State of Alaska
Department of Natural Resources

SPECIAL REPORT 16

SURFICIAL GEOLOGY AND PROCESSES, PRUDHOE BAY OIL FIELD, ALASKA, WITH HYDROLOGIC IMPLICATIONS

by
Randall G. Updike and Mark D. Howland

Published by
Division of Geological and Geophysical Surveys
Anchorage, Alaska
1979

SURFICIAL GEOLOGY AND PROCESSES PRUDHOE BAY OIL FIELD, ALASKA, WITH HYDROLOGIC IMPLICATIONS

By
Randall G. Updike and Mark D. Howland

SPECIAL REPORT 16

STATE OF ALASKA
Jay S. Hammond, Governor
DEPARTMENT OF NATURAL RESOURCES
Robert E. LeResche, Commissioner
DIVISION OF GEOLOGIC and GEOPHYSICAL SURVEYS
Ross G. Schaff, State Geologist

Published by
DIVISION OF GEOLOGICAL and GEOPHYSICAL SURVEYS
Anchorage, Alaska
1979

CONTENTS

ILLUSTRATIONS

NOTE: In this report most data are presented exclusively in the metric system. For the convenience of the reader, a conversion table to the English system is provided below.

MULTIPLY	BY	TO OBTAIN
centimeters (cm)	0.3937	inches
meters (m)	3.281	feet
meters (m)	1.094	yards
kilometers (km)	0.6214	miles
square centimeters (cm^2)	0.1550	square inches
square kilometers (km^2)	0.3861	square miles
cubic centimeters (cm^3)	0.0610	cubic inches
cubic meters (m^3)	1.308	cubic yards
liters (l)	0.2641	USA gallons
grams (gm)	0.0353	ounces
kilograms (kg)	2.205	pounds
meters per kilometer (m/km)	5.28	feet per mile

Cover Photograph: Aerial view of Arctic Coastal Plain near Prudhoe Bay. Several drained and partially drained lake basins are visible. Tractor trails are visible at lower center and upper right. Photograph by R. G. Updike, 16 August 1977.

SURFICIAL GEOLOGY AND PROCESSES PRUDHOE BAY OIL FIELD, ALASKA, WITH HYDROLOGIC IMPLICATIONS

By

Randall G. Updike and Mark D. Howland

PURPOSE OF THE REPORT

The Prudhoe Bay Oil Field is a unique experimental model of industrialization and dense habitation in one of the most difficult environments of North America. The intent of this report is to (a) present information on the surficial geology of the field that may be used as base-line information for future development, (b) locate areas of potential aggregate resources for facility and roadway construction, and (c) evaluate potential water resources that have become critical due to increased demand.

ACKNOWLEDGMENTS

The authors wish to thank the following individuals and organizations for providing information and data for this report: Sy Price, Alaska State Pipeline Coordinators Office; Don Keyes, U. S. Bureau of Land Management Alaskan Pipeline Office; Charles Sloan and Gordon Nelson, U. S. Geological Survey (USGS); Brent Petrie, Alaska Department of Natural Resources; Jerry Arnold and Pat Metz, Atlantic Richfield Oil Company (ARCO); Tom Matthews, Exxon Corporation; Harry Haywood, British Petroleum (BP); Tom Lewis, Gulf Oil Company; Garth Olson, Air Photo Tech; Meg Hayes, Alaska Division of Lands; Jim Kross and Dennis Ward, Environmental Services, Ltd.

Particular appreciation is expressed to Church Campbell, Prudhoe Field Manager, ARCO, and Slim Gilchrist, Prudhoe Field Manager, BP, who greatly assisted in field access and logistics. Base maps and aerial photography were provided by Air Photo Tech, Anchorage, by permission of BP. The personnel of the Alaska State Division of Geological and Geophysical Surveys (DGGS) provided helpful comments and criticisms throughout the project, and particularly Richard Reger provided extensive background information and his own expertise in permafrost geology.

PHYSICAL SETTING

In the ten years that have passed since the success of Atlantic Richfield's discovery well, over 150 additional wells have been drilled in the Prudhoe Bay Oil Field. The majority of these wells are located on the Arctic Coastal Plain, within 15 to 20 km of the Beaufort Sea. This field of approximately 700 square km is bounded on the west by the Kuparuk River and on the east by the Sagavanirktok River. The area now supports an extensive network of exploration, production, and supportive service facilities.

The severe climate is a dominant factor of the ecosystem in which the Prudhoe field is located. This is, of course, due to its far northern location: 147° 48' to 149° 5' west longitude, 70° 10' to 70° 25' north latitude. Although continuous climatological data are lacking for Prudhoe Bay, conditions are similar to Barrow where data are recorded: mean annual maximum daily temperature = -9° C (16° F.), mean annual minimum daily temperature = -15.5° C (4° F.), 320 days per year with temperatures below 0° C, 10 cm (4.1 inches) of precipitation per year, 65 cm (27 inches) of snowfall per year (U. S. Department of Commerce, 1961).

VEGETATION

A brief description of the plant communities occurring in this part of the Arctic Coastal Plain is included because (a) variations of vegetation are often visible on aerial photographs and are valuable indicators of slope, drainage, and permafrost conditions, (b) the vegetation mat is important to the maintenance of the underlying permafrost, and (c) vegetation often aids surface stabilization.

Five major plant communities are recognized in the Prudhoe Bay area: (1) freshwater vegetation, (2) aquatic waterways and beaches (including gravel bars, embankments, and deltas), (3) wet sedge meadows, (4) tussock-dwarf heath tundra, and (5) dwarf shrub-heath tundra (Churchill, 1955; Britten, 1957; Drew and others, 1958; Spetzman, 1959; Wiggins and Thomas, 1962; and Hussey and Anderson, 1963).

The freshwater aquatic vegetation inhabits both lakes and thermokarst streams. In lakes, the vegetation often forms concentric zones parallel to the shoreline, reflecting water depths in the lake. Most plants inhabit water less than 1.3 m deep and three depth-sensitive zones can be recognized: (a) the submerged, rooted aquatic plants, chiefly pondweed (Potamogeton), (b) rooted emergents occurring in water 0.3 to 1.0 m, including pondgrass (Arctophila), horsetail (Equisetum), mares tail (Hippuris), and cinquefoil (Potentilla), and (c) transitionally emerged plants occurring in water less than 0.2 to 0.3 m deep, including sedge (Carex aquatilis), cottongrass (Eriophorum angustiofolum), and mountain foxtail (Alopecurus alpinus). Also seeking wet environments is the aquatic waterways community, found along large streams, rivers, and in protected areas along the coast. Several species of dwarf willow (Salix), vetches (Astragulus), saxifrages (Saxifraga), and louseworts (Pedicularis) are found, with Saxifraga becoming dominant over Salix in more saline coastal waters.

The wet sedge meadows are broad, flat areas which are poorly drained. The low-center ice-wedge polygons which enclose marshes are the most typical environment. Sedge (Carex), cottongrass (Eriophorum), sphagnum moss (Sphagnum), and arctic grass (Dupontia) are most common.

Grasses dominate in the tussock-dwarf heath community which is on poorly to moderately drained soils typically covered by standing surface water during spring melt. Chief among these are several species of Eriophorum, as well as Dryas integrifolia (mountain vens), Betula nana (dwarf birch), and Arctagrostis latifolia (polar grass).

The dwarf shrub-heath tundra is drier (moderate to well-drained) due to being elevated along polygon ridges, on pingos, stream banks, or on well-drained gravel substrates such as wind-scoured river terraces. Numerous species are found in this association including Poa arctica (arctic bluegrass), Salix reticulata, Dryas integrifolia, Eriphorum, Carex, Actagrostis, as well as numerous lichens, mosses, and miniature composites.

TECHNIQUES OF INVESTIGATION

Prior to initiation of mapping and field evaluation, the authors reviewed an extensive published literature pertaining to Prudhoe Bay and other areas of the Arctic Coastal Plain. In addition, unpublished data and reports were provided by the oil producers, and by state and federal agencies. In conjunction with the literature review, communication was established and maintained with agencies and companies having interests in the Prudhoe Bay Field. All petroleum companies with leases in the Prudhoe Bay area were contacted. BP-Sohio and ARCO are the primary operators in the field and provided perspectives on present operations, problems they have encountered, and projected expansion needs they foresee.

The surficial geologic mapping utilized aerial photography, topographic base maps, and field study. Aerial photographs at three scales were used: black-and-white 1:24,000 photography (Air Photo Tech, 1973), U-2 high-altitude multispectral near-IR imagery (1974), and ERTS satellite imagery (Bands 5 and 7, 14 June 1973 and 2 July 1973). The high-altitude U-2 and ERTS photography were primarily used in evaluating lake conditions during June and July. Sellman, Brown, and others (1975) demonstrated that ERTS imagery can be used to establish relative depths of lakes on the Arctic Coastal Plain. This technique was effectively utilized in this project. The U-2 photography also provided details of lake and stream conditions during summer break-up and supplemented the low-level black-and-white photography.

The surficial geology was initially mapped at a scale of 1:6,000 on 34 manuscript topographic maps made by Air Photo Tech, in 1973, for BP-ARCO, and kindly released for DGGS use by BP. Final geologic maps were reduced to a scale of 1:12,000 (pls. 2-12). Several USGS topographic maps were also used: Beechey Point A-1, A-3, A-4, B-2, B-3, and B-4 (1:63,360 series) and Beechey Point A-2NW, A-3NE, A-3NW, A-4NE, B-2SW, B-3SE, B-3SW, B-3NW, B-4SE, and B-4NE (1:24,000 Orthophoto series). Field work was facilitated by the network of gravel roads traversing the field. Remote areas were reached by foot or helicopter. ARCO and BP allowed free access to all areas of the field.

GEOLOGIC SETTING

The study area lies entirely within the Arctic Coastal Plain physiographic province. Although Tertiary sedimentary rocks are exposed along the Sagavanirktok River to the south, no bedrock crops out in the study area. The Gubik Formation of Pleistocene age (Black, 1964) completely blankets Tertiary and Cretaceous bedrock, often to thicknesses greater than 500 m. The formation consists of coastal marine sands and gravels interbedded with fluvial channel and deltaic sediments. Much of the Gubik Formation is overlain by silt deposits less than 5 m thick, and variously interpreted as loess, marine silt, or lacustrine silt (Dave Hopkins and Oscar Ferrians, Jr., 1978, personal communications). The Quaternary history of the Arctic Coastal Plain is discussed by O'Sullivan (1961), Black (1964), Hopkins (1967), and Sellman, Brown, and others (1975).

The single most important factor governing the geomorphic processes which affect the Quaternary sediments is the severe temperature regime of the arctic environment. This results in continuous permafrost conditions to depths greater than 650 m (Stoneley, 1970). This permanently frozen condition has been maintained since the Pleistocene Epoch (Péwé, 1975). Usually, only the upper 1 to 3 m of ground is thawed, either seasonally (active layer) or adjacent to bodies of surface water. Ice within the permafrost may take several forms, most commonly as ice coatings surrounding sediment clasts and as pore ice filling the voids between clasts. Massive ice lenses, which may be several centimeters thick, are typically (but not exclusively) found in finer sediments (e.g., organic silts) and along minor unconformities. All of these varieties of ground ice are found in both the permafrost and seasonally frozen ground. Intense chilling of near-surface permafrost often causes contraction and cracking of the ice-bonded sediment in polygonal patterns. These open fractures subsequently are filled with foliated ice to form ice-wedge polygons (Lachenbruch, 1962). Processes such as strong, unidirectional east-northeast winds, stream erosion and deposition, lacustrine and coastal erosion and deposition, and mass movement alter the surface of the perennially frozen sediments and will be discussed below.

MAP UNIT PARAMETERS

Four parameters considered in establishing and mapping the surficial geologic units are: type of landform, relative age, composition, and transient conditions. During the mapping process, landforms (e.g. eolian dunes, river terraces, lake basins) were first recognized and relative ages were determined where possible (e.g., stabilized dunes older than active dunes). Relative age determinations were based upon the preservation of the primary landform, thickness of silt overburden, type and amount of vegetation, cross-cutting or superimposed relationships, and development of ice-wedge polygons. Composition, including sediment size range, variation with depth, and ice conditions (foliated ice wedge polygons, pore ice, ice lenses), was determined by field examination, communication with field operators, and on-file subsurface data. Transient conditions include responses of the mapped unit to seasonal fluctuations of surface conditions such as spring flooding of rivers, thawing of the active layer, deflation, tundra-polygon flooding, surface drainage characteristics, and thermokarst erosion. Transient conditions are most significant in environmental and engineering considerations. The parameters of physiography (process and landform) and relative ages are discussed in the text below. Composition and transient conditions are present in table form (pls. 15-16). Representative size-distribution histograms for the sediment types are given on plate 17.

DESCRIPTION OF SURFICIAL GEOLOGIC UNITS

Upland tundra deposits (ut)

As previously noted the entire mapped area is underlain by at least 500 m of unconsolidated stratified silt, sand, and gravel, and generally is covered by 1 to 3 m of silt. Except for the upper 1 to 2 meters, this sediment is perennially frozen and bonded by interstitial ice. Where the upper surface of this sequence has not been disturbed by erosion, surface flooding, or rapid burial, an equilibrium is established with annual atmospheric temperatures. These areas are herein referred to as upland tundra deposits.

The upland tundra unit (ut) is distinguished as being the oldest map unit. All other units either overlie it, or cut across it, and there is no indication of fluvial or lacustrine modification (fig. 1). The unit is related to the original Quaternary marine coastal plain sedimentation, forming an unbounded upland surface with an average slope of about 2 to 4 m/km toward the north or northeast.

