Permafrost and Ground Water in Alaska

By DAVID M. HOPKINS, THOR N. V. KARLSTROM, *and* OTHERS

A SHORTER CONTRIBUTION TO GENERAL GEOLOGY

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A study of the interrelations of permafrost and ground water, and a discussion of the role of aerial photographs in the mapping and evaluation of permafrost conditions. Includes descriptions of areas by Robert F. Black, John R. Williams, Troy L. Péwé, Arthur T. Fernold, and Ernest H. Muller.

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A SHORTER CONTRIBUTION TO GENERAL GEOLOGY

PERMAFROST AND GROUND WATER IN ALASKA

By David M. Hopkins, Thor N. V. Karlstrom, and Others*

ABSTRACT

The distribution of ground water in Alaska affects and is affected by the distribution of permafrost. Present knowledge of permafrost and ground-water conditions is summarized for the following representative areas of Alaska: The Arctic slope and northern Seward Peninsula in the continuous-permafrost zone; southern Seward Peninsula, the Yukon Flats, the middle Tanana Valley, and the upper Kuskokwim Valley in the discontinuous-permafrost zone; the Bristol Bay region in the sporadic-permafrost zone; and the Kenai lowland in the no-permafrost zone. The application and limitations of aerial-photograph interpretation in permafrost studies also are discussed.

Regional climatic differences result in a transition from thick, continuous permafrost in northern Alaska to permafrost-free terrain in southern Alaska. However, local differences in topography, lithology, and drainage result in sharp local differences in the character and distribution of permafrost that tend to obscure the regional zonation. Moreover, frozen ground formed during past cold periods persists to the present time in many areas, so that the distribution pattern is not exclusively the product of present-day climates.

Much of the ancient frozen ground is differentially thawing today. Recently formed frozen ground also thaws locally where natural or artificial alteration of the landscape alters the thermal regimen of the ground. Thus, both recent and ancient permafrost are interrupted horizontally and vertically by thawed zones through which ground water may circulate. Conditions that favor active circulation of water, both at the surface and at depth, promote thawing of permafrost and retard formation of new permafrost. Consequently, potential aquifers are similar in character but more restricted in size and abundance in permafrost areas than in areas of no permafrost.

Aerial photographs are almost indispensable to geomorphic studies in Arctic and subartic regions. Their use permits recognition of many features and geomorphic relationships difficult to discern on the ground and allows controlled extrapolation of field data into nearby areas. However, many geomorphic interpretations based solely on a study of aerial photographs are inadequate; to be valid, photointerpretation must be supported by field observations.

Photointerpretation is also of potential assistance in the evaluation of permafrost conditions, but the limitations of the method are even more stringent here than in more general geomorphic studies. The detailed boundaries of permafrost cannot be delineated by photointerpretation alone, but a generalized estimate can be developed by establishing, preferably by field studies, the regional distribution pattern of frozen and unfrozen zones in various types of terrain. These terrain types then can commonly be mapped from aerial photographs.

Assessment of permafrost conditions is aided by recognition on aerial photographs of positive and negative indicators such as certain plant associations, polygonal microrelief patterns, surface features produced by local thawing of permafrost, pingos, and hydrologic phenomena such as flood-plain icings. Individual indicators are found to be ambiguous to varying extents, erratically distributed, and generally difficult to recognize even on large-scale photographs. With rare exceptions, no single feature recognizable on aerial photographs can be taken as an infallible indication of the presence or absence of permafrost. When considered collectively in the context of the geologic and climatic setting, the significance of the indicators increases, but the limitations remain severe.

Comprehensive photointerpretation keys for the photointerpretation of permafrost are extremely difficult to construct and are practically useless as a tool for the interpretation of permafrost conditions because of the poor relationship between surface manifestations and underlying permafrost.

INTRODUCTION

An adequate supply of water is essential for intensive land utilization throughout the world. The needs of pioneer communities commonly can be satisfied by small amounts obtained from minor streams, caught in cisterns, or melted from snowdrifts that persist during most of the summer. The establishment of large towns, industrial centers, agricultural communities, or military bases, however, results in an increased demand for water and an increased danger of contamination of local surface supplies. The distribution system necessary to import water from distant sources is costly to construct, is subject to sabotage or military attack, and, in cold regions, must be protected from freezing. (See Alter, 1950a, 1950b, and unpublished report.[1]) Development of local ground-water

*Robert F. Black, John R. Williams, Troy L. Péwé, Arthur T. Fernald, and Ernest H. Muller.

[1] Alter, A. J., 1950, Water-supply problems in low-temperature areas: Mimeo, rept. distributed at the 1st Alaska Sci. Conf., Washington, D. C., 13 p.

resources, therefore, can aid materially in the growth of population centers in northern regions.

Water supply is one of the factors limiting settlement of many parts of Alaska and restricting the expansion of some existing communities. Surface water in Alaska commonly is poor in quality owing to a heavy silt load in some streams and a high organic content in others. Many surface streams in the colder parts of Alaska dry up during winter and thus do not offer a dependable supply of water. A few coastal settlements, such as Kotzebue, have been established in areas without surface streams. Obviously, ground-water supplies are increasingly needed for the further development of Alaska.

The distribution of ground water in many parts of Alaska affects and is affected by the distribution of permafrost. General geological and geographical investigations by the Geological Survey have resulted in the accumulation of considerable information on ground-water and permafrost conditions in some representative areas. This report is a summary of data that have been collected in these areas (pp. 118–134) and of generalizations formulated (pp. 115–118) concerning the distribution and interaction of permafrost and ground water in Alaska. Aerial photographs are useful aids in the search for ground water and the exploration of permafrost, but their strictly supplementary role has been misunderstood by several nongeological authors. The use of aerial photographs in permafrost studies and the significance of certain patterns recognizable on aerial photographs for the interpretation of permafrost conditions are discussed on pages 134–143.

DEFINITIONS

Several of the geologic and botanical terms used in this paper may not be well known; some terms have been used by other authors in different ways. The writers' usage of these terms is given below.

Permafrost is defined by Muller (1947, p. 219) as "a thickness of soil or other surficial deposit or even of bedrock, at a variable depth beneath the surface of the earth in which a temperature below freezing has existed continuously for a long time (from two to tens of thousands of years)." *Perennially frozen ground* (Taber, 1943, p. 1436) and *pergelisol* (Bryan, 1946) are equivalent terms. The character of permafrost in various sediments, soils, and rock types is discussed by Muller (1947), Taber (1943), Black (1951), and Ray (1951).

The *active layer* is the thin surface layer of the ground that freezes in winter and thaws in summer (Muller, 1947, p. 213). The base of the active layer commonly but not invariably coincides with the top of permafrost. *Seasonally frozen layer* is an equivalent term.

A *pingo* is an isolated steep-sided hillock 10 to 50 feet high that is composed of a core of massive ice overlain by a few feet of silt, sand, and peat (Porsild, 1938). Pingos generally appear suddenly during the winter, persist for a few years, and ultimately collapse when the ice core melts. *Hydrolaccolith* is an equivalent term (Muller, 1947, p. 217).

Flood-plain icings, also called *aufeis* or "*glaciers*"—are thick masses of ice that cover large areas on valley floors of nearly every large Arctic and subarctic stream. They form in reaches where drainage is blocked by ice freezing to the bottom of the channel during early winter. Water breaks through to the surface near the upstream end of the constriction, flows in thin sheets over the flood plain, and freezes. Successive sheets of overflow ice build up icings as much as 10 feet thick. Most of them on Seward Peninsula melt during late summer, but many icings on the Arctic slope persist several years without melting.

Tundra in this report refers to a wide variety of vegetation types that are found above or beyond the latitudinal and altitudinal limits of trees in central and northern Alaska (fig. 11). *Muskeg* is a tundralike vegetation occupying swampy areas scattered in the forests of interior Alaska; however, muskeg may contain scattered black or white spruce trees of poor growth form.

Bog flats[2] consist of irregular areas overgrown by black spruce and *Sphagnum* mosses interspersed among slightly lower marshy areas in which the vegetation consists chiefly of sedges and *Sphagnum* mosses. The bog-flat association is a characteristic cover on poorly drained, gently sloping or flat surfaces within the interior forest.

Cottongrass is the common name applied in Alaska to plants of the genus *Eriophorum.* The grasslike plant bears a white, cottony flower during its blooming season.

ACKNOWLEDGMENTS

This report is the product of the experience of many members of the Geological Survey. D. B. Krinsley, D. R. Nichols, and L. L. Ray, geologists, and W. S. Benninghoff and R. S. Sigafoos, botanists, and the individual authors of parts of this report contributed many of the ideas and generalizations presented throughout the report. The group is not in complete agreement concerning some of the generalizations presented; for

[2] Drury, W. H., Jr., 1951, Formation and destruction of bog flats in some areas of perennially frozen ground: Paper presented in Section G (Botanical Sciences) of 118th Annual Meeting of Am. Assoc. for Advancement of Science.

these the senior authors, Hopkins and Karlstrom, accept complete responsibility.

D. J. Cederstrom, of the Geological Survey, conducted test-drilling projects in search of ground water in several parts of Alaska and collected data on existing wells (Cederstrom, 1952). A later, more general study of ground-water occurrences and development in permafrost regions (Cederstrom, Johnston, and Subitzky, 1953) was made available in manuscript form to the authors of the present report. The United States Smelting, Refining and Mining Co. and its subsidiary, the Fairbanks Exploration Co., generously made unpublished records of extensive prospect drilling near Nome and Fairbanks available. Many other mining companies, salmon canneries, government agencies, and private individuals contributed data that aided this work significantly.

The descriptions of bedrock geology are largely generalized from Geological Survey bulletins and professional papers too numerous to cite individually. Smith (1939) summarizes the bedrock geology in more detail than is possible here and gives an extensive bibliography for most of the areas discussed. Most of the climatic data were compiled by the U. S. Weather Bureau (1943).

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REGIONAL ZONATION OF PERMAFROST

On the Arctic slope of Alaska (fig. 5), soils, sediments, and bedrock are frozen nearly everywhere to depths of about a thousand feet. Southward, perennially frozen ground is progressively thinner, and permafrost-free areas are progressively more abundant. The Pacific coastal region of Alaska is nearly free of permafrost. Local differences in topography, lithology, and drainage result in sharp local differences in the character and distribution of permafrost that tend to obscure the regional zonation. For example, permafrost conditions in bog-flat areas in central Alaska differ more sharply from conditions in nearby flood-plain areas than they do from bog-flat areas along the coast of Cook Inlet in southern Alaska.

For purposes of description, four permafrost zones are delineated on figures 5 and 11, although they are not rigidly defined, and their boundaries must be somewhat arbitrarily drawn. The ground is perennially frozen nearly everywhere in the continuous-permafrost zone; unfrozen ground is found only at a few widely scattered sites. Perennially frozen ground is less widely distributed in the discontinuous-permafrost zone, and areas of unfrozen ground predominate in the southern part. In the sporadic-permafrost zone perennially frozen ground is confined to isolated sites where vegetation, topography, soil, and drainage permit its continued existence or its formation. Permafrost also is encountered locally in the no-permafrost zone, but is so rare as to have little influence on the landscape or human activities.

FACTORS AFFECTING THE DISTRIBUTION OF PERMAFROST

PAST AND PRESENT CLIMATES

Permafrost in Alaska is a product of both the present climate and of colder climates that have prevailed at interrupted intervals during the past hundred thousand years (Péwé and others, 1953). The regional transition from thick, continuous permafrost in northern Alaska to the permafrost-free terrain of southern Alaska reflects present and past regional climatic differences.

New permafrost forms today in all three permafrost zones and possibly in a few exceptional sites in the no-permafrost zone. If the present climates persist unchanged for an indefinitely long time, materials at the base of the zone affected by annual temperature fluctuations ultimately will have temperatures approximately equal to the local mean air temperatures. Linear temperature gradients will be established at greater depths, and heat loss to the air will be balanced by heat flow from the interior of the earth. Permafrost will reach thicknesses determined by the equilibrium between local mean air temperatures and heat flow from the earth's interior, and all of the permafrost can be said to be in equilibrium with the climate of that time (Birch, 1948; Reduzobov, 1954).

Heat loss at the surface was greater during past cold periods, and consequently permafrost extended to greater depths and developed in places where it cannot form today. Much of the ancient frozen ground is slowly thawing as geothermal gradients approach equilibrium with the present climate, but much has persisted to the present time. Relict masses of frozen ground are found chiefly in impermeable soils and rocks, commonly adjoined or overlain by permeable layers and zones that have been thawed by circulating ground water. Recently formed permafrost also thaws in areas where artificial or natural alteration of the landscape alters the thermal regimen of the ground. Thus, permafrost of both ages is interrupted hori-

FIGURE 5.—Index map of Alaska showing permafrost zones.

zontally and vertically by thawed zones in which ground water can circulate.

LOCAL ENVIRONMENTAL FACTORS

The local distribution of permafrost is determined largely by subsurface drainage and surface insulation. In the rigorous climate of northern Alaska, local differences in these conditions generally result only in differences in the depth to permafrost. Farther south, differences in drainage and insulation can determine the presence or absence of permafrost, and in southern Alaska permafrost is found only in materials and areas where the combination of these factors is extremely favorable.

The role of insulating surface materials upon the formation and preservation of permafrost is well known (Muller, 1945, p. 6–10, 33–34; Black, 1951, p. 278–279). In general it may be said that permafrost lies at shallowest depth in areas mantled with peat, organic silt, or a dense mat of living vegetation, and it lies at greatest depth beneath bare gravel or in exposed bedrock. Recently formed permafrost in southern Alaska is found only in areas mantled with a thick layer of peat or silt; the rare permafrost found in areas of bare gravel lies well below the zone of annual freezing and thawing and probably is relict.

Permafrost is absent or lies at great depths beneath lakes and ponds throughout Alaska. Bodies of standing water readily absorb the sun's heat during summer; agitation caused by waves carries the heated water to the bottom and sides of shallow lakes and ponds. Heat loss during winter is largely absorbed in converting the water in the ponds into surface ice. Thus, new frozen ground is not formed.

Heat is distributed through earth materials more rapidly by circulating water than by direct conduction. Thus, active circulation of water, both at the surface and at depth, promotes thawing of permafrost and retards formation of new permafrost. Owing to more active water movements, streams generally are underlain by deeper and wider unfrozen areas than are lakes, and coarse, permeable sand or gravel is more likely to be free of permafrost than is impermeable silt. An abundant source of ground water, steep slopes, and coarse, permeable sediments or fractured bedrock favor the presence of unfrozen zones in all of the permafrost regions of Alaska. Because of these relationships, unfrozen zones in the continuous- and discontinuous-permafrost zones generally are good aquifers. All potential aquifers in the sporadic zone are unfrozen, and frozen ground occurs only where the material is relatively impermeable.

Differences in the factors affecting drainage, insulation, and exposure are sufficient in adjacent areas of contrasting topography to produce appreciable differences in the relative proportions and systematic distribution of permafrost. For example, permafrost commonly is more widely and continuously distributed at shallow depth in extensive lowlands than in adjoining areas of more rugged relief, because near-surface circulation of ground water generally is restricted in the lowlands by fine-grained soils and gentle slopes. Surface drainage also is impeded, and consequently a thick, insulating layer of peat or turf is likely to develop over much of the lowland surface. Thick peat and shallow permafrost are self-perpetuating because they further impede surface and subsurface drainage.

Relatively little information is available concerning the distribution of permafrost in mountainous areas. It can be argued on theoretical grounds, however, that unfrozen zones at shallow depth are likely to be more common in mountains than in adjoining areas of low relief, despite the colder climates characteristic of high altitudes. A thick snow cover insulates the ground from deep freezing during winter and furnishes abundant melt water in spring to promote thawing of the seasonally frozen ground. Surface drainage is good on steep mountain slopes. Discontinuous coarse-grained soils overlying frost-shattered bedrock on ridges, and coarse-grained till and outwash in mountain valleys, permit active near-surface circulation of ground water and result in good subsurface drainage. Vegetation commonly is sparse, and any thick turf or peat mats present are likely to be confined to broad interfluves and to a few poorly drained areas in valley bottoms. These factors permit surface water to infiltrate during summer and to carry heat to considerable depths beneath the surface. Consequently, abundant unfrozen zones at shallow depth can be expected in mountainous areas, especially on south slopes. The most favorable sites for formation or preservation of permafrost in mountain areas are on north slopes and beneath poorly drained surfaces on broad interfluves and valley bottoms.

Past glaciations and orogenic events also are factors affecting the distribution of perennially frozen ground in areas of high relief. Most mountain ranges in Alaska were occupied by valley glaciers, and several ranges were completely buried beneath ice during cold periods of Quaternary age (Péwé and others, 1953). The large areas insulated by ice were protected from low air temperatures at the same time that perennially frozen ground was forming to great depths in adjoining ice-free lowlands. Permafrost beneath glaciated surfaces has formed largely in periods of less cold

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climate during and since deglaciation and thus probably is limited to relatively shallow depths.

Many mountain ranges in Alaska have been actively rising during Quaternary time. Steepened thermal gradients due to orogenic heat or cooling granite bodies in these ranges probably have limited the depths to which freezing temperatures can penetrate during both glacial and interglacial periods. Thawing of relict permafrost also probably proceeds more rapidly in mountain areas of orogenically steepened thermal gradients than in adjoining lowlands where there has been no recent orogenic activity.

Permafrost conditions in upland areas of rolling topography generally are intermediate between those of lowlands and mountains in the same region.

FACTORS AFFECTING THE DISTRIBUTION OF GROUND WATER

Supplies of ground water in central and northern Alaska are limited by the perennially frozen conditions of many potential water-bearing soils and rocks. It was shown earlier, however, that the few unfrozen zones found in the continuous-permafrost zone generally are good aquifers, and that many potential aquifers in the discontinuous-permafrost zone and nearly all the potential aquifers in the sporadic zone are unfrozen. Thus, the ground-water distribution pattern in permafrost regions is similar to but more restricted than the pattern of ground-water distribution in geologically analogous regions that are free of permafrost.

Low precipitation is a factor potentially limiting ground-water supplies throughout much of Alaska away from the Pacific coast. Anchorage, about 70 miles inland from the open ocean, receives a mean annual precipitation of 15 inches; most of interior and northern Alaska receives less. Even the relatively humid coast of the Bering Sea north of Bristol Bay has a mean annual precipitation of less than 20 inches. However, low temperatures, high humidities, and prevailingly cloudy skies minimize the rate of evaporation and tend to conserve the small total precipitation for surface and ground-water supplies.

Low infiltration rates reduce the rate of ground-water recharge in many parts of Alaska. Thick layers of eolian, fluvial, and residual silt mantle most areas of low to moderate relief and retard downward percolation of surface water. Peat-forming vegetation grows on these poorly drained, flat and gently sloping surfaces and further diminishes subsurface drainage. Transpiration returns some of the moisture to the atmosphere. In cold areas shallow permafrost forms readily beneath the poorly drained surfaces and tends to seal off deeper aquifers. In slightly warmer areas the deep layer of frozen ground formed each winter persists through most of the summer, so that surface water can infiltrate only during a few weeks preceding autumn frosts. When no frozen ground is present, water slowly filters through the fine-grained surface materials and carries particles of silt and clay downward to be deposited in underlying coarser sediments. Permeability in potential aquifers at shallow depth is thus reduced, and percolation to deeper aquifers is further restricted.

PERMAFROST AND GROUND WATER IN SOME REPRESENTATIVE AREAS

ARCTIC SLOPE

By R. F. Black

PHYSIOGRAPHY, CLIMATE, AND VEGETATION

The Arctic slope lies entirely within the continuous-permafrost zone (fig. 5). It is bounded on the south by the crest of the Brooks Range and on the north by the Arctic Ocean. It consists of three main provinces: the Brooks Range, the Arctic foothills, and the Arctic coastal plain (Payne and others, 1951). The Brooks Range, the Alaskan counterpart of the Rocky Mountains, comprises several groups of rugged, glaciated mountains having a relief of 3,000 to 6,000 feet and maximum altitudes of 3,600 to 9,200 feet. The Arctic foothills province is a hilly region between the mountains and the coastal plain. It is divided topographically and geologically into the southern foothills, characterized by irregular topography with isolated hills and ridges that rise 500 to 2,000 feet above areas of low relief, and the northern foothills, characterized by persistent ridges, mesas, and hills generally of 500 to 1,000 feet relief and having approximately accordant summits. The Arctic coastal plain is characterized by abundant lakes and swampy areas, wet tundra, and meandering streams. Local relief rarely exceeds 100 feet.

The climate on the Arctic slope is cloudy, cold, and windy. The annual mean temperature is 10° F at Barrow on the Arctic coast and 10.8° F at Umiat, 175 miles to the southeast. The recorded extreme temperatures are 79° and −57° F at Umiat and 78° and −56° F at Barrow. July, the warmest month, has an average of 13 days of freezing temperatures at Barrow. Mean annual precipitation is 4.2 inches at Barrow and 5.4 inches at Umiat. Half the precipitation is represented by rainfall during the months of July, August, and September. Annual snowfall is about 29 inches at Barrow and 33 inches at Umiat.

The Arctic slope lies beyond the north limit of spruce. Tall willows, alders, and scattered poplars grow along the channels of large streams in the southern part of the region. Tundra vegetation consisting primarily of dwarf shrubs, grasses, sedges, lichens, and herbaceous plants cover all other areas.

GEOLOGY

The Brooks Range consists of limestone, schist, phyllite, and quartzite in the southern part and complexly folded and faulted sandstone and limestone in the northern part. Moraines and gravel outwash terraces are common in most valleys. Most slopes are partly covered with frost-rived rubble, but bedrock outcrops are abundant.

The Arctic foothills consist of shale, sandstone, conglomerate, limestone, and chert. The rocks of the southern foothills are tightly folded along east-west axes; the rocks of the northern foothills are more broadly folded and have a regional northward dip. Moraines are conspicuous along the south border of the Arctic foothills province near the mouths of large valleys of the Brooks Range. Gravel outwash terraces are common along parts of most major streams. Windblown silt is widespread but generally is thin and mixed with frost-stirred soil derived from underlying bedrock.

Unconsolidated silt and sand of the Gubik formation covers the Arctic coastal plain. Siltstone and sandstone underlie the unconsolidated mantle at depths of a few tens of feet. Regional dips are low and variable in direction but are generally northward.

PERMAFROST

Permafrost is present nearly everywhere beneath the Arctic slope of Alaska. Frozen ground generally extends to a depth of at least 1,000 feet; thicknesses ranging from 600 to 1,300 feet are recorded in wells near Point Barrow on the Arctic coast. The soil thaws in the summer to depths of ½ to 4 feet, depending upon the surface material, drainage, vegetation cover, and exposure.

Permafrost lies at considerable depth or may be absent beneath major rivers, such as the Colville, which flow throughout the winter and have flood plains several thousand feet wide. Permafrost also lies at considerable depth or is absent beneath most lakes deeper than 8 feet and wider than 2,000 feet. It is absent in the immediate vicinity of hot springs and may be lacking in a few other areas in which geothermal gradients are steepened by recent igneous activity.

GROUND WATER

Potable ground water in large quantities is known only in deep lakes and major perennial streams scattered throughout the Arctic slope and in hot-spring areas in the Brooks Range. The low ground temperatures measured in many drill holes indicate that there is little possibility of finding water-bearing thawed zones within permafrost. Potable subpermafrost ground water possibly is available in several untested bedrock formations of favorable lithology and structure in the Brooks Range and the Arctic foothills. Subpermafrost water encountered in wells in the Arctic coastal plain, however, has a salinity of several thousand parts per million.

Several hot springs are known in the Brooks Range. The largest are the Shublik Springs on the Canning River (Leffingwell, 1919, p. 58–59). The springs emerge at the contact of the Lisburne limestone and the overlying Sadlerochit sandstone, and they discharge an estimated 1,000 gallons per minute (Marvin Mangus, U. S. Geological Survey, oral communication). Summer water temperatures of 43° and 48° F are reported. The springs flow all winter and keep the Canning River open in their vicinity. The Sadlerochit Springs on the Sadlerochit River are about the same size but may be slightly warmer. Other, much smaller, springs are reported on the Sagavanirktok River, the Shaviovik River, and the Okpilak River, but it is not known whether these springs flow throughout the winter. Other perennial springs may be present.

Flood-plain icings are present on nearly every trunk stream on the Arctic slope and indicate that some flow of water continues after the fall freezeup. The water may originate within the stream channel, within the bed of the stream, in terrace gravel, in local gravel fill associated with lakes, or from springs in bedrock. Areas upstream from icings thus are relatively favorable sites for near-surface ground-water prospecting.

Ground water may be available in unfrozen zones beneath some lakes more than 8 feet deep and 2,000 feet wide. A few such deep lakes are scattered over the Arctic coastal plain; they are less common within the Brooks Range and are rare in the Arctic foothills. Their beds commonly consist of unconsolidated silt or clay resting on bedrock of various types. Each lake presents individual problems in determining amount and quality of ground water available.

The Lisburne limestone and the overlying Sadlerochit sandstone are among the most widespread formations in the Brooks Range, and because of favorable structure and lithology they are the most likely reservoirs of ground water below permafrost. No wells have been drilled in them, and no geologic investigations for ground water have been made.

