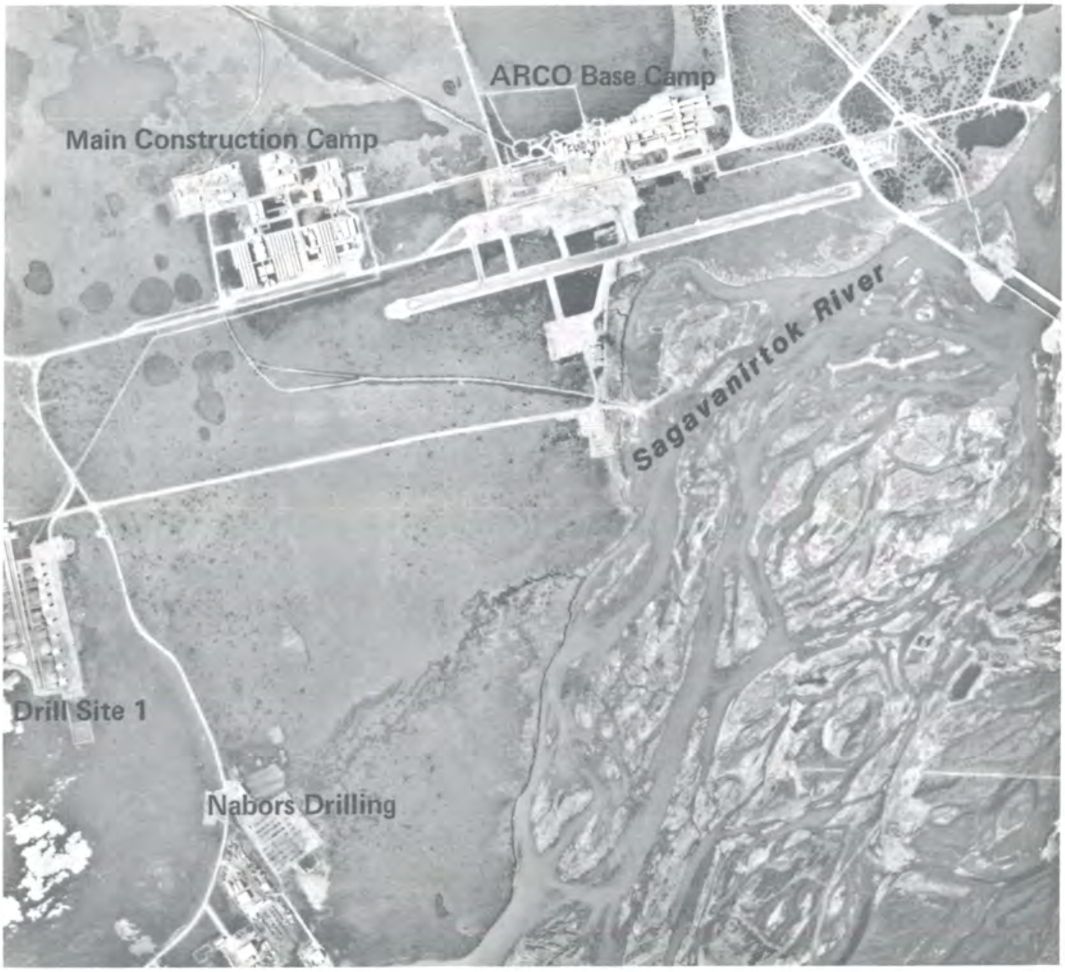


Figure 42. West Dock route (NPAS Prudhoe Bay photograph 13-23, 1980).

lake in the top-left corner of figure 44. At this boundary, the route crosses an abandoned road flanked by water-filled thaw depressions.

The route along the southwest shore of the large thaw lake in the bottom-right corner of figure 45 initially crosses ground characterized by low-center ice-wedge polygons. The large-diameter ice-wedge polygons and strangmoor that follow extend to the Little Putuligayuk River. North of the route, vehicle traffic to the discovery well before road construction deeply rutted the tundra by disturbing the insulating vegetative cover and causing the underlying permafrost to thaw. The northwestern side of the Little Putuligayuk River flood plain is the eastern limit of Putuligayuk River terrace deposits.

The West Dock route continues northwestward from the Little Putuligayuk River across terrace deposits and past the intersection of the Putuligayuk River route. It turns northeastward just south of the Putuligayuk River; the river crossing is normal to the channel. Within the turn, the pipeline that connects the Central Compression Plant and Flow Station 1 is near the route. At this point, an abandoned road that intersects the route continues northwestward and leads to the Prudhoe Bay field discovery well, about 2.5 km

Figure 43. West Dock route (NPAS Prudhoe Bay photograph 13-21, 1980). See also Section B (fig. 74; fig. 75) and Section C (ice-wedge polygons, reticulate patterned ground, thaw lakes, and strangmoor).

(1.6 mi) from the Putuligayuk River. North of the intersection, the West Dock route enters the Putuligayuk River flood plain and crosses the river. North of the river, the route continues across flood-plain deposits as it turns northwestward and skirts the edge of terrace deposits. The scarp between coastal-plain and terrace deposits west of the route and flood-plain deposits east of the route appears in figure 45 as a faint line from the top of the large river meander to the western shore of Prudhoe Bay.

Inundation of terrain by seawater on both sides of the mouth of the Putuligayuk River lowered the ground surface and killed or stripped the tundra vegetation. However, halophytic vegetation is present in these salt marshes. Thaw gullies along the bluff facing the salt marsh are small and partially obscured by eolian sand.

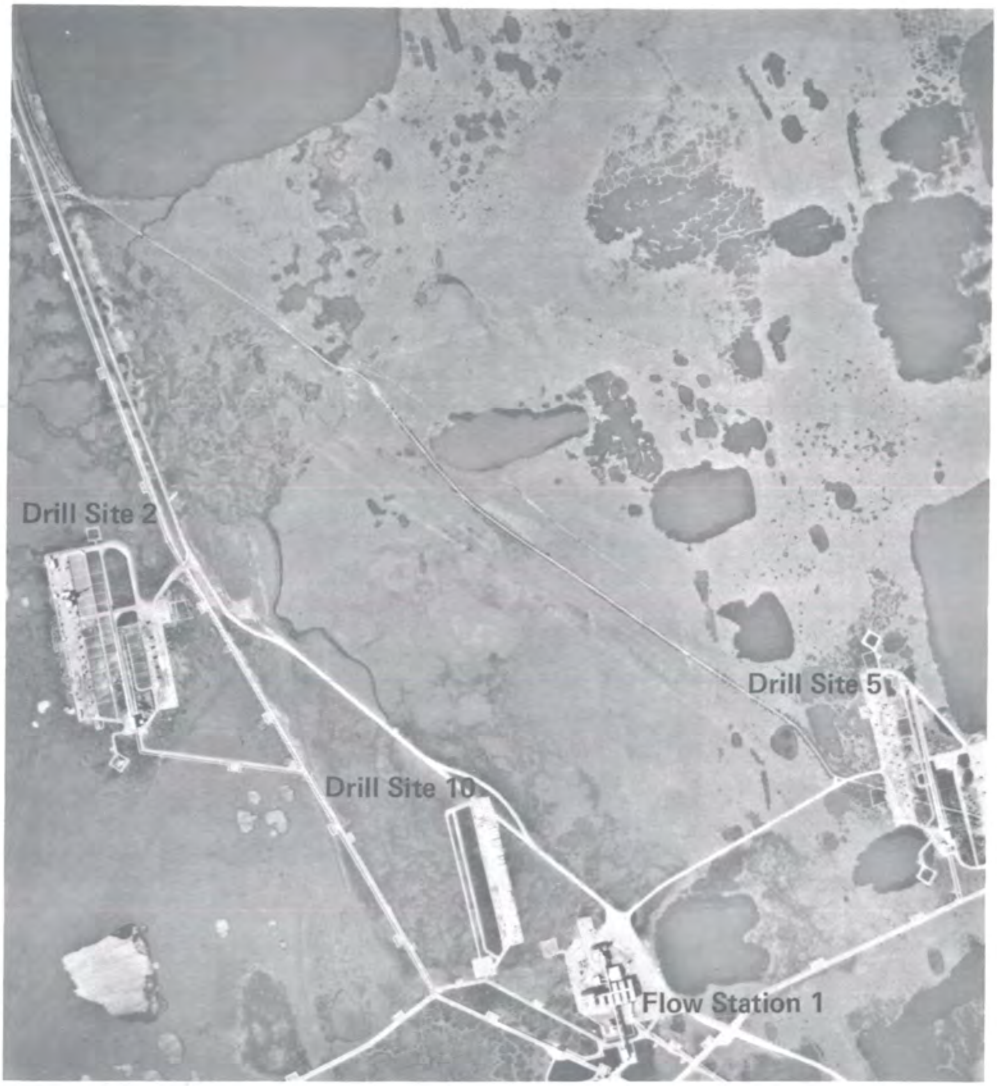


Figure 44. West Dock route (NPAS Prudhoe Bay photograph 12-32, 1980). See also Section B (fig. 75; fig. 76) and Section C (ice-wedge polygons, thaw lakes, reticulate patterned ground, pingos, linear and polygonal depressions, and strangmoor).

Stop 14.

The bluffs and salt marsh adjacent to the Central Compression Plant (CCP) are the 'Putuligayuk River Delta Overlook' site, an area used periodically by ancient hunters and gatherers. The majority of remains from localities within this area indicate temporary camps and flint knapping workshops about 4,000 yr B.P. However, some evidence suggests that the site may be as old as 5,500 yr B.P. (Lobdell, 1981).

The CCP compresses local natural gas from 42 to 316 Kg per cm^2 (600 to 4,500 lb per $in.^2$). The compressed gas is then transported via pipelines to 18 injection wells and injected into the field reservoir. A Field-Fuel Gas

Unit adjacent to the CCP processes up to 2.8 million m^3 of gas per d (100 million ft^3) to power the Prudhoe Bay field (ARCO Alaska, Inc., 1982).

The West Dock route continues northeastward from the CCP along the west shore of Prudhoe Bay. Gas-flaring facilities and gas-injection wells associated with the CCP are west of the route. The route turns slightly to the north at the injection-well facility and crosses ground characterized by low-center ice-wedge polygons. A road to the back entrance of the CCP and associated facilities intersects the route as it skirts the east shore of a drained thaw-lake basin dotted with thaw ponds. A small drill site is adjacent to this lake basin east of the route. From the drill site, the route continues northeastward across ground characterized by low-center ice-wedge polygons and thaw ponds. The route turns northward south of an estuary that

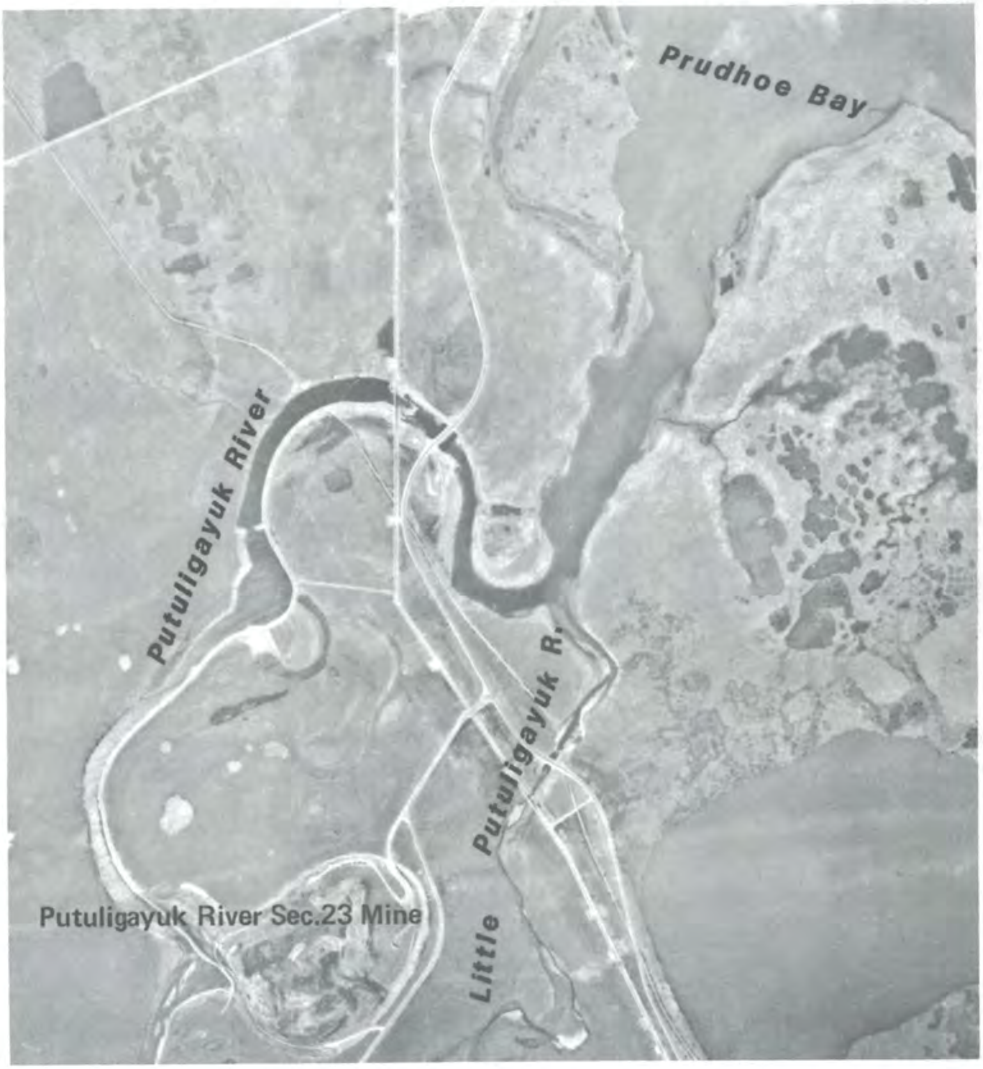


Figure 45. West Dock route (NPAS Prudhoe Bay photograph 11-32, 1980). See also Section B (fig. 76) and Section C (thaw lake, ice-wedge polygons, salt marshes, eolian forms and processes, strangemoor, and linear and polygonal depressions).

connects the aforementioned drained lake basin with Prudhoe Bay. The estuary began as a thaw stream that was widened and deepened by thaw and erosion as sea water inundated the channel during high tide and storm surge. North of the estuary, the route crosses a drained lake basin characterized by large-diameter ice-wedge polygons and thaw ponds. About one-fourth of a thaw lake that was formed by the coalescence of two thaw lakes is visible adjacent to the route at the top center of figure 46. The coalesced lakes are about 2.5 km (1.6 mi) long. (Photographs of this lake and the route are not in this guidebook.)

The West Dock route trends westward from the bottom-right corner of figure 47 across a drained lake basin to the large staging pad. Very wet ground south of the route indicates that flow of suprapermafrost ground water has been inhibited. The large pad is used as a staging area for building modules brought in on sea-going barges in late July and early August.

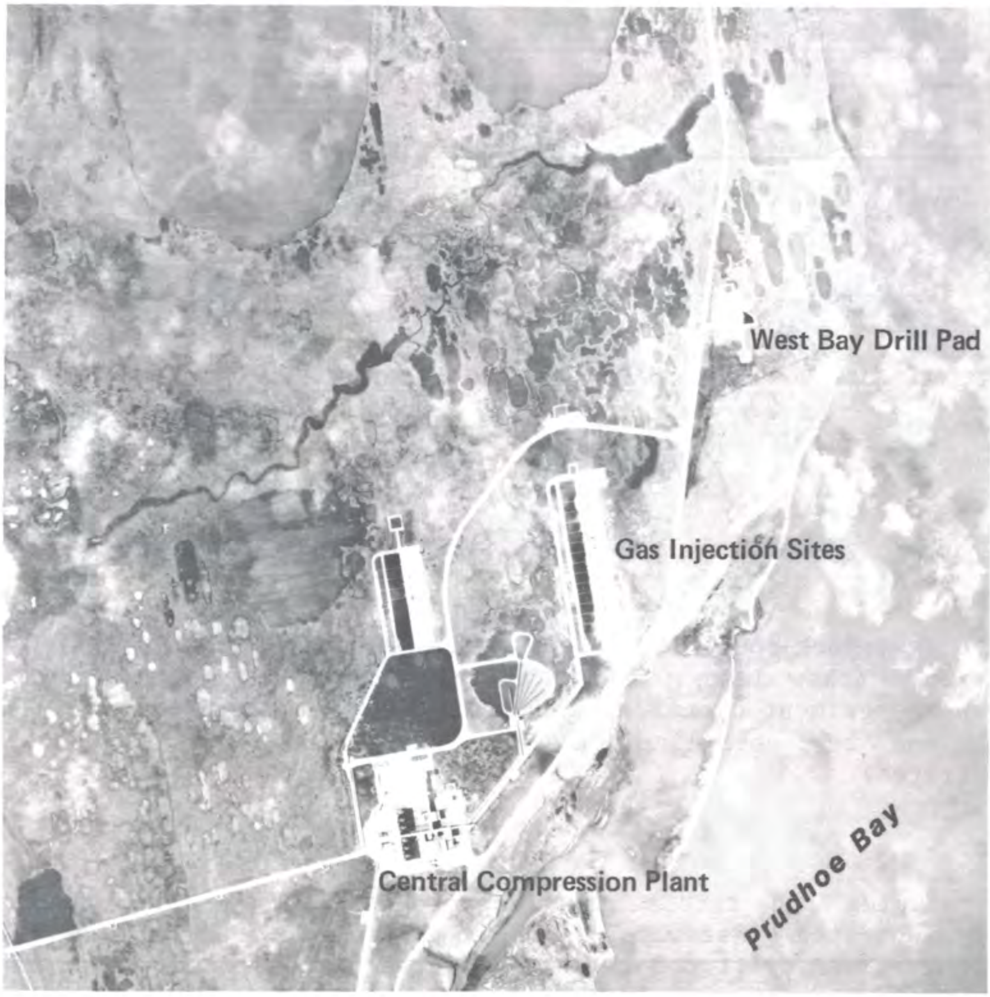


Figure 46. West Dock route (NPAS Prudhoe Bay photograph 10-21, 1980). See also Section C (salt marshes, ice-wedge polygons, and thaw lakes).

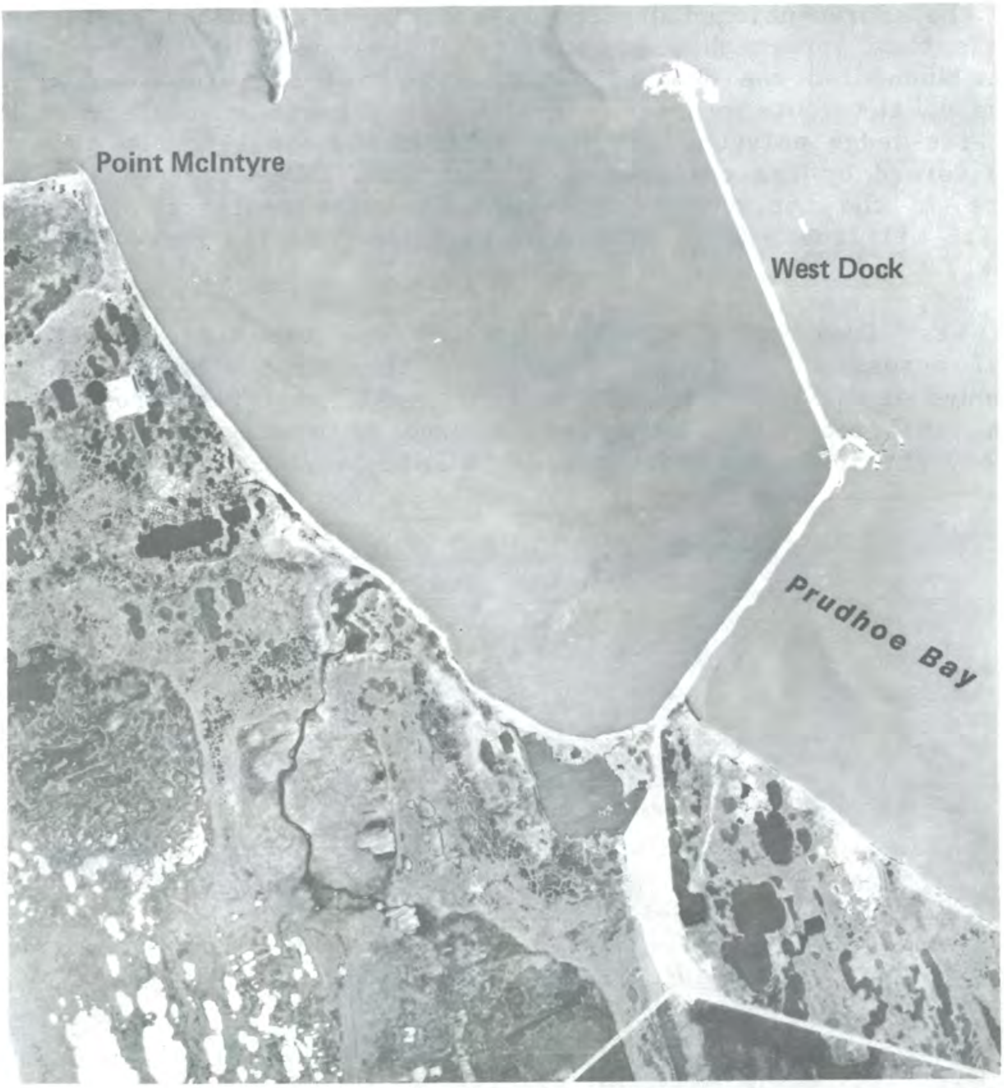


Figure 47. West Dock route (NPAS Prudhoe Bay photograph 8-37, 1980). See also Section C (thaw lakes, linear and polygonal depressions, salt marshes, offshore sediment dynamics, Waterflood Project, profile and stability of high and low coastline, eolian forms and processes, and lagoonal substrates).

Stop 15.

The staging pad trends north across a drained lake basin that is frequently inundated by seawater. An irregular white line east of the staging pad in figure 47 is driftwood that accumulated before construction of the dock and pad. The low topography of the basin, especially in the central trough, and frequent inundation by the sea have caused greater erosion in the basin than along adjacent bluffs. West of the lake basin, beach deposits are relatively stable. Although tundra vegetation in the eroding lake basin has been killed or stripped, halophytic vegetation is present. Beach sand and gravel west of the dock overlie lake-basin deposits. East of the dock the beach is narrow. Light-toned areas shoreward of the beach are eolian sand and some gravel deposited during storm surges. Fine sand, silt, and disseminated peat transported by the westward current have accumulated east of the dock in the acute angle between the dock and the shore. Barnes and Minkler (1982) reported an increase in sedimentation west of the dock caused by blockage of dominant northeast winds and westward currents.

In 1975, West Dock causeway was constructed by ARCO Alaska, Inc., between Prudhoe Bay channel and Stump Island. Initially, the causeway extended 3 km (1.9 mi) offshore perpendicular to the coast. During the winter of 1975-76, the causeway was extended 1.5 km (0.9 mi) northwest to facilitate offloading of barges stranded during the fall of 1975 (Barnes and others, 1977). Both segments of the causeway were constructed of compacted gravel, and each terminates at a dockhead where tug and barge activity is concentrated (Grider and others, 1978). According to boreholes near the elbow of the two segments (Hopkins and Hartz, 1978b), permafrost is present about 29 m (95 ft) beneath the causeway. During the summer of 1981, a third segment of compacted gravel was added to the causeway as part of the Waterflood Project (see Section C, Waterflood Project).

East Dock Route

The East Dock route extends from the Kuparuk route north of Deadhorse Airport to East Dock along the east shore of Prudhoe Bay. The route also includes a road that crosses the Sagavanirktok River to several drill pads (fig. 48).

North of Deadhorse Airport, the East Dock route heads eastward along the shore of Colleen Lake (fig. 49). The terrain around Colleen Lake is characterized by low-center ice-wedge polygons. Both roads that trend eastward from the road around Colleen Lake are considered part of the East Dock route.

During the past few years, development has been rapid in the area east of Colleen Lake, and thus many new facilities do not appear in these 1980 photographs. New storage pads have been built between Colleen Lake and the intersection of the southern end of the two east-trending roads (fig. 50). East of the intersection, the southern road crosses a strip of reticulate patterned ground and enters a large, partially drained lake basin. The road network there has blocked the flow of suprapermafrost ground water so that previously dry areas are covered by standing water (March, 1980). Within the lake basin, the route turns northeastward, skirting the edge of a small pingo south of the route. The bottom of the basin is characterized by nonpatterned ground and low-center, large-diameter polygons and strangmoor. Drill Site 12 is in the top center of the lake basin. From the drill site, the route continues across the lake basin past the new North Slope Borough office building on the pad south of the route near the right center of the lake basin, to the four-way intersection near the west bank of the Sagavanirktok River. Truncation of the thaw-lake basin indicates westward migration of the Sagavanirktok River channel.

The road south of this intersection intersects the Dalton Highway, which traverses over 560 km (348 mi) of northern and central Alaska to the Elliott Highway near Livengood. The road east of the intersection leads to the NANA

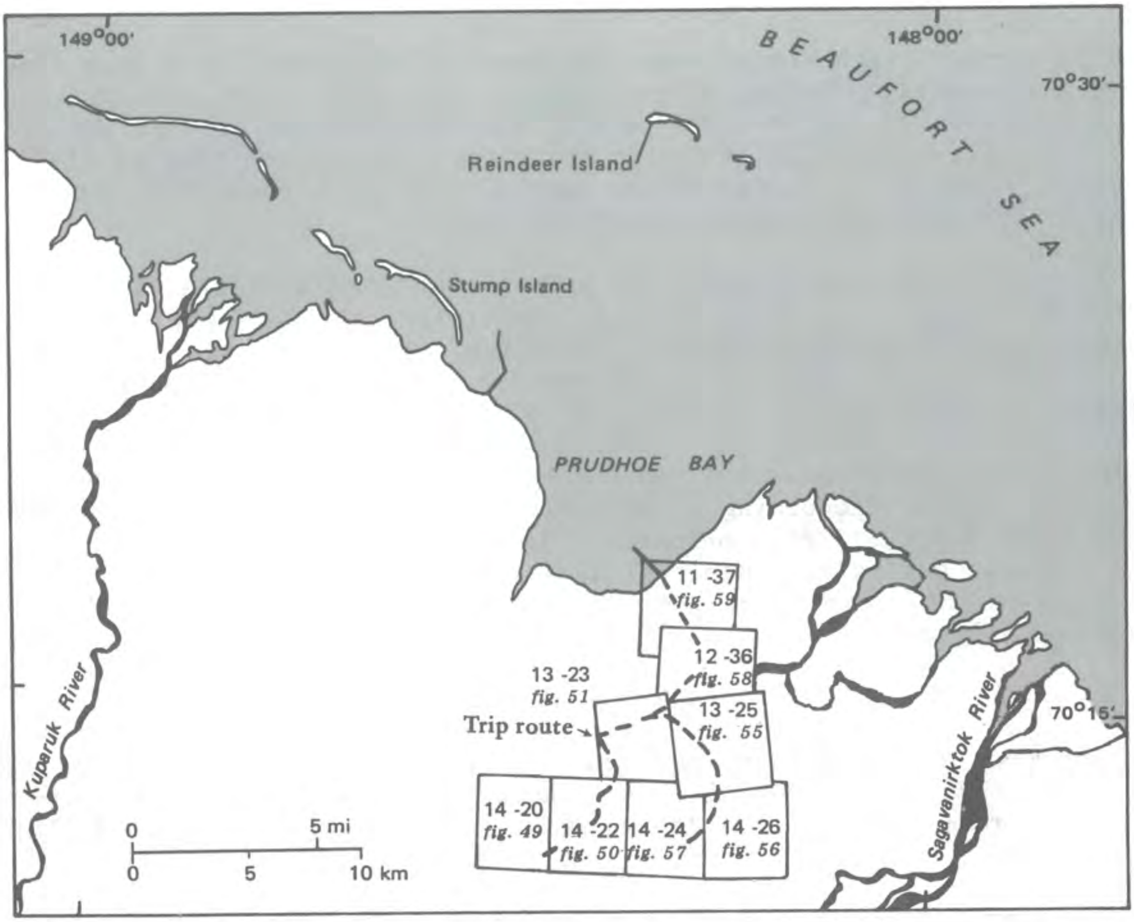


Figure 48. Index map of aerial photographs of the East Dock route, Prudhoe Bay, Alaska.

Corporation water reservoir built on the active flood plain of the Sagavanirktok River. The road north of the intersection that skirts the shore of the Sagavanirktok River provides access to several oil-field service companies and connects with the northern road of the East Dock route. The reticulate patterned ground that occurs just north of the intersection adjacent to the Sagavanirktok River is replaced by large-diameter ice-wedge polygons and strangmoor over the northern one-third of the lake basin. North of the lake basin, low-center ice-wedge polygons are ubiquitous.

The northern of the two roads trending eastward from the road encircling Colleen Lake skirts the southern end of a drained thaw-lake basin. Non-patterned ground is present in the southeast corner of this basin, but low-center ice-wedge polygons are the dominant surface features.

The Arctic Gas Test Facility is one of many service companies based along the East Dock route. This facility is marked by two connected white rectangles on the tundra surface north of the route near the southeast corner of the drained lake basin previously described. Construction techniques for burial of the Trans-Alaska Pipeline and their effects on the surface and underlying permafrost were evaluated at this site (Walker and others, 1980). Walker and others (1980) and Brown and Kreig (1983) show a detailed cross section of part of the trench in which the pipe was buried. The general

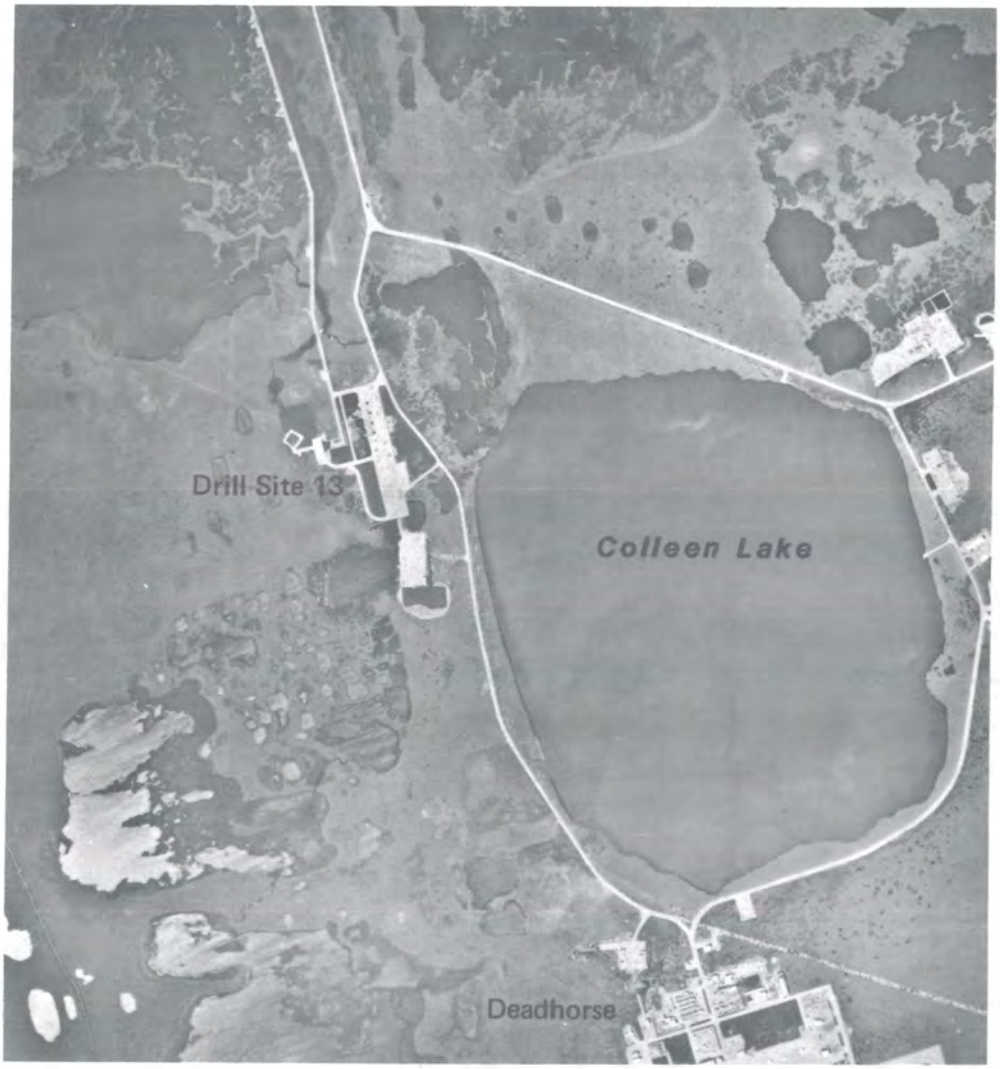


Figure 49. East Dock route (NPAS Prudhoe Bay photograph 14-20, 1980). See also Section B (fig. 78) and Section C (ice-wedge polygons).

stratigraphy (from top to bottom) of sediments between large ice wedges includes 0.5 m (1.6 ft) fibrous organic material, 1 to 1.5 m (3.3 to 4.9 ft) silt with lens or boxwork ice segregations, 0 to 0.5 m (0 to 1.6 ft) organic silt, and 0.5 to 0.8 m (1.6 to 2.6 ft) of gravelly sand. Ice segregations accumulate in the active layer each fall as capillary action moves water along a moisture-tension gradient to the freezing plane. Ice segregations below the active layer indicate a period during which the enclosing sediments were seasonally thawed and refrozen. The rate of freezing and the amount of soil moisture determine the thickness of individual ice segregations. The position and form of the segregations are determined primarily by the microstratigraphy of the enclosing sediments (Walker and others, 1980).

From the Arctic Gas Test Facility, the route continues northeastward across low-center ice-wedge polygons, crosses the pipeline that connects Drill site 12 with Flow Station 1, passes several service companies, and continues to the intersection of the road trending northward along the Sagavanirktok River. A large, drained thaw-lake basin is located north of this intersection. Reticulate patterned ground occurs on the scarp between the basin floor and the surrounding terrain on the south and east sides of the basin. The route continues around the southeast end of this lake basin past more service companies and along the eastern shore.

Facilities south of the route are within a lake basin that was drained as the Sagavanirktok River migrated westward and cut into the basin. A small thaw channel connects the lake basins north and south of the route. The channel crosses the southern basin and connects with the Sagavanirktok River. Drainage of these two basins was probably almost simultaneous because both basins are characterized by nonpatterned ground, large-diameter ice-wedge polygons, and strangmoor.

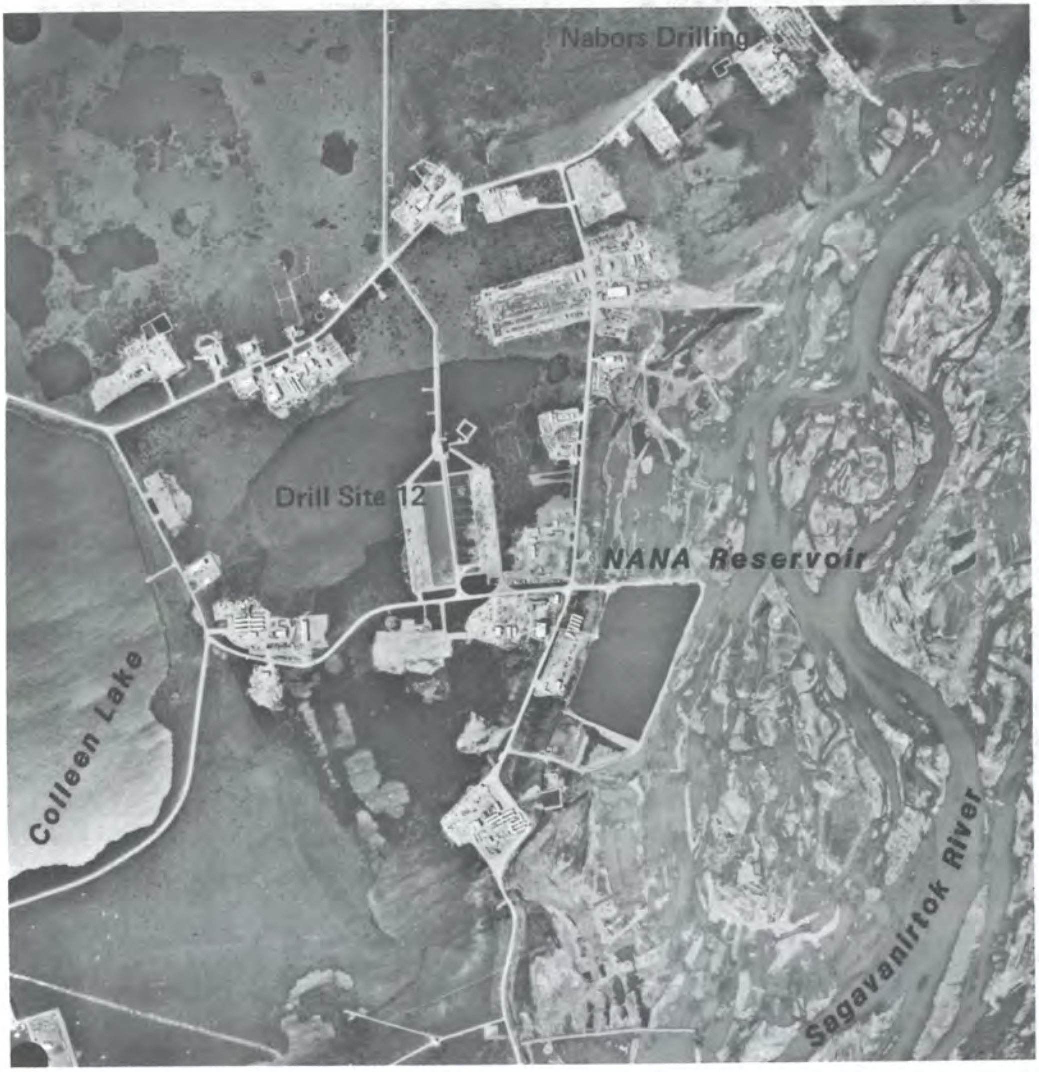


Figure 50. East Dock route (NPAS Prudhoe Bay photograph 14-22, 1980). See also Section B (fig. 78; fig. 79) and Section C (reticulate patterned ground, thaw lakes, linear and polygonal depressions, pingos, ice-wedge polygons, strangmoor, and cryoturbation features).

Drill Site 1 west of the route at the left edge of figure 51 is partially within the large aforementioned lake basin. Terrain around the northern half of the drill site and east of the route to the Sagavanirktok River is characterized primarily by low-center ice-wedge polygons. Notable exceptions are a northwest-trending zone of frost-boil tundra south of ARCO Construction Camp and a truncated lake basin along the river. This basin contains large-diameter ice-wedge polygons and strangmoor. An ARCO security checkpoint is located at a small turnout on the route adjacent to Drill Site 1. North of this checkpoint, a road built to bypass traffic from ARCO Construction Camp, air field, and Operations Center intersects the route. This bypass road now connects with the road that crosses the Sagavanirktok River near the top-right corner of figure 51. North of the intersection, the route trends northwestward to the intersection of the West Dock route and turns northeastward toward ARCO Construction Camp. The construction camp is within a drained lake basin characterized by large-diameter ice-wedge polygons and strangmoor. A small

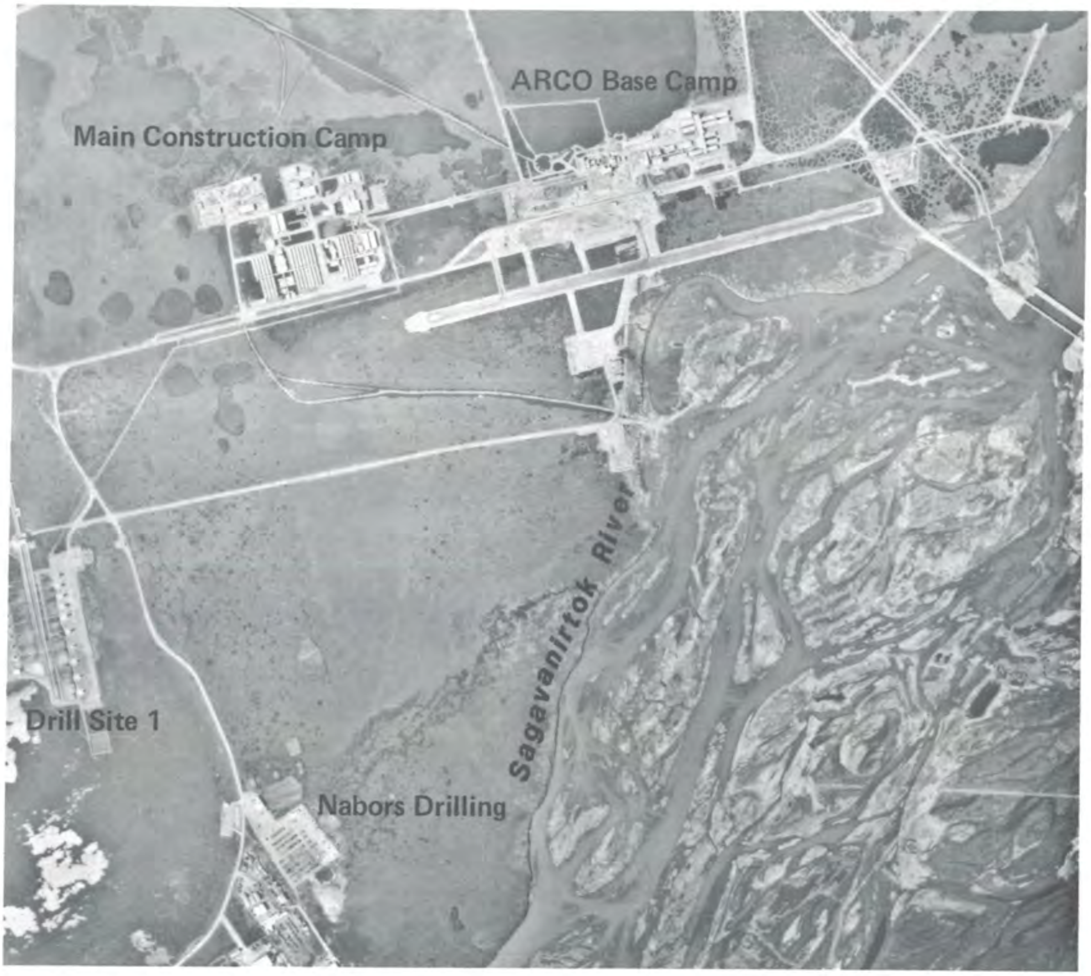


Figure 51. East Dock route (NPAS Prudhoe Bay photograph 13-23, 1980). See also Section B (fig. 80; fig. 81; fig. 82) and Section C (thaw lakes, ice-wedge polygons, nonsorted circles, pingos, ice wedges, strangmoor, and taliks).

pingo in the center of the lake basin is nestled among the construction-camp buildings. The route continues eastward from the construction camp toward the ARCO airfield and Operations Center. The unpaved airfield is 1,675 m (5,500 ft) long and serves aircraft chartered by ARCO. Initial construction of the self-contained Operations Center was started in 1969 and completed in 1970. Expansion of the center has been in phases, and now the complex can accommodate over 600 people. The Sag River State No. 1 well confirmed the Prudhoe Bay field. The well is marked by an orange tubular structure in front of the Operations Center. The well, which was spudded in May and completed in November 1968, is the deepest well in the Prudhoe Bay field at 3,945 m (12,942 ft) (ARCO Alaska, Inc., 1982).

East of ARCO Operations Center, a road turns northward across the west side of a drained lake basin to Flow Station 2. The basin is characterized by low-center ice-wedge polygons. The route continues eastward from this intersection a short distance to the intersection of the road that crosses the Sagavanirktok River. The Sagavanirktok River road trends southwestward across low-center ice-wedge polygons in the lake basin and along the margin of terrace deposits of the Sagavanirktok River. The boundary of the deposits forms an arc from the middle of the airfield to the Operations Center, along the East Dock route, and along the Sagavanirktok River road. These deposits and terrace deposits near the Deadhorse Airport indicate that the Sagavanirktok River migrated eastward, cut deeper into the coastal-plain deposits, and is now migrating westward.

Stop 16.

Good examples of high-center ice-wedge polygons and thaw gullies are present in the western Sagavanirktok River bluff south of the bridge (figs. 52a,b). North of the Sagavanirktok River bridge, low-center ice-wedge polygons are ubiquitous. Excellent examples of ice wedges are exposed in several small thaw gullies. A large ice lens is also exposed in the bluff north of the Sagavanirktok River bridge. Thermoerosional undercutting of the bluff has exposed gray silt and fine sand that are common in most coastal exposures below organic-rich deposits. Similar deposits near the mouth of the east Sagavanirktok River channel overlie marine gravelly sand; the silt and sand may also be marine (figs. 53 and 54). Determination of the inland extent of marine deposits and their stratigraphic position in the Prudhoe Bay area is in progress.

The east branch of the East Dock route trends southeastward across a braided active channel of the Sagavanirktok River (fig. 55). North of the road, low, partially vegetated sand dunes appear on the horizon. Near the west edge of the active flood plain, gravel has been mined in the Sagavanirktok 'C' mine. Sand and gravel were previously scraped only from the surface of active channels.

Stop 17.

The Sagavanirktok 'C' mine is an open pit excavated to a depth of about 10 m (33 ft). A berm has been built around the pit to prevent flooding during ice breakup. Sand and gravel from the pit were used for construction of nearby Sagavanirktok River drill pads.

Figure 52a. Inception of thaw gully south of the Sagavanirktok River bridge in 1979; organic ice-rich permafrost is beginning to thaw and collapse along ice wedges. The large depression in the foreground marks the intersection of four ice wedges. Photograph by S.E. Rawlinson, 1979.

Figure 52b. Thaw gully in figure 52a in 1982. Further thaw and collapse of the permafrost has widened the gully significantly. Mud flows extend from the gully onto the river flood plain. Photograph by S.E. Rawlinson, 1982.

