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Chapter 28

Permafrost in Alaska

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INTRODUCTION

Permafrost is defined as soil or rock material, with or without included moisture or organic matter, that has remained at or below 0°C for two or more years (Muller, 1945, p. 3). It is defined exclusively on the basis of temperature; however, one of the most important properties of permafrost is the amount of ice it contains. Permafrost with little or no ice generally does not cause engineering or environmental problems, but permafrost that is ice rich can cause extremely serious problems if allowed to thaw. Ice in active glaciers is not considered permafrost even though it fits the general definition of permafrost.

Permafrost underlies approximately 20 percent of the world's land mass (Muller, 1945, p. 3), and most of it is present in the Northern Hemisphere because the land area is much greater there than it is in the Southern Hemisphere (Fig. 1). However, permafrost is widespread in Antarctica. In addition to Alaska, where 85 percent of the land is within the permafrost region, extensive areas of permafrost are present in other countries in the Northern Hemisphere. These are Canada (50 percent), the U.S.S.R. (50 percent), and the People's Republic of China (20 percent).

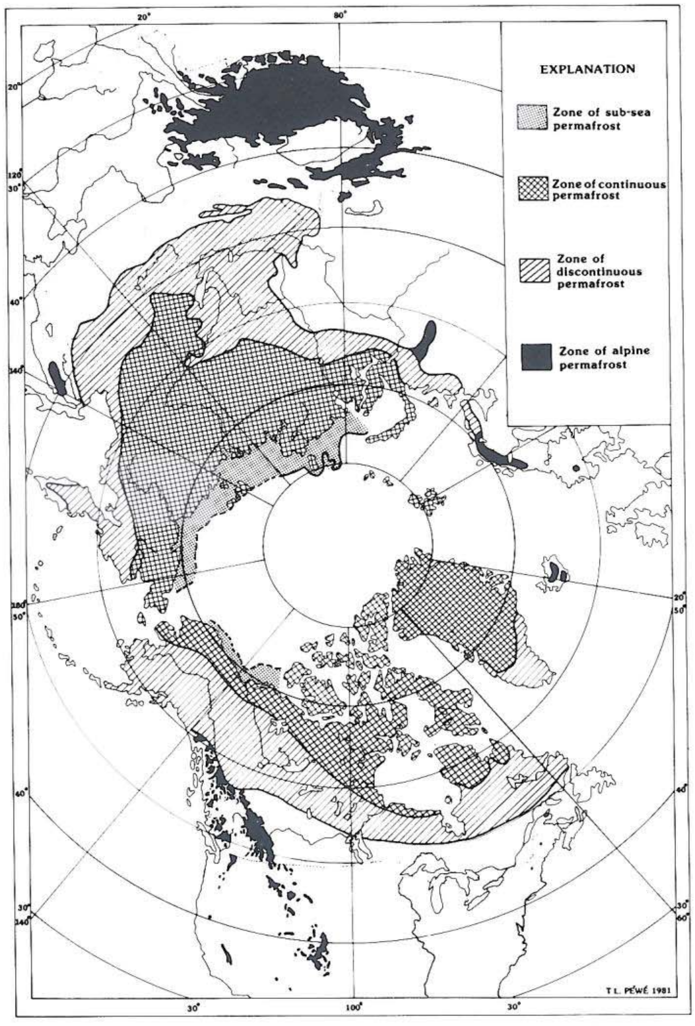

Figure 1. Map showing extent of permafrost in the Northern Hemisphere (from Péwé, 1982, Fig. 21).

ORIGIN AND THERMAL REGIME

Permafrost forms when the mean annual air temperature is low enough to maintain a mean annual near-surface ground temperature at or below 0°C. If climatic conditions in an area change in such a way as to reduce the average near-surface ground temperature to below 0°C, the depth of winter freezing will exceed the depth of summer thawing, and if the mean near-surface ground temperature remains below 0°C, a layer of frozen ground will be added each year to the base of the permafrost until the downward penetration (aggradation) of the frozen ground is balanced by heat flowing upward from the Earth's interior. Thus, the thickness to which permafrost can grow depends on the mean near-surface ground temperature and the geothermal gradient. The lower the temperature and gradient, the greater the thickness of the permafrost. In this manner, permafrost hundreds of meters thick can form during a period of several thousand years.