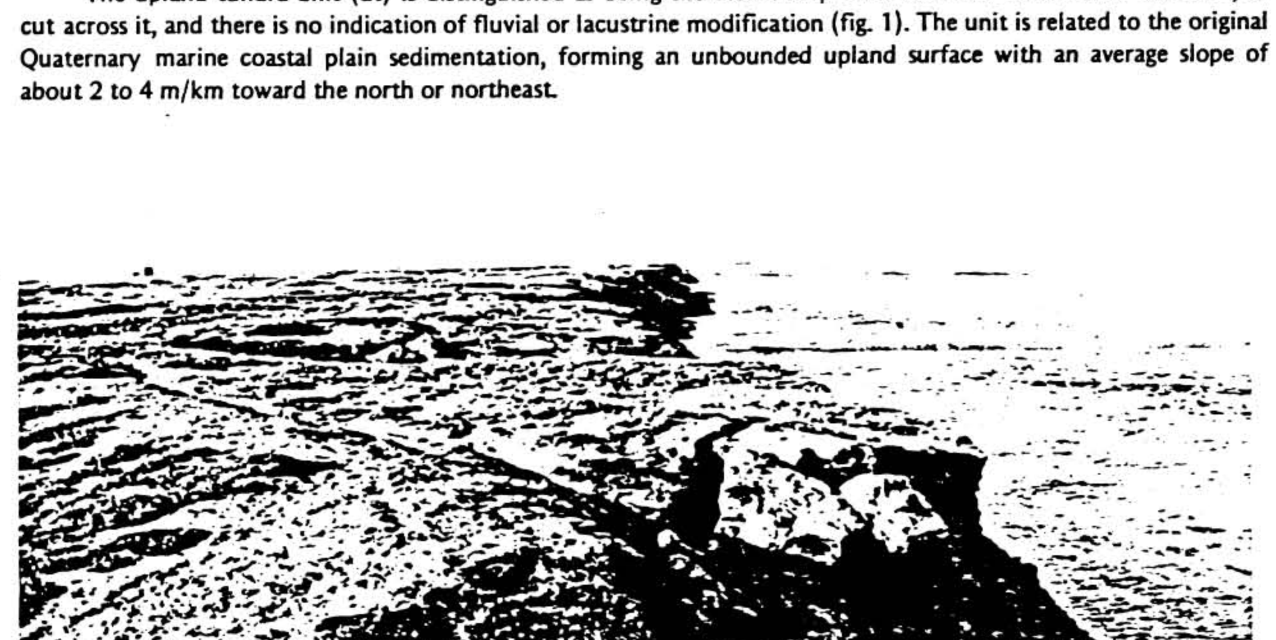


Figure 1. Downstream view along the west bank of the Sagavanirktok River, about 150 m northeast of the Webster Lake Reservoir, showing active thermokarst erosion along ice-wedge polygons (plage 6). Scarp separating the upland tundra surface (ut) from the active floodplain (af) is approximately 7 m high. Photograph by R. Updike, 21 July 1977.

During summer months the upper 1 to 2 m of the upland tundra deposits thaw. It is within this active layer that the arctic tundra plant community thrives, establishing a thick, continuous organic mat. The silt blanket and organic mat act together as a heat-flow regulator, inhibiting heat flow to the underlying permafrost in summer when thawed, and conducting heat from the ground in winter. Thus, although perennially frozen, the temperature of the upper permafrost zone fluctuates seasonally. During winter the extreme heat loss from the upper permafrost causesit to contract, resulting in polygonal cracking of the ground from below the permafrost table to the surface. Summer meltwater and water vapour can enter these cracks and freeze. Over a period of several years large masses of foliated ground ice accumulate to form ice wedge polygons. As long as the negative thermal regime is maintained the ice wedge polygons continue to form and are preserved. During summer the frozen sediment expands as it warms but, due to the added increment of ground ice, the expanding sediment is forced to rise vertically adjacent to the ice wedges, resulting in double raised ridges which outline the ice-wedge polygons. In several localities (e.g., west of BP Operations Center) these low-center polygons are currently subdividing into smaller polygons. Thus, the presence of well-developed active ice-wedge polygons throughout the upland tundra unit suggests a dynamic equilibrium between the permafrost and both summer and winter atmospheric conditions. The degree of development of polygons appear to be time related, becoming more pronounced in micro-relief and more extensively subdivided with increasing time. The low centers bounded by uplifted tundra ridges can often trap water produced either by melting snow or release of active layer water. This ponding is important because continuous flooding of polygons in summer inhibits the tundra vegetation, accelerates summer heat flow, and eventually may initiate the thaw lake cycle.

Fluvial deposits

Two types of streams traverse the mapped area: those with waters originating from the south, outside the mapped area, and local streams derived from surface runoff and dewatering of the active layer. Three streams fall into the first category: Sagavanirktok River, Putuligayuk River, and Kuparuk River. The second category comprises numerous, unnamed streams, controlled in part by local thaw of the underlying permafrost, and which are herein referred to as thermokarst streams. Deposits associated with these two stream types are quite different and are discussed separately.

ACTIVE FLOODPLAIN SANDS AND GRAVELS (af)

Within the present-day floodplains of the Sagavanirktok, Kuparuk, and Putuligayuk Rivers are areas which are at least periodically flooded and may be submerged throughout much of the year. These areas consist predominantly of sand and gravel with minor amounts of silt (fig. 2). The deposits are in constant flux during spring and summer, being redistributed through a complex system of braided channels. Large-scale transportation and channel shifting occur during late spring to early summer floods, but channels remain stationary throughout the reduced flow regime of summer. The sands and gravels are primarily in-transport bedload from source areas to the south (Arctic Foothills-Brooks Range). Some gravel is yielded from thaw and mobilization of older local units but due to the low rates of lateral planation and downcutting this source in minimal. All three rivers have low-energy regimes except during early summer flooding so that gravel "recharge" in the lower reaches of each river is undoubtedly slow and episodic.

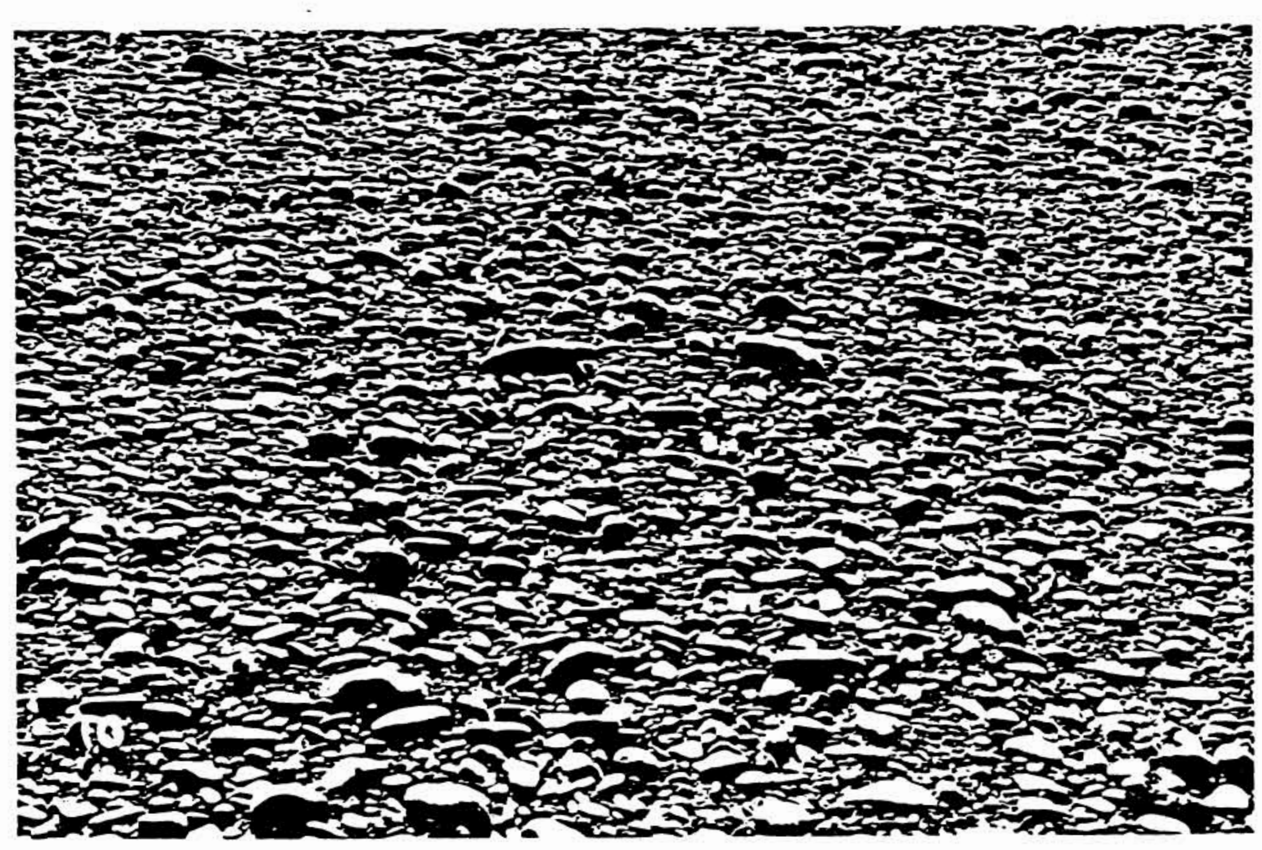


Figure 2. Oblique view of the surface of sandy gravel bar associated with the active floodplain (af), Kuparuk River. Pocket watch for scale is at lower left. Upstream is at the top of the picture. Note the long-axis orientation of cobbles normal to stream flow direction. Photograph by R. Updike, 22 July 1977.

INACTIVE FLOODPLAIN SANDS AND GRAVELS (if)

Both the Sagavanirktok and Kuparuk Rivers have broad floodplains with braided drainage. Parts of the floodplains have been abandoned for perhaps several years even though they are at or near the elevation of active channels. In general, characteristics are identical to sands and gravels of the active floodplain with the exceptions that a thin (less than 1 m thick) silt cover and open grass vegetation are typically present.

The Putuligayuk River has a meandering channel morphology with abandoned meander loops and meander scars at or near present channel elevation and gradient. These channel deposits have compositional characteristics similar to inactive floodplain deposits of the Sagavanirktok and Kuparuk Rivers.

LOWER FLUVIAL TERRACE DEPOSITS, ICE-WEDGE POLYGONS (ltp)

Both the Sagavanirktok and Kuparuk Rivers have a low fluvial terrace which is 2 to 3 m above the active floodplain. Remnants of these terraces project above the present deltas. The terrace is bounded below by well-defined scarps descending to the present floodplain and above by scarps 2 to 5 m high, ascending to older units. Gradients and direction trend are similar to the present floodplains, 1.0 to 2.5 m/km toward the northeast. The undisturbed parts of the low terrace have well-developed, low-center ice-wedge polygons. Sediment beneath the silt-tundra overburden is identical to that of the active floodplain.

LOWER FLUVIAL TERRACE DEPOSITS, PARTIALLY SCOURED (lts)

Parts of the lower terraces associated with the Sagavanirktok and Kuparuk Rivers lack visible ice-wedge polygon development. The Putuligayuk River also has a low fluvial terrace upon which ice-wedge polygons are poorly defined or absent. In all three instances the silt cover, although continuous, is thin (1.0 to 1.5 m thick). Old braided channel or meander scars are still visible on the terrace surface, often made noticeable by subtle changes in vegetation and surface moisture. In some instances these old channels remain as sloughs or meander scar ponds, and in the lower reaches of the Sagavanirktok drainage system, some deep lakes occupy old braided drainage channels (pl. 13).

The three prime differences between the two low terrace map units are (a) thickness of silt cover, (b) development of ice-wedge polygons, and (c) preservation of channel scour marks. Although the partially-scoured terraces are typically slightly lower in relief than the polygonal low terrace, the two units often grade into each other with little break in slope. It appears that occasionally parts of the low terrace are flooded, possibly by aufeis sheets (icings) which thaw in summer. This rare flooding removes part of the silt cover and, due to the presence of surface meltwater, adds unusual heat to the permafrost. Both effects impede ice-wedge formation and induce ground ice melting. Aufeis build-up permits the rise of water above the floodplain and promotes erosion in the flooded area. Sands and gravels of a recent flood were found deposited on the edge of the low terrace surface along the lower Kuparuk River, indicating that spring flood waters reach the elevation of the lower terrace tread.

UPPER FLUVIAL TERRACE DEPOSITS (ot)

Along the Sagavanirktok River a second, higher fluvial terrace is present. In the southern part of the mapped area the extent and slope of the terrace approximately parallel the existing floodplain (pl. 12); however, downstream the terrace diverges toward the northeast. The point of inflection occurs directly east of Lake Colleen. The earlier drainage which deposited the sediment of this high terrace reached the ocean midway between the present east and west channels of the Sagavanirktok River. This situation suggests that the Sagavanirktok River has not only eroded its channel deeper during Holocene times but, in its lower 10 km, has shifted westward. The antiquity of this older terrace is indicated by (a) extensive dissection of the feature by the river at the levels of both the present floodplain and the lower terrace, (b) the presence of stabilized sand-silt dunes on the terrace tread, (c) post-terrace drained lake basins on the terrace tread, and (d) development of pingos, massive ice-wedge polygons, and thermokarst lakes on the terrace (pls. 6 and 12).

THERMOKARST STREAM CHANNEL DEPOSITS (ts)

In areas where ice-wedge polygons are in an advanced stage of development a trough occurs directly over the ice wedge. During the summer, the upper zone of permafrost expands laterally against the ice wedges. This expansion is translated as upraised ridges adjacent to the ice wedge with an intervening trough. Through thermokarst modification these furrows commonly are deepened, extended, integrated, and eventually form continuous drainage channels draining into a lake, another stream, or the ocean. Thermokarst streams may flood polygons or connect thermokarst lakes. Typically, the channels are composed of short linear segments, changing direction at angles greater than 90°. Channels are generally less than 2 m deep and less than 10 m wide. Thawing of adjacent permafrost causes a subtle depression of the tundra surface near the channel. There is very little sheet wash or rill wash adjacent to the channels because the tundra vegetation is continuous to the channel banks and surface water is conducted by both low-polygon centers and raised-rim furrows. Sediment transport is minimal and much of the channel bank and bottom is vegetated. Some segments of channel have sandy gravel exposed and in transport, but this material is probably locally derived by thawing of the underlying sediment. Sediment transport is thus slow or nonoperative. During winter months these streams and the underlying sediment are entirely frozen. After spring thaw the systems have gradient flow but velocities are quite low, often imperceptible.