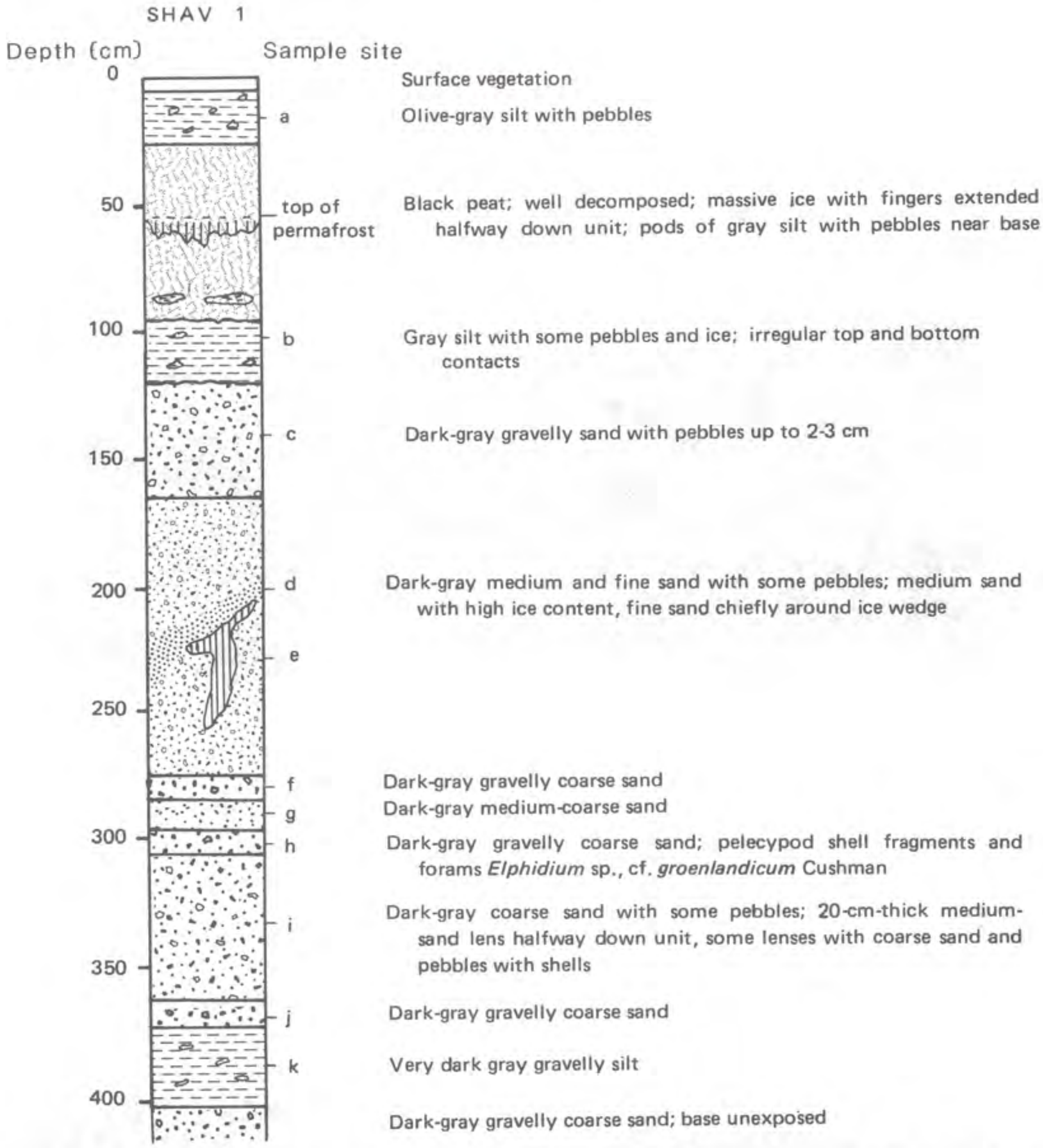


Figure 53. Stratigraphic section of deposits exposed near the mouth of the Shaviovik River.

From the Sagavanirktok 'C' mine, the route continues southeastward onto abandoned flood-plain deposits characterized by low-center ice-wedge polygons and several oxbow lakes. The road splits at a three-way intersection. One road trends eastward along the boundary of the abandoned flood-plain deposits and inactive flood-plain deposits to Drill Site 9. This drill site is located amid large-diameter, low-center ice-wedge polygons, and ice-wedge polygons are visible within the water-filled containment areas of the drill site. Another road trends southward to Drill Site 3 and on to Drill Sites 16 and 17. An abandoned road north of the intersection has well-developed, water-filled thaw depressions along both sides. This road continues eastward across inactive flood-plain deposits. The thaw depressions are only moderately developed in these deposits because the ice content is much lower than in the abandoned flood-plain deposits.

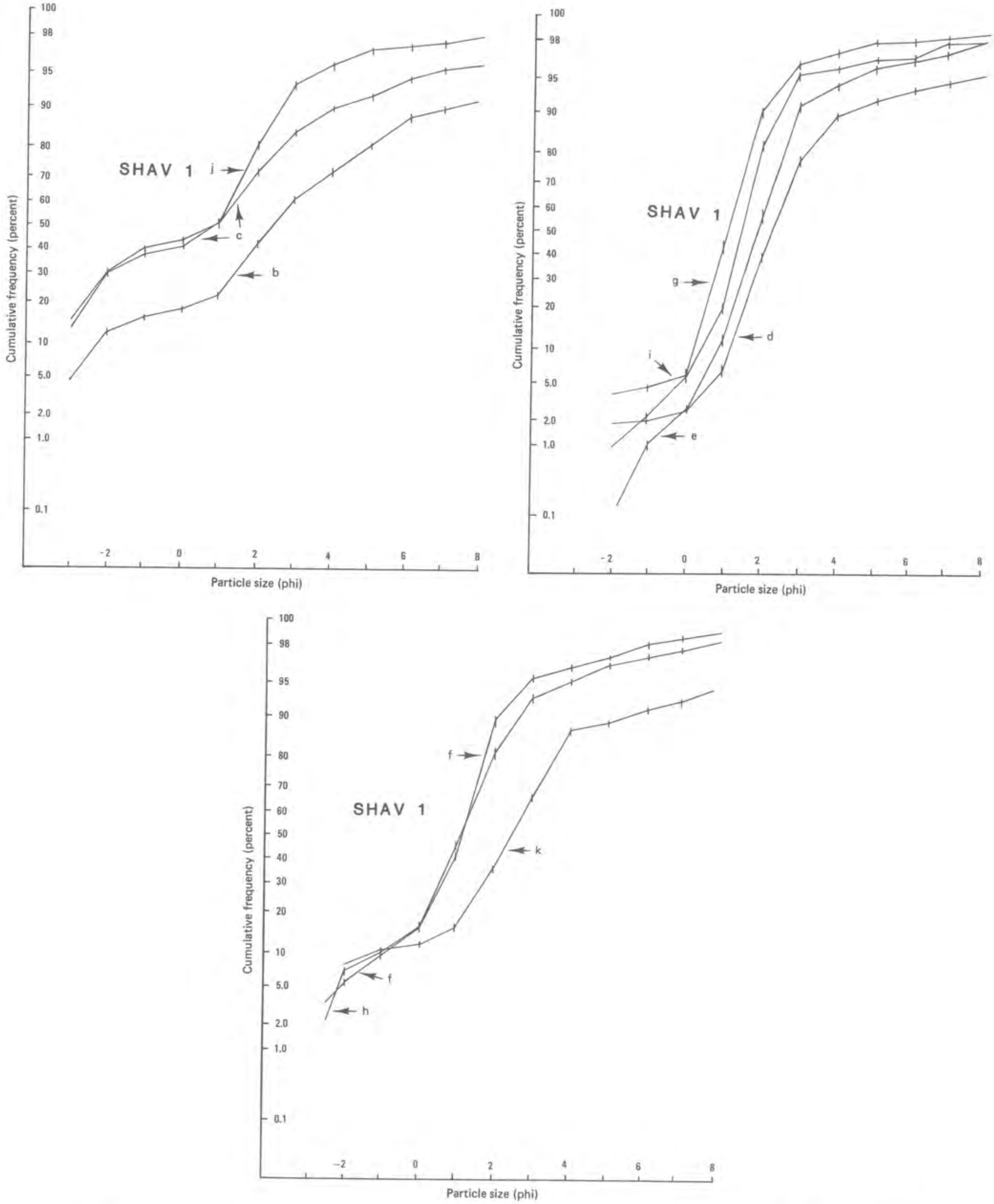


Figure 54. Grain-size distribution of samples from sites shown in figure 53.

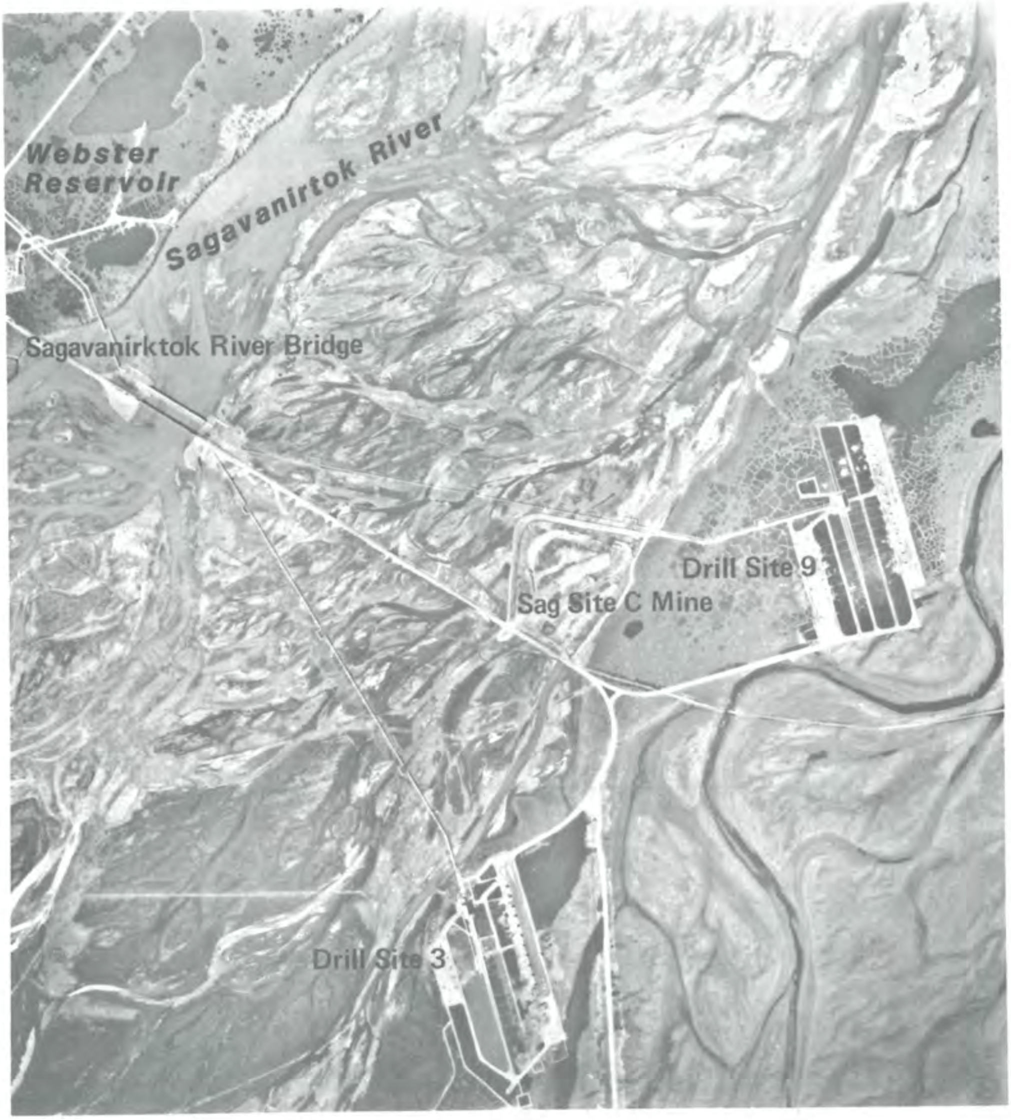


Figure 55. East Dock route (NPAS Prudhoe Bay photograph 13-25, 1980). See also Section B (fig. 82) and Section C (eolian forms and processes, gravel removal, ice-wedge polygons, thaw lakes, and linear and polygonal depressions).

Vegetation-stabilized sand dunes are present on the inactive flood-plain deposits and along the east edge of the abandoned flood-plain deposits. One dune intersects the route south of the intersection about half the distance to the road to Drill Site 3. In the past, this dune east of the route was the burrow of numerous arctic fox. Drill Site 3 is located on abandoned flood-plain deposits.

From the intersection of the road to Drill Site 3, the route continues southward across inactive flood-plain deposits. These deposits include bedded silt and sand over sandy gravel and are thinly covered by vegetation.

South of Drill Site 3, the route splits at a three-way intersection (fig. 56). One road trends southeastward across the inactive flood-plain deposits to Drill Site 16. The other road trends southwestward across the same deposits to Drill Site 17. These roads have blocked the flow of water within individual channels of the inactive flood plain. About 20 km (12 mi) south of Drill Site 16, the Sagavanirktok River splits into two active braided flood plains; the eastern distributary is the main channel. These flood plains isolate a narrow area of coastal-plain deposits that extends northward to about 8 km (5 mi) from the Beaufort Sea coast. Drill Site 16 is on the western edge of this island.

Stop 18.

Low-center ice-wedge polygons characterize coastal-plain deposits near Drill Site 16. An abandoned road along the bottom of figure 56 crosses inactive flood-plain deposits and coastal-plain deposits to an exploratory-well drill site adjacent to drill Site 16. Polygonal thaw depressions in this road are better developed in the ice-rich coastal-plain deposits than in the inactive flood-plain deposits. Two small thaw-lake basins south of the drill site were drained by a thaw stream that passes northeastward along the east side of the drill site and connects with inactive flood-plain deposits. A small pingo is located in the center of the eastern lake.

Drill Site 17 is on the eastern edge of abandoned flood-plain deposits adjacent to inactive flood-plain deposits (fig. 57). These abandoned deposits are characterized by low-center, large-diameter ice-wedge polygons and oxbox lakes. Linear marks on braided active flood-plain deposits west of the abandoned deposits were made during gravel removal.

The East Dock route continues northeastward from the intersection of the Sagavanirktok River road toward Drill Site 4 (fig. 58). Low-center ice-wedge polygons are the dominant surface feature. About half the distance to the drill site, the route passes west of Webster Reservoir, a thaw lake that has been deepened to provide a year-round water supply. The route passes west of Drill Site 4 and crosses the pipeline from the drill site to Flow Station 2. North of the pipeline crossing, the route enters a shallow lake basin that is marked by large-diameter ice-wedge polygons and partially infilled by sand dunes in the northern part. The route crosses these dune deposits and turns northward toward East Dock. Two roads intersect the route in the turn. The northern road trends eastward across a partially drained lake basin to a large storage pad. The southern road splits again; one road trends eastward along dune deposits to the Prudhoe Bay landfill, and the other road leads back to Drill Site 4.

The route continues from the intersection on the sand dunes into a partially drained lake basin. Deeper parts of this basin contain low-center ice-wedge polygons. Eolian deposits in shallow parts of the basin have obscured the underlying ice-wedge polygons, and the surface is virtually featureless. The route leaves this lake basin, crosses a raised area covered by eolian sand, and crosses another featureless lake basin.

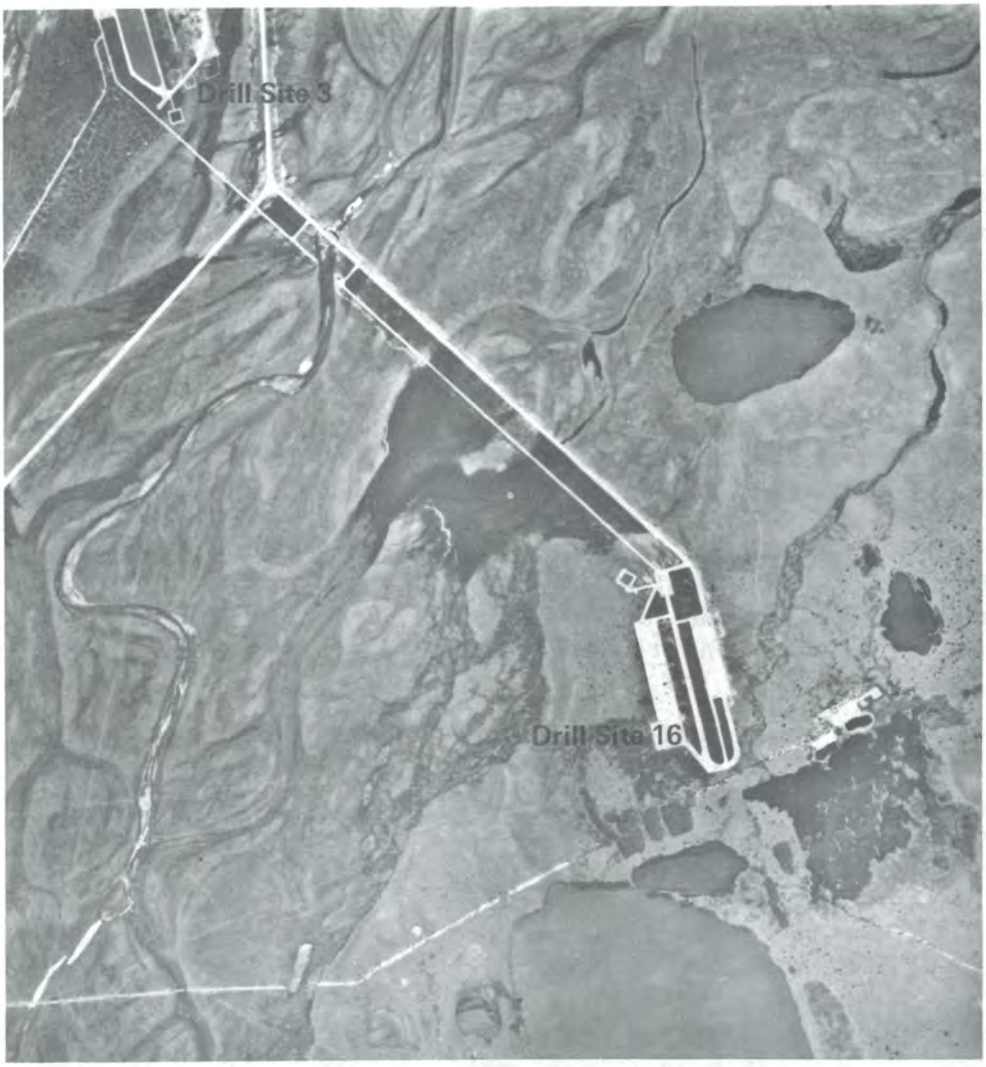


Figure 56. East Dock route (NPAS Prudhoe Bay photograph 14-26, 1980). See also Section C (ice-wedge polygons, thaw lakes, pingos, aufeis, and linear and polygonal depressions).

Stop 19.

North of the small featureless thaw-lake basin, the East Dock route enters a field of active sand dunes that extend northeastward about 4 km (2.5 mi) to the Sagavanirktok River delta (fig. 59). Sand that composes the dunes is derived from the delta. The dunes partially obscure the southern half of a large thaw-lake basin east of the route. A wet, dark-toned area adjacent to the route south of light-toned dunes marks the southern extent of the lake basins. A collapsed, sand-covered pingo is at the top of the dark-toned area. Another collapsed pingo (very small ring with dark center in fig. 59) is near the road within the basin north of the major sand-dune occurrence. The ground in the northern half of the basin is virtually featureless. Most vegetation in the northern part of the basin is dead because of inundation by seawater; a

Figure 57. East Dock route (NPAS Prudhoe Bay photograph 14-24, 1980). See also Section C (ice-wedge polygons, gravel removal, linear and polygonal depressions).

thaw channel at the north end of the basin connects it with Prudhoe Bay. Driftwood is present within the basin and along its perimeter. Boulders of the Flaxman Member of the Gubik Formation are strewn across the basin surface near the East Dock facilities. Lithologies of the boulders include granite (dated at 2.4 billion yr), diabase, and quartzite.

Stop 20.

From the lake basin, the route continues to the East Dock facilities, where offshore oil operations are based. Bluffs northeast of the dock expose thaw-lake sediments and sediments of the Flaxman Member. Flaxman boulders are visible offshore in the shallow waters. The effects of erosion on high, tundra-capped bluffs are evident.

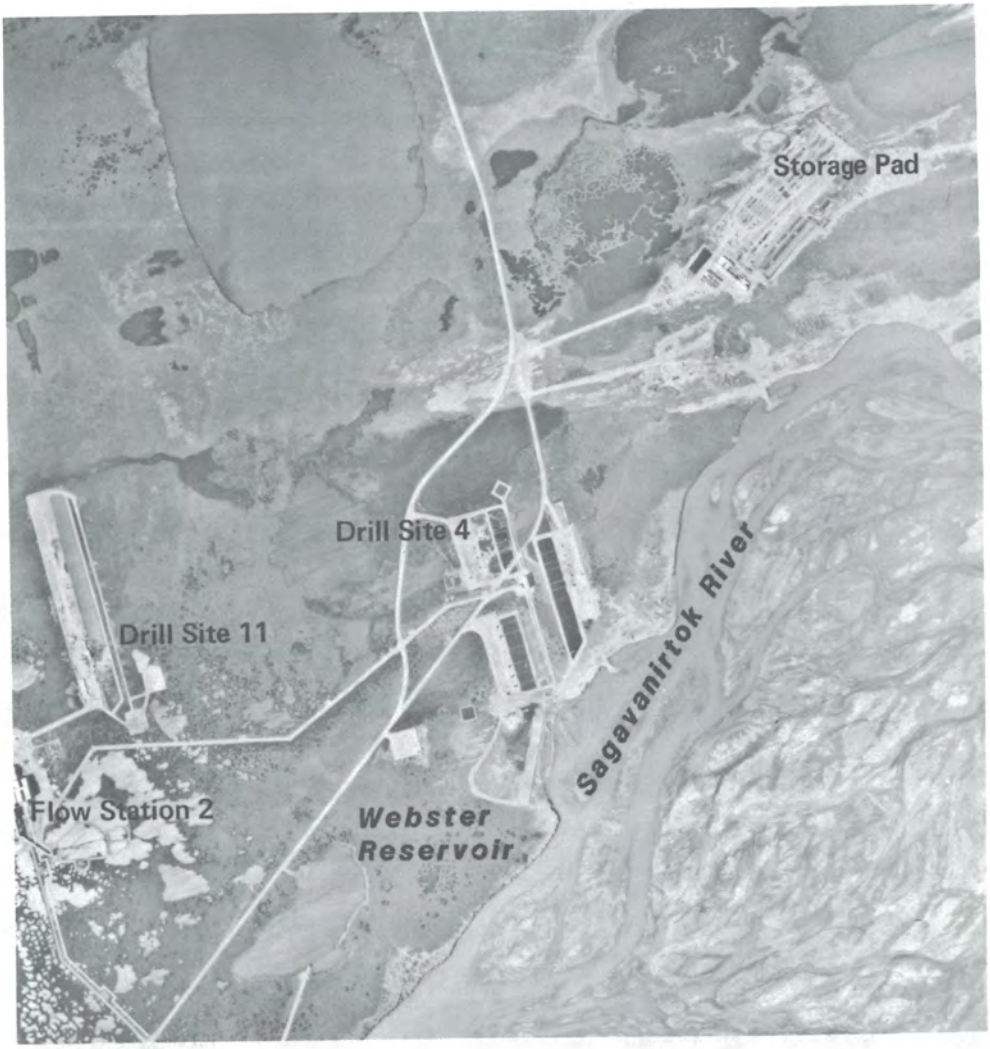


Figure 58. East Dock route (NPAS Prudhoe Bay photograph 12-36, 1980). See also Section C (ice-wedge polygons, thaw lakes, and eolian forms and processes).

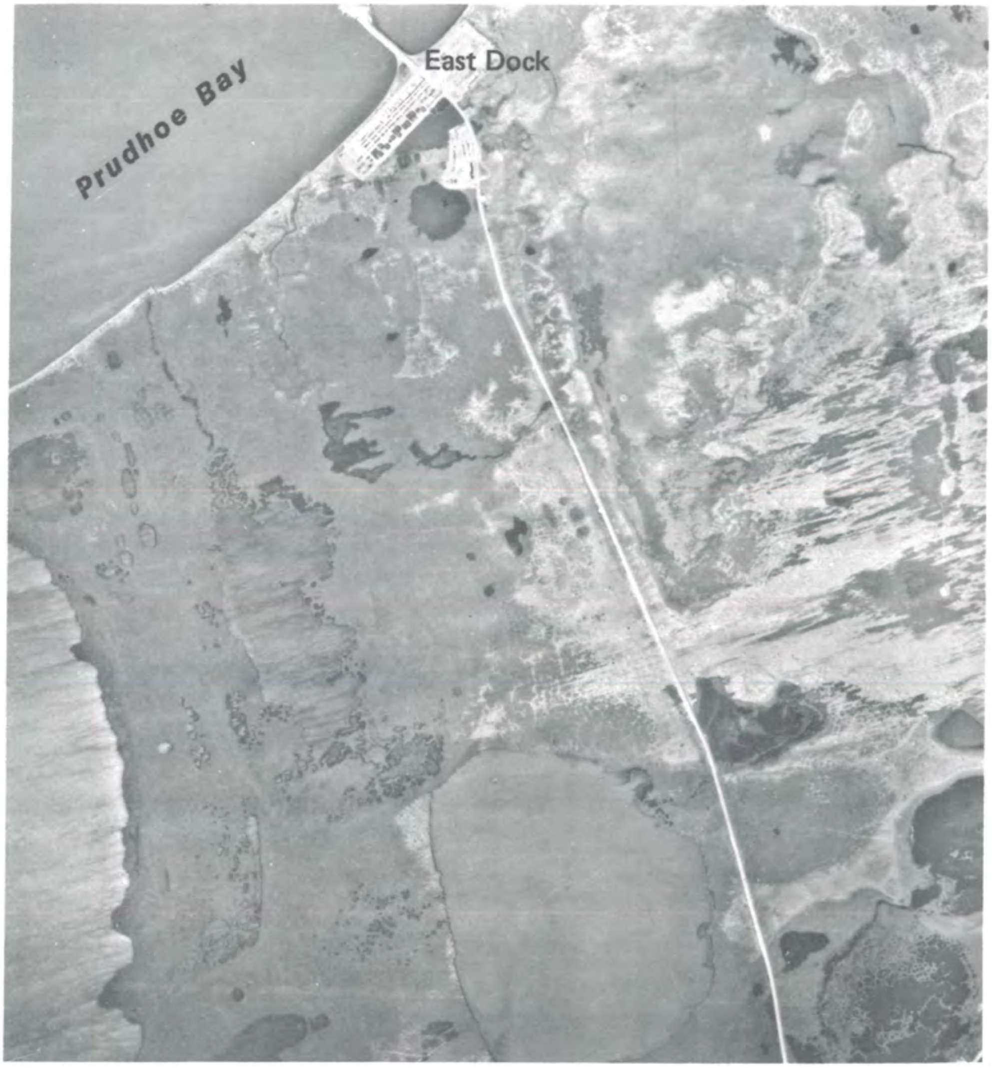


Figure 59. East Dock route (NPAS Prudhoe Bay photograph 11-37, 1980). See also Section B (fig. 83) and Section C (eolian forms and processes, pingos, thaw lakes, salt marshes, Gubik Formation and Flaxman Member, and profile and stability of high and low coastline).

SECTION B
VEGETATION, LANDFORMS, AND SOILS MAPS

Vegetation, landforms, and soils maps cover a corridor along part of the Kuparuk route (figs. 60 - 70), the Putuligayuk River route (figs. 71, 72), the West Dock route (figs. 73 - 76), and the East Dock route (figs. 77 - 83).

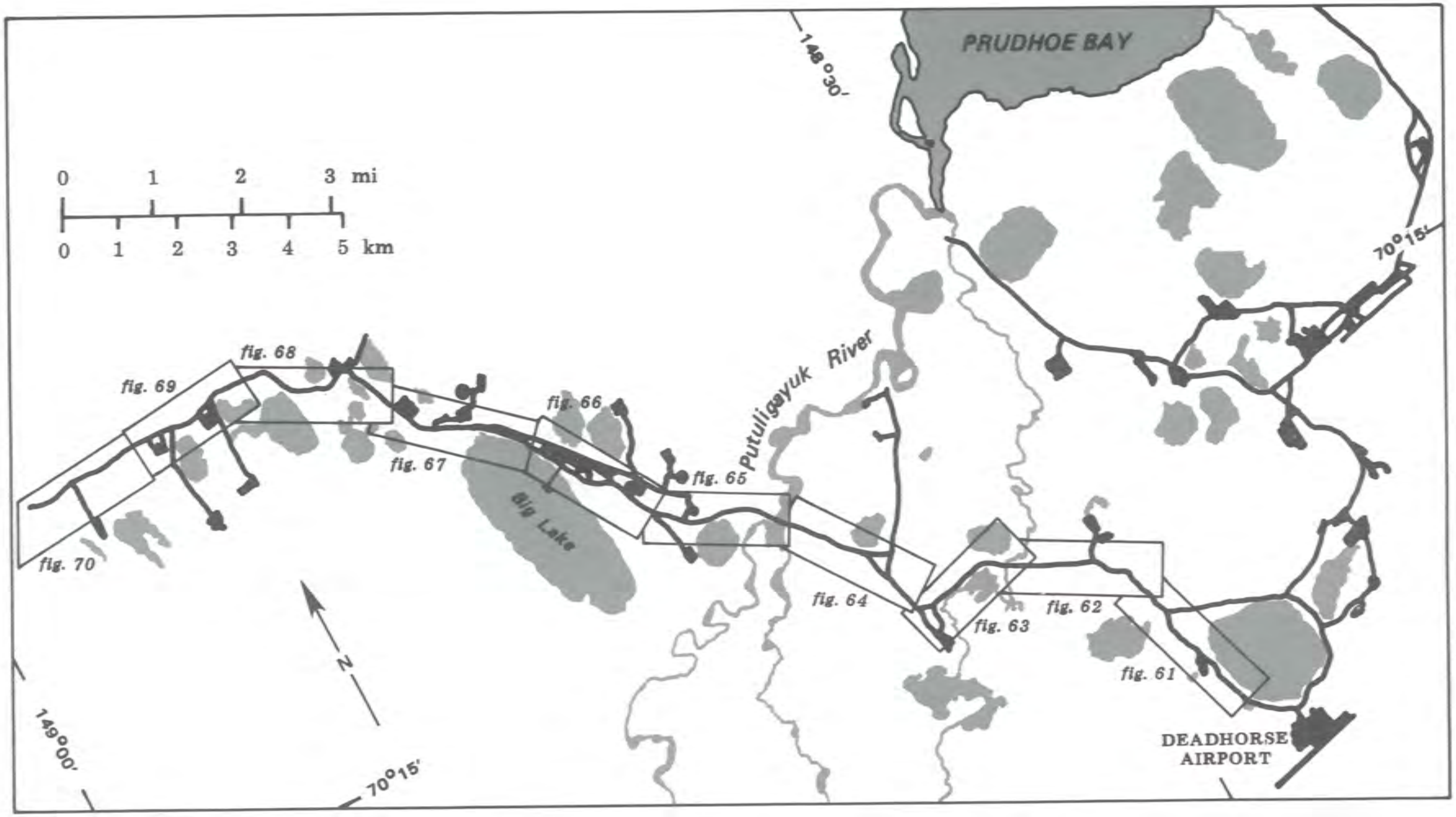
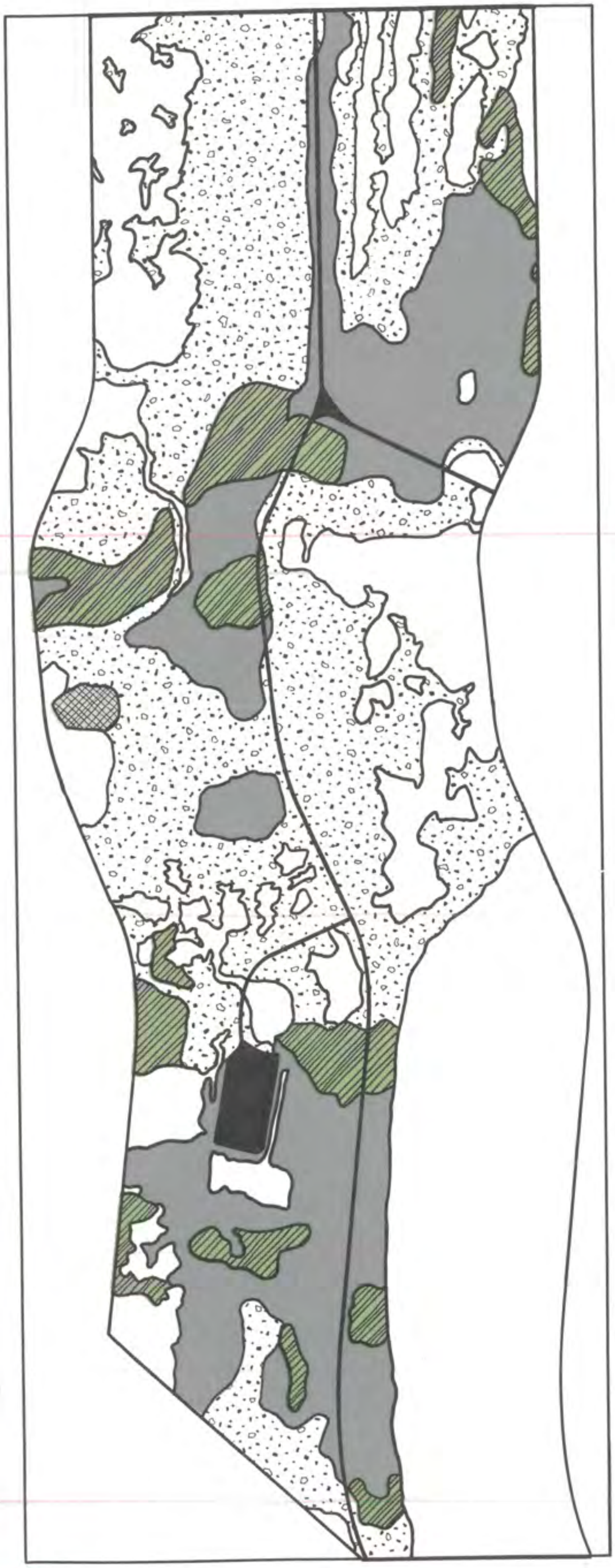


Figure 60. Index map of vegetation, landforms, and soils maps of part of the Kuparuk route, Prudhoe Bay, Alaska.



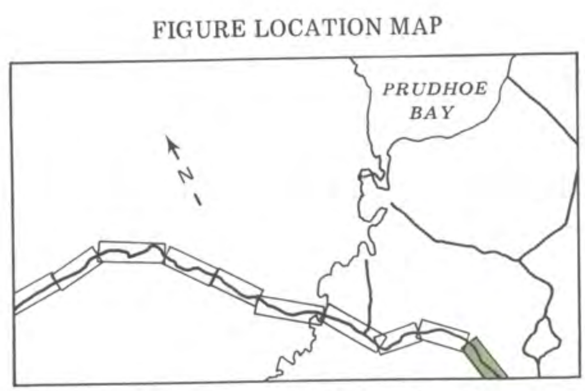
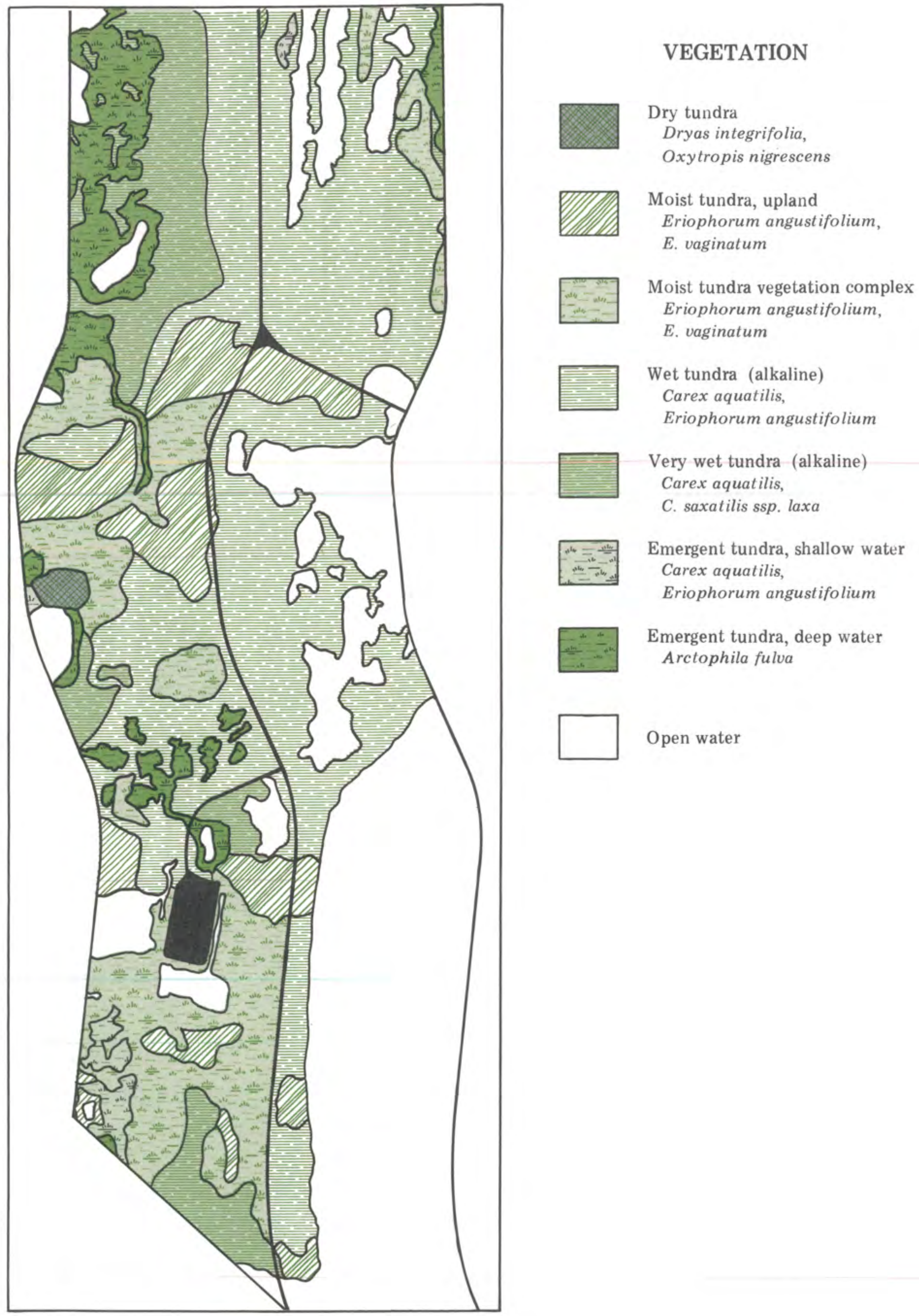
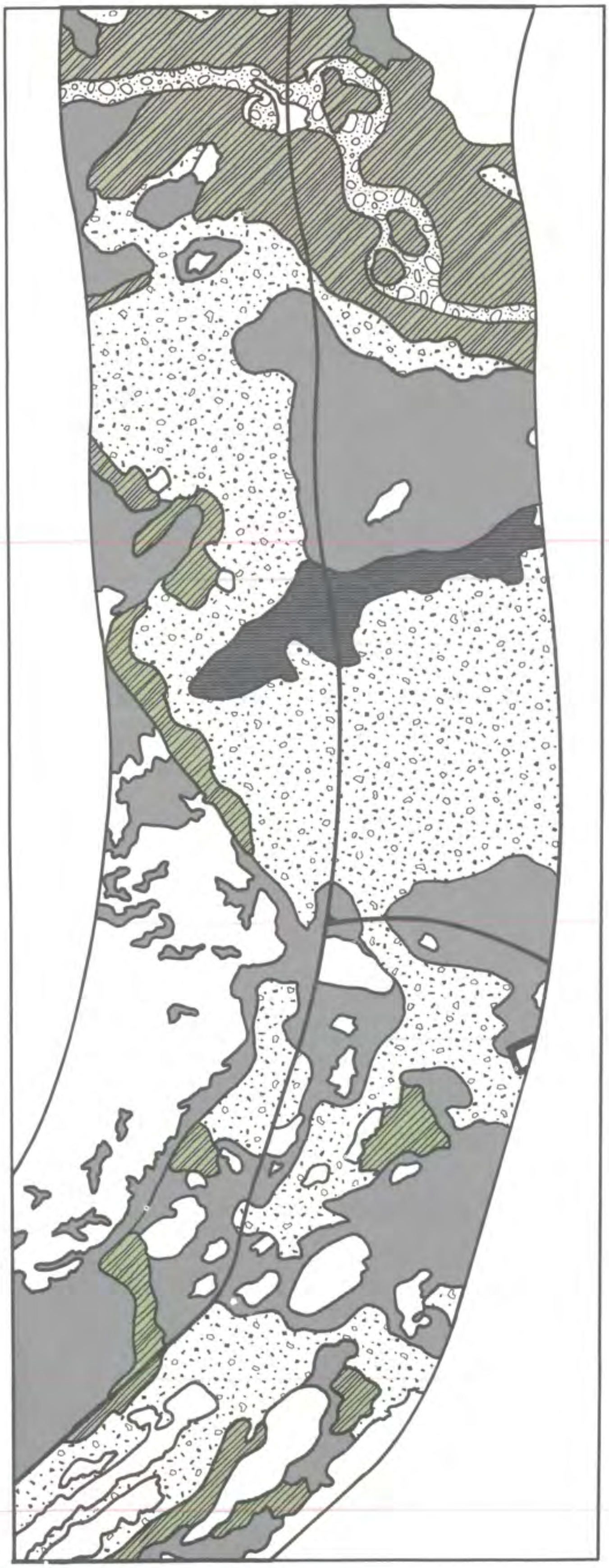


Figure 61. Vegetation, landforms, and soils of the Kuparuk route, leg 1.


VEGETATION
Dry tundra
Dryas integrifolia,
Oxytropis nigrescens
Moist tundra, upland
Eriophorum angustifolium,
E. vaginatum
Moist tundra vegetation complex
Eriophorum angustifolium,
E. vaginatum
Wet tundra (alkaline)
Carex aquatilis,
Eriophorum angustifolium
Very wet tundra (alkaline)
Carex aquatilis,
C. saxatilis ssp. laxa
Emergent tundra, shallow water
Carex aquatilis,
Eriophorum angustifolium
Emergent tundra, deep water
Arctophila fulva
Open water


LANDFORM
High-center polygons, low relief
Low-center polygons, low relief
High- and low-center polygons
Strangmoor or large-diameter, low-center polygons or both
Reticulate-patterned ground
Nonpatterned or limited-patterned ground
Pingo
Water
N
0
200
400 m
0
500
1000 ft



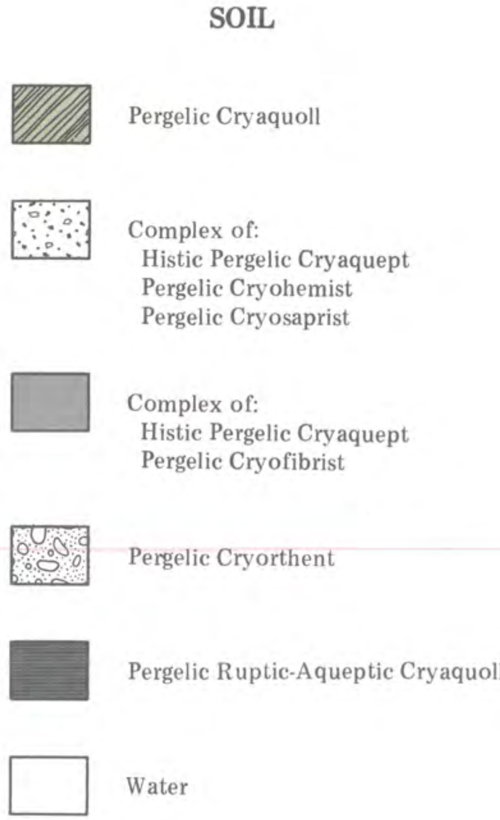


FIGURE LOCATION MAP

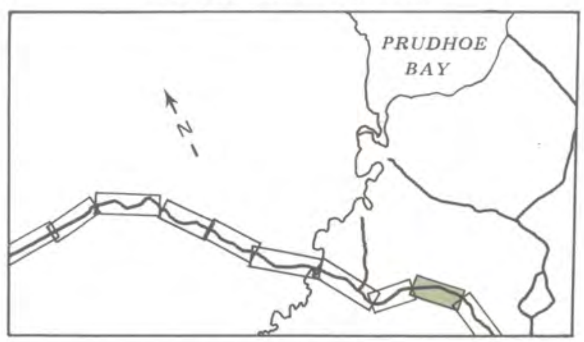
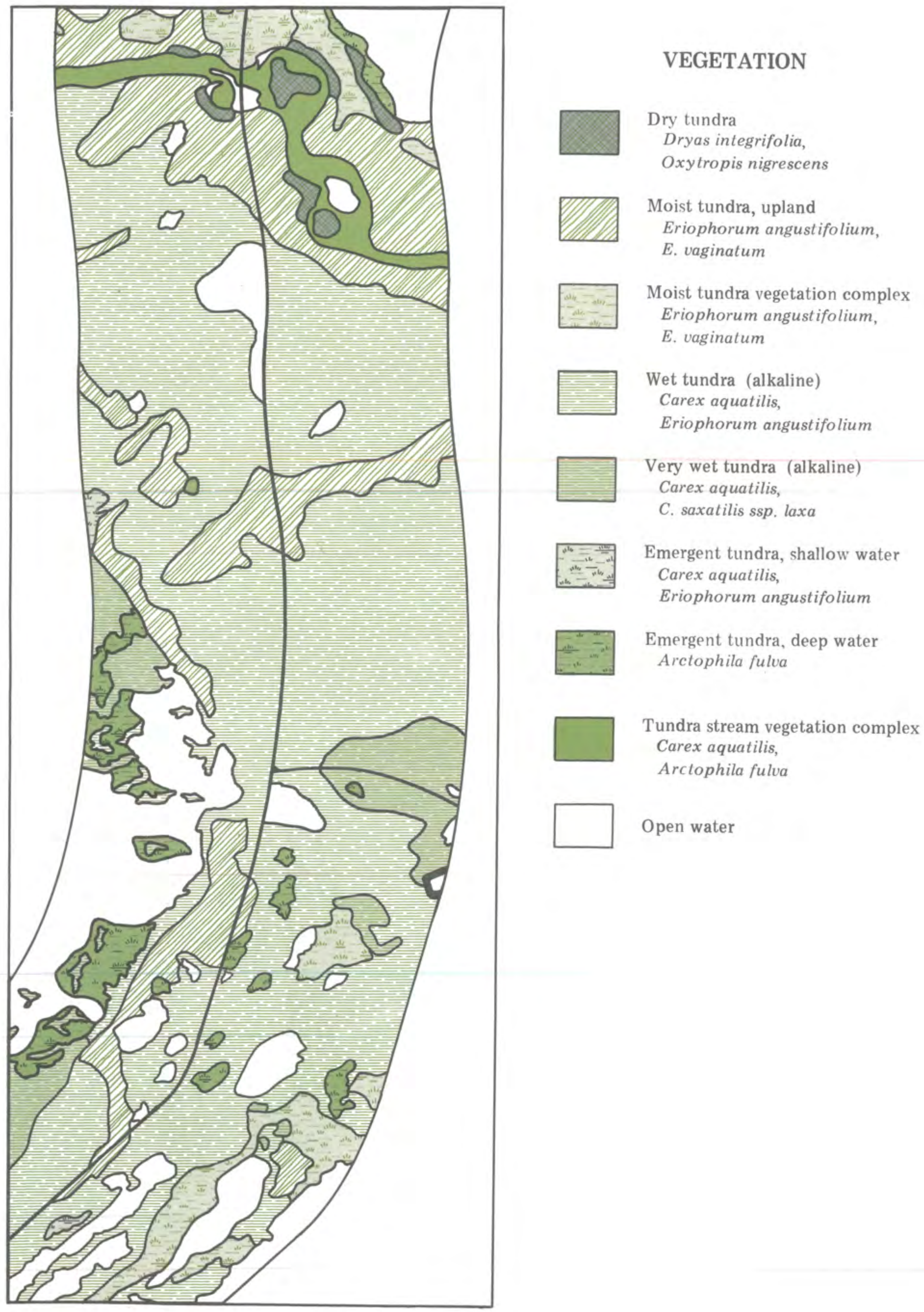


Figure 62. Vegetation, landforms, and soils of the Kuparuk route, leg 2.