Because the formation of permafrost depends on ground

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temperature near the surface, the thickness and areal distribution of permafrost are directly affected by the kind and size of natural surface features (bodies of water, topography, drainage, and vegetation) that act as a heat source or heat sink or as insulation. Changes in the surface environment—such as would be produced by a transgressing (or regressing) sea, or building of roads and other surface structures, draining of lakes, and clearing of vegetation—produce profound changes in the permafrost (Péwé, 1954, 1982; Lachenbruch, 1957a, b; Greene and others, 1960; Hok, 1969; Ferrians and others, 1969; Haugen and Brown, 1971; Brown, 1973; Lawson and Brown, 1978; Lawson and others, 1978; Brown and Grave, 1979a, b; Brown and Hemming, 1980; Nelson and Outcalt, 1982; Lawson, 1983, 1986; Walker, 1983, 1988; Walker, D.A., and others, 1987; Carter and others, 1987).

Although the permafrost table and the temperature in the upper part of permafrost may be quick to respond to surface changes (Lachenbruch and Marshall, 1986), centuries, or even tens of centuries, are required for surface changes to affect the bottom of thick permafrost. Therefore, the present thickness and distribution reflects former thermal environments (Lachenbruch and others, 1966).

In the absence of various modifying surface conditions such as those described previously, the top and bottom of the permafrost layer tend to parallel the ground surface, rising under hills and lowering beneath valleys.

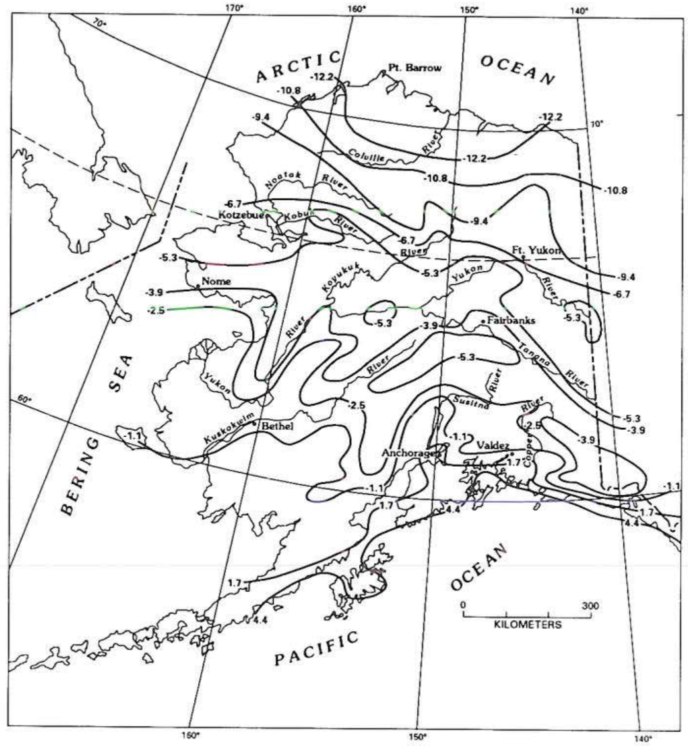

Figure 2. Map of Alaska showing mean annual air isotherms in degrees Fahrenheit (from Johnson and Hartman, 1969, Plate 35).

CLIMATE

Climate is the major factor that controls the regional (and global) distribution of permafrost. Within the continuous permafrost zone of Alaska, Barrow has the lowest recorded mean annual air temperature, –12.2°C, whereas Anchorage, just outside of the permafrost region, has a mean annual air temperature of 1.7°C (Fig. 2).

The climatic control is also reflected by the thickness of permafrost which ranges from more than 630 m at Prudhoe Bay to lenses less than a meter thick in the southernmost part of the permafrost region. Naturally, the thermal conductivity of the rock and soil material and the heat flow from the interior of the Earth also affect the depth to which permafrost can form.

Even though annual precipitation is low in most areas within permafrost regions, ground conditions generally are wet, especially in areas underlain by fine-grained sediments. This poor drainage is caused by the impervious permafrost layer, generally within a meter of the surface, and by the low evaporation rate at the prevailing low temperatures. Also, the low annual precipitation produces a thin snow cover, which limits the effectiveness of the snow cover as a ground insulator during the winter months when air temperatures are very cold.

In an area where the mean annual air temperature is about 0°C, microclimates, which are governed largely by local features, can be critical in determining whether or not permafrost is present. For example, the mean annual air temperature at a site underlain by unvegetated dry soils can be a few degrees higher than a nearby site underlain by vegetated wet soils. In addition, the great variability in the thermal conductivity of peaty soils between the summer when they are dry (low conductivity) and in the winter when they are wet and frozen (high conductivity) can cause permafrost to form and persist in areas where conditions are marginal for its formation. Slope exposure also controls microclimate in mountainous or hilly areas where south-facing slopes may receive considerably more solar heat than north-facing slopes. This is particularly important in southern parts of the permafrost region where south-facing slopes often are completely free of permafrost, whereas nearby north-facing slopes are underlain by permafrost.