THERMOKARST STREAM TERRACE DEPOSITS (tt)

Adjacent to some thermokarst streams with well-defined channels a subdued terrace commonly extends a few tens of meters away from either or both stream banks. Because lateral planation rarely occurs along most channels, these terraces are neither cut nor fill terraces. A distinctive characteristic of these terraces is the general lack of well-defined surface polygons, or the presence of polygonal ghosts outlining the former extent of ice wedges. Due to increased discharge and volume capacity of the stream, increased transfer of heat to the adjacent permafrost causes melting of ground ice and general surface lowering. These areas may be flooded during peak spring flow or when the channel is blocked by ice in the fall or the spring. Partial stripping of surface silts or removal of silt and sand by piping in superpermafrost ground water may also occur but were not observed.

Lacustrine Deposits

Numerous shallow perennial lakes are a prominent feature of the Arctic Coastal Plain, and play an important role in surface dynamics acting on the terrain. The water serves as a long-term heat source, even if the lake is quite shallow, promoting thaw of the underlying permafrost. Depth of thaw is a function of the conductance of heat from the water body into the underlying sediments. The effectiveness of this process is dependent upon the total volume of water which can provide heat, as well as the surface area of the water/sediment interface over which this heat is dispersed. Water depth, surface area, shoreline morphology, and currents play important roles in this heat transference. Ultimately massive ground ice in the upper few meters of the permafrost thaws and the surface polygons are destroyed. Recently drained lakes (e.g., at Pump Station 1, pl. 8) lack surface expression of ice wedges except at former shorelines. Wind-induced lake currents further modify the lake basin by thermal erosion coupled with hydraulic removal and redistribution of sediment. This is most effective on the leeward side of the lake and along the axis of the lake normal to the dominant summer wind. These currents usually transport a mixture of silts, fine sand, and organic matter. Gravel is rarely involved. The aquatic environment (marsh or open lacustrine) is well suited to a wide range of biota which add organic debris to the bottom sediments. Dislodged fragments of the tundra mat ranging from a few centimeters to over a meter in diameter are also rafted or shifted into the lake. The lake acts as a local sediment trap collecting wind-born silt and fine sand, as well as sediment from thermokarst streams.

The origin of these lakes has been extensively discussed in the literature (Carson and Hussey, 1962; Black, 1969; Sellman and others, 1975) and a "lake cycle" is apparent. The cycle begins with a formative phase in which low-center polygons are flooded, gradually coalescing to form a progressively larger lake. Wind-induced currents, thermal erosion, and sediment transport gradually modify the lake to an elliptical or quadrilateral outline. The lake subsequently may be partially or entirely drained and, during this phase, has an irregular shoreline and abandoned strandlines.

DEPOSITS ASSOCIATED WITH LARGE AREA LAKES (ldl), INTERMEDIATE AREA LAKES (ldi) AND SMALL AREA LAKES (lds)

These three map units share the basic criteria of being perennially submerged. The distinction between the units is based on the approximate area of the lake: "large" refers to lakes greater than 0.50 km^2, "intermediate" lakes are 0.15 to 0.50 km^2, and "small" are lakes less than 0.15 km^2. Determination of lake size and depth is important because these parameters usually influence bottom and subsurface conditions as well as indicating the potential of the lake as a winter water resource. Larger lakes may have a lens of liquid water at the bottom throughout the winter whereas smaller lakes freeze to the bottom. The subdivisions used here attempt to distinguish deeper lakes having a zone which remains thawed throughout the winter (or into late winter) from those lakes that freeze to the bottom by middle to late winter and from those lakes which freeze to the bottom in early winter. The extent of winter freezing of the lakes determines whether or not a perennial thaw bulb exists in the sediments below intermediate and many large area lakes, even where the lake freezes to the bottom. Utilizing satellite and high-altitude U-2 imagery, water depths and winter ice conditions were examined for all intermediate and large area lakes in the Prudhoe Bay area. By comparing bands 5 and 7 of ERTS photography it is possible to determine if a lake is ice free, contains a submerged ice cake, or retains a surface ice cover. Lakes less than a meter deep freeze to the bottom in winter but thaw quickly in May to June. Lakes 1 to 2 m deep also freeze to the bottom in winter but the thicker ice mass persists into June, frozen to the lake bottom, and melts downward from the surface. The deepest lakes retain thick, floating ice well into summer (Sellman, Brown and others, 1975). In this manner relative depths of lakes have been determined and, in several cases, documented by actual depth measurement (pls. 13-14).

The thickness of the thaw bulb affects the degree of destruction of massive ground ice. Small shallow lakes retain submerged polygons whereas large lakes have no polygons preserved. Large and some intermediate lakes usually have existed long enough for fine sediment to accumulate and for reworking to be extensive. The large and intermediate lakes usually have silt/sand accumulations as thick as 5 to 8 m. Even though the lacustrine deposits are thawed to a depth of up to 5 m in midwinter, this thaw bulb may still be well above the perennially frozen gravels.

Figure 3. A view of partially drained lacustrine deposits (ldp) as seen from the crest of a pingo. Note the incomplete ice-wedge polygons. Vegetation emphasizes the difference in drainage characteristics from dwarf shrub-heath tundra (pingo slope, foreground) to tussock-dwarf heath (left middle distance) to wet sedge meadows (right middle distance). Location: extreme southeast corner, plate 5, looking southeast. Flow Station 1 (left horizon) and Drill Pad 2 (right horizon). Photograph by R. Updike, 21 July 1977.

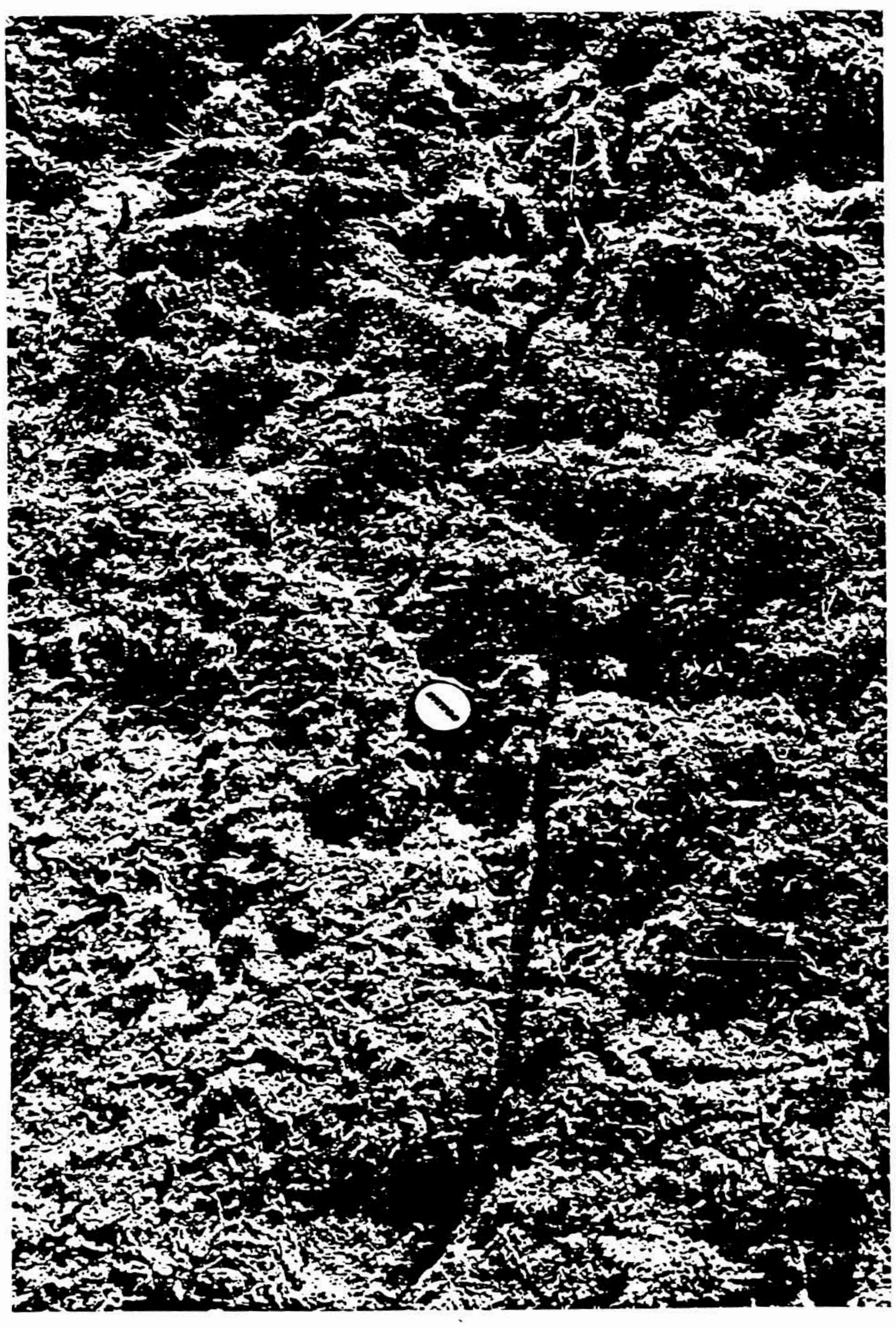


Figure 4. Close-up of the surface of a recently drained lake basin. The surface sediment consists of organic-rich silt. Seasonal frost heave causes the sediment to have a puffy texture. Note the development of incipient ice-wedge cracks. Photograph by R. G. Updike, 10 August 1977.

DEPOSITS ASSOCIATED WITH PARTIALLY DRAINED LAKE BASINS (ldp)

Partially drained lake basins are those which, although perennially flooded, contain areas emergent above the static surface water level. This condition may occur either where several adjacent polygon centers are flooded and ridges are exposed, or where a lake formerly existed in the basin and has subsequently been partially drained. In either case, winter freezing is rapid, complete, and no thaw bulb exists. If pronounced polygonal ridges are present, the underlying sediment will be the same as the upland tundra unit with the exception that the active layer is thicker due to summer and fall surface water (fig. 3). Where polygons are absent or very subdued, the surface deposits have been affected by thaw lake activity, silts several meters thick overlie the gravels, and massive ground ice is absent to very discontinuous in the upper 5 to 10 m.

DEPOSITS ASSOCIATED WITH DRAINED LAKES (ldd)

In some cases, lake basins have been entirely drained of their water, or large segments of those basins have been drained and the remainder of the basin is either partially drained or submerged. With the exception of marshy areas and scattered ponds, the deposits of drained lakes are subaerially exposed to the arctic climate throughout the year. The floors of some recently drained basins are featureless except for thermal contraction cracks (fig. 4). Drained lake basins typically contain only scattered remnants of former ice-wedge polygons. The basin surface may be as much as a meter below the elevation of the surrounding tundra surface. The permafrost table is static or has prograded since the drainage of the basin. The degree to which "new" polygons have developed is a relative indicator of time since the basin was drained.

DEPOSITS ASSOCIATED WITH ABANDONED LACUSTRINE STRANDLINES (lda)

The deposits of former strandlines occur in areas where a lake shoreline has recently receded due to (a) a change in the shape of the lake, causing water volume readjustment, (b) the westward "migration" of the lake due to wind, or (c) a general decrease in size of the lake. Abandoned strandlines are visible as subtle terraces with narrow treads 10 to 20 m wide between scarps. This distinct morphology, often paralleling the present lake shoreline, is apparent from the ground or air. Three separate areas of abandoned strandlines were noted to have active "young" polygons with low rims, open thermal cracks, diameters between 7 and 12 m, and some incomplete polygon development (fig. 5). These polygons occurred on benches with broken tundra along the adjacent strand scarps.

Deposits of marine shorelines (cd)

The beach in and near Prudhoe Bay is a narrow strip of unvegetated sandy gravel with minor silt, ranging from 2 to 10 m in width, and extending virtually uninterrupted between the river deltas. On the landward side of the beach a scarp 1 to 3 m high is cut into the tundra, silt, and occasionaally, into the underlying gravels. Polygonal cells of tundra are tilted toward the beach and nearby upland polygons are high centered due to thawing of the underlying ice-wedges (fig. 6). In winter the sea ice is broken and shoved against and onto the coast, leaving large tundra mats curled back upon themselves. Though tides are very slight along this coast, the driving force of the wind causes breaking waves to continue unceasingly for days or weeks.