VEGETATION
Dry tundra
Dryas integrifolia,
Oxytropis nigrescens
Moist tundra, upland
Eriophorum angustifolium,
E. vaginatum
Moist tundra vegetation complex
Eriophorum angustifolium,
E. vaginatum
Wet tundra (alkaline)
Carex aquatilis,
Eriophorum angustifolium
Very wet tundra (alkaline)
Carex aquatilis,
C. saxatilis ssp. laxa
Emergent tundra, shallow water
Carex aquatilis,
Eriophorum angustifolium
Emergent tundra, deep water
Arctophila fulva
Tundra stream vegetation complex
Carex aquatilis,
Arctophila fulva
Open water

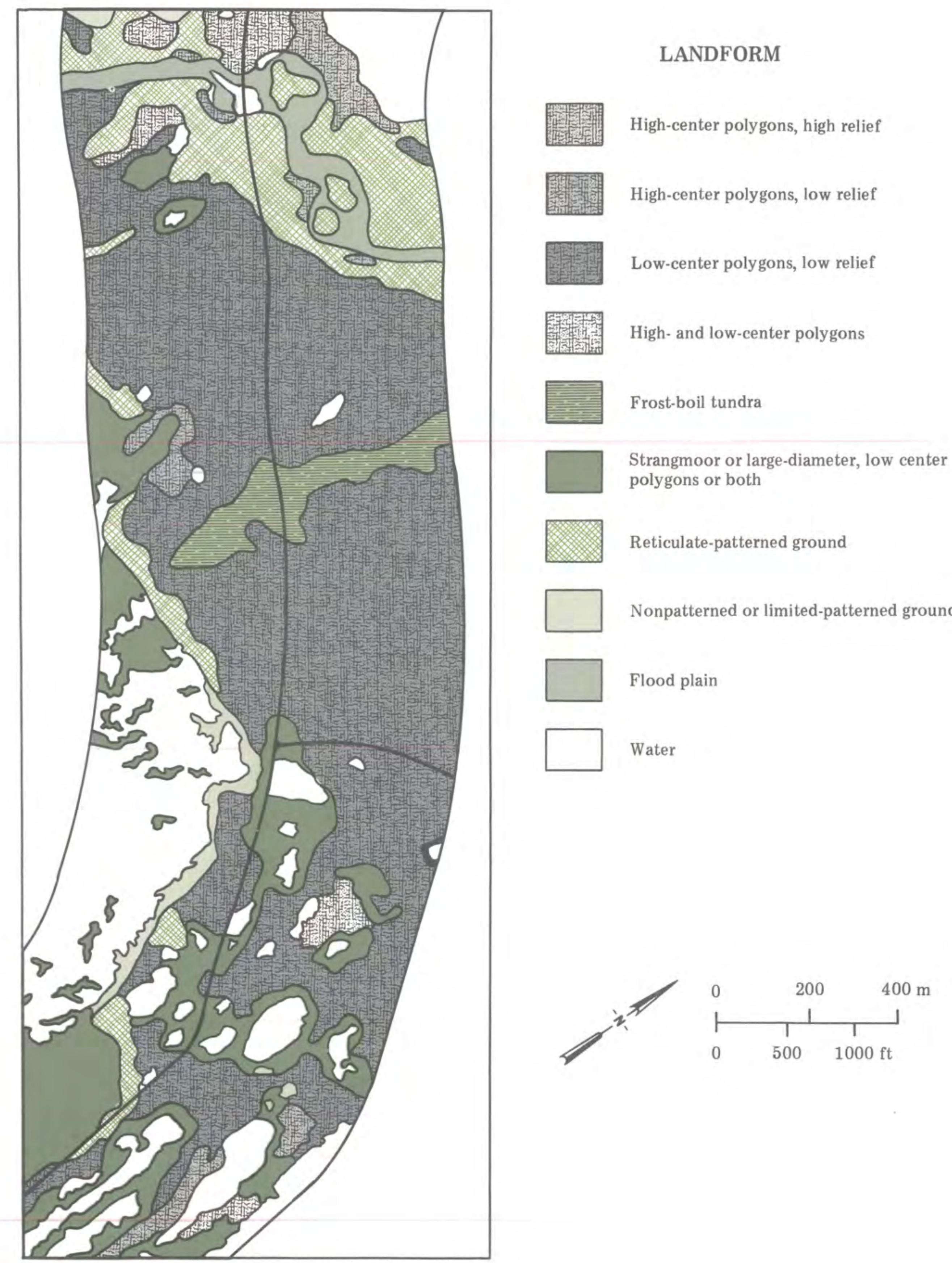
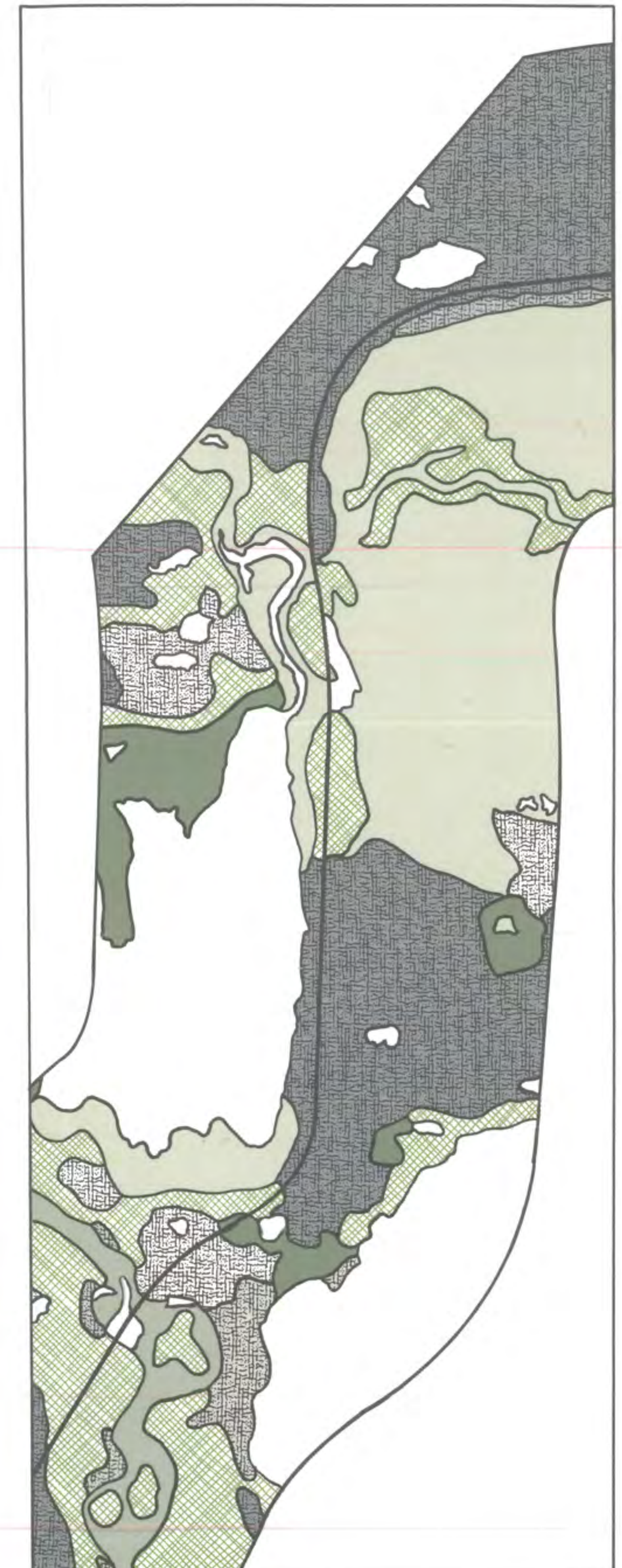

LANDFORM
High-center polygons, high relief
High-center polygons, low relief
Low-center polygons, low relief
High- and low-center polygons
Frost-boil tundra
Strangmoor or large-diameter, low center polygons or both
Reticulate-patterned ground
Nonpatterned or limited-patterned ground
Flood plain
Water
N
0
200
400 m
0
500
1000 ft

Figure 63. Vegetation, landforms, and soils of the Kuparuk route, leg 3.

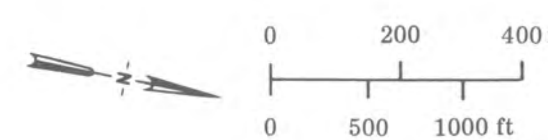
VEGETATION

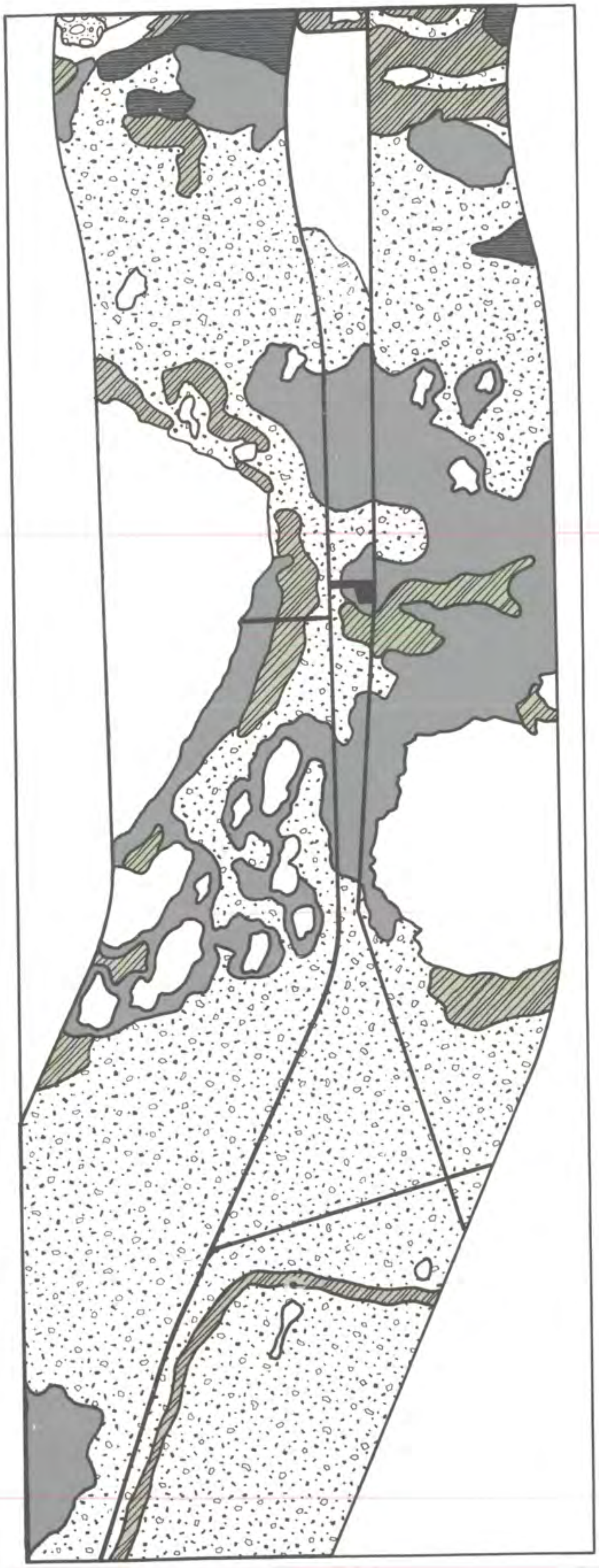
- Dry tundra
  Dryas integrifolia,
  Oxytropis nigrescens
- Moist tundra, upland
  Eriophorum angustifolium,
  E. vaginatum
- Moist tundra vegetation complex
  Eriophorum angustifolium,
  E. vaginatum
- Wet tundra (alkaline)
  Carex aquatilis,
  Eriophorum angustifolium
- Very wet tundra (alkaline)
  Carex aquatilis,
  C. saxatilis ssp. laxa
- Emergent tundra, shallow water
  Carex aquatilis,
  Eriophorum angustifolium
- Emergent tundra, deep water
  Arctophila fulva
- Tundra stream vegetation complex
  Carex aquatilis,
  Arctophila fulva
- Open water



LANDFORM

- High-center polygons, high relief
- High-center polygons, low relief
- Low-center polygons, low relief
- High- and low-center polygons
- Strangmoor or large-diameter, low center polygons or both
- Reticulate-patterned ground
- Nonpatterned or limited-patterned ground
- Flood plain
- Water





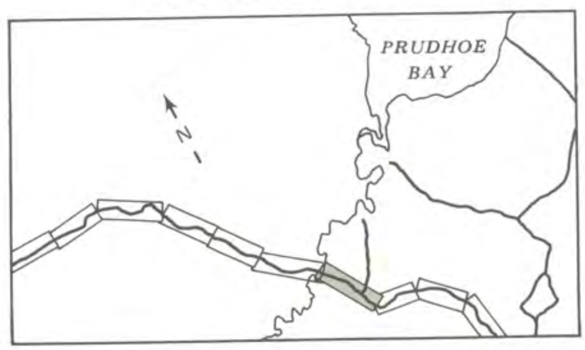
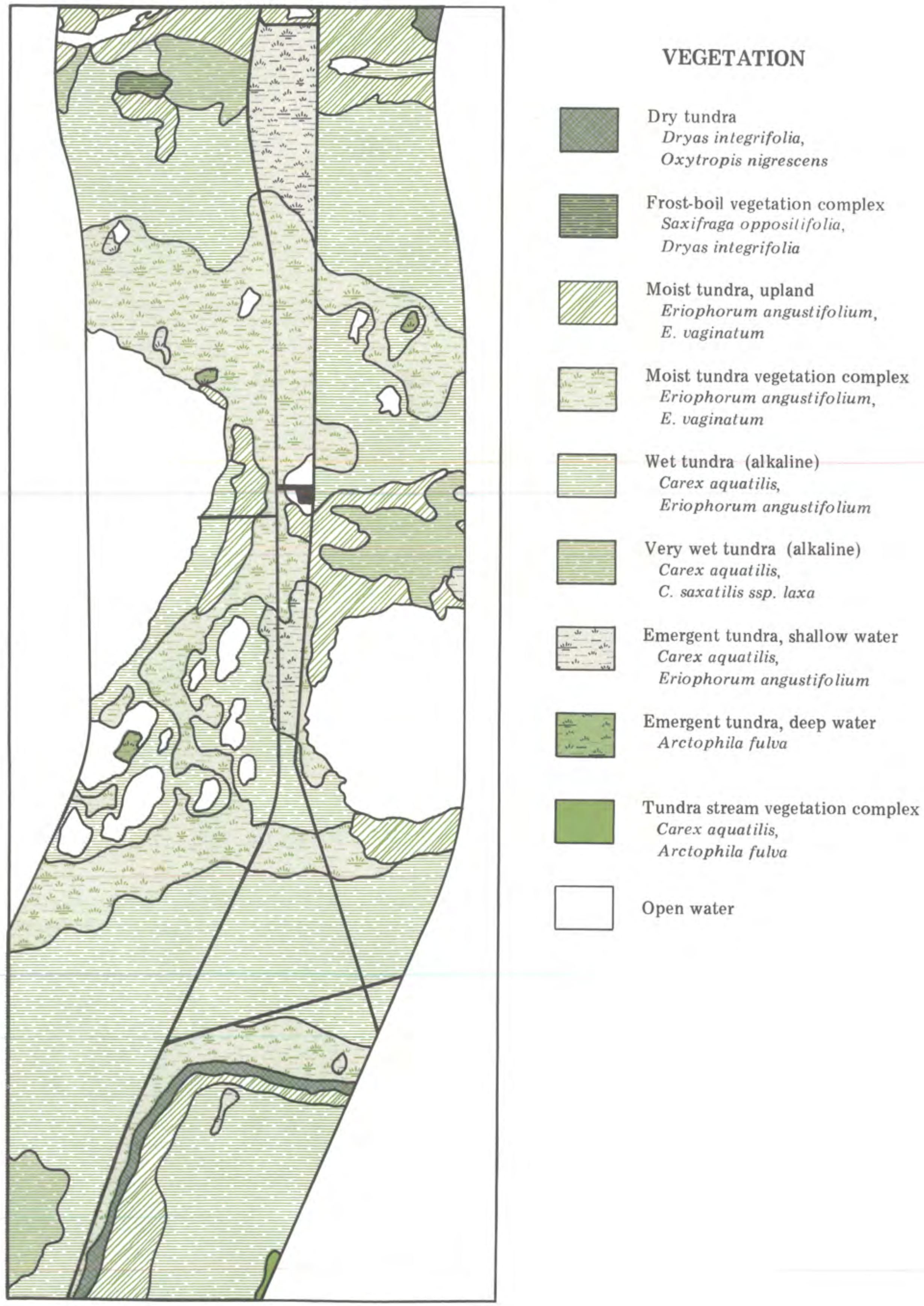
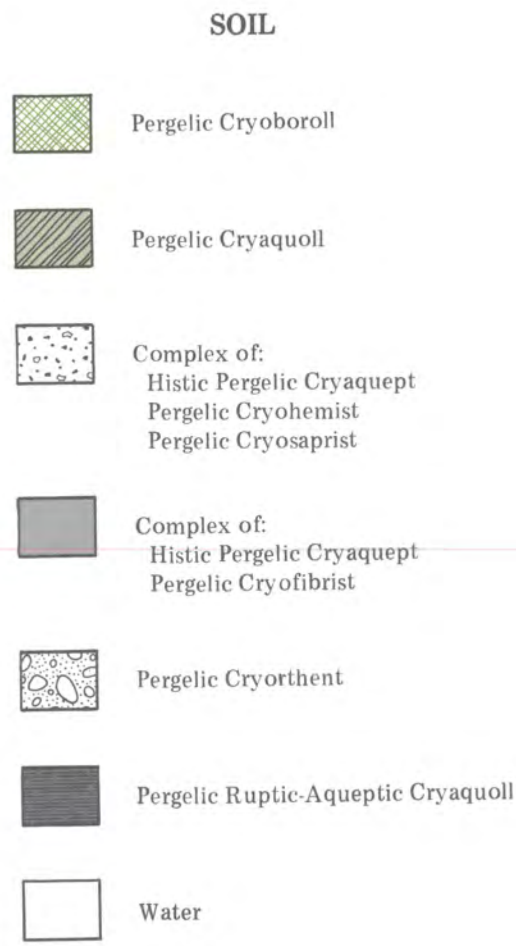


Figure 64. Vegetation, landforms, and soils of the Kuparuk route, leg 4.


VEGETATION
Dry tundra
Dryas integrifolia,
Oxytropis nigrescens
Frost-boil vegetation complex
Saxifraga oppositifolia,
Dryas integrifolia
Moist tundra, upland
Eriophorum angustifolium,
E. vaginatum
Moist tundra vegetation complex
Eriophorum angustifolium,
E. vaginatum
Wet tundra (alkaline)
Carex aquatilis,
Eriophorum angustifolium
Very wet tundra (alkaline)
Carex aquatilis,
C. saxatilis ssp. laxa
Emergent tundra, shallow water
Carex aquatilis,
Eriophorum angustifolium
Emergent tundra, deep water
Arctophila fulva
Tundra stream vegetation complex
Carex aquatilis,
Arctophila fulva
Open water


LANDFORM
High-center polygons, low relief
Low-center polygons, low relief
High- and low-center polygons
Frost-boil tundra
Strangmoor or large-diameter, low-center polygons or both
Reticulate-patterned ground
Nonpatterned or limited-patterned ground
Flood plain
Water
N
0
200
400 m
0
500
1000 ft



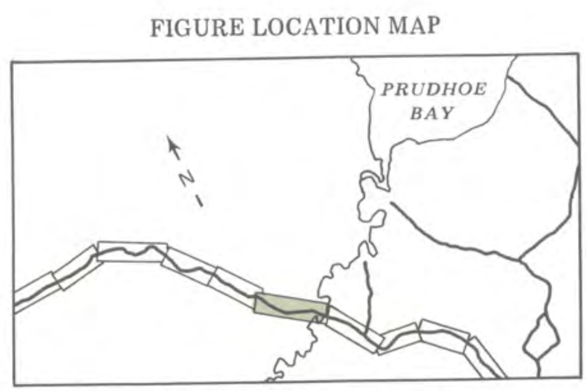
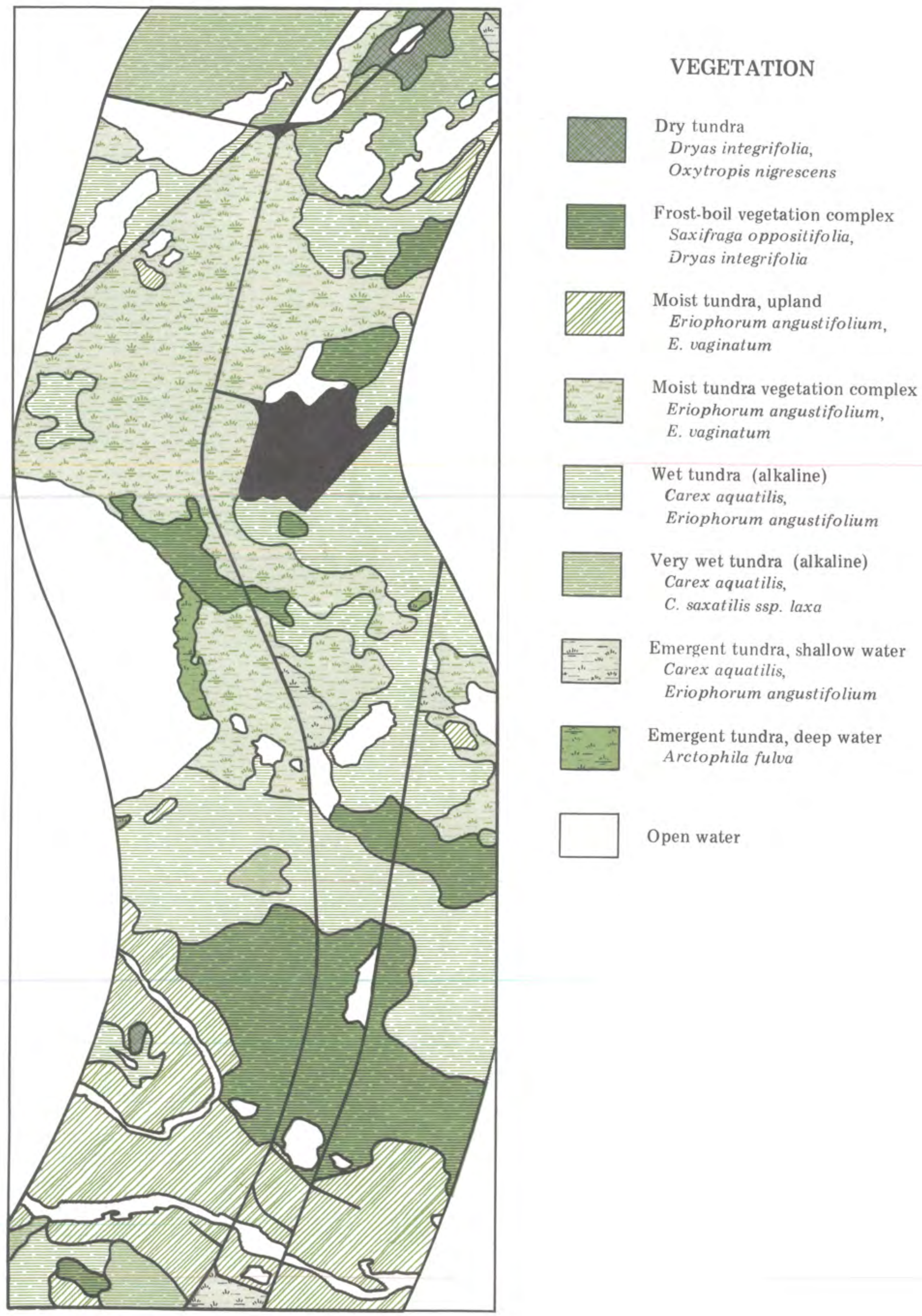


Figure 65. Vegetation, landforms, and soils of the Kuparuk route, leg 5.


VEGETATION
Dry tundra
Dryas integrifolia,
Oxytropis nigrescens
Frost-boil vegetation complex
Saxifraga oppositifolia,
Dryas integrifolia
Moist tundra, upland
Eriophorum angustifolium,
E. vaginatum
Moist tundra vegetation complex
Eriophorum angustifolium,
E. vaginatum
Wet tundra (alkaline)
Carex aquatilis,
Eriophorum angustifolium
Very wet tundra (alkaline)
Carex aquatilis,
C. saxatilis ssp. laxa
Emergent tundra, shallow water
Carex aquatilis,
Eriophorum angustifolium
Emergent tundra, deep water
Arctophila fulva
Open water


LANDFORM
High-center polygons, high relief
High-center polygons, low relief
Low-center polygons, low relief
High- and low-center polygons
Frost-boil tundra
Strangmoor or large-diameter, low-center polygons or both
Hummocky terrain
Reticulate-patterned ground
Nonpatterned or limited-patterned ground
Flood plain
Water
N
0
200
400 m
0
500
1000 ft

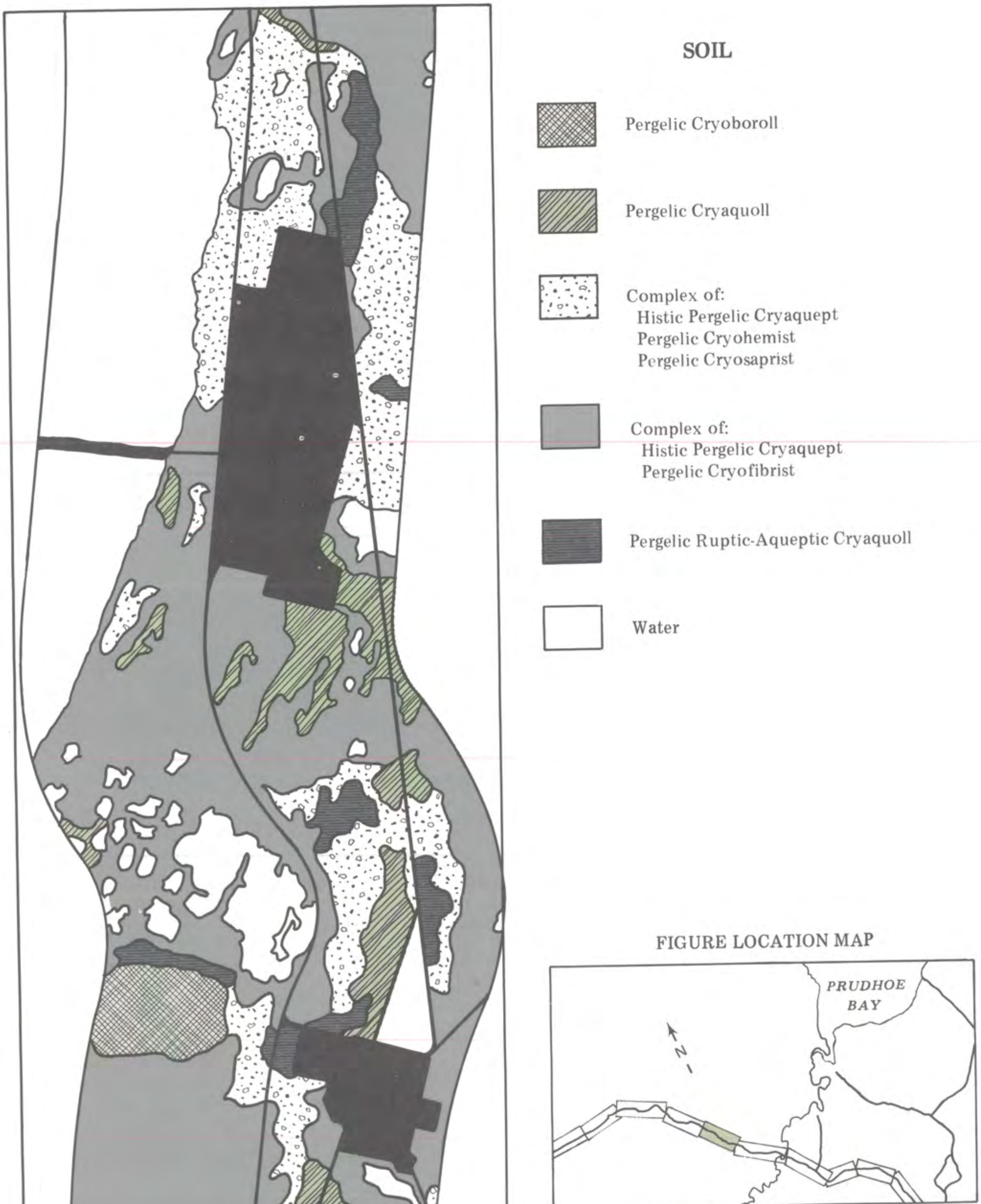
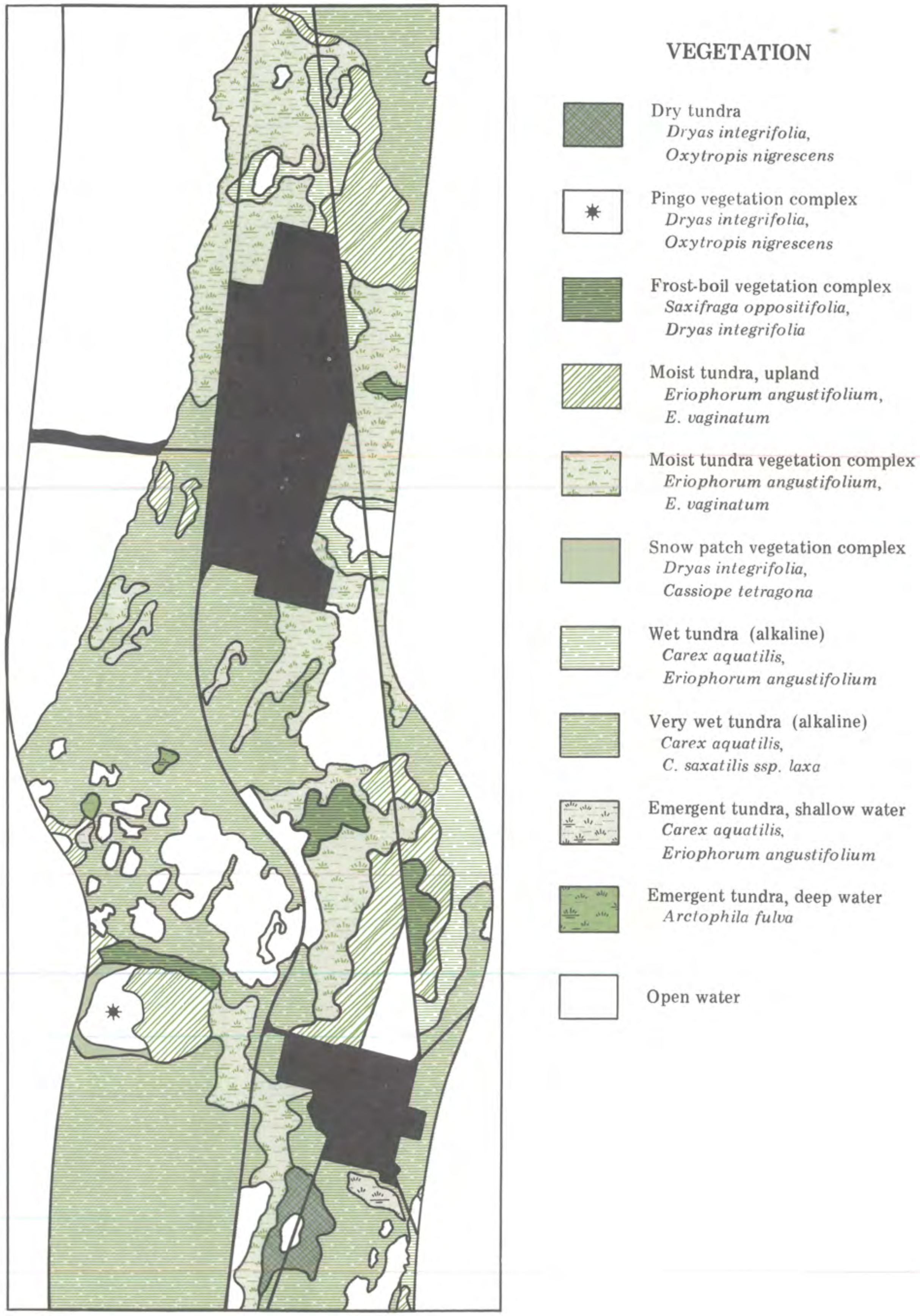


Figure 66. Vegetation, landforms, and soils of the Kuparuk route, leg 6.


VEGETATION
Dry tundra
Dryas integrifolia,
Oxytropis nigrescens
Pingo vegetation complex
Dryas integrifolia,
Oxytropis nigrescens
Frost-boil vegetation complex
Saxifraga oppositifolia,
Dryas integrifolia
Moist tundra, upland
Eriophorum angustifolium,
E. vaginatum
Moist tundra vegetation complex
Eriophorum angustifolium,
E. vaginatum
Snow patch vegetation complex
Dryas integrifolia,
Cassiope tetragona
Wet tundra (alkaline)
Carex aquatilis,
Eriophorum angustifolium
Very wet tundra (alkaline)
Carex aquatilis,
C. saxatilis ssp. laxa
Emergent tundra, shallow water
Carex aquatilis,
Eriophorum angustifolium
Emergent tundra, deep water
Arctophila fulva
Open water


LANDFORM
High-center polygons, high relief
High-center polygons, low relief
Low-center polygons, low relief
High- and low-center polygons
Frost-boil tundra
Strangmoor or large-diameter, low-center polygons or both
Reticulate-patterned ground
Nonpatterned or limited-patterned ground
Pingo
Water
N
0
200
400 m
0
500
1000 ft

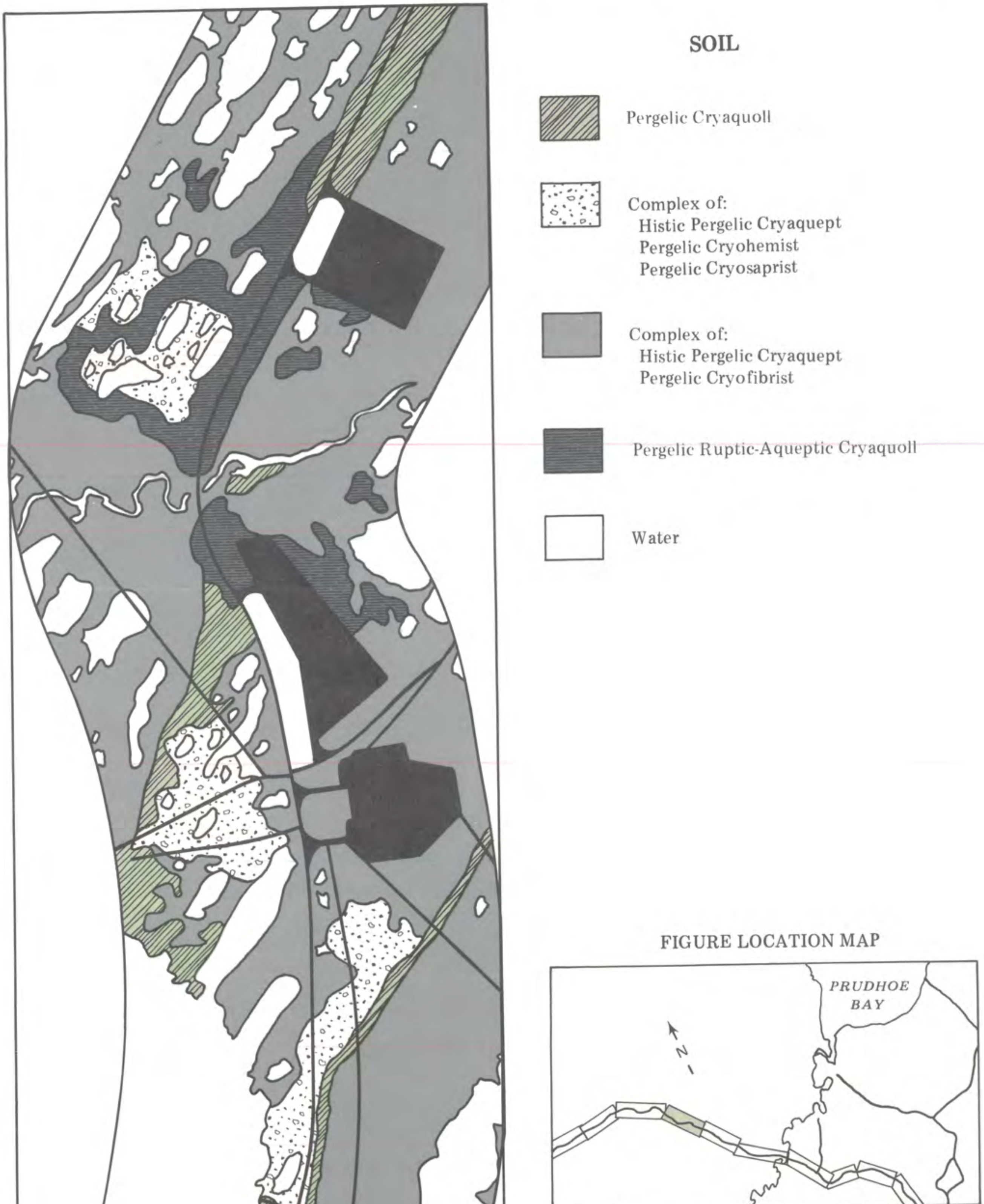
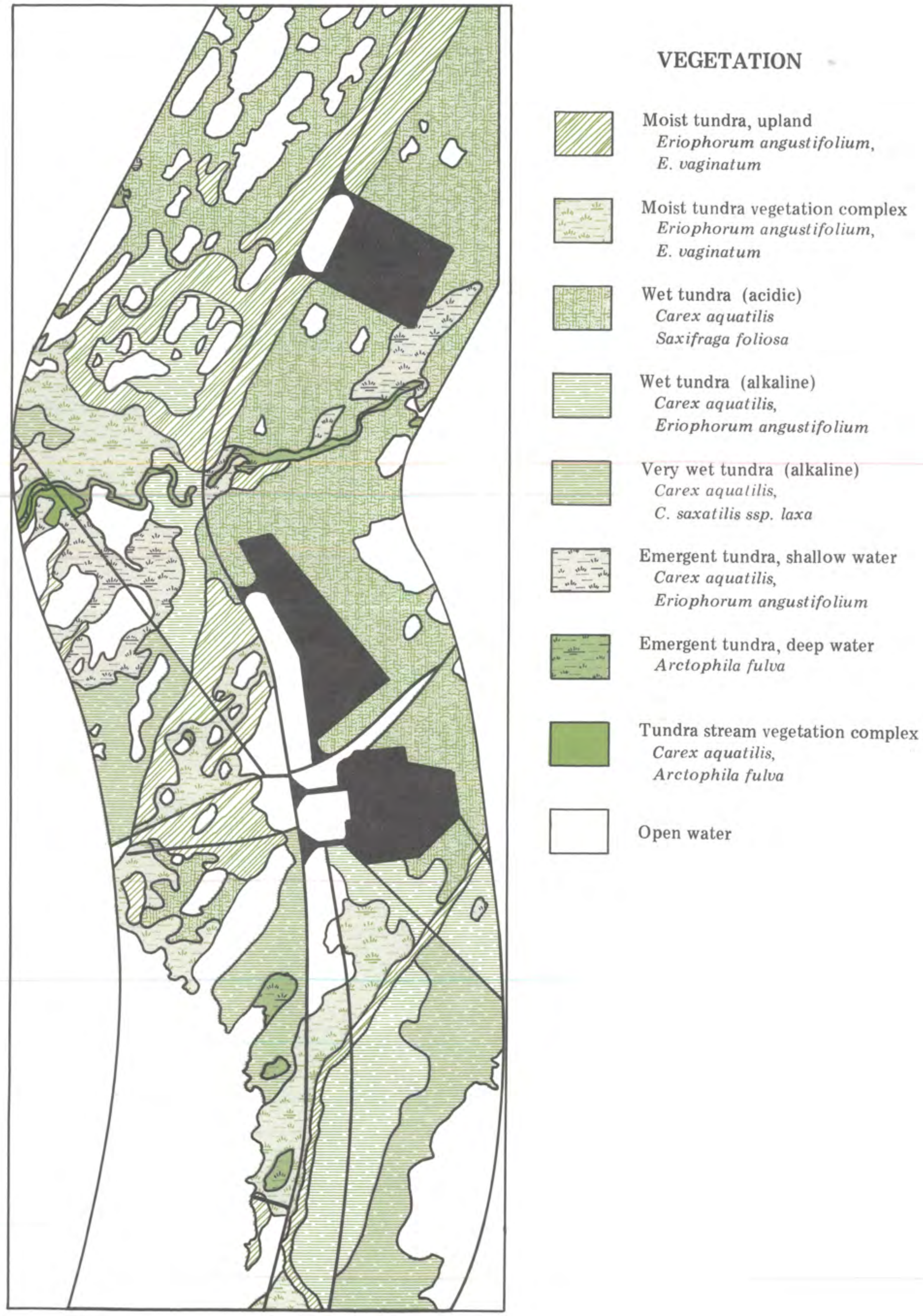


Figure 67. Vegetation, landforms, and soils of the Kuparuk route, leg 7.


