Permafrost and Related Engineering Problems in Alaska

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PERMAFROST AND RELATED ENGINEERING PROBLEMS IN ALASKA

By Oscar J. Ferrians, Jr., Reuben Kachadoorian, and Gordon W. Greene

ABSTRACT

Permafrost, or perennially frozen ground, is a widespread natural phenomenon. It underlies approximately 20 percent of the land area of the world. The permafrost region of Alaska, which includes 85 percent of the State, is characterized by a variety of permafrost-related geomorphic features including patterned ground, pingos, thaw lakes, beaded drainage, thaw or thermokarst pits, and muck deposits. Known permafrost thickness ranges from about 1,300 feet near Barrow in northern Alaska to less than a foot at the southern margin of the permafrost region. The distribution of permafrost is controlled by climatic, geologic, hydrologic, topographic, and botanic factors.

The extensive permafrost region of Alaska poses special engineering problems for the design, construction, and maintenance of all types of structures. Lack of knowledge about permafrost has resulted in tremendous maintenance costs and even in relocation or abandonment of highways, railroads, and other structures. Because of the unique geologic-environmental conditions that exist in permafrost areas, special engineering procedures should be used, not only to minimize disruption of the natural environment, but also to provide the most economical and sound methods for developing the natural resources of the permafrost region of Alaska.

INTRODUCTION

The recent discovery of potentially vast reserves of oil at Prudhoe Bay in northeastern Alaska (estimates range from 2 to 40 billion barrels) has focused attention on the geologic-environmental factors unique to the Arctic which pose special engineering problems for the design, construction, and maintenance of roads, railroads, airfields, pipelines, buildings, and other structures. Permafrost, or perennially frozen ground, is the most significant of these environmental factors.

A road and railroad from Fairbanks in interior Alaska to the Arctic North Slope have been proposed to aid in the development of the mineral wealth of this remote and presently inaccessible region. Preparatory work is under way for the construction of an 800-mile-long pipeline extending from the oil fields to Valdez, a year-round seaport. A winter road connecting Fairbanks with Sagwon on the Arctic North Slope has been completed. These major engineering activities are just a part of the overall construction effort that will take place in northern Alaska because of the recent oil discovery and because of potential future discoveries of other natural resources.

All this activity requires an understanding of the arctic environment, to establish sound cost-saving engineering procedures and to preserve the natural environment insofar as possible. In most areas where roads or buildings are constructed on permafrost, the procedures that cost the least in the long run are those that disturb the natural environment the least, and therefore, are conservation oriented. Generally, the initial capital investment is greater when correct procedures are used; however, maintenance cost is considerably less. If improper procedures are used, expensive maintenance cost far exceeds the additional expense of the initial investment, and in some cases, structures are damaged to the extent that they become unusable after just a few months or years. The financial losses caused by such problems as impassable roads, unusable airstrips, or damaged machinery in buildings which have settled differentially can be extremely high.

Very few people realize the geographic extent of permafrost or the magnitude of the problems it causes. Approximately 20 percent of the land area of the world is underlain by permafrost. Figure 1 shows the extent of the permafrost zones in the northern hemisphere where most of it occurs. In the southern hemisphere, the main land area underlain by permafrost is Antarctica. About 50 percent of both Canada and the U.S.S.R. and 85 percent of Alaska are within the permafrost zones (figs. 1 and 2).

To date most permafrost research has been carried on in the U.S.S.R.; major industrial cities have been