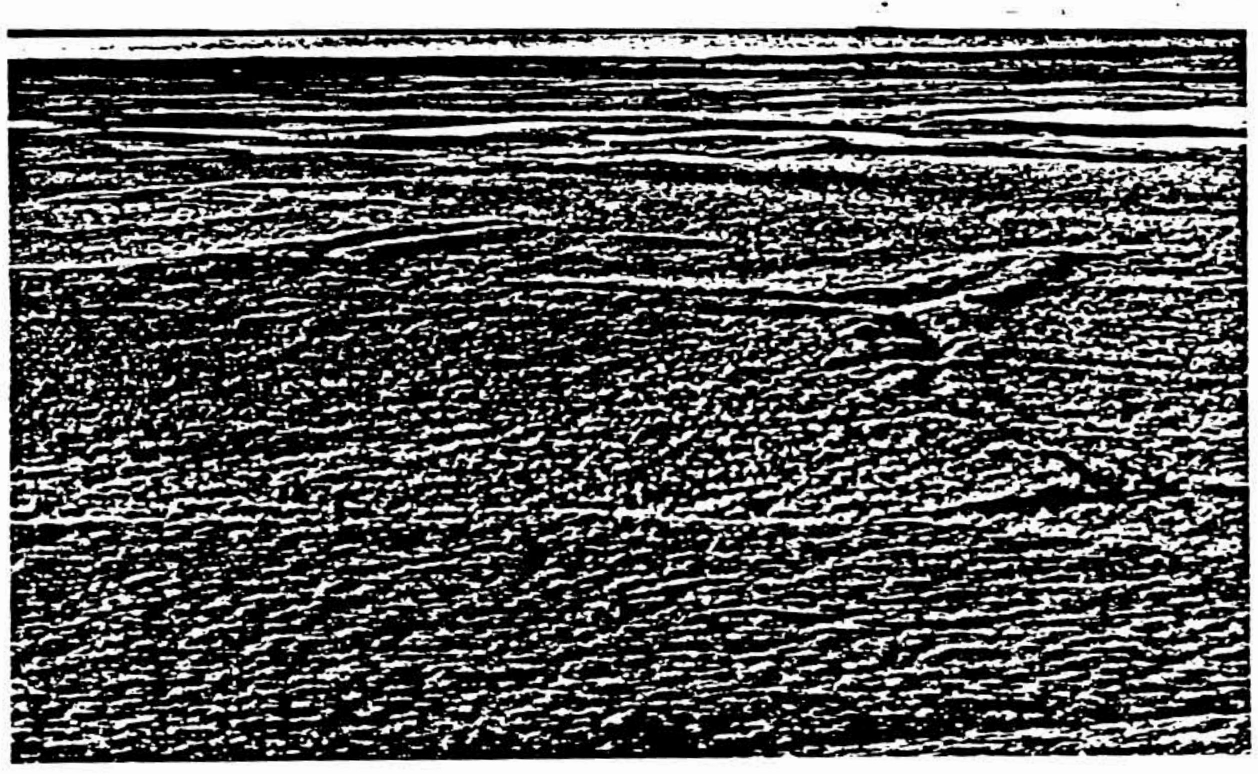


Figure 5. Incomplete ice-wedge polygons associated with abandoned lacustrine strandlines. Note the distinct double raised rim and intervening troughs of ice-wedge traces. Strandline scarps are visible in foreground. Photograph by R. G. Updike, 11 August 1977.

Figure 6. Low-altitude aerial view of coast at Prudhoe Bay, looking west toward the Putuligayuk River. Scarp at the lower left is approximately 6 m in height. Note thermokarst erosion along ice-wedge polygons. Photograph by R. G. Updike, 18 August 1977.

Occasionally, sand and gravel bars and spits develop across small stream outlets and on points indicating east to west longshore currents (pls. 2, 3, 4, 5). The offshore submarine surface has a very gradual slope, quite similar to that of the land. Several offshore islands of sand and gravel (not here mapped) occur between 1.5 and 25 km from the coast.

Sands and silts of river deltas (ad and id)

Within the lower 2 to 3 km of the Kuparuk River and 6 to 7 km of the Sagavanirktok River drainages, the braided rivers grade into deltaic systems. Braided distributary channels continually change position and the entire active delta systems appear to be shifting westward. The distributary drainage pattern is due to the very low gradient of the river (less than 0° 20' slope), loss of inertial velocity due to approaching sea level, water density changes, and coastal current influence. As a result coarse sand and gravel is deposited in the lower braided drainage, prograding to fine sand and silt in the deltas (unit ad).

During times of greater river discharge, high tides (outer delta only), storm surges, and channel shifting, parts of the normally exposed delta are submerged. Sediments in these areas are redistributed to form subsequently subaerial segments of active deltas. Other parts of the delta system, compositionally identical to the active delta, stand in relief up to 1.5 m above the active areas. These high areas (unit id) may represent earlier periods of greater mean discharge, greater silt and sand load in transport, or minor sea level transgressions. Eolian deflation is retransporting the fine surface sediment westward. Thaw bulbs extend beneath most of the delta; therefore, the permafrost table is quite deep and ice-wedge polygons are absent.

Eolian deposits

ACTIVE EOLIAN SILT AND SAND DUNES (aa)

On stable surfaces of deltas, floodplains, river terraces, and adjacent uplands of the Sagavanirktok and Kuparuk Rivers, windblown sand and silt locally accumulate to depths in excess of 10 m. These wind-transported sediments are actively being moved and form eolian dunes. The dunes are seasonally frozen and contain interstitial ice during winter and spring. Summer thaw is followed by dessication at the surface with resultant wind-mobility of surface sediment. Depth to permafrost is unknown although the interiors of large dunes are probably perennially frozen. Active dunes are generally located directly west of the sediment source areas. The most extensive dunes occur in, or downstream from, the floodplain-to-delta transition zone where most of the water-laid sediment is in the sand and silt size range (pls. 2, 4, and 6). Although barchans and parabolic forms occur, longitudinal dunes are most typical (fig. 7). Maximum relief is approximately 5 m, but most dune crests are less than 2 m above adjacent troughs. The crest of some longitudinal dunes exceed 10 m in length.

Figure 7. Active eolian deposits (aa) composed of fine sand and silt, located west of the Sagavanirktok River delta (plate 4). View is looking south; prevailing wind is from left to right. Note the sparse vegetation at left on the crest of the longitudinal dune and the deflation surface at right center. Photograph by R. Updike, 20 July 1977.

INACTIVE EOLIAN SILT AND SAND DUNES (ia)

Several localities near to the Sagavanirktok and Kuparuk Rivers are covered by stabilized dunes that are compositionally identical to active dunes. However, the inactive dunes are typically covered by tundra vegetation except along oversteepened slopes. Permafrost depth and type is unknown and ice-wedge polygons are generally not visible.

Dune form is highly subdued compared to active dunes; however, dimensions and forms are similar. Although locally active, most dunes of this unit are stabilized. The area covered by inactive dunes is more extensive than that of the active dunes. Inactive dunes occur on both the upper and lower river terraces east of the present active delta and floodplain, perhaps implying that the deltas were formerly more extensive to the east or northeast. Dunes on the lower river terraces indicate that at least part of the eolian deposition occurred during the present cycle of river erosion. Dune form consistently indicates east to northeast winds regardless of location.

SAND AND SILT ASSOCIATED WITH DEFLATION BASINS (db)

Deflation hollows and basins are common within areas of active and inactive dunes. These areas are relatively flat, unvegetated, wind-scoured depressions, bounded by truncated dune margins (often with oversteepened slopes). Eroded remnants of former dunes are exposed in the basins (fig. 8). Although most basins are less than 100 m long, some exceed 600 m. The basins are approximately elliptical or digitate and long axes parallel the east-northeast wind direction. Sediment in the basins is generally silt and sand, but in some of the deeper basins fine gravels are apparently in traction transport and show weak ventification. Local drainage within a dune field occasionally produces shallow lakes in these basins.

Pingos

Pingos are intrapermafrost features which, at Prudhoe Bay, have surface expression as isolated hills ranging up to 9 m in height. They are oval in plan view and vary from about 50 to 600 m in length and 30 to 380 m in width. They are the closed-system type (Mackay, 1966), which form when a saturated zone of unfrozen permeable sediments begins to freeze downward from the ground surface. The volume of saturated sediment becomes entirely confined between the downward-freezing zone and the underlying impermeable permafrost table. Excess pore water is expelled ahead of the advancing freezing front resulting in excess hydrostatic pressure. As the excess water is frozen in a roughly lenticular ice mass, the overlying permafrost is arched upward due to the underlying hydrostatic pressure. Mackay (1966) indicates that in the Mackenzie Delta this type of pingo is commonly associated with shoaling of large, shallow lakes. In the Prudhoe Bay area pingos generally occur in upland tundra deposits, partially drained lacustrine deposits, and drained lacustrine deposits. Where pingos occur in upland tundra deposits the location is directly adjacent to drained, partially drained, or existing lakes. These locations provide the general conditions necessary for closed-system pingo growth as described by Mackay.

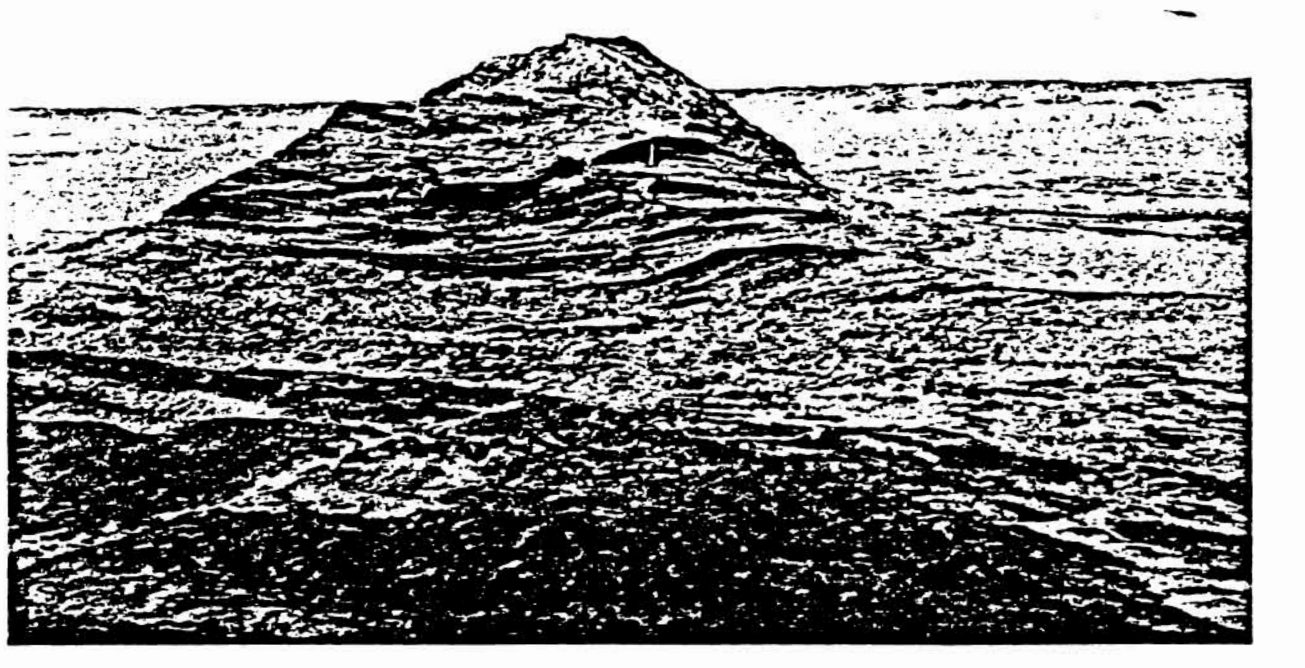


Figure 8. The remnant of an eolian dune, now partially removed by deflation. Floor of deflation basin (db) is in foreground. Dunes remnant was partially frozen. Surface of basin was near saturation, and was being removed as it dessicated. The scale at center is 15 cm long. Wind is from right to left. Location is west of the Sagavanirktok River delta (plate 4). Photograph by R. Updike, 20 July 1977.

HYDROLOGY

General statement

A number of hydrologic studies have been made in the Prudhoe Bay area. Most have been carried out to determine the occurrence of water resources and to indicate where year-round reliable sources of potable water exist. In the past, reliable winter supplies of potable water have been very difficult to obtain due to the extreme arctic conditions and the existence of permafrost.

This section briefly summarizes the hydrology of the Prudhoe Bay area. Hydrologic data were obtained from several sources including USGS, BP, ARCO, and Arctic Gas Alaska (AGA).

Rivers

The Sagavanirktok River drains an area of roughly 12,000 km^2. On the border of the study area it consists of a braided channel network which varies from 1.6 to 2.4 km in width. The main active channel is on the west side of the floodplain. For most of the winter and spring the river is completely ice-covered and there is no surface evidence of flow. Spring thaw occurs dramatically, normally in early to middle June, and discharge is voluminous. After the initial thaw is complete, flows decline to normal summer levels. Flows peak again during occasional summer storms. During the fall, discharge gradually declines as the river freezes and groundwater base flow becomes minimal.

A few specific studies have been conducted on the Sagavanirktok River in the winter to determine the occurrence and extent of free-water pools and closely associated groundwater zones beneath the river ice. These studies were conducted to determine if there are any reliable volumes of winter water beneath the river ice and above the permafrost table. These studies indicate that pools of free water and associated groundwater zones do exist and appear to be most prominent at meander loops within the braided system. Based on borings, Sherman (1973) has shown the extent of pools and groundwater zones (i.e., taliks) in the river near ARCO's operation center during January and April of 1969. Results show that a thawed zone approximately 100 m wide and 7 m thick in January was 50 m wide and 3 m thick in April. Exploration by BP, in April, 1975, near the Deadhorse Airport also indicates the presence of thawed ground beneath the river ice (Harry Haywood, 1977, personal comm.). Temperatures were measured in boreholes to delineate the distribution of the thawed zone. In April, 1976, geophysical exploration was conducted by AGA. Using electromagnetic (VLF radiohm) and shallow resistivity methods near ARCO's operation center and Kodiak Company facilities, groundwater zones beneath the stream bed were again indicated (Northern Engineering Services, 1976). These surveys suggest that sub-ice pools and associated groundwater zones of the Sagavanirktok River are not continuous.

The Kuparuk River drains an area of approximately 8,000 km^2. It has been gaged by the USGS since June, 1971, 16 km south of its mouth at Gwyder Bay. Streamflow records (U. S. Geological Survey, 1971-1976) indicate that the river floods during early June. Mean flow for the month of June is 12,500 cubic feet per second (cfs)(350 cubic meters per second, m^3/s). Peak flows for the past six years of record have ranged from 22,600 cfs (640 m^3/s) to 82,000 cfs (2,300 m^3/s) (average of 55,000 cfs, 1,600 m^3/s), occurring from June 7 to June 17. During the summer, rainfall produces peak flows ranging from 1,000 cfs (30 m^3/s) to as much as 9,000 cfs (260 m^3/s). Throughout the fall, flows decline gradually as freeze-up occurs, and as snowmelt runoff and groundwater flow decline.