VEGETATION
Moist tundra, upland
Eriophorum angustifolium,
E. vaginatum
Moist tundra vegetation complex
Eriophorum angustifolium,
E. vaginatum
Wet tundra (acidic)
Carex aquatilis
Saxifraga foliosa
Wet tundra (alkaline)
Carex aquatilis,
Eriophorum angustifolium
Very wet tundra (alkaline)
Carex aquatilis,
C. saxatilis ssp. laxa
Emergent tundra, shallow water
Carex aquatilis,
Eriophorum angustifolium
Emergent tundra, deep water
Arctophila fulva
Tundra stream vegetation complex
Carex aquatilis,
Arctophila fulva
Open water


LANDFORM
High-center polygons, high relief
High-center polygons, low relief
Low-center polygons, low relief
High- and low-center polygons
Frost-boil tundra
Strangmoor or large-diameter, low-center polygons or both
Reticulate-patterned ground
Nonpatterned or limited-patterned ground
Water
0
200
400 m
0
500
1000 ft

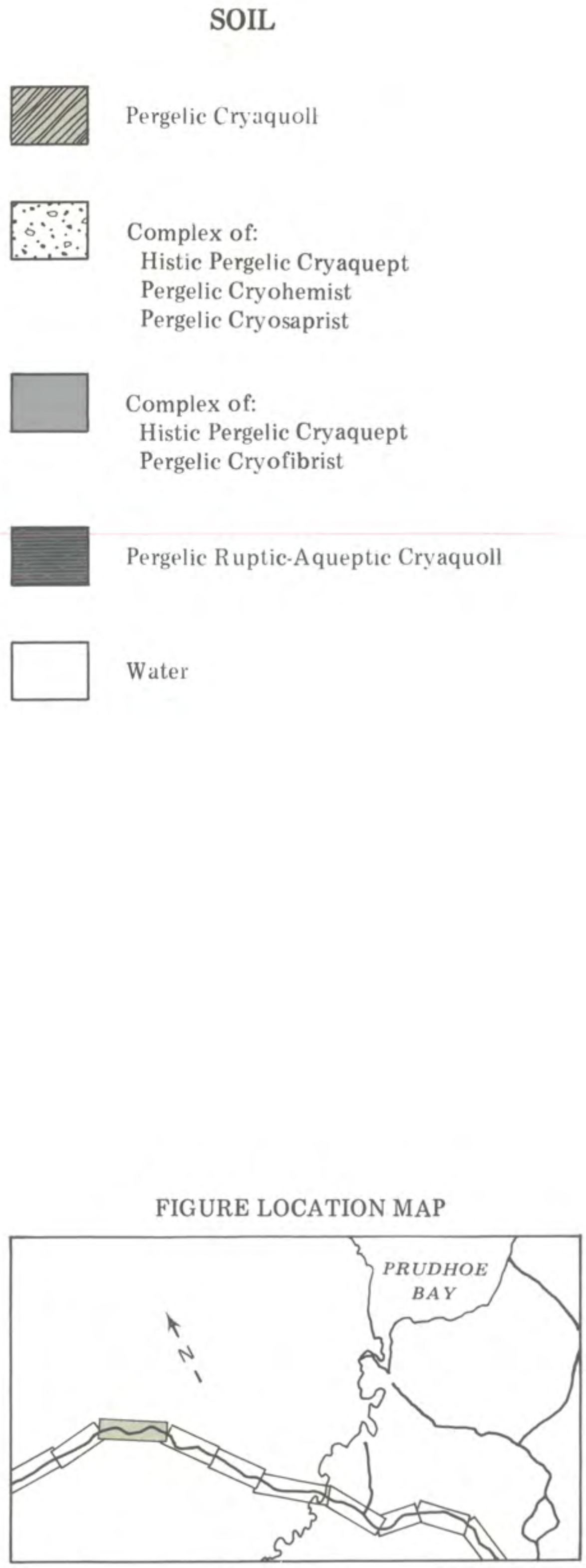
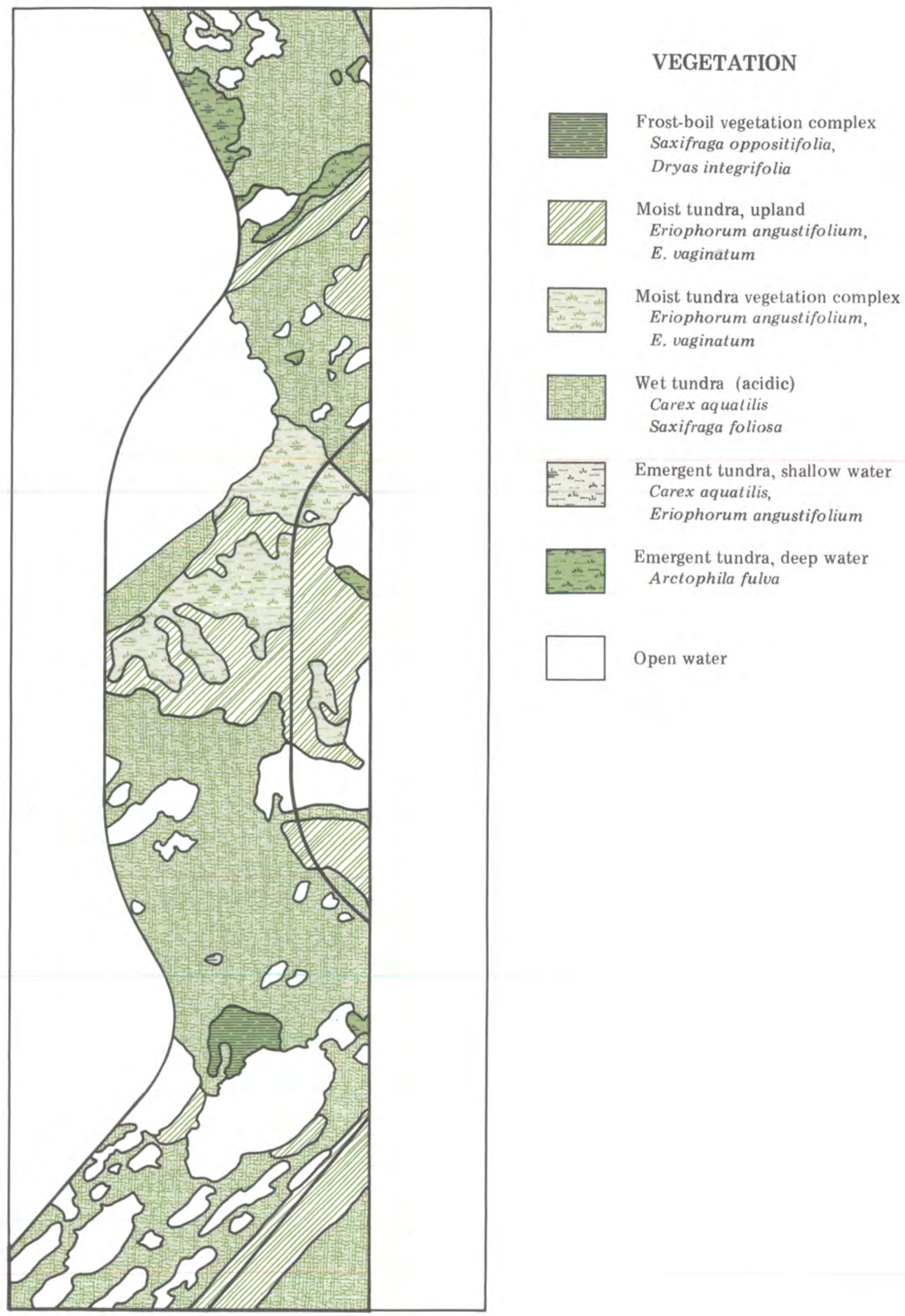
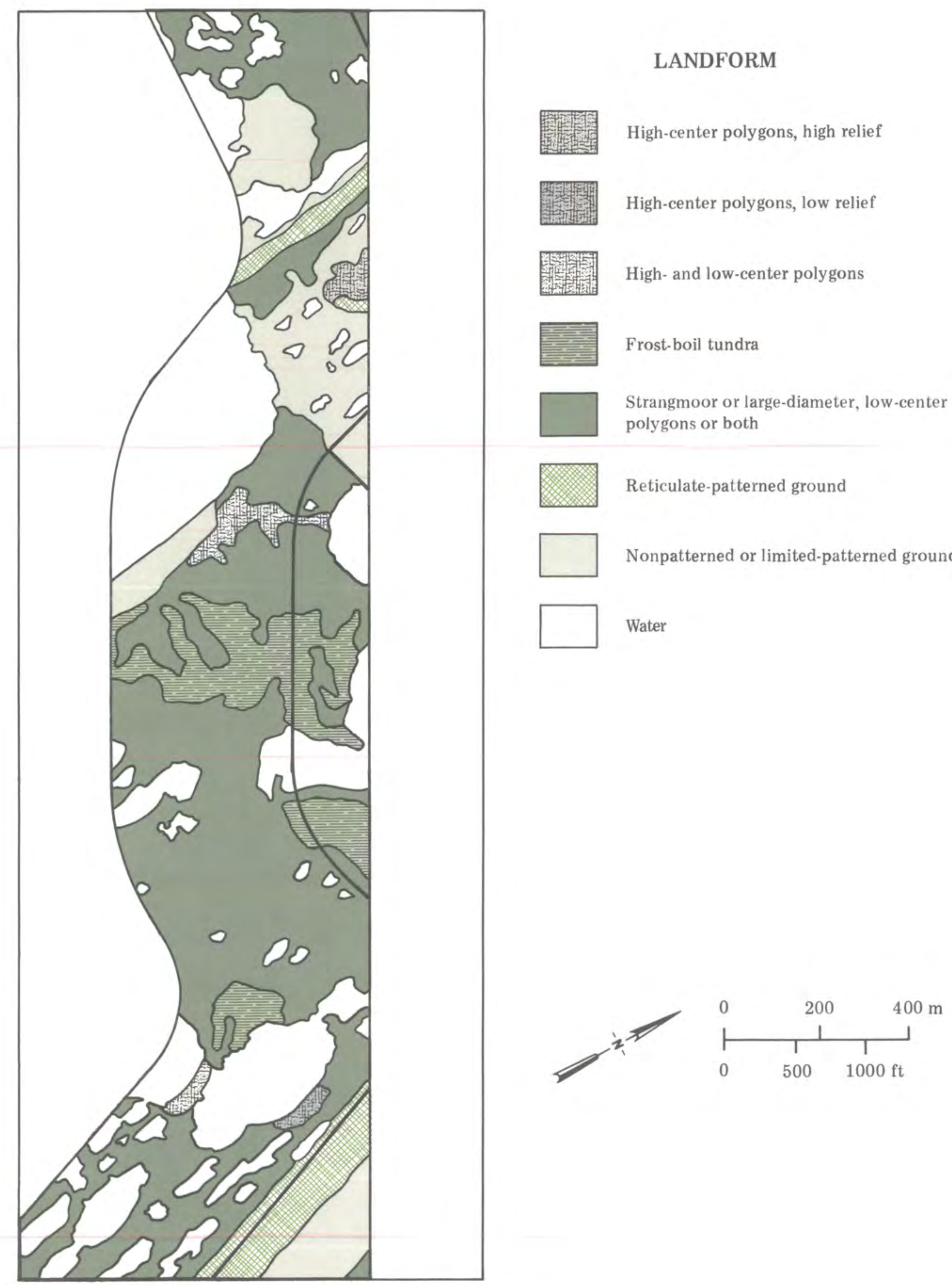


Figure 68. Vegetation, landforms, and soils of the Kuparuk route, leg 8.


VEGETATION
Frost-boil vegetation complex
Saxifraga oppositifolia,
Dryas integrifolia
Moist tundra, upland
Eriophorum angustifolium,
E. vaginatum
Moist tundra vegetation complex
Eriophorum angustifolium,
E. vaginatum
Wet tundra (acidic)
Carex aquatilis
Saxifraga foliosa
Emergent tundra, shallow water
Carex aquatilis,
Eriophorum angustifolium
Emergent tundra, deep water
Arctophila fulva
Open water


LANDFORM
High-center polygons, high relief
High-center polygons, low relief
High- and low-center polygons
Frost-boil tundra
Strangmoor or large-diameter, low-center polygons or both
Reticulate-patterned ground
Nonpatterned or limited-patterned ground
Water
N
0
200
400 m
0
500
1000 ft

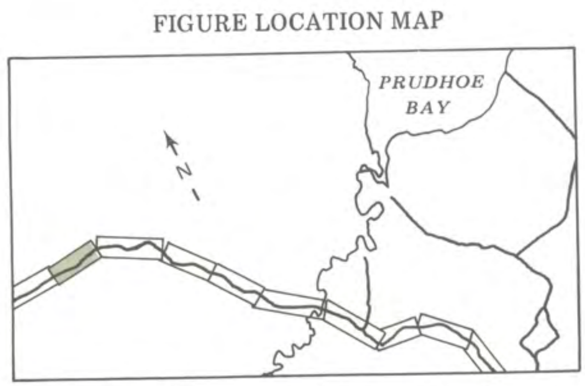
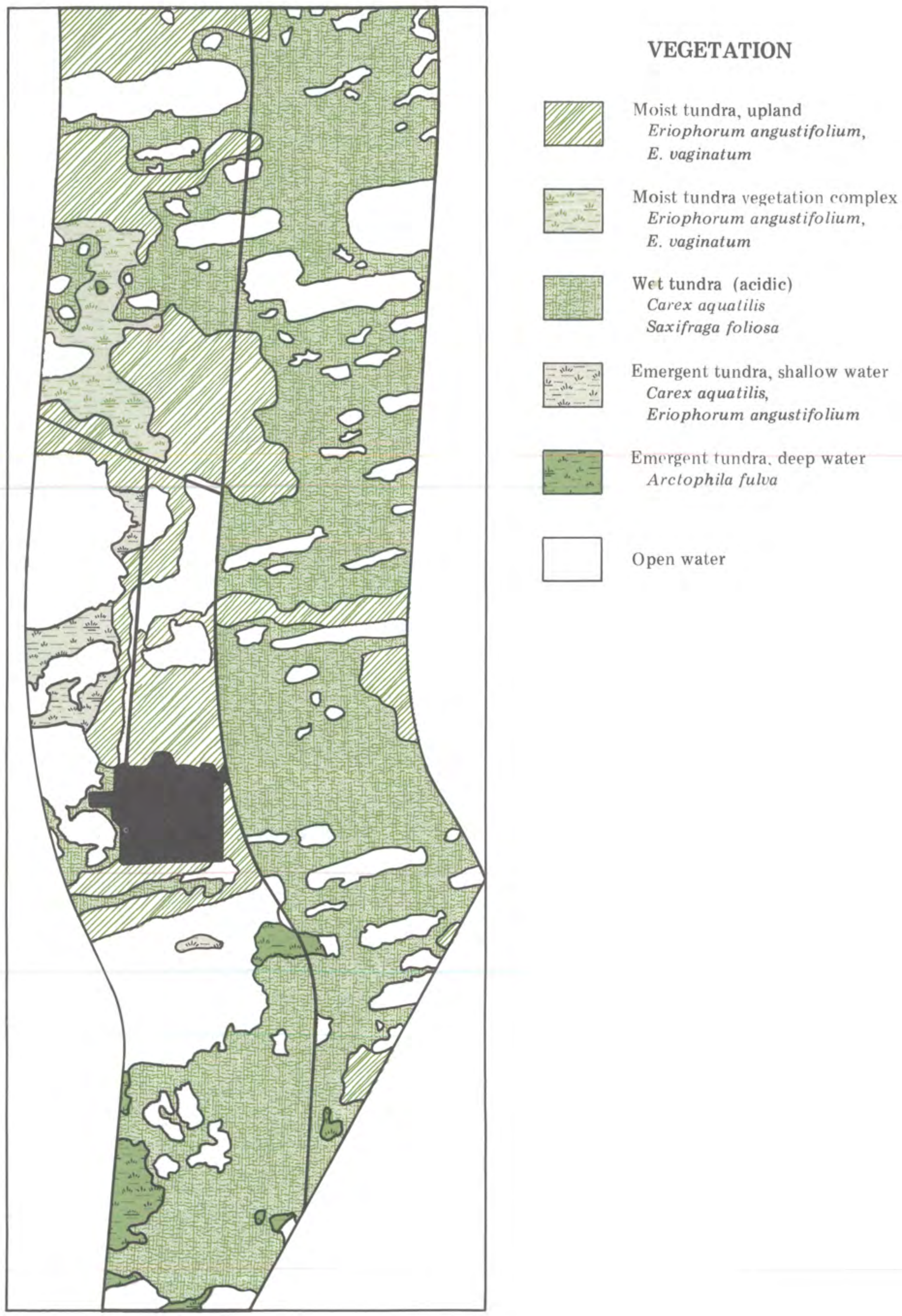
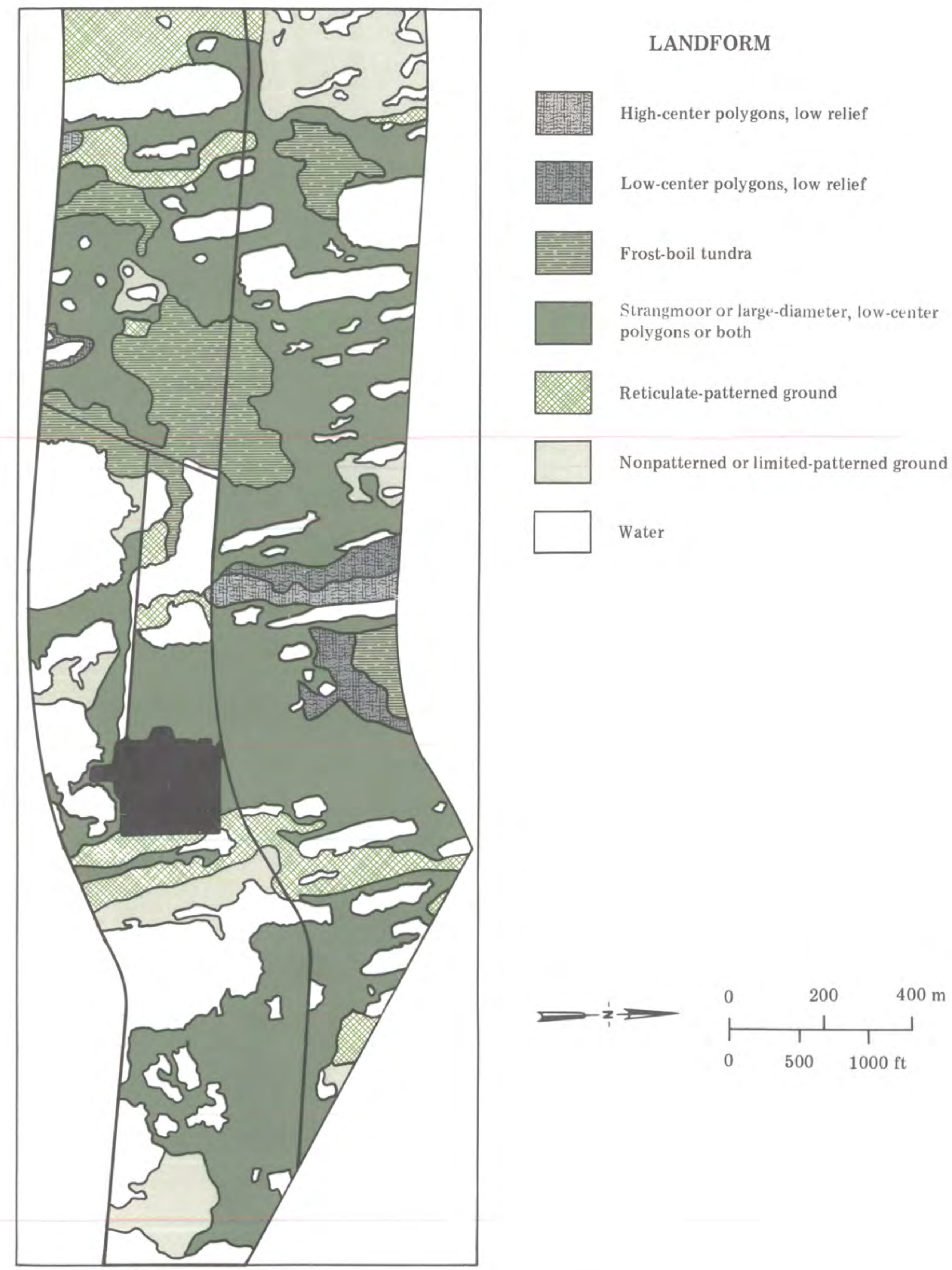


Figure 69. Vegetation, landforms, and soils of the Kuparuk route, leg 9.


VEGETATION
Moist tundra, upland
Eriophorum angustifolium,
E. vaginatum
Moist tundra vegetation complex
Eriophorum angustifolium,
E. vaginatum
Wet tundra (acidic)
Carex aquatilis
Saxifraga foliosa
Emergent tundra, shallow water
Carex aquatilis,
Eriophorum angustifolium
Emergent tundra, deep water
Arctophila fulva
Open water


LANDFORM
High-center polygons, low relief
Low-center polygons, low relief
Frost-boil tundra
Strangmoor or large-diameter, low-center polygons or both
Reticulate-patterned ground
Nonpatterned or limited-patterned ground
Water
N
0
200
400 m
0
500
1000 ft

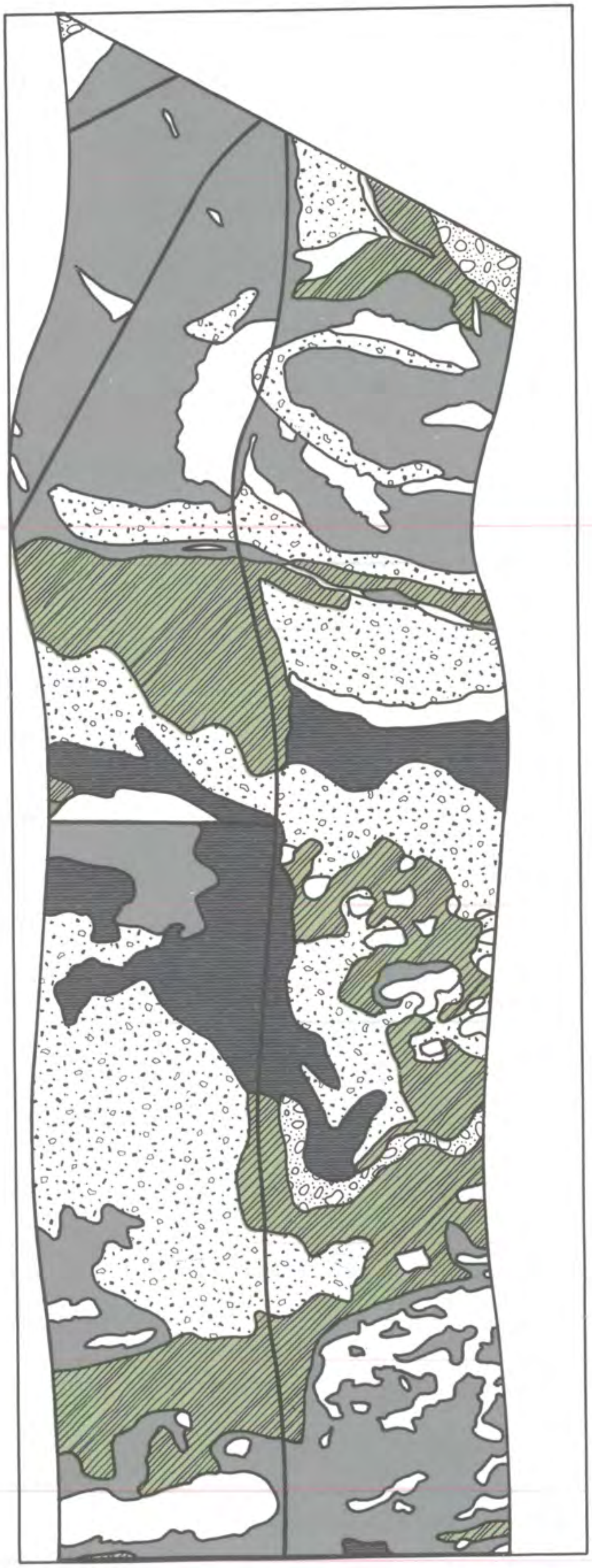


FIGURE LOCATION MAP

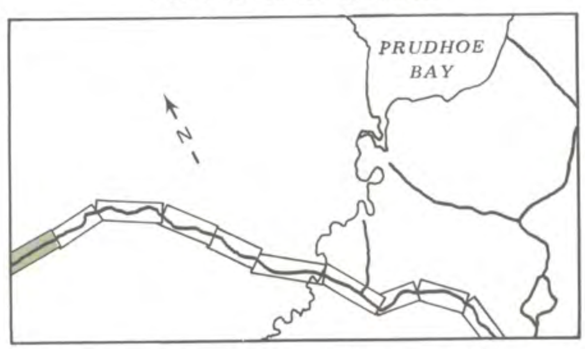
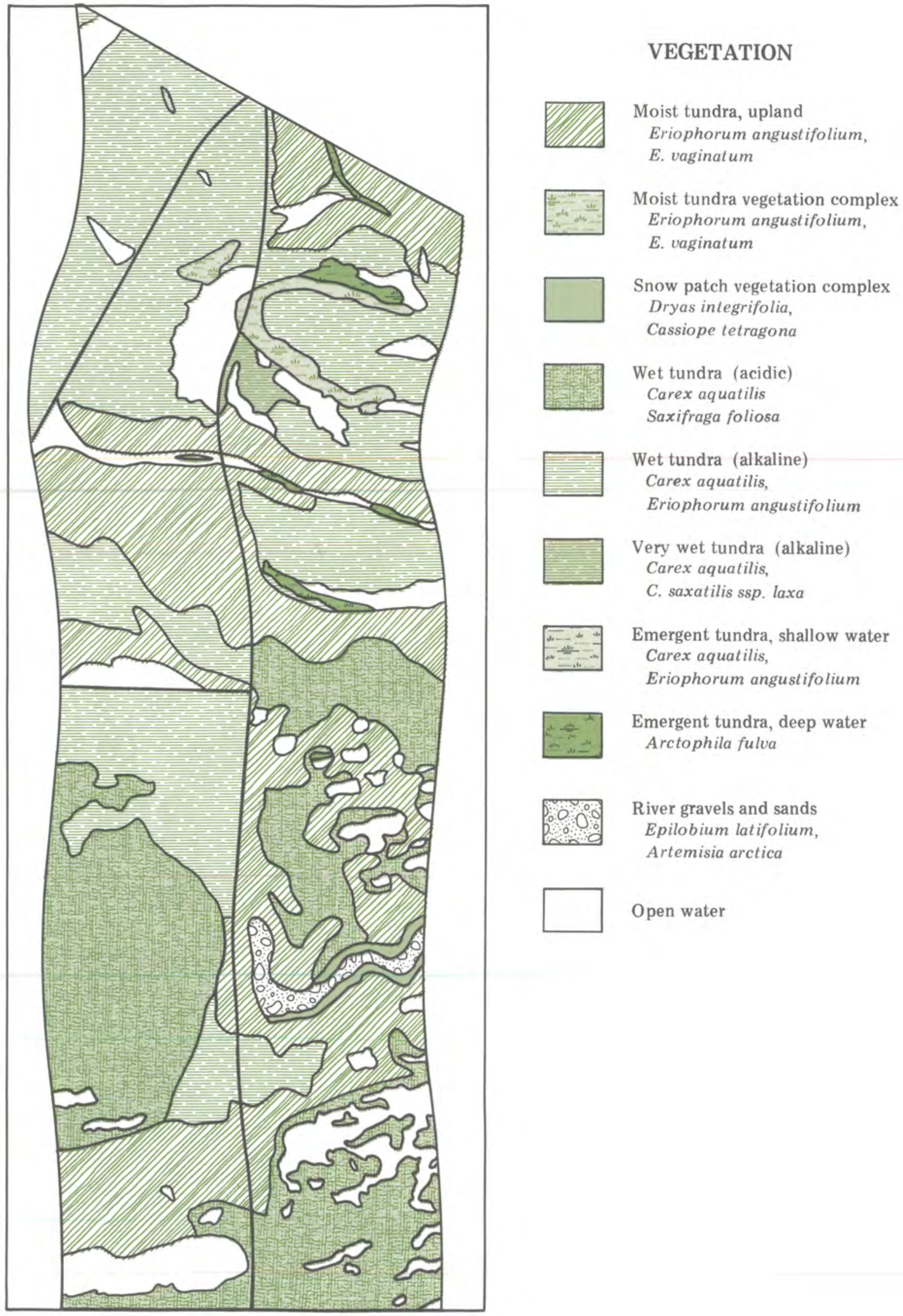


Figure 70. Vegetation, landforms, and soils of the Kuparuk route, leg 10.


VEGETATION
Moist tundra, upland
Eriophorum angustifolium,
E. vaginatum
Moist tundra vegetation complex
Eriophorum angustifolium,
E. vaginatum
Snow patch vegetation complex
Dryas integrifolia,
Cassiope tetragona
Wet tundra (acidic)
Carex aquatilis
Saxifraga foliosa
Wet tundra (alkaline)
Carex aquatilis,
Eriophorum angustifolium
Very wet tundra (alkaline)
Carex aquatilis,
C. saxatilis ssp. laxa
Emergent tundra, shallow water
Carex aquatilis,
Eriophorum angustifolium
Emergent tundra, deep water
Arctophila fulva
River gravels and sands
Epilobium latifolium,
Artemisia arctica
Open water


LANDFORM
High-center polygons, high relief
Low-center polygons, low relief
Frost-boil tundra
Strangmoor or large-diameter, low-center polygons or both
Reticulate-patterned ground
Nonpatterned or limited-patterned ground
Flood plain
Water
N
0
200
400 m
0
500
1000 ft

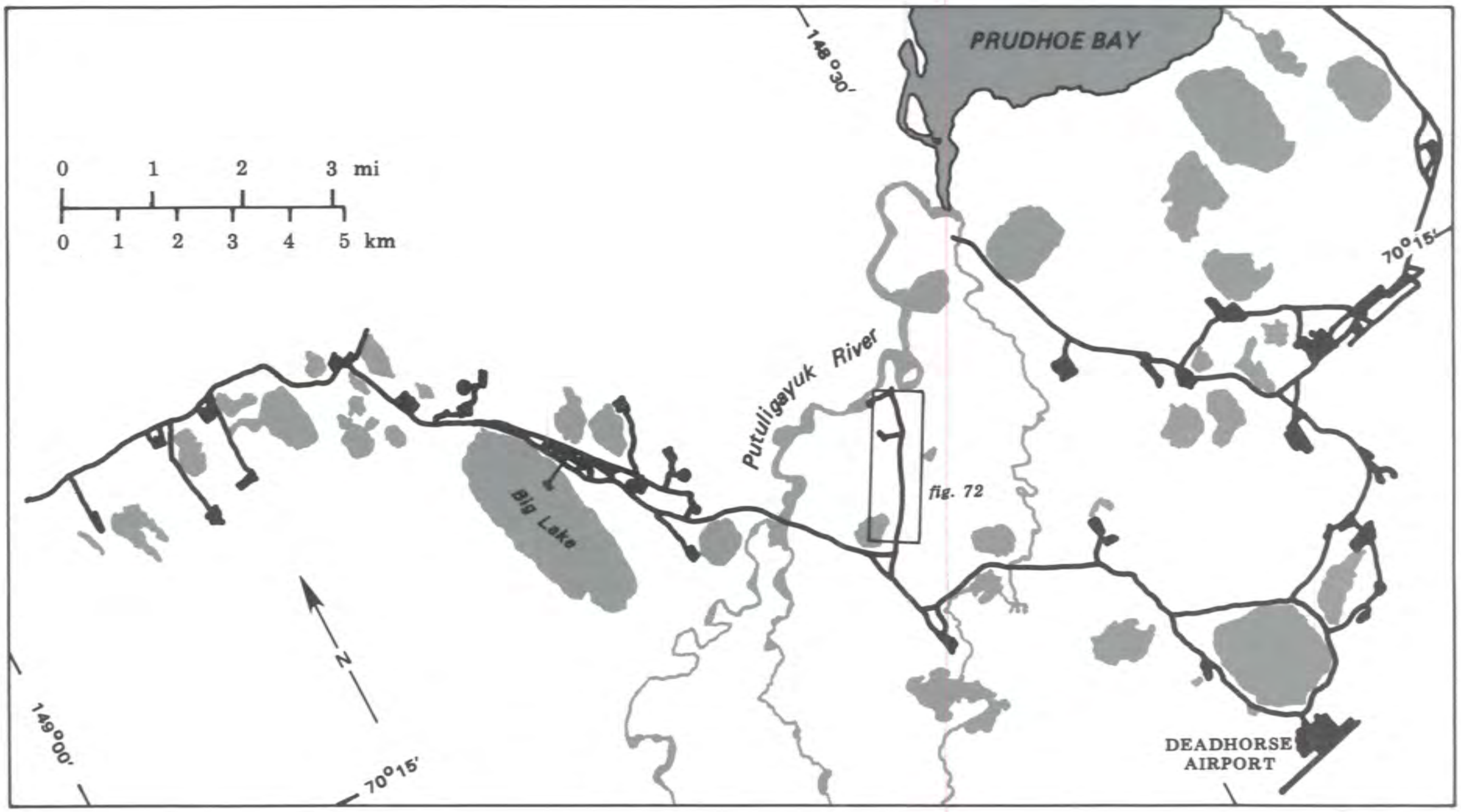
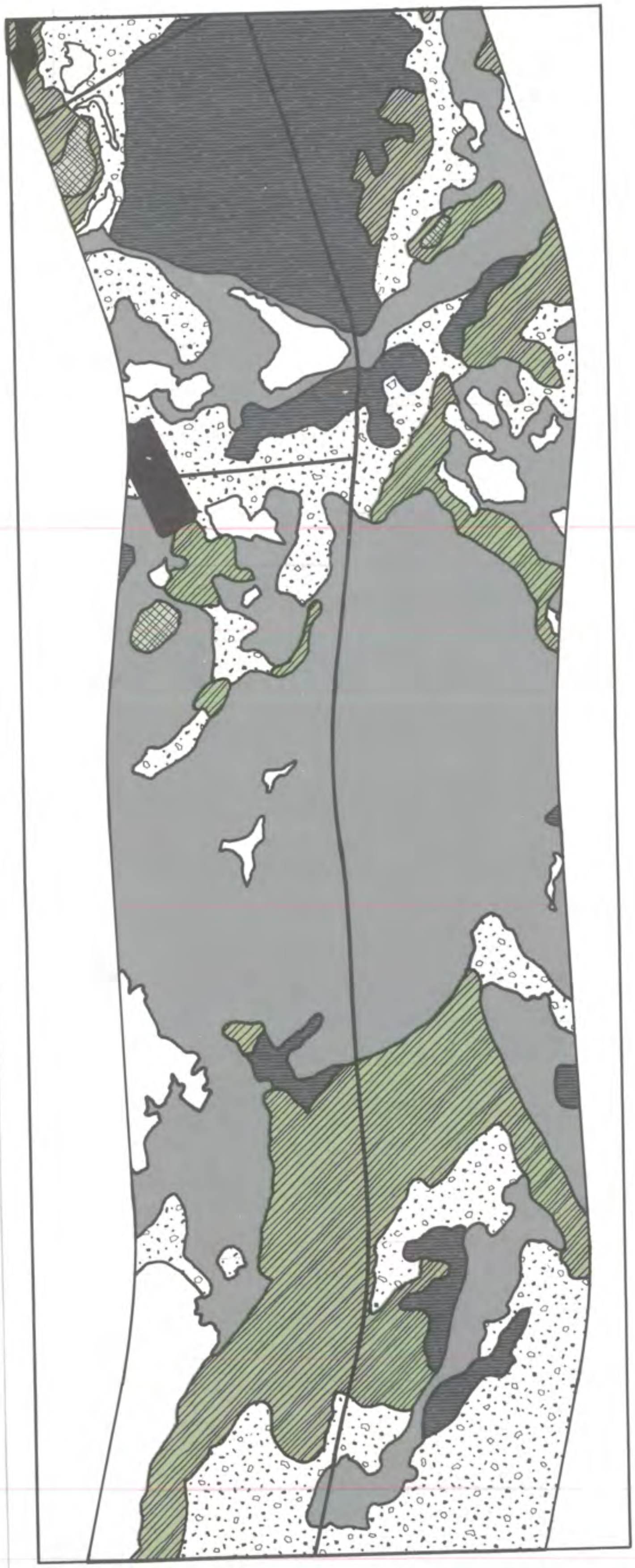


Figure 71. Index map of vegetation, landforms, and soils maps of part of the Putuligayuk River route, Prudhoe Bay, Alaska.



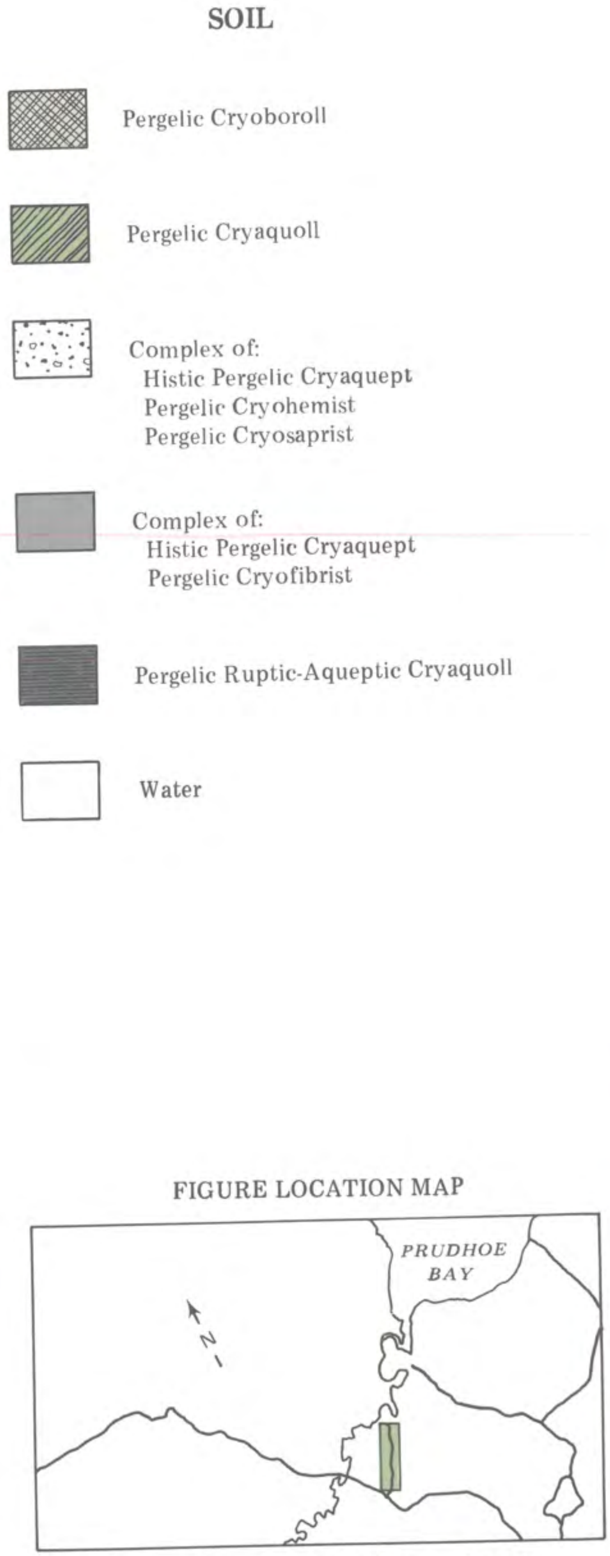
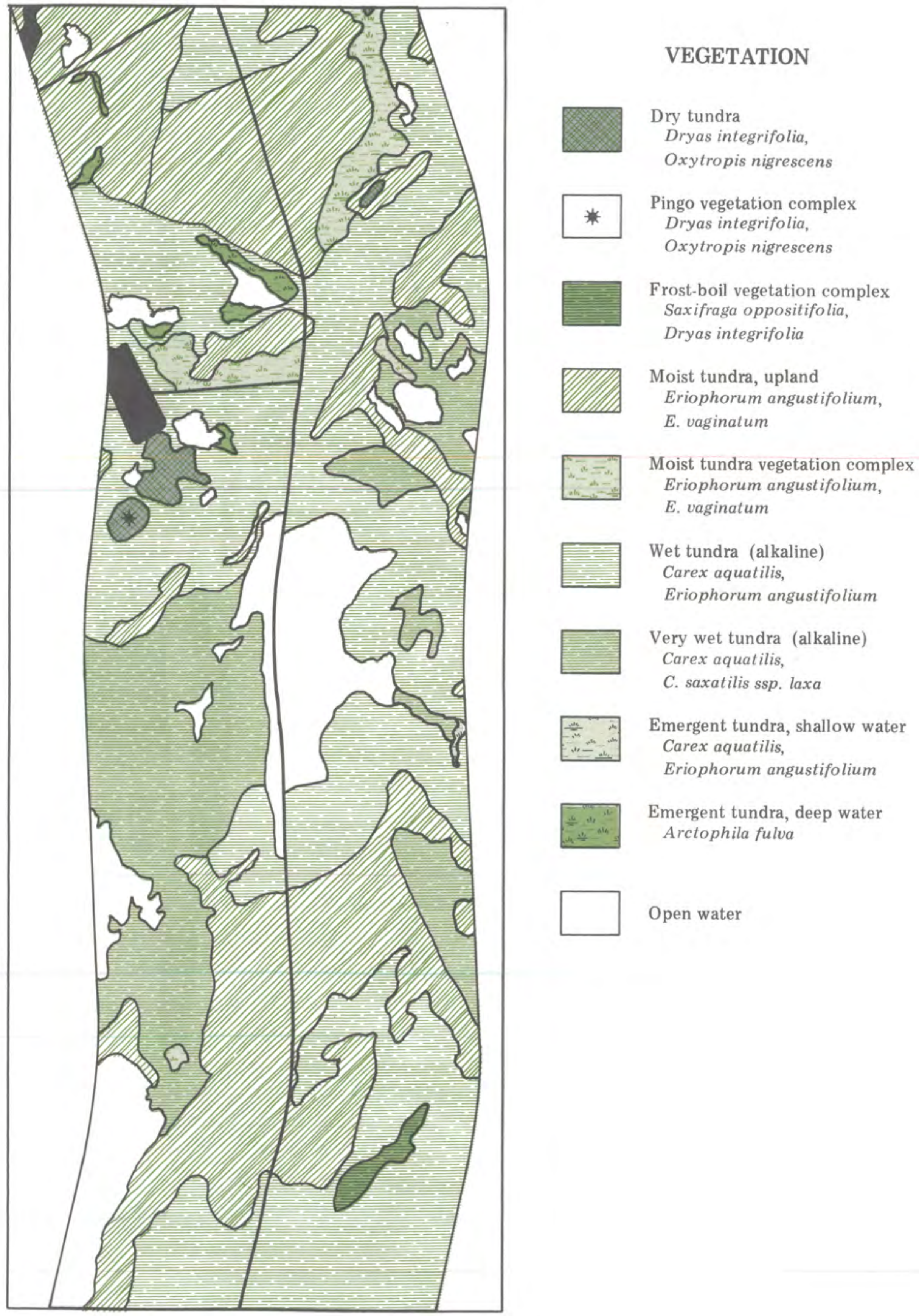


Figure 72. Vegetation, landforms, and soils of part of the Putuligayuk River route.


VEGETATION
Dry tundra
Dryas integrifolia, Oxytropis nigrescens
Pingo vegetation complex
Dryas integrifolia, Oxytropis nigrescens
Frost-boil vegetation complex
Saxifraga oppositifolia, Dryas integrifolia
Moist tundra, upland
Eriophorum angustifolium, E. vaginatum
Moist tundra vegetation complex
Eriophorum angustifolium, E. vaginatum
Wet tundra (alkaline)
Carex aquatilis, Eriophorum angustifolium
Very wet tundra (alkaline)
Carex aquatilis, C. saxatilis ssp. laxa
Emergent tundra, shallow water
Carex aquatilis, Eriophorum angustifolium
Emergent tundra, deep water
Arctophila fulva
Open water


LANDFORM
High-center polygons, high relief
High-center polygons, low relief
Low-center polygons, low relief
High- and low-center polygons
Frost-boil tundra
Strangmoor or large-diameter, low-center polygons or both
Hummocky terrain
Reticulate-patterned ground
Nonpatterned or limited-patterned ground
Pingo
Water
N
0 200 400 m
0 500 1000 ft

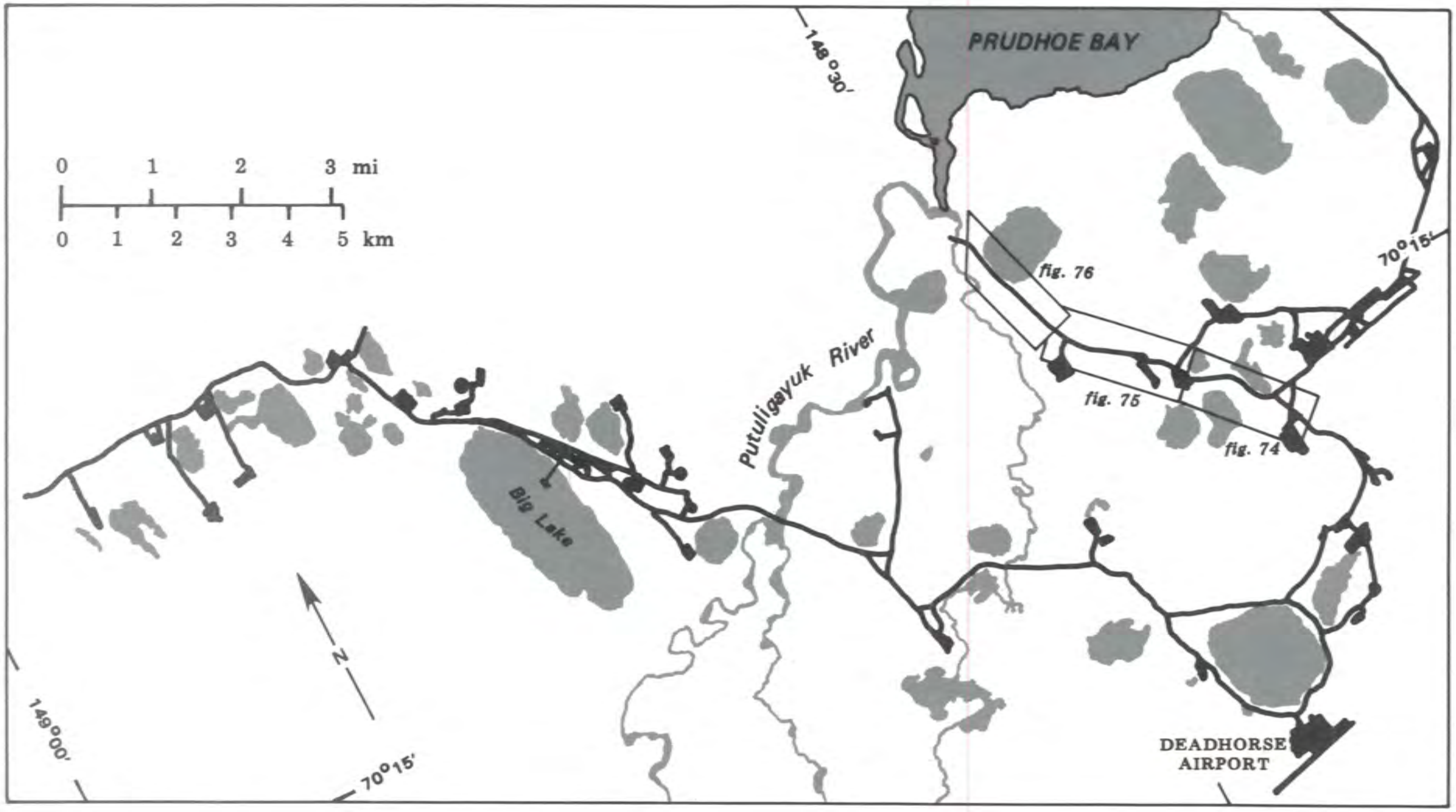
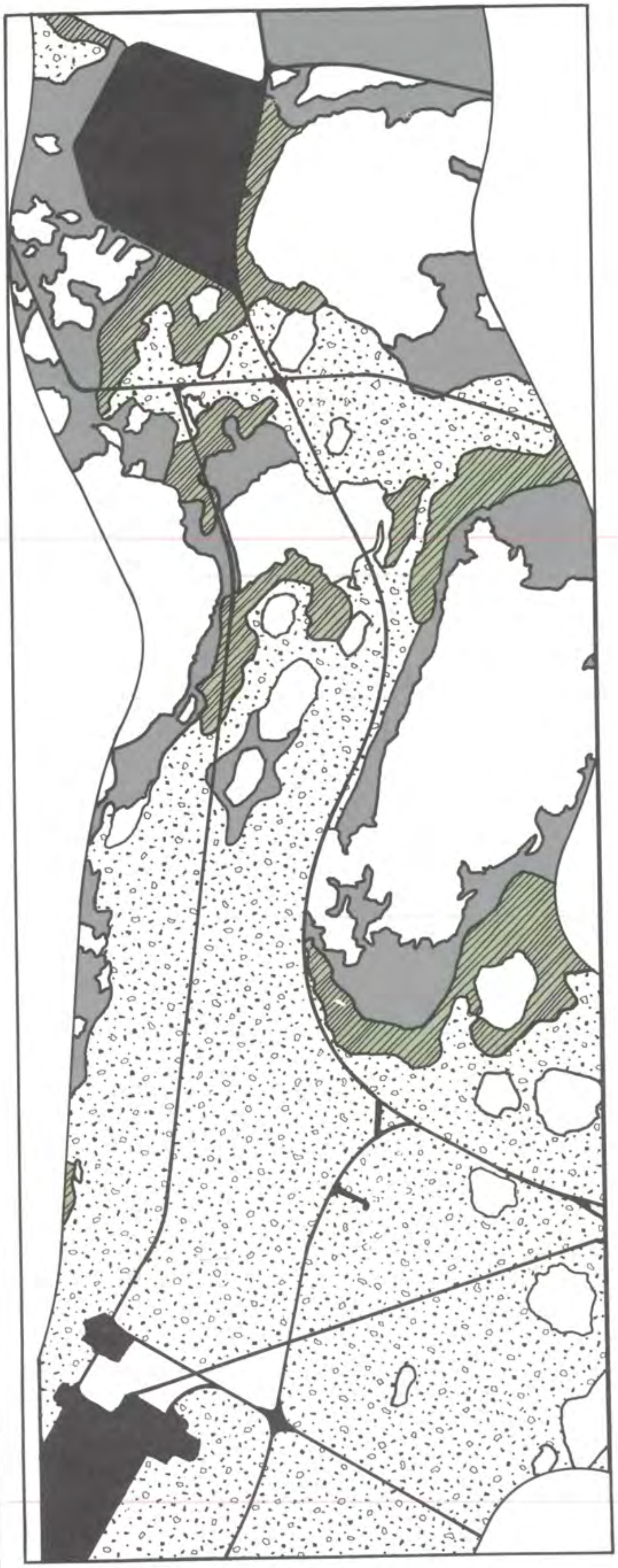
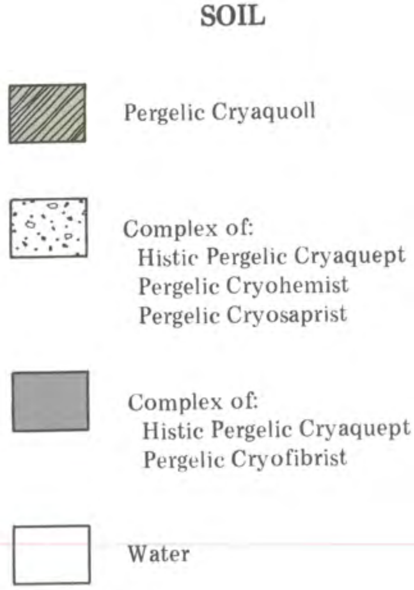


Figure 73. Index map of vegetation, landforms, and soils maps of part of the West Dock route, Prudhoe Bay, Alaska.