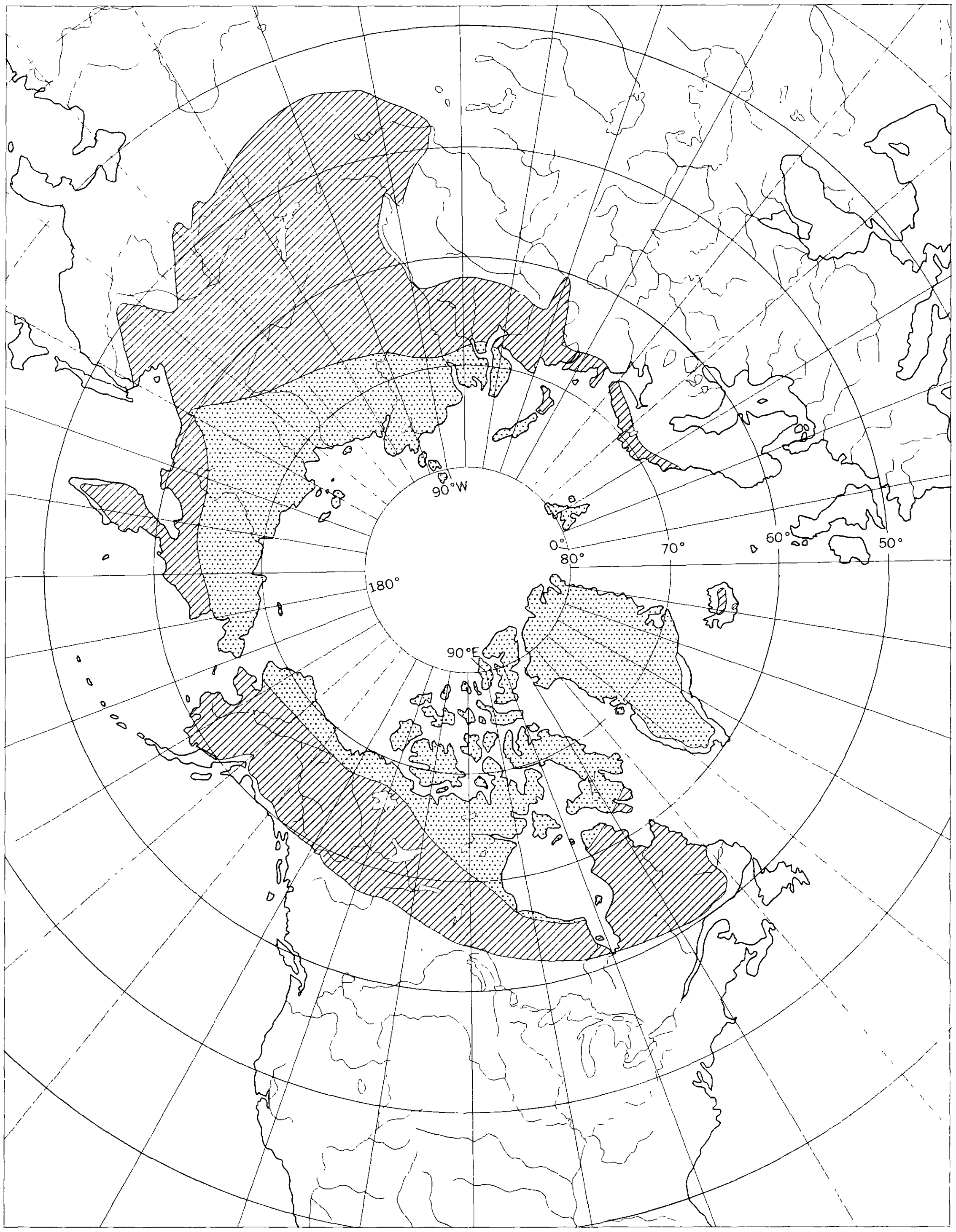
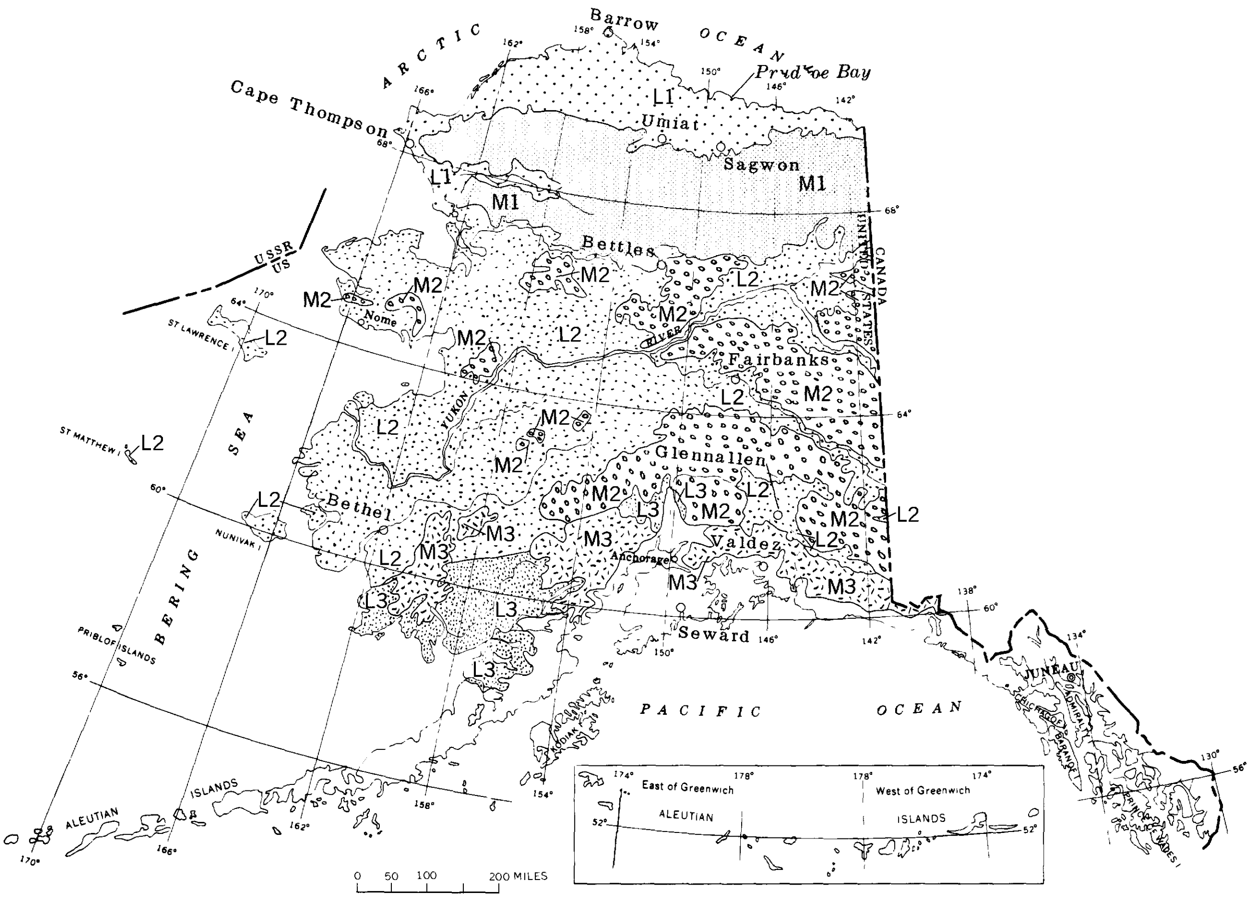