NORTHERN SEWARD PENINSULA

By D. M. Hopkins

PHYSIOGRAPHY, CLIMATE, AND VEGETATION

Seward Peninsula north of the Kigluaik Mountains and east of Cape Darby lies in the continuous-permafrost zone (fig. 5). Lowland areas with local relief of generally less than 100 feet are interspersed in rolling uplands with relief of up to 2,000 feet and mountains locally reaching altitudes of 4,000 feet.

Northern Seward Peninsula has a cold, rigorous climate strongly continental in the eastern part but moderated somewhat by oceanic influences in the western part. The mean annual temperature ranges from 20.3° F at Candle to 26.4° F at Shishmaref. Recorded extreme temperatures are 85° and −60° F at Candle and 73° and −45° F at Shishmaref. Mean annual precipitation ranges from about 7 inches at Candle and Shishmaref to 14.9 inches at Wales. More than half the annual precipitation occurs during a well-defined rainy season from July through September. Annual snowfall ranges from 30 inches at Candle to 34 inches at Shishmaref.

Winters are cold and relatively dry; clear weather predominates, but intense storms accompanied by high winds and precipitation are frequent. Summers are cool and moist, especially in the western part of the peninsula; a low overcast and drizzle are common, and few days pass without at least a trace of precipitation.

Vegetation throughout most of northern Seward Peninsula is tundra consisting chiefly of dwarf shrubs, sedges, grasses, other herbaceous plants, lichens, and mosses. Large shrubby willows are found along watercourses. Alder thickets are scattered on the steep, well-drained slopes of the mountains and hills in the east. Spruce trees are confined to hill slopes and river flood plains of the eastern part of the area (fig. 11). Isolated stands of cottonwood trees occur locally in the east and southwest.

The vegetation on well-drained slopes mantled with muck or windblown silt consists primarily of cotton-grass tussocks, dwarf birch, and heath shrubs. A sod of dense sedges (*Carex*) grows on poorly drained hill summits and slopes, in minor drainage courses, and around the margins of many ponds.

Terraces and upland surfaces having gravelly or rocky soils and lacking a mantle of windblown silt support an inconspicuous cover of low, matted woody plants and dwarf grasses generally less than 12 inches high. Rocky or gravelly soils derived from siliceous bedrock bear dwarf birch and heath shrubs commonly separated by patches of bare ground. Mats of *Dryas* and other dwarf tufted plants grow in isolated patches or form a complete turf cover on calcareous rocks.

GEOLOGY

Bedrock throughout most of the area consists of metamorphic rocks; schist predominates, but extensive outcrops of marble are present. Granite stocks are present at several localities. Folded unmetamorphosed limestone predominates in the York Mountains. Belts of folded sandstone and shale extend across the peninsula from the east edge of Kotzebue Sound to Norton Bay. Quaternary lava flows cover large areas near Imuruk Lake and in the valley of the Koyuk River.

Lowland areas are underlain by unconsolidated sediments as much as several hundred feet thick. The fill generally consists of 10 to 20 feet of silt, muck, and peat over thick layers of gravel. In a few areas, however, the lowland fill consists almost entirely of fine-grained sediments and includes only scattered lenses of gravel. Aprons of alluvial gravel mantled with only a few feet of silt and peat occur along the coast north of Teller and at the margins of some lowland areas adjoining the Bendeleben Mountains. Volcanic ash mantled with 10 to 20 feet of silt, muck, and peat underlies a large area south of Cape Espenberg.

Most upland ridges (cross section, pl. 30) are mantled by a few feet of windblown silt beneath which lies frost-rived bedrock rubble; on some ridges the rubble is exposed. The fine-grained mantle thickens in saddles and on slopes, reaching a thickness of several tens of feet on the lower slopes. Swales and minor valleys generally are underlain by V-shaped bedrock gullies filled with 20 to 50 feet of unconsolidated sediments. This fill generally consists of 2 to 6 feet of gravel overlain by silt, muck (silt rich in organic debris), and peat. The flood plains of larger valleys generally are underlain by 5 to 30 feet of gravel and a few feet of silt.

The bedrock of the upper slopes and summits of mountain ridges is mantled by 5 to 10 feet of coarse rubble. Gravelly glacial till as much as 50 feet thick is present on lower valley walls. Valley floors are covered with alluvial and outwash gravel several tens of feet thick. A young fault scarp extends for 20 miles along the south front of the Bendeleben Mountains. Glacial moraines and alluvial fans are displaced locally.

Bare rock is exposed throughout areas occupied by the youngest Quaternary lava flows. Coarse, openwork rubble as much as 10 feet thick mantles areas underlain by slightly older flows. Still older flows (cross section, pl. 31) are covered with silty soil 1 to 20 feet thick.

Permeable beds of gravel or flow breccia are interstratified with lava flows at depths of 50 to 200 feet.

PERMAFROST

Subsurface materials are perennially frozen nearly everywhere in northern Seward Peninsula except beneath and near lakes, channels of perennial streams, some ocean beaches, and hot springs. The frozen layer ranges in thickness from 15 to more than 260 feet; in most places subsurface materials probably are perennially frozen to depths of at least 200 feet.

The surface layers of the soil thaw to depths of 1 to 10 feet, depending on the surface material, vegetation cover, and exposure. In general the depth of summer thaw increases with increase in coarseness of surface material and sparseness of vegetation. Depth of thaw is less on steep north slopes than on steep south slopes; the difference is imperceptible, however, on slopes of less than 15°.

Unfrozen zones within permafrost are scarce and generally localized by conditions that promote ground-water circulation. Thus, the bed gravels of the larger streams generally are unfrozen, and unfrozen zones are common in weathered bedrock and basal gravel beneath flood plains and low terraces (cross section, pl. 30). Improved ground-water circulation in the vicinity of abandoned underground mine workings commonly results in maintenance of thawed zones in their vicinity. Unfrozen zones, probably in flow breccias, are indicated in areas of Quaternary lava flows by springs and closed depressions having interior drainage (cross section, pl. 31). The presence of springs in many places indicates that unfrozen fracture zones are common in marble or limestone bedrock. Unfrozen zones are scarce in terrain where other rock types are at the surface and extremely scarce in areas mantled by 5 feet or more of silt and peat.

Unfrozen zones probably are more abundant in mountains than in other terrain types because of past glaciation, steepened thermal gradients due to orogenic heating of rocks at depth, steep slopes, coarse-grained soils and sediments, and an abundant supply of surface water from precipitation and melting snow. Unfrozen zones are extremely scarce in lowlands and generally can be found only along the channels of large streams.

GROUND WATER

Unfrozen gravel near and beneath channels of large streams (cross section, pl. 30) constitutes the most dependable and widely available source of ground water in the continuous-permafrost zone in northern Seward Peninsula. Water probably can be obtained from this source in all types of terrain. Surface flow is greatly reduced during the winter and ceases entirely in many streams, but considerable underflow probably is maintained in the channel gravels of the larger streams.

Flood-plain icings are useful guides to ground-water supplies in stream valleys on Seward Peninsula. Many icings are closely associated with perennial springs; others form in reaches where bedrock underlies the stream bed at shallow depth, forcing to the surface water that had been moving through deep channel gravel farther upstream. Thus, perennial supplies of ground water can be expected in stream-bed gravels of stream segments upstream from icings. Some flow probably also is maintained downstream from icings which overlie fairly deep channel gravels. Field measurement of the amounts of ground water available near typical icings would be an important contribution to information concerning water resources in the continuous-permafrost zone and in the northern part of the discontinuous-permafrost zone.

Limited supplies of ground water are available in upland and mountain valleys in unfrozen zones in terrace gravel and in flood-plain gravel around and beneath stream channels (cross section, pl. 30). Water-bearing unfrozen zones are most common at the contact between gravel and bedrock. Ground-water supplies in terraces may diminish sharply during the winter because of lack of recharge.

Unfrozen zones in alluvial fans in the mountains and in alluvial aprons at the margins of some mountain ranges offer large supplies of ground water during summer and limited supplies during winter. Streams crossing the fans lose much or all of their surface flow by percolation into the underlying coarse gravel. The water emerges again as springs near the bases of the fans. Wells should be located along the projected course of the stream, upslope from the springs. Several exploratory wells may have to be driven before an unfrozen zone is encountered.

Limited supplies of ground water may be obtained from thawed zones beneath some lakes. Many lakes, however, are underlain by layers of silt and peat that are incapable of transmitting appreciable quantities of ground water to replace that withdrawn during pumping. Moreover, the thawed zones beneath lakes are likely to be isolated from any source of water except the lake itself (fig. 6).

Locally, large springs are present near the young fault scarp at the south front of the Bendeleben Mountains. It is likely that the fault provides channels along which ground water from the adjoining highlands rises to the surface. Large perennial supplies of ground water probably can be obtained in wells that intersect the fault at depth. Water in the fault zone may be highly mineralized.

Marble, limestone, and basaltic lava flows are promising sources of ground water in bedrock in upland and mountain areas. Unfrozen crevices, lava tubes, and interstratified flow breccias and gravel beds are potential aquifers in basaltic lava (cross sections, pls. 30, 31). Unfrozen fracture zones and solution cavities in limestone and marble are ground-water channels. Wells in rock of these types should be drilled on the lower slopes of hills or in valley bottoms, near known springs, or upstream from large flood-plain icings. Contact zones between marble and schist are especially favorable sites. Several test wells may have to be driven before a productive unfrozen zone is encountered. Natural springs could be developed as sources of ground water at many localities.

Limited ground-water supplies are available during summer and fall above permafrost in the active layer in areas where coarse materials lie at the surface. Summer thaw extends to depths of 6 to 10 feet in coarse gravel or rubble. Water from precipitation and melting snow accumulates in the active layer, where it is retained by irregularities in the surface of the perennially frozen layer. A small airbase at Point Spencer, 15 miles west of Teller, derived its entire water supply from suprapermafrost water in beach gravels during operations which extended through summer and late fall.[3] Suprapermafrost water is not available during the winter, however, unless storage is provided in an artificial lake 10 feet or more in depth. Suprapermafrost water is subject to contamination almost as readily as is surface water.

In summary, ground water is abundant throughout the year in the mountainous regions where it can be obtained beneath stream channels, in alluvial fans, in unfrozen zones in coarse-grained glacial deposits on valley walls, and in limestone or marble bedrock. Ground water is much less abundant in the uplands, but adequate supplies can be obtained locally beneath the flood plains of large streams and in basalt, limestone, or marble bedrock. Ground water is extremely scarce in the lowland areas and generally can be obtained only beneath the channels of a few large streams.

SOUTHERN SEWARD PENINSULA

By D. M. Hopkins

PHYSIOGRAPHY, CLIMATE, AND VEGETATION

Seward Peninsula south of the north front of the Kigluaik Mountains and west of Cape Darby lies in the discontinuous-permafrost zone (fig. 5). Most of this area consists of rugged uplands. Lowlands extend along much of the coast and inland along several large streams. The topography is generally similar to that of northern Seward Peninsula but the uplands are more rugged and have steeper slopes and wider valley bottoms.

The climate is cold and rigorous but less strongly continental than that of northern Seward Peninsula. The mean annual temperature is 26.0° F at Nome and 27.1° F at White Mountain, 33 miles northeast of Cape Darby. Recorded extreme temperatures are 89° and −55° F at White Mountain and 84° and −47° F at Nome. Mean annual precipitation ranges from 14.5 inches at the town of White Mountain to 17.7 inches at Nome. Stream-gage records indicate about 50 inches of annual precipitation in the Kigluaik Mountains (Henshaw and Parker, 1913, p. 31). About half the annual precipitation falls during the rainy season, from July through September. Snowfall is notably heavier than in northern Seward Peninsula and ranges from 49 inches at White Mountain to 67 inches at Nome.

Winters are cold, but the temperatures generally are less extreme than those of northern Seward Peninsula. The predominantly clear winter weather is interrupted more frequently by intense storms accompanied by high winds and precipitation. Summers are cool and moist; clear days are unusual at the coast but are more frequent a few miles inland.

The vegetation consists of tundra in the western part and mixed tundra and white spruce forest in the eastern part. A complex assemblage of *Dryas* and heath mats forms a nearly complete cover on moderately well drained slopes west of the partly forested region. Low thickets of birch and heath shrubs grow on river terraces and the best drained hill slopes. Sedge sod that is similar to that which grows on marshy sites in northern Seward Peninsula occurs where the drainage is poor. Willow thickets are more common and more extensive than in northern Seward Peninsula; they grow on river flood plains, along streams, and at sites of ground-water seeps. Dense alder thickets grow on well-drained slopes in the mountains and locally in the uplands.

Spruce forest grows on well-drained soils on the middle slopes of hills, on river flood plains, and along minor drainage channels in the eastern part of the peninsula. The largest trees range from 20 to 50 feet in height, and their trunks attain a maximum diameter of 18 inches. The canopy is open so that sunlight penetrates to the forest floor or to the tops of the underbrush. Dense underbrush of willows and heath shrubs forms thickets under the trees on the upper slopes.

[3] Black, R. F., 1946, Permafrost investigations at Point Spencer, Alaska: U. S. Geol. Survey Permafrost Program Prog. Rept. no. 2, 20 p. (Unpublished report.)

Balsam poplar trees grow in the wetter parts of the forest where some of the spruce trees have been cut for lumber.

GEOLOGY

Bedrock throughout southern Seward Peninsula consists of metamorphic and granitic rocks. Quartz-mica-calcite schist and chlorite schist predominate; marble is abundant. Brittle graphitic slate and graphitic quartzite are present locally.

Most lowland areas are underlain by 100 feet or more of unconsolidated glacial outwash and gravelly till with some marine gravel and sand. A layer of silt, generally less than 6 feet thick, covers the coarse sediments. Lagoons-deposited silt and peat underlie parts of some lowlands.

Most upland and mountain ridges are mantled with frost-rived bedrock rubble 2 to 20 feet thick. Upper slopes are mantled with rocky soil which merges at lower elevations with glacial till 10 to 100 feet thick. The larger valleys of perennial streams are underlain by a few feet of silt and as much as 100 feet of gravel.

A young fault scarp extends several miles along the north front of the Kigluaik Mountains; end moraines and alluvial fans of late Quaternary age are displaced locally. Similar escarpments are present at boundaries between uplands and lowlands in several other localities.

PERMAFROST

Much of the subsurface material of southern Seward Peninsula is perenially frozen, but thawed zones are considerably more abundant than in the northern part of the peninsula (fig. 6). Measured thicknesses of the perennially frozen ground range from a few feet to more than 350 feet; in most places it probably is 100 to 200 feet thick. The surface layers of the soil thaw each summer to depths of 3 to 10 feet.

As in northern Seward Peninsula, thawed zones are localized by conditions that favor ground-water circulation and surface heat absorption. Upland and mountain ridges, generally underlain by frozen ground in northern Seward Peninsula, commonly are unfrozen in southern Seward Peninsula (fig. 6). Slopes of ridges generally are underlain by frozen ground, but unfrozen zones are found locally on south slopes where soil and vegetation are thin. Ground water that percolates into bedrock in the ridge crests commonly emerges as springs and seeps within the till or gravel that mantles the lower slopes. Unfrozen zones are common at the spring line, a few hundred yards below the break in slope that marks the upper edge of these deposits.

Unfrozen zones along perennial streams are more extensive than in northern Seward Peninsula, and they are also found along smaller streams. They are present not only beneath channels and gravel bars but also beneath much of the flood plain. Alluvial fans, common in upland valleys as well as in mountain areas, generally contain extensive unfrozen zones. Ancient beach deposits interbedded with coastal-plain sediments ("second" and "third" beaches, fig. 6; also, see Moffit, 1913, pp. 40–49) generally are unfrozen. Spits, bay bars, young raised-beach deposits, and older gravels

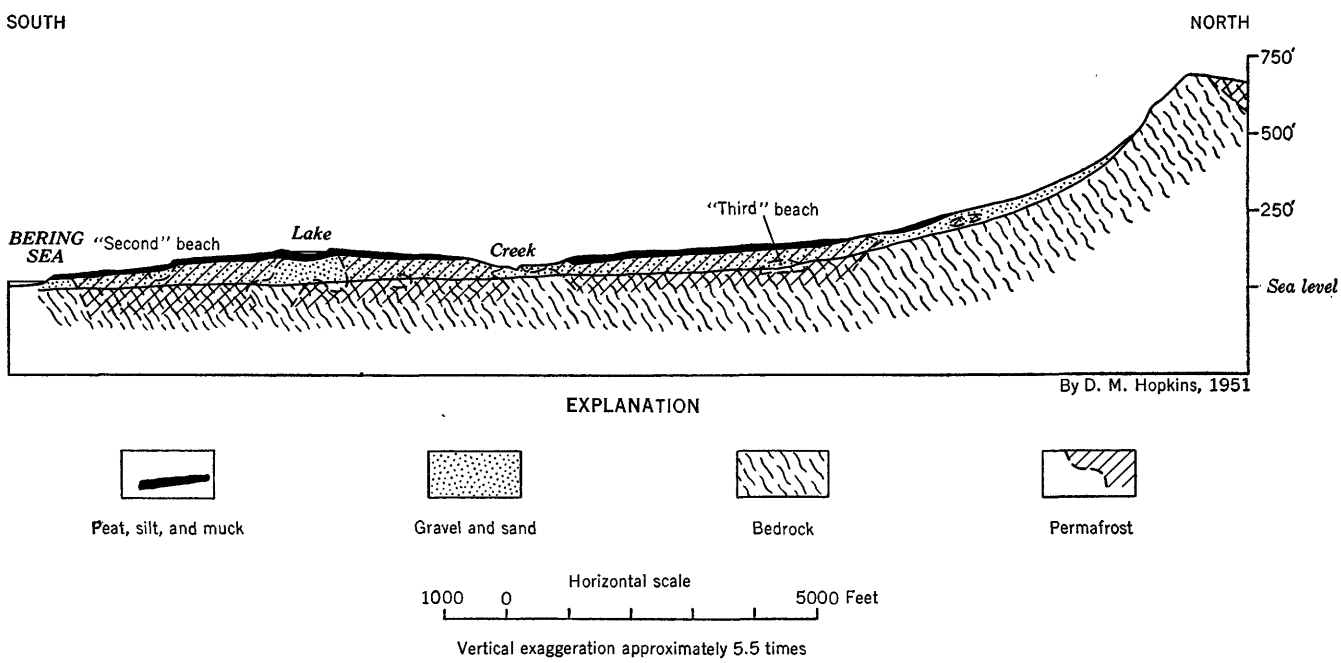

FIGURE 6.—Diagrammatic cross section showing distribution of permafrost in coastal plain at Nome.

within a few hundred feet of the coast generally are unfrozen.

Topographic and stratigraphic characteristics combine with climatic differences to make the thawed zones in each physiographic province more widespread in southern Seward Peninsula than in equivalent terrain in northern Seward Peninsula. As in the northern region, unfrozen zones are most abundant in the mountains, less abundant in the uplands, and relatively scarce in the lowlands. Steeper slopes, wider distribution of coarse-grained unconsolidated sediments, and higher precipitation promote ground-water movement and make unfrozen zones more common in each of these areas, however, than in equivalent areas in northern Seward Peninsula.

GROUND WATER

Ground water is more widely available in the discontinuous-permafrost zone of southern Seward Peninsula than in the continuous-permafrost zone of northern Seward Peninsula, primarily because unfrozen zones are more extensive and widely distributed and secondarily because precipitation is heavier. Large perennial supplies of ground water can be obtained from gravel beneath the flood plains of streams as well as beneath the channels. Streams along which icings occur are particularly promising sources of supply.

Unfrozen zones in alluvial fans in large mountain and upland valleys and at the edges of lowlands contain large supplies of ground water during the summer and smaller supplies during the winter. Wells should be located upslope from springs where ground water emerges at the edges of the fans.

Unfrozen zones beneath lakes in uplands and mountains may offer considerable perennial ground-water supplies. Many of these lakes occupy depressions in morainal topography and are underlain by coarse-grained, relatively permeable sediments. Most of the lowland lakes, however, are underlain by fine-grained impermeable sediments in which ground-water movement is restricted by the same factors that limit the water supply beneath lakes in northern Seward Peninsula.

Large springs are present near young fault scarps. Large perennial supplies of ground water probably can be obtained in wells that intersect these faults, but the water may be highly mineralized. Fractured or cavernous zones in marble commonly are unfrozen and carry considerable supplies of ground water. Large springs are common near contacts between marble and schist. The brittle graphitic quartzite and graphitic slate contain thawed fracture zones in which ground water circulates. Mine shafts in rocks of these types have encountered large flows of ground water. Wells in marble, slate, or quartzite should be drilled on the lower slopes of hills, near known springs, or upstream from flood-plain icings. Several test wells may have to be drilled before a productive thawed zone is encountered. Natural springs could be developed as sources of ground water at many localities.

Marine gravel and sand in spits, barrier bars, raised beaches, and some deltas contain small supplies of ground water and are used as a source of water for households near Nome. Heavy pumping would soon result in contamination by salt water.

YUKON FLATS

By J. R. Williams

PHYSIOGRAPHY, CLIMATE, AND VEGETATION

The Yukon Flats lie in the discontinuous-permafrost zone and consist of a broad lowland extending along the Yukon River from Circle to Stevens (fig. 5). Upstream and downstream from the flats the Yukon is confined to a relatively narrow valley. The flats are about 10,000 square miles in area and are located approximately between 144° and 149° west longitude and 66° and 69° north latitude. Most of the area consists of a complex series of low alluvial terraces that slope gently toward the Yukon River. About a third of the area consists of the flood plain of the Yukon River and its tributaries. The Yukon and several other large streams have built broad gravel fans along the eastern and northern margins of the flats. Bedrock escarpments 100 to 500 feet high, capped with gravel, separate the flats from a rolling upland to the north. A 200-foot escarpment in which bedrock generally is not exposed extends along the south edge of the flats. A gently rolling upland with a relief of approximately 150 feet grades into the flats on the east.

The Yukon Flats are characterized by a cold, continental climate. Fort Yukon, near the center, has a mean annual temperature of about 20° F; recorded extreme temperatures are 100° and −76° F. The mean annual precipitation is 6.67 inches, but annual precipitation ranges from 3 to 10 inches. August is the rainiest month, having a mean rainfall of 1.23 inches. Average snowfall is 42 inches per year.

Summer, considered to begin in May at the breakup of the river ice and to end in September when the first snow falls, is brief and warm. Summer temperatures generally are between 50° and 75° F, but occasionally are as high as 80° to 100° F. Thundershowers are common along tributary valleys and marginal escarpments but rare in the central part of the flats.

Winter is characterized by one to three 2-week periods of extremely low temperatures and calm, clear weather. During the remainder of the winter, temperatures range from 10° to −40° F, and winds are from the north or northeast. Midwinter thaws occur at intervals of several years at the foot of the White Mountains along the south boundary.

Vegetation on the Yukon Flats consists of spruce forest; mixed spruce and birch forest; tall, dense brush; and muskeg vegetation. Mature forests composed dominantly of pure stands of white spruce and secondarily of mixed stands of white spruce and white birch and of white spruce and balsam poplar cover much of the flood plain. The forest on the low terraces has been modified by fires and consists of patches of mature white spruce and white birch mixed with a mosaic of brush types, including stands of young spruce, mixtures of aspen and willow, and thickets of young white birch. Poorly drained areas, especially common on the low terraces, are occupied by muskeg vegetation consisting chiefly of black spruce, sedge tussocks, and *Sphagnum* mosses. Uplands bordering the flats are covered with dense forests of mixed white and black spruce, pure stands of birch, and scattered muskegs. Fire-swept areas in the uplands, like those on the low terraces, are covered with a willow, aspen, and birch scrub.

GEOLOGY

Silt, organic silt, and peat, as much as 25 feet thick, are the principal surficial materials on flood plains, low terraces, and outwash fans. Gravel is present at the surface in river beds, on some low terraces, and on a few of the outwash or alluvial fans (fig. 7).

Alluvial or glacial-outwash gravel and sand, as much as 200 feet in thickness, is present beneath the silt. Bedrock is reported at a depth of 237 feet in a well at Fort Yukon (Mertie, 1937, p. 16). No other information is available on the depth and nature of the bedrock surface beneath the Yukon Flats. Extrapolation from marginal exposures indicates that bedrock probably consists of greenstone and associated sediments of early Mississippian age. Tertiary deposits also may be present beneath the Quaternary alluvium in parts of the basin.

Windblown silt, 4 to 100 feet thick, overlies alluvial gravel on the high terrace south of the Yukon Flats. The silt cover probably thins southward toward the White Mountains. Bedrock lies at depths of more than 150 feet at the northern, frontal edge of the terrace and at shallower depths near the White Mountains.

Sand and gravel, generally less than 30 feet thick and mantled with 1 to 2 feet of silt, covers the bedrock in the gently rolling country beyond the north margin of the Yukon Flats. Rubble occurs at the surface where bedrock is at shallow depth. Creek valleys contain a thick fill of organic silt.