Specific studies on the winter hydrology of the Kuparuk River have been less extensive than those on the Sagavanirktok River. Three holes were drilled by BP on the river ice during January, 1976, and AGA performed geophysical surveys in April, 1976. Both surveys indicate the presence of discontinuous sub-ice pools and thawed groundwater zones.

The Putuligayuk River is a relatively small local arctic river that flows into Prudhoe Bay from the south, draining approximately 450 square km. The river has been monitored since May, 1970, at a point 11.7 km south of its mouth at Prudhoe Bay (U. S. Geological Survey, 1971-1976). Peak flows during spring runoff occur in early to middle June and average 3,750 cfs (110 m^3/s). Normal summer flows are relatively low ranging from 1 to 100 cfs (0.03 to 2.8 m^3/s) and flow ceases by late September-early October.

Water quality in all three rivers varies seasonally. Runoff in June from snowmelt in both the Kuparuk and Putuligayuk Rivers is excellent in quality, varying from 24 to 113 miligrams per liter (mg/l) in total dissolved solids (U. S. Geological Survey, 1971-1976). Flooding during the June thawing period imparts average suspended sediment concentrations of 105 mg/1 for the Kuparuk River and 33.4 mg/1 for the Putuligayuk River. At considerably lower summer flows in August, the Kuparuk and Putuligayuk Rivers have higher average total dissolved solids of 72.8 and 171.3 mg/1, respectively. Suspended sediment concentration in August for these rivers is less than 10 mg/1. Data for winter months indicate that total dissolved solids can reach as high as several hundred mg/1, evidently caused by freeze concentration.

Figure 9. Aerial view of BP-Sohio water reservoirs in the east channel of the Kuparuk River active floodplain (af), looking downstream. The reservoir furthest from the observer was under construction at the time the photo was taken. The lower fluvial terrace (lts) is visible beyond the scarp in the upper part of the picture. The pipelines at the bottom of the picture transport oil from Drill Pad M (see plate 7). Photography by R. Updike, 18 August 1977.

Lakes

Lakes were the first hydrologic feature in the area to be explored for a source of water. They cover a significant portion of the area and have a wide range of sizes and shapes. The majority of stabilized lakes have a rounded rectangular shape with their long axis oriented approximately 13° west of north. They range from about 1,100 m to 2,400 m in their longest dimension and 750 m to 1,200 m in width. There are many smaller ponds with lengths of a few tens of meters. Most lakes are very shallow, being less than 2 m deep (pl. 13-14). Lakes deeper than 2 m can have free water between the winter ice cover and the sediment bottom.

Sherman (1973) studied a few lakes in the vicinity of ARCO operations center during June, 1969. He found that lakes between 2.5 m and 3.5 m deep had as much as 1.5 m of free water beneath 2 m of ice. As much as 4 m of sediment below the lakes was unfrozen.

British Petroleum surveyed Big Lake, located 8.8 km southwest of Prudhoe Bay, in February, 1970 (Harry Haywood, 1977, personal comm.), and data were obtained from 21 borings. The thickness of surface ice varied from 0.45 to 1.68 m. In a few places, a small amount of free water was found below the surface ice. The lake bottom consists of 0.9 to 3.9 m of silt, the upper part of which was frozen at the time of drilling. Below the frozen silt, thawed sediments commonly occurred to depths ranging from 1.4 to 6.1 m. The water in the thawed sediment at one locality was poor in quality, containing 3,440 mg/1 chlorides.

Groundwater

In the Prudhoe Bay area continuous permafrost, which extends several hundred meters below the surface, affects groundwater by limiting its occurrence, movement, and quality. Groundwater commonly occurs within perennially thawed sediments, or taliks, which depress the permafrost table beneath surface water bodies. When the lake or river is thawed, heat is continuously conducted from the water to the underlying sediment. Throughout the year the water body also insulates the sediment by decreasing heat loss to the atmosphere. These taliks are more restricted in winter (Sherman, 1973).

Summer data on the depths of taliks below rivers are lacking. In the winter, groundwater appears to occur in discontinuous zones of limited extent. Groundwater quality beneath rivers is good throughout the year because it is associated with surface flows. These river taliks are quite permeable because of the predominance of sand and gravel.

Restricted groundwater also occurs under lakes and usually the deeper lakes are underlain by a thicker talik. The water quality of these taliks is poor.

Taliks not clearly associated with existing surface water bodies have been penetrated by drillers. These random unfrozen zones appear to be either remnant or incipient features where permafrost is either degrading or aggrading depending upon changing geologic and climatic conditions (Williams, 1970). Like other taliks, these are isolated in or above the permafrost. Water in the taliks is usually saline, either originating from ionic concentration through freezing or by melting of saline permafrost.

Conclusions

The natural occurrence of water in the Prudhoe Bay area is very limited for more than 6 months of the year because of the extreme environment. Surface water of good quality is readily available in rivers and lakes throughout the summer. Groundwater occurs below these surface water bodies in taliks above the permafrost to varying depths. Their extent depends on the size and depth of the surface water body. In general, water quality is good in river taliks and poor in lake taliks.

In winter, potable water demands of the Prudhoe Bay operators are quite large in comparison to natural supplies. Rivers have very low (if any) flows in the winter. Groundwater in taliks directly below the rivers is available and of good quality, but is limited to discontinuous zones in the winter. In addition, well maintenance on the river floodplains is difficult. Many lakes freeze to the bottom in the winter. Deeper lakes have limited free water storage in the winter and tend to have concentrated impurities. Taliks beneath lakes and those of random occurrence are difficult to locate, usually limited in extent and have a high total dissolved solids concentration.

The best method for providing reliable year-round potable water supplies is by development of artificial reservoirs. Construction of reservoirs in gravel deposits near the Kuparuk (fig. 9) and Sagavanirktok Rivers is being carried out by BP and NANA Corporation, respectively. ARCO has deepened an existing lake and draws water from the Sagavanirktok River to recharge the lake-reservoir, except during spring break-up when the river becomes turbid. These artificial reservoirs are deep enough so that sufficient capacity is retained beneath the winter ice. Excellent quality water is available from the rivers to supply these reservoirs.

EXPLANATION OF DERIVATIVE MAPS, PLATES 13 AND 14

Two of the prime concerns of this study are to evaluate potential sources of construction material (sand/gravel aggregate) and potable water. Plates 13 and 14 are intended to delineate areas which may be of specific value in these two concerns.

In the discussion of the surficial geology it was noted that sand and gravel underlie essentially the entire area. In order to locate the best areas for excavation of this gravel the following criteria were considered:

a) maintain the natural integrity of the river floodplains to minimize modification of existing hydraulic geometry and sediment transport characteristics
b) prevent damage to the aquatic wildlife habitat
c) distinguish areas with minimal overburden (tundra plus silt)
d) utilize areas where the seasonally active layer is thickest, i.e., where the gravels are seasonally thawed to a considerable depth
e) if permafrost is to be encountered, locate areas where massive ground ice will be minimal (benefiting slope stabilization and maximum gravel yardage per finite volume excavated)
f) locate areas where excavated gravel can be readily drained of pore water.

These criteria are best fulfilled in certain restricted areas of the active and inactive floodplains (units af and if) of the Kuparuk and Sagavanirktok Rivers. Secondary selection sites are less desirable considering economic and engineering aspects, but are both feasible and environmentally sound. In addition to the prime sand/gravel sites, areas where reasonably well-sorted gravel-free sand can be obtained are indicated on the plates.

Alternatives for year-round potable water supply have been discussed above. Existent lakes may be utilized as a seasonal supply until freezedown, or, if of sufficient area and depth to prevent total freeze, may be perennial sources. Certain lakes, by virtue of their proximity to a river and their accessibility, may be deepened by excavation and filled during summer months by river water diversion. This procedure has been successful at Webster Reservoir.

The other alternative is excavation of reservoirs within a river floodplain. Such projects have been, or are being, completed on all three rivers. The advantages include (a) utilization of the excavated gravels for construction, (b) good quality water, (c) gravity recharge from the adjacent river, and (d) ease of excavation, maintenance, and expansion. Design and location must be closely monitored so that disturbance of the river dynamics does not occur.

MAN-INDUCED ENVIRONMENTAL HAZARDS

Several potential environmental problems are associated with man's activities in the Prudhoe Bay area. The following brief discussion summarizes some of those problems that are most apparent. Wind-transported silt (loess) is being generated from haul roads, and is carried downwind over the tundra causing inhibition of vegetation growth, change in surface albedo, and resultant modification of the thermal equilibrium of the ground. On segments of heavily used road, oil has been sprayed on the road surface. During rain and melt periods this oil is carried to the tundra by runoff and as an aerosol. During dry periods, the combination of the road oil and wind-deflation of silt produces an oil-coated loess. Aerosols and particulate matter from other areas of activity such as drill pads and vehicle repair sites are also carried downwind onto the tundra. Contamination of natural waters and reservoirs can result from all of these processes.

Figure 10. Abandoned road near Deadhorse, rendered unusable due to thermokarst subsidence along ice-wedge polygons. The problem would have been averted by proper thickness of gravel fill. Photograph by R. G. Updike, 20 July 1977.

Natural drainage systems, particularly thermokarst streams, may have their flow either impeded or accelerated by the oil field development. Particularly, roadways and pads have not, in some cases, allowed for natural drainage, resulting in ponding and the initial stages of thermokarst subsidence. Elsewhere, drainage channels have been too efficient, resulting in partial or total drainage of natural lakes.

Several areas of excavation (e.g., Sagavanirktok River floodplain, Putuligayuk River oxbows) have produced hydraulic geometry changes including (a) restrictions of stream flow dynamics by deep barrow pits, high storage piles, and the cutting and removal of gravel bars, (b) stream gradient changes due to channelization or meander extraction, (c) width to depth ratio changes by scraping and dredging, and (d) artificial stabilization of natural cutbanks.

The process of excavation and removal of sand and gravel from an active floodplain modifies the sediment load characteristics of the stream. Suspended load is increased due to agitation of the excavated sediment, giving downstream water a turbid appearance, as noted on the lower reaches of the Kuparuk and Putuligayuk Rivers in July, 1977. Further, the sand and gravel being extracted are part of the riverbed load. No estimates have yet been made concerning rates of bed load transport on these rivers but if rates are low, long-term disruption of the rivers' transport budgets has occurred.

The thawing of permafrost liberates pore moisture which was bonding the sediment, and may also melt massive ground ice. The results are loss of bearing strength and differential ground subsidence. This process is often accidentally initiated or accelerated by oil field activities. Where gravel pad construction has been insufficiently thick, heat flow into the ground is enhanced, extending the depth of the active layer (fig. 10). Reservoirs greatly increase year-round heat flow into the ground, resulting in a thaw bulb beneath the reservoir and potential subsidence. Artificial modification of lake basins by excavation, fill, or causeway construction can alter lake circulation patterns. This may cause shoreline modification, thawing of permafrost beneath or adjacent to the lake, and thicker lake ice in restricted areas.

Winter haul roads across river ice or frozen lakes compact or remove snow cover, resulting in thicker ice development. This may seal off sub-ice channels and pools, restricting movement of overwintering fish, and could cause fish kills due to oxygen deficiency in restricted pools.

REFERENCES CITED

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

Britton, M. E., 1958, Vegetation of the arctic tundra in Arctic Biology: Oregon State Coll., Ann. Biology Coloquium, 18th Corvallis 1957, p. 26-61.

Carson, C. C., and Hussey, K. M., 1962, The oriented lakes of arctic Alaska: Jour. Geology, V. 70, p. 417-439.

Carter, L. D., Repenning, C. A., Marincovich, L. N., Hazel, J. E., Hopkins, D. M., McDougall, K., and Naeser, C. W., 1977, Gubik and pre-Gubik Cenozoic deposits along the Colville River near Ocean Point, North Slope, Alaska: U. S. Geol. Survey Circ. 751-B, p. B12-B14.

Churchill, E. D., 1955, Phytosociological and environmental characteristics of some plant communities in the Umiat region of Alaska: Ecology, V. 36, p. 606-627.

Drew, J. V., Tedrow, J.C.F., Shanks, R. E., and Koranda, J. J., 1958, Rate and depth of thaw in Arctic soils: Am. Geophys. Union Trans., V. 39, p. 697-701.

Hopkins, D. M., 1967, Quaternary marine transgressions in Alaska in Hopkins, D. M., ed., The Bering Land Bridge: Stanford, Stanford Univ. Press, p. 47-90.

Hopkins, D. M., Karlstrom, T.N.V., and others, 1955, Permafrost and groundwater in Alaska: U. S. Geol. Survey Prof. Paper 264F, p. 113-146.

Hussey, K. M., and Anderson, G. S., 1963, Environment and distribution of thermal relief features in the Northern Foothills Section, Alaska: Office of Naval Research Contract Report, unpubl., 76 p.

Lachenbruch, A. H., 1962, Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost: Geol. Soc. America Spec. Paper 70, 69 p.

Mackay, J. R., 1966, Pingos in Canada, in Permafrost Internat. Conf., Lafayette, Ind., 1963, Proc.: Natl. Acad. Sci.-Natl. Research Council Pub. 1287, p. 71-76.

Northern Engineering Services Co., Ltd., 1976, Geophysical investigations on the rivers of the Arctic Coastal Plain in Alaska: Draft report for Arctic Gas Alaska.

O'Sullivan, J. B., 1961, Quaternary geology of the Arctic coastal plain, northern Alaska: Iowa State Univ., unpub. Ph.D. thesis, 191 p.

Pewe, T. L., 1975, Quaternary geology of Alaska: U. S. Geol. Survey Prof. Paper 835, 145 p.

Sellman, P. V., Brown, J., Lewellen, R. I., McKim, H., and Merry, C., 1975, The classification and geomorphic implications of thaw lakes on the Arctic Coastal Plain, Alaska: U. S. Army C.R.R.E.L. Res. Rept. 344, 21 p.