FIGURE 1 —Extent of permafrost zones in Northern Hemisphere.



EXPLANATION

AREAS WITHIN PERMAFROST REGION

Mountainous areas, generally underlain by bedrock at or near the surface

M1

Underlain by continuous permafrost

M2

Underlain by discontinuous permafrost

M3

Underlain by isolated masses of permafrost

Lowland areas, generally underlain by thick unconsolidated deposits

L1

Underlain by thick permafrost in areas of either fine-grained or coarse-grained deposits

L2

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

L3

Underlain by isolated masses of permafrost in areas of fine-grained deposits, and generally free of permafrost in areas of coarse-grained deposits

AREAS OUTSIDE OF PERMAFROST REGION

Generally free of permafrost, but a few small isolated masses of permafrost occur at high altitudes, and in lowland areas where ground insulation is high and ground insolation is low, especially near the border of the permafrost region

FIGURE 2.—Distribution of permafrost in Alaska. Modified after Ferrians (1965).

built in the permafrost region. This construction demonstrates that the deleterious effects of permafrost can be overcome, and that major development can take place in the arctic regions. In regard to the success of the Soviets, the following statement (Muller, 1943, p. 2) is pertinent: "It is worth noting that in Soviet Russia since about 1938 all government organizations, municipalities, and cooperative societies are required to make a thorough survey of permafrost conditions according to a prescribed plan before any structure may be erected in the permafrost region."

The purpose of this report is to present a survey of some of the more important aspects of permafrost and to create an awareness of the tremendous problems that can be caused by constructing on, or otherwise disturbing, permafrost if proper procedures are not used. It is hoped that the information presented will facilitate the development of the natural resources of northern Alaska and at the same time minimize disruption of the natural environment.

PERMAFROST

DEFINITIONS

Permafrost is defined exclusively on the basis of temperature. It is rock or soil material, with or without included moisture or organic matter, that has remained below 0° C (32° F) continuously for two or more years. In most areas it has remained frozen for many thousands of years; however, permafrost can be quite young in areas where very recent sediments have been laid down, where very recent changes in the location of water bodies have taken place, and where man has disturbed the terrain.

Permafrost may be ice free at 0° C when the water it contains is saline or when it contains no water at all. The latter is commonly referred to as *dry permafrost.* When permafrost contains clay, substantial amounts of unfrozen moisture can persist at temperatures several degrees below 0° C because of the depression of the freezing point by capillary forces. Ice in permafrost can occur as coatings, grains, veinlets, or masses, and in unconsolidated materials it commonly acts as a cementing agent making the mass of unconsolidated materials hard as a rock.