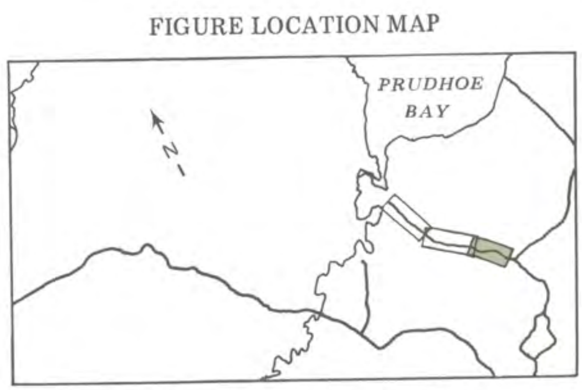
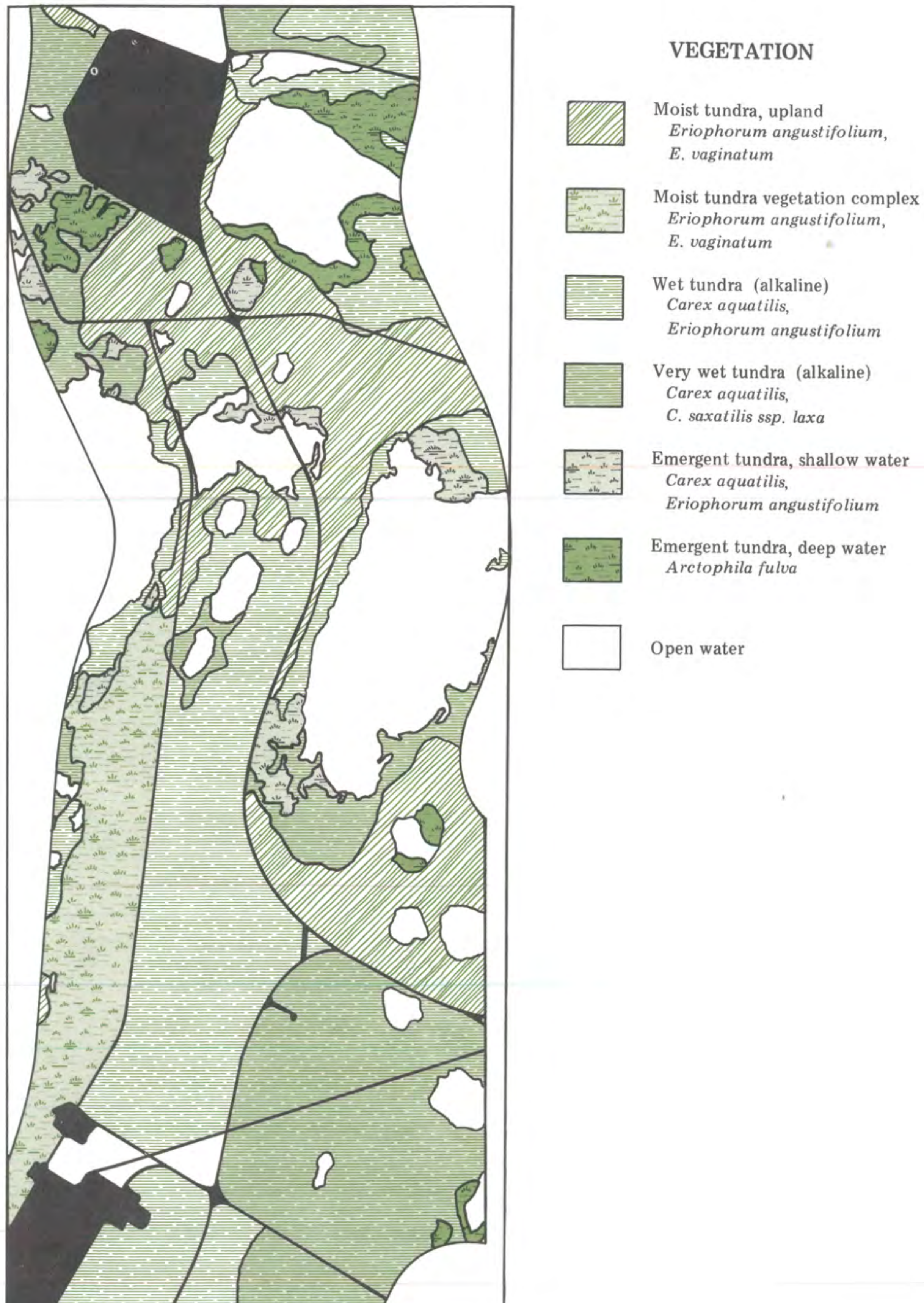
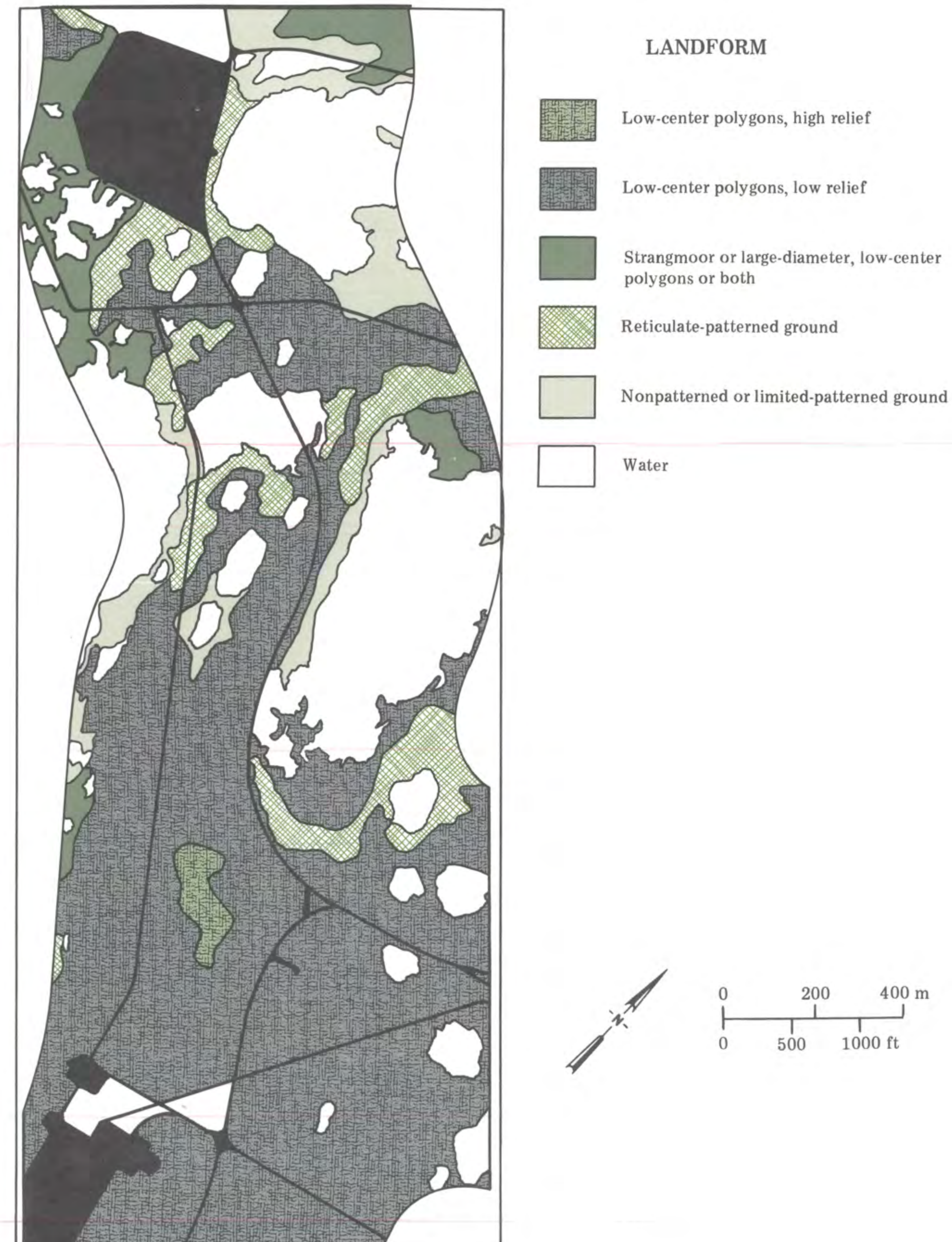


Figure 74. Vegetation, landforms, and soils of the West Dock route, leg 1.


VEGETATION
Moist tundra, upland
Eriophorum angustifolium,
E. vaginatum
Moist tundra vegetation complex
Eriophorum angustifolium,
E. vaginatum
Wet tundra (alkaline)
Carex aquatilis,
Eriophorum angustifolium
Very wet tundra (alkaline)
Carex aquatilis,
C. saxatilis ssp. laxa
Emergent tundra, shallow water
Carex aquatilis,
Eriophorum angustifolium
Emergent tundra, deep water
Arctophila fulva
Open water


LANDFORM
Low-center polygons, high relief
Low-center polygons, low relief
Strangmoor or large-diameter, low-center polygons or both
Reticulate-patterned ground
Nonpatterned or limited-patterned ground
Water
N
0
200
400 m
0
500
1000 ft

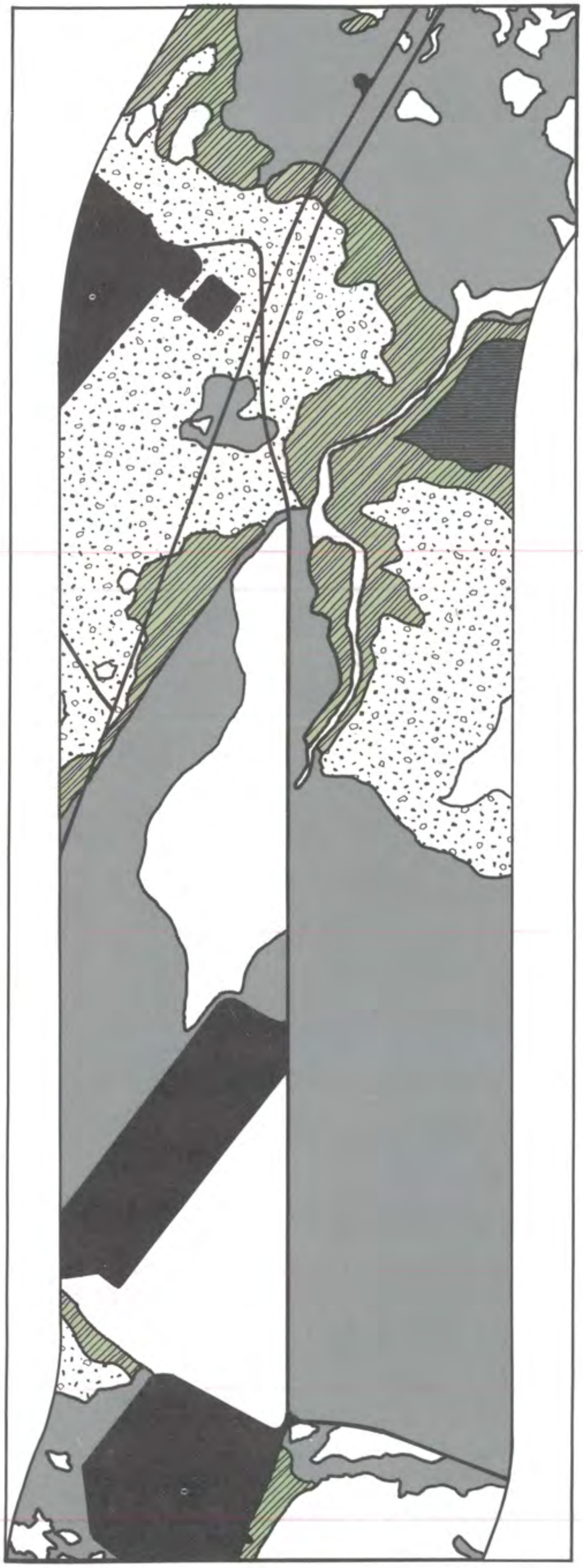


FIGURE LOCATION MAP

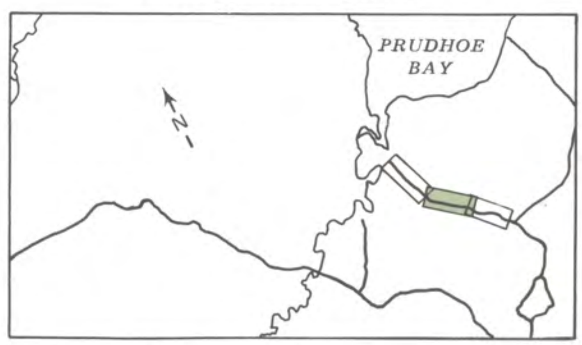
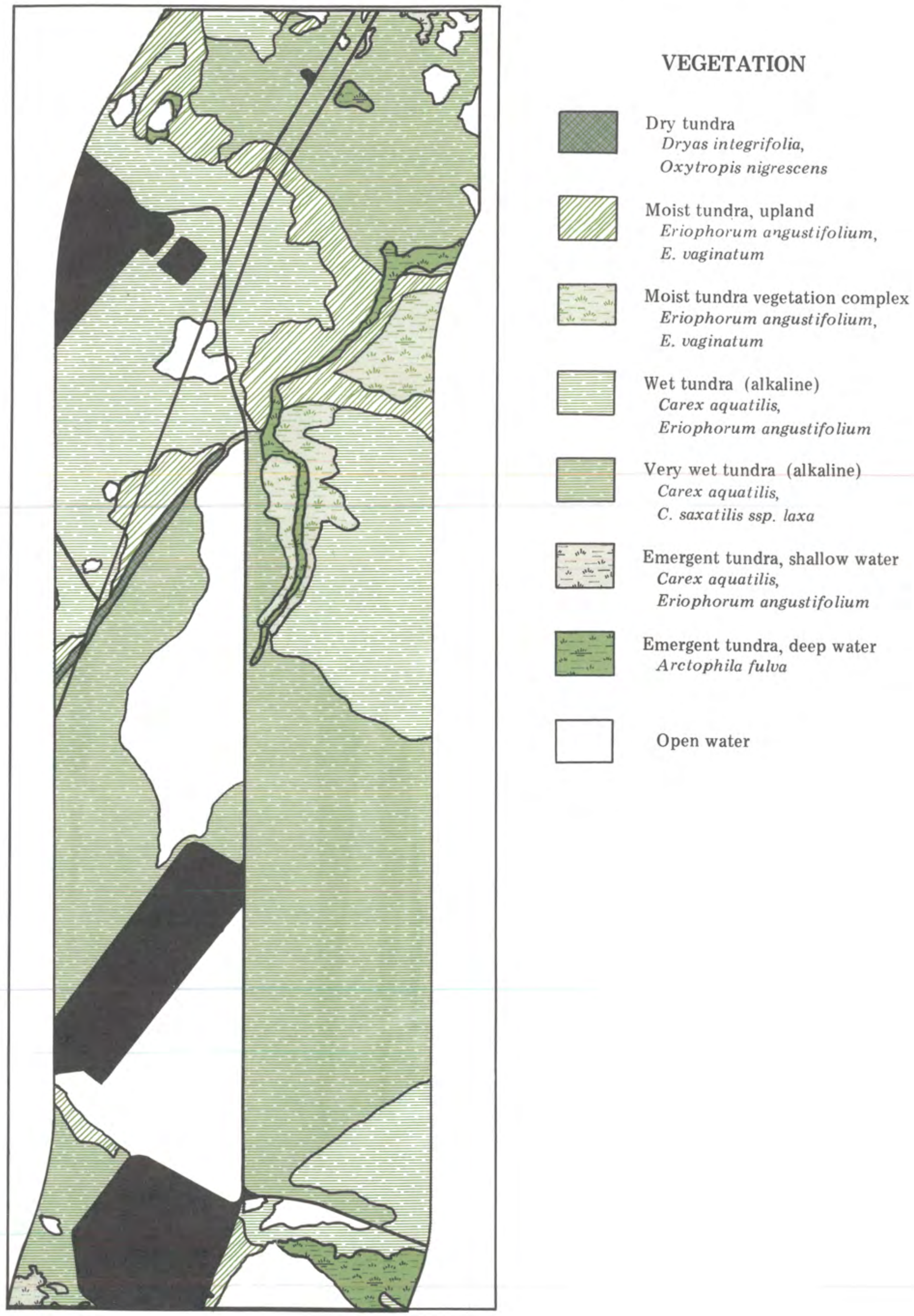
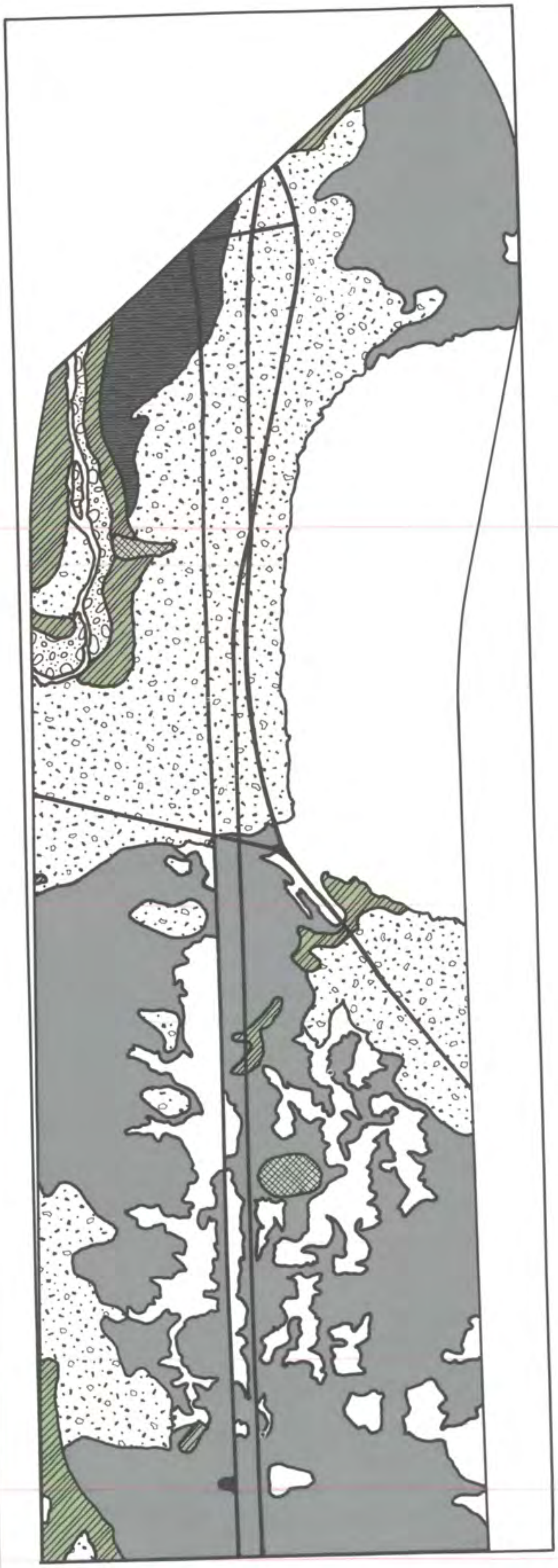


Figure 75. Vegetation, landforms, and soils of the West Dock route, leg 2.


VEGETATION
Dry tundra
Dryas integrifolia,
Oxytropis nigrescens
Moist tundra, upland
Eriophorum angustifolium,
E. vaginatum
Moist tundra vegetation complex
Eriophorum angustifolium,
E. vaginatum
Wet tundra (alkaline)
Carex aquatilis,
Eriophorum angustifolium
Very wet tundra (alkaline)
Carex aquatilis,
C. saxatilis ssp. laxa
Emergent tundra, shallow water
Carex aquatilis,
Eriophorum angustifolium
Emergent tundra, deep water
Arctophila fulva
Open water


LANDFORM
High-center polygons, high relief
High-center polygons, low relief
Low-center polygons, low relief
Frost-boil tundra
Strangmoor or large-diameter, low-center polygons or both
Reticulate-patterned ground
Nonpatterned or limited-patterned ground
Water
N
0
200
400 m
0
500
1000 ft



SOIL

- Pergelic Cryoboroll
- Pergelic Cryaquoll
- Complex of: Histic Pergelic Cryaquept, Pergelic Cryohemist, Pergelic Cryosaprist
- Complex of: Histic Pergelic Cryaquept, Pergelic Cryofibrist
- Pergelic Cryorthent
- Pergelic Ruptic-Aqueptic Cryaquoll
- Water

FIGURE LOCATION MAP

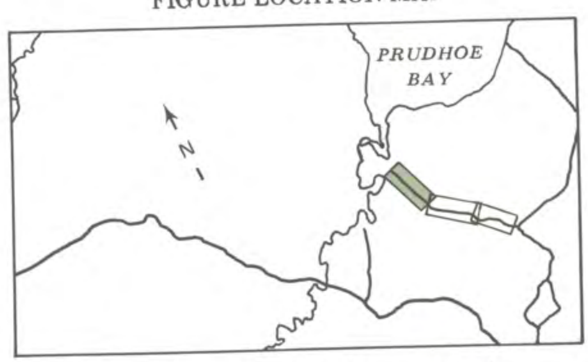
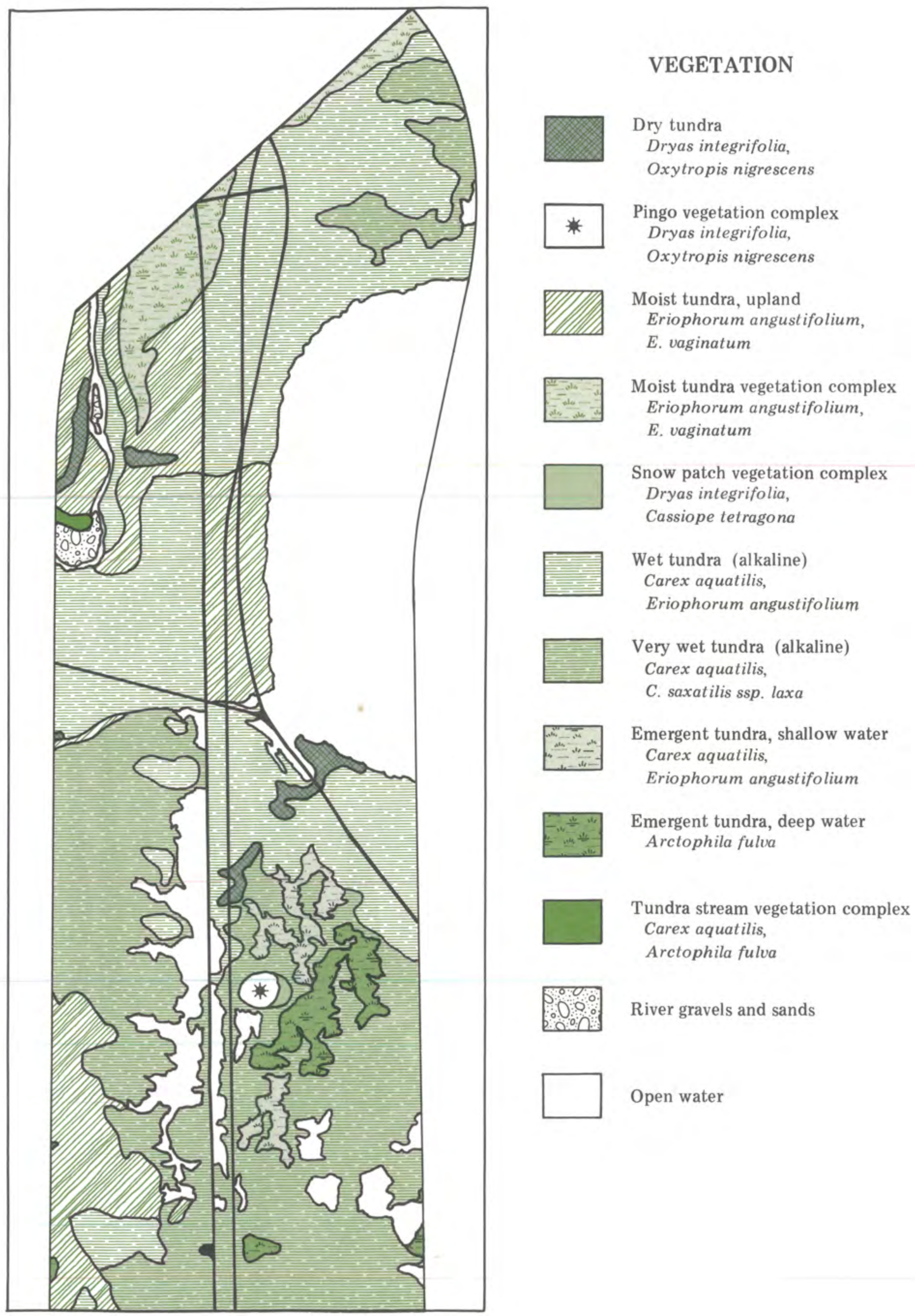
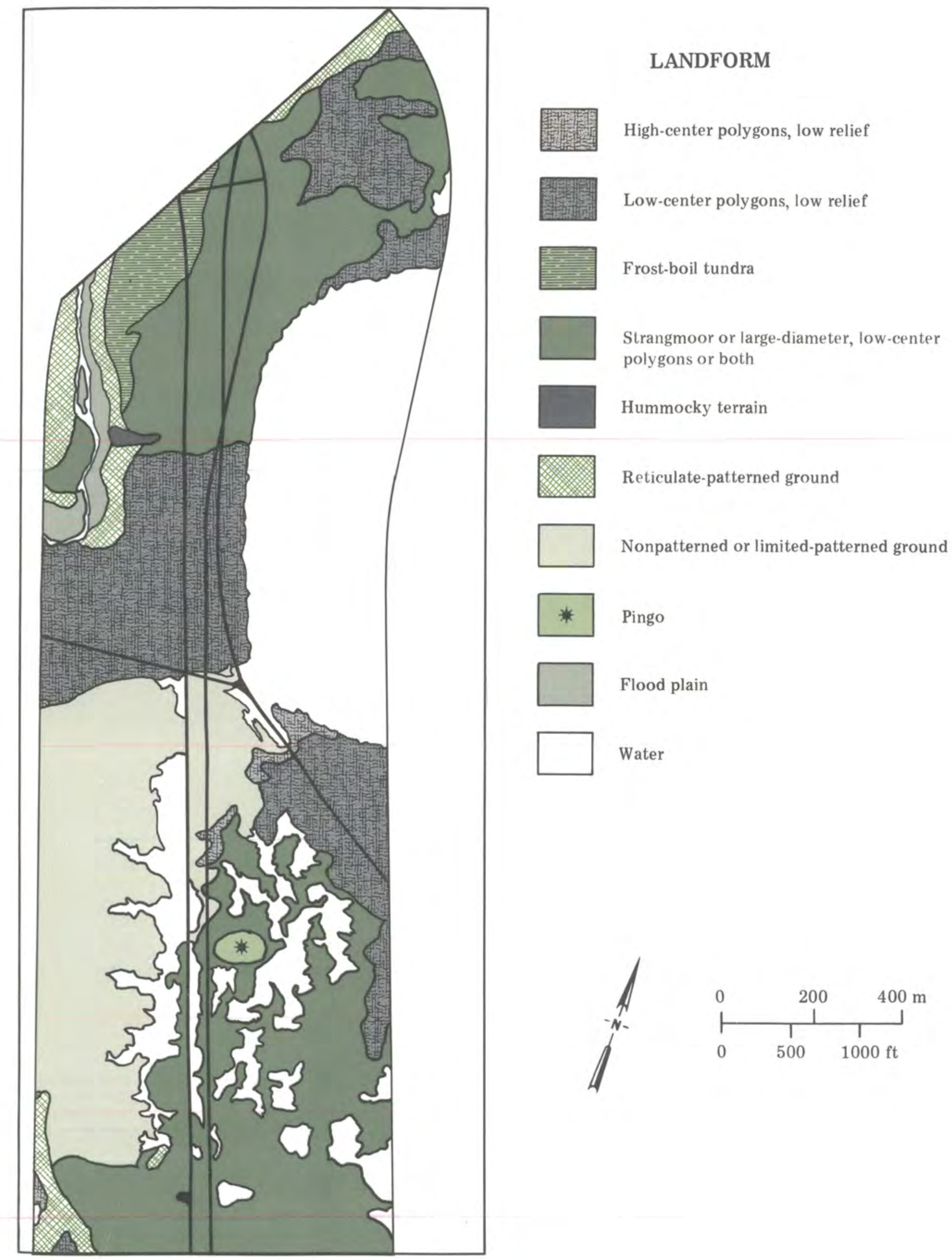


Figure 76. Vegetation, landforms, and soils of the West Dock route, leg 3.


VEGETATION
Dry tundra
Dryas integrifolia,
Oxytropis nigrescens
Pingo vegetation complex
Dryas integrifolia,
Oxytropis nigrescens
Moist tundra, upland
Eriophorum angustifolium,
E. vaginatum
Moist tundra vegetation complex
Eriophorum angustifolium,
E. vaginatum
Snow patch vegetation complex
Dryas integrifolia,
Cassiope tetragona
Wet tundra (alkaline)
Carex aquatilis,
Eriophorum angustifolium
Very wet tundra (alkaline)
Carex aquatilis,
C. saxatilis ssp. laxa
Emergent tundra, shallow water
Carex aquatilis,
Eriophorum angustifolium
Emergent tundra, deep water
Arctophila fulva
Tundra stream vegetation complex
Carex aquatilis,
Arctophila fulva
River gravels and sands
Open water


LANDFORM
High-center polygons, low relief
Low-center polygons, low relief
Frost-boil tundra
Strangmoor or large-diameter, low-center polygons or both
Hummocky terrain
Reticulate-patterned ground
Nonpatterned or limited-patterned ground
Pingo
Flood plain
Water
N
0
200
400 m
0
500
1000 ft

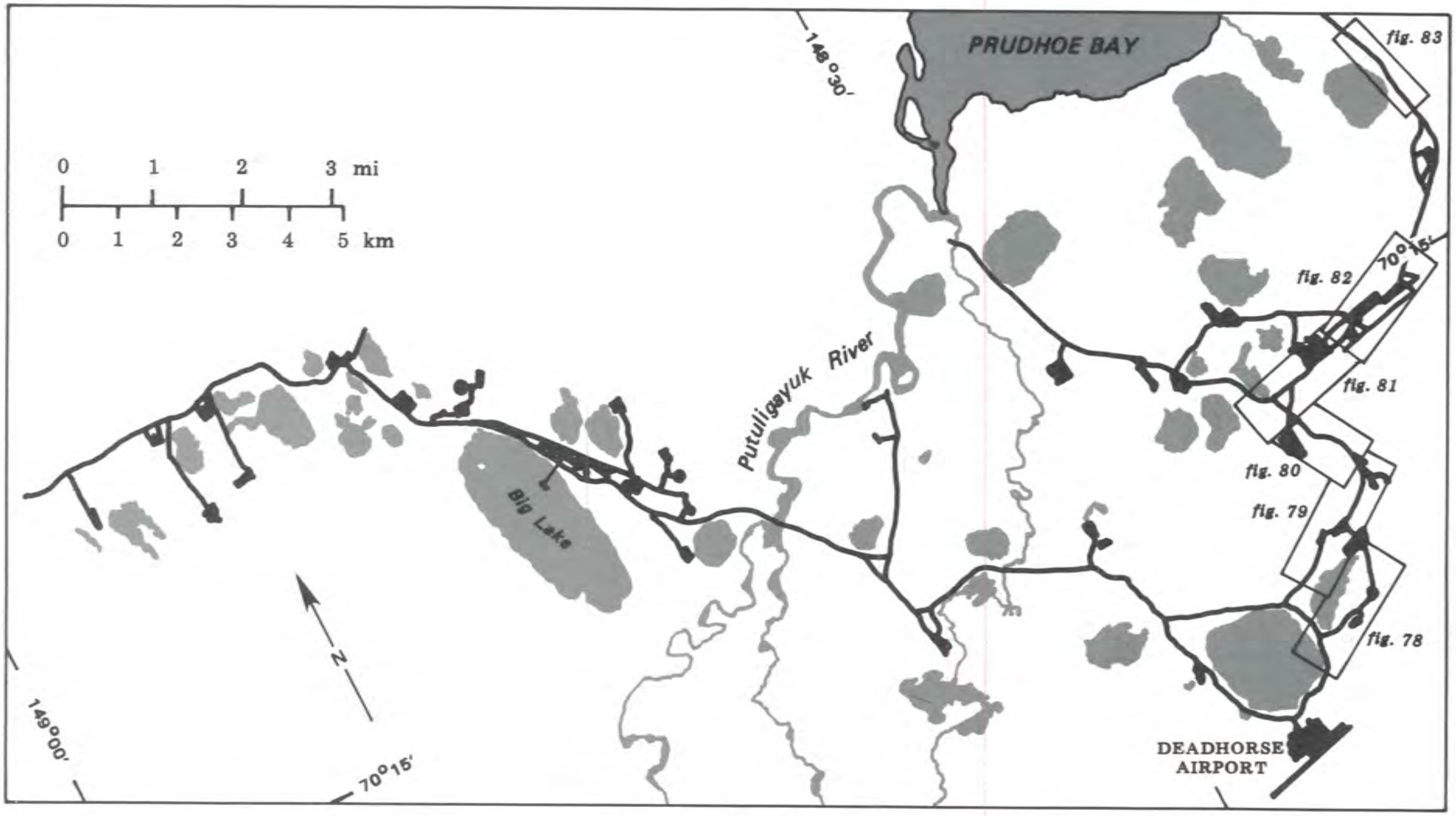


Figure 77. Index map of vegetation, landforms, and soils maps of part of the East Dock Route, Prudhoe Bay, Alaska.

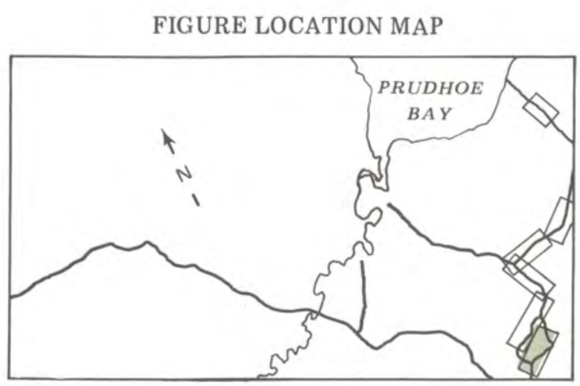
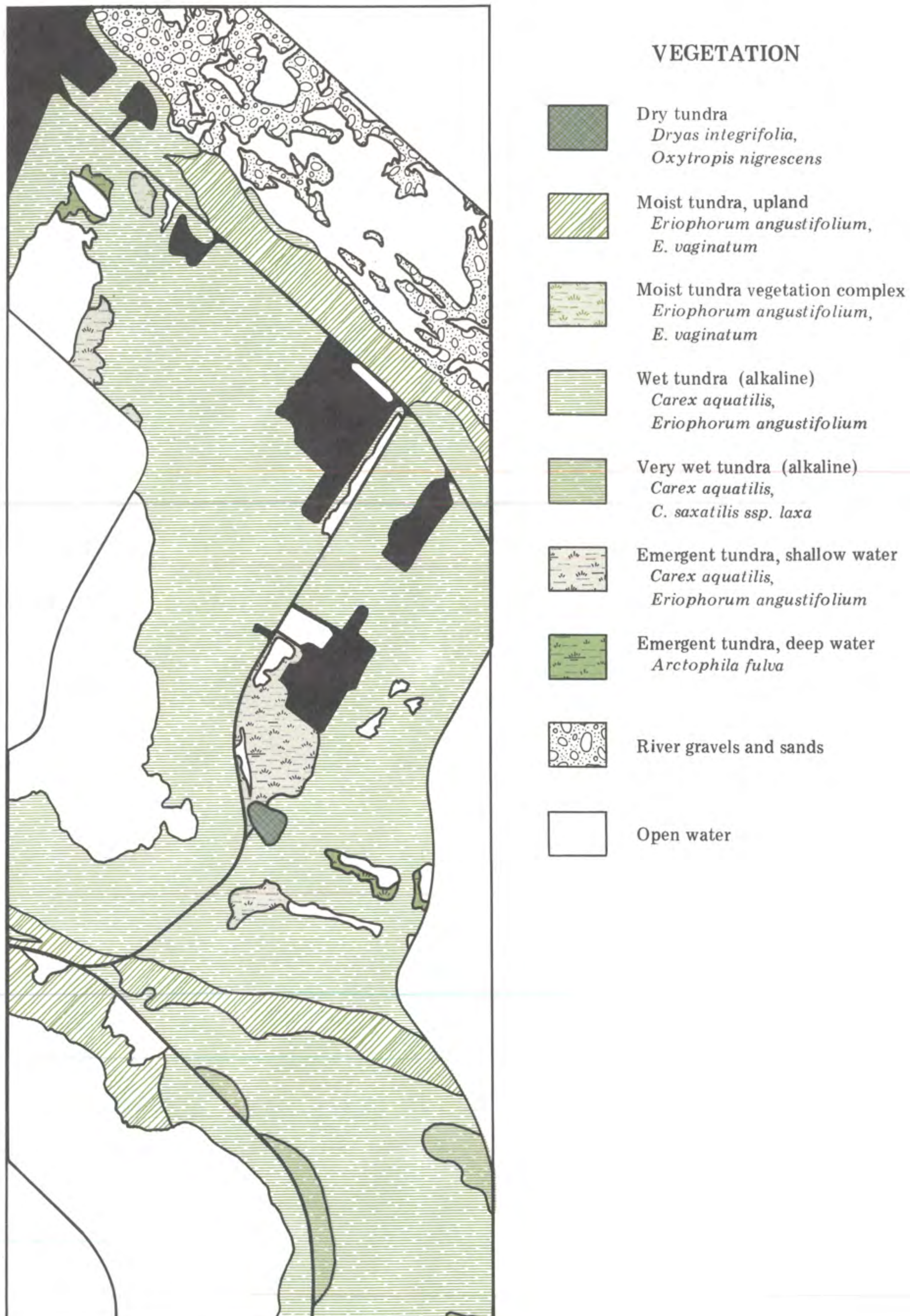
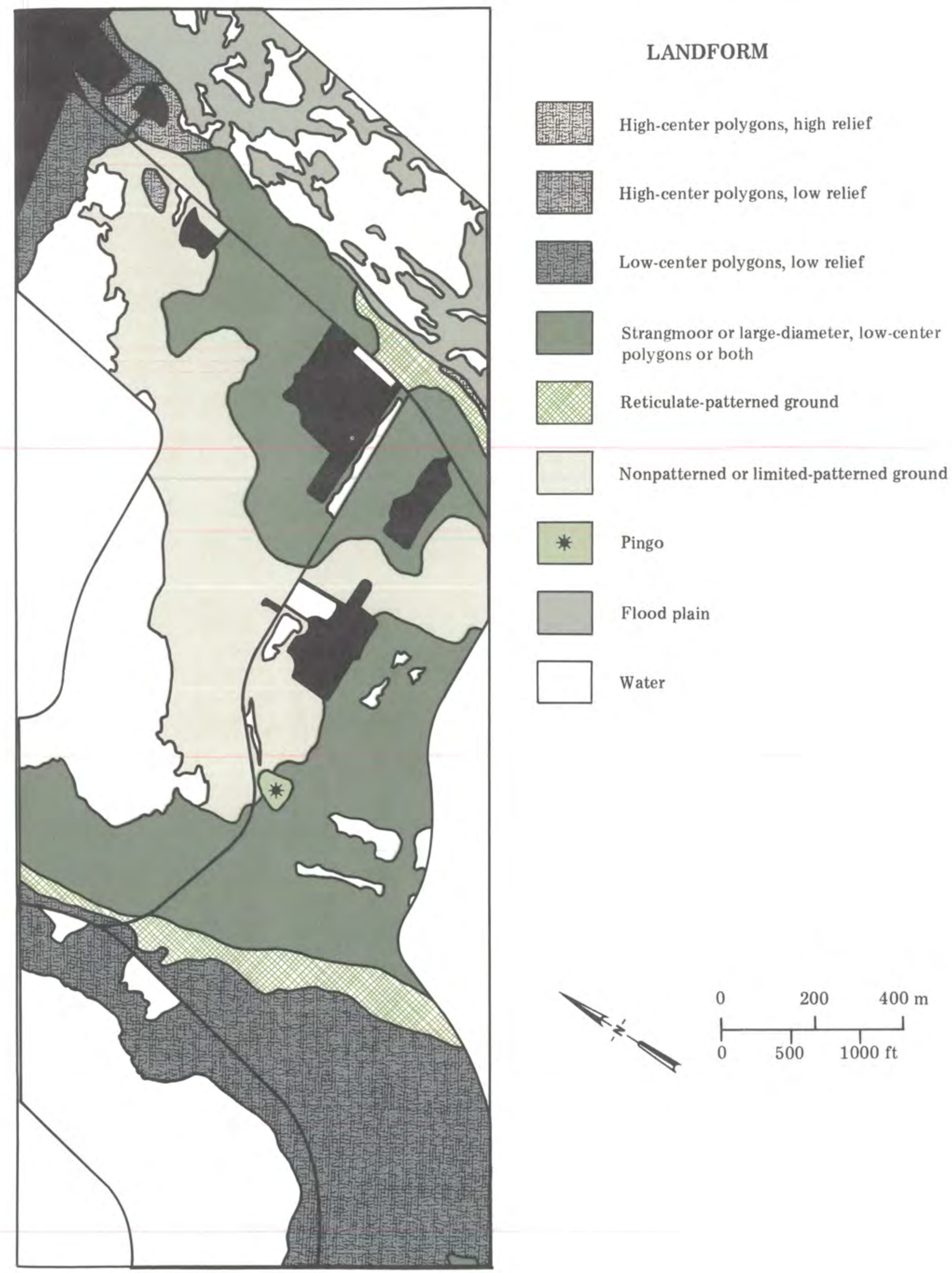
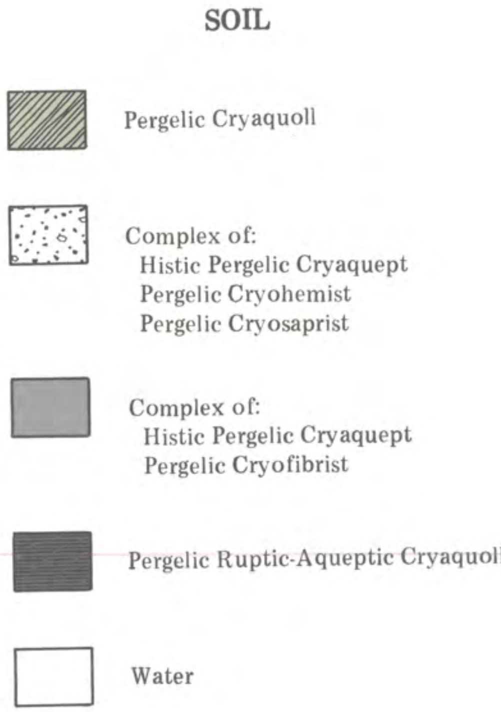


Figure 78. Vegetation, landforms, and soils of the East Dock route, leg 1.