EARLY INVESTIGATIONS IN ALASKA

In 1816, during an exploratory sailing mission to America to find a northwest passage, Otto von Kotzebue observed large masses of ground ice exposed in bluffs bordering Eschscholtz Bay of Kotzebue Sound in northwestern Alaska. His observations (von Kotzebue, 1821) are the earliest known published record of the presence of permafrost in Alaska. Subsequently, other explorers and scientists made observations and studies of frozen ground (Beechey, 1831; Richardson, 1841, 1854; Seemann, 1853; Dall, 1881; Hooper, 1881, 1884; Muir, 1883; Cantwell, 1887, 1896; Russell, 1890). Maddren (1905) prepared an excellent summary of this early work. He also described his own observations of frozen ground in Alaska and adjacent territory in this report. Many of these early observations and studies, limited to northwestern Alaska, were in conjunction with the study of rich Pleistocene fossil remains preserved in the frozen sediments exposed in bluffs bordering Eschscholtz Bay and in other areas. Even though most workers debated the origin of the ground ice, the existence of perennially frozen ground was clearly demonstrated. In fact, in the early 1880s, systematic ground temperature measurements were taken at the base of a 37.5-ft-deep (11.4 m) shaft at Point Barrow. A constant 12°F (–11°C) temperature was recorded (Ray, 1885). In addition, R. S. Woodward, U.S. Geological Survey, determined mathematically that over a period of a few thousand years, perennially frozen ground could reach depths of several hundred meters under the climatic conditions that exist today in northern Alaska (Russell, 1890, p. 130–132).

After the discovery of gold in the Circle district of Alaska in 1893, widespread prospecting and mining activity throughout Alaska and numerous geological studies by scientists provided considerable data about permafrost occurrences and factors that control its distribution. In interior Alaska the frozen ground posed major problems for placer miners (Purington, 1905). The organic-rich fine-grained sediments or "muck" deposits at the surface were frozen, and thus their removal was very difficult. The underlying gold-bearing gravel deposits were also frozen and, consequently, had to be thawed before they could be mined. With this new information about permafrost occurrences, it became possible to make estimates of the general distribution of permafrost.

DISTRIBUTION OF PERMAFROST

General distribution

One of the first efforts in the North American literature to show the distribution of permafrost in Alaska was by Nikiforoff (1928, Fig. 5). His page-size sketch map of the Northern Hemisphere shows only the southern boundary of "area of perpetually frozen ground," which approximately follows the 65th parallel across Alaska.

As part of a major report entitled "Areal Geology of Alaska," Smith (1939, Plate 14) prepared a map (scale 1:5,000,000) showing 72 areas of "Alaskan ground frost." These areas extend from Point Barrow in northernmost Alaska to as far south as the 60th parallel and from the Alaska/Yukon Territory border westward to the Bering Sea. No lines are shown delineating zones of permafrost or the southern boundary of permafrost; however, a 30°F (–1.1°C) isotherm shown on the map approximately coincides with the southernmost areas of permafrost.

The classic paper by Taber (1943) entitled "Perennially frozen ground in Alaska: Its origin and history" includes a page-size map of Alaska showing the "approximate boundary of perennially frozen ground." The boundary is largely similar to the southern boundary of permafrost shown on modern maps, particularly in the eastern half of the state.

Muller (1945, Fig. 1) and Terzaghi (1952, Fig. 9), on small-scale maps of the Northern Hemisphere, also show only the southern limit of the permafrost region; however, Black (1950, Fig. 1; 1953, Fig. 1; 1954, Fig. 1), Ives (1974, Fig. 4A.2), and Karte (1982, p. 16), on similar small-scale base maps, divided the permafrost region into three zones: continuous, discontinuous, and sporadic.

Benninghoff (1952, Fig. 1), Péwé (1954, Fig. 69; 1963, Fig. 32), and Hopkins and others (1955, Fig. 5), on small-scale index maps of Alaska, also divided the permafrost region into the continuous, discontinuous, and sporadic permafrost zones. The boundaries on three of these maps are compared on Figure 3.