The gently rolling country along the eastern margin of the flats is believed to be underlain by thick deposits

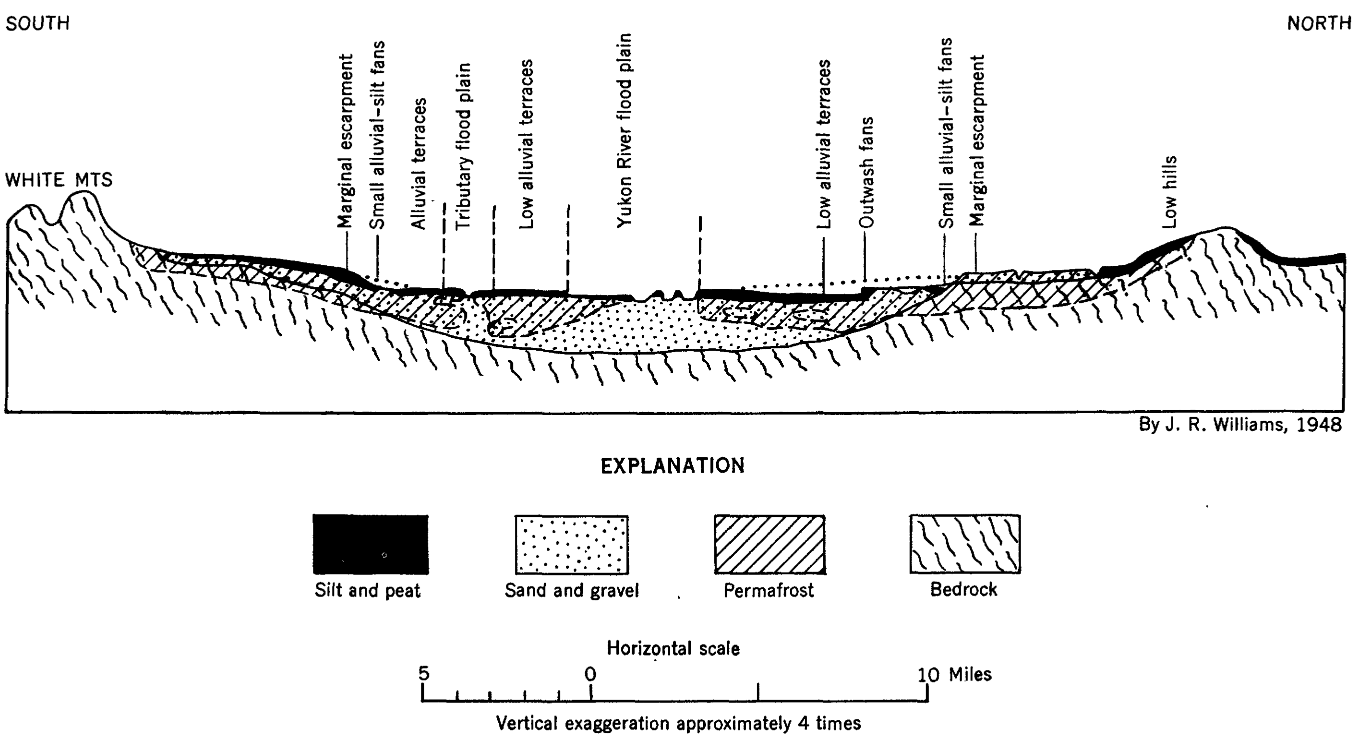

FIGURE 7.—Diagrammatic cross section showing distribution of permafrost in the Yukon Flats.

of windblown silt. The presence or absence of gravel between bedrock and the silt mantle is not known.

PERMAFROST

Subsurface materials are perennially frozen at depths of 1½ to 10 feet in most environments in the Yukon Flats. Test pits 6 to 8 feet deep at several sites failed to encounter frozen material, but frozen ground may be present at greater depth. The thickness of the frozen layer is not known. Drill holes in the low terrace at Fort Yukon penetrated 25 to 89 feet into frozen sand and gravel without passing into unfrozen material.

Unfrozen zones probably are present beneath some large lakes and most rivers (fig. 7). Permafrost is present, however, in some of the higher islands in the Yukon River (Purington, 1905, p. 158). Some streams that cross alluvial fans percolate into the gravel, suggesting the presence of permeable unfrozen zones. Unfrozen zones may be present elsewhere but can be located only by deep drill holes.

Most of the rivers are eroding frozen banks. As the banks are cut back, new deposits of unfrozen sand and gravel are formed on the slip-off slopes of the meanders. These deposits gradually freeze, the frozen layer thickening at an unknown rate. Unfrozen ground thus is most likely to be found in the most recently deposited part of the flood plain (fig. 7).

GROUND WATER

The Yukon Flats are believed to lie in the discontinuous-permafrost zone and thus probably contain permeable unfrozen zones of possible importance for ground-water supplies. The best and most dependable source of ground water consists of thawed gravel beneath beds and slip-off slopes of major streams. Local residents obtain water by driving pipes equipped with sand points into unfrozen gravel along the Yukon River margin. Water filtering through the gravel from the river is silt-free; however, wells driven in these sites are subject to seasonal flooding. Ground water probably can be obtained beneath some large lakes and in local unfrozen zones in gravel fans. A water-bearing unfrozen zone was found beneath permafrost at a depth of 40 feet in a high island in the Yukon River near Eagle (Purington, 1905, p. 158). Water-bearing unfrozen zones may be present elsewhere but cannot be located by ground observation nor by photointerpretation.

MIDDLE TANANA VALLEY

By T. L. PÉWÉ

PHYSIOGRAPHY, CLIMATE, AND VEGETATION

The middle Tanana Valley is that part of the valley of the Tanana River between Big Delta on the east and Nenana on the west (fig. 5). The valley is 50 miles wide and includes an area of about 5,000 square miles. The northern part lies about 100 miles south of the Arctic Circle.

The valley is bordered on the south by the rugged Alaska Range, in which many peaks rise to altitudes of more than 10,000 feet and in which local relief is as much as 4,000 feet. Uplands bordering the north side of the valley consist of rounded hills and ridges about 2,500 feet in altitude, separated by broad valleys containing small meandering streams and many lakes; local relief ranges from 100 to 1,500 feet.

The Tanana River lies near the north side of the valley and is adjoined by a low plain 5 to 25 miles wide that is subject to annual floods. The flood plain, marked by many oxbow lakes, lies at an altitude of 400 to 800 feet. A sloping alluvial plain composed of coalesced silt fans leads northward from the river to the upland. A much broader alluvial plain composed of piedmont gravel fans, 40 to 50 miles wide, slopes upward from the flood plain to the front of the Alaska Range, where it reaches an altitude of about 1,500 feet. Glacial moraines and outwash plains occupy small fan-shaped areas on the piedmont at the mouths of several major canyons in the Alaska Range. The morainal areas consist of complex systems of ridges, hillocks, and small lakes; the outwash plains are smooth, gently sloping surfaces. In several places isolated bedrock hills project 50 to 400 feet above the surface of the Tanana Valley.

The Tanana Valley has a continental climate characterized by short, warm summers and long, cold winters. The mean annual temperature is 26.1° F at Fairbanks and 26.7 F at Nenana. Extreme temperatures of 99° and −66° F are recorded at Fairbanks. Mean annual precipitation ranges from 11.7 inches at Fairbanks to 10.6 inches at Nenana. More than 60 percent of the precipitation falls during the period from May through September. Mean annual snowfall ranges from 67 inches at Fairbanks to 52 inches at Nenana.

The Tanana Valley supports mixed forest, tundra, and muskeg vegetation. White spruce, birch, willow, and balsam poplar grow in pure and mixed stands along rivers, sloughs, lakes, and minor drainage courses. Birch, aspen, and white spruce grow on bedrock slopes, morainal knobs, and hillocks, and burned-over areas on glacial-outwash plains. Dense black spruce forest covers undisturbed areas on outwash plains. Tundra vegetation consisting of sedges, grasses, dwarf birch, small heaths, mosses, and lichens is the predominant vegetation on the lower parts of alluvial silt fans north of the Tanana River. Valleys in the upland are covered by tundra or stands of stunted black spruce, larch, and willow.

GEOLOGY

Bedrock in the upland consists of well-jointed micaceous schist and isolated masses of granite and basalt. Similar rocks are exposed in the isolated bedrock hills that project above the alluvium of the Tanana Valley. Hills in the upland are generally mantled with windblown silt as much as 100 feet thick on the lower, gentle slopes (Péwé, 1950). Valleys in the upland are filled to depths of 50 to 300 feet with silt, muck (organic silt), and peat, beneath which lies 10 to 200 feet of coarse creek gravel.

The flood plain of the Tanana River is underlain by silt, sand, and fine gravel at least 400 feet thick near Fairbanks and at least 500 feet thick near Nenana. Micaceous silt 1 to 15 feet thick mantles the surface; clean, sandy gravel is present just beneath the silt. The narrow, sloping, alluvial plain north of the Tanana River flood plain is underlain by silt as much as 200 feet thick that overlies coarser sediments. Silt also predominates in the northern part of the sloping piedmont fans south of the flood plain, but the sediments are progressively coarser farther south, and gravel predominates near the mountain front. The glacial-outwash plains are underlain by medium- to coarse-grained, clean, sandy gravel locally mantled by 5 to 10 feet of windblown silt. The morainal ridges are underlain by an unsorted aggregate of sand, gravel, and boulders.

PERMAFROST

Areas of unfrozen ground are distributed much more widely in the Tanana Valley than on southern Seward Peninsula; they probably are comparable in distribution to unfrozen zones in the Yukon Flats but are more abundant.

In the upland north of the Tanana Valley, silt and bedrock are frozen to unknown depths beneath north slopes. South slopes, however, are unfrozen except near valley bottoms where slope gradients are low and drainage is sluggish (fig. 8). The flat, swampy valley floors are underlain by frozen ground to depths of 50 to 200 feet. Muck, gravel, and, in places, bedrock are frozen.

Unfrozen areas are lacking in the narrow alluvial plain north of the Tanana River; sediments in this zone are frozen from the mouths of the silt-filled creek valleys in the upland to the flood plain of the Tanana River. Frozen ground is thickest near the flood plain and at the mouths of the creek valleys and becomes thinner toward the base of the permafrost-free south slopes. The ground is frozen to depths of about 175 feet at the edge of the flood plain. Summer thaw extends to depths of 1 to 3 feet adjacent to the flood plain and to depths of 3 to 4 feet in upland creek valleys. Permafrost lies at depths of 5 to 20 feet at the inner, north edge of the alluvial plain, near the contact with the unfrozen, silt-covered bedrock slopes.

Large masses of clear ice occur as horizontal and vertical sheets, wedges, and saucer-shaped or irregular masses in the frozen silt of the alluvial plain and the creek valley bottoms north of the Tanana River. Much of the ice forms a polygonal or honeycomblike network that encloses silt polygons as much as 40 feet in diameter.

The thickness of perennially frozen sediments in the Tanana flood plain varies widely and irregularly; depths as great as 242 feet are reported.[4] No large ice masses are present; unfrozen areas and layers are common. Frozen ground is lacking beneath present or former river channels, sloughs, and lakes. Elsewhere, frozen and unfrozen layers are intercalated. In general, silt and sand layers are frozen and gravel layers are unfrozen. Gravel in the flood plain occurs in lenses for the most part; thus, no single broad unfrozen layer exists. Connections between unfrozen areas and unfrozen layers, however, form a network of irregular thawed passages throughout the perennially frozen sediments of the Tanana River flood plain.

Little information is available concerning the distribution of frozen sediments in the broad piedmont fans south of the Tanana River. The lower part nearest the river is poorly drained and probably frozen to depths of 20 to 130 feet. Large ice masses probably are not present. The higher, southern part of the plain is underlain by coarser sediments, and drainage is relatively good; unfrozen zones may be widespread.

Permafrost is sparsely distributed in the outwash fans on the piedmont slope and has no surface expression (fig. 9). Frozen ground is lacking in many places, especially where ground-water circulation is active. Elsewhere, layers of frozen ground 20 to 130 feet thick lie within 10 to 30 feet of the surface. Thick layers of windblown silt commonly are perennially frozen below depths of 4 to 5 feet. In places a layer of frozen silt 5 feet thick overlies unfrozen gravel. Large ice masses probably are not present.

No subsurface data are available concerning the distribution of permafrost in the hummocky topography of the glacial moraines. Permafrost is probably absent in the well-drained till hillocks. Fine-grained sediments in depressions are frozen below depths of 1 to 3 feet. The thickness of the frozen layer probably is at least equal to the thickness of the fine-grained fill.

[4] Péwé, T. L., 1948, Permafrost investigations, Fairbanks area, Alaska: U. S. Geol. Survey Permafrost Program Prelim. Rept., 16 p. (Unpublished report.)

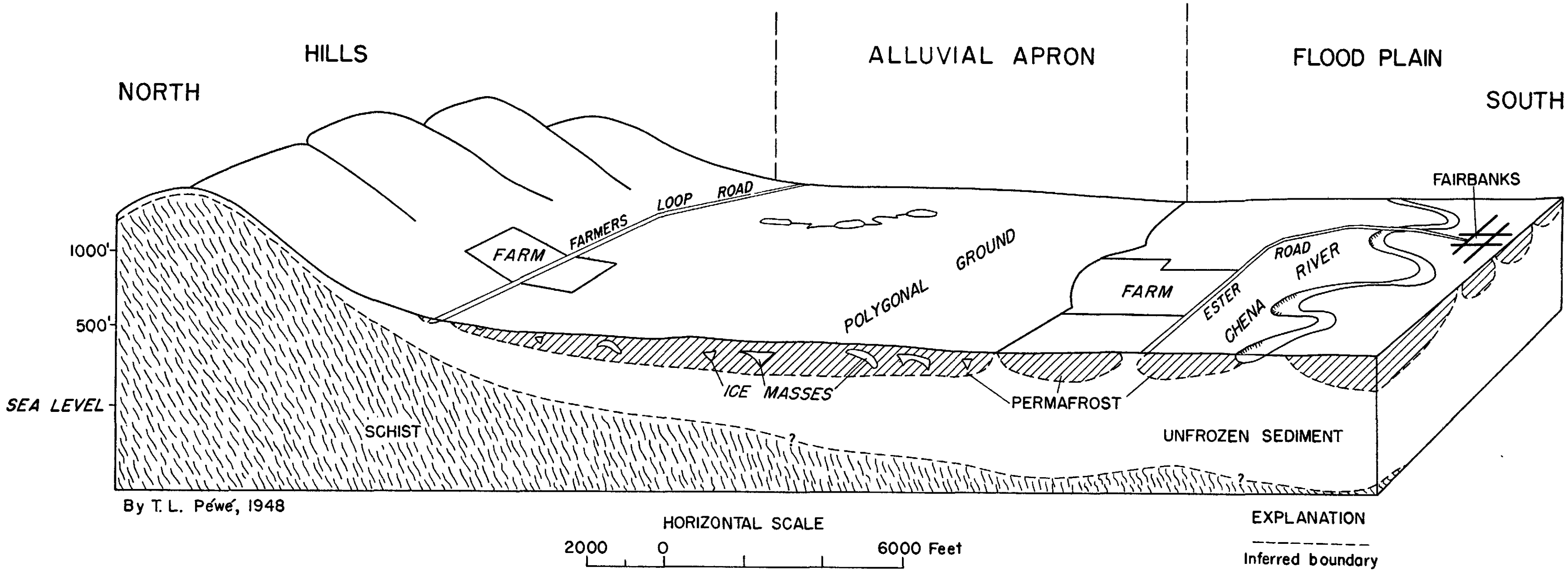

FIGURE 8.—Diagrammatic sketch showing character and distribution of permafrost in the Fairbanks area.

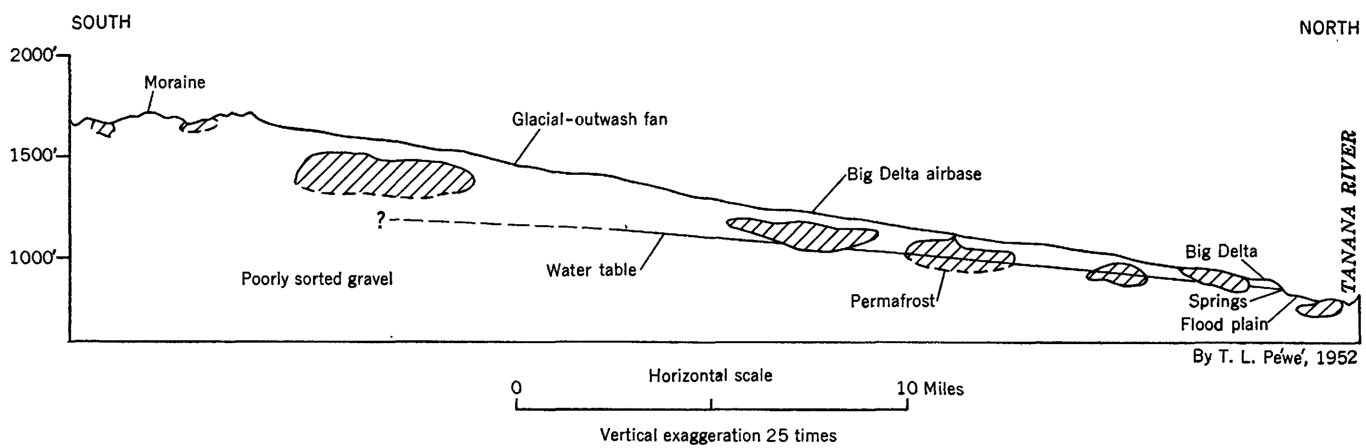

FIGURE 9.—Diagrammatic cross section showing distribution of permafrost and ground water in the Big Delta area

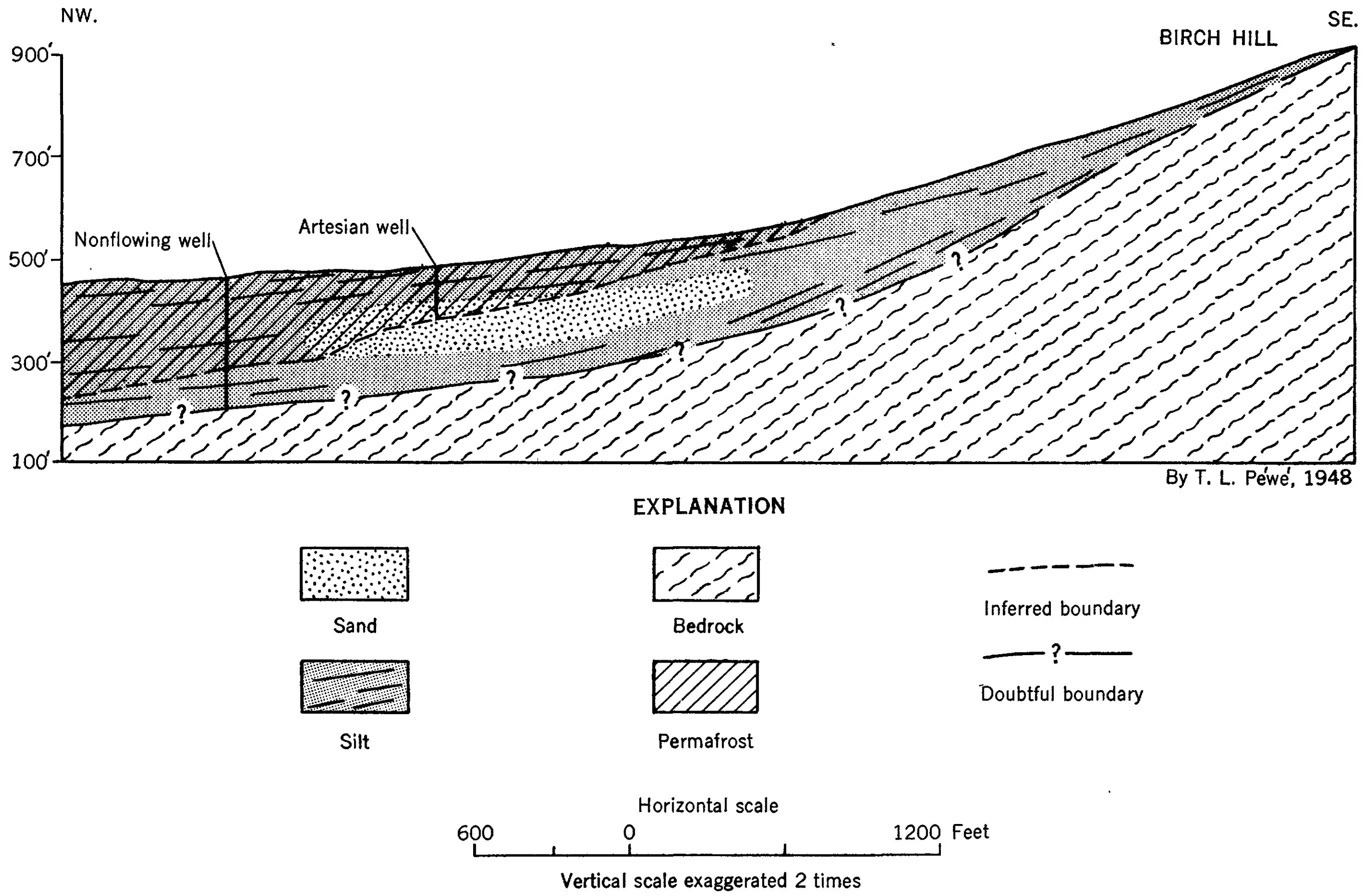

FIGURE 10.—Diagrammatic cross section showing artesian water confined by permafrost in the Fairbanks area.

GROUND WATER

Ground water in the Tanana River flood plain has been exploited extensively in the Fairbanks area. Water circulates freely below permafrost, through unfrozen channels within permafrost, and above permafrost where the top of frozen ground lies below the water table. Water is supplied to residents of the Fairbanks area by hundreds of small-diameter private wells. Many are only 15 to 30 feet deep and take water from above permafrost or from unfrozen zones within permafrost. Others, 100 to 250 feet deep, take water from unfrozen sediments below the frozen layer. Large yields are available both above and below the permafrost. Some 2-inch wells yield as much as 40 gallons per minute, and records indicate that yields as high as 3,000 gallons per minute with a drawdown of 10 to 15 feet are available to large-diameter wells less than 100 feet deep.

Ground water is found only below permafrost in the alluvial plain north of the Tanana River and in valleys of the upland in the Fairbanks area; wells on the lower slopes must penetrate 100 to 200 feet of frozen ground to obtain water. Some wells drilled on the lower slopes have encountered artesian water in sandy or gravelly layers that are overlain by permafrost (fig. 10). A flowing artesian well drilled in 1946 yields more than 40 gallons per minute.[5]

Permafrost is thinner on the upper slopes of the alluvial-silt apron; however, the water table is at considerable depth and here, too, wells must extend to depths of 100 to 200 feet. Because permeable beds are few, ground water is scarce even below permafrost; some wells must penetrate bedrock to obtain water.

The quality of ground water generally is poor in the flood plain, in the northern alluvial apron, and in valleys in the upland because much of it percolates through organic sandy silt, which adds organic matter and iron that imparts a dark color and a bad taste.

The water table is low in interstream areas in the upland. The silt mantle yields water so slowly that wells must be continued into the underlying schist bedrock. Deep wells are necessary, and the yield generally is small and of poor quality.

Ground water of good quality is abundant in the gravel of outwash plains south of the Tanana River.

[5] Péwé, T. L., op. cit.

Much of the water is derived from mountain streams that recharge the gravel in the higher, southern parts of the plains. Ground water issues from springs at the north end of the outwash plain near Big Delta. Depth to water increases upslope at a rate of 15 feet per mile to as much as 200 feet, halfway up the outwash plain (fig. 9).

No data are available concerning ground-water conditions in the alluvial plains south of the Tanana River. Conditions probably are similar to those in the glacial outwash plains.

UPPER KUSKOKWIM VALLEY

By A. T. Fernald

PHYSIOGRAPHY, CLIMATE, AND VEGETATION

The upper Kuskokwim Valley is in the discontinuous-permafrost zone along the northwest flank of the Alaska Range between 62° and 64° north latitude and 152° and 156° west longitude (fig. 5). The region is divided into lowlands along the Kuskokwim and Nixon Rivers, and a piedmont slope, which extends northward from an altitude of about 2,000 feet at the base of the Alaska Range to an altitude of about 500 feet where it merges with the Kuskokwim River lowland.

The climate of the upper Kuskokwim Valley is characterized by cool, wet summers and cold, relatively dry winters. At McGrath the mean annual temperature is 25.5° F, the extremes being 89° and −64° F. The January mean temperature is −8.7° F and the July mean temperature, 58.7° F. The mean annual precipitation is 19.1 inches, of which 10.4 inches falls during the 4 months from June through September. Variability of precipitation is quite high; the annual total ranges from 15 to 25 inches. The average snowfall is 92 inches; the greatest annual depth of snow on the ground is approximately 4 feet. Clear weather prevails during the spring months, the driest of the year.

Farewell, near the base of the Alaska Range and about 1,000 feet higher than McGrath, has a mean annual temperature of 25.7° F. The January mean temperature is 2.0° F; the July mean temperature is 54.9° F. Strong and frequent foehn winds in the winter months are a major factor in producing the warmer temperatures at Farewell than at McGrath. Mean annual precipitation at Farewell is 16.3 inches.

The upper Kuskokwim Valley supports forests of mixed white spruce and white birch, a black spruce and *Sphagnum* association, and tundra. Tundra is confined to the tops of the higher mountains and the crests of many interfluves on the piedmont slope. At lower altitudes mixed white spruce and white birch cover hill summits, steep or southward-facing slopes, and the youngest parts of flood plains. The black spruce and *Sphagnum* association is widespread on the older parts of flood plains, other alluvial plains and terraces, and on gentle or northward-facing bedrock slopes. Patches of the black spruce and *Sphagnum* association also are integral parts of the bog flats.