The *permafrost table* is the upper surface of the permafrost, and the ground above the permafrost table is called the *suprapermafrost layer.* The *active layer* is that part of the suprapermafrost zone that freezes in the winter and thaws in the summer, or simply, seasonally frozen ground. Because water in the soil tends to reduce temperature fluctuations from summer to winter, the summer thawing—and hence the active layer—is deeper in drier materials. Seasonal frost penetrates down to the permafrost table in most places; however, if it does not, an unfrozen zone called a *talik* remains between the bottom of the seasonal frost and the permafrost table. Unfrozen zones within and below the permafrost also are called taliks (fig. 3). If the thickness of permafrost is increasing, permafrost is said to be *aggrading,* and if decreasing, permafrost is said to be *degrading.*

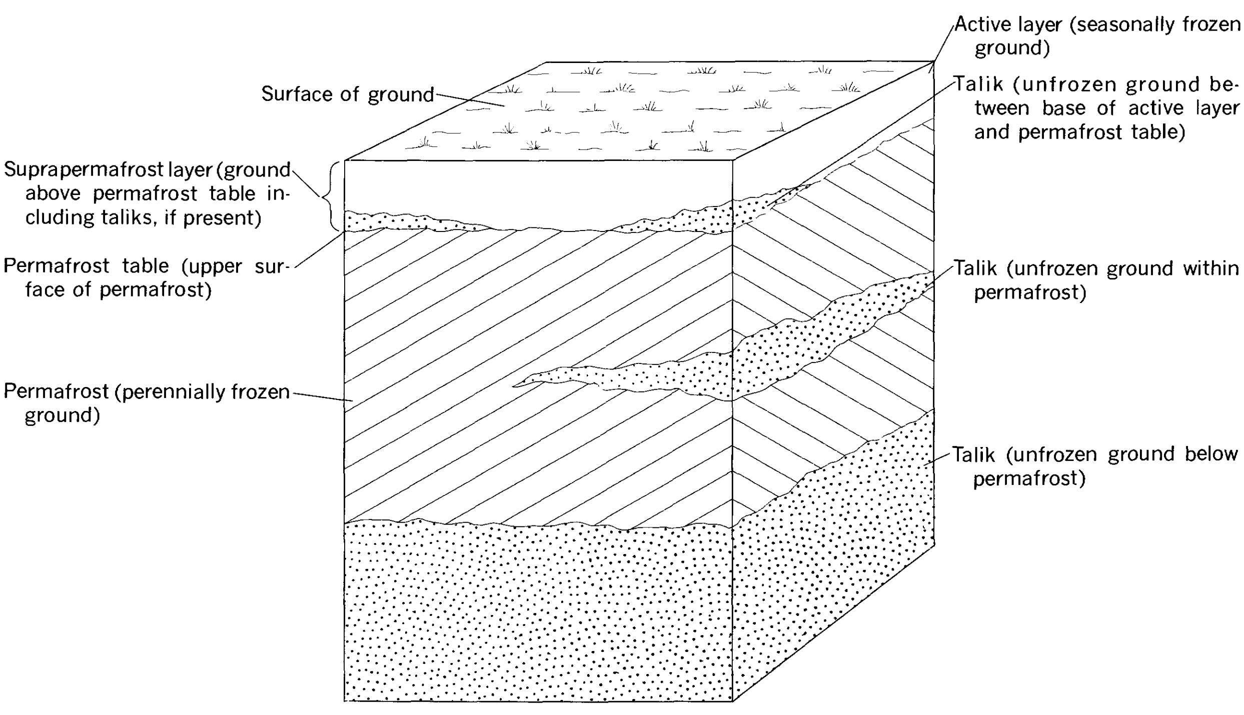


FIGURE 3.—Occurrence of taliks in relation to the active layer, suprapermafrost zone, permafrost table, and permafrost.

ORIGIN AND THERMAL REGIME

Permafrost forms when the mean annual air temperature is low enough to maintain a mean annual ground-surface temperature below 0° C (32° F). If climatic conditions in an area change in such a way as to reduce the mean surface temperature below 0° C, the depth of winter freezing will exceed the depth of summer thawing and if the mean surface 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 the heat flowing upward from the earth's interior. Thus, the thickness to which permafrost can grow depends upon the mean surface temperature and the geothermal gradient. The lower the temperature and gradient, the greater the thickness of the permafrost. In this manner, permafrost, hundreds of feet thick, can form over a period of several thousand years.

Because the formation of permafrost depends upon temperature at the ground 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 (Lachenbruch, 1957a, 1957b; Greene and others, 1960).

Although the surface of the permafrost may be quick to respond to surface changes, it requires centuries, or tens of centuries, for surface changes to affect the bottom of the permafrost. Therefore, the present thickness and distribution reflect former thermal environments (Lachenbruch and others, 1966).