VEGETATION
Dry tundra
Dryas integrifolia, Oxytropis nigrescens
Moist tundra, upland
Eriophorum angustifolium, E. vaginatum
Moist tundra vegetation complex
Eriophorum angustifolium, E. vaginatum
Wet tundra (alkaline)
Carex aquatilis, Eriophorum angustifolium
Very wet tundra (alkaline)
Carex aquatilis, C. saxatilis ssp. laxa
Emergent tundra, shallow water
Carex aquatilis, Eriophorum angustifolium
Emergent tundra, deep water
Arctophila fulva
River gravels and sands
Open water


LANDFORM
High-center polygons, high relief
High-center polygons, low relief
Low-center polygons, low relief
Strangmoor or large-diameter, low-center polygons or both
Reticulate-patterned ground
Nonpatterned or limited-patterned ground
Pingo
Flood plain
Water
0 200 400 m
0 500 1000 ft



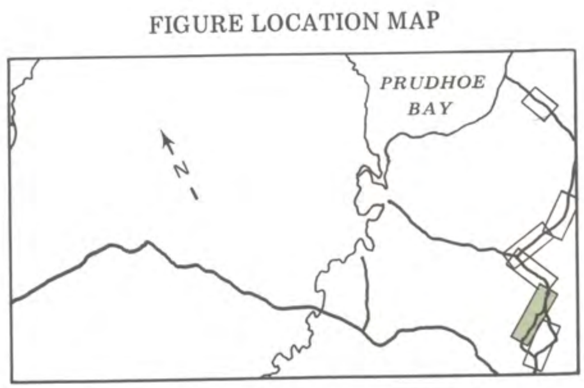
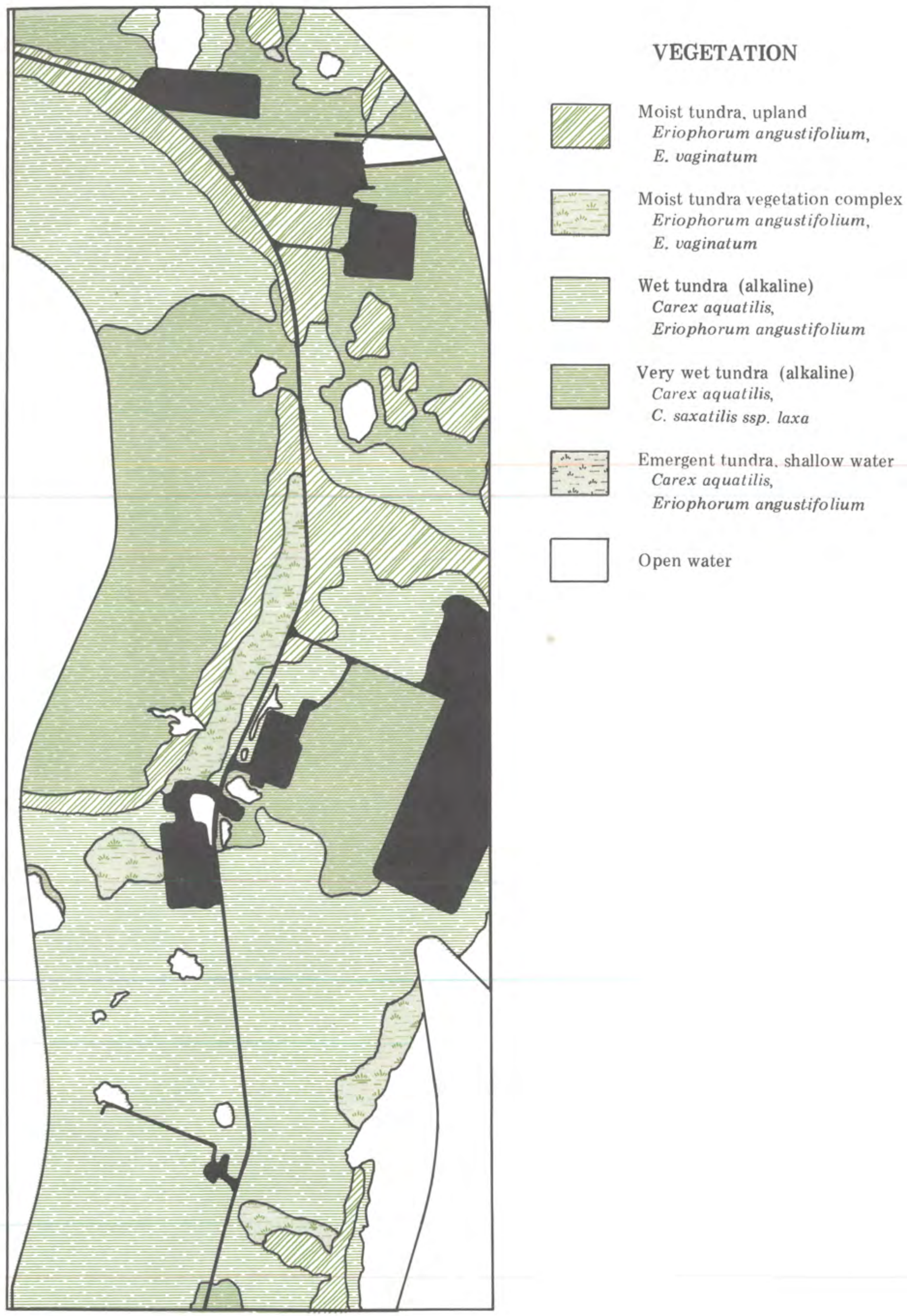
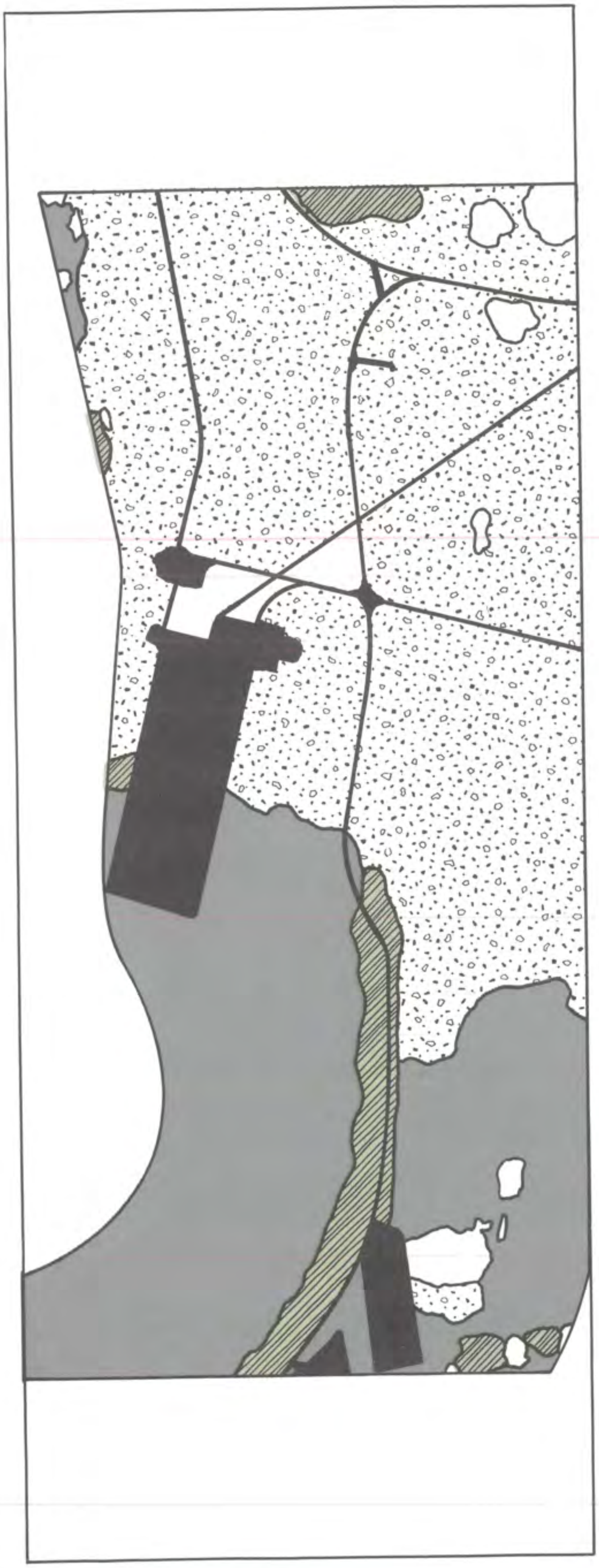
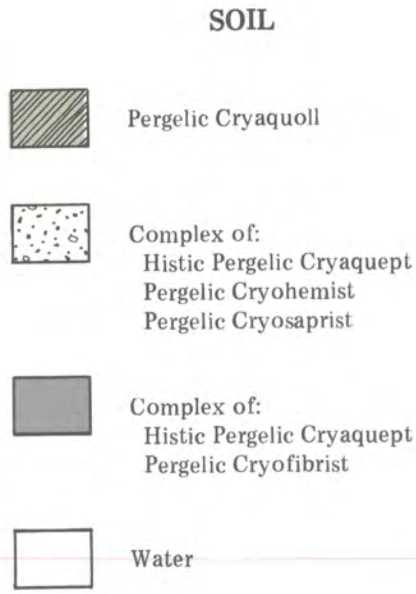


Figure 79. Vegetation, landforms, and soils of the East Dock route, leg 2.


VEGETATION
Moist tundra, upland
Eriophorum angustifolium,
E. vaginatum
Moist tundra vegetation complex
Eriophorum angustifolium,
E. vaginatum
Wet tundra (alkaline)
Carex aquatilis,
Eriophorum angustifolium
Very wet tundra (alkaline)
Carex aquatilis,
C. saxatilis ssp. laxa
Emergent tundra, shallow water
Carex aquatilis,
Eriophorum angustifolium
Open water


LANDFORM
Low-center polygons, low relief
Frost-boil tundra
Strangmoor or large-diameter, low-center polygons or both
Reticulate-patterned ground
Nonpatterned or limited-patterned ground
Water
0
200
400 m
0
500
1000 ft





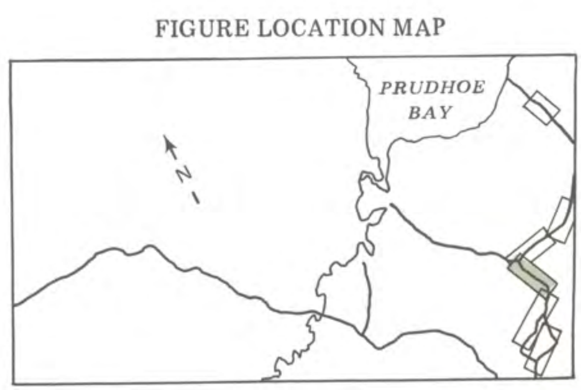
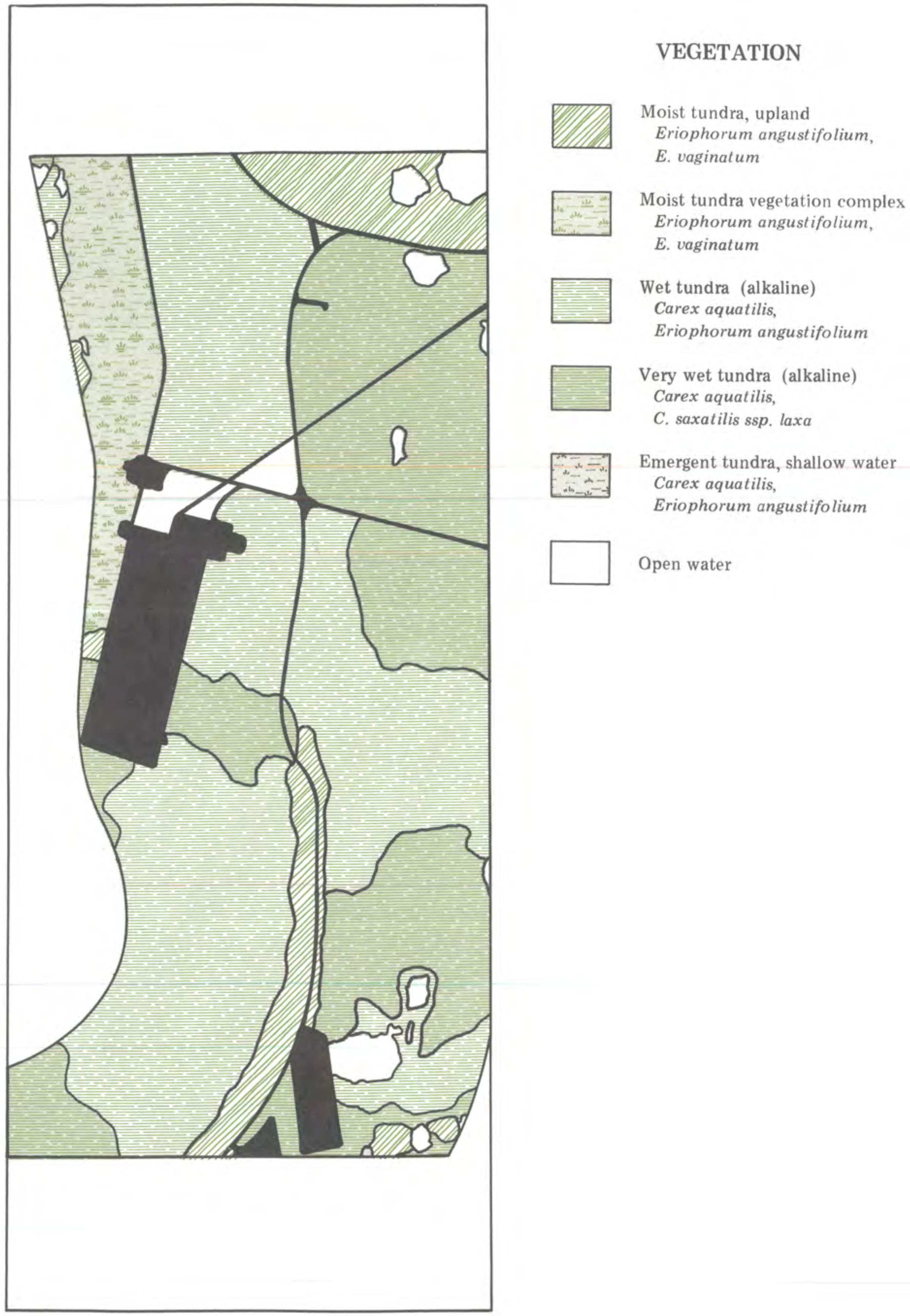


Figure 80. Vegetation, landforms, and soils of the East Dock route, leg 3.


VEGETATION
Moist tundra, upland
Eriophorum angustifolium, E. vaginatum
Moist tundra vegetation complex
Eriophorum angustifolium, E. vaginatum
Wet tundra (alkaline)
Carex aquatilis, Eriophorum angustifolium
Very wet tundra (alkaline)
Carex aquatilis, C. saxatilis ssp. laxa
Emergent tundra, shallow water
Carex aquatilis, Eriophorum angustifolium
Open water


LANDFORM
Low-center polygons, high relief
Low-center polygons, low relief
Strangmoor or large-diameter, low-center polygons or both
Reticulate-patterned ground
Nonpatterned or limited-patterned ground
Water
N
0
200
400 m
0
500
1000 ft

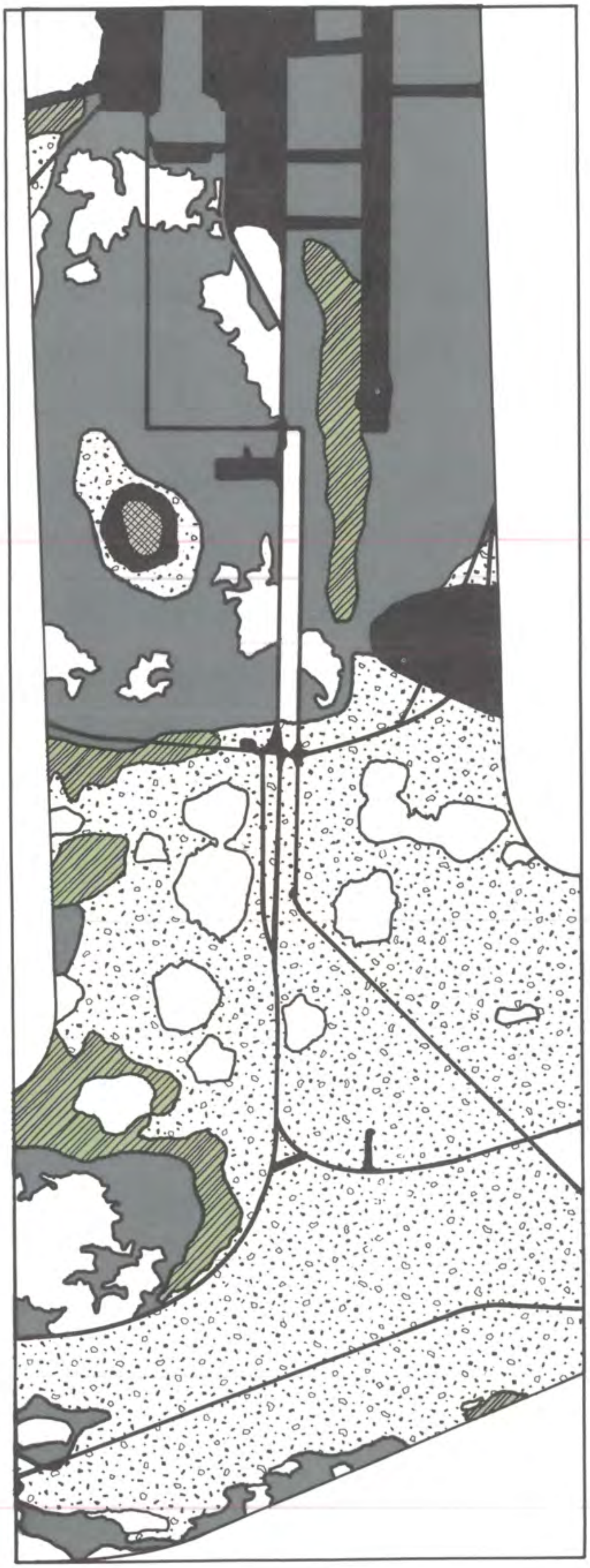


FIGURE LOCATION MAP

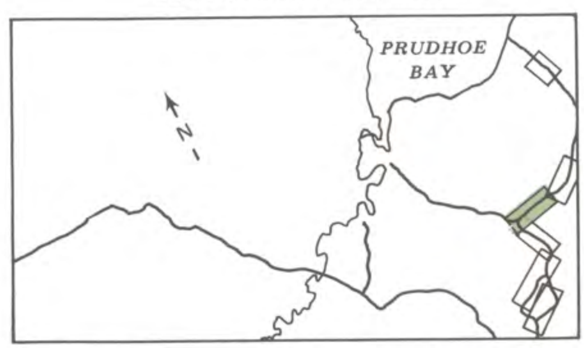
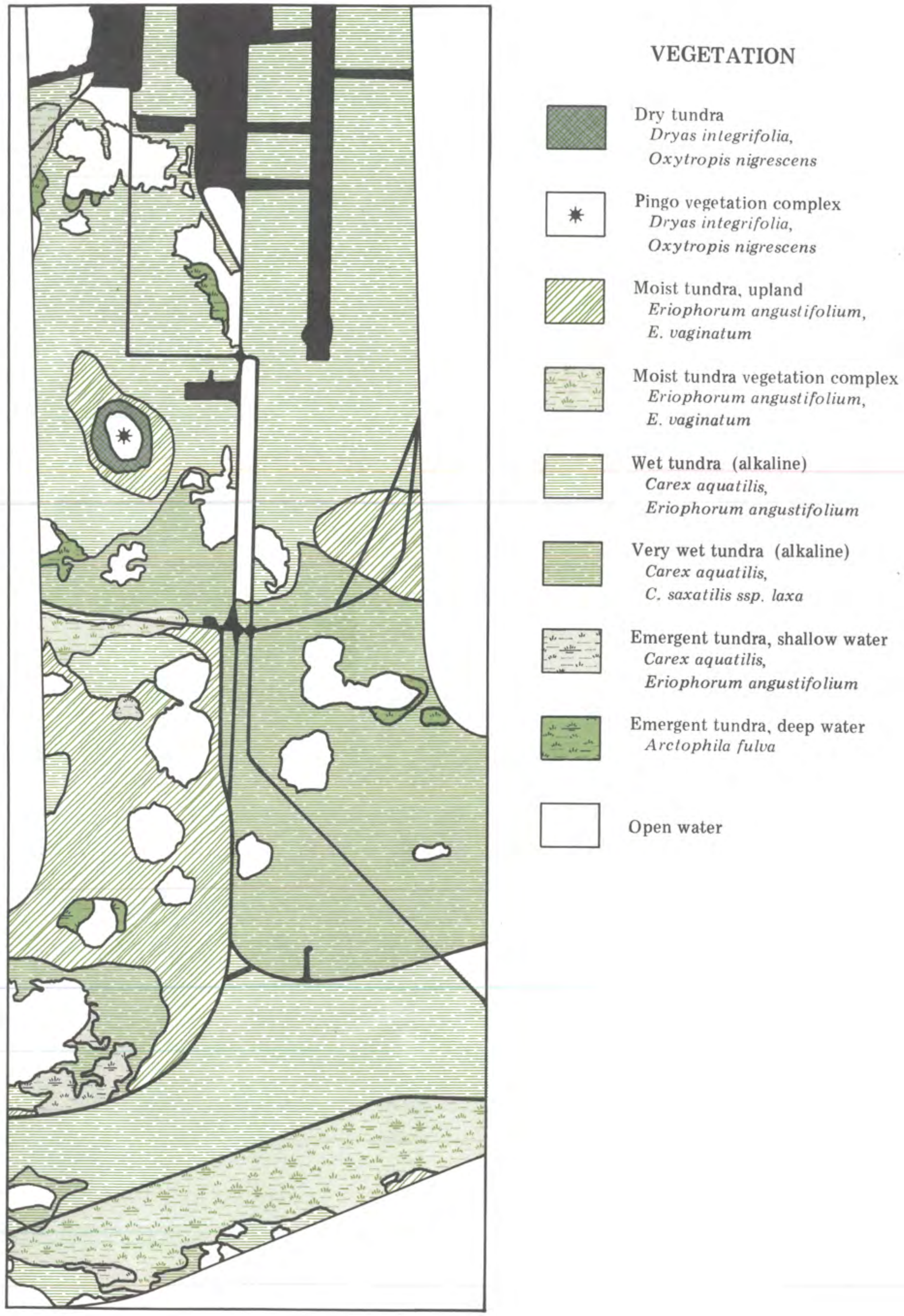
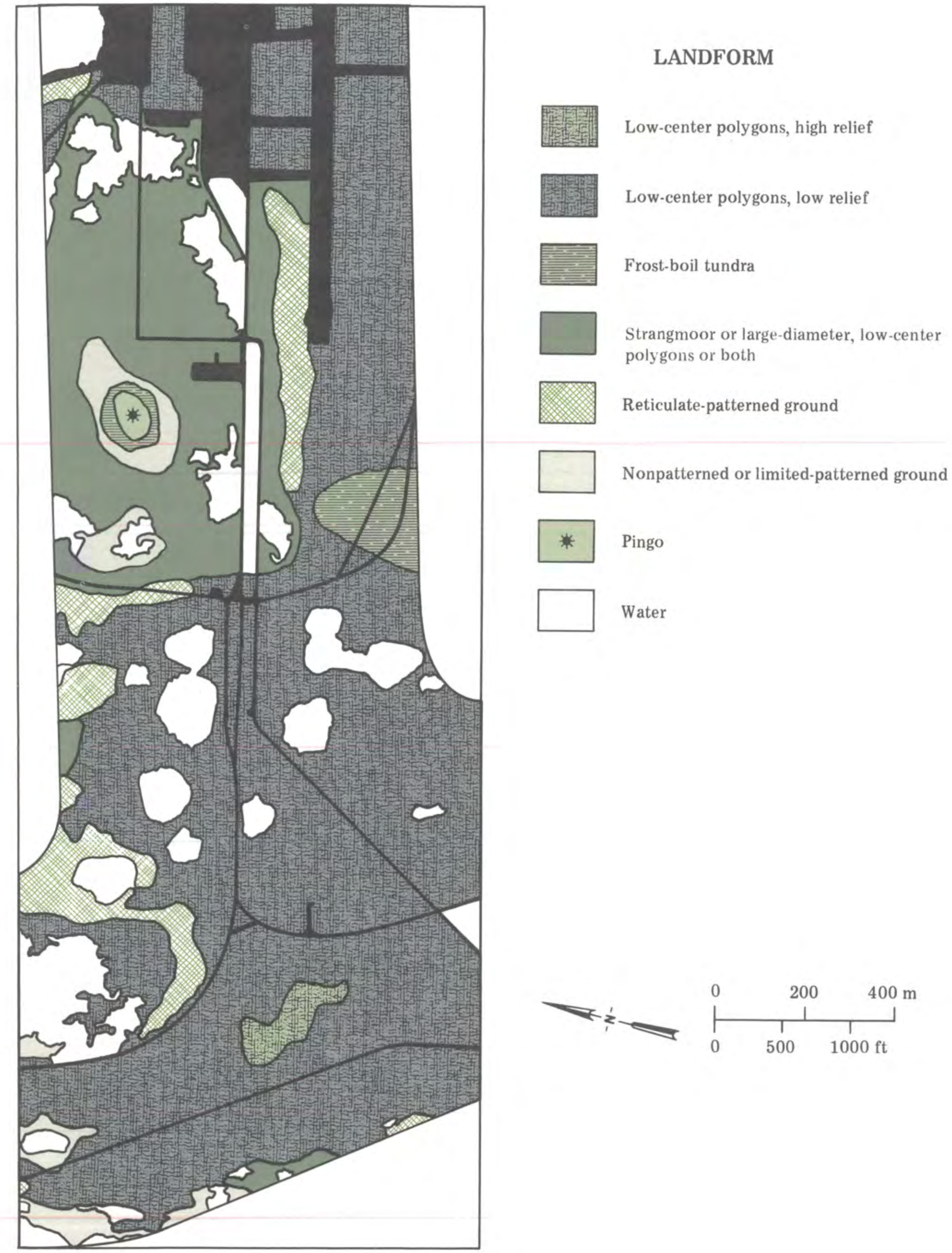


Figure 81. Vegetation, landforms, and soils of the East Dock route, leg 4.


VEGETATION
Dry tundra
Dryas integrifolia,
Oxytropis nigrescens
Pingo vegetation complex
Dryas integrifolia,
Oxytropis nigrescens
Moist tundra, upland
Eriophorum angustifolium,
E. vaginatum
Moist tundra vegetation complex
Eriophorum angustifolium,
E. vaginatum
Wet tundra (alkaline)
Carex aquatilis,
Eriophorum angustifolium
Very wet tundra (alkaline)
Carex aquatilis,
C. saxatilis ssp. laxa
Emergent tundra, shallow water
Carex aquatilis,
Eriophorum angustifolium
Emergent tundra, deep water
Arctophila fulva
Open water


LANDFORM
Low-center polygons, high relief
Low-center polygons, low relief
Frost-boil tundra
Strangmoor or large-diameter, low-center polygons or both
Reticulate-patterned ground
Nonpatterned or limited-patterned ground
Pingo
Water
N
0
200
400 m
0
500
1000 ft

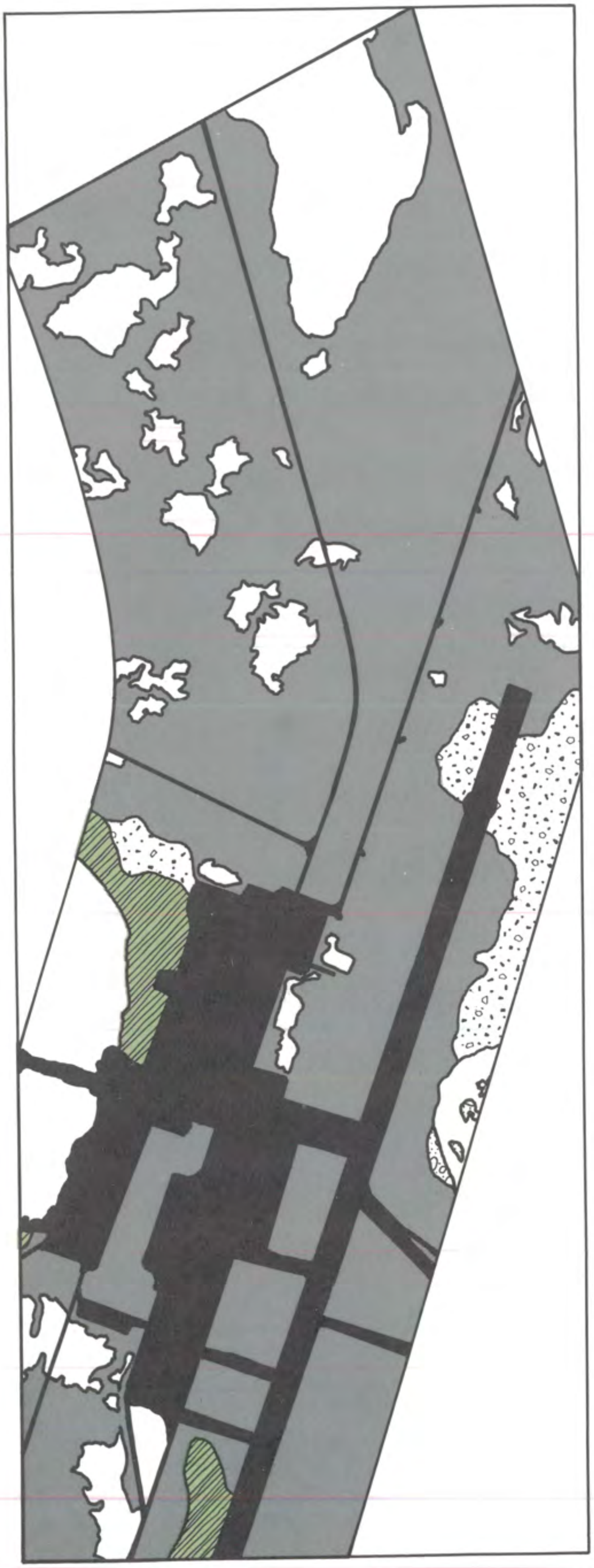


FIGURE LOCATION MAP

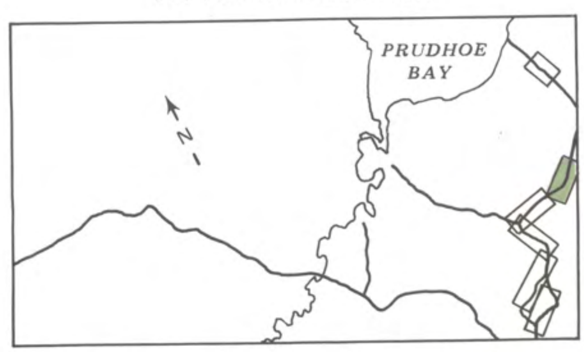


Figure 82. Vegetation, landforms, and soils of the East Dock route, leg 5.


VEGETATION
Moist tundra vegetation complex
Eriophorum angustifolium,
E. vaginatum
Wet tundra (alkaline)
Carex aquatilis,
Eriophorum angustifolium
Emergent tundra, deep water
Arctophila fulva
Emergent tundra, deep water in sand-dune area
Scorpidium scorpioides
Stabilized dunes
Dryas integrifolia,
Salix ovalifolia
Open water


LANDFORM
Low-center polygons, low relief
High- and low-center polygons
Strangmoor or large-diameter, low-center polygons or both
Reticulate-patterned ground
Nonpatterned or limited-patterned ground
Flood plain
Water
N
0
200
400 m
0
500
1000 ft

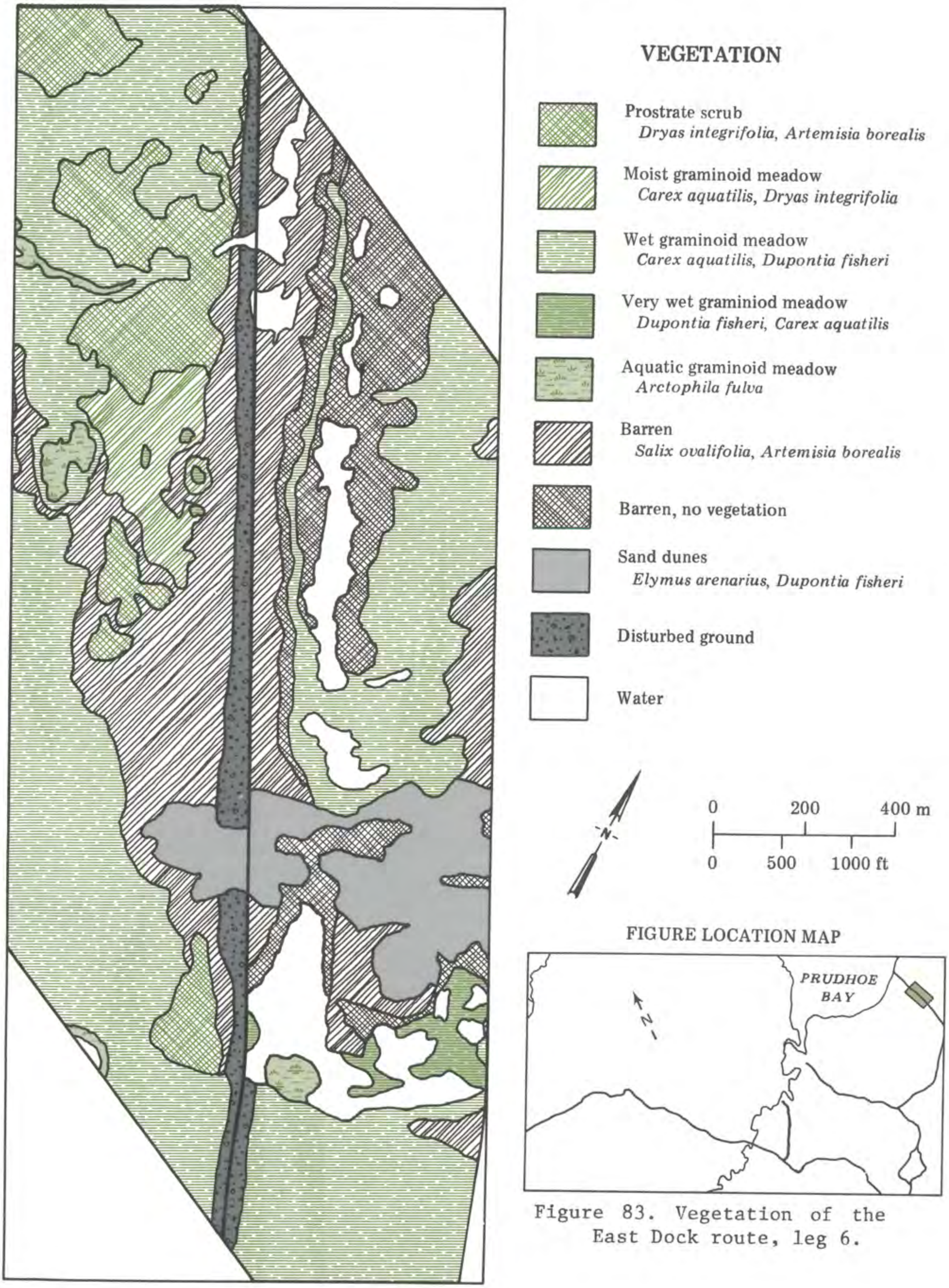


Figure 83. Vegetation of the East Dock route, leg 6.

SECTION C
SELECTED TOPICS

Patterned-ground Forms and Processes

Patterned ground refers to roughly symmetrical patterns characteristic of regolith subject to frost action, diapirism, and in some cases, dessication. Frost-related forms include circles, polygons, nets, steps and stripes. Washburn (1956) recognized sorted and nonsorted forms, terms which correspond to marked uniformity or nonuniformity in grain-size distribution between the borders and interior areas, respectively. On slopes, circles, polygons, and nets form steps (Washburn, 1956) or stripes (Nicholson, 1976). In the Prudhoe Bay area, nonsorted circles, ice-wedge polygons, and nets are most common.

Nonsorted circles

Nonsorted circles lack a stone border. Frost scars (Hopkins and Sigafoos, 1951), mud boils (Shilts, 1978), frost boils (Walker and others, 1980), and peat rings, which evolve from frost scars (Hopkins and Sigafoos, 1951), are synonymous with nonsorted circles. The term 'frost boil' is used only in Section B. Nonsorted circles range from about 0.5 to 5 m (1.6 to 16 ft) in diameter (Poiré, 1949; Rousseau, 1949; Hopkins and Sigafoos, 1951; Shilts, 1978).

Frost boils are present in the Prudhoe Bay area and are very common along the Putuligayuk River, where silty Pergelic Cryaquept soils interrupt silty-sandy Cryaquoll soils (Walker and others, 1980). The central area of the circles is generally raised less than 0.5 m (1.6 ft) above the surrounding surface and consists of dry, cracked mud with scattered pebbles and no vegetation (fig. 84). The central area of nonsorted circles with a peat ring [usually less than 0.5 m (1.6 ft) high] is nearly level with the surface and is generally wet and vegetated. These circles are common in areas of low-center ice-wedge polygons, where a peaty substrate and shallow permafrost inhibit drainage (fig. 85).

Excavations of nonsorted circles in Greenland typically show sandy, silty clay laterally surrounded by humic peat and sand at the surface and in part, at depth, and a marginal disturbance (Washburn, 1969). The central fine-grained soil is continuous with fine-grained soil below the sandy border. Shilts (1978) reported similar subsurface relationships in Keewatin, Canada. These relationships indicate displacement of underlying fine-grained soil into overlying coarser soil.

Recently, some researchers attribute nonsorted circles to diapirism of poorly sorted, silty soil with low liquid and plastic limits during thaw periods (Shilts, 1978; Washburn, 1980), rather than to upward heaving and lateral thrusting during periods of freezing (Hopkins and Sigafoos, 1951). The diapirism may result from hydrostatic or artesian pressure on a slope, excessive pore pressure from addition of water, or pressure from loading (Shilts, 1978).

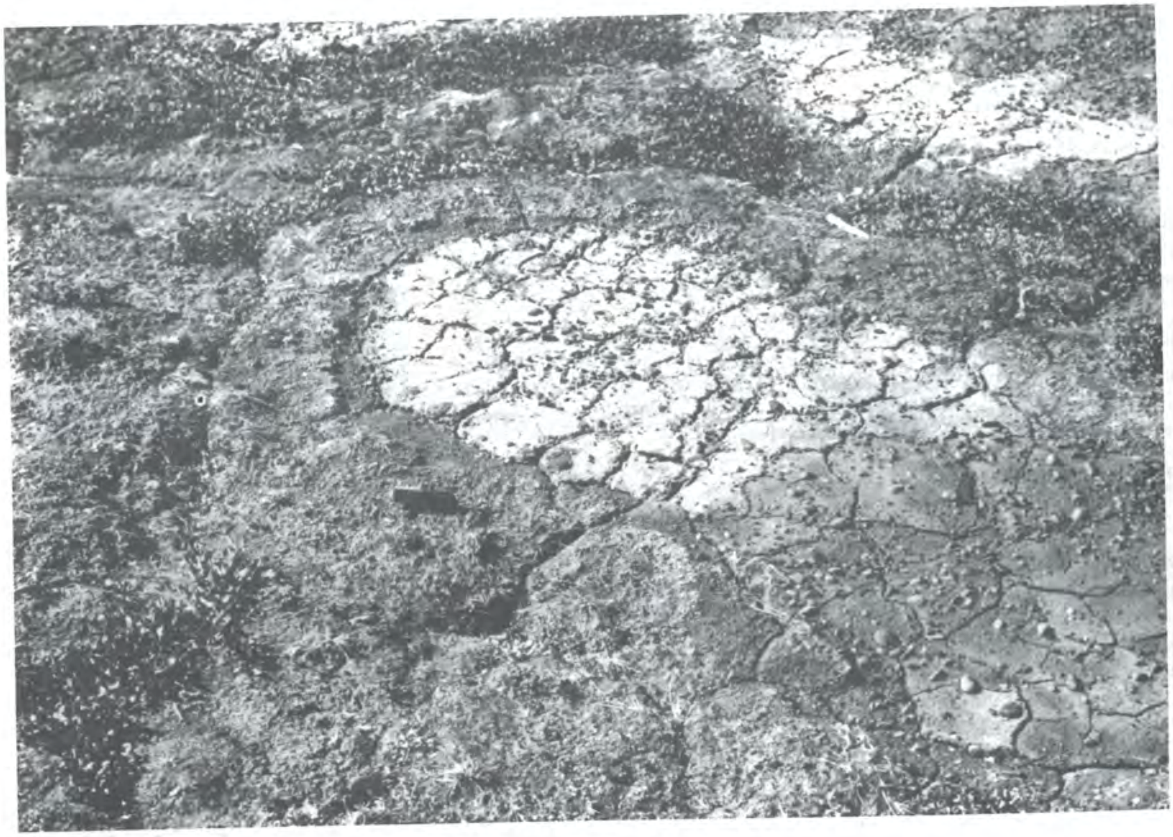


Figure 84. Nonsorted circle (frost boil) on Bodfish Island near Prudhoe Bay. Photograph by S.E. Rawlinson, 1981.

Hopkins and Sigafoos (1951) attributed the peat ring around some circles to frost thrusting of the soil from the center to the perimeter and consequent pushing aside of peat deposits. Diapirism could also push aside peat deposits to form the peat ring.

Ice wedges

Ice wedges are foliated masses of ice that taper toward a base that is generally less than 10 m (33 ft) below the surface (fig. 86). The tops of these wedges range from a few millimeters to 6 m wide (Black, 1976). Near Barrow, Alaska, the largest ice wedges are at least 6 to 10 m (20 to 33 ft) wide (Brown, 1967).

The most widely accepted origin of ice wedges is explained by the thermal-contraction theory (Leffingwell, 1919). During winter, low temperatures and rapid cooling cause seasonally frozen soil and permafrost to contract and crack (Lachenbruch, 1962). Contraction cracks measured at Barrow in 1974 were generally 3 to 10 mm (0.1 to 0.4 in.) wide at the top of the permafrost table and decreased in width with depth. Snow blows into these cracks and hoar frost grows. During summer, rain and meltwater that carry organic and mineral matter freeze in the cracks. Repeated winter cracking and winter and summer addition of ice increase the width and depth of the ice wedge (Billings and Peterson, 1980).

Figure 85. Vegetation-rimmed nonsorted circles (peat rings) on wet coastal-plain surface south of Prudhoe Bay; circles are 2 to 3 m (6.6 to 9.8 ft) in diameter. Photograph by S.E. Rawlinson, 1981.

Chemical analysis of ice and microscopic examination of incorporated organic and mineral residue from an ice wedge at Barrow suggest that some residue at the base of a wedge is from adjacent soil (Brown, 1966), but this deviation was not apparent in all wedges. Folding of adjacent soil into the wedge, growth of the wedge into adjacent soil, or introduction of soil through fractures are possible mechanisms for incorporation of residues from adjacent soil (Brown, 1966).

Black (1974) reported that near the top of permafrost, 1 to 3 mm (0.04 to 0.1 in.) of ice was added to a wedge each time it cracked (usually annually). Assuming that a wedge cracked half the years of its life, he calculated an annual mean growth rate of 1 mm (0.04 in.). Large ice wedges, he concluded, formed in 5,000 to 7,000 yr or more, a formational time that is consistent with radiocarbon dates of peat associated with ice wedges (Brown, 1965; Sellmann and Brown, 1973). Billings and Peterson (1980) noted that the crack in ice wedges is not always in the middle, but may be at or over each shoulder, which indicates that ice accretion can occur near the edges of a wedge.

Ice wedges have a linear fabric that is determined by parallel alignment of elongate ice grains, bubbles, and inclusions. Layers of these grains, bubbles, and inclusions determine the planar fabric (Black, 1974). Foliation

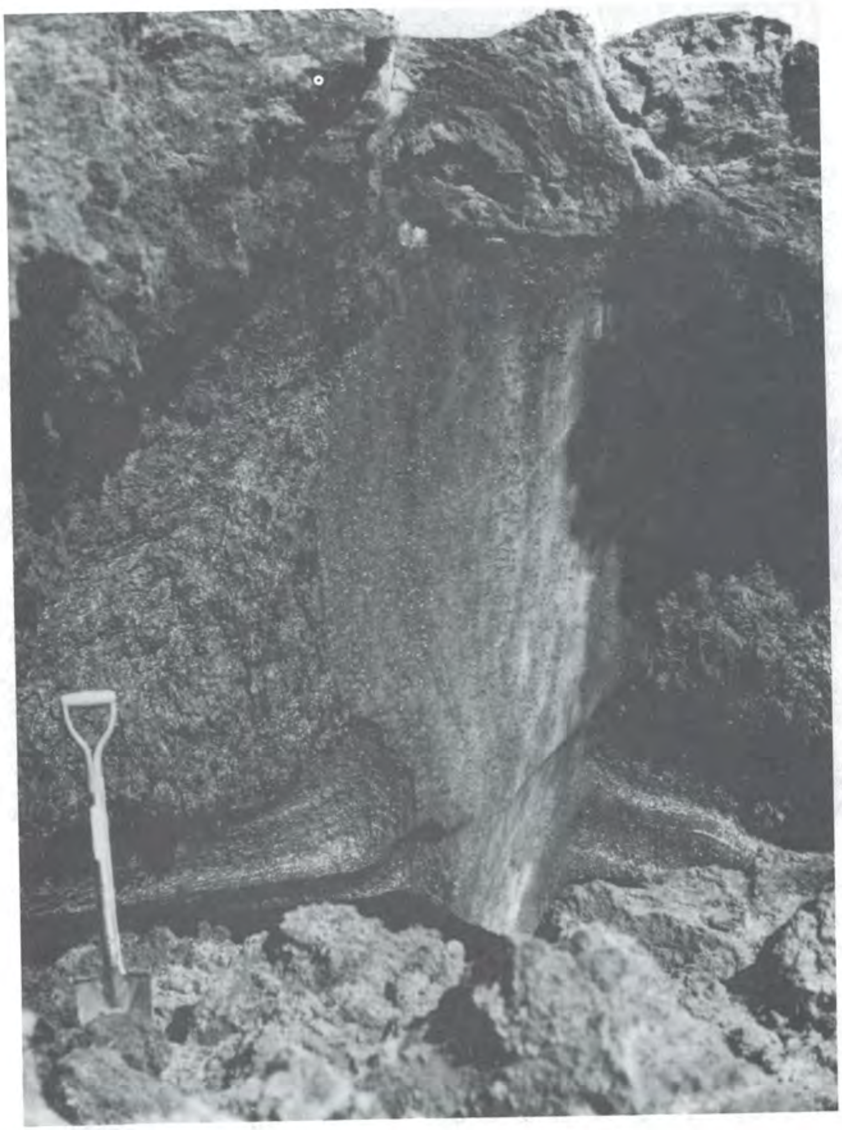


Figure 86. An ice wedge in the western Sagavanirktok River bluff north of the Sagavanirktok River bridge. Uninterrupted vertical foliation indicates that horizontal wedges near the base of the wedge are secondary. Photograph by S.E. Rawlinson, 1982.

in ice wedges results from differences in adjacent layers that may result from the effects of temperature, pressure, composition, and time. Seasonal temperature changes of 20°C (36°F) or more at Prudhoe Bay produce vertical and horizontal stresses in unconsolidated, supersaturated soil that are sufficient to cause cracking upon cooling and shear and flowage upon warming, with subsequent recrystallization of ice grains. These stresses are not uniform because of variations in ground composition and effects of snow and vegetation covers (Black, 1974).

Nearly vertical and horizontal contraction cracks in ice wedges are primary planes in which ice crystals grow. Thermal gradients and the influence of adjacent ice determine the fabric of these crystals, which in turn determines initial orientations of air bubbles or inclusions. Near the ground surface, a strong vertical thermal gradient vertically orients new ice crystals and thus air bubbles and inclusions. Away from the ground surface, thermal gradients are normal to cracks that generally parallel the axial plain of the wedge. Thus, bubbles and inclusions tend to be initially oriented horizontally and away from the axial plane. In active wedges, these orientations are quickly modified by shear, flow, or recrystallization. Shear and flow are generally upward (Black, 1974). Active ice wedges can sometimes be differentiated from inactive wedges by the shape of bubbles, which in the former tend to be elongated in the presence of strong thermal gradients. Bubbles in inactive wedges that lack strong thermal gradients tend to be rounded.

The optic axes of seedling ice grains in ice wedges tend to be oriented in response to orientation of crystals or nuclei on which they grow, directional supply of water, directional heat conduction, and grain interference (Black, 1974). These initial optic-axis orientations are quickly modified by the same processes that modify initial orientations of ice grains, air bubbles, and inclusions. Directions of optic-axis lineations are variable within an ice wedge, but generally vertical lineations and lineations normal to the horizontal wedge axis (inclined or horizontal) are best developed (Black, 1974).

Ice-wedge polygons

Ice-wedge polygons are nonsorted polygons bordered by ice wedges (Washburn, 1956). Primary ice-wedge polygons may exceed 100 m (328 ft) in diameter. These polygons subdivide through time into secondary polygons commonly 4 to 8 m (13 to 26 ft) in diameter, which in turn, subdivide into tertiary polygons commonly 1 to 3 m (3.3 to 9.8 ft) in diameter (Black, 1952).

Ice-wedge polygons on the Arctic Coastal Plain are commonly tetragonal (Black, 1952), but trigonal (Britton, 1957), hexagonal, and pentagonal shapes are also present (Washburn, 1956). Polygon shape is determined by thermally induced stress fields within the permafrost. The contraction-crack pattern most common in permafrost is described as 'randomly orthogonal' (Lachenbruch, 1966). In previously uncracked and homogenous ground, a new crack follows randomly distributed zones of weakness and destroys the isotropy of the surficial tension, creating an encircling zone of stress relief. A subsequent crack that enters this zone of weakness tends to trend perpendicular to the greatest tension, which is perpendicular to the first crack. Hence, orthogonal polygons are formed (Lachenbruch, 1966).