Sellman, P. V., Weeks, W. F., and Campbell, W. J., 1975, Use of side-looking airborne radar to determine lake depth on the Alaskan North Slope: U. S. Army C.R.R.E.L. Special Rept. 230, 6 p.

Sherman, R. G., 1973, Groundwater supply for an oil camp near Prudhoe Bay, Arctic Alaska in Second Permafrost Internat. Conf., 1966, Proc.: Natl. Acad. Sci.-Natl. Research Council, p. 469-472.

Spetzman, L. A., 1959, Vegetation of the Arctic Slope of Alaska: U. S. Geol. Survey Prof. Paper 302B, p. B19-B58.

Stoneley, R., 1970, Discussion, in Lachenbruch, A. H., Thermal consideration in permafrost, in Adkison, W. L., and Brosge, M. M., eds., Proc. Seminar on the North Slope of Alaska: Los Angeles, Pacific Sec. Am. Assoc. Petroleum Geologists, p. J3-J4.

U. S. Geological Survey, 1971-1976, Water resources data for Alaska water year (as indicated).

Wiggins, I. L., and Thomas, J. H., 1962, A flora of the Alaskan Arctic Slope: Univ. of Toronto Press, Arctic Inst. of North America Spec. Publ. 4, 425 p.

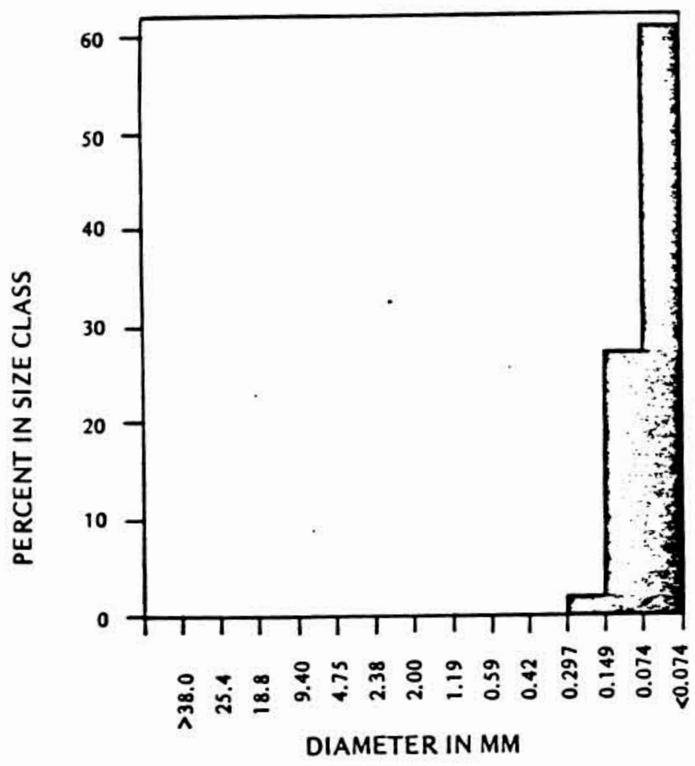
Williams, J. R., 1970, Groundwater in the permafrost regions of Alaska: U. S. Geol. Survey Prof. Paper 696, 83 p.

PLATE 15. COMPOSITION AND TRANSIENT CONDITIONS OF SURFICIAL GEOLOGIC UNITS MAPPED ON PLATES 2 THROUGH 12.

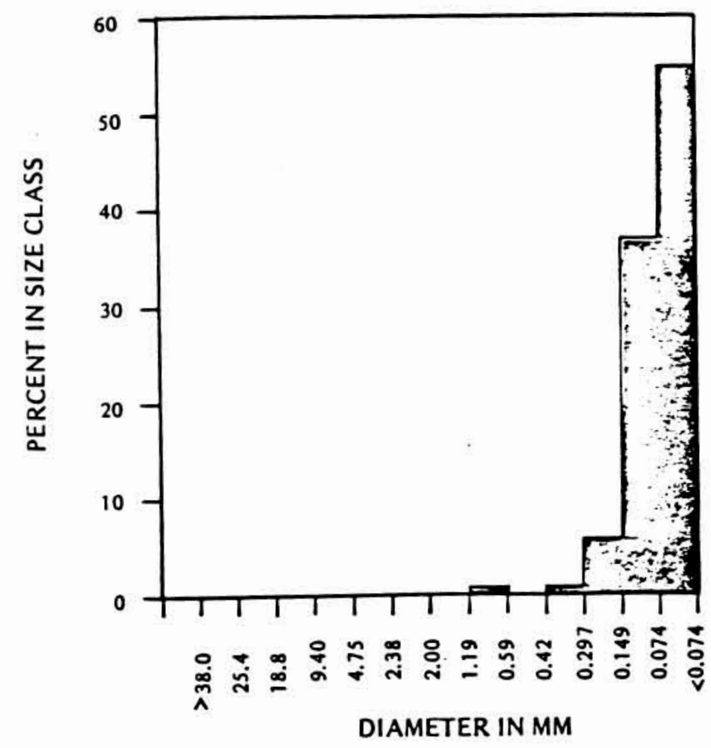
ENGINEERING GEOLOGIC UNIT	STRATIGRAPHY	GRAIN SIZE DISTRIBUTION	ICE CONTENT AND TYPE	MOISTURE CONTENT OF ACTIVE LAYER	ORGANIC CONTENT	VEGETATION AND SOIL CHARACTERISTICS	DRAINAGE/SURFACE WATER	DEPTH OF ACTIVE LAYER	BOUNDARY CONDITIONS	SLOPE AND SLOPE STABILITY	BEARING STRENGTH, THAWED
Silt, sand, and gravel associated with upland tundra areas—ut	Stratified sandy-gravel to great depths (>400 m) with interbedded lenses of sand, silty sand, and gravelly sand (individually up to 3 m thick); overlain by poorly stratified sandy silt 0.5-3.5 m thick, often organic-rich; overlain by organic silt-tundra mat up to 15 cm thick.	Sandy-silt blanket generally less than 0.5 mm, <15% coarse sand and occasional pebbles. Sandy gravel dominantly 0.2 to 20 mm with *mean about 7.5 mm.*	Interstitial seasonal ice in silt; perennial interstitial ice in sandy gravel, ice wedges in interval 1.0 to 5.0 m below surface, in 7-10 m polygons; ice lenses occasionally in silt, particularly where organic-rich. * pingos adjacent to units **ldl, ldi, lds, ldp, ldd.**	In silts and silty sands, commonly 50-200%, occasionally higher, dependent on ice content; sandy gravels 5-20%; sand with minor gravel and silt 10-35%.	Some organic material in silt common, particularly in upper 0.5 m; sandy gravel usually organic-free; organic mat at surface up to 15 cm thick.	Continuous tussock-dwarf heath tundra and dwarf shrub-heath tundra. Tundra soil continuous and up to 3 cm thick, except where broken by frost heaving or raised polygon rims.	Moderately well-drained except during spring and early summer; locally, shallow (<0.25 m) pools of water occur within low-center ice wedge polygons and in trough along raised rims.	Typically 0.5 to 1.5 m, although locally up to 2.5 m, e.g., near unit boundaries.	Generally the boundaries of this unit are being modified by adjacent units by (a) erosion, e.g., streams and lakes, (b) deposition, e.g., eolian dunes, (c) thaw. Therefore, boundaries of this unit are, in most cases, static or diminishing.	2.0 to 4.0 m/km toward the north or northeast; natural slope stability during active layer thaw, good; natural slope stability during upper permafrost thaw fair, generally, poor near some boundaries; cut slopes, thawed, above 10% (5°), poor in silt and upper sandy gravel.	Moderate if only active layer thawed; poor to very poor if permafrost thawed. Progressive failure under static loading as duration increases.
Active floodplain gravels—af	Stratified sand and gravel greater than 100 m thick, interbedded with thin lenses of silty sand; occasionally sequence overlain by thin (<1.0 m) silt and sand cap on braided interfluves.	>90% *sand and gravel, dominantly* in range of 20 mm to 0.20 mm (see pl. 17); interfluve caps of fine sand and silt (<0.5 mm).	*Free of perennial ground ice* to *considerable depth due to* thaw bulb; seasonally frozen *particularly on exposed interfluves* with interstitial ice.	Saturated to or near surface, water table at or near surface. 5-20% moisture content, slightly higher in sands (to 35%).	Free of organic material, except for stream-washed organic fragments.	Free of vegetation except for scattered patches of aquatic waterways community on interfluves. No soil.	Well-drained except for static water in back channels isolated from through flowing channel. Fluctuations due to channel migration and variation of discharge.	Not measured, estimate 1.0-2.0 m, underlain by perennially thawed zone to several meters' depth.	Bounded on channel limits by upland tundra or inactive fluvial units; scarps define boundaries; thermal erosion, undercutting, and mass movement typical at scarps. West boundaries generally more active than east boundaries. Downstream gradational to deltaic units.	2.0 to 2.5 m/km toward north to northeast; cut slopes stable at less than 2:1 (57%).	Very good in situ, particularly if surface drained, excellent if compacted.
Inactive floodplain gravels—if	*Stratified sand and gravel greater than 100 m thick,* interbedded with thin lenses of silty sand, commonly overlain by silt and fine sand cover up to 1.0 m thick.	>90% sand and gravel, dominantly *in range of 20 mm to* 0.20 mm (see pl. 17), covered by fine sand and silt (<0.5 mm) with minor coarse sand and fine gravel.	Free of perennial ground ice to considerable depth due to *thaw bulb, except in some distal areas from unit af where pore ice may persist annually. Seasonally frozen with pore ice* to several meters.	Water table shallow, saturated to or near surface, except well-drained in areas above water table; moisture content generally in range of 5-20% in sandy gravels, slightly higher where sand predominates.	Same as unit af. Some organic debris occurs in silt-sand cover.	Aquatic waterways plant community, thin and often separated by stream channels. No soil.	Well-drained except for static water in channel depressions. May be flooded seasonally during peak discharge or continuously by channel modifications.	Same as unit af.	Bounded by upland tundra, active floodplain and/or fluvial terrace units. Scarps usually define boundaries. Along unit af *undercutting and mass movement potential. Boundaries with* older units usually stabilized. Downstream transition to deltaic units.	Same as unit af.	Same as unit af.
Lower fluvial terrace gravels, *partially scoured—* lts	Stratified sand and gravel of considerable thickness, interbedded with thin lenses of silty sand; overlain by continuous *silt and fine sand blanket* less than 2.5 *m thick, commonly* less than 1.5 m; often overlain by organic silt layer less than 15 cm thick.	Same as unit if.	Foliated ice wedge polygons *rarely or weakly expressed at* surface, present in subsurface, but less extensive than unit ltp. Permafrost table in excess of 1.0 *m depth, moderate to* excessive pore ice in permafrost, pore ice and some ice lenses in active layer.	Moderate to highly supersaturated, in sand/silts dependent on ice content 50-150% moisture content. In sandy gravels 5-20%, pore spaces saturated. Sands up to 35%.	Organic mat 5-10 cm thick at surface, may be organic-rich to 20 cm in silt-sand matrix, trace of organic material in underlying sediments.	Tussock-dwarf heath tundra and dwarf shrub-heath tundra, with some wet sedge meadows along abandon channels. Tundra soil continuous but broken along steeper slopes and ter*race scarps.*	Generally good except along abandoned drainage channels where shallow water (static) may occur during summer months.	Shallow, less than 2 m, except along boundary scarps where variable to greater depths.	Scarp transitions with floodplain and upland tundra units, otherwise gradational. Scarps often show thermal erosion and mass movement, other boundaries stable except subject to frost heaving and cracking.	General slope toward north at about 2.5 m/km and stable. Local undulation of surface due to stream scouring, resultant slopes up to 15° (25%); considered stable. Scarps have variable inclination; unstable. Artificial cuts susceptible to slump, rotation, and flow.	Moderate to poor; however, generally better than unit **ltp** due to less massive ice.
Lower fluvial terrace gravels, ice wedge polygons—ltp	*Stratified sand and gravel of considerable thickness,* interbedded with thin lenses of silty sand; overlain by continuous silt and fine sand blanket less than 3 m thick; often overlain by organic silt layer less than 15 cm thick.	Same as unit if.	Foliated ice wedge polygons abundant and expressed at *surface. Also visible pore ice in permafrost. Permafrost table* from <1.0 m to 3.0 m depth. Little to *moderate visible pore* ice in active layer, occasional massive ice lenses.	Same as unit **lts.**	Same as unit **lts.**	Tussock-dwarf heath tundra and dwarf shrub-heath tundra. Tundra soil continuous but broken along raised polygon ridges and within 50 m of terrace scarps.	Moderate, generally free of intrapolygonal surface water except in some low centers. Drainage along polygon troughs. Occasional standing water during spring surface melt.	Same as unit **lts.**	Same as unit **lts.**	Natural slopes less than 2.5 m/km toward the north or northeast and stable. Scarps have variable inclination and often unstable. Artificial cuts deemed unstable due to thaw of massive ice.	Moderate to poor under seasonal thaw conditions; poor if permafrost thawed, but slightly better near boundaries with unit **lts.**
Upper fluvial terrace gravels—ot	Stratified sand and gravel, interbedded with thin lenses of silty sand, overlain by continuous silt and fine sand blanket greater than 2 m thick, often overlain by organic silt layer less than 15 cm thick.	Same as unit if.	Same as unit **ltp.** * pingo adjacent to floodplain.	Moderate to supersaturated in silts, 50-200%; where ice content high, above 200%. In sandy gravels 5-20%, in sands to 35%, occasionally higher due to massive ice.	Same as unit **lts.**	Tussock-dwarf heath tundra and dwarf shrub-heath tundra, except local low center polygons with wet sedge meadows. Tundra soil continuous but broken along raised polygon ridges and within 50 m of terrace scarps.	Poor to moderate due to static intrapolygonal surface water. Some drainage along integrated polygon troughs. Particularly wet from spring to midsummer.	Same as unit **lts.**	Scarp transitions with floodplain, otherwise gradational with other units. Scarps often show thermal erosion and mass movement, other boundaries stable but subject to frost heaving and cracking, with surface creep of thawing silts.	Same as unit **ltp.**	Moderate to poor under seasonal thaw conditions; hazardous if permafrost thaws due to massive ground ice.
Thermokarst stream channel *gravels—ts*	Same as unit ut.	Same as unit ut.	Surface ice during winter, frozen to tundra, trace to >2.0 m thick; silts and sands contain moderate to extensive visible pore ice and lens ice; remnant ice wedges may be present at *depth but not actively forming; pore ice present in gravels of* permafrost.	Saturated throughout year from surface to permafrost table; moisture contents similar to unit ut.	High organic content probable throughout active layer in silt and sand.	Aquatic waterways community dominant, also fresh water aquatic community in broader areas and wet sedge meadow community along boundaries. Soils mixed or absent.	Submerged to partially emergent at boundaries, varies from wet tundra surface to >2.0 m of surface water, moving at low to moderate velocity.	Variable, generally thawed zone above permafrost table greater than unit ut.	Transitional to unit tt or upland units, boundaries gradational and vegetation mat seldom broken.	Natural slopes less than 2 m/km, except very locally up to 4 m/km; very unstable when thawed along boundaries.	Very low, should be avoided, or traversed via conduits or bridgework.
Terrace gravels associated with thermokarst streams—tt	*Same as unit ut.*	*Same as unit ut.*	*Silts and sands contain moderate to* extensive pore ice and lens ice; *remnant ice wedges at* >2.0 *m but only weakly* active to inactive; pore ice present in permafrost.	Varies from moderate to supersaturated. Silts to >200%; sands with silt, up to 60%; otherwise <35% moisture content.	Organic mat less than 10 cm thick but considerable organic material in underlying silt-sand layer. Occasional traces in sandy gravels.	Tussock dwarf-heath tundra dominates, with local wet sedge meadows. Continuous tundra soil, in part disturbed by overbank stream flow.	Poor to moderately drained, dependent on microtopography, occasional ponding with water less than 0.5 m deep throughout the summer.	Undertermined, assumed to be 1.0-3.0 m. Thawed zone over permafrost thicker than that in unit **ut.**	Gradational transitions to upper tundra units, usually gradational to unit ts except locally along small (<1.0 m) cutbank scarps.	Very gentle slopes, less than 2 m/km; natural slopes stable; cut clopes unstable when thawed.	Variable from very poor to moderately good dependent upon degree of saturation.
Silts and gravels associated with large area lakes—ldl	*Stratified* sand and gravel interbedded with lenses of sand and silt, *much in excess of 100 m thickness; overlain by sandy* silt, from less than 2 m to more than 5 m thickness.	Sand and gravel predominantly *in range of 20 mm to 0.20 mm;* overlying fine sand and silt less than 0.5 mm with organic debris.	Perennially thawed, often to greater than 5 m, except along *marginal shelves where shallow seasonal freeze occurs;* no ice *wedge polygons expected, except as inactive relicts; perma*frost gravels contain *pore ice.*	Perennially saturated.	Organic debris incorporated in sandy silts, including dislodged tundra mats up to 1.5 m in diameter, higher organic content expected near margins of unit.	In deeper water, mostly free of rooted vegetation; in shallow areas and near lake margins (<1.3 m water depth) the zoned freshwater aquatic community is common. No soil.	Continuously submerged. Liquid water usually present beneath ice throughout winter. Near coast waters may be brackish or saline, diminishing winter freeze magnitude and duration.	Perennially thawed, except at margins where the lake was frozen to the bottom and freeze-thaw of the underlying sediment occurs to 2-m depth.	Usually marked by either a small scarp <1.0 m high, where tundra mat has been eroded, or by a gradational slope. Ice-wedge polygons on adjacent units partially thawed.	Essentially horizontal, with very slight grade from east to west. Slope stability—not applicable.	Not applicable.
Silts and gravels associated with *intermediate* area lakes—ldi	Same as unit **ldl.**	Same as unit **ldl.**	Shallow, central perennially thawed zone, however winter lake ice may freeze to bottom throughout much of lake basin resulting in seasonal freeze of shallow sediments. Seasonal *pore ice and local segregated ice lenses several centimeters thick in silt. Ice wedge polygons may occur beneath areas* where water is very shallow.	Perennially saturated.	Same as unit **ldl.**	Same as unit **ldl.**	Continuously submerged. Liquid water usually present beneath ice until midwinter, however, total freeze down generally occurs by February-March; local pools beneath ice may persist through winter. Near coast waters may be brackish or saline, diminishing winter freeze magnitude and duration.	Most of unit underlain by thaw bulb; much of lake freezes to bottom during winter and underlying sediment frozen to shallow depth from midwinter to late spring.	Same as unit **ldl.**	Same as unit **ldl.**	Not applicable.
Silts and gravels associated with *small area lakes—* lds	Same as unit **ldl**, but with sandy-silt layer generally thinner, usually less than 3 m thick.	Same as unit **ldl.**	Lake freezes to bottom from midwinter to early spring, underlying silt frozen seasonally resulting in pore ice and segregated ice lenses several centimeters thick. Ice wedge polygons often bound lake and may extend beneath lake, *however ice wedges usually inactive or being thawed.*	Perennially saturated.	Organic tundra mat often continuous across unit or extensive along margins; underlying silts rich in organic debris, including dislodged fragments of tundra mat.	Zoned freshwater aquatic community extends across most of lake unit.	Continuously submerged. Total freeze-down usually occurs in fall or early winter. Some exceptionally deep lakes may be similar to unit **ldi.**	Perennially thawed zone very limited or absent; shallow (<3 m) active layer above permafrost table.	Often bounded by raised-ridge polygons, or gradational to adjacent units; tundra mat at boundaries often not broken.	Same as unit **ldl**, although more irregular surface due to submerged remnant polygons.	Not applicable.