GEOLOGY

The piedmont slope is a huge compound fan of unconsolidated alluvial, eolian, glacial, and organic deposits. A series of end moraines is present on the piedmont in front of major valleys in the Alaska Range. Two distinct glacial episodes are recognized and are represented by two sets of end moraines and associated outwash aprons at different levels. The present-day rivers dissect the piedmont surface most deeply near the range, where they flow northward in braided channels confined in valleys up to 200 feet deep. The confining banks disappear 5 to 25 miles north of the range, and the rivers spread out to form alluvial fans.

The piedmont slope is underlain by till, gravel, sand, silt, and organic material. Organic material and windblown silt, ranging in thickness from an inch to many feet, covers much of the surface. Few data are available concerning the total thickness of the unconsolidated sediments. As much as 200 feet is exposed in the valley walls of the two largest rivers. A well at Farewell near the north front of the Alaska Range penetrates 360 feet of unconsolidated material.

The two outwash aprons formed on the piedmont during the two glacial episodes can be traced into two surfaces at different levels in the lowland. The older and higher surface, a greatly dissected plain, has a widespread surficial cover of organic material, and windblown sand and silt of varied thickness. Large parts of the younger surface are covered with sand dunes, which reach a maximum height of 50 feet. A surficial cover of windblown silt and organic material exists locally.

The rivers traversing the piedmont join in the lowland to form the main Kuskokwim River. This river has dissected the two older surfaces and has formed a third, the Kuskokwim alluvial plain, consisting of the flood plain and a marginal area of bog flats away from the river. The Kuskokwim alluvial plain is underlain mostly by sand, silt, and organic material reaching a thickness of 260 feet at McGrath. Lenses of gravel are present at depth and locally near the surface.

In the Nixon lowland, an alluviated slope leads down from the surrounding bedrock uplands to a broad alluvial plain, which also consists of the flood plain of the river and a bordering area of bog flats. Sand, silt, and organic material underlie the alluvial plain.

PERMAFROST

Subsurface data are scarce in the upper Kuskokwim Valley. The presence or absence of frozen ground at depths greater than 8 feet is established only at McGrath and Farewell.

Permafrost is known to be present at shallow depths in three types of terrain in the upper Kuskokwim Valley. In the alluvial plains and slopes of the lowlands, permafrost occurs at depths of 1½ to 3 feet beneath black spruce and *Sphagnum* moss growing as a nearly continuous cover in peat a foot or more thick. Permafrost is lacking at such shallow depths where the peat is less than a foot thick. Six wells in an area of black spruce and *Sphagnum* moss on the Kuskokwim River flood plain at McGrath passed through the bottom of frozen ground at depths of 40 to 50 feet. Permafrost also is present in the black spruce and *Sphagnum* islands of the bog flats. It is lacking within 6 feet of the surface in the adjoining quaking bogs, but may be present at greater depth. Tundra areas on the interfluves of the piedmont slope are underlain by permafrost at depths of 1 to 3 feet. A well 360 feet deep in the tundra area at Farewell apparently passed through the bottom of permafrost at 12 feet, and no frozen ground was encountered at greater depth.[6]

GROUND WATER

Information on ground-water supplies is available at only two localities in the upper Kuskokwim Valley—at McGrath on the flood plain of the Kuskokwim River and at Farewell on the piedmont slope.

Shallow wells supply households in the McGrath area with water from sand or gravel lenses in the flood-plain alluvium. Wells in the older part of the flood plain penetrate water-bearing sediments below permafrost at depths of 40 to 50 feet. Wells in the younger part penetrate no permafrost and generally range in depth from 12 to 40 feet. A well drilled for the Civil Aeronautics Administration reached water at a depth of a few tens of feet but was continued until bedrock was penetrated at a depth of 262 feet. The water level in wells in the unfrozen sediments fluctuates from a few feet to 30 feet beneath the surface; the fluctuations are synchronous with and evidently due to fluctuations in the level of the Kuskokwim River. The well at Farewell extends through 360 feet of unconsolidated sediments, and the water level was 338 feet below the land surface in 1943.

[6] The thickness of permafrost encountered in the well at Farewell is uncertain. Cederstrom (1952, p. 29) reports that permafrost was found throughout the upper 125 feet of the well at Farewell. However, a summary of the well log inspected by the writer in the office of the Civil Aeronautics Administration at Anchorage, Alaska, recorded "Boulders, gravel, and frost" in the upper 12 feet and "Boulders, gravel" between depths of 12 and 125 feet.

Ground water probably is available at unknown depth beneath the flood plains of braided streams, in alluvial fans, and in outwash aprons on the piedmont slopes.

BRISTOL BAY REGION

By E. H. Muller

PHYSIOGRAPHY, CLIMATE, AND VEGETATION

The Bristol Bay region lies principally in the zone of sporadic permafrost but extends southwestward into the no-permafrost zone (fig. 5). This area of about 16,000 square miles extends from 155° 30′ to 159° west longitude and from the axis of the Alaska Peninsula northward to 60° north latitude. It includes the lowlands of the Nushagak River drainage basin, the lowland along the north side of the Alaska Peninsula, and portions of the adjacent mountains. Glaciated bedrock foothills form a piedmont zone between the Alaska Peninsula lowland and the Aleutian Range.

The Alaska Peninsula lowland, along the southeast coast of Bristol Bay, is 50 miles wide at its northeast end but narrows southwestward to 10 miles in the vicinity of Port Heiden. The land surface rises gently from sea level to an altitude of a few hundred feet at the south edge of the piedmont. End moraines of glaciers from the Aleutian Range form arcuate belts of low gravel ridges and knobs on the nearly level lowland. Large lakes occupy glacier-scoured basins in the piedmont.

The Nushagak River drains another broad lowland about 75 miles wide that is enclosed by mountains on the east, north, and west. Isolated bedrock hills rise 1,000 to 2,000 feet above the surrounding plain.

The Bristol Bay region is cool, humid, and windy. Its climate is intermediate between the constant storminess and moderate temperatures of the Aleutian Islands and the extreme temperatures of interior Alaska. The mean annual temperature at King Salmon and Dillingham is about 35° F; extreme temperatures recorded at Dillingham are 89° and −41° F. Although total annual precipitation is about 25 inches at both towns, snowfall at King Salmon averages 37.5 inches as compared with 62.4 inches at Dillingham.

Airflow from the south dominates the summer climate. Temperatures are mild, averaging 50° to 55° F. Fog is common, particularly along the coast. About 40 percent of the annual precipitation falls as light showers during July, August, and September.

In winter the dominant airflow is from the north, resulting in continental modification of the climate with fair weather and temperatures that average near 0° F. The snow cover may be 1 or 2 feet deep, but exposed surfaces are often blown free, especially on the lowlands of the Alaska Peninsula. Southerly airflow in advance of migrating low-pressure systems may produce freezing rain and thawing temperatures during any month of the winter.

North of 58°30′ north latitude the Bristol Bay region is covered with intermixed forest and tundra vegetation, but tundra covers all the southwestern part. White spruce grows in sheltered areas at low altitudes in the northeast, either in pure stands or associated with white birch, poplar, aspen, and willow. The best development of woodland is along the major rivers and near the western (lowland) ends of the piedmont lakes east and northeast of Naknek.

Elsewhere in the lowland areas, tundra vegetation dominated by sedges, cottongrass, and *Sphagnum* mosses occupies wet areas; heaths and mosses predominate in slightly better drained areas. Above altitudes of 800 to 1,000 feet and in exposed locations nearer sea level, a sparse cover of dwarf heaths and alpine meadow plants is characteristic.

GEOLOGY

The Nushagak River lowland is a broad bedrock basin partly filled with unconsolidated glacial and glaciofluvial materials derived from adjacent uplands. Isolated bedrock hills on the floor of the basin consist of granitic rocks and impure quartzite. The mountains west of the lowland are composed of tightly folded impure quartzite, metamorphosed sandy argillite, and minor intrusive granitic masses. Intrusive and extrusive igneous rocks predominate in the mountains east of the lowland.

The Alaska Peninsula consists of a broad geanticline of gently folded and faulted sediments intruded by both fine- and coarse-textured igneous rocks; the Quaternary volcanic rocks of the Aleutian Range are superposed upon an ancient erosion surface that bevels the older rocks. The lowlands are underlain by dominantly coarse-textured, unconsolidated materials, including glacial till and outwash sand, gravel, and silt reaching thicknesses of more than 600 feet near Naknek. A few thin beds of peat and organic silt are interbedded with the coarser sediments. Windblown silt a few feet thick mantles much of the surface of the Alaska Peninsula and Nushagak River lowlands.

PERMAFROST

The climate of the Bristol Bay region is marginal for the formation or preservation of frozen ground. The probability of encountering microclimates or soil climates favorable for the development of permafrost decreases southwestward down the Alaska Peninsula. Areas beyond Egegik are considered to be in the no-permafrost zone.

Frozen ground in lowlands of the Bristol Bay region is found chiefly in silt, especially in silt having a high organic content, but it also occurs in fine sand and glacial till. Shallow permafrost is found most commonly beneath swampy lowlands. Perennially frozen ground has not been observed in the till of terminal moraines, but irregular pockets may be present in favorable sites. Layers of frozen fine-grained sediments more than 10 feet thick, interbedded with unfrozen sand and gravel, have been found in wells at depths as great as 175 feet. Permafrost generally is absent in coarse-textured materials and in areas of moderate relief; thus, shallow permafrost is lacking in sand-dune areas, in gravelly outwash, in sediments beneath flood plains, and in river and lake terraces composed of coarse sediments.

The rigor of the environment in the higher part of the piedmont and in the mountains indicates that areas of frozen ground are probably present. However, the coarse texture of the soil materials and the availability of abundant water from melting snow favor a deep zone of summer thaw. Permafrost bodies, if present, probably are irregular in form and cannot be recognized by surface criteria.

Much of the perennially frozen ground of the Bristol Bay area probably is relict from past periods of colder climate. Permafrost can form to depths of a few tens of feet at the present time, however, under favorable conditions. Restricted ground-water percolation, a thick layer of insulating organic material, and a predominance of silt in the surface soil favor formation of perennially frozen ground. Ice in perennially frozen sediments formed under present climatic conditions is chiefly interstitial, but small veins and irregular thin ice laminae also are present. Ice in relict permafrost occurs as laminae as much as an inch or two in thickness interlayered with frozen layers a few inches thick. No larger ice segregations have been observed.

GROUND WATER

Ground-water supplies adequate for large communities can be obtained throughout the lowlands of the Bristol Bay region from wells 100 to 600 feet deep. Several wells may have to be driven in order to obtain a sufficiently large yield. Supplies for single dwellings can be obtained from shallower wells 15 to 50 feet deep.

Most wells in the lowlands penetrate several water-bearing zones at depths of 30 to 600 feet. In general, the yield of wells near the piedmont is greater than the yield of those near the coast. Water in the lowland sediments generally is under hydrostatic pressure; artesian flows of from 6 to 138 gallons per minute have been obtained from depths of 90 to 600 feet.

The quality of the water in most wells is good, but water associated with peat or muck layers has a high organic content and a bad taste. An artesian flow of unpalatable water containing 5,800 ppm of dissolved solids was encountered at 600 feet in a well at Koggiung, 20 miles north of Naknek. Water from depths of less than 300 feet in the same area has a lower mineral content and is potable.

Slight difficulties may be encountered in drilling wells through the discontinuous lenses of permafrost in fine sediments in the lowlands of the Bristol Bay region, in bypassing the flow of unpotable ground water in organic layers, and in flushing out flowing quicksand in certain water-bearing horizons. Excessive pumping in wells near the coast may result in encroachment of salt water.

KENAI LOWLAND

By T. N. V. Karlstrom

PHYSIOGRAPHY, CLIMATE, AND VEGETATION

The Kenai lowland lies in south-central Alaska in the no-permafrost zone. The area is a broad, low shelf, 20 to 60 miles wide, lying between the Kenai Mountain Range and Cook Inlet (fig. 5). The lowland covers an area of about 3,600 square miles between 150° and 152° west longitude and 59° and 61° north latitude.

The Kenai lowland is a product of repeated episodes of glacial erosion and deposition within a bedrock trough, with subsequent modification by wind, stream, tidal, and frost processes. The topography exhibits a wide range of glacial and associated glaciofluvial forms such as moraines, outwash aprons and plains, kames, and eskers. Most of the lowland lies within 400 feet of sea level, surfaces are flat to undulating, and local relief varies from a few feet to more than 200 feet. The Caribou Hills, a broad upland northeast of Homer, rise abruptly 1,000 to 2,000 feet above the general lowland level.

The Kenai lowland has a cool, moderately maritime climate; the warmest temperatures and greatest precipitation are in the southern part. The mean annual temperature ranges from 33.3° F at Kenai in the north to 38.3° F at Homer in the south. Extreme recorded temperatures are 89° F and −46° F at Kenai and 79° F and −17° F at Homer. The mean annual precipitation is 19 inches at Kenai and 32 inches at Homer; most of the precipitation falls as rain during the months of July and August. The average annual snowfall ranges from 55 inches at Kenai to 82 inches at Homer. The average number of days with freezing temperatures is 219 at Kenai and 189 at Homer.

The vegetation of the Kenai lowland consists of intermixed forest, muskeg, grassland, and subalpine shrub tundra. Forests cover about half the area and consist of pure stands of black, white, or Sitka spruce and mixed stands of spruce, birch, aspen, and balsam poplar. The mixed forests of spruce and birch and of spruce and aspen are limited to the better drained portions of the lowland where seasonal frost thaws relatively early. Pure stands of stunted white or black spruce grow in areas of more restricted drainage and lingering seasonal frost.

Muskeg vegetation—mosses, grasses, sedges, heath shrubs, and scattered black spruce—covers more than a third of the Kenai lowland. This vegetation is found in broad, shallow drainage basins and abandoned glacial drainage channels, where subsurface drainage is poor and frost persists at shallow depth during most of the summer.

Grasslands predominate in the rest of the Kenai lowland. They are found chiefly on slopes and in depressions on the broad interfluves of the Caribou Hills. Soil in the grasslands generally consists of a thick layer of silt that is subject to intense frost action during winter but which thaws early and becomes well drained during summer. Grasslands also cover the better drained abandoned drainage channels in the lowland.

Subalpine shrub tundra is restricted to coarse rubble and fractured bedrock on slopes above 1,500 feet in altitude.

GEOLOGY

Bedrock in the Kenai lowland and Caribou Hills consists of poorly consolidated siltstone, sandstone, and lignite. It is mantled with glacial till, outwash, and alluvial silt, sand, and gravel. The thickness of the unconsolidated mantle varies widely. In the Caribou Hills, bedrock is exposed at the surface or is mantled by only a thin veneer of till and gravel. Depth to bedrock increases northward, in general, and the northern part of the lowland is underlain locally by as much as several hundred feet of unconsolidated deposits.

Topographic depressions are partly or completely filled with peat and organic silt. Knobs, ridges, and terraces are covered with 2 to 5 feet of windblown silt.

PERMAFROST

It is believed that permafrost cannot form in the present climate of the Kenai lowland. Permafrost that probably formed under a more rigorous climate in the past is preserved locally, however, in areas where conditions are exceptionally favorable. Known occurrences of permafrost are restricted to black spruce islands in bog flats in the northern interior part of the area where a dense forest cover, a thick insulating mat of moss, and tightly compacted peat soils favor its preservation (pl. 34). The mean annual temperature of the northern part of the lowland is so close to freezing that areas having microclimates favorable for preservation of permafrost may be found in other types of terrain. No information is available concerning the maximum depths at which these small bodies of frozen sediment may be found.

GROUND WATER

An estimate of ground-water supplies is hindered by the lack of wells or other subsurface data throughout most of the Kenai lowland. Present knowledge of the geology, however, permits speculation as to the probability of obtaining adequate supplies of ground water in various terrains. Permafrost is so rare that it has little effect on the distribution of ground water. Persistent seasonal frost reduces infiltration over wide areas but does not affect circulation of ground water at depth.

Shallow ground-water supplies probably are available in the lowland in permeable materials of surface outwash plains, stream terraces, and alluvial fans. In upland valleys, shallow ground water is likely to be found in granular material lying on the buried bedrock valley floor.

Ground-water supplies probably are available at depth throughout the lowland in sand and gravel lenses or beds in buried outwash or alluvium. Granular sediments in buried bedrock valleys and porous bedrock sandstone layers also may be sources of ground water at considerable depth. Ground water probably is most abundant in the lowland adjacent to the mountain front and in terraces and bed gravels of major streams that head in the mountains. Elsewhere the ground-water supplies are restricted by a predominance of fine-grained, tight sediments and by limited surface recharge. In these areas the best aquifers are likely to be found just above the bedrock floor.

Ground water generally is of fair to good quality but locally may have a high organic and iron content. Wells drilled near the coast probably would be subject to encroachment of sea water if they were heavily pumped.

PHOTOINTERPRETATION OF PERMAFROST CONDITIONS

Aerial photographs are useful aids in mapping geology, soils, and vegetation. In addition to serving as base maps on which to plot field observations, aerial photographs may be used to extrapolate the results of field mapping into nearby areas by photointerpretation. Many geomorphic features and relationships are more readily recognized when seen on aerial photographs than when viewed on the ground; moreover, many inaccessible localities are brought into view. Thus, aerial photographs expand considerably the understanding of the area portrayed. They are an almost indispensable supplement to regional reconnaissance studies of natural phenomena in Arctic and subarctic regions.

The interpretation of aerial photographs alone, however, is a poor substitute for field observations in terrain studies of any kind. The topographer does not attempt to construct an accurate topographic map without ground control; neither should the earth scientist expect to prepare accurate maps of vegetation, geology, soils, or permafrost without the control of field observations.

Permafrost is an especially difficult phenomenon to map by aerial photography alone, for perennially frozen ground rarely is exposed at the surface and thus seldom can be observed directly from the air. Field studies lacking subsurface data from drill holes, wells, or mines fail to delineate with much precision the horizontal and vertical boundaries of frozen ground. Still less precision is possible in a study that depends mostly upon the interpretation of aerial photographs.

Some recent publications indicate a misunderstanding of the strictly supplementary role of photointerpretation in mapping permafrost. Several authors have implied that permafrost conditions can be interpreted in considerable detail by photointerpretation alone (Sager, 1951, p. 551–571; Frost, 1951, p. 223–246; Wilson, 1948, p. 164). However, examination of aerial photographs of various regions in Alaska where ground conditions are known indicates that, except for rare actual exposures of frozen ground containing large masses of clear ice, no single feature recognizable on aerial photographs can be taken as unequivocal evidence of the presence of permafrost. Thus, the detailed boundaries of permafrost in most parts of Alaska cannot be delineated solely from aerial photographs.

A similar misunderstanding of the supplementary role of photointerpretation is implicit in proposals for the establishment of general aerial-photograph keys for the interpretation of permafrost conditions throughout Arctic and subarctic regions. Keys can be prepared for the generalized interpretation of permafrost conditions in small areas, but they lose validity rapidly with increasing distance from the area where the criteria employed were first established by means of detailed ground studies.

MAPPING PERMAFROST FROM AERIAL PHOTOGRAPHS

Although the detailed boundaries of permafrost generally cannot be mapped from aerial photographs, the photographs can be the source of considerable information concerning the distribution of landforms and terrain units in which the probable permafrost conditions can be estimated. The first step in such a study consists of establishing, preferably by field studies, the regional distribution pattern—the prevailing distribution of frozen and unfrozen zones in various types of terrain. If the area is inaccessible to field studies, the pattern commonly can be estimated, though with much less accuracy, by study of available information concerning the climate, geology, vegetation, and topography of the region to be mapped and by comparison with an analogous region in which the permafrost distribution pattern is known.

Having established the regional pattern, the investigator begins intensive study of the photographs and delineates terrain units such as flood plains, poorly drained lowlands, glacial moraines, and mountain valleys. Permafrost conditions in these are assumed to be generally similar to conditions at ground-control points in similar terrain units or at comparable sites in an analogous area.

PERMAFROST INDICATORS

Recognition on aerial photographs of certain indicators helps the investigator to estimate permafrost conditions in areas in which they occur if he understands their significance and limitations. Useful indicators include certain plant species and assemblages and microrelief features of several types.

VEGETATION

TUNDRA AND FOREST ASSOCIATIONS

It is occasionally suggested that tundra vegetation indicates the presence or absence of permafrost in Alaska (for example, Woods, Hittle, and Frost, 1948, p. 498). Detailed studies indicate, however, that the distinction of tundra and forest vegetation has only limited value in the photointerpretation of permafrost conditions.

The term "tundra" is applied to a wide variety of vegetation types including sparse covers of matted dwarf shrubs, herbs, and grasslike plants separated from one another by large areas of bare ground; dense, continuous covers of cottongrass, dwarf birch, heaths, mosses, and lichens; and rank growths of willow, alder, or dwarf birch shrubs. Each type of tundra in a given region reflects different soil, moisture, and permafrost conditions. On Seward Peninsula, for example, dry tundra composed of matted dwarf plants separated by areas of bare ground occupies areas of rocky soil in which permafrost either lies at depths of 5 to 10 feet or is absent. Tundra composed of cottongrass, birch shrubs, and heaths, on the other hand, is found in areas of silty soil in which permafrost lies at depths of 2 or 3 feet. Dense growths of willows or alders are confined to areas where permafrost either lies at depths of more than 5 feet or is lacking.

Similarly, the term "forest" applies to widely differing vegetation types, including forests of aspen beneath which permafrost generally is lacking and stands of black or white spruce growing in peat in which permafrost lies at depths of only 2 or 3 feet. Thus, permafrost conditions differ as widely beneath different types of tundra or forest vegetation as they do between these two major types of vegetation.

Areas of tundra vegetation are interspersed in forested areas throughout most of Alaska (fig. 11), and both forest and tundra occur in all of the permafrost zones as well as the no-permafrost zone. The commingling is even more complex than is suggested in figure 11. Throughout much of Alaska, forests are limited to slopes at low altitudes and to the better drained parts of the valley bottoms. Extensive areas of tundra cover high ridges and plateaus, while smaller tundra areas are found on poorly drained sites in the lowlands and valleys. An almost uninterrupted belt of tundra extends along the coasts of western and northern Alaska from the Alaska Peninsula to the Canadian boundary. Thus, the presence of tundra does not necessarily indicate the presence of permafrost, nor does the presence of forest necessarily indicate the absence of permafrost.

DISTRIBUTION PATTERNS OF TREES AND LARGE SHRUBS

The distribution patterns of trees and tall shrubs supplement topographic expression in the recognition of landforms such as end moraines (pl. 34), outwash plains, and abandoned stream channels. Thus they contribute indirectly to the interpretation of probable permafrost conditions based upon inferences concerning the age of the land surface, the climate, and the character of the underlying material.

Observation of the kinds of trees and shrubs and their manners of growth and association also permits inferences concerning the depth to permafrost in local areas (Stoeckeler, 1948, 1952). The exact significance of these vegetation phenomena varies from one region to another, however, and they must be used with caution and full understanding of their variability.