A few examples demonstrate how these considerations can be applied to make a qualitative appraisal of permafrost conditions beneath various surface features. (For quantitative calculations see Lachenbruch and others, 1962, and references cited therein.) Example 1. Shallow lakes freeze completely in the winter; thus, they behave like the active layer of the nearby terrain. However, the spring warming is accomplished efficiently by water circulating around and beneath the deteriorating ice, whereas the fall cooling is achieved inefficiently by conduction through the ice. The result is that mean annual temperatures on shallow lake bottoms are higher than those of the surroundings and permafrost is thinned beneath them (fig. 4). Example 2. Deeper lakes (greater than 6 ft deep) that do not freeze completely during the winter have mean annual bottom temperatures above freezing and thus are underlain by a thawed basin. The permafrost beneath a thawed basin is also thinned by upward indentation (fig. 4). If the lake is drained, the thawed basin refreezes and expansion of the ice within it creates a pingo (see p. 12). If the minimum horizontal dimension of a deep lake is greater than approximately twice the local undisturbed permafrost thickness, the upward indentation coalesces with the thawed basin to form an unfrozen "chimney" through the permafrost beneath the lake (fig. 4). Such features provide a potential year-round source of ground water in regions of continuous permafrost.

A river behaves like a long thin lake, and the ocean can be viewed as a large deep lake (fig. 4). Example 3. Well-drained areas will generally have summer surface temperatures several degrees higher than nearby poorly drained bogs because of the thermal effects of the water. Inasmuch as the best drained areas are generally underlain by gravels and have a temperature anomaly, aerial infrared mapping might show the best locations for constructing roads and buildings and indicate likely sources of gravel for construction purposes.

In the absence of various modifying conditions such as those described above, the top and bottom of the permafrost layer tend to parallel the ground surface, rising under hills and lowering beneath valleys (fig. 4).

A gradual climatic warming during the last century has caused a warming of the permafrost to depths of several hundred feet (Lachenbruch and Brewer, 1959; Lachenbruch and others, 1962, 1966). Hence near Barrow, Alaska, the temperatures at a depth of 150 feet (about −9.7° C) are lower than those at 50 feet (about −9.4° C). Below 300 feet, however, the temperatures increase in accordance with the anticipated geothermal gradient (Lachenbruch and others, 1962). Near the southern limit of permafrost the effect of the climatic warming is to keep the permafrost very close to 0° C throughout its entire depth. The permafrost is, therefore, very vulnerable to deep thawing and often will not regenerate when active construction procedures are used.

It should be pointed out that in a given area the mean ground-surface temperature is usually higher than the mean air temperature, largely because the ground is insulated by snow during the cold winter but is bare during the summer.

It is important also that the fluctuations of air temperature from summer to winter are normally substantially greater than corresponding fluctuations at the ground surface. Typically, ground-surface