PLATE 16. COMPOSITION AND TRANSIENT CONDITIONS OF SURFICIAL GEOLOGIC UNITS (CONTINUATION OF PLATE 15).

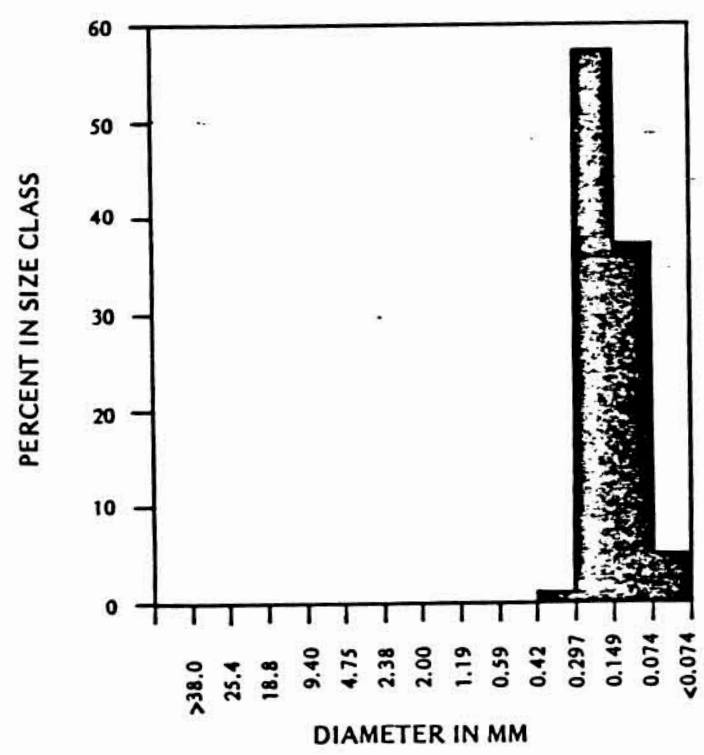
ENGINEERING GEOLOGIC UNIT	STRATIGRAPHY	GRAIN SIZE DISTRIBUTION	ICE CONTENT AND TYPE	MOISTURE CONTENT OF ACTIVE LAYER	ORGANIC CONTENT	VEGETATION AND SOIL CHARACTERISTICS	DRAINAGE/SURFACE WATER	DEPTH OF ACTIVE LAYER	BOUNDARY CONDITIONS	SLOPE AND SLOPE STABILITY	BEARING STRENGTH, THAWED
Silts and gravels associated with partially drained lakes–ldp	Stratified sand and gravel, interbedded with lenses of sand and silt, much in excess of 100 m thickness; overlain by continuous silt and fine sand of variable thickness, from less than 2 m to greater than 5 m.	Same as unit **ldl**.	Unpredictable, although ice wedge polygons should be expected, even beneath extensive surface water areas; permafrost table shallow; pore ice and segregated ice lenses present in active layer during winter and spring. * pingos occasional.	Same as unit **ldl**.	Organic tundra mat often continuous across unit; sandy silt unit organic-rich, particularly in regressive stage of lake development (see text).	Same as unit **lds**.	Much of surface continuously submerged or marshy; positive areas such as raised polygon rims may be emergent; water currents very localized due to shallow water and topography; total freeze-down of surface water from fall to spring; drainage very poor.	Generally 1.5 to 3.0 m; perennially thawed zones may locally exist between active layer and permafrost table.	Boundary area often defined by active or inactive raised-rim ice wedge polygons (<10-m diameter), by gradational unbroken slopes, or by low broken-tundra scarps; boundary conditions dependent upon stage in lake cycle (see text).	Same as unit **lds**.	Extremely poor due to marshy to shallow-submerged condition; unit should be avoided, or if necessary both drained and insulated with thick (>2 m) gravel pad.
Silts and gravels associated with drained lake basins–ldd	Same as unit **ldp**.	Same as unit **ldl**.	Variable, dependent on time interval since being drained, and character of previous lake (size, depth, etc.). Commonly contains ice wedge polygons from incipient to massive; pore ice and ice lenses common in active layer, lenses as much as 25 cm thick. * pingos present, often adjacent to existing lakes.	Sandy silt near saturation to supersaturated dependent on segregated ice, moisture content up to 40%, to >200% *where ice lenses occur;* 5-30% in underlying sandy gravels.	Organic tundra mat absent in some recently drained areas; broken to continuous elsewhere; sandy silts commonly organic rich.	Variable, chiefly wet sedge meadow and tussock-dwarf heath tundra, may be absent in recently drained areas. Tundra soil less than 10 cm thick.	Moderate to poorly drained, poorer where low center polygons have developed; usually some surface water present during spring and early summer; marshy conditions typical but sporadic.	Less than 2 m; frost heaving considerable. Perennial thaw zones between active layer and permafrost table due to earlier thaw cycle.	Generally gradational to upper tundra unit, or to submerged lake areas. Remnant scarps may occur along former lake strandlines and along outlet channels.	Generally nearly horizontal, except along boundary areas where scarps and slopes up to 5° may occur. Surface may be disrupted by raised-rim polygons; slopes stable except for seasonal frost action; excavated slopes susceptible to permafrost thaw, resultant flow and subsidence.	Moderate to poor, dependent on local drainage, vegetation a good indicator tussock dwarf-heath tundra being most favorable; best conditions July-August.
Silts and gravels associated with abandoned lacustrine strandlines–lda	Same as unit **ldp**.	Same as unit **ldl**.	Same as unit **ldd**, but with polygons oriented along old strandlines.	Same as unit **ldd**.	Same as unit **ldd**.	Tussock-dwarf heath tundra, variable in assemblage along slopes of strandlines. Tundra soil less than 10 cm thick.	Moderate, slightly poor where low center polygons have developed, but generally better than unit **ldd**.	Less than 2 m; frost heaving considerable. Perennial thaw zone may occur between active layer and permafrost table, beneath most recently abandoned strandlines and adjacent to present lake.	This unit is transition zone between present lacustrine units and drained tundra units; shallow thaw zone may occur adjacent to present lake.	Subtle transitions from horizontal to up to 5°; generally no scarps. Moderate to good stability when undisturbed; poor in excavated slopes due to thaw of massive ice lenses and wedges.	Moderate to poor; better where drained; relatively good for dynamic loading from midsummer to late summer.
Silt, sand, gravel associated with marine shorelines–cd	Weakly stratified to moderately well-stratified sand and gravel along coastal beaches; locally at spits and bars, poorly stratified silty sand interbedded with lenses of sandy gravel.	Dominantly sand and gravel, some cobble size gravel, but generally less than 20 mm in diameter. Bars and spits dominantly sand (0.15 to 0.5 mm) with lesser amounts of silt and minor gravel; some offshore bars comprised chiefly of gravel with some sand.	Seasonally thawed to considerable depth, winter pore ice only.	Saturated to the surface or a few cm below surface; usually less than 15% moisture content, except sand bars up to 30%.	Generally organic free, except for occasional fragments mixed with sediment and for dislodged pieces of organic tundra mat from adjacent units.	Vegetation sparse to absent; aquatic waterways community with Saxifraga dominant. No soil.	Generally well-drained of surface water; saline groundwater table near the surface.	Not known.	Gradational to submarine surface; beaches bounded landward by scarps 1.0-3.0 m high which are being cut by thermal, marine hydraulic, and sea-ice-shore erosion.	Beaches horizontal to 1.5 m/km; bars and spits have steeper side slopes (up to 15°) down to marine surface. Beach surfaces stable but sediment being washed; bar and spit slopes moderately stable; all surfaces unstable in steep cuts (>20°); backscarp to beaches unstable and undergoing slow mass movement as permafrost thaws. Entire unit subject to winter-spring ice shove from sea ice.	Moderate to good, particularly if well-drained.
Silt and sand of subaerial segments of active deltas–ad	Moderate to well-stratified silt and very fine sand of undetermined thickness, with occasional lenses of coarser sand and fine gravel.	Greater than 95% very fine sand and silt <0.15 mm; particle sizes rarely larger than 1.0 mm (see pl. 17).	Seasonal pore ice only, no massive ice. Depth to permafrost unknown, but presumed to be several meters.	Saturated to or near surface, moisture content up to 40%.	Small amounts of organic material incorporated in silt.	Vegetation very sparse, aquatic waterways community, saline to brackish water tolerance favored. No soil.	Frequently inundated by river and/or tidal waters, particularly in spring.	Not known, although total thawed zone presumed to be several meters thick.	Adjacent to active river channels, causing perennial thaw zone in deltaic deposits; erosion and deposition active along stream boundaries; other boundaries range from gradational slopes to abrupt scarps up to 3 m relief.	Less than 0°10' (2 m/km); poor stability along active channel boundaries; minor thermal erosion and mass movement along scarps; frost heaving along gradational boundaries with associated creep; artificial cuts in silt unstable due to slow flowage and slump.	Moderate under low stress, diminishes to poor under increasing dynamic stress (e.g., heavy vehicles), or under long-term static loading (e.g., pilings, fabricated structures).
Inactive deltaic sands and silts–id	Same as unit **ad**.	Same as unit **ad**.	Same as unit **ad**.	Saturated to within 1.5 m of surface, sometimes to shallower depths. Moisture content 10-40%.	Same as unit **ad**.	Sparse aquatic waterways community, more common than on unit **ad**; particularly occurs toward center of interfluves; saline to brackish water tolerance favored. No soil.	Moderately well-drained, although potential of flooding during periods of high river discharge, ice damming, or unusual sea-level fluctuations.	Not known; perennially thawed subsurface zone may occur in proximity to unit **ad**, to rivers, and to ocean.	Same as unit **ad**.	Same as unit **ad**.	Slightly better than unit **ad** due to lower moisture content in upper 1.5 m.
Active aeolian silt and sand dunes–aa	1.0 to 5.0 m of moderately well-stratified, cross-bedded fine sand, overlying stratified sand and gravel containing lenses of silty sand.	Greater than 90% medium to fine sand, 0.07 to 0.3 mm, with minor amounts of silt and occasional pebbles; underlying sediment is sand and gravel similar to unit **ut**.	Seasonal pore ice only, permafrost table depth unknown, in excavated exposures voids only partially filled with ice but visible.	Not determined but below saturation.	Very minor amounts of fine organic debris incorporated in sand.	Dwarf shrub-heath tundra association, sparse distribution. No soil.	Moderate to well-drained, surface water unlikely; good permeability above permafrost table.	Not determined but believed to be >3 m; perennial thawed zone may occur above permafrost table where dunes have accumulated. Talik may also exist beneath dunes.	Fluctuating boundaries as dunes advance over, or are removed from older underlying units; fluctuations annual.	Highly variable, up to 27° measured on lee side of dunes. Natural slopes unstable during thaw or when subjected to dynamic stress. Artificial cut slopes >25° unstable except when frozen.	Fair to moderate when frozen, poor when thawed; slightly better under static loading than under dynamic loading.
Inactive aeolian silt and sand dunes–ia	Same as unit **aa**.	Same as unit **aa**.	No evidence of massive ice within dunes, although probable that permafrost table may extend into dune interiors. Pore ice only, pores only partially filled in upper part of active layer.	Not determined. Water table presumed to be several meters below surface except where unit occurs in active delta or floodplain.	Same as unit **aa**.	Dwarf shrub-heath tundra association, extensive but broken. No soil.	Same as unit **aa**.	Same as unit **aa**.	Stabilized boundaries, although localized deflation and stream erosion may be acting on unit.	Same as unit **aa**, although primary eolian forms more subdued so that most slopes are less than 20°.	Slightly better than unit **aa** due to more extensive vegetation.
Deflation basins of sand and silt–db	Generally less than 3 m of moderately well-stratified, cross-bedded fine sand, underlain by stratified sand and gravel containing lenses of silty sand.	Same as unit **aa**.	Seasonal pore ice in sand, permafrost table presumed shallow (<2 m) and evidence suggests inactive ice wedges may be present below 2 m.	Near saturation to saturated; may be partially submerged by static surface water <1.0 m deep.	Same as unit **aa**.	Same as unit **aa**.	Depressions with centripetal drainage, often contain static bodies of water; probably due to seasonal dewatering of surrounding dunes as well as surface snowmelt; impermeable at shallow depth due to perennially frozen sediments.	Not determined, generally believed to be shallow (<2 m, see text).	Fluctuate annually; boundaries extended due to thaw, dessication, and deflation; boundaries retreat due to active dune transgression and to erosion by streams.	Generally very low angle in basins; gradational slopes at margins into adjacent units. Partially frozen erosional remnants of dunes, often with high angle slopes occur within basins. Stability varies from good (frozen basin floors), to moderate (partially thawed low-angle slopes), to poor (partially thawed moderate to steep slopes). Artificial cuts unstable when thawed due to high moisture content.	Fair to moderate when frozen, poor when thawed and/or saturated.
Pingo–P	A suprapermafrost feature associated with various map units, as indicated by * under "Ice content and type." Because of their size and potential hazards, pingos are indicated on the surficial geologic maps.		Massive ice lenses, formed within saturated sediments above the permafrost zone. Ice accumulates due to groundwater flow to a freezing interface (see text). Resultant ice mass circular or eliptical in plan view, with a convex upper surface.	Not applicable.	Not applicable.	Surface tundra mat and soil fragmented due to ground heave; resultant mounds 10-20 cm in diameter.	Rills forming radial pattern develop from crest of pingo, rills follow fragmented tundra cracks; crest often possesses small crater, which may contain a small pond; if pingo is thawing, springs may emanate from crest or flanks; small alluvial fans sometimes occur at toe of slopes due to rill wash of silts and sands.	Not applicable.	Not applicable.	Slopes uniformly steep, up to 20° inclination, crests small and rounded, or cratered; toe of slopes gradational for several tens of meters until map unit slope attained. Surface of slopes somewhat unstable due to cracking, high angle, and sporadic surface runoff.	Very poor due to release of very large volume of meltwater. Static conditions of pingos should not be disturbed by excavation or surface compaction.