The distribution patterns of tree and shrub vegetation are functions of several variables including climate, character and stability of the soil, drainage conditions, topographic position, age of the land surface, plant succession, and disruptive factors such as fire and disease. Permafrost is a controlling factor only when it occurs at a depth shallow enough to influence subsurface drainage, soil stability, and soil temperature

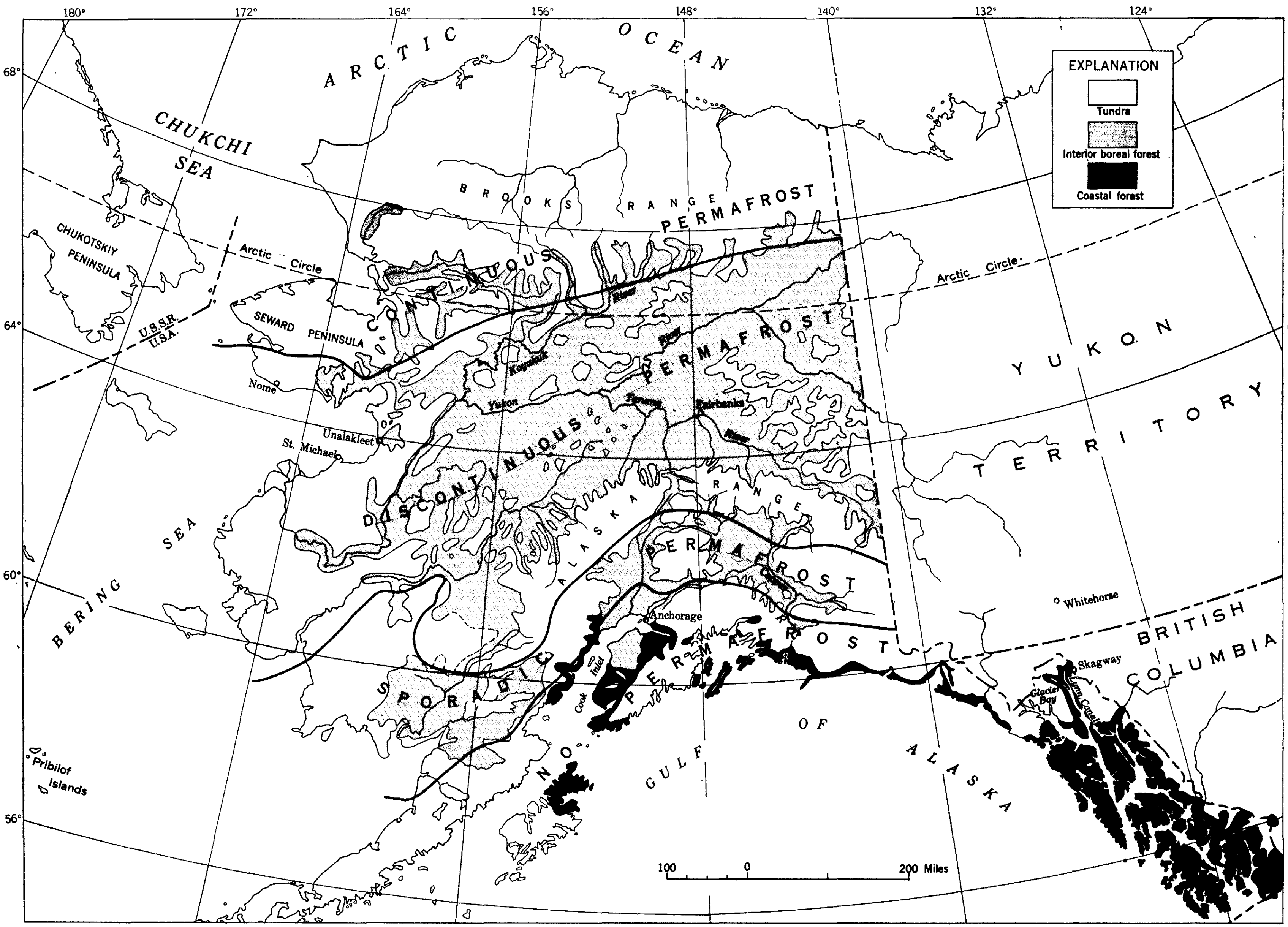

FIGURE 11.—Distribution of forested and treeless areas in Alaska and part of Canada. Treeless areas are predominantly tundra but also include exposed bedrock, glaciers, sand dunes and grasslands. Compiled by R. S. Sigafoos.

within the zone of root growth. Some trees, such as larch and black spruce, have shallow root systems and manage to grow in wet areas where permafrost lies at shallow depth. Others, such as white spruce, aspen, balsam poplar, white birch, alder, and several kinds of willows, have deeper roots and grow best in relatively well drained areas where the ground thaws to depths of at least several feet in midsummer. Stunted specimens of some of the usually deeper rooted trees, however, grow on sites where permafrost lies at shallow depth. Recognition of the shallow-rooted species on aerial photographs aids in delineating the areas where permafrost is most likely to occur at shallow depth, and recognition of deep-rooted species, especially those of good growth, helps delineate areas least favorable for the formation or preservation of permafrost. The tree- and shrub-distribution patterns are significant, however, only when considered in the light of other information concerning permafrost distribution in the region under study.

Information concerning permafrost conditions under various types of trees and shrubs can be systematized into vegetation keys for local areas. The keys indicate only the probable minimum depth to permafrost; they do not indicate the maximum possible depth, nor do they permit distinction between forests growing on perenially frozen ground and those growing on unfrozen ground. They decrease in usefulness rapidly with increasing distance from the area of the geobotanical field work upon which they were based.

The following tabulation indicates the minimum depth to permafrost, if it is present, beneath some vegetation assemblages that are widespread in Alaska:

	Feet
Tall willows on flood plains	8
Pure stands of mature aspen or white birch	4
Mixed willow, alder, and white birch	3–4
Pure stands of balsam poplar	3–4
Mixed white spruce and balsam poplar	3
Pure stands of white spruce	2–3
Mixed stands of white birch and white spruce	2–3
Mixed white and black spruce	1–2
Black spruce in wet tundra or muskeg	1

Areas overgrown by black spruce are among those most likely to be underlain by permafrost at shallow depth in Alaska. In the interior of Alaska, open uniform stands of black spruce growing on flat or gently sloping moss-covered ground are found mainly in areas that have peaty soil and permafrost at shallow depth (foreground, pl. 32). Permafrost generally is lacking beneath similar forest in southern Alaska (*c*, pl. 34), but seasonal frost frequently persists during most of the summer.

Bog flats are especially useful permafrost indicators in the discontinuous, sporadic, and no-permafrost zones. These distinctive patchworks of black spruce forest and sedge marsh have a ragged, mottled appearance that is readily recognized on aerial photographs (pls. 32–34). Permafrost is absent or lies at depths of more than 6 feet beneath the marshy areas, but the black spruce islands are favorable sites for the formation and preservation of permafrost. Black spruce islands underlain by permafrost are generally distinguished by the presence of steep banks, a marginal moat or trench of standing water, and an abrupt contact between the dense spruce vegetation of the island and the tundra vegetation of the surrounding marsh. Spruce islands that lack permafrost generally have less distinct margins which grade into the adjoining open marsh (*e*, pl. 34).

Tall willow shrubs and isolated pure stands of balsam poplar on river flood plains generally indicate the presence of unfrozen ground (*a*, pl. 33). The lateral limits of the patches of tall shrubs in tundra regions commonly indicate closely the lateral limits of the unfrozen zones (*d*, pl. 35). Tall shrubs are particularly useful indicators in the continuous-permafrost zone and in the northern part of the discontinuous-permafrost zone, where thawed zones are rare and difficult to locate.

POLYGONAL MICRORELIEF PATTERNS

Intensive frost action produces distinctive microrelief patterns which aid in interpreting aerial photographs of many areas in Alaska. Two broad categories of polygonal patterns may be distinguished: frost-stirred or frost-sorted polygons, including stone polygons, vegetation polygons, and related striped features; and contractional or tensional polygons, including ice-wedge and frost-crack polygons. The two types of polygons generally differ in size and shape as well as in origin (contrast stone polygons at *b* and ice-wedge polygons at *f*, pl. 31; contrast vegetation polygons and ice-wedge polygons at *w* and frost-crack polygons at *z*, pl. 43 *A*). Individual frost-stirred polygons generally are rounded and range in diameter from a few inches to 25 feet. Individual contractional polygons are sharply angular, have 4 to 8 sides, and generally are 25 to 100 feet in diameter, although ice-wedge polygons 5 to 400 feet in diameter are present on the Arctic coastal plain near Point Barrow (R. F. Black, personal communication). The pattern of ice-wedge and frost-crack polygons is closely similar to the pattern of desiccation polygons, formed by mud cracks, but desiccation polygons generally are much smaller.

FROST-STIRRED POLYGONS

Frost-stirred polygons and stripes are products of processes in the surface zone of annual freeze and thaw (Washburn, 1950). On flat surfaces these processes result in heaving and thrusting which operate with equal force in all directions to give rise to roughly equidimensional polygonal forms. On slopes they act most strongly in the direction of maximum slope, giving rise to elongate polygons or stripes. The formation of frost-stirred polygons and stripes is favored by the presence of permafrost at shallow depth, but they are common in many areas where permafrost lies at great depth or is absent.

Stone polygons and stripes (*e*, pl. 36) form in initially coarse-grained soils (Sharp, 1942, p. 275–277). The largest rock fragments are segregated in marginal ridges or channels that adjoin central areas of fine-grained or unsorted soil. Active stone polygons and stripes are common in areas where the ground is not perennially frozen, and thus they are not reliable indicators of permafrost. Moreover, they are persistent features of the landscape; relict polygons formed during past periods of more rigorous climate are common (*b*, pl. 31).

Most types of vegetation polygons and stripes result from frost-stirring in fine-grained soils. Certain types on Seward Peninsula (tiny stipples superimposed on ice-wedge polygons at *s* and *w*, pl. 40 *A*, and on slopes in pl. 43 *A*; also see Hopkins and Sigafoos, 1951, p. 98–99) and in the Bristol Bay region (*d*, pls. 36 and 39) have been found only in areas underlain by permafrost, but other types not easily differentiated on aerial photographs bear a much less consistent relationship to perennially frozen ground. Vegetation polygons probably are not persistent features of the landscape, and relict forms are uncommon. Unfortunately, relict stone polygons overgrown with tundra vegetation commonly are indistinguishable on aerial photographs from active vegetation polygons.

Widely distributed frost-stirred polygons and stripes found both on well-drained and poorly drained sites suggest the presence of permafrost. However, the presence locally of frost-stirred polygons on such favorable sites as lake margins, bottoms of ephemeral lakes, and borders of late snowbanks has no significance in regard to the presence or absence of permafrost.

Most frost-stirred polygonal and striped patterns can be identified readily on aerial photographs of scale 1:10,000 and under favorable conditions on photographs of scale 1:20,000. They generally cannot be distinguished on photographs of scale 1:40,000.

CONTRACTIONAL POLYGONS

Three interrelated types of contractional polygons are recognized: frost-crack polygons, high-center ice-wedge polygons, and low-center ice-wedge polygons. Contractional polygons result from the cracking of ice-cemented soils and sediments during sharp declines in winter air temperatures. Ice forms in the resulting fractures. If the ice masses persist through the following summer and become enlarged during subsequent winter freezing cycles, ice-wedge polygons are formed. If the ice masses melt each summer, frost-crack polygons are formed. The size and shape of contractional polygons are dominantly functions of winter temperatures and the physical character of the soil materials; thus frost-crack and ice-wedge polygons differ only slightly in size and shape (compare frost-crack polygons at *z* and ice-wedge polygons at *w*, pl. 43 *A*), and both are much larger than frost-stirred polygons. The origin of contractional polygons is discussed in detail by Leffingwell (1919, p. 205–214) and Black (1952, p. 129–131).

LOW-CENTER ICE-WEDGE POLYGONS

Low-center polygons are common in the continuous-permafrost zone, rare in the discontinuous-permafrost zone, and lacking in the sporadic-permafrost zone. They are among the most dependable indicators of permafrost. They are limited to wet tundra areas and are found chiefly in basins of drained lakes and lagoons and abandoned river channels (pls. 35, 37, 40, 41). The polygons consist of networks of broad marginal ridges surrounding low central areas that commonly contain standing water. The marginal ridges of adjoining polygons are separated by troughs or crevices which often are the site of active frost cracking (*a*, pl. 38). The polygons are underlain by perennially frozen ground at depths of less than 2 feet. Upon thawing of the perennially frozen ground, the form of the low-center polygon is modified to that of the high-center polygon, but it may also evolve into a high-center polygon without thawing of permafrost.

HIGH-CENTER ICE-WEDGE POLYGONS

High-center polygons are abundant in the continuous-permafrost zone, common in the northern part of the discontinuous zone, and rare in the southern part of the discontinuous zone and in the sporadic zone. They form, for the most part, in silty and peaty soils on hilltops, on gentle slopes, in depressions, and along minor drainage courses, although high-center polygons are also found locally in sand, gravel, or bedrock on the Arctic slope. High-center polygons are found in slightly better drained areas than those in which low-center polygons are found (pls. 38, 40). Generally, the centers are relatively level; however, extremely active high-center polygons on the Arctic slope have domed centers, and deeply thawed and eroded ice-wedge polygons throughout Alaska have rounded, moundlike profiles (*c*, pl. 42; *y*, 43 *A*). The marginal trenches extend a few inches to a few feet lower than the centers and are underlain by large masses of clear ice. Drainage is concentrated in the trenches, and pools of standing water are common at trench intersections (*c*, pl. 38). Areas of high-center polygons locally contain small "thaw gullies," which are angular drainage courses that have worked headward along interconnecting ice wedges (*h*, pl. 31; *a*, pl. 37; *x*, pl. 43 *A*).

High-center polygons that have formed in the present climate are underlain by perennially frozen ground at depths of 1½ to 3 feet, but relict polygons are common in which perennially frozen ground lies at much greater depth or is absent. High-center ice-wedge polygons are less dependable than low-center polygons as criteria for the recognition of areas underlain by permafrost, because active polygons underlain by permafrost are not readily distinguished from relict ice-wedge polygons or frost-crack polygons in which permafrost may be lacking.

FROST-CRACK POLYGONS

Frost-crack polygons are common in all permafrost zones and may be found locally in the permafrost-free zones of Alaska. They generally form in coarse sand or gravel and are largely confined to well-drained areas such as stream terraces, alluvial fans, spits, and bay bars. In form they are similar to high-center ice-wedge polygons, but the marginal troughs commonly are shallower and less sharply defined (compare frost-crack polygons at *z* and ice-wedge polygons at *w*, pl. 43 *A*). Frost-crack polygons commonly are less regular, less complete, and slightly larger than ice-wedge polygons occurring in the same areas. Perennially frozen ground is present beneath most frost-crack polygons in the continuous-permafrost zone; in other zones, frost-crack polygons commonly are found in areas free of permafrost. In the Bristol Bay region they indicate absence of permafrost (*e*, pl. 39).

RECOGNITION OF CONTRACTIONAL POLYGONS ON AERIAL PHOTOGRAPHS

Low-center ice-wedge polygons are generally easily recognizable on photographs of scale 1:20,000 and less easily so on photographs of scale 1:40,000 (*x*, pl. 40). A location in poorly drained depressions and the presence of pools of standing water in the centers of some polygons are diagnostic of these features. The trenches between the marginal ridges appear as thin dark lines on photographs of scale 1:20,000 but are rarely recognizable on photographs of scale 1:40,000. High-center polygons, pingos, thaw lakes, and beaded drainage commonly can be recognized in areas adjoining low-center polygons.

Generally, high-center ice-wedge polygons and frost-crack polygons are easily seen on photographs of scale 1:20,000. On photographs of scale 1:40,000, ice-wedge polygons are fairly easily observed (*w*, pl. 40) but frost-crack polygons commonly are invisible or only barely discernible. The following features aid in making the difficult distinction between them:

1. The slightly larger dimensions and less pronounced regularity of frost-crack polygons cause them to contrast with adjoining high-center ice-wedge polygons.
2. Frost-crack polygons generally are found in relatively well drained sites underlain by coarse, granular soils; ice-wedge polygons generally are confined to sites underlain by fine-grained, impermeable soils.
3. Commonly, vegetation is sparse on frost-crack polygons, and the characteristic light tones of underlying sand and gravel may contrast sharply with the darker tones of nearby areas in which fine soils bear a more complete cover of vegetation. Frost-crack polygons formed in gravel mantled with a few feet of silt, however, generally support a complete cover of vegetation and cannot be distinguished by color tone from nearby ice-wedge polygons.
4. The presence of small pools of water at channel intersections suggests high-center ice-wedge polygons. Frost-crack polygons, however, may contain similar pools for brief periods during spring thaw or after rainy weather.
5. Active high-center ice-wedge polygons commonly are closely associated with pingos, beaded drainage, thaw gullies with angular courses, thaw lakes, and low-center polygons.

PINGOS

Pingos are reliable indicators of the presence of permafrost. They are common in the continuous-permafrost zone but are rare in other zones. They consist of isolated steep-sided hills, generally circular to oval in ground plan, that range from 10 to 100 feet or more in height. Well-developed pingos commonly bear a summit crack or craterlike depression several feet deep that extends along the long axis of the hill. Some pingos also are cut by radial cracks or by several short cracks normal to the long crack. Pingos are confined to nearly level, poorly drained areas generally in basins of former lakes (pl. 40). They are composed of a core of massive ice overlain by a few feet of silt, sand, and peat (Porsild, 1938). Potable water can be obtained in small springs near the summits of some pingos.

Pingos can be seen on aerial photographs of scale 1:40,000 or larger but commonly can be identified definitely only by viewing stereoscopic pairs (pl. 40). Relatively few landforms simulate the characteristic pingo form, but cones of mud or travertine surrounding large springs, small basalt cinder cones, and conical erosional remnants can be mistaken for pingos that lack the summit crack (*h*, pl. 37).

FEATURES RESULTING FROM THAWING

THAW LAKES

Recognition of thaw lakes aids in the interpretation of permafrost conditions. Thaw lakes occupy shallow depressions caused by local thawing of perennially frozen ground on flat surfaces and gentle slopes underlain by 10 feet or more of peat and silt. They are common in the continuous- and discontinuous-permafrost zones and are rare in the sporadic zone. Their use as permafrost indicators is severely limited by the difficulty of distinguishing on aerial photographs between active thaw lakes, relict thaw lakes, and similar-appearing lakes that are in no way related to permafrost.

The origin of thaw lakes is discussed by Wallace (1948), Black and Barksdale (1949), and Hopkins (1949). Frozen fine-grained sediments generally contain a volume of ice in the form of clear ice lenses and masses greatly in excess of the porosity of the unfrozen material. Upon melting of the ice the ground subsides, and a basin is formed in which a thaw lake may accumulate. The lake increases in size by thawing and wave erosion of its banks and is eventually drained when the retreating banks intersect a stream valley or other low ground (*k*, pl. 31).

The well-known oriented lakes of the Arctic coastal plain (pl. 38; Black and Barksdale, 1949, p. 113–115), formed largely by thawing of perennially frozen ground, are as much as several miles in length and several tens of feet in depth. Lakes elsewhere in Alaska that have originated chiefly by thawing rarely exceed 1,000 feet in length and 10 feet in depth. The banks generally are 5 to 10 feet high but locally reach heights approaching 100 feet. Simple lakes are round, oval, or roughly rectangular in outline, but groups of lakes commonly coalesce to form compound water bodies with scalloped outlines (lakes in pl. 37 and shores of Imuruk Lake, pl. 31). The outlines of drained thaw lakes commonly can be discerned in the vicinity of existing thaw lakes (*k*, pl. 31; *g*, pl. 35; *dd*, pl. 37; pl. 38; pl. 41).

Actively caving banks are ragged and steep or overhanging. Tilted trees leaning over the water along the banks afford evidence of active caving in forested areas; dead trees with bases submerged commonly can be seen adjacent to the active banks. In treeless areas, active caving is indicated by crevices parallel to the banks (*z*, pl. 40), marking the inner edge of undercutting and slumping. Thawing proceeds most rapidly along ice wedges on shores retreating into areas of high-center ice-wedge polygons, and the banks are etched by closely spaced thaw gullies developed along the thawing ice wedges (*h*, pl. 31 and shores of large lake in pl. 37). Where low-center polygons adjoin the lake, however, thawing commonly proceeds more rapidly into the frozen ground of the polygon centers, and the ice wedges project into the water as miniature peninsulas (*b*, pl. 38; *y*, pl. 40).

Oxbow lakes on flood plains in areas of perennially frozen ground commonly are enlarged by thawing and caving of the banks.[7] Series of abandoned meanders show progressive modification with increasing distance from the river and range from the characteristic arcuate or U-shaped outline of the recently formed oxbow lakes to the oval, rectangular, or scalloped form typical of thaw lakes (pl. 41).

Thaw lakes probably persist in recognizable form in areas in which no perennially frozen ground remains; lakes similar in outline but lacking evidence of active caving are common in areas in Alaska where little or no permafrost exists today (pl. 44). Several types of lakes in whose development thaw-collapse plays no part can be confused with thaw lakes. The distinctive landforms characteristic of young, unmodified glacial and volcanic deposits prevent confusion of the associated lakes with thaw lakes, but older, modified glacial deposits and lava flows commonly contain rounded, oval, and rectangular lakes (pl. 39) that are difficult to distinguish from thaw lakes. Lakes resembling thaw lakes are common in the basins of former lagoons and estuaries on the recently uplifted coastal-plain areas that border much of the west and north coasts of Alaska.

Thaw lakes can be seen easily on aerial photographs of all commonly used scales (pl. 40), but evidence of active caving, required for absolute identification, is difficult to detect on a scale smaller than 1:20,000. Many thaw lakes lack discernible evidence of active caving on any aerial photographs. The following characteristics may permit identification of thaw lakes when evidence of active caving cannot be recognized:

1. Steep banks are present along part of the perimeter.
2. Short, sharp-walled gullies with angular courses are incised in the steep lake banks; the shores are minutely irregular, and evenly spaced minor peninsulas project into the water where the lake banks are low.
3. Pingos, ice-wedge polygons, beaded drainage, and circular, oval, or rectangular depressions, which appear to represent the basins of drained lakes, are present nearby.
4. A gradational series of lakes that ranges from those formed by some means other than thawing, such as oxbows, to typical thaw lakes, can be discerned.

[7] Péwé, T. L., 1948, Terrain and permafrost, Galena area, Alaska: U. S. Geol. Survey Permafrost Program Prog. Rept. no. 7, 52 p. (Unpublished report.)

BEADED DRAINAGE

The term "beaded drainage" is applied to a characteristic pattern of minor streams in areas underlain by perennially frozen peat and silt containing ice wedges. Beaded drainage is common in the continuous- and discontinuous-permafrost zones and rare in the sporadic zone. The pattern consists of series of small pools connected by short watercourses (*g*, pl. 31; *h*, pl. 35; *b*, pl. 41). The pools form in areas of collapse due to the thawing of large ice masses and consequently have steep banks; they range in depth from 2 to 10 feet and in diameter from a few to a hundred feet. The connecting watercourses commonly follow ice wedges and thus are straight or sharply angular. The watercourses generally but not everywhere are sharply incised a few feet below their banks.

A drainage pattern of similar appearance, unrelated to permafrost, occurs in swampy areas in many parts of Alaska. The pattern consists of shallow vegetation-choked pools with sloping banks, separated by straight or curving watercourses (near *f*, pls. 39 and 44). The pools generally are less than 3 feet deep.

Beaded drainage can be seen on photographs of scale 1:40,000 or larger. Care must be exercised to avoid confusion between beaded drainage, whose pattern is due to the thawing of permafrost, and swamp drainage in which permafrost plays no role. The following criteria assist in recognizing beaded drainage:

1. Beaded-drainage pools and channels are sharply defined; swamp-drainage courses unrelated to permafrost have indistinct, gradational borders.
2. Beaded-drainage channels generally are straight or consist of series of straight segments separated by angular bends; swamp-drainage courses are straight or smoothly curved.
3. Beaded-drainage courses generally are associated with ice-wedge polygons and locally with pingos and thaw lakes.

COLLAPSE ALONG TRAILS, NEAR INSTALLATIONS, AND IN CULTIVATED FIELDS

Human activities in areas of perennially frozen peat and silt frequently disrupt the insulating vegetation cover and expose the underlying dark soil to the summer sun, so that rapid thawing ensues. This results in thermokarst topography, local subsidence of the surface, tilting of small buildings, or accentuation of microrelief of ice-wedge polygons. Small thaw lakes and beaded drainage may develop along tractor trails. Care must be exercised, however, in distinguishing between trails along which thaw features have formed and similar-appearing trails where water stands in original depressions crossed by the tractor. Conspicuous accentuation of the microrelief of ice-wedge polygons is noted in cultivated fields in the Fairbanks area (pl. 42; Péwé, 1948, 1954). Generally, thaw features resulting from human activities can be discerned easily on aerial photographs of scale 1:10,000 and with difficulty on smaller scales.

HYDROLOGIC PHENOMENA

Subterranean drainage, springs, and flood-plain icings offer indirect evidence of the presence of unfrozen zones in areas where permafrost is widespread.

Subterranean drainage—the disappearance of streams in the bottoms of closed depressions or by percolation into a gravel-covered surface—commonly can be observed directly on aerial photographs (*a*, pl. 31). The following phenomena suggest subterranean drainage through unfrozen zones:

1. Abrupt diminution of the apparent volume of streams crossing alluvial fans, gravel plains, or limestone areas as suggested by decrease in width or complete disappearance of streams.
2. The presence of dry depressions without surface drainage.
3. Streams draining into small lakes having no visible outlet.
4. Significant changes in the levels of small lakes when observed on aerial photographs taken at different times.

Springs rarely can be observed directly on aerial photographs. Differences in vegetation near springs commonly aid in their detection (*x*, pl. 30; *d*, pl. 31; *s*, pl. 43 *C*), but the character of these differences varies from one area to another, so that interpretation requires that the observer be familiar with the area. The following phenomena are suggestive of the presence of springs:

1. Streams heading in clusters of small lakes, especially at the toes of alluvial fans or near contacts between bedrock slopes and unconsolidated valley or lowland deposits.
2. Patches of luxuriant vegetation, commonly expressed on aerial photographs as local areas of dark tones extending downslope from the base of a conspicuous bedrock escarpment.

Flood-plain icings (pl. 43) on small streams are indirect evidence of the presence of perennial springs. Surface water freezes in the winter in the continuous-permafrost zone and in the northern part of the discontinuous zone in Alaska, and slope runoff ceases. Small streams whose discharge consists entirely of surface runoff generally dry up, but spring-fed streams continue to flow throughout the winter. The presence of icings on small streams in the continuous- and discontinuous-permafrost zones indicates perennial flow, probably due to perennial springs, and thus suggests the presence of water-bearing thawed zones in the drainage basin.

The sites of flood-plain icings can be recognized readily on aerial photographs of scale 1:40,000 and larger. The flat, white surface of the ice deposit itself can be observed in early summer; dissected remnants of large icings persist in some areas throughout the year (pl. 43 *C*). After the ice has melted, the icing site is distinguishable as a braided segment of a stream that elsewhere is confined to a single channel. Vegetation, if present, consists for the most part of patches of grasses, sedges, and heaths; trees are lacking, but a few ragged patches of low willows may be present. More commonly the icing site is bare and free of vegetation. The ground surface generally is a rough, patternless jumble of channels, gravel bars, and conical gravel piles and ridges having a local relief of 1 to 4 feet.