This system of dividing the permafrost region into three zones was used first by the Soviets during the 1930s and 1940s. These permafrost zones generally are defined as follows. The continuous zone is underlain by permafrost almost everywhere except under large water bodies that are deep enough not to freeze to their bottoms during the winter. Also, most investigators consider that the temperature of continuous permafrost at a depth at which seasonal variation is barely detectable (10 to 20 m) is generally lower than –5°C. The discontinuous zone is mostly underlain by permafrost but includes numerous areas without permafrost, and the sporadic zone is mostly without permafrost but includes numerous areas of permafrost. Temperatures of permafrost also have been used to help define the discontinuous (from –5°C to –1°C) and sporadic (higher than –1°C) permafrost zones. Because of the small scale of these maps and the great difficulty in accurately delineating the boundary between the discontinuous and sporadic permafrost zones, most workers divided the onshore permafrost region into two zones: continuous and discontinuous (Brown, 1963, Fig. 3, 1970, Fig. 1; Williams, 1965, Plate 1, 1970, Figs. 1 and 10; Stearns, 1965, Fig. 6, 1966, Figs. 1 and 2a; Péwé, 1966, Fig. 1, 1969, Fig. 1, 1974a, Fig. 1, 1974b, Fig. 3.4, 1975, Figs. 22 and 23, 1976, Fig. 1, 1983b, Fig. 9.2; Ferrians and others, 1969, Fig. 1; Sater and others, 1971, Fig. 46; Mackay, 1972, Fig. 1; Price, 1972, Fig. 8; Brown and Péwé, 1973, Fig. 2; Jahn, 1975, Fig. 8; French, 1976, Fig. 4.3; Tedrow, 1977, Fig. 4-4; Linell and Tedrow, 1981, Fig. 3.2; Kreig and Reger, 1982, Fig. 1). On these maps, the continuous zone is defined essentially the same as it is above, but the discontinuous zone includes all of the general permafrost region south of the zone of continuous permafrost.

The most detailed and largest scale (1:2,500,000) map available showing the distribution and character of permafrost in Alaska was compiled by Ferrians (1965). On this map, the permafrost region is divided into two major units. One unit encompasses mountainous areas in which summits generally exceed 900 m in altitude, and which are underlain predominantly by bedrock at or near the surface. The other unit consists of lowland and upland areas, including hilly and mountainous areas in which summits are less than 900 m in altitude. The lowland and upland

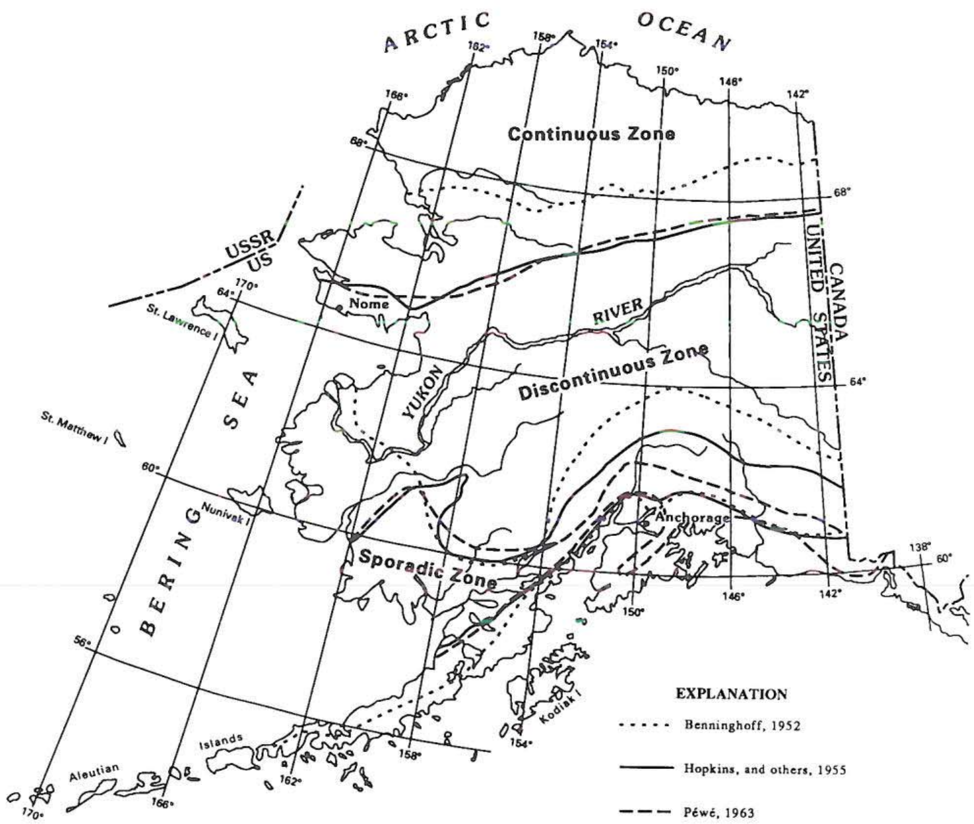

Figure 3. Map comparing permafrost boundaries of permafrost zones in Alaska (from Benninghoff, 1952, Fig. 1; Hopkins and others, 1955, Fig. 5; Péwé, 1963, Fig. 32).

areas are underlain predominantly by thick unconsolidated deposits, but locally they are underlain by bedrock at or near the surface.