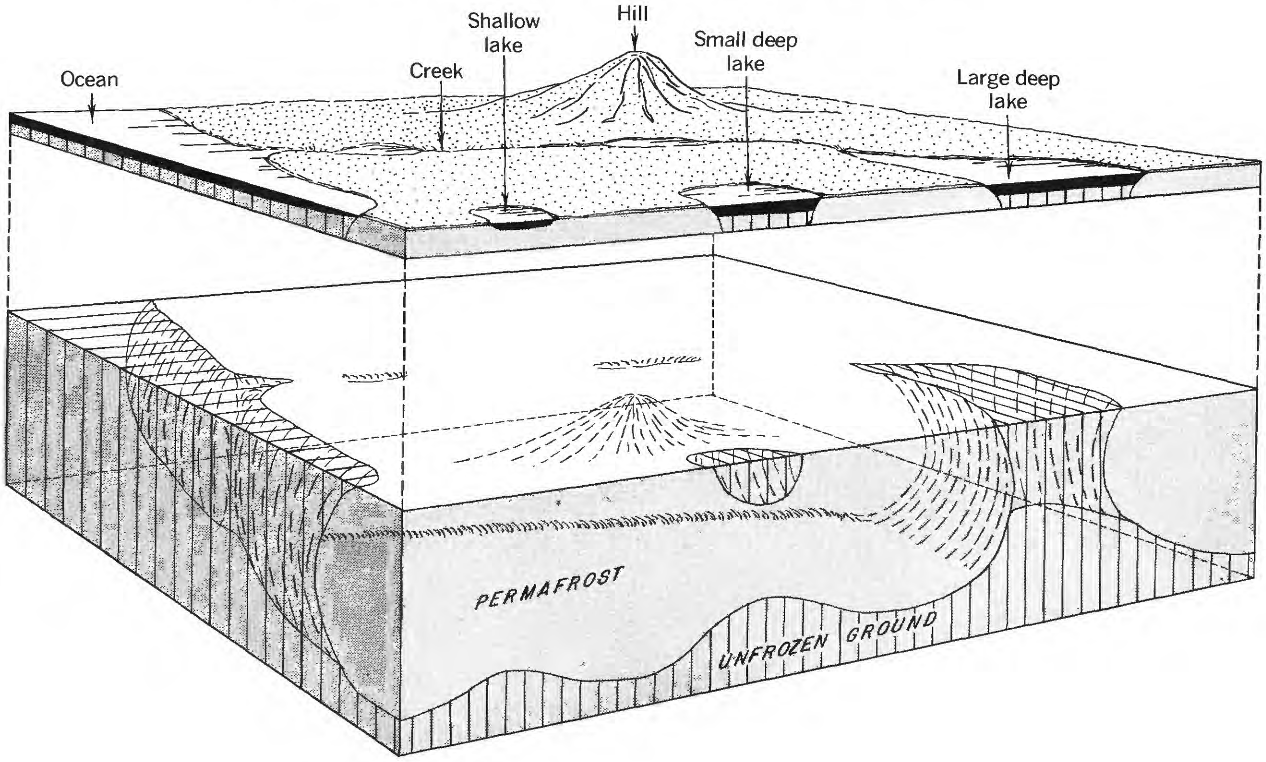


FIGURE 4.—The effect of surface features on the distribution of permafrost in the continuous permafrost zone. After Lachenbruch (1968, p. 837).

temperatures fluctuate 20° C to 50° C seasonally, the smaller values occurring in wetter terrains. The fluctuations diminish rapidly with depth, normally by a factor of 10 for approximately every 20 feet. Thus the seasonal variation of temperature at 20 feet is a few degrees, at 40 feet it is a few tenths of a degree, and at 60 feet it is barely detectable. Seasonal fluctuations normally propagate into the earth at the rate of about 5 feet per month. Because of this lag the minimum temperature at 30 feet occurs in midsummer. This explains the summer freezing of some water wells in the subarctic.

Curve *A* in figure 5 shows how the change in annual ground-surface temperature, assumed here to be sinusoidal, produces thawing of the permafrost even though the mean annual ground-surface temperature is well below 0° C. The stippled area indicates the amount of thawing that takes place. Note that if either the mean annual temperature or the amplitude of the temperature fluctuations is increased there will be a greater amount of thawing. If the permafrost is dry, that is, without interstitial ice or water, the temperatures will follow curve *A*. However, if water is present the latent heat released when water freezes will cause the temperature to remain at the freezing point while this heat is dissipated as shown by curve *B*. The latent heat absorbed in the spring and liberated in the fall by moisture in the arctic layer tends to reduce the temperature fluctuations at the permafrost table.

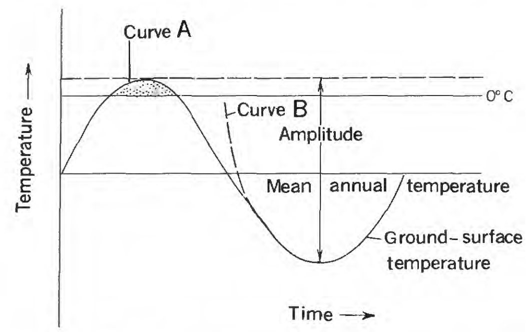


FIGURE 5.—Relations of amplitude of ground-surface temperature fluctuations to amount of thawing.

AREAL DISTRIBUTION AND THICKNESS

Two broad zones of permafrost can be differentiated in the northern hemisphere (fig. 1)—the continuous zone which is underlain by permafrost nearly everywhere, and the discontinuous zone which includes numerous permafrost-free areas. Within the discontinuous zone the extent of the permafrost-free areas increases progressively from north to south. South of the discontinuous permafrost zone, permafrost generally is absent except for a few isolated occurrences, usually at high altitudes. The distribution of permafrost is largely controlled by temperature variations related to differences in latitude, altitude, and major climatic patterns.

In Alaska (fig. 2), the two broad permafrost zones can be subdivided into: (1) mountainous areas where bedrock generally is at or near the surface, and (2) lowland areas commonly underlain by thick unconsolidated deposits. The thickness, distribution, and temperature of permafrost are extremely variable in the mountainous areas; in the lowland areas these characteristics are more uniform.