LIMITATIONS

Several basic factors limit the usefulness of aerial photographs in the interpretation of permafrost conditions. Many aerial photographs are unsatisfactory because of small scale or poor quality. Most of the suggested indicators are ambiguous; some are found in relict form today in poorly drained soils in which permafrost is lacking but seasonal frost persists throughout most of the summer. Finally, distinctive surface indicators are lacking in many areas in which permafrost is present (pl. 44).

Most of the photographs used in this report were selected because the permafrost indicators are depicted with especial clarity. Probably 90 percent of the available aerial photographs of Arctic and subarctic regions are less satisfactory for the photointerpretation of permafrost conditions because of small scale, poor light conditions, improper exposure, poor printing, or because they were taken at a season when snow or foliage concealed many features of the terrain.

Permafrost plays an essential role in the development of only a few microrelief features; most of these are difficult to distinguish from similar-appearing features in which permafrost plays no role. Most microrelief features proposed as permafrost indicators actually form in the active layer of seasonally frozen and thawed ground. Perennially frozen ground at shallow depth restricts drainage and offers favorable conditions for intense frost action and for the formation of these microrelief features in the overlying active layer. Almost equally favorable conditions are offered, however, by the presence of a layer of seasonally frozen ground which persists during most of the summer or by a substratum of hardpan, dense bedrock, or other impermeable material. Thus, many of the microrelief features and vegetation patterns present in permafrost areas are duplicated elsewhere by frost action independent of permafrost.

Many distinctive microrelief patterns are persistent and exist as relict forms long after permafrost has thawed. Positive distinction of relict and active features is difficult on the ground and generally impossible on aerial photographs (for example, see stabilized stone polygons at *b*, pl. 31, and probable relict thaw lakes, pl. 44).

The importance of permafrost in controlling surface vegetation and microrelief decreases with increasing depth to permafrost. If permafrost lies below a depth of several feet, its effect upon surface phenomena is negligible. The critical depth is variable, depending upon interrelated factors of surface insulation, type of vegetation, soil permeability and stratigraphy, and slope. No surface indicators of the presence or absence of permafrost are known in areas where bedrock is exposed at the surface or lies beneath a few feet of rubble. Thus, the absence of microrelief features and vegetation patterns that are elsewhere associated with permafrost does not necessarily mean the absence of permafrost in a given area.

The photographs used as illustrations in this report were selected after examining several thousand aerial photographs of regions where permafrost is known to be present. Most of the aerial photographs showing lowland and upland areas in the continuous-permafrost zone contained recognizable surface features that suggest the presence of permafrost, but less than half of the photographs depicting mountainous areas contained such evidence. In the discontinuous- and sporadic-permafrost zones, only a small percentage of the photographs examined contained strong evidence of the presence or absence of permafrost.

Analysis of these basic factors emphasizes the following general limitations in the use of indicators for the recognition of permafrost:

1. Most indicators merely suggest the presence of permafrost; the more that can be recognized in a given area, the more likely is the presence of permafrost.
2. Most indicators are significant only when considered in relation to the climate, topography, and geology of the region in which they occur.
3. Most indicators reflect near-surface soil conditions and offer little or no information concerning the thickness, extent, and character of permafrost below depths of a few feet.
4. Absence of indicators does not constitute evidence that permafrost is not present.

PHOTOINTERPRETATION KEYS

Several categories of information can be obtained from aerial photographs. First-order information, such as topography, microrelief, drainage patterns, and form and distribution of vegetation, can be observed or measured directly on the photographs. Analysis of the primary information yields second-order data concerning, for example, the species of plants represented and the probable geologic and geomorphic origin of landforms and microrelief. This in turn permits third-order inferences concerning probable composition and texture of subsurface materials and surface and subsurface drainage conditions. The interpretation of permafrost and ground-water conditions is still further removed from the original observational data and depends largely upon fourth-order inferences based on the conclusions concerning regional climate, the insulating properties of the vegetation, the character of the substratum, drainage conditions, and the geomorphic history.

Reasonably accurate photointerpretation keys are readily constructed for obtaining second-order information from primary observational data; less accurate keys can be established for the derivation of third-order information. Keys for fourth-order interpretations—in determining the presence or absence of permafrost, for example—become so subjective and so encumbered with lists of modifications and exceptions that they are practically useless.

A complete key for the evaluation of permafrost conditions in a given region must consist of several partial keys leading to correct analysis of second- and third-order information. However, the partial keys, at best, lead only to the evaluation of various sites in relative terms of favorability or unfavorability for the formation of permafrost, rather than to evaluation in absolute terms of presence or absence of permafrost. Moreover, the answers given by the partial keys will be conflicting and will have little significance unless they are integrated by an interpreter having specialized experience in the study of permafrost. An individual trained only in the reading of aerial photographs cannot be expected to produce dependable fourth-order interpretations from second- and third-order conclusions that are speculative at best.

A comprehensive photointerpretation key for permafrost conditions in all of Alaska would consist of an encyclopedic collection of local keys. Compilation of such a comprehensive key is hardly justified in view of the low degree of reliability to be expected when the key is used by an interpreter lacking specialized field experience. The permafrost specialist, on the other hand, finds little need for such a comprehensive key, but needs instead a general understanding of the basic geologic, geomorphic, botanical, and climatic factors that determine the distribution of permafrost. He will be aided by partial keys for vegetation and microrelief features.

CONCLUSIONS

The discussion of permafrost indicators illustrates some of the problems of applying photointerpretation techniques to the study of permafrost. Indicators taken individually are ambiguous, erratically distributed, and generally difficult to recognize. They are significant only when considered as a group in the context of their geographic and climatic setting. Photointerpretation of permafrost requires a synthesis of all the features of the landscape.

Reliable interpretation of permafrost conditions by use of aerial photographs can be achieved only by individuals trained in the natural sciences and armed with field experience in regions where permafrost occurs. However, the limitations of the method are severe, even when employed by well-trained and experienced individuals. The detailed boundaries of permafrost at shallow depth are difficult to establish on the ground and impossible to delineate on aerial photographs, even by experienced interpreters. The presence or absence of relict permafrost at depths of more than 10 feet and the depth to which any permafrost extends cannot be established by use of aerial photographs. The reliability of photointerpretation in any area is greatly increased by ground studies at representative sites within the area.

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PLATES 30–44

PLATE 30

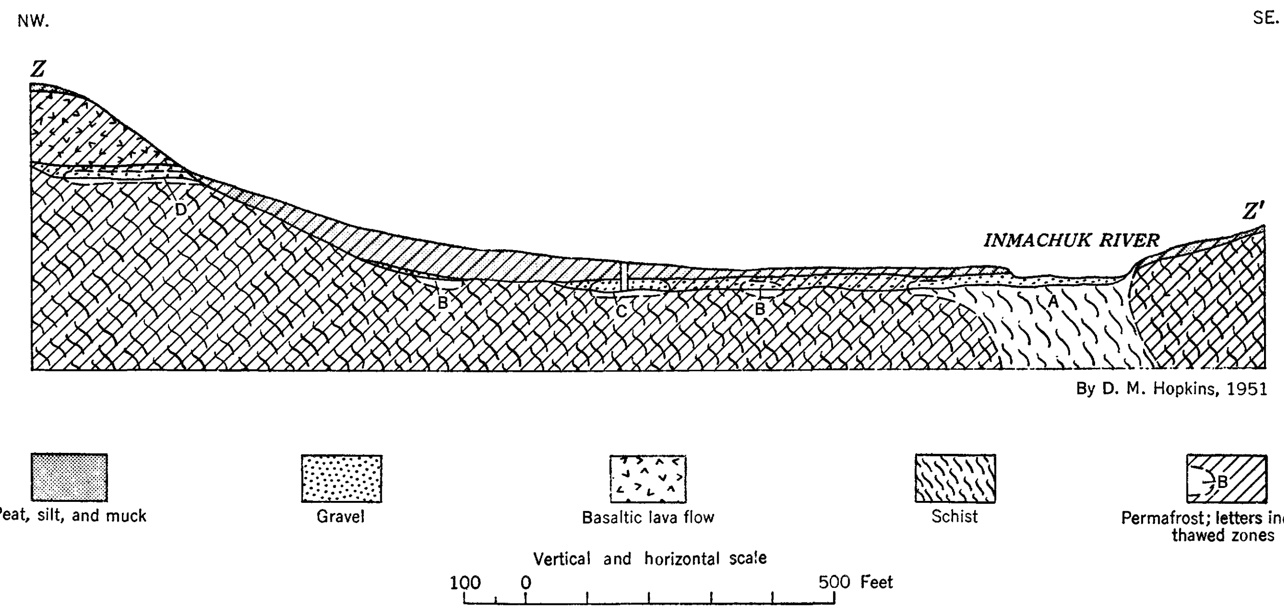
[Scale at lower edge of photograph 1:20,000 (north arrow=about 1,000 feet). U. S. Army Air Force, Oct. 2, 1946]

Location.—Valley of Inmachuk River, 20 miles south of Deering, Seward Pensinsula, in the continuous-permafrost zone.

Geology.—Bedrock mostly schist. Dissected basaltic lava flow (*t*) forms cliffs along valley walls. Gold-bearing gravel, mantled with silt and peat, underlies valley floor and lower valley walls and is mined in open pits (*v*) and by dredges (*u*).

Permafrost.—Permafrost underlies most of area but is lacking beneath river channel and adjoining gravel bars and in mined-out areas. Springs at base of basalt cliff indicate that unfrozen zones also are present beneath the lava flow. Location of other unfrozen zones is shown in cross section along line *ZZ'*.

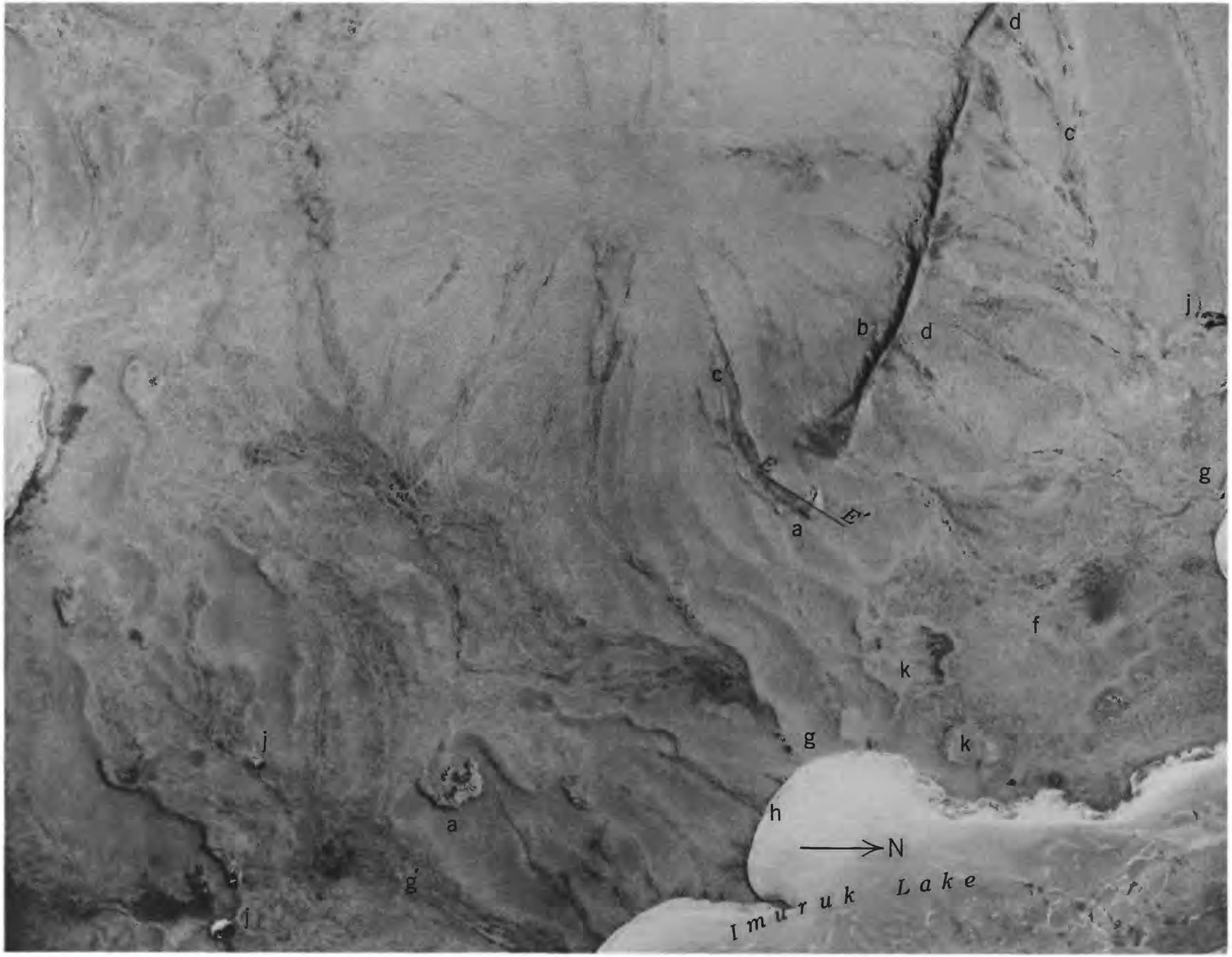
Photointerpretation.—Stream gravel bars (*w*), which are unfrozen, can be recognized by light tone, arcuate bar-and-swale pattern, and location adjacent and parallel to stream channel. Mined-out areas, also unfrozen, can be recognized by light areas of flat or hummocky relief and irregular outline (*u*), by rectangular dredge ponds, and by deep pits in valley walls (*v*). Springs are indicated by patches of willows (dark tongues and bands extending downslope from base of escarpment at *x*) and by gully heading at escarpment (*y*).



DIAGRAMMATIC CROSS SECTION ALONG LINE *ZZ'*

Large perennial water supply can be obtained in wells in unfrozen gravel beneath and adjoining river channel (A). Small, fluctuating supply can be obtained in wells penetrating unfrozen zones near abandoned underground mine (C), in local permeable unfrozen zones near contact between gravel and bedrock (B), and in unfrozen gravel beneath lava flow on west wall of valley (D).

TYPICAL UPLAND TERRAIN, NORTHERN SEWARD PENINSULA, ALASKA



BASALTIC LAVA FLOWS, NORTHERN SEWARD PENINSULA, ALASKA

PLATE 31

[Scale of photograph 1:20,000 (north arrow = about 1,000 feet). U. S. Army Air Force, Oct. 2, 1946]

Location.—Near Imuruk Lake, 35 miles south of Deering, Seward Peninsula, in the continuous-permafrost zone.

Geology.—Basaltic lava flows containing thin, interbedded gravel layers and overlain by 5 to 20 feet of silt everywhere except in flow-front escarpments (*b*).

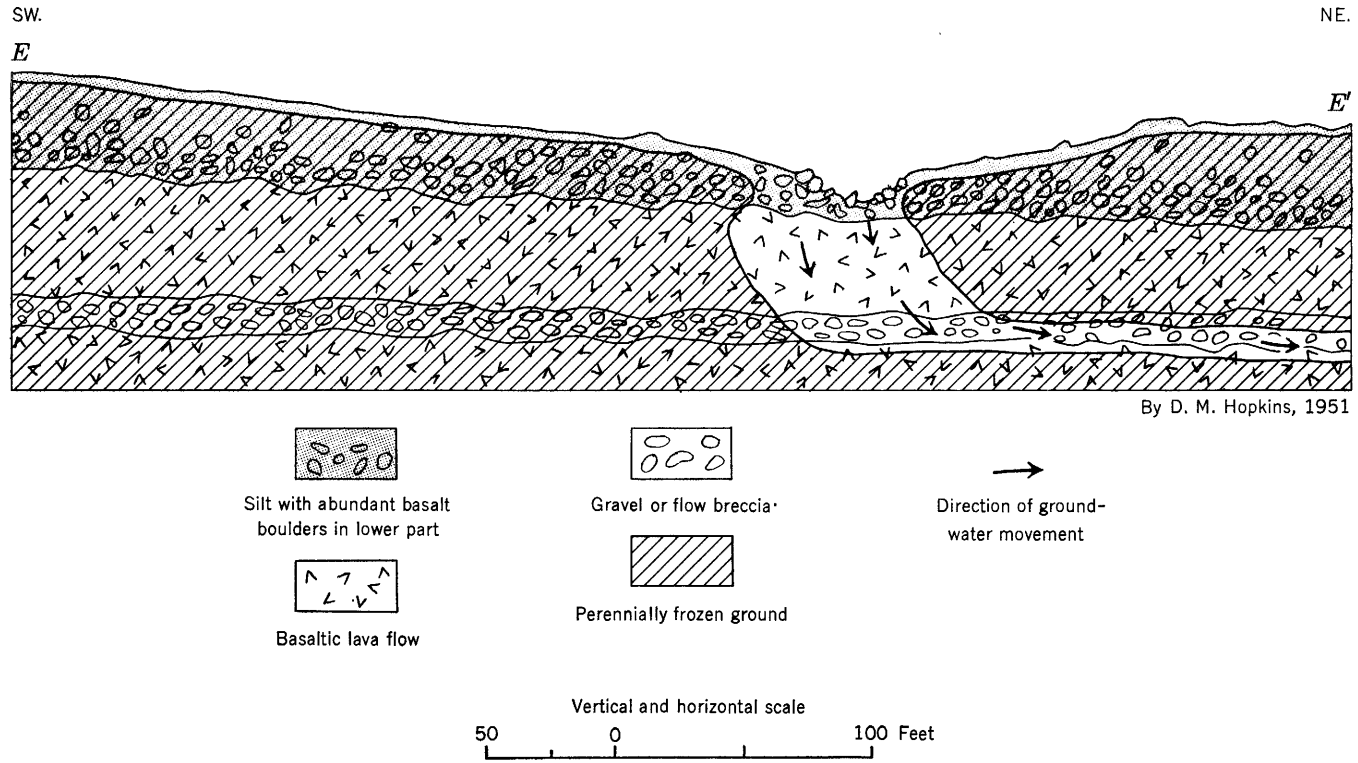
Permafrost.—Permafrost underlies most of area, but unfrozen galleries and layers are present locally. See cross section along line *EE'*.

Photointerpretation.—Drainage courses are dark lines arranged in linear or dendritic patterns (*c*).

Extensive permafrost is indicated by high-center ice-wedge polygons (*f*), beaded drainage (*g*), scalloped shore of Imuruk Lake and thaw gullies in shore at *h*, thaw lakes (*j*), and basins of drained thaw lakes (*k*).

Presence of local thawed zones is shown by springs (indicated by dark patches of tall willows, *d*, along flow front) and by subterranean drainage of streams such as *c'* which empty into closed depressions (*a*).

Tiny stipples at *b* are stabilized stone polygons formed during a past cold period.



DIAGRAMMATIC CROSS SECTION ALONG LINE *EE'*

Small stream draining into depression percolates into rubble at lowest point, enters thawed permeable zone in or between basaltic lava flows.

PLATE 32

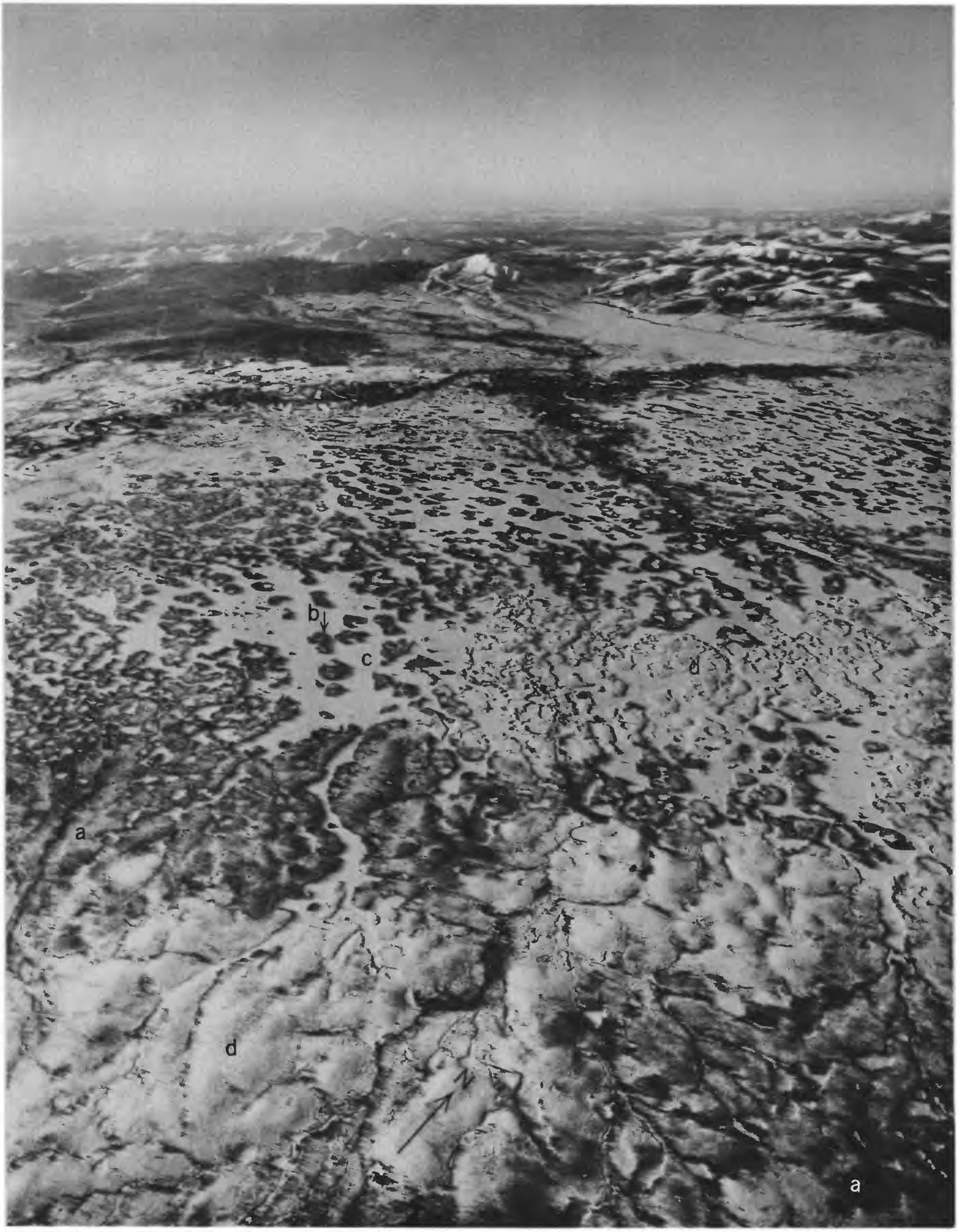
[Scale at lower edge of photograph 1:20,000 (north arrow=about 1,000 feet). U. S. Army Air Force, Feb. 16, 1949]

Location.—Nixon River lowland, upper Kuskokwim Valley, in the discontinuous-permafrost zone. Kuskokwim Mountains in the background.

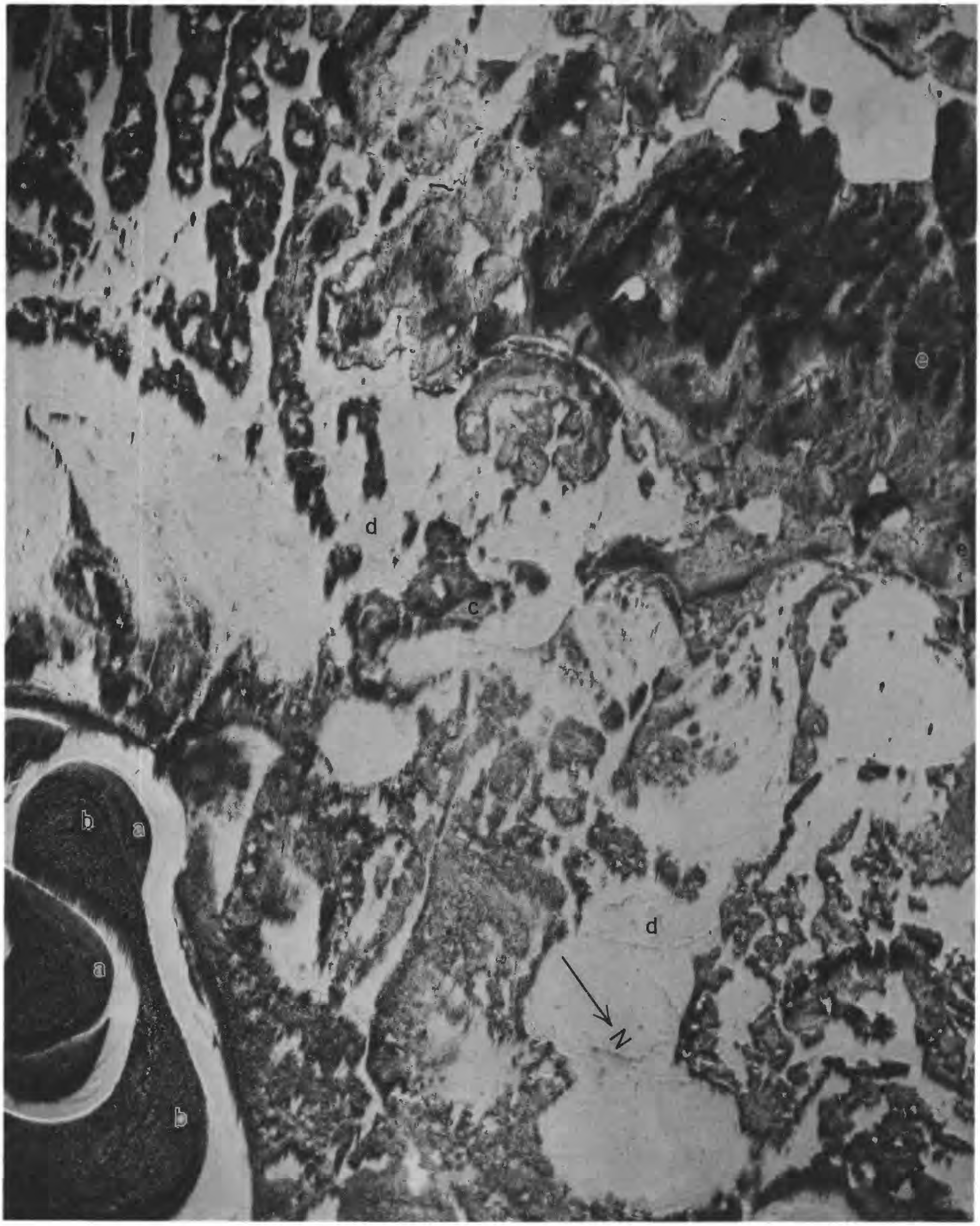
Geology.—Entire lowland underlain by organic silt, sand, and peat.