In drained lake basins, inactive and abandoned flood plains, and river terraces, orthogonal ice-wedge-polygon systems are generally oriented with respect to old shorelines (fig. 87). These shorelines are anisotropic borders where first cracks in newly exposed or prograding deposits are normal to the greatest tension, either perpendicular or parallel to the shoreline, depending on the temperature field and the distance from shore. Because these cracks are also oriented, subsequent orthogonal cracks are oriented (Lachenbruch, 1966). Nonorthogonal polygons are common in the Prudhoe Bay area in areas that show little modification by lacustrine or fluvial processes.

Figure 87. Drained lake basin west of Prudhoe Bay with abandoned strandlines and orthogonal ice-wedge polygons. Photograph by S.E. Rawlinson, 1982.

The polygonal form is expressed on the ground surface by double, parallel raised rims with a central trough, or simply by a trough. Growth of ice wedges and expansion of soil upon warming result in upward plastic flow and shear of adjacent permafrost, which produce the rims adjoining the wedges (Black, 1976). Troughs are produced by rapid thaw of the wedge ice relative to the surrounding permafrost. Trough depth is determined by the volume of water the troughs drain, but rarely exceeds 2 m (6.6 ft) (Britton, 1957).

Difference in relief between the raised rim or trough and the central area is a criterion for classifying ice-wedge polygons. Leffingwell (1919) first described low-center and high-center polygons, and Black (1952) noted gradations between these extremes. Walker and others (1980) classified ice-wedge polygons in the Prudhoe Bay area as: 1) high center, with center-to-trough relief greater than 0.5 m (1.6 ft); 2) high center, with center-to-trough relief less than or equal to 0.5 m (1.6 ft); 3) low center, with rim-to-center relief greater than 0.5 m (1.6 ft); and, 4) low center, with rim-to-center relief less than or equal to 0.5 m (1.6 ft). In the Prudhoe Bay area, high-center ice-wedge polygons are most common in a narrow band along streams, and shorelines of drained thaw lakes, on some upland surfaces, and on broadly convex interfluves (Walker and others, 1980). The distribution of low-center ice-wedge polygons in the Prudhoe Bay area is extensive, and they are particularly common in drained lake basins, and on flood plains and river terraces. Areas of high-center ice-wedge polygons surrounded by low-center ice-wedge polygons (both within a drained or partially drained lake basin) are common in the Prudhoe Bay area.

Black (1950) proposed a cycle that progressed from a flat surface with polygonal cracks (youthful) through low-center ice-wedge polygons (mature) to high-center ice-wedge polygons (old age). Development of ridges and vegetation around ice wedges inhibit surface drainage and cause flooding of central areas. These flooded areas are conducive to growth of hydrophilous vegetation. Lateral growth of ice wedges, mass wasting, thaw, and vegetation growth eventually convert low-center ice-wedge polygons into high-center ice-wedge polygons. According to Black (1952), this cycle is restricted to flat, wet areas; mass wasting, thaw, and surface erosion on slopes of only a few degrees cause only high-center ice-wedge polygons to form. In contrast, Britton (1957) noted that near Barrow, low-center ice-wedge polygons are common on ridge tops and low-angle slopes, and high-center ice-wedge polygons are common on many lowland areas.

Lachenbruch (1966) and French (1974) suggested that material type primarily determines the occurrence of low-center or high-center ice-wedge polygons. Low-center ice-wedge polygons form where the material has a finite shear strength when thawed, for example, sand, long-fiber peat, and some silt. This material is extruded into the active layer and accumulates as peripheral ridges. High-center ice-wedge polygons form where the permafrost is fluid when thawed, such as where considerable silt or clay and ice are present. When this material flows and disperses into the active layer, it leaves either no surface trace of the polygon or a trough over the ice wedges. Lachenbruch (1966) acknowledged that high-center ice-wedge polygons also form where polygonal troughs are deepened by erosion and where peripheral ridges, if present, are destroyed.

Reticulate patterned ground

Reticulate patterned ground includes nonsorted, high-center polygons that are generally less than 1 m (3.3 ft) in diameter with a hummocky microrelief (Walker and others, 1980). This landform is common in the Prudhoe Bay area on well drained sites such as low interfluves, uplands adjacent to active drainageways, and pingos. The assorted soil is a Pergelic Ruptic Aqueptic Cryaquoll (Everett and Parkinson, 1977); Pergelic Cryaquept soil (silty fine sand and fine sand) intrudes Pergelic Cryaquoll soil (sandy humic peat). Excavations of reticulate patterned ground show that the underlying silty sand and fine sand generally intrude the peaty layer below the surface troughs. Nonsorted circles (frost boils) are also associated with this soil type in less well-drained sites (Walker and others, 1980).

The origin of reticulate patterned ground is a combination of origins described for high-center ice-wedge polygons, where water drainage and thaw deepen the troughs and frost heaving or mass displacement processes disrupt the substrate.

Hummocks

A hummock is a type of oval nonsorted net that ranges from 0.25 to 2 m (0.8 to 6.6 ft) in diameter with a convex or flattened top that is 0.2 to 0.8 m (0.6 to 2.6 ft) high (Zoltai and Pettapiece, 1973; Walker and others, 1980). According to Washburn (1956), a net is patterned ground with a mesh that is intermediate between a circle and a polygon. The diameter of hummocks in the Prudhoe Bay area is generally toward the smaller extreme. Hummocks are usually earth cored and always have a vegetation cover (Washburn, 1980). Raup (1965) reported hummocks without an earth core or with a stone core in Greenland. Hummocks commonly occur in groups on the slopes of flood-plain embankments and on the flanks of pingos (Walker and others, 1980). Sharp (1942) reported hummocks on slopes up to 20 degrees in the Yukon Territory, Canada.

Hummock development is not well documented. According to Washburn (1969), hummocks in Greenland form as a result of downward movement at net borders with concurrent upward displacement of central mineral soil by cryoturbation. Although cryoturbation is a factor in the development of most hummocks (Zoltai and Pettapiece, 1973), the presence of permafrost is not a requisite (Washburn, 1980). Zoltai and Tarnocai (1974) indicated that ice-rich permafrost in the Mackenzie River valley of Canada was conducive to hummock development.

In the Prudhoe Bay area, reticulate patterned ground often grades into hummocks with an increase in ground slope. Hummocks generally occur on slopes greater than 6 degrees. Walker and others (1980) recognized this change and speculated that these hummocks are derived from reticulate patterned ground. Thermal erosion and erosion related to slope runoff apparently accentuate polygon relief and modify the polygonal pattern to a net pattern.

Strangmoor

Strangmoor refers to peatlands with ridges of peat, vegetation, and ice (at least part of the year) separated by shallow ponds. The term string fen is synonymous and frequently used to describe this landform (Washburn, 1980). The spacing of ridges (strangs) may be from less than 1 m (3.3 ft) to many meters (Schenk, 1966). They may be up to 2 m (6.6 ft) high and tens of meters long (Washburn, 1980), but ridges in the Prudhoe Bay area are generally less than 0.5 m (1.6 ft) high (Walker and others, 1980). Ridges are commonly linear and transverse to slope and hydrologic gradient, ringlike and anastamosing, or netlike (Washburn, 1980). In the Prudhoe Bay area, the ridges are often discontinuous and sometimes aligned (Walker and others, 1980), with the alignment trending parallel to shorelines of recently drained lakes.

Hypotheses that explain the origin of strangmoor may be categorized as biotic, ice and frost action, and gravity. Many influences and processes within these categories may be collectively involved in development of strangmoor (Moore and Bellamy, 1975). Plants grow in hummocks, which may in turn be further developed by cryoturbation and finally oriented by slope and drainage (Washburn, 1980).

Many investigators agree that strangmoor are most common in the zone of discontinuous permafrost and that their occurrence tends to be climatically zoned (Washburn, 1980). Although poorly developed strangmoor are present at Prudhoe Bay, which is in the continuous permafrost zone, their condition corroborates the hypothesis that climate and perhaps the absence of permafrost are important factors that influence development.

Pingos

Pingos are ice-cored, conical mounds that grow and persist in areas of permafrost (fig. 88).

Figure 88. Large pingo east of the Kadleroshilik River. Photograph by S.E. Rawlinson, 1981.

Closed-system pingos form under cryostatic pressure in areas of continuous permafrost (Washburn, 1980). Initiation of pingo development involves exposure of high-moisture lake sediments to a freezing environment (Muller, 1959). Pore water expelled below the freezing surface freezes into an ice core (Mackay, 1978). The ice core grows and pushes up the ground surface as pore water is continually expelled and supplied to the ice core by permafrost aggrading into the thaw bulb (Mackay, 1973; 1978). The tops of some pingos may alternately rise and fall in response to the rate of accumulation and loss of pore water beneath them (Mackay, 1977). The pingo stops growing when unfrozen pore water is exhausted.

Few ice cores are composed of pure ice. With depth, lens ice and soil are commonly interlayered (Mackay, 1973; Pissart and French, 1976) although boreholes in pingos at Prudhoe Bay encountered no interlayered sediment (Brockett, 1982) (figs. 89 and 90).

Pingos attain maximum diameters early, then grow higher rather than wider, with the tops growing faster than the sides. The growth rate for a young pingo is about 1.5 m per yr (5 ft per yr) in the first 1 or 2 yr. The

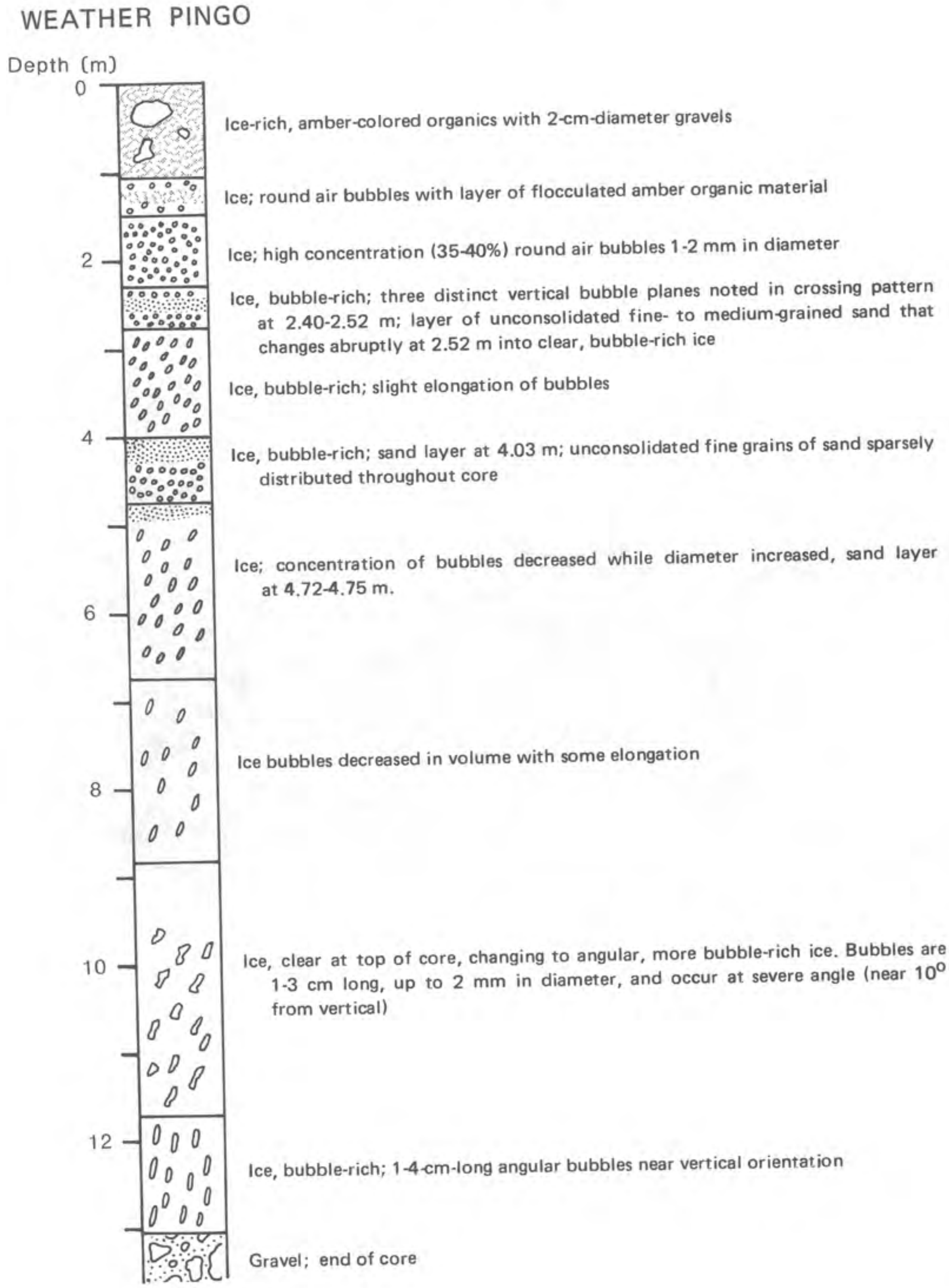


Figure 89. Stratigraphy of Weather Pingo, located along the Putuligayuk River route. From Brockett, 1982.

growth rate decreases inversely with the square root of time (Mackay, 1973). Large pingos may continue to grow for more than 1,000 yr. Radial tension cracks that produce star-shaped summits are common on actively growing pingos (Pissart and French, 1976). Expansion fractures of material capping the ice core cause it to thaw, which leads to destruction of the pingo.

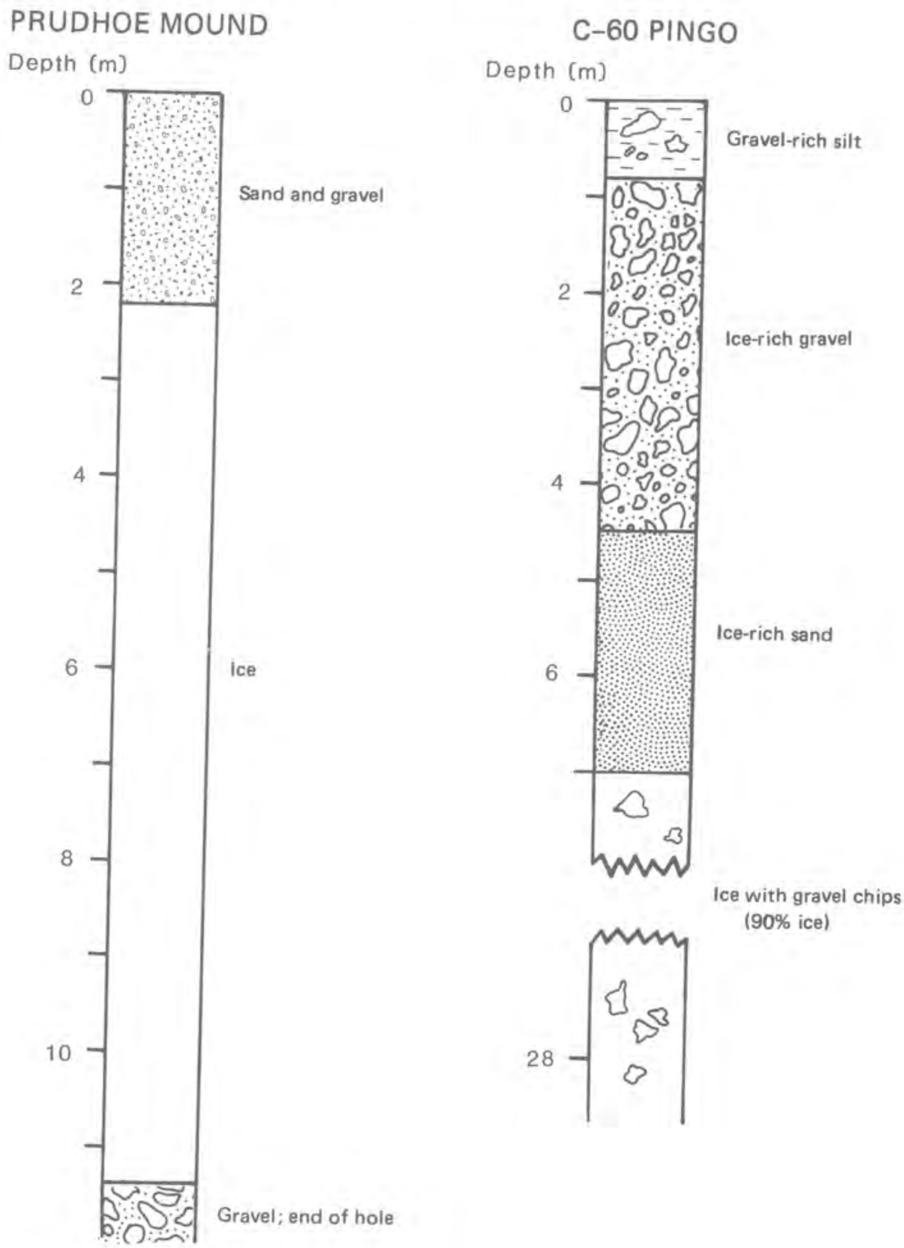


Figure 90. Stratigraphy of Prudhoe Mound, located along the West Dock route, and Pingo C-60, located along the Kuparuk route. From Brockett, 1982.

Thermokarst Forms and Processes

Linear and Polygonal Depressions

Disruption of the thermal equilibrium of frozen sediments by human activity, such as construction of airports and roads or passage of a vehicle, can result in linear and polygonal depressions in the ground surface. Disruption of frozen soil increases the downward heat flux in summer and leads to thickening of the active layer and thawing of permafrost. If the thawed soil is supersaturated with respect to water, the excess water will drain and the ground will subside (Mackay, 1970). Because fine-grained soils such as glaciolacustrine silt and clay, have a higher water content, they are more susceptible to subsidence than sand and gravel (Heginbottom, 1973).

Water-filled depressions are especially common along the sides of abandoned roads in the Prudhoe Bay area. If the insulating value of the gravel roadbed and the compacted active layer is less than the insulating effect before construction, the active layer thickens and permafrost thaws. If the insulating value of the roadbed and the compacted active layer is greater than the insulating effect before construction, permafrost aggrades into the roadbed (Ferrians and others, 1969). In either case, water-filled depressions along the road can result; in the first case, water collects in the thawed depressions, and in the second case, water blocked by permafrost in the road fill flows along the road and thaws underlying permafrost (March, 1980).

Subsidence also occurs preferentially along ice-wedge polygons, producing an irregular topography of mounds and linear depressions (French, 1975; Lawson, 1979). French (1975) described a hummocky terrain on Banks Island [maximum relief 1 to 1.5 m (3.3 to 4.9 ft)] that is produced by progressive subsidence and thermokarst modification. Water that is drawn to the surface by capillary action during melting of the ground ice accumulates in the depressions and enhances thawing and subsidence (Price and others, 1974). The magnitude of the disturbance is most dependent on the intensity of human activity and on local terrain properties (Brown and Grave, 1979).

Thaw lakes

The Arctic Coastal Plain is characterized by large, elliptical, oriented lakes that range from small ponds several meters long to lakes more than 15 km (9 mi) long and 5 km (3 mi) wide (Black and Barksdale, 1949). Most shorelines are scalloped or jagged because of erosion along ice wedges. Lake depth varies from 0.6 to 6 m (2 to 20 ft) and is related to ground-ice volume, local relief, and basin age (Sellman and others, 1975). Lakes shallower than 1.8 m (6 ft) freeze to the bottom in winter.

The thaw-lake cycle, first presented by Britton (1957), is fundamental in the development of the regional landscape of the Arctic Coastal Plain. Most landforms in the area (excluding active and abandoned flood plains of the major rivers) are either currently undergoing modification by lacustrine processes or have been modified in the past. Billings and Peterson (1980) elaborated on the thaw-lake cycle by noting 1) emergence of the coastal-plain sediments, 2) development of permafrost, 3) formation of thermal-contraction cracks in permafrost, 4) growth of ice wedges, and 5) development of low-center ice-wedge polygons (fig. 91).

The formation of thaw lakes is related to melting of permafrost, which can be caused by disruption of the vegetation mat by mass movement, the action of wind or water, or accelerated thaw beneath pools at intersections of ice wedges or the centers of ice-wedge polygons (Hopkins, 1949; Billings and Peterson, 1980). Pools of water coalesce by thawing to form thaw ponds, and continued thawing and slumping at the pond margins enlarge the pond. Wave erosion of thawed banks becomes an important process after the lake has attained a diameter of about 30 m (100 ft) (Hopkins, 1949; Black, 1969).

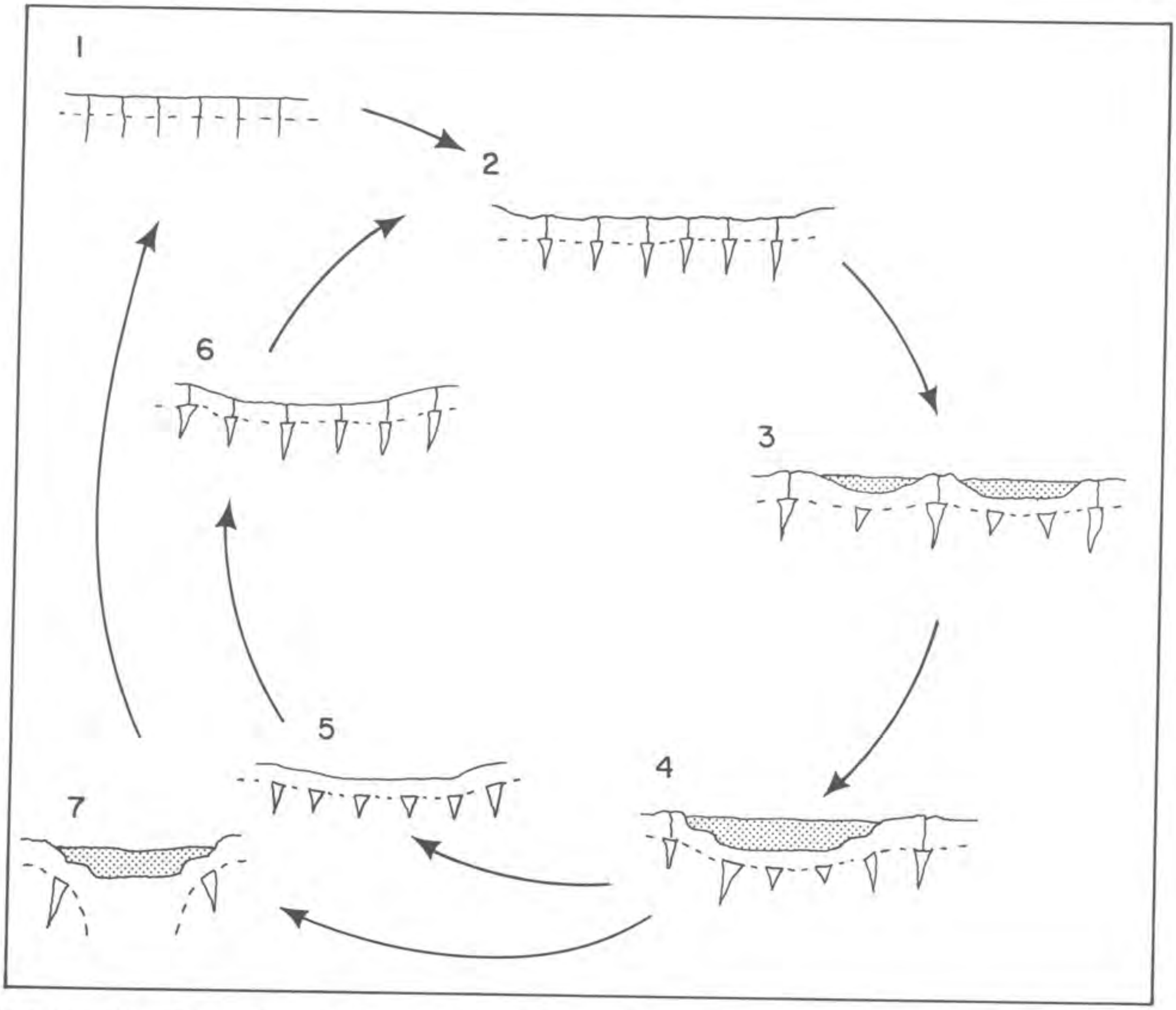


Figure 91. The thaw-lake cycle: 1) newly exposed sediments with thermal-contraction cracks permafrost, the top of which is delineated by the dashed line; 2) growth of ice wedges and low-center polygons in the sediments; 3) formation of thaw ponds by erosion and coalescence of low-center polygons; 4) a mature, but shallow thaw lake with benches; polygons remain visible on the bench because of persistence of ice wedges; 5) a drained, shallow thaw lake; 6) a shallow thaw-lake basin in which old ice wedges are reestablished; 7) a deep, large thaw lake with thaw bulb. Modified from Billings and Peterson, 1980.

Through time, the lakes continue to enlarge by thaw and erosion and as a lake enlarges, it incorporates various types of sediment. Fine materials are carried to the lake center and larger and heavier materials grade from the shoreline toward the center (Britton, 1957). Large chunks of peat are moved short distances from the lake margins, and the resultant peripheral zone of coarse peat grades inward to a silt zone. This sequence is preserved vertically as the lake grows (Britton, 1957).

Removal of interlake divides results in coalescence of two lakes into a single, broad body of water (Britton, 1957). Expansion continues until drainage lines open and the lake is partially or completely drained; abandonment of lakes on the coastal plain is not generally caused by infilling of sediment. Repeated cycles of lake formation (in which the lake drains before erosion and scouring begin) are indicated by peat and silt layers formed by lacustrine peat and subaerial silt deposition. Intermixed deposits of peat and silt and peat pods and truncated tundra deposits are also indicative of lacustrine deposition (fig. 92). A surface polygonal pattern quickly develops in the drained basins if the ice wedges were not completely destroyed earlier in the cycle (Walker and others, 1980). Even if the ice wedges were completely destroyed, permafrost and ice-wedge polygons are eventually reestablished in the basins. Subsequent thawing of ice wedges and permafrost and displacement of soil results in a pool of standing water that ultimately becomes another thaw lake.

Figure 92. Drained lake basin near the Beaufort Sea coast. Top sediments are intermixed silt and organic material. The expanding lake basin has cut into surrounding coastal-plain deposits. Photograph by S.E. Rawlinson, 1981.

Elongate thaw lakes in the Arctic Coastal Plain are generally oriented from N. 9° W. to N. 21° W. (Rex, 1960). Cannon and Rawlinson (1979) reported a lake orientation of N. 10° W. in the Prudhoe Bay area. Several hypotheses have been proposed to explain orientation of these lakes. Agents that could cause preferred thaw and erosion are prevailing winds and fracture system patterns (Carson and Hussey, 1959).

Black and Barksdale (1949) postulated that former predominant winds blowing parallel to the major axes of the lakes were the cause of orientation, and stated as evidence the erosion of eastern and western shores under the present predominant northeast winds. However, Rosenfeld and Hussey (1958) observed in the field and on air photos that eastern and western shores are not being eroded. Livingston (1954) postulated that present prevailing winds, which are almost normal [N. 75° E. in the Prudhoe Bay area during the ice-free period (Walker and Webber, 1979)], produce longshore currents that scour lake ends faster than they scour the sides. However, Carson and Hussey (1959) reported that field experiments do not confirm the presence of these longshore currents. Utilizing hydrodynamic principals, Rex (1960) maintained that longshore currents are created by winds parallel to the minor axes of the lakes and are responsible for the observed lake orientation on the Arctic Coastal Plain. Sellman and others (1975) reported that photographic records show concentration of erosion at lake ends.

Evidence for structural control includes the presence of a well-developed drainage pattern in which most streams are oriented north-northwest (Rosenfeld and Hussey, 1958) and alignment of coastal-plain lakes with dominant jointing directions in the northern foothills of the Brooks Range (Maurin and Lathrum, 1977). A fracture system that favored development of ice wedges is postulated to have formed when the sediments froze. Thaw along the ice wedges could create oriented lakes (Rosenfeld and Hussey, 1958).

Carson and Hussey (1959) evaluated numerous hypotheses for the lake orientation, but favored a composite hypothesis of lake development in stages in which one or more processes are dominant. Although little has been done to determine which mechanism most affects lake orientation, wind is the most accepted mechanism among North Slope investigators.

Radiocarbon dates of peat samples in the Prudhoe Bay area give indications of times of lacustrine activity. A date from the basal peat in a drained lake basin beneath Pump Station 1 of 9,330 ± 150 yr B.P. (Everett, 1975) is considered a minimum age for modification of the coastal plain by thaw-lake activity (Everett, 1980b). Hopkins and others (1980) listed radiocarbon dates for 16 different thaw-cycle sequences, all less than 11,000 yr B.P. Seven radiocarbon dates from peats throughout the Beechey Point Quadrangle indicate peat deposition from 2,900 to 7,700 yr B.P. Lakes older than 2,000 yr are unknown on the Arctic Coastal Plain (Hopkins and others, 1980).

Cryoturbation Features

Cryoturbation features (periglacial involutions) are soil structures produced by frost action (French, 1976; Washburn, 1980) (fig. 93). The structures are best developed on flat surfaces where they cannot be destroyed by downslope movement (French, 1976). Plug and pocket involutions are typical of homogeneous, fine-grained sediments and are common in the Prudhoe Bay area, where they often disrupt lake-basin sediments (fig. 94). Flamelike and club-shaped involutions are produced by the injection of fine-grained sediments into overlying sands and gravels. Stone pillars, blunt-nosed cones, and festoons involve tongues of frost shattered and disintegrated rock that rise into overlying fine-grained soil. Amorphous structures are those in which the

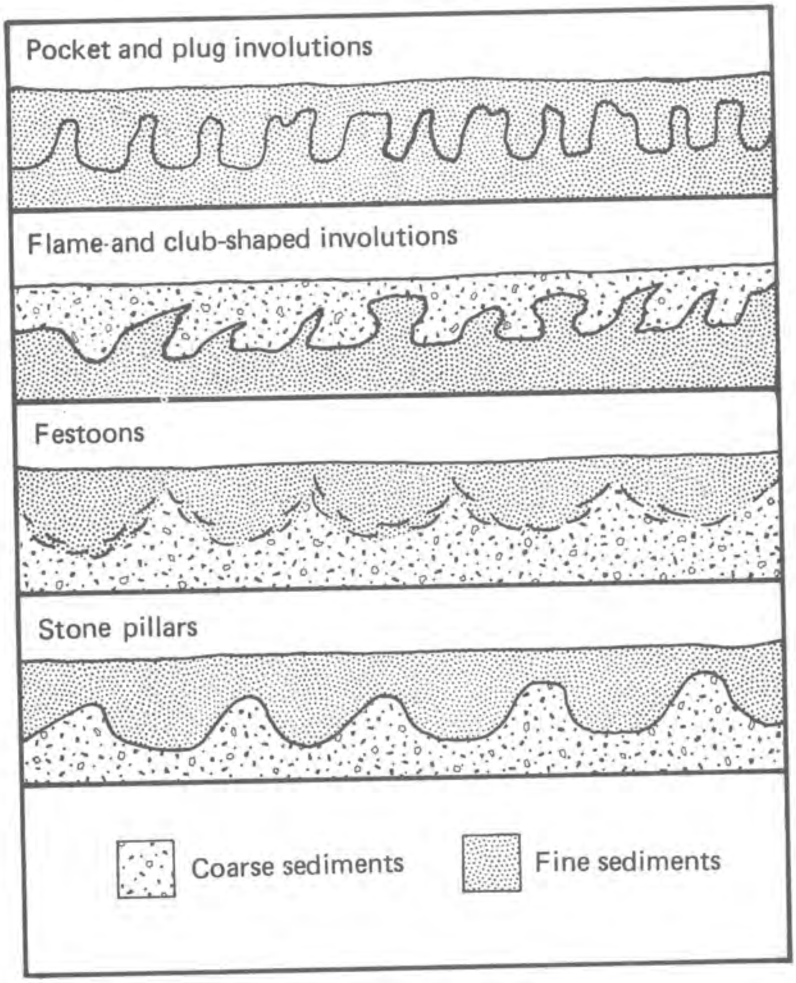


Figure 93. Various cryoturbation features. From French, 1976.

original structure has become so deformed that it is unrecognizable (Embleton and King, 1975).

Formation of regular and simple structures is attributed to cryostatic pressure (French, 1976). The more complex structures originate from changes in intergranular pressure during thawing, differential volume changes in frozen soil, and density differences in soils (Washburn, 1980). These processes are related to mass displacement and occur when a moist layer is compressed between rigid permafrost (below) and advancing frozen sediments (above). Because the sediments contain variable amounts of water, unequal deformation results (Embleton and King, 1975). Corte (1962) proposed a model that involved mass displacement for the formation of cryoturbation structures. Horizontal and vertical sorting occur in areas where the soil freezes from the top and sides, which implies that a well-graded gravelly soil will be sorted if subjected to numerous freeze-thaw cycles.

Fluvial Forms and Processes

River flooding

The dominant hydrologic event on the Arctic Coastal Plain is the spring ice-breakup flood, which is dependent on the amount and timing of snowmelt.

Figure 94. Simple cryoturbation features on Pingok Island. Gray silt intrudes organic-rich silt at the margin of a drained thaw-lake basin. Photograph by S.E. Rawlinson, 1981.

On coastal rivers, meltwater begins to accumulate during mid- to late May, and virtually all river ice is removed in two or three days (Walker, 1973). Up to 80 percent of the seasonal flow is concentrated during breakup. Although snow is the most important source of water for river runoff, rainfall contributes to summer stream activity. Rainfall on the coastal plain is generally less than 25 cm (10 in.) annually and is seldom responsible for flash floods, although rapid fluctuations in water level reflect the timing of rainstorms (Walker, 1973).

Flood characteristics of rivers on the coastal plain are especially interesting because floods may inundate and erode structural foundations or cause pipeline rupture that may result in oil spillage. Childers (1974) examined flood characteristics of the Kuparuk and Sagavanirktok Rivers (table 6) to determine hydrologic hazards to the Trans-Alaska Pipeline, which was designed to withstand a flood of 3,455 m^3 per s (122,000 ft^3 per s). The maximum flood was computed by measuring high-water-mark indicators after extreme floods, including driftwood and recently transported silt, sand, and gravel. Some surveys yielded poor discharge estimates due to lack of flood evidence, poor hydraulic conditions, and uncertainties about the presence of channel ice during floods (Childers, 1974).

Table 6. Flood survey results of two arctic rivers. Modified from Childers, 1974.

	Kuparuk River near Deadhorse (lat 70°17'54", long 148°57'35")	Sagavanirktok River near Sagwon (lat 69°05'15", long 148°45'10")
Drainage area	8107 sq km^2 (3130 sq m)	5719 sq km^2 (2208 sq mi^2)
Flood characteristics		
2-yr flood	198m^3/sec (7000 ft^3/sec)	328 m^3/sec (11,600 ft^3/sec)
50-yr flood	566 m^3/sec (20,000 ft^3/sec)	637 m^3/sec (22,500 ft^3/sec)
Bankfull channel characteristics		
Width	516 m (1890 ft)	165 m (540 ft)
Mean depth	1.8 m (5.9 ft)	2.42 m (7.94 ft)
Discharge	1869 m^3/sec (66,000 ft^3/sec)	991 m^3/sec (35,000 ft^3/sec)
Maximum evident flood		
Top width	914 m (3000 ft)	171 m (560 ft)
Discharge	2832 m^3/sec (100,000 ft^3/sec)	1756 m^3/sec (62,000 ft^3/sec)

Aufeis

Aufeis, or seasonal icing, consists of surface ice formed during winter by successive freezing of thin sheets of water that seep from the ground or from rivers or springs (Sloan and others, 1976; Harden and others, 1977; Washburn, 1980). Aufeis commonly forms on braided rivers with shallow channels that are readily frozen. The braided Sagavanirktok and Canning Rivers both have large areas of aufeis. Williams and van Everdingen (1973) estimated the volume of aufeis in the Sagavanirktok River to be 1.23×10^8 m^3 (1.61×10^8 yd^3). When flow is confined to a narrow or single channel, aufeis rarely forms because of greater channel depth (Sloan and others, 1976). After development of a seasonal ice cover on a river, the water below may become restricted. Hydrostatic pressure increases until the water breaks through the ice cover (usually through thermal-contraction cracks) and flows out over the river ice (Sloan and others, 1976). Although aufeis begins to form as soon as rivers are frozen, the major period of growth is the mid-winter to early-spring period (French, 1976). The total thickness of aufeis may reach 10 m (33 ft) in Alaska (Washburn, 1980). The size and location of aufeis is a function of discharge source, hydrostatic head, and geologic setting (Harden and others, 1977). Road building may alter these factors and induce aufeis formation.

Aufeis may have an influence on braiding of rivers during summer. Aufeis remnants divert channels around ice patches and make the river flood plain wider (Harden and others, 1977). Flooding and erosion by ice and water also occur during the summer. Flooding produces an abundant ground-water supply that enhances the continued development of aufeis at the same location. A heavy snowfall in early winter produces an insulating effect that is unfavorable to aufeis formation (Harden and others, 1977).

Taliks

Taliks are zones of unfrozen ground that occur above, below, and within permafrost layers (Muller, 1943; Washburn, 1980). Closed taliks are completely enclosed by permafrost and result from a change in the thermal regime (such as draining of a lake), downward encroachment of permafrost, or fluctuations in regional climate (French, 1976). Open taliks reach the active layer and result from local heat sources such as lakes and river channels (French, 1976). Due to the high heat capacity of water and the insulation provided by snow and ice in winter, extensive thawed zones occur under large bodies of water (Smith, 1976). By measuring the resistivity of the ground under large lakes in the Prudhoe Bay region, Sellman and others (1974) discovered several thaw bulbs. Resistivities from a traverse across the Sagavanirktok River were less than 4×10^4 ohm-cm, which indicates unfrozen sediments under the channel (Sellman and others, 1974).

Individual taliks commonly serve as aquifers and provide the major source of water in some areas of continuous permafrost. Test work by Sherman (1973) in the Prudhoe Bay area showed that a year-round supply of potable water exists in a talik beneath the Sagavanirktok River.

Removal of flood-plain gravel

In the Prudhoe Bay area, gravel is used as pads for structures or as roadways to reduce permafrost thaw. The gravel pad replaces the vegetative mat as an insulator. Because the insulative effect of vegetation is greater than that of gravel, the gravel pad must be thicker than the previous vegetative cover to prevent thawing of permafrost (Joyce and others, 1980). Gravel roads and pads in the Prudhoe Bay area are about 1.5 m (5 ft) thick (ARCO Alaska, Inc., 1982) Primary sources of gravel are flood plains of the Kuparuk, Putuligayuk, and Sagavanirktok Rivers. About 26,000 m^3 of gravel are required per km (55,000 yd^3 per mi) of road and about 69,000 to 77,000 m^3 (90,000 to 100,000 yd^3) of gravel are required for an eight-well drilling pad (ARCO Alaska, Inc., 1982).

Two common types of gravel removal are pit excavated or scraped. Depth of excavation and permanent inundation by water after site closure (Joyce and others, 1980) dictate the gravel-removal method. Pit sites can have major effects on the local environment, because there is usually a change in appearance of the flood plain and a loss of vegetated habitat. Where pit sites are located on the inside of river meanders, the possibility of diversion of the channel through the pit to eventually form a channel in the meander exists (Joyce and others, 1980). Regulations require placement of a buffer between the pit site and the river if the site is located adjacent to an active channel. Scraped sites offer several operational advantages. The sites are dry and provide better working conditions and more efficient gravel extraction. One drawback is that scraped sites disturb a larger area because the extraction is more shallow (Joyce and others, 1980).

Channel configuration is an important river characteristic that must be considered in site selection. Large, braided rivers are the most desirable gravel-removal sites because there is an abundance of well-graded material and because the environmental effects are minimal (Joyce and others, 1980). In a meandering or straight river system, the flood plain is too narrow and usually overgrown with the vegetation. Disturbance of stable banks decreases the lateral stability of active channels and allows water to spread over a large area (Joyce and others, 1980). The optimum site for gravel removal is a large, braided river where shallow scraping of unvegetated gravel bars is possible. Disturbance to active channels, banks, and vegetated areas is minimal, and rehabilitation of the site is easier.

Eolian Forms and Processes

Eolian processes are most evident in the Prudhoe Bay area along major rivers that serve as sources of fine sand and silt. Sediment is transported to the west by the prevailing east-northeast winds. Active eolian dunes occur chiefly along the Sagavanirktok River and locally along the Kuparuk River. The dune field near the Sagavanirktok delta consists mainly of longitudinal dunes up to 5 m (16.4 ft) high (fig. 95).

Presently active dune and interdune areas are barren or sparsely vegetated, chiefly with *Elymus arenarius mollis* and *Salix ovalifolia*, respectively (Walker and Webber, 1980). Partially stabilized dunes support *Salix ovalifolia* and *Artemisia borealis*, and stabilized dunes support *Dryas*

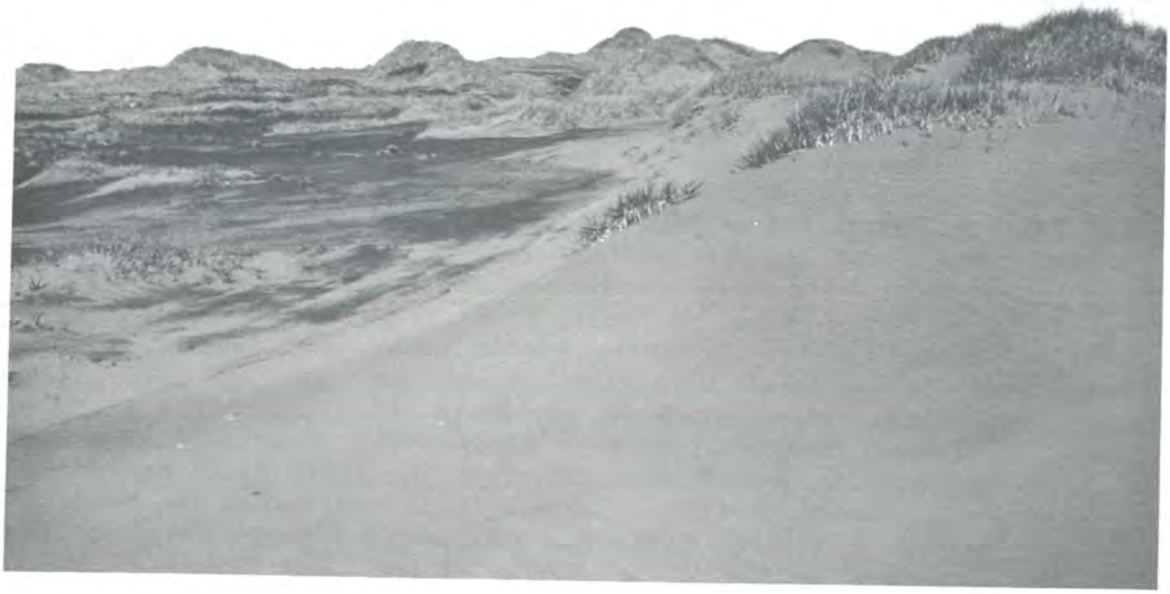


Figure 95. Active longitudinal sand dunes west of the Sagavanirktok River. Photograph by S.E. Rawlinson, 1981.

integrifolia, Kobresia myosuroides, and Oxytropis nigrescens (Walker and Webber, 1980).

Older eolian dunes in the Prudhoe Bay area and other regions of the Arctic Coastal Plain indicate a colder and drier climatic regime than at present. Sand-wedge casts have been observed in the Prudhoe Bay area, and Updike and Howland (1979) reported stabilized sand-silt dunes on upper fluvial-terrace (abandoned flood-plain) deposits of the Sagavanirktok River. Carter (1983) studied fossil sand wedges and associated dune fields on the Arctic Coastal Plain west of the Prudhoe Bay area and concluded that desertlike conditions existed at the time of their formation. Radiocarbon dates show the sand wedges and dunes are Wisconsinan.

Beach and Marine Forms and Processes

Gubik Formation and Flaxman Member

The Gubik Formation includes all Quaternary unconsolidated deposits that overlie Cretaceous or Tertiary rocks in the Arctic Coastal Plain. The formation is up to 76 m (250 ft) thick (Black, 1964). East of the Colville River, the Gubik Formation overlies early Tertiary nonmarine conglomerate, silty sandstone, and siltstone of the Sagavanirktok Formation (Payne and others, 1951; Black, 1964). The Gubik Formation crops out along the coast and major rivers below Holocene thaw-lake deposits in the Prudhoe Bay area. Gubik

Formation deposits are chiefly admixtures of silt and fine sand with locally common basal clay. Coarse-grained sand and gravel are thinly distributed throughout the section, but locally absent. Marine sediments are dominant, but lacustrine, fluvial, eolian, glacial, and glaciomarine sediments are also present (Black, 1964).

Leffingwell (1919) defined the 'Flaxman Formation' from glaciomarine deposits on Flaxman Island. These deposits of glaciomarine mud contain glacially striated dropstones of dolomite, dolomitic chert, red quartzite, diabase, red granite, pyroxenite, and granulite-facies metamorphic rocks that are foreign to northern Alaska (Hopkins, 1979b). A sample of the granite yielded a potassium-argon age date of 2.4 billion yr. The dropstones may have been ice-rafted from the Coronation Gulf area in Canada (A.S. Naidu, oral commun., 1982) or northern Greenland (Hopkins, 1979b), and are scattered along the Beaufort Sea coast as far west as Barrow. In the Prudhoe Bay area, 'Flaxman Formation' boulders are abundant along the east shore of Prudhoe Bay and at Point McIntyre west of West Dock (figs. 96 and 97). Several glaciomarine deposits occur along the arctic coast, but only those younger than the last interglacial (Pelukian) event are part of the 'Flaxman Formation' (Hopkins, 1979b), which restricts the age of the 'Flaxman Formation' to younger than 120,000 yr. Black (1964) described glaciomarine deposits at Cape Simpson and grouped them into the Skull Cliff Member of the Gubik Formation. Hopkins (written commun., 1982) correlated the deposits at Cape Simpson with the 'Flaxman Formation' on Flaxman Island and redesignated the 'Flaxman Formation' as the Flaxman Member of the Gubik Formation.

Profile and stability of high and low coastline

Large segments of the arctic coast are bordered by plains of unconsolidated sediments that are bonded by perennially frozen interstitial pore waters. Over 7,000 km (4,350 mi) of shoreline in the arctic are subject to thermo-erosional processes (Harper, 1978a). Despite low mean annual wave-energy levels, tundra cliffs on these coasts undergo intensive erosion (table 7). Typical coastal retreat rates are 1 to 2 m per yr (3.3 to 6.6 ft per yr), and some regional retreat rates exceed 10 m per yr (33 ft per yr).