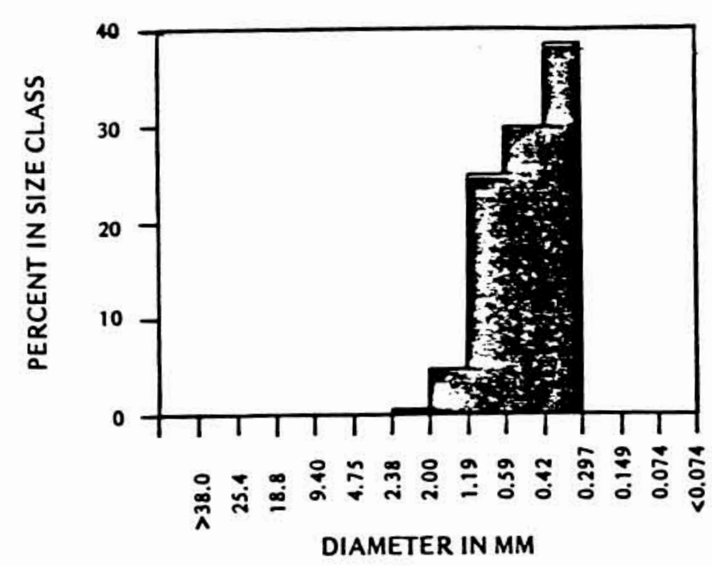
DELTAIC SANDY-SILT
SAGAVANIRKTOK RIVER
(Unit ad)



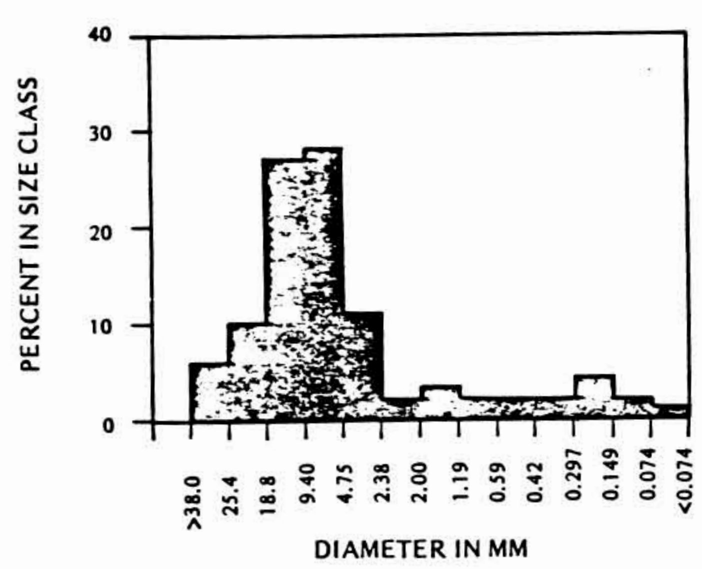
DELTAIC SANDY-SILT
KUPARUK RIVER
(Unit ad)



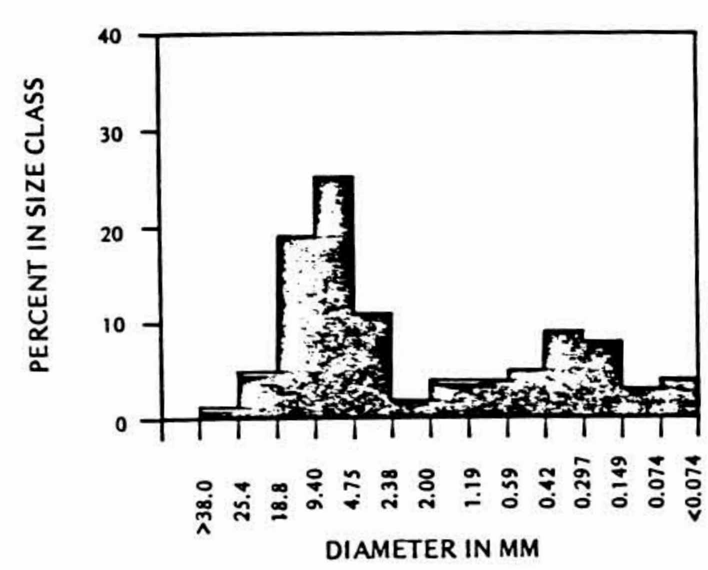
SILTY-SAND FROM ACTIVE DUNE
WEST OF SAGAVANIRKTOK RIVER
(Unit aa)



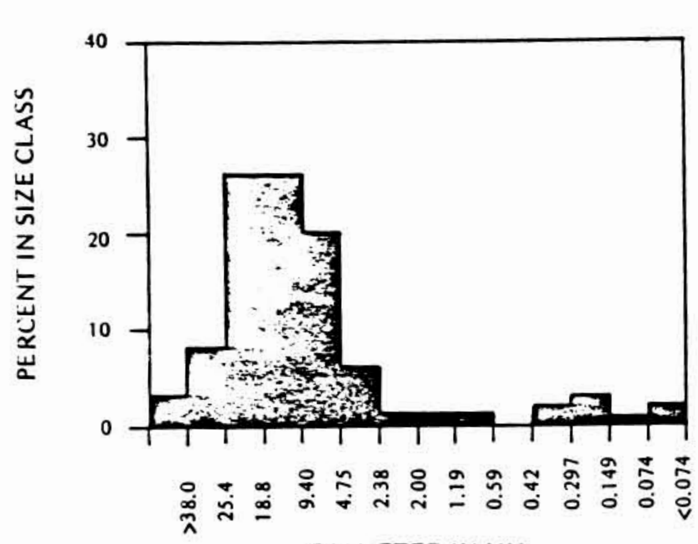
SANDY-SILT COVER ON INACTIVE FLOODPLAIN
SAGAVANIRKTOK RIVER
(Unit if)



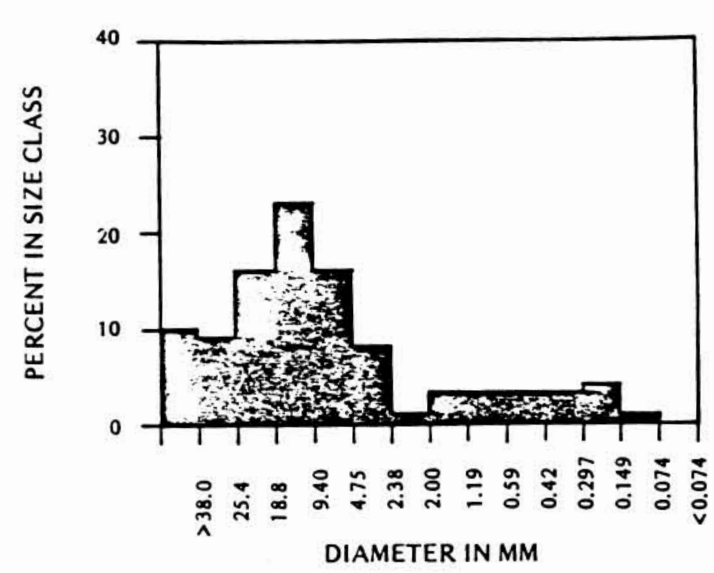
SANDY-GRAVEL FROM ACTIVE CHANNEL
PUTULIGAYUK RIVER
(Unit af)



SANDY-GRAVEL FROM INACTIVE FLOODPLAIN
SAGAVANIRKTOK RIVER
(Unit if)



SANDY-GRAVEL FROM ACTIVE CHANNEL
SAGAVANIRKTOK RIVER
(Unit af)



SANDY-GRAVEL FROM ACTIVE CHANNEL
KUPARUK RIVER
(Unit af)

PLATE 17. HISTOGRAMS SHOWING RELATIVE PARTICLE SIZE DISTRIBUTION OF SEDIMENT SAMPLES REPRESENTATIVE OF SURFICIAL GEOLOGIC MAP UNITS.