From north to south, the mountainous areas can be further subdivided into areas underlain by continuous permafrost, areas underlain by discontinuous permafrost, and areas underlain by isolated masses of permafrost.

The lowland portion can also be subdivided into (a) a northern area (largely north of the Brooks Range) which is underlain by thick permafrost; (b) a central area (between the Brooks and Alaska Ranges but including the Copper River basin), which is 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 (c) a southern area (including the Bristol Bay area and the eastern and western margin of the Susitna Lowland north of Anchorage), which is 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.

Because climate is the major factor that controls the regional (and global) distribution of permafrost, the permafrost regions in Alaska can be characterized by the mean annual air temperature and precipitation data for representative stations (table 1). Within the continuous permafrost zone, Barrow has the lowest mean annual air temperature, 10° F, whereas Anchorage, just outside of the permafrost region, has a mean annual air temperature of 35° F.

TABLE 1.—*Mean annual temperature and precipitation data from representative stations in Alaska*

[Data from U.S. Weather Bureau records]

Station	Mean annual temperature (°F)	Mean annual precipitation (inches)
Continuous permafrost zone		
Barrow	10	4
Umiat	10	6
Discontinuous permafrost zone		
Bettles	22	—
Nome	26	19
Fairbanks	26	12
Glennallen (Gulkana)	27	12
Bethel	30	18
No permafrost		
Anchorage	35	15
Valdez	36	62
Seward	40	69
Juneau	41	56

The climatic control is also reflected by the thickness of permafrost which ranges from more than 1,300 feet near Barrow to lenses less than a foot thick in the southernmost part of the permafrost zone.

Even though the annual precipitation is low at the stations within the permafrost region, 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 few feet of the surface, and by the low

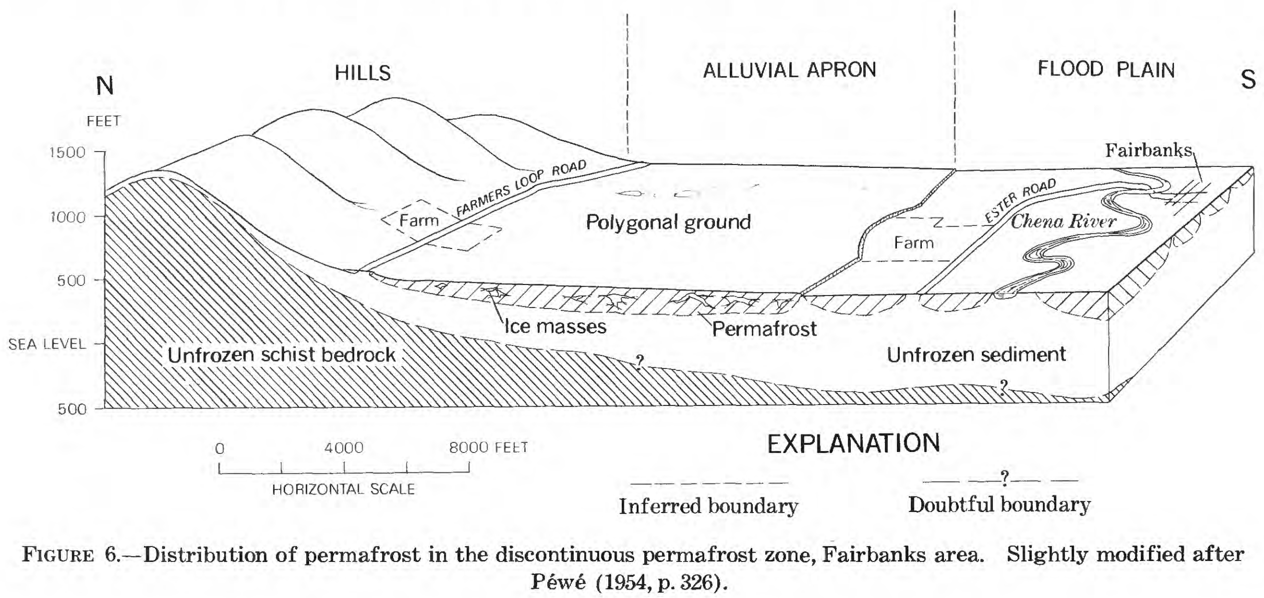


FIGURE 6.—Distribution of permafrost in the discontinuous permafrost zone, Fairbanks area. Slightly modified after Péwé (1954, p. 326).

evaporation rate at the prevailing low temperatures. Also, the low annual precipitation indicates that the snow cover is not thick.