In the mountainous areas, great differences in altitude, character of bedrock and surficial deposits, soil moisture, insolation received at ground surface, snow cover, and vegetative cover cause extreme variation in thickness and temperature of permafrost. Because of this variation, the mountainous areas are divided into three broad map units, primarily on the basis of differences in latitude and resultant climatic differences. From north to south, these map units are (1) areas generally underlain by permafrost, which include the Brooks Range and adjacent mountainous areas; (2) areas generally underlain by discontinuous permafrost, which include numerous mountainous areas in central Alaska (e.g., White, Ray, Bendeleben, Kigluaik, Wrangell, and Talkeetna Mountains and the Alaska Range); and (3) areas generally underlain by isolated masses of permafrost, which include the Chugach and Kilbuck Mountains and the northern part of the Aleutian Range.

The lowland and upland areas, where the thickness and temperature of permafrost are less variable than they are in the mountainous areas, are divided into six map units, which can be grouped into three broad zones: (1) the northern zone (largely north of the Brooks Range), which is generally underlain by thick permafrost in areas of both fine- and coarse-grained deposits; (2) the central zone (between the Brooks Range and the Alaska Range but including the Copper River Basin), which is generally underlain by moderately thick to thin permafrost in areas of fine-grained deposits and by discontinuous or isolated masses of permafrost in areas of coarse-grained deposits; and (3) the southern zone (including the Bristol Bay area and the eastern and western margins of the Susitna Lowland north of Anchorage), which is generally underlain by numerous isolated masses of permafrost in areas of fine-grained deposits, and which generally is free of permafrost in areas of coarse-grained deposits.

Outside the permafrost region, there are a few isolated occurrences of permafrost at high altitudes and in lowland areas where the ground is well insulated by peat and where solar radiation received at ground surface is low, especially near the border of the permafrost region.

The map also shows selected data from wells and borings concerning the presence or absence of permafrost and, if present, its thickness at 68 sites throughout the permafrost region.

Features shown on the map include the location of known thermal springs and active volcanoes. Permafrost is absent near these features, which are surface manifestations of high near-