Vegetation.—Open black spruce forest with mossy floor covers rolling terrain in foreground (densely stippled areas at *a*). Forest fire probably burned off spruce in lightly stippled areas at *d*. Bog flats, consisting of black spruce islands (*b*) separated by lower sedge marshes (*c*), extend from forest in foreground to the Nixon River (dark strip extending across photograph near base of mountains).

Permafrost.—Permafrost lies at a depth of a few feet beneath black spruce forest and black spruce islands in bog flats. Permafrost is lacking or lies at depths greater than 6 feet beneath sedge marshes.



BOG FLATS, OBLIQUE VIEW, UPPER KUSKOKWIM VALLEY, ALASKA



BOG FLATS, VERTICAL VIEW, UPPER KUSKOKWIM VALLEY, ALASKA

PLATE 33

[Scale 1:20,000 (north arrow=about 1,000 feet). U. S. Air Force, Feb. 16, 1949]

Location.—Twenty-two miles southeast of McGrath, upper Kuskokwim Valley, in the discontinuous-permafrost zone.

Geology.—Present-day flood plain, enclosed by the Big River in the lower left corner, is underlain by sand, silt, and peat, and at greater depth by gravel and sand. Surface relief consists of bar-and-swale topography.

Low terrace extending from upper left to lower right corner is an older, elevated flood plain of silt, sand, and organic debris, mantled in places by peat several feet thick. Surface relief consists of bog flats.

High terrace extending across top of photograph is an ancient glacial-outwash plain of sand covered by a discontinuous blanket of peat. Surface relief consists of ancient dunes (*e*) surrounded by areas of muskeg (*f*).

Vegetation.—Slip-off slopes on inside of meanders are covered with young willows (*a*); slightly older parts of present flood plain support dense tall white spruce forest (*b*). Bog flats consist of high areas overgrown by black spruce and *Sphagnum* (*c*) surrounded by sedge marsh (*d*). Dunes are covered with white spruce and birch forest (*e*) and intervening muskeg supports black spruce and *Sphagnum* (*f*).

Permafrost.—Permafrost lies at depths of 1 to 3 feet beneath muskeg on high terrace and beneath islands of black spruce in bog flats on low terrace. Permafrost is lacking at depths less than 6 feet but may be present at greater depth in dunes and in sedge marsh of bog flats. There is no permafrost in the present flood plain.

PLATE 34

[Scale at lower edge of photograph 1:20,000 (north arrow=about 1,000 feet). U. S. Army Air Force, Sept. 27, 1946]

Location.—At east edge of Kenai lowland, 20 miles east of Kenai in the no-permafrost zone. Kenai Mountains in the distance.

Geology.—End-moraine complex in right middle ground; outwash plain in foreground and left middle ground. End moraine is underlain by till in ridges and peat in depressions. Older parts of outwash plain (*c*) are underlain by stratified, predominantly fine-grained gravel, sand, and silt, mantled by a few feet of windblown silt. Bog flats (*a*, *b*) are developing along drainage lines in the outwash plain at expense of older surfaces and are underlain by peat and organic silt.

Vegetation.—End moraine is covered with mixed aspen, birch, and white spruce (*f*) on ridges underlain by gravelly till and with black spruce (*g*) in depressions and on ridges underlain by silty till. Older surfaces on outwash plain are covered with black spruce (*c*); bog flats consist of islands of black spruce (*b*) surrounded by sedge marsh (*a*).

Permafrost.—Permafrost is present beneath some of the black spruce islands (see Photointerpretation). Permafrost is absent elsewhere, but seasonally frozen ground persists most of the summer beneath some other black spruce islands and beneath older surfaces of the outwash plain and parts of the end moraine that are covered with black spruce.

Photointerpretation.—In this area, morainal topography is distinguished from bog-flat topography by higher relief, arcuate pattern of ridges that extend transverse to the trunk streams, and presence of deciduous trees on many ridges and knobs, indicating a coarse-grained substratum. Bog-flat islands are lower than the morainal ridges, irregular in pattern, extend parallel to drainage lines, and are covered with black spruce.

Bog-flat islands underlain by permafrost are characterized by sharply defined scalloped edges (*b*), marginal moats (narrow, light-toned zone at right edge of island *d*), and by circular pockmarklike bogs on their summits. Black spruce islands that lack permafrost are characterized by gradational margins with adjoining sedge marsh (*e*).

BOG FLATS, KENAI LOWLAND, ALASKA

MIXED FOREST AND TUNDRA, NORTHERN SEWARD PENINSULA, ALASKA

PLATE 35

[Scale 1:40,000 (north arrow=about 1,000 feet). U. S. Navy, Aug. 15, 1950]

Location.—Pargon River, 65 miles northeast of Nome, in the continuous-permafrost zone.

Geology.—Hills in southern third of area are underlain by marble mantled with thin rocky soil. Rest of area underlain by glacial till mantled by a few feet of silt and peat.

Vegetation.—White spruce forest (dark-gray, finely stippled areas at *a*) or shrub tundra (light-gray areas of cloudlike texture at *c*) covers most of the hill slopes. Dark-gray areas on flood plain (*d*) are tall willows; rest of area is sedge tundra.

Permafrost.—Both forest and tundra are underlain by permafrost. Thawed zones are found only beneath tall willows on flood plain (*d*) and beneath lakes.

Photointerpretation.—Presence of permafrost at shallow depth is suggested by low-center ice-wedge polygons (*j*), beaded drainage (*h*), thaw lakes (*g*), peat-mound stripes in shrub tundra (*e*), vegetation stripes in forest (*f*). Note characteristic scalloped outline, steep banks of thaw lakes, and occurrence in a larger, older lake basin. Low-center ice-wedge polygons are expressed by dark lines surrounding light centers on this photograph; these relationships are reversed in the low-center polygons shown on plate 37. High-center polygons also are present but cannot be recognized on this photograph.

PLATE 36

[Scale 1:40,000 (north arrow = about 1,000 feet). U. S. Army Air Force, June 8, 1943]

Location.—Lowland between Mulchatna Hills (lower right) and Mulchatna River (upper left) in the sporadic-permafrost zone.

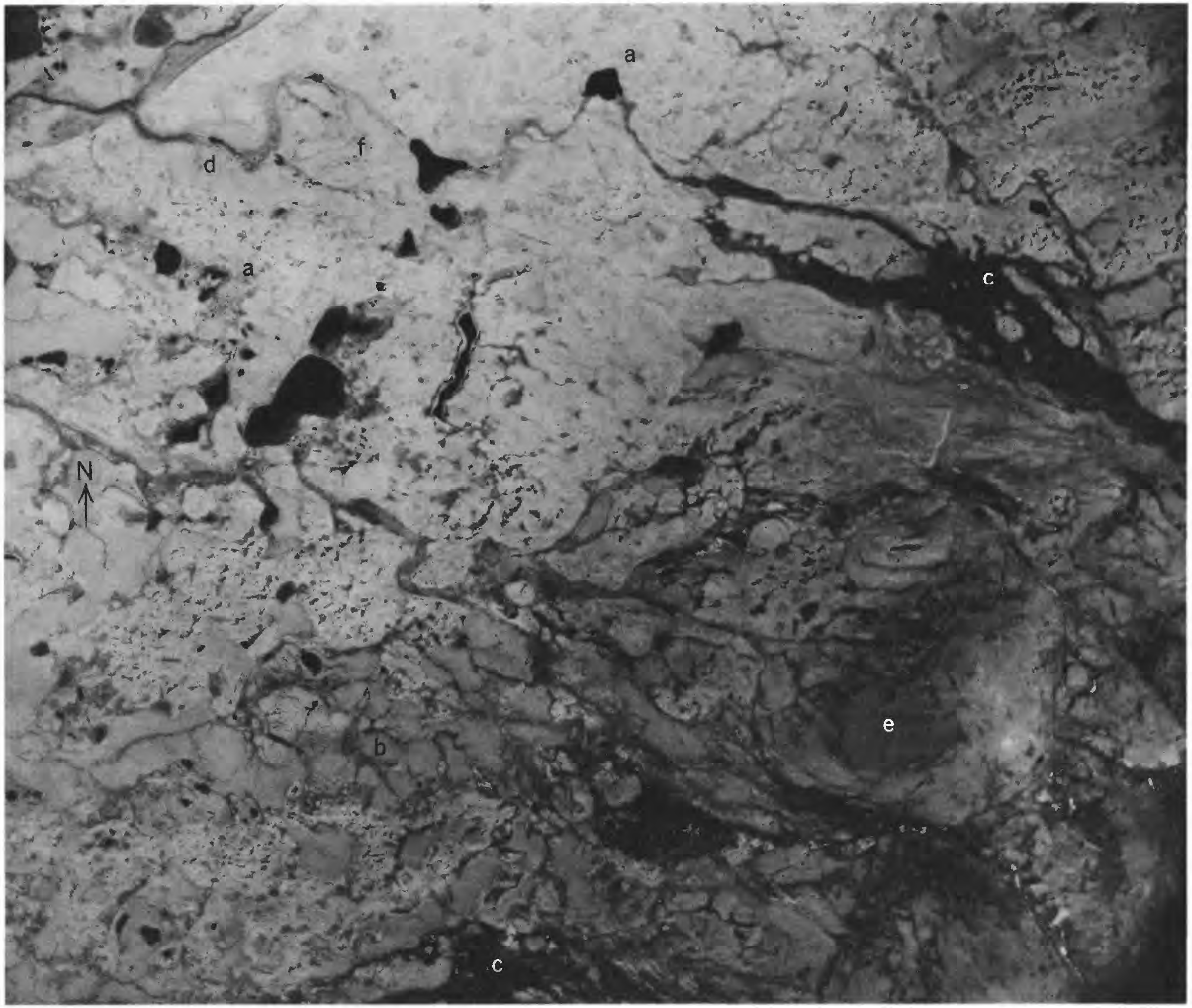
Geology.—Lowland underlain predominantly by glacial till. Kettle-pocked morainal ridges appear mottled and dominantly light toned (*a*). Broad depressions, mantled by a few feet of peat, are expressed in uniform, slightly darker tones (*b*, *d*, *f*). Granite bedrock is near surface in hills at lower right (*e*).

Vegetation.—Sparse subalpine tundra and a few scattered spruce trees cover light ridges (*a*). Sedge and heath tundra grows in the broad depressions (*b*, *d*, *f*). Dark, stippled areas (*c*) are spruce forest growing along major drainage lines.

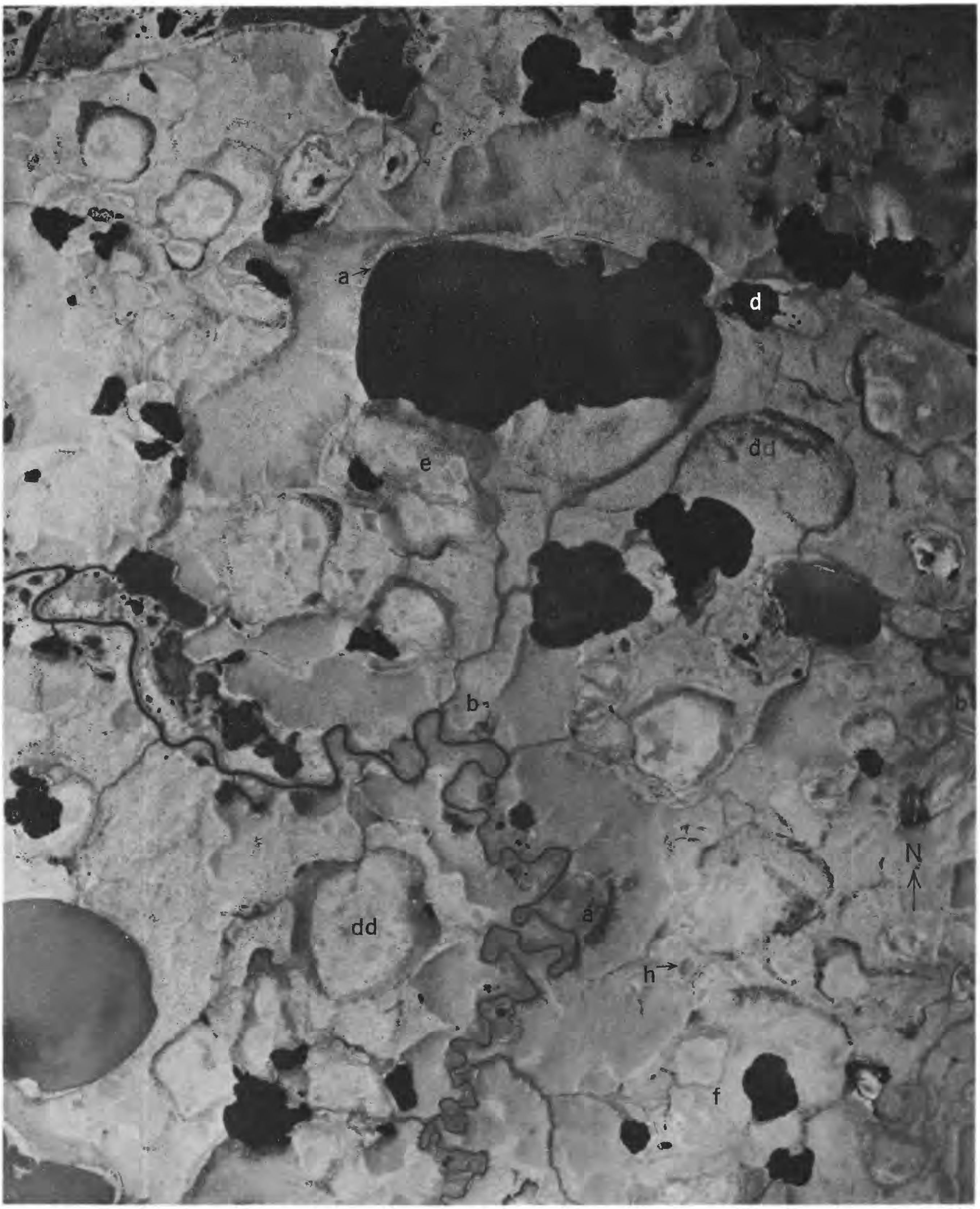
Permafrost.—Permafrost is present at shallow depth in areas of sedge and heath tundra growing in peat soil (*b*, *d*, *f*). Permafrost is absent in light morainal ridges (*a*), in dense spruce forest (*c*), and in bedrock hills (*e*).

Photointerpretation.—Vegetation stripes, expressed as faint dark lines perpendicular to small stream at *d*, are good indicators of permafrost in Bristol Bay region but are difficult to distinguish from stone stripes (*e*), which here are found in unfrozen ground.

Small pools in drainage lines on each side of *f* may be beaded drainage caused by thawing of permafrost or may be caused by choking of drainage by frost-heaved mounds; thus they are not dependable indicators of permafrost in this area.



STONE STRIPES AND VEGETATION STRIPES, BRISTOL BAY REGION, ALASKA



ICE-WEDGE POLYGONS AND THAW LAKES, NORTHERN SEWARD PENINSULA, ALASKA

PLATE 37

[Scale 1:40,000 (north arrow = about 1,000 feet). U. S. Navy, July 27, 1949]

Location.—Coastal plain near Shishmaref Inlet in the continuous-permafrost zone.

Geology.—Entire area underlain by silt and peat.

Permafrost.—Perennially frozen ground present at depth of 1½ to 3 feet everywhere except beneath rivers and lakes.

Photointerpretation.—Indicators of permafrost can be recognized over most of photograph. Thaw lakes (*d*) and basins of drained thaw lakes (*dd*) cover about three quarters of photograph. Following features suggest active thawing and caving at lake shores: scalloped margins of lakes, steep banks and thaw gullies (*a*), lack of beaches, and lack of aquatic vegetation in shallow water near shores.

Other evidence of permafrost includes beaded drainage (*b*), low-center ice-wedge polygons (light lines surrounding dark centers at *e*) in most poorly drained areas, and high-center ice-wedge polygons (dark lines surrounding light centers at *f*) in slightly better drained sites. Note moundlike form of deeply thawed polygons on hilltop at *c* and small ponds at junctions of ice wedges in polygons at *g*.

Mound at *h* may be an erosional remnant of dissected higher surface near *a* or it may be a pingo. Compare with known pingos in plates 40 and 41.

PLATE 38

[Scale 1:20,000 (north arrow=about 1,000 feet). U. S. Navy, Aug. 1948]

Location.—Arctic coastal plain near Point Barrow, in the continuous-permafrost zone.

Geology.—Entire area underlain by stratified silt and sand.

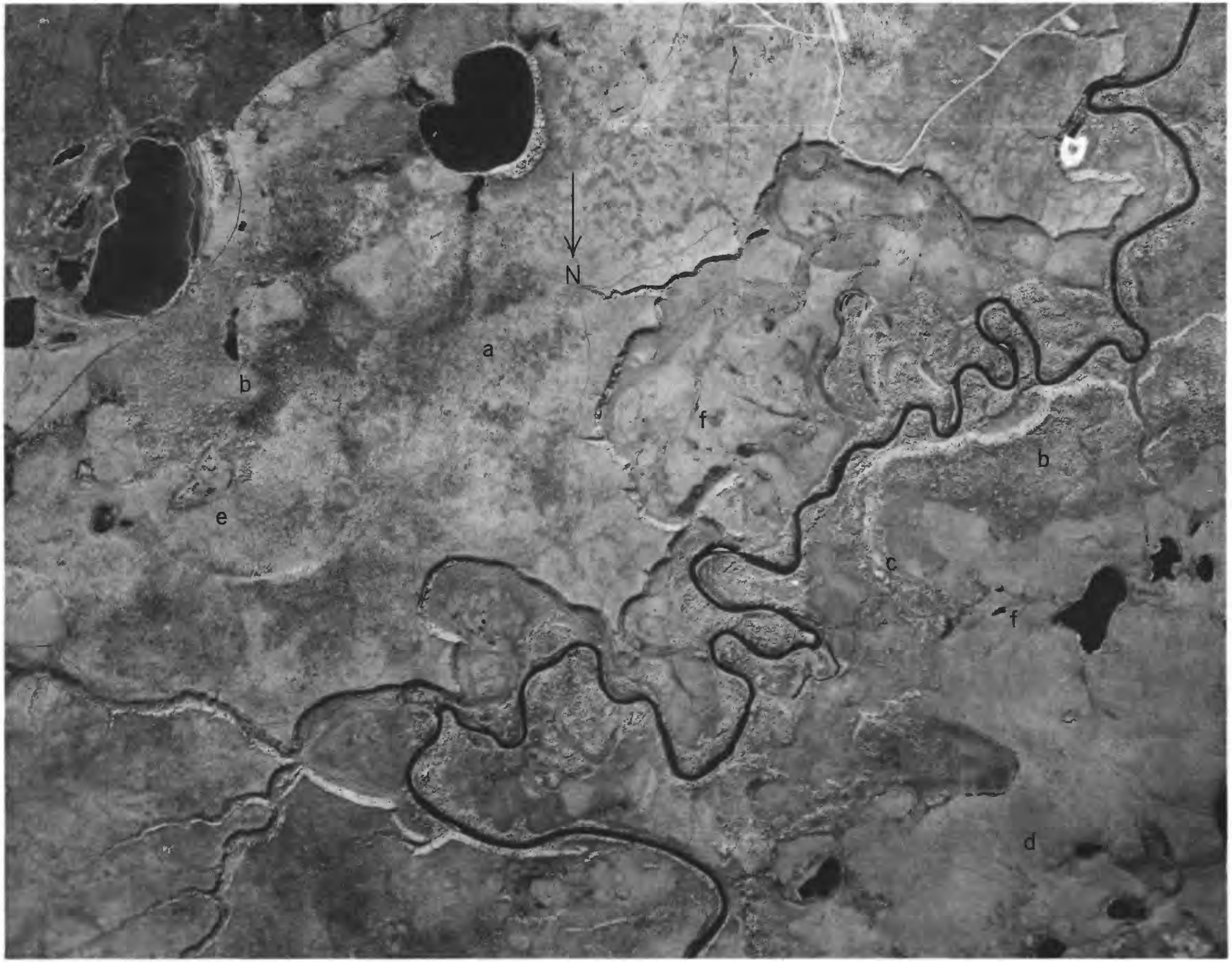
Permafrost.—Permafrost present at shallow depth throughout area, including beneath lake.

Photointerpretation.—Large thaw lake is one of the well-known oriented lakes of the Arctic coastal plain. It occupies a larger, older lake basin and is adjoined by several other basins of former lakes.

Low-center ice-wedge polygons (*a*) have dark centers and light marginal ridges in this photograph and are confined to lake basins. Trenches separating marginal ridges of adjoining polygons are expressed by thin dark lines. Note the saw-toothed shoreline at *b*, where some ice wedges, thawing less rapidly than the frozen centers of the polygons, extend into lake as a series of minute peninsulas.

High-center polygons (*c*) are expressed by light centers and dark marginal trenches and are confined mostly to high, relatively well drained areas between lake basins. Black spots near *c* are small ponds at intersections of ice wedges. Polygons are obscured by rapid solifluction in striped slopes between *c* and the lake.

ICE-WEDGE POLYGONS, ARCTIC SLOPE, ALASKA



FROST-CRACK POLYGONS, BRISTOL BAY REGION, ALASKA

PLATE 39

[Scale 1:20,000 (north arrow=about 1,000 feet). U. S. Army Air Force, Sept. 26, 1947]

Location.—Lowland near King Salmon Airfield, Bristol Bay region, in the continuous-permafrost zone.

Geology.—Most of area underlain by sand covered by a few inches of turf. Area of lakes (*d*, *f*) in lower right corner underlain by silt mantled with peat several feet thick.

Vegetation.—Most of sand plain and river flood plain covered with open, parklike black spruce forest (area of widely spaced dark stipples near *a*) or with white spruce and white birch forest (areas stippled with very light gray flecks at *b*). Area of peaty soils is covered with sedge and heath tundra (uniform gray areas at *d*, *f*).

Permafrost.—Permafrost present locally in tundra areas at *d*, *f*; absent elsewhere.

Photointerpretation.—Well-developed frost-crack polygons (*e*) cover much of sand plain. Note that they are less well defined and less complete than ice-wedge polygons shown in plate 38. Frost-crack polygons in the Bristol Bay region are considered good evidence of unfrozen coarse-grained soils. Blowouts (very light-gray patches near *c*) also indicate sandy soil, probably unfrozen.

Well-developed vegetation stripes (*d*) are considered good indicators in the Bristol Bay region of peaty or silty soils and favorable conditions for development of permafrost. Small ponds along stream at *f* are dammed by frost mounds or vegetation; they are not beaded drainage caused by the local thawing of permafrost. Large black area at upper left is a lake.

PLATE 40

[*A*, scale 1:8,400 (north arrow=about 1,000 feet). U. S. Army Air Force, Oct. 1, 1946. *B*, scale 1:20,000 (north arrow=about 1,000 feet). U. S. Army Air Force, Oct. 1, 1946 *C*, scale 1:40,000 (north arrow=about 1,000 feet). U. S. Navy, June 20, 1951]

Location.—Kuzitrin Flats, 55 miles east of Teller, Seward Peninsula, in the continuous-permafrost zone. *A*, northern part of flats; *B*, southwestern part of flats; *C*, same locality as *B*.

Geology.—Entire area underlain by silt and peat as much as 20 feet thick.

Permafrost.—Permafrost present 1½ to 3 feet beneath surface everywhere except beneath lakes and streams.