Much of the mainland coast along the Beaufort Sea is retreating 1 to 2 m per yr (3.3 to 6.6 ft per yr). The coastal segment immediately west of Harrison Bay is retreating approximately 10 m per yr (33 ft per yr), with a maximum documented rate of 20 m per yr (66 ft per yr) (fig. 98). Coastal retreat along the Chukchi Sea coast south of Barrow, where cliffs are up to 14 m (4.6 ft) high, is nearly an order of magnitude less, averaging 0.3 m per yr (1 ft per yr) (Harper, 1978b). Detailed measurements of coastal retreat indicate that retreat in Prudhoe Bay is generally typical of the Beaufort Sea coast (fig. 98).

The exceptionally high rates of retreat are attributed primarily to the 'excess-ice effect' (Harper, 1978a). Periglacial processes tend to concentrate ice in the surface layers of the tundra, in the form of excess pore ice and massive ice (ice wedges). When these ice-rich sediments are exposed to thermomechanical wave action, much of the coastal cliff is melted, with little mechanical removal of sediment.

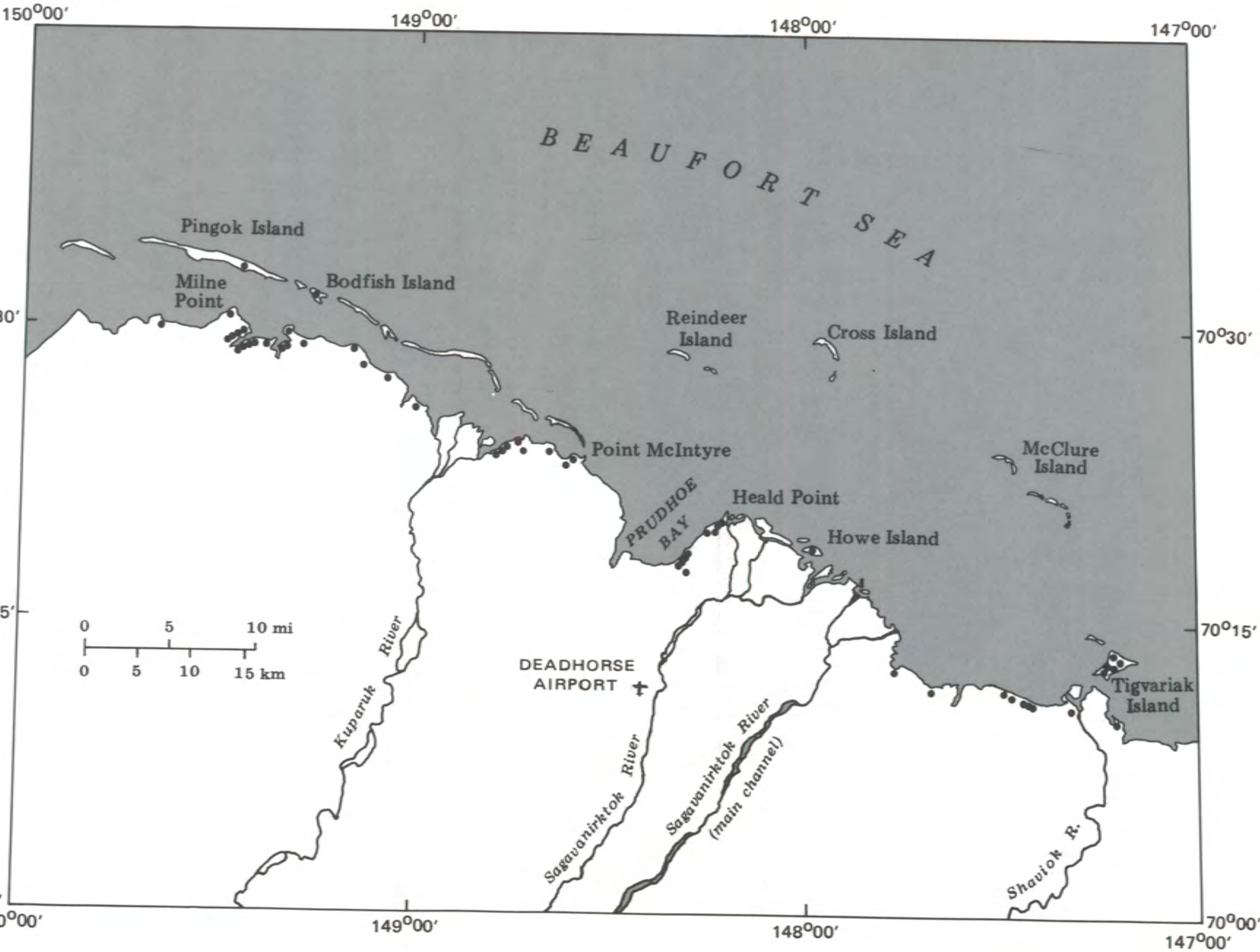


Figure 96. Map showing the distribution of Flaxman Member boulders along the coast near Prudhoe Bay. Dots represent numerous boulders.

Figure 97. Flaxman Member boulders in lake bed near East Dock at Prudhoe Bay. Photograph by S.E. Rawlinson, 1981.

The relative difference in coastal retreat between ice-poor sediments (approximately 30 to 40 percent pore space by volume) and ice-rich sediments (up to 70 percent ice by volume) can be quantitatively related by assuming typical ice-content values for surficial sediments (Sellman and others, 1975) (fig. 99). The relationship illustrates two significant points:

1) A cliff of ice-rich material will retreat faster than a cliff of ice-poor material
2) Low, ice-rich cliffs retreat faster than high, ice-rich cliffs because the ice content is highest in the upper 1 to 2 m (3.3 to 6.6 ft) of tundra sediments.

Comparison of estimates of regional retreat rates provides a qualitative agreement with the results (fig. 99) because cliffs along the Beaufort Sea coast are low [<2 m (<6.6 ft)], are therefore ice-rich, and retreat at rates of >1 m per yr (>3.3 ft per yr) despite very low wave-energy levels (fig. 98). High cliffs (6 to 15 m) (20 to 49 ft) of the Chukchi Sea coast are relatively ice-poor (fig. 99) and retreat at rates of 0.2 to 0.3 m per yr (0.7 to 1.0 ft per yr).

Calculations suggest 1) that the degradation of low cliffs typical of the Beaufort Sea coast is primarily a thermal-melting process and 2) that retreat rates may be limited by rates of heat exchange rather than by sediment removal rates. A survey of tundra-cliff morphology (Harper 1978a) indicates that low

Table 7. Rates of retreat of tundra cliffs.

Geographic area	Maxima (m/yr)	Mean (m/yr)	Source
Soviet Arctic			
Semyenovsky Island	- -	20	Gakkel, 1958
Semyenovsky Island	55*	- -	Aré, 1983
Mostakh Island	18	10-12	Grigor'yev, 1976
Yakutia Coast	15-20	5	Grigor'yev, 1976
Yakutia Coast	20	- -	Tolstov, 1962
Eastern Siberia	- -	4	Klyuyev, 1965
Alaskan Arctic			
Beaufort Sea	30	2-4	Hopkins and Hartz, 1978a
West of Prudhoe Bay	3	1-2	Barnes and others, 1977
Prudhoe Bay	3.8	1.8	Cannon and Rawlinson, 1979
Oliktok Point	- -	1.4	Dygas and Burrell, 1976
Barrow to Peard Bay	1.5	0.27	Harper, 1978b
South to Barrow	- -	2.2	Hume and others, 1972
Barrow to Demarcation Point	20.5	3.0	Lewellen, 1977
South to Barrow	- -	0.25	MacCarthy, 1953
Canadian Arctic			
Tent Island, Yukon Terr.	27	15	Gill, 1972
Garry Island, N.W.T.	7.3	2.3	Kerfoot and Mackay, 1972
Yukon Territory	5	- -	Lewis and Forbes, 1974
Yukon Territory	- -	1	Mackay, 1963
Tutkoyaktuk Peninsula**	5-8	- -	Mackay, 1971
Alaskan Border to MacKenzie River Delta	2	1	McDonald and Lewis, 1973
Tuktoyaktuk Peninsula**	6-9	- -	Rampton and Mackay, 1971

*Measured over a 2-yr period.
**Same area but different time intervals.

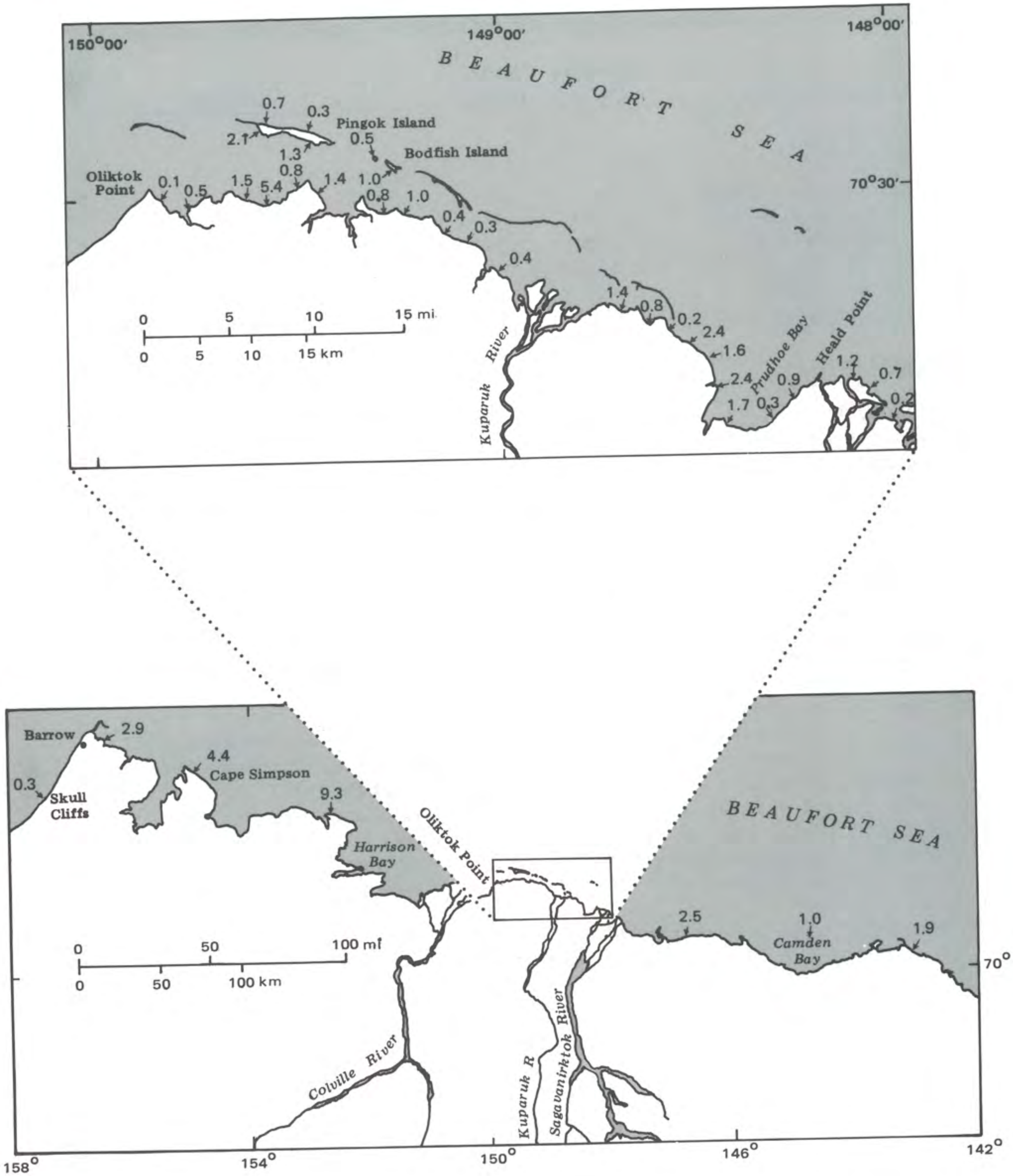


Figure 98. Coastal retreat rates (m per yr). Modified from Cannon and Rawlinson, 1979. Lower map shows average long-term coastal-retreat rates (m per yr) for various segments of the Alaskan Beaufort and Chukchi Sea coasts. Summarized from Harper, 1978b, and Lewellen, 1977.

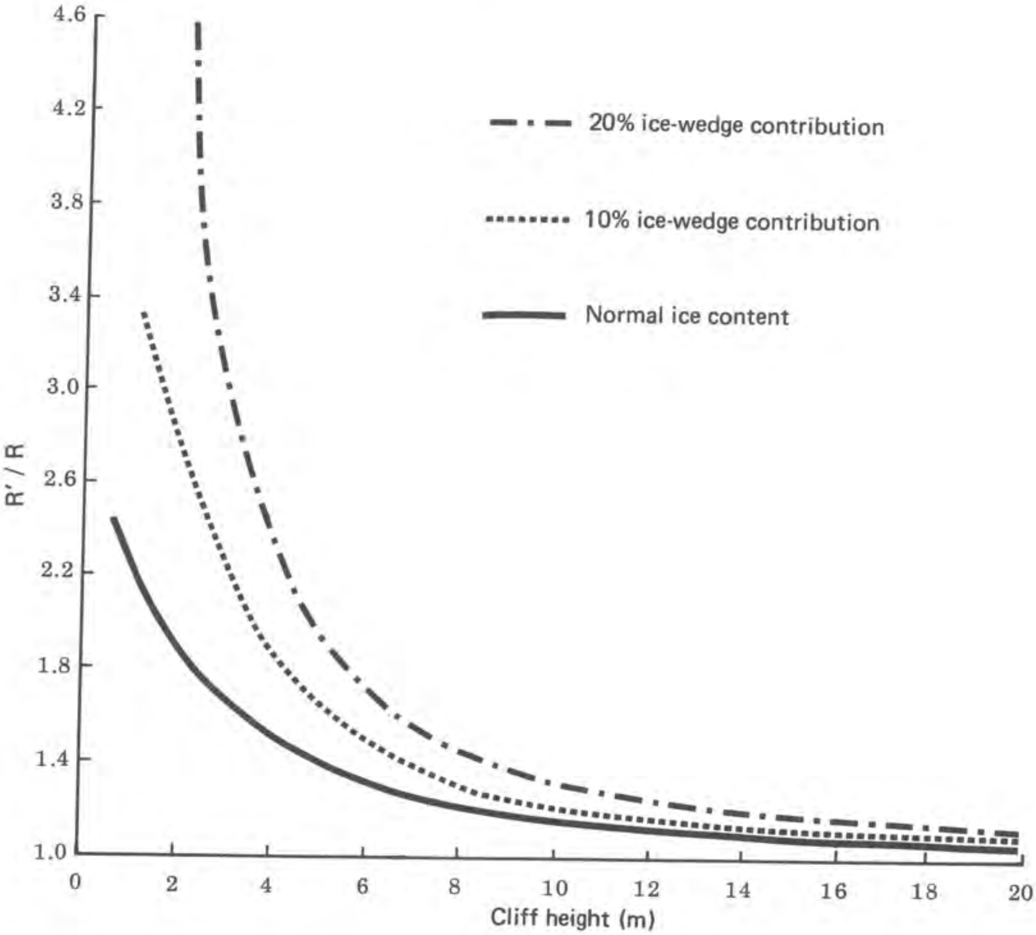


Figure 99. Plot of the ratio of retreat rates for ice-rich sediments, R', to retreat rates for ice-poor sediments, R, versus cliff height. The curve for 'normal ice content' is based on sediment ice contents from the Barrow area (Sellman and others, 1975). From Harper, 1978a.

tundra cliffs tend to be dominated by ice-related mass-wasting processes (fig. 100). Retreat rates of high cliffs (>6 m) (>20 ft), are probably limited by wave-related sediment-removal rates and are dominated by nonice-related mass-wasting processes (fig. 100).

The coast near East Dock at Prudhoe Bay is an intermediate height (approximately 3 m or 10 ft) rapidly retreating cliff exposure. Physical parameters relevant to the East Dock area are shown in table 8.

Offshore sediment dynamics

Sediment dynamics in the Beaufort Sea are dependent on levels of wave energy, sea-ice conditions, and current action. The intensity of these processes varies seasonally.

Sediments are primarily derived from coastal erosion and river effluent during the summer (Barnes and Reimnitz, 1974; Owens and others, 1980). This open-water period is 2 to 4 mo long, and the beach and nearshore zones respond

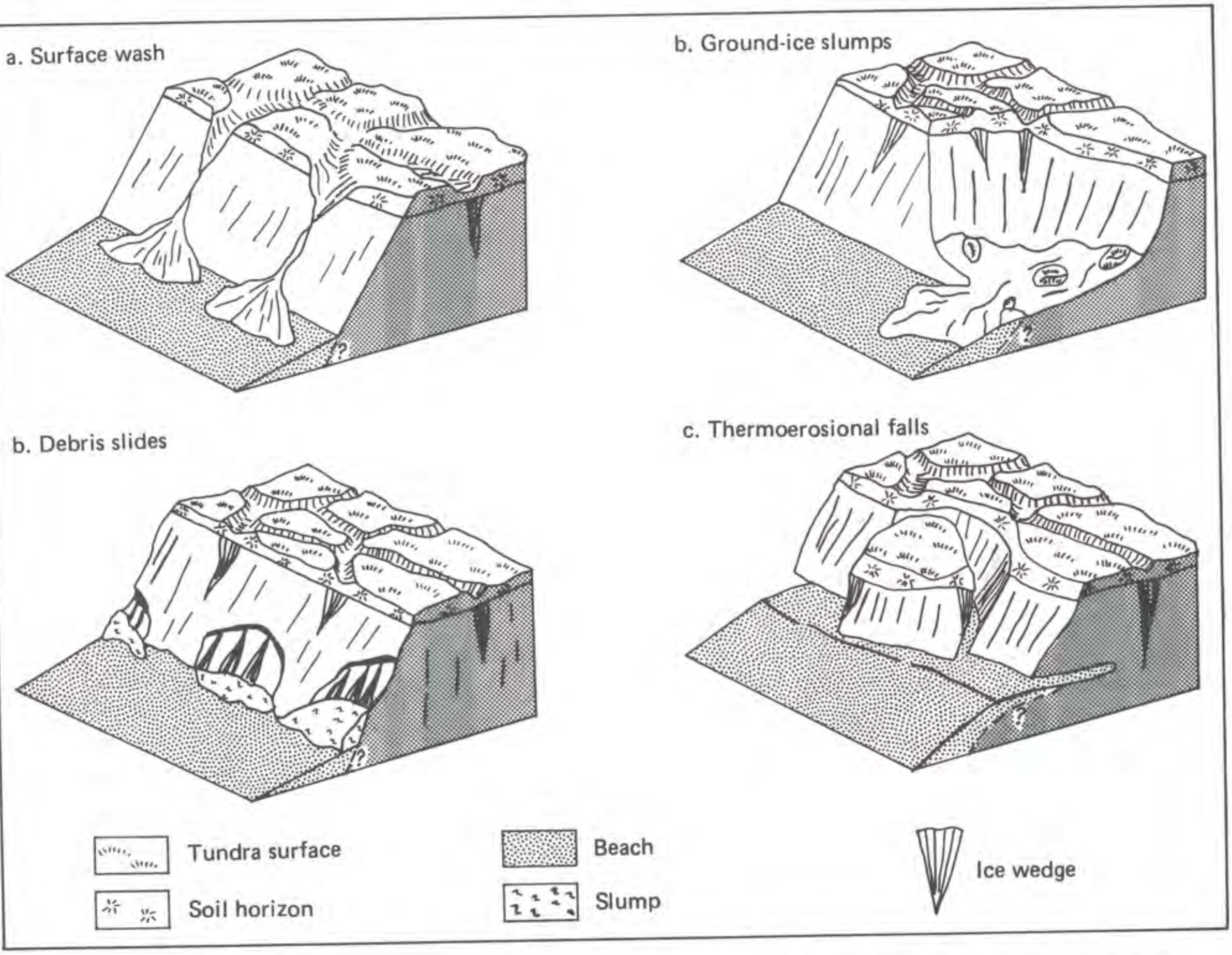


Figure 100. Typical mass-wasting processes that affect coastal tundra cliffs. Processes (a) and (c) are dominant on high, ice-poor cliffs and processes (b) and (d) are dominant on low, ice-rich cliffs.

to winds, waves, and currents. The magnitude and duration of these dynamic forces depend on prevailing wind and pressure conditions and distance to the pack ice (Short, 1973). Winds are largely from the east during the summer, resulting in generally westward currents parallel to the coastline, a condition reflected in the westward migration of insular spits on many coastal islands (Barnes and Smith, 1976) and the presence of fine-grained, sorted sediment along the shelf (Barnes and Reimnitz, 1974). Tidal currents that range from 0.1 to 0.3 m per s (0.3 to 1.0 ft per s) move only suspended material (Nummedal, 1979). Because of the presence of higher energy longshore currents, ebb-tidal deltas are absent, and flood-tidal deltas are poorly developed along the Beaufort coast (Nummedal, 1979).

The wave regime in the Beaufort Sea is primarily controlled by the location of the permanent ice pack. In summer, the distance from shore to pack ice varies from 20 to over 60 km (12.4 to 37.2 mi) (Barnes and Reimnitz, 1974). The overall effect is to reduce wave energy because of limited fetch.

Storms play an important role in sediment transport due to the low-energy environment. Sediment transport on the coast primarily occurs as a series of

Table 8. Physical parameters related to the East Dock area. From Harper, 1978a.

Mean annual temperature	-12.8°C (9°F) (on Oliktok)
Mean temperature 0°C (32°F)	June-September
Prevailing open-water winds	E Quad. 54.1% (on Oliktok) W Quad. 30.0% (on Oliktok) (strongest winds from west)
Open water	July to October
Maximum open-water fetch	Approximately 10 km from N
Typical wave heights and periods	0.2 to 0.3 m (0.6 to 1.0 ft), 2-4 sec.
Tidal range and type	0.2 m (0.6 ft), semi-diurnal
Meteorological tides	+3 m (+9.8 ft), recurrence interval 25-50 yr
Bedrock	None
Surficial sediments	Flaxman Formation, a marine sandy mud with ice-drop cobbles and boulders
Morphology	Eroding tundra cliff (3 m high) (9.8 ft) with narrow erosional wave-cut platform in places, fringing gravel beaches in other areas, some concentrations of Flaxman boulders. Very low offshore gradient.
Coastal erosion rates	0.9 m/yr (3 ft/yr) (Cannon and Rawlinson, 1979)

storm-related pulses rather than as a continuous process (Owens and others, 1980). Particularly severe storms may do considerable damage, often transporting more sediment than would be moved over several decades by longshore currents (Dygas and Burrell, 1976). In the fall of 1970, gale-force westerly winds produced a storm surge as high as 3 m (10 ft) that inundated the coastal plain for distances of 5 km (8 mi) inland; the surge was 3.4 m (11 ft) above normal sea level. Storm surges of this magnitude historically occur about every 25 years, but this surge may not have been exceeded for the past 100 years (Reimnitz and Maurer, 1979). Geologic effects of storm surges include accelerated shoreline erosion, changes in island size and configuration, ice gouging, and flooding.

The dynamics of sedimentation can be altered by changes in both sediment source and existing transport pathways. Construction of West Dock west of Prudhoe Bay decreased longshore current activity and caused increased sedimentation in an area dominated by seabed erosion (Barnes and Minkler, 1982). If openings similar to those in existing barrier island chains had been provided, the original transport regime might have been maintained (Barnes and Minkler, 1982).

In winter, an ice canopy eliminates waves and wind-generated currents, and the sedimentary regime is relatively quiescent. During freezeup and breakup, dynamic processes that are unique to high latitudes, including ice gouging, ice wallow, strudel scour, and ice rafting, dominate.

Moving ice in contact with shelf sediments forms gouges up to 5 m (16 ft) deep (Reimnitz and Barnes, 1974). The maximum concentration of ice gouges is found where sediments are soft and least resistant and along the steeper slopes of the shelf (Kovacs and Mellor, 1974). Reimnitz and Barnes (1974) reported that the winter shear zone between the shorefast ice and the polar ice pack is an area of high gouge density where deep-keeled pressure ridges gouge the bottom. Ice gouging effectively destroys any lateral continuity of sediment beds. Extensive recent reworking by ice gouging is suggested by the absence of significant bioturbation on the central shelf (Barnes and Reimnitz, 1974).

Ice-wallow bedforms occur nearshore in noncohesive sediments. Ice-wallow terrain is characterized by an irregular, undulating bottom covered by 50- to 100-m (164 to 328 ft) diameter potholes and mounds with 2 to 3 m (6.6 to 9.8 ft) of relief (Reimnitz and Kempema, 1982). This topography is produced by the scouring action of water around grounded ice flows (Reimnitz and others, 1972; Reimnitz and Kempema, 1982). The grounded ice represents an obstacle to currents and causes greater current velocities adjacent to the grounded ice, which results in the scouring of irregular depressions (Reimnitz and Barnes, 1974). The ice may also oscillate vertically or wallow in a seaway, displacing water forcefully from the ice-bottom contact (Reimnitz and Kempema, 1982). The result is to transport sediment away from the grounded ice, creating a depression-and-mound topography.

The breakup of rivers along the coast of northern Alaska results in extensive flooding of the sea ice. Drainage of large volumes of fresh water through cracks and holes in sea ice causes scour depressions (strudel scours) in the seabed (Reimnitz and others, 1974). Strudel scours occur within 30 km (19 mi) of river mouths, but are not found landward of the 2-m (6.6 ft)-depth contour because ice rests on the seafloor (Reimnitz and others, 1974). Reimnitz and others (1974) described two types of strudel scours: 1) widely spaced circular holes formed by drainage of water through a single hole in the ice, and 2) connecting holes trending along a line formed by drainage of water through a crack in the ice.

Ice rafting of fine-grained sediments is one of the major transport processes on the arctic shelf. Barnes and others (1982) observed a consistent pattern in the stratigraphy of ice cores: a relatively clear surface layer 10 to 15 cm (4 to 6 in.) thick that overlies a dirty-ice zone discolored by sediment that ranges in thickness from a few centimeters to over 1 m (3.3 ft); this overlies a clear, brine-rich zone. Sediment confined to the upper part of the ice suggests that sediment accumulates early during ice growth (Barnes and others, 1982). A mechanism for the formation of sediment-laden ice and preferential sorting of fine sediment involves resuspension of nearshore bottom sediment during severe fall storms accompanied by formation of sea ice (Barnes and others, 1982). This hypothesis explains the sporadic and sometimes rare occurrence of sediment-rich sea ice. Barnes and others (1982) suggested that this mechanism may be responsible for most fine-grained sediment transport to the deep Arctic Ocean basin.

Lagoonal substrata

Simpson Lagoon lies west of Prudhoe Bay between the Colville and Kuparuk Rivers. The Jones Islands form the seaward margin of the lagoon and protect it from pack-ice pushing and gouging. Because water depths range from less than 1 to 3 m (5.3 to 9.8 ft), most of the lagoon is frozen to the bottom in winter (Tucker and Burrell, 1977). Sandy mud and sandy silt are the predominant sediment types; gravel occurs only adjacent to the shorelines (Burrell and others, 1974). Naidu (1978) delineated two major substrate habitats in Simpson Lagoon: 1) a relatively sandy (>50 percent sand) region adjacent to the barrier islands and mainland, and 2) the central lagoon characterized by sandy muds (>50 percent mud). These substrate differences result from decreasing water turbulence toward the central lagoon.

Prevailing east-to-west winds and currents make the Kuparuk River the major sediment source for Simpson Lagoon. Naidu (1978) showed that illite is the dominant clay mineral in Simpson Lagoon, followed by chlorite and minor amounts of kaolinite and smectite. The clay mineralogy of the Kuparuk River is dominately illite, whereas smectite characterizes the Colville River clays. In Simpson Lagoon, smectite is present in high concentrations near the Colville River and absent near the eastern end of the lagoon. These observations substantiate westward transport of fine-grained particles in Simpson Lagoon.

The climatic cycle is the major factor controlling local sedimentological processes. This relationship is reflected by sediment-size parameters. Generally, poorly sorted, lagoonal sediments are the result of sedimentation under abrupt cyclic seasonal patterns with alternating periods of water quiescence in winter and brief, open-water conditions in summer (Tucker and Burrell, 1977). Positive skewness and mesokurtic to platykurtic kurtosis within the lagoon are also the result of a complex interaction between available sedimentary populations (sand and silt) and seasonally fluctuating energy conditions (Tucker, 1973). The mean of a majority of the Simpson Lagoon sediment lies in the silt-size range. Tucker and Burrell (1977) suggested that this reflects ready availability of material with a dominant silt-size mode (Gubik Formation) or sedimentation under relatively quiet conditions that might be provided in an environment sheltered by barrier islands and covered by ice much of the year.

Analysis of organic-carbon content revealed a negative correlation between sediment type and organic-carbon content on a regional scale. The presence of more organic carbon in coarser sediments adjacent to the mainland is related to larger influx of detrital peat from coastal erosion (Naidu, 1978).

Even though the sedimentological processes are climate controlled in Simpson Lagoon, grain-size data reveal that this arctic lagoon is sedimentologically indistinguishable from similar environments in lower latitudes (Tucker and Burrell, 1977).

Salt marshes

Areas subject to frequent inundation along the Beaufort Sea coast are called salt marshes by area investigators. Salt marshes completely freeze in winter. Once thaw begins, usually in late May or early June, ice in these shallow wetlands melts from top to bottom within a few days (Bergman and others, 1977). During breakup, salt marshes receive silt from melting snow and ice that has accumulated on land (Chapman, 1960).

Bergman and others (1977) distinguished salt marshes from other classes of wetlands by their occurrence in low areas connected to the sea beach, deep reddish-brown halophytic vegetation, and characteristic line of driftwood deposited by storm tides. Bergman and others (1977) proposed two modes of origin for most coastal wetlands: 1) thaw basins breached by outward thawing through the dam between the basin and the sea beach or from inward erosion by sea ice or water, and 2) lagoons and ponds that result from the formation of sand or gravel spits or barriers by currents.

Artificial islands

Offshore drilling in the Arctic requires drilling platforms able to withstand an obstacle not encountered in most other major oilfields---drifting sea ice. The potential hazards of ice in arctic seas involve more than the freeze-up of the waters surrounding a drilling operation. Artificial islands that serve as drilling pads have been constructed to safely drill in this environment where pack ice may move tens of kilometers a day and ice ridges 15 m (50 ft) high may form.

The first artificial island was constructed in 1972 in the MacKenzie Delta area off the Canadian coast. By 1980, 17 successful artificial islands had been built for exploration off the Canadian coast, and several were also present in the Prudhoe Bay area. The average cost of an exploration well in Prudhoe Bay averages about $20 million (Exxon Company, USA, 1979).

Artificial islands are constructed of gravel, emplaced either by truck in the winter or by dredging in the summer. The fill required for construction of artificial gravel islands ranges from about 0.76×10^6 to 1.3×10^6 m^3 (0.36×10^6 to 1.7×10^6 yd^3), depending on whether the island is constructed by trucking or dredging of fill and whether the structure is an exploration or production island (Exxon Company, USA, 1979).

Artificial-island designs incorporate features to protect drilling operations from foreseeable environmental hazards. The maximum 100-yr storm surge, maximum wave height, and ice loads are some parameters considered in island design. Generally the islands consist of a sloped, gravel-fill approach 3 to 6 m (10 to 15 ft) high with a 1.5-m (5 ft) berm surrounding the working surface. Sandbags, riprap, and filter cloth are used to stabilize the slope and berm. Ice sheets that approach the islands are broken up as they ride up the slope. The berm is designed to trigger ice pileups when advancing sheets are not broken on the approach slope. Slotting of the ice around the island with a trenching machine facilitates breakup of advancing ice sheets. In addition, monitoring techniques provide data on changing conditions that may affect the continuation of safe drilling operations on the island (Exxon Company, USA, 1979).

Morack and Rogers (1981) conducted seismic investigations on Exxon's 'Duck Island' and Sohio's 'Niakuk No. 3' as part of a study of shallow permafrost beneath islands in the Beaufort Sea. The data indicated loosely compacted material. Because the artificial islands lack a tundra cover, permafrost and ice development should be indicative of the processes acting on constructional islands that also lack a tundra cover in the Beaufort Sea.

Temporal changes in natural and artificial islands

Tundra-covered and nontundra-covered natural islands occur in the Prudhoe Bay area. Islands with a tundra cover resemble the coastal plain and consist of peat and silt to thicknesses of over 1 m (3.3 ft) overlying Pleistocene, ice-bonded sand and gravel. Pingok, Bodfish, and Cottle Islands are examples of tundra-covered islands. Islands without a tundra cover are referred to as gravel or constructional islands and consist of gravel and sand that are generally not ice bonded. Reindeer and Cross Islands are examples of constructional islands.

Islands off the Arctic Coastal Plain are coastal-plain remnants. Thermal and wave erosion of the coastline and subsequent inundation of inland lakes or topographic lows by the sea resulted in the creation of islands. At least some of the constructional islands are lag deposits, which are the culmination of erosional processes on tundra-covered islands.

Constructional barrier islands of the Alaskan arctic coast are migrating westward, in the direction of net sediment movement, causing short-term changes in island geometry, especially length. Migration rates that range from 19 to 30 m per yr (62 to 98 ft per yr) west and 3 to 7 m per yr (10 to 23 ft per yr) landward have been established for various islands (Hopkins and Hartz, 1978a). Reimnitz and others (1977) reported a loss of 6 to 7 m per yr (20 to 23 ft per yr) on the seaward side of Cross Island over a 25-yr period. Stump Island has changed shape over a 20-yr interval from lunate to almost linear (Barnes and others, 1977).

Long-term comparisons indicate the islands are migrating with little loss of area and mass (Hopkins and Hartz, 1978a). During storm surges, sand and gravel are removed from the nearshore zone onto the island, and drifting ice rakes coarse particles from deep water onto the island (Hopkins and Hartz, 1978a; Reimnitz and Maurer, 1979). This activity, when coupled with a rapidly retreating tundra coastline, will cause the islands to eventually disappear. Introduction of coarse-grained clastics to preserve the islands is unlikely over a geologically short period of time. Because coarse clastics are not presently supplied by major river systems, this material is nonrenewable (Cannon and Rawlinson, 1979). Dinkum Sands, northeast of Prudhoe Bay, is an example of a barrier island that eventually lost mass and is now nearly submerged (Hopkins and Hartz, 1978a).

Barnes and Reiss (1982) studied the erosion and migration of Niakuk III, an artificial sand and gravel island north of Prudhoe Bay. Over three open-water seasons, the northeast quadrant of the island eroded more than 80 m (262 ft), and spits of the eroded material developed to the west and south. The unnaturally steep slopes of the artificial island and lack of a well-developed permafrost core increased sediment erosion rates (Barnes and Reiss, 1982).

Beach morphology and processes on offshore islands

Arctic beach morphology is controlled primarily by processes that operate during the 2- to 4-mo open-water period, when wave action is relatively free of the influence of ice. Winds are largely from the east in the summer, which results in generally westward waves and currents. Wave intensity and beach response can be directly related to position of the pack ice (Short, 1973). When the pack ice is near shore, low wave energies dominate, and beach response is contained in the low, narrow surf zone. Higher wave energies caused by increased fetch reduce beach deposition, and upper beach erosion is soon followed by erosion across most of the beach (Short, 1973). Beach width is controlled by shoreline rhythms generated by offshore bars (Short, 1973), which results in relatively steep and narrow beach faces in the bays and gentle and wider beach faces on the horns. Gently sloping beaches characterize the lagoon side of the offshore islands (Cannon and Rawlinson, 1979). Spit development is common on the barrier islands, and multiple recurved spits toward the western ends of the islands reflect the pulsating nature of sediment transport westward along the coast (Short, 1979).

Unique arctic-beach features are produced when open-water processes are coupled with a freezing environment. During high-wave conditions, ice boulders may be stranded on beaches and form kettle holes that range from a few centimeters to 10 m (33 ft) in diameter and up to 1.5 m (5 ft) deep (Short and Wiseman, 1974). Occasionally, loose pack ice may gouge, transport, and deposit beach sediment in irregular mounds or ridges called 'ice-push ridges' (Hume and Schalk, 1964) (fig. 101).

Engineering

Waterflood Project

Sohio Alaska Petroleum Company and ARCO Alaska, Inc., operators of the Prudhoe Bay oil field, are jointly constructing facilities to flood the Prudhoe Bay oil reservoir with water (U.S. Army Corps of Engineers, Alaska District, 1980). Project design began in 1979, and start-up is expected in 1985, providing permits are issued on schedule (fig. 102). The estimated project cost was $2 billion in 1980, and estimates of operation and maintenance costs are $60 to $70 million per yr.

Water flooding is a secondary recovery method that will allow production of 1 billion bbl of the estimated recoverable reserves of 9.6 billion bbl of oil (ARCO Alaska, Inc., 1982). While this method retains pressure on oil in the reservoir and increases the amount of oil removed from pore space, it also reduces surface subsidence by replacing oil with water. Alternatives to water flooding that were considered but abandoned by the oil-field operators are

Figure 101. Ice gouges on the seaward side of a gravel island near Prudhoe Bay. Photograph by S.E. Rawlinson, 1982.

injection of steam, chemicals, or carbon-dioxide gas and in-situ combustion of the oil. All but the latter alternative are compatible with water flooding and may be used as tertiary recovery methods early in the 21st century.

About 367 million l of water per d (97 million gal per d) are required for water flooding of the Prudhoe Bay oil reservoir, and the most practical source of water is the Beaufort Sea. A seawater intake at the end of a 1,128-m (3,700 ft) extension of the existing ARCO causeway will provide an ice-free water supply in 3.7 m (12 ft) of water, be relatively easy to operate and maintain, and have the least environmental impact of several alternatives. The causeway and extension include features to minimize adverse environmental effects. All power lines will be buried to avoid possible injury to birds, and a breach in the causeway and a flow-through fish bypass at the end of the causeway will maintain fish migration along the coast.

Seawater will be filtered, deoxygenated, and chemically treated to eliminate bacteria and algae before being pumped along the causeway at low pressure to two injection centers. From the injection centers, water will be piped at high pressure to existing and new gravel pads and injected into the ground through water wells (fig. 103). The causeway extension, enlargement of existing pads, and new pads will require about 2.5 million m^3 (3.3 million yd^3) of gravel between 1981 and 1983 (table 9).

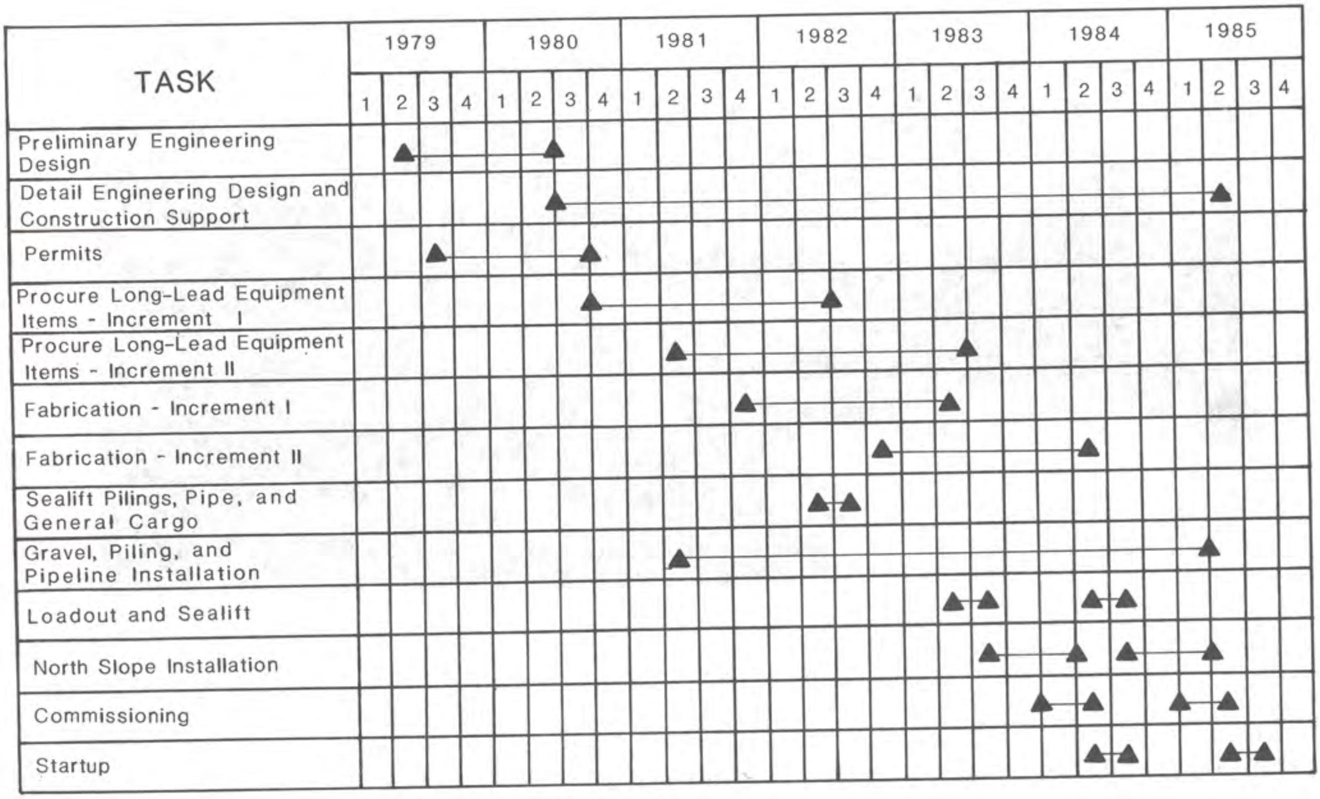


Figure 102. Construction schedule for the Prudhoe Bay Waterflood Project. From U.S. Army Corps of Engineers, Alaska District, 1980.

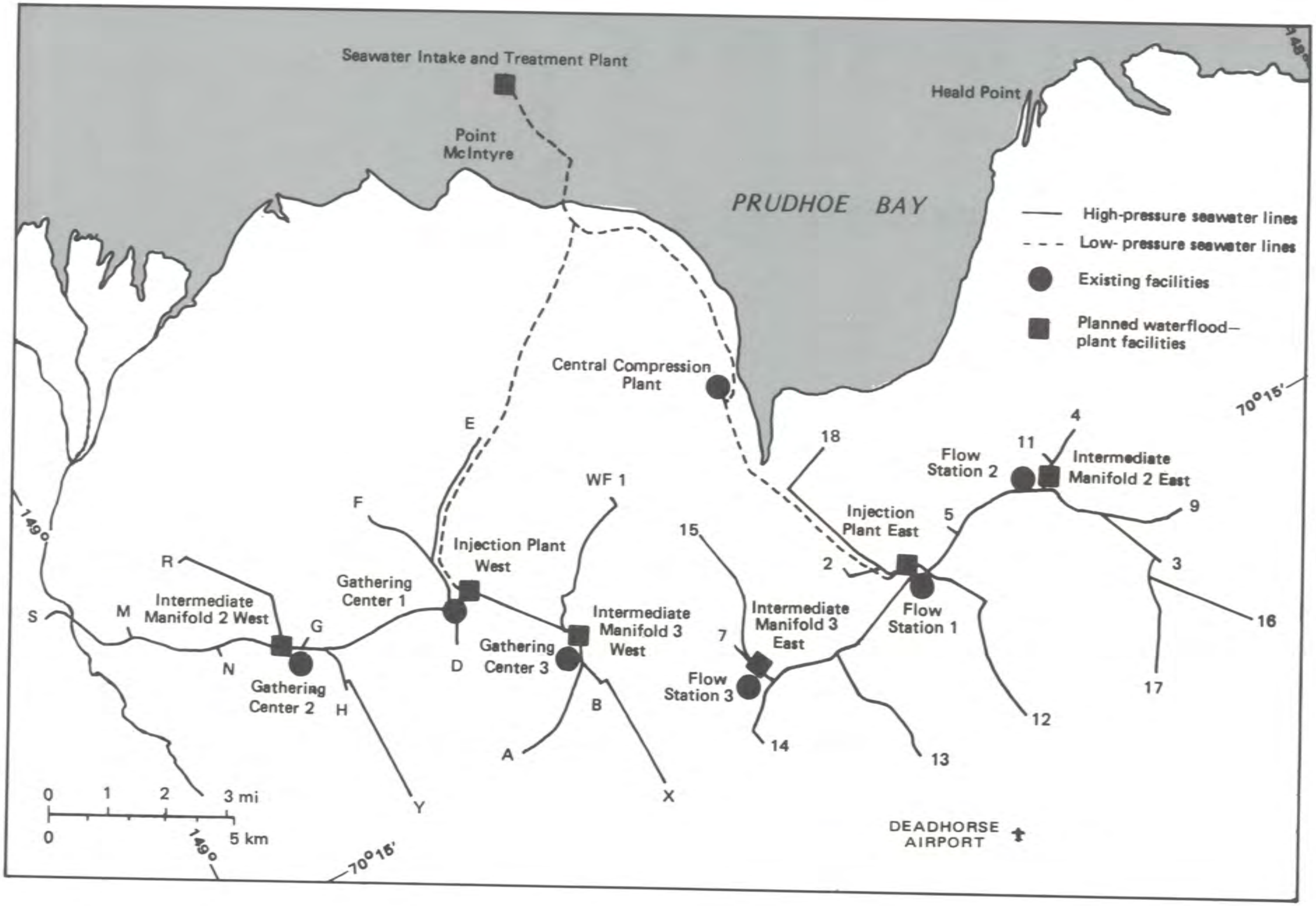


Figure 103. Map showing the Waterflood Project network and existing Prudhoe Bay facilities (U.S. Army Corps of Engineers, Alaska District, 1980). Numbers (ARCO) and letters (SOHIO) are existing drill pads.

Table 9. Estimated gravel-requirement summary, Prudhoe Bay unit, Waterflood Project[a] (U.S. Army Corps of Engineeers, Alaska district, 1980).

Yr	Facility	Gravel ($m^3 \times 10^3$)	Gravel ($yd^3 \times 10^3$)
1981	Road-staging area to Injection Plant West	99	130
	Seawater Treatment Plant	191	250
	Causeway extension	459	600
	DH3 and causeway modifications	115	150
	Total 1981	864	1130
1982	Causeway extension	229	300
	Causeway modification	191	250
	Pipeline construction pad	84	110
	Injection plants	92	120
	Intermediate manifolds	31	40
	Well-pad extension and emergency pits	535	700
	Total 1982	1162	1520
1983	Seawater treatment plant	229	300
	Well-pad expansion and emergency pits	268	350
	Total 1983	497	650
	Waterflood total 1980-1983	2523	3300

[a]Initial actions only; does not include maintenance which could add another 50,000 to 100,000 m^3/yr (65,400 to 130,800 yd^3/yr).

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