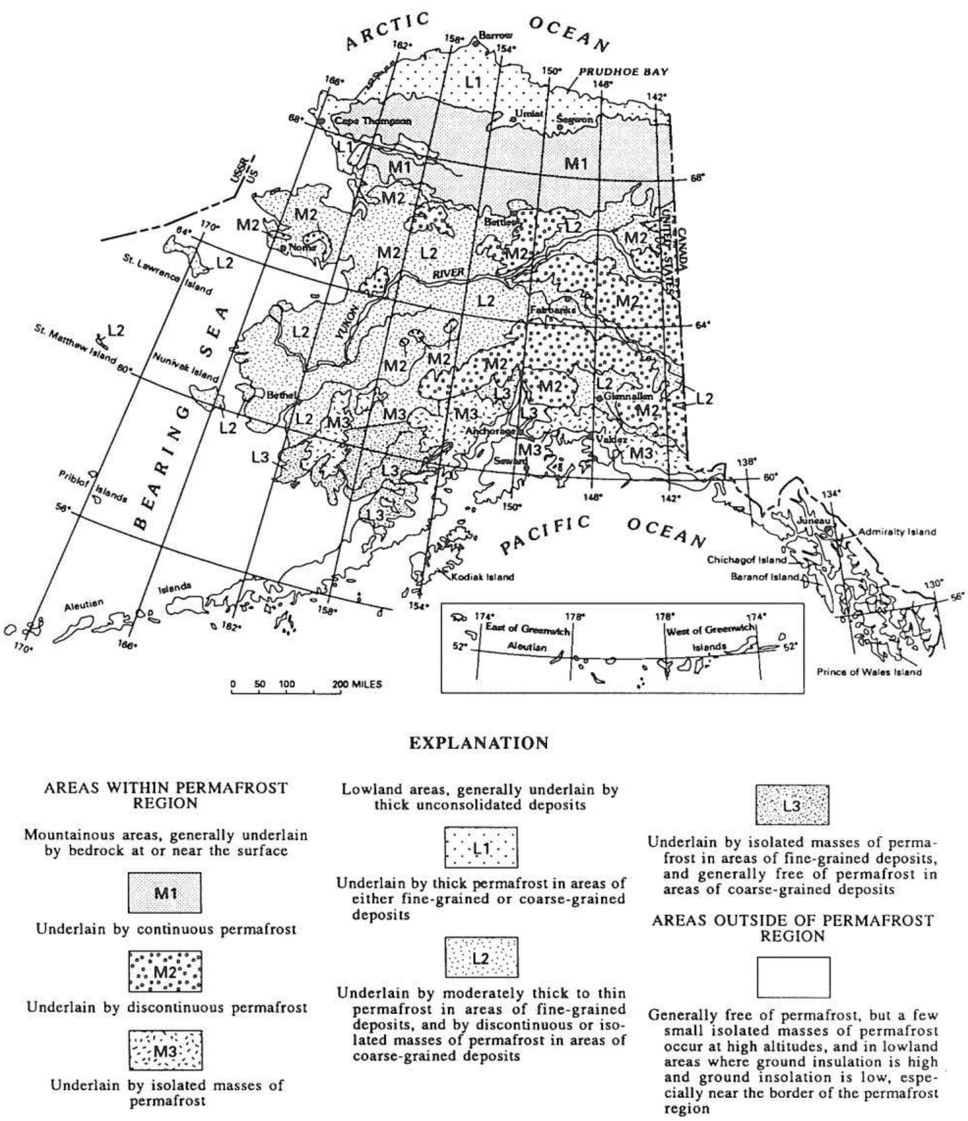

Figure 4. Generalized permafrost map of Alaska (from Ferrians and others, 1969, Fig. 2).

surface temperatures. Also, permafrost is either absent or at considerable depth beneath large rivers and large deep lakes throughout the permafrost region. The heat in these large water bodies, and also in the ocean waters, tends to decrease the thickness and to increase the temperature of permafrost in adjacent areas.

Corte (1969) included a large foldout map (no scale given) of the Northern Hemisphere in a review paper entitled "Geocryology and Engineering." The map shows the extent of perennially frozen ground, seasonal systematic freezing and thawing, and short duration and non-systematic freezing and thawing. The boundaries for these map units were taken from a permafrost map of the world by Baranov (1959, Fig. 22). Within Alaska, the southern boundary of the permafrost region is similar to that shown on most modern maps.

Permafrost maps of Alaska by Ferrians and others (1969, Fig. 2) and by Johnson and Hartman (1969, Plate 10) are generalizations of the larger scale permafrost map by Ferrians (1965). Figure 4 is a modified and generalized version of this map.

A 1:6,300,000-scale (approximately) map of Alaska by Williams (1970, Figs. 3 to 8) shows the location of pertinent shafts, borings, and wells and gives the depth of frozen ground and occurrence of ground water at these sites. No permafrost boundaries are shown on this map, but a large amount of permafrost-related data is presented.

A map of the Arctic region at a scale of 1:5,000,000 (American Geographical Society, 1975) shows the boundaries of the continuous and discontinuous permafrost zones. The boundaries within Alaska were taken from the "Permafrost Map of Alaska" (Ferrians, 1965).

A recent version of a page-size map showing the distribution of permafrost in the Northern Hemisphere (Fig. 1) compiled by Péwé (1982, Fig. 21, 1983a, Fig. 1, 1983b, Fig. 9.1) not only delineates the continuous and discontinuous zones, but it also delineates subsea and alpine permafrost. Subsea permafrost occurs under the sea, and alpine permafrost occurs at high altitudes in the middle and lower latitudes south of the southern boundary of the permafrost region. Subsea permafrost is present off the northern coast of Alaska under the continental shelf of the Beaufort Sea, and alpine permafrost is present locally in high mountainous areas in southern Alaska and the southeastern Alaska panhandle.

Another version of the Northern Hemisphere map, compiled by Heginbottom (1984, Fig. 1), has five map units: (1) continuous permafrost, (2) widespread discontinuous permafrost, (3) sporadic and alpine permafrost, (4) known subseabottom permafrost, and (5) Greenland ice-cap. Within Alaska, the extent of the continuous permafrost zone is similar to that shown on several other earlier maps and includes all of northern Alaska north of the southern flank of the Brooks Range; however, the discontinuous zone does not extend as far south as it does on the earlier maps, and sporadic and alpine permafrost are combined into one zone that covers the southern part of mainland Alaska and the higher mountainous areas of the southeastern Alaska panhandle. The distribution of subsea permafrost in Alaska is similar to that shown on the previously described map (Fig. 1) by Péwé.