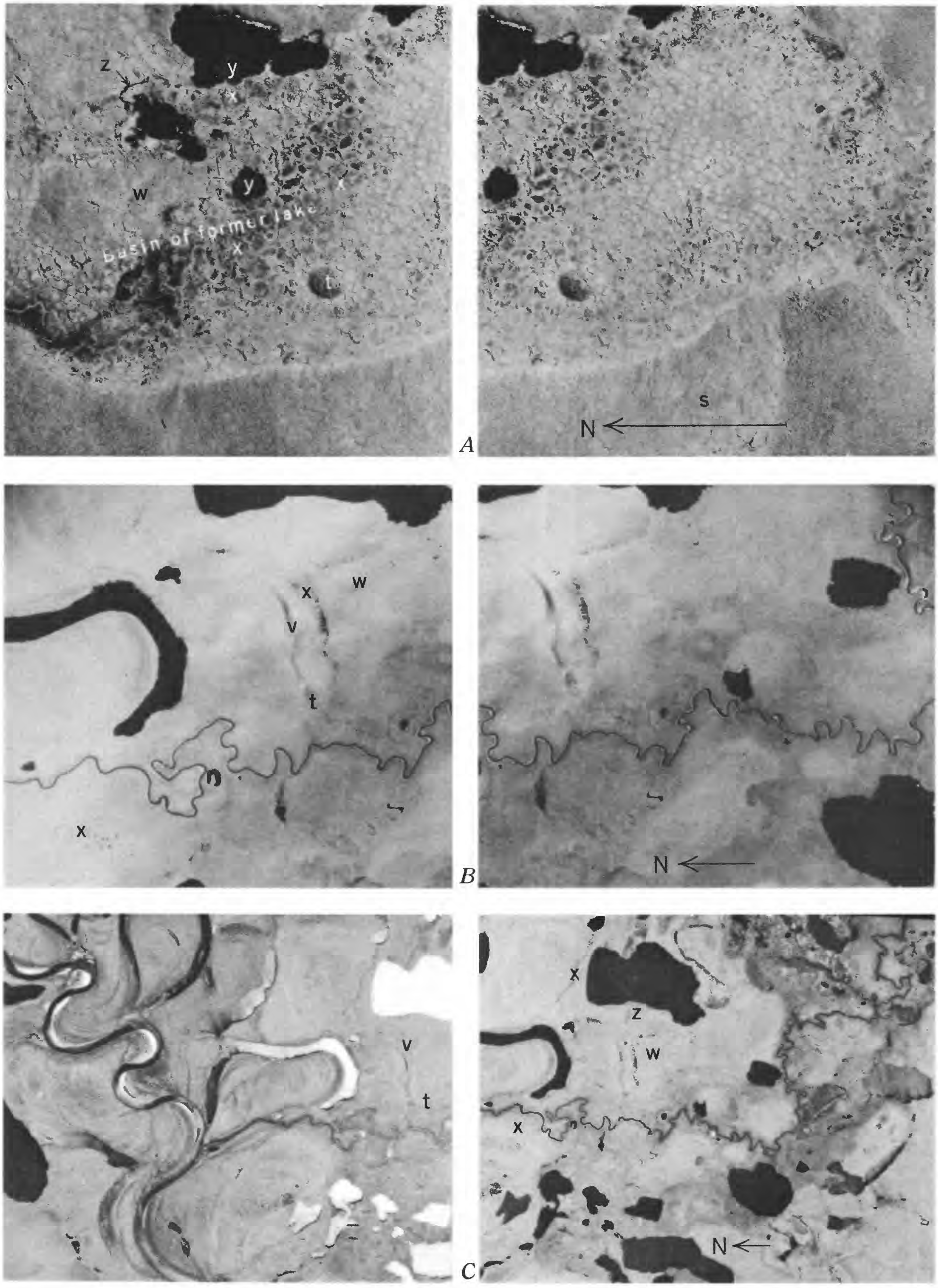
Photointerpretation.—Circular pingos (*t*) can be distinguished in drained lake basins in all three figures. *B* and *C* also show a linear, eskerlike pingo (*v*) with a longitudinal crevice at its summit.

Ice-wedge polygons can be distinguished easily at large scales of *A* and *B* but are discernible only with difficulty at small scale of *C*. High-center polygons (*w*) have light centers and dark marginal trenches; low-center polygons (*x*) have dark centers and light marginal ridges. Narrow trenches separating marginal ridges of adjoining low-center polygons appear as thin or beaded dark lines in *A* but cannot be seen on small scale of *B* and *C*.

Small frost-stirred vegetation polygons are expressed as tiny, light stipples on a slightly darker background and are superimposed upon the much larger ice-wedge polygons at *s* and *w* in *A*. These tiny polygons cannot be seen at the smaller scales of *B* and *C*.

Thaw lakes having characteristic rounded or scalloped outlines appear in all three figures. The detailed irregularities of the lake shores at *y* in *A* represent ice-wedges projecting into the water along banks actively retreating into an area of low-center polygons. These minor irregularities are too small to be recognized on *B* and *C*.

Dark line near to and parallel to lake shore at *z* on *A* and *C* marks the edges of large blocks of frozen ground that have been undercut at the water's edge and that have begun to slump into the lake.



STEREOPAIRS SHOWING EFFECT OF SCALE ON APPEARANCE OF PERMAFROST INDICATORS, NORTHERN SEWARD PENINSULA, ALASKA

PINGOS AND MODIFIED OXBOW LAKES, NORTHERN SEWARD PENINSULA, ALASKA

PLATE 41

[Scale 1:40,000 (north arrow=about 1,000 feet). U. S. Navy, June 20, 1950]

Location.—Kuzitrin Flats, 55 miles east of Teller, northern Seward Peninsula, in the continuous-permafrost zone.

Geology.—Northern three-quarters of area underlain by 20 to 25 feet of peat and silt. Southern quarter underlain by fluvial and glaciofluvial sand and gravel mantled by only a few feet of peat and silt.

Permafrost.—Permafrost lies 1½ to 5 feet beneath surface everywhere except beneath rivers and lakes.

Photointerpretation.—Widespread shallow permafrost is indicated by thaw lakes, drained thaw-lake basins, modification of oxbow lakes by thawing, pingos (*p*), beaded drainage (*b*), and high- and low-center ice-wedge polygons.

All of the lakes away from the flood plain are thaw lakes having characteristic rounded or scalloped outlines. Abandoned meanders (oxbow lakes) on the flood plain also are undergoing modification by thawing and caving of banks. t_1 is very recently abandoned and has not yet been modified, t_2 is older and its shores are scalloped in a few places, and t_3 is completely modified in shape and can be recognized as an oxbow only by its general arcuate shape and its position on the flood plain.

Pingos are found in almost every lake basin. Only a few are indicated by *p*. Note craterlike depression at summits of some pingos.

Low-center ice-wedge polygons are confined to lake basins and areas of bar-and-swale topography on the flood plain. They are expressed on these photographs as dark polygonal flecks on a honeycombed light-gray background. High-center polygons are outlined by discontinuous dark lines near *a* that represent pools of water in the polygon trenches. High-center polygons are present in other areas but cannot be seen on a scale this small.

PLATE 42

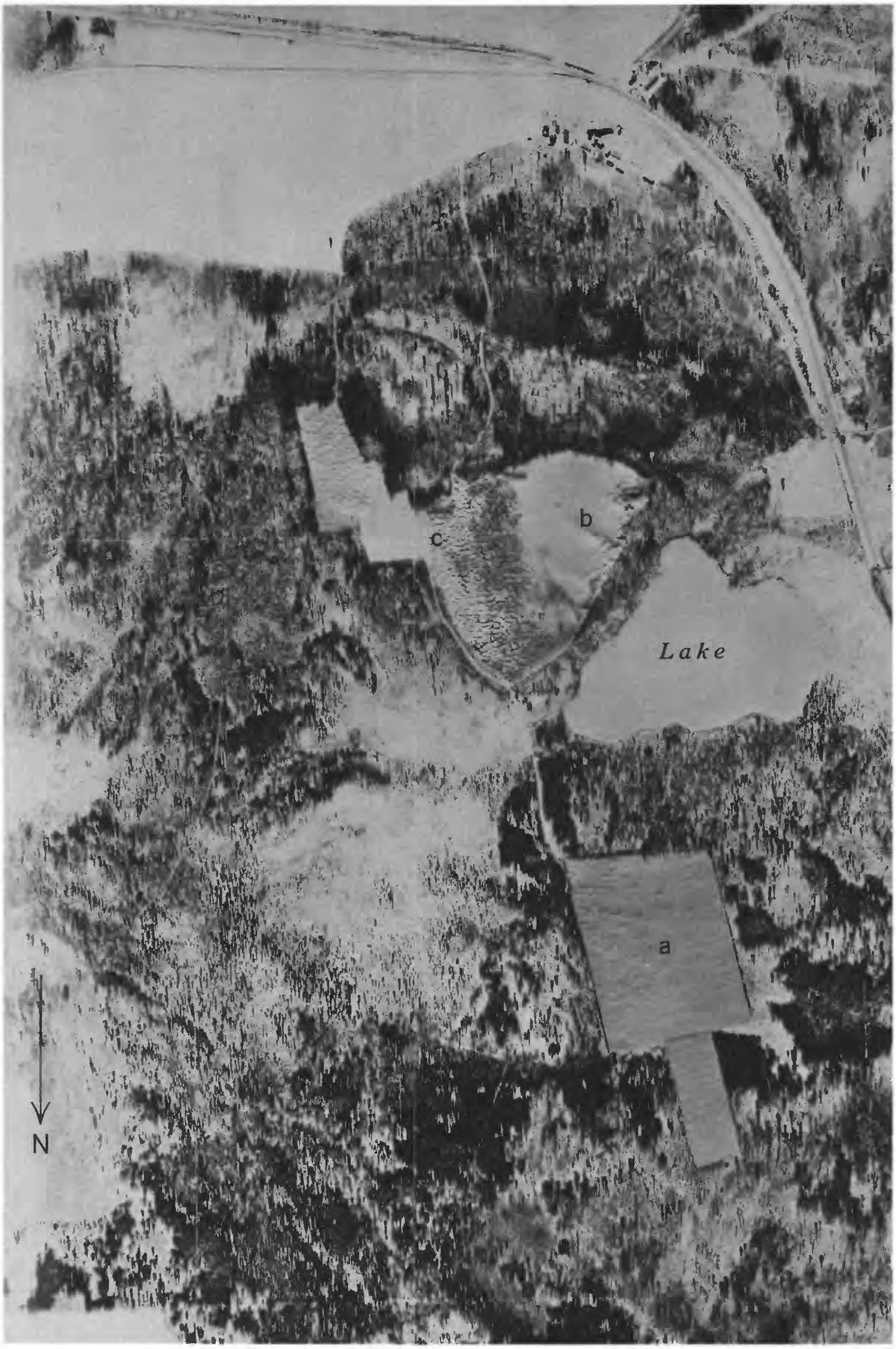
[Scale 1:12,000 (north arrow=about 1,000 feet). U. S. Army Air Force, Mar. 24, 1948]

Location.—U. S. Department of Agriculture Experimental Farm near Fairbanks, in the discontinuous-permafrost zone.

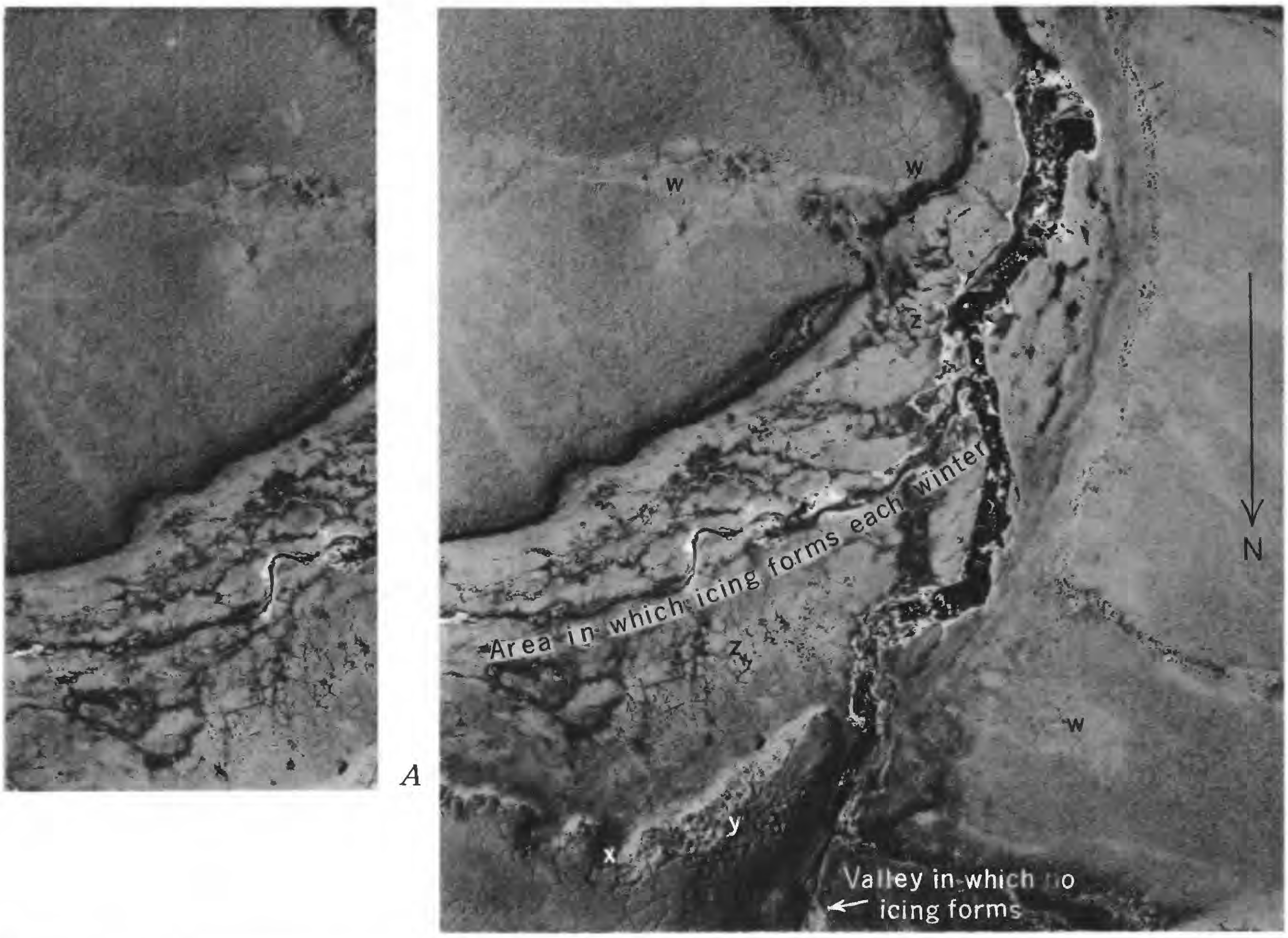
Geology.—Entire area underlain by muck and silt.

Permafrost.—Entire area shown here underlain by permafrost containing ice-wedge polygons. Adjoining southward-facing slopes, not shown in this picture, underlain by unfrozen ground.

Photointerpretation.—Ice-wedge polygons cannot be recognized where the forest is undisturbed, but wherever vegetation has been cleared, ground has thawed and ice wedges have melted down, leaving shallow trenches (*a*), deep, sharp gullies (*b*), or closely spaced mounds up to 8 feet high (*c*) depending upon depth and distribution of ground ice. Mounds and trenches begin to develop 3 to 10 years after clearing.



ACCENTUATION OF MICRORELIEF DUE TO THAWING IN CLEARED FIELDS, MIDDLE TANANA VALLEY, ALASKA



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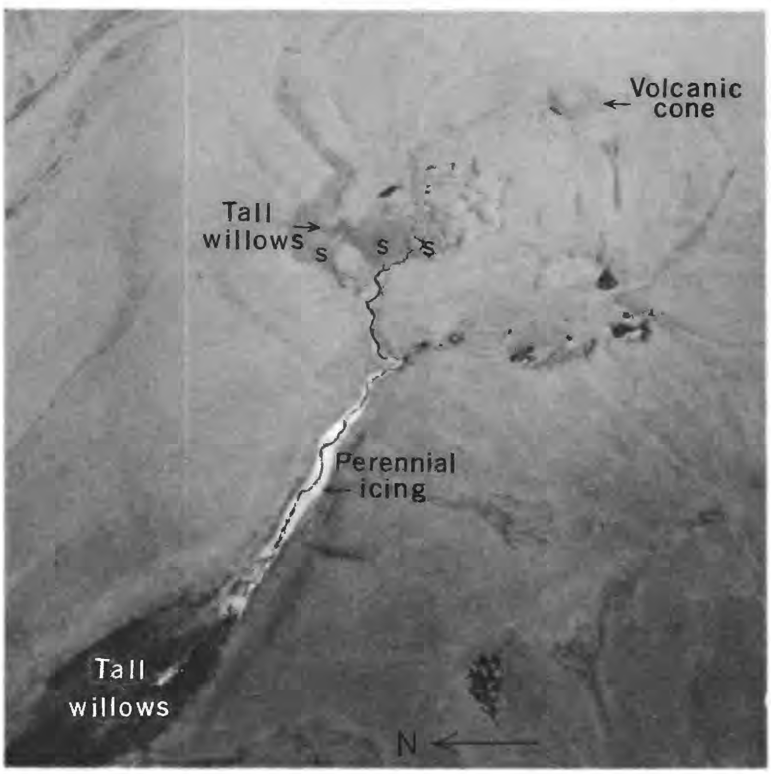
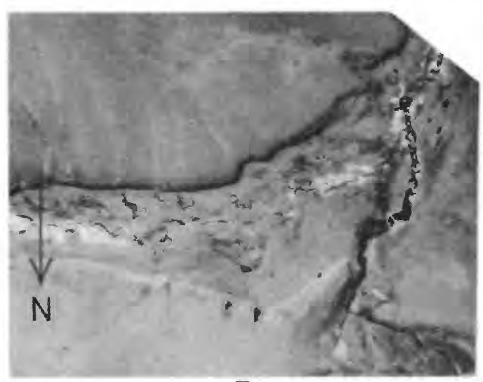


C



B

FLOOD-PLAIN ICINGS, NORTHERN SEWARD PENINSULA, ALASKA

PLATE 43

[*A*, scale 1:8,400 (north arrow=about 1,000 feet). *B*, scale 1:20,000 (north arrow=about 1,000 feet). *C*, scale 1:20,000 (north arrow=about 1,000 feet). Photographs by U. S. Army Air Force, Oct. 1, 1946]

Location.—Noxapaga River, 15 miles west of Imuruk Lake, northern Seward Peninsula, in the continuous-permafrost zone. *A*, vertical stereopair of confluence of Noxapaga River and Carex Creek; *B*, vertical photograph of same area; *C*, oblique photograph looking east toward head of Noxapaga River from above area depicted in *A* and *B*.

Geology.—Valley bottoms underlain by silt, sand, and gravel up to 10 feet thick. Slopes underlain by basaltic lava flows covered with silt as much as 20 feet thick.

Permafrost.—Permafrost underlies slopes 1½ to 3 feet beneath surface. Flood plains of streams probably underlain by permafrost at depth of less than 10 feet.

Photointerpretation.—Noxapaga River heads in hot springs (*s* on *C*) issuing near base of volcanic cone. Site of springs is marked by dense growth of tall willows expressed as dark patch at *s*.

Continuous flow of river, maintained through winter by springs, results in development of thick perennial icing near head of river (white band along course of river on *C*). Note sinuous dark line marking channel that river has carved through ice that formed during previous winter.

Site of thinner icing that melts each summer is shown on *A* and *B*. Narrow bands of white along margins of stream channel are new ice that had just begun to accumulate when photograph was taken. The wide, flat, steep-walled, and sparsely vegetated flood plain and the irregular, locally braided channel are typical of sites of flood-plain icings and contrast sharply with narrow, V-shaped valley of tributary at lower right on which icings do not form.

Frost-stirred vegetation polygons are expressed by tiny light-gray stipples in a slightly darker background on slopes at upper left in *A* but are too small to be seen on *B*. Frost-stirred vegetation polygons are superimposed upon much larger high-center ice-wedge polygons at *w* (*A*). Thaw gullies are developed along ice wedges at *x* (*A*). Nearby, deeply thawed and eroded ice-wedge polygons at *y* have developed a moundlike form.

Frost-crack polygons (*z* on *A*) cover much of icing site. Note that they are similar in size but less continuous and sharply defined than nearby high-center ice-wedge polygons at *w*.

PLATE 44

[Scale 1:40,000 (north arrow=about 1,000 feet). U. S. Army Air Force, Sept. 15, 1942]

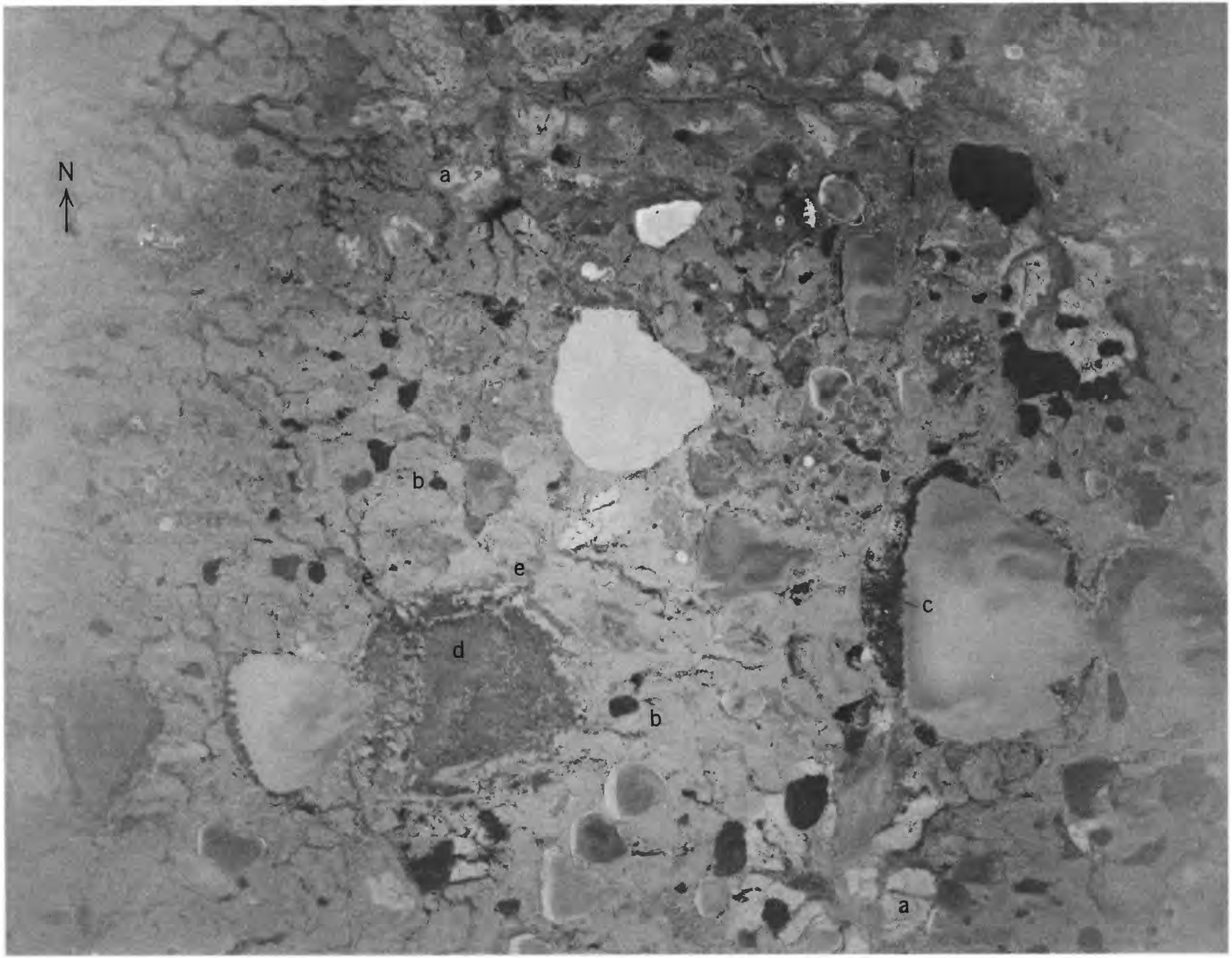
Location.—Lowland 45 miles east of Dillingham, Bristol Bay region, in the sporadic-permafrost zone.

Geology.—Entire area underlain by ground moraine, blanketed in most areas by several feet of peat. Till and sand exposed locally in small hillocks expressed as light-gray patches (*a*).

Vegetation.—Medium-gray areas (*b*) covering most of photograph are sedge and heath tundra. Floating-bog vegetation grows in mottled dark-gray areas adjoining lake shores (*c*), in drained lake basins (*d*), and along drainage lines (*e*).

Permafrost.—Thin permafrost present locally at depths of 2 to 3 feet in areas of peat soils covered with sedge and heath tundra (*b*). Permafrost lacking or at depths greater than 8 feet elsewhere.

Photointerpretation.—No dependable indicators of permafrost can be recognized on this photograph. Lakes resemble thaw lakes and may have originated in the past by thaw-collapse, but they are not actively enlarging by thawing at present. Pools along stream at *f* suggest beaded drainage, but they probably are due to disruption of drainage by growth of peat-forming vegetation and by formation of frost-heaved mounds along watercourses. Thus, permafrost conditions in this area can be evaluated only by field observations.



PERMAFROST THAT CANNOT BE IDENTIFIED BY PHOTOINTERPRETATION, BRISTOL BAY REGION, ALASKA