A page-size map of North America by Harris (1986a, Fig. 7) shows permafrost zones similar to those compiled by Heginbottom (1984, p. 79) described above, but the boundaries between the zones are slightly different; moreover, unfortunately, on Harris' map a large part of the Arctic Coastal Plain in northernmost Alaska is erroneously shown as being underlain by "sub-seabottom" permafrost. Harris (1986b, Fig. 1.1) also compiled a permafrost map of the Northern Hemisphere.

The most recent version of a Northern Hemisphere permafrost map, prepared by P. J. Williams and M. W. Smith (1989, Fig. 1.7), uses intensity of shading to show increases in extent, both laterally and with depth. On their map the distribution of permafrost in Alaska was modified from Péwé (1983a).

Regional and local distribution

To help solve the serious permafrost-related engineering problems encountered in Alaska by the military during the early 1940s, special terrain investigations were carried out by the U.S. Geological Survey. As an outgrowth of these investigations, large-scale maps, some including profiles, showing permafrost distribution, were prepared for various areas including Galena (Elias and Vosburgh, 1946; Péwé, 1948b), Point Spencer (Black, 1946), Northway (Wallace, 1946), Umiat (Black and Barksdale, 1948), Fairbanks (Péwé, 1948a), and Dunbar (Péwé).

Using satellite imagery and available ground data, Anderson and others (1973, Fig. 25) prepared a 1:1,100,000-scale "permafrost terrain" map covering approximately 150,000 km^2 of north-central Alaska. Four different map units are differentiated. These are bedrock, alluvium-colluvium, active flood plain, and abandoned flood plain and terrace. According to the authors, the bedrock unit is characterized by a few scattered taliks, which are unfrozen zones, and a thaw depth of 0.3 to 1.0 m, except on south-facing slopes where thaw depths may exceed 2 m. The alluvium-colluvium unit has numerous taliks and a thaw depth of less than 0.5 m in areas of poor drainage, and from 0.5 to 2.0 m on moderately well-drained slopes. The active flood plain has numerous taliks and a thaw depth of more than 2.0 m. The abandoned flood plain and terrace unit has numerous taliks and many small thaw lakes; permafrost usually occurs at depths of less than 0.5 m.

Péwé and Bell (1975a, b, c, d, e), as part of a comprehensive engineering-geologic and hazards study of the Fairbanks area, prepared 1:24,000-scale maps showing the distribution of permafrost. They classified eight map units in order of increasing ice content, from permafrost free through permafrost with high ice content.

By using data from oil well logs, Osterkamp and Payne (1981, Fig. 2) and Osterkamp and others (1985, Figs. 1, 2, 3) prepared contour maps of the Prudhoe Bay and adjacent areas in northern Alaska showing estimated depth to base of ice-bearing permafrost. The ice-bearing permafrost is thickest (more than 600 m) in the Prudhoe Bay area and it thins rapidly to less than 350 m offshore to the north and to about 200 m to the south in the Northern Foothills of the Brooks Range.

Lachenbruch and others (1982, Fig. 1, 1987, Fig. 1, 1989, Fig. 28.1) prepared maps of northern Alaska showing generalized contours of long-term mean surface temperature, which is a major factor in controlling permafrost thickness. They concluded that even though these surface temperatures vary systematically from north to south (about −12.5°C to −4.6°C, respectively), there are large local variations and no conspicuous regional trends in permafrost thickness.

Collett and others (1989) prepared a map of the North Slope of Alaska that shows the depth to the base of the deepest ice-bearing permafrost as determined from well logs. They evaluated logs from 440 wells and summarized and tabulated data from 156 of them. Their map indicates a linear trend of maximum thickness of ice-bearing permafrost that parallels and is within 25 km of the coastline between the Colville and Canning Rivers. The ice-bearing permafrost ranges from less than 200 ft (61 m) in the west to greater than 2,000 ft (610 m) in the east, and it thins to the north and south.

Geophysical studies

Various types of geophysical sensors have been used to determine the distribution and thickness of ice-rich permafrost; however, because of the great vertical and horizontal variations in the character of permafrost and the limitations of the sensors used, remote sensing has not been successful in mapping large areas. Nevertheless, geophysical techniques have provided valuable information in certain local areas, and they have been especially helpful as a means of extrapolating between sites where permafrost conditions are known. Barnes (1966) described the geophysical methods used for delineating permafrost, and Ferrians and Hobson (1973) reviewed both traditional and geophysical methods used for mapping permafrost in North America.

Hoekstra and others (1975, Figs. 7, 12) made ground and airborne electrical resistivity surveys near Fairbanks and prepared resistivity contour maps as a means of delineating areas underlain by ice-rich permafrost. By using electromagnetic soundings, Daniels and others (1976, Fig. 16) prepared permafrost thickness and electrical resistivity contour maps in the Prudhoe Bay area of northern Alaska. Unfortunately, the data were proprietary, and consequently the exact location of the mapping could not be given. Olhoeft and others (1979) tested six different electromagnetic techniques to study permafrost in the National Petroleum Reserve in northwestern Alaska. Transient electromagnetic soundings were used by Ehrenbard and others (1983) in onshore and offshore areas west of Prudhoe Bay to map the bottom of thick permafrost, and Walker, G.G., and others (1987) also used transient electromagnetic techniques to detect subsea permafrost near Prudhoe Bay. In addition, seismic data have been used to delineate areas of ice-bonded subsea permafrost (high-velocity material) in the Beaufort Sea (Rogers and Morack, 1978, 1980, Fig. 9; Morack and Rogers, 1981a, b, 1982, 1984; Neave and Sellmann, 1983, Fig. 1, 1984, Fig. 1; Sellmann and Hopkins, 1984, Fig. 5). Kawasaki and Osterkamp (1989) discussed mapping shallow permafrost by using electromagnetic induction techniques.

PERMAFROST—RELATED LANDFORMS

Various geomorphic landforms in Alaska indicate the presence of permafrost; however, certain other landforms that are especially well developed in the permafrost regions also occur in nonpermafrost areas. Most types of patterned ground that develop owing to frost action fit in the latter category. Patterned ground includes sorted and nonsorted circles, polygons, nets, and stripes (Washburn, 1950, p. 8–9, 1956, p. 826, 1973, p. 103, 1980, p. 123). Solifluction features and string bogs or string moors also are common in permafrost regions, but they too occur in nonpermafrost areas.

The most significant landforms that indicate the presence of permafrost are the aggradational features, which include ice-wedge polygons, pingos, palsas (and peat plateaus), and frost blisters, and the various types of degradational features, which include thermokarst lakes, depressions, pits, gullies, and mounds, beaded drainage, and retrogressive thaw slumps. Aggradational features develop because of the formation of ground ice, whereas the degradational or thermokarst features develop because of the thawing of ground ice. Other significant landforms whose relations to permafrost are still being debated include cryoplanation terraces and active rock glaciers.

ENGINEERING PROBLEMS

In addition to the construction of roads, airstrips, buildings, and the various utilities in response to normal development, the critical need for finding and developing new and dependable sources of hydrocarbon and mineral resources has caused a tremendous increase in activities in the permafrost regions of Alaska. These regions pose special engineering problems and are environmentally "sensitive." Consequently, they require careful study and consideration to ensure the integrity of engineering structures and to minimize adverse environmental impacts.

There are two basic methods of constructing on permafrost: the active method and the passive method. The active method is used in areas where permafrost is thin and generally discontinuous, or where it contains relatively small amounts of ice. The object of this method is to thaw the permafrost and, if the thawed material has a satisfactory bearing strength, then proceed with construction in a normal manner. The object of the passive method is to keep the permafrost frozen so that it will provide a firm foundation for engineering structures. The passive method has wide application in interior and northern Alaska where permafrost is widespread, thick, and generally ice rich near the surface. When using this method, every effort should be made to minimize disturbing the ground surface, and when the ground surface is disturbed, to take carefully planned mitigative measures immediately. Various techniques used to help keep permafrost frozen include using different kinds of insulation (both natural and manmade), elevating heated structures above the ground surface, and using mechanical refrigeration.

Thawing of ice-rich permafrost is the most serious permafrost-related engineering problem. The thawing results in a loss of strength and a change in volume of the ice-rich soil. Under severe conditions, the ice-rich soil can liquefy and lose essentially all of its strength. A more common problem is differential settlement of the ground surface.

CONCLUSIONS

During the past 40 years, considerable progress has been made in determining the distribution and character of permafrost in Alaska; however, much remains to be done. The greatest shortcoming is the limited amount of borehole and ground temperature data; little or no information is available for most areas of Alaska. Because of the great expense, it is not practical to obtain permafrost data everywhere from boreholes. Nevertheless, as Alaska is developed, more borehole and ground temperature data in areas that represent various geologic and physiographic settings are essential to determine the temperature, thermal conductivity, thickness, and ice content of permafrost. Deep temperature measurements in permafrost are necessary to measure accurately the heat flow from the interior of the Earth, which limits the depth to which permafrost can form. Additional areas of research should include how climatic, geologic, hydrologic, topographic, and botanic conditions interact to control the distribution and character of permafrost. A better understanding in these and other subjects would make it possible to extrapolate more accurately between the widely scattered areas where permafrost conditions are known.

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