In any area where the mean annual air temperature is around 0° C (32° F), the microclimate, which is governed largely by local features, can be critical in determining whether or not permafrost is present. For example, the mean annual air temperature recorded at a site underlain by unvegetated dry soils can be 1° or 2° warmer than a nearby site underlain by vegetated wet soils. Slope exposure also controls microclimate in mountainous or hilly areas where south-facing slopes may receive considerably more solar heat than the north-facing slopes. This is important in the southern margin of the permafrost region where south-facing slopes often are completely free of permafrost, whereas nearby north-facing slopes are underlain by thick permafrost.

Permafrost thickness also varies depending upon the amount of heat flowing outward from the earth's interior. Generally, the temperature of the earth increases 1° C (1.8° F) for each 100 to 200 feet of depth; however, locally, the near-surface temperatures can be relatively high.

In the discontinuous zone where the permafrost layer is thinner, surface features affect the distribution of permafrost in much the same way as in the continuous zone (fig. 4); thus lakes and rivers cause smaller anomalies because their temperature does not contrast as much with the surroundings. The distribution of permafrost in the Fairbanks area, as shown in figure 6, is typical of much of interior Alaska. Permafrost is absent under the south-facing hillslope, continuous under the flood plain, and absent under the Chena River.

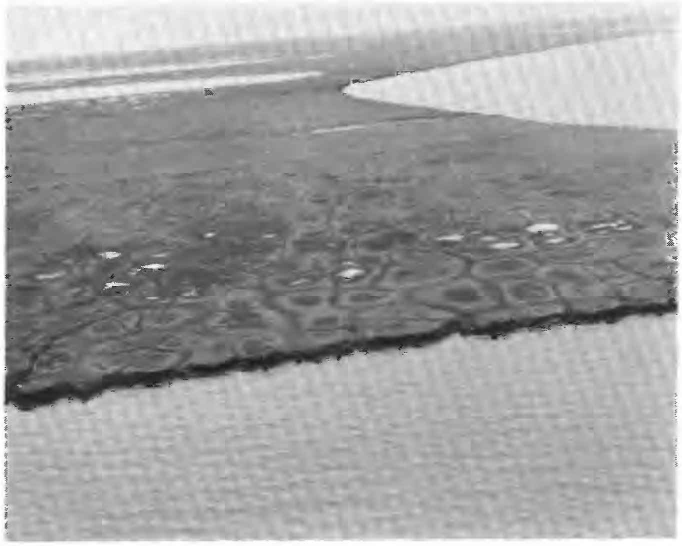


FIGURE 7.—Aerial view of coastal plain near Barrow, in northern Alaska showing polygonal markings on ground surface caused by underlying ice-wedge polygons. The bank along Elson Lagoon in foreground is being undercut by thawing of permafrost and by wave action. Photograph taken in August 1958.

RELATED GEOMORPHIC FEATURES

Permafrost and frost action produce several types of geomorphic features (Washburn, 1956; National Academy of Sciences, National Research Council, 1966). Among these features are polygonal ground (ice wedges), stone nets, garlands and stripes, solifluction sheets and lobes, thaw lakes and thaw pits, beaded drainage, and pingos. Because these features are closely related to the permafrost problems a brief description of each is warranted.

POLYGONAL GROUND

Polygonal ground (figs. 7 and 8), which covers many thousands of square miles of northern Alaska is caused by shallow troughs which overlie a honeycomblike network of vertical wedge-shaped ice masses (ice wedges) that have joined to form polygons in the permafrost. Individual polygons range from 30 to a few hundred feet in diameter. Figure 9 shows a typical ice wedge. Where the surface of the ground is disturbed and the thermal regime upset, the ice wedges can melt, causing severe differential settlement of the ground surface. For example, clearing of the ground near Fairbanks caused ice wedges to melt, and large mounds were left (figs. 10 and 11.)

Polygonal ground indicates relatively fine grained unconsolidated sediments with the permafrost table near the ground surface. It also occurs in coarser sediments and gravels where the formation of ice wedges is less extensive than in the fine-grained sediments.

Many different hypotheses for the origin of ice-wedge polygons have been proposed; however, the thermal contraction theory first clearly described by Leffingwell (1915, 1919) has been generally accepted by most workers. A quantitative appraisal of the mechanics of the thermal contraction theory was made by Lachenbruch (1962), and he concluded that the theory is compatible with the thermal and mechanical properties and thermal regime of the permafrost in which the ice-wedge polygons occur.

STONE NETS

Stone nets, garlands, and stripes are extensive in the arctic. Frost heaving in granular soils produces netlike concentrations of the coarser rocks (fig. 12). If the area is gently sloped, the net is distorted into garlands by downslope movement. If the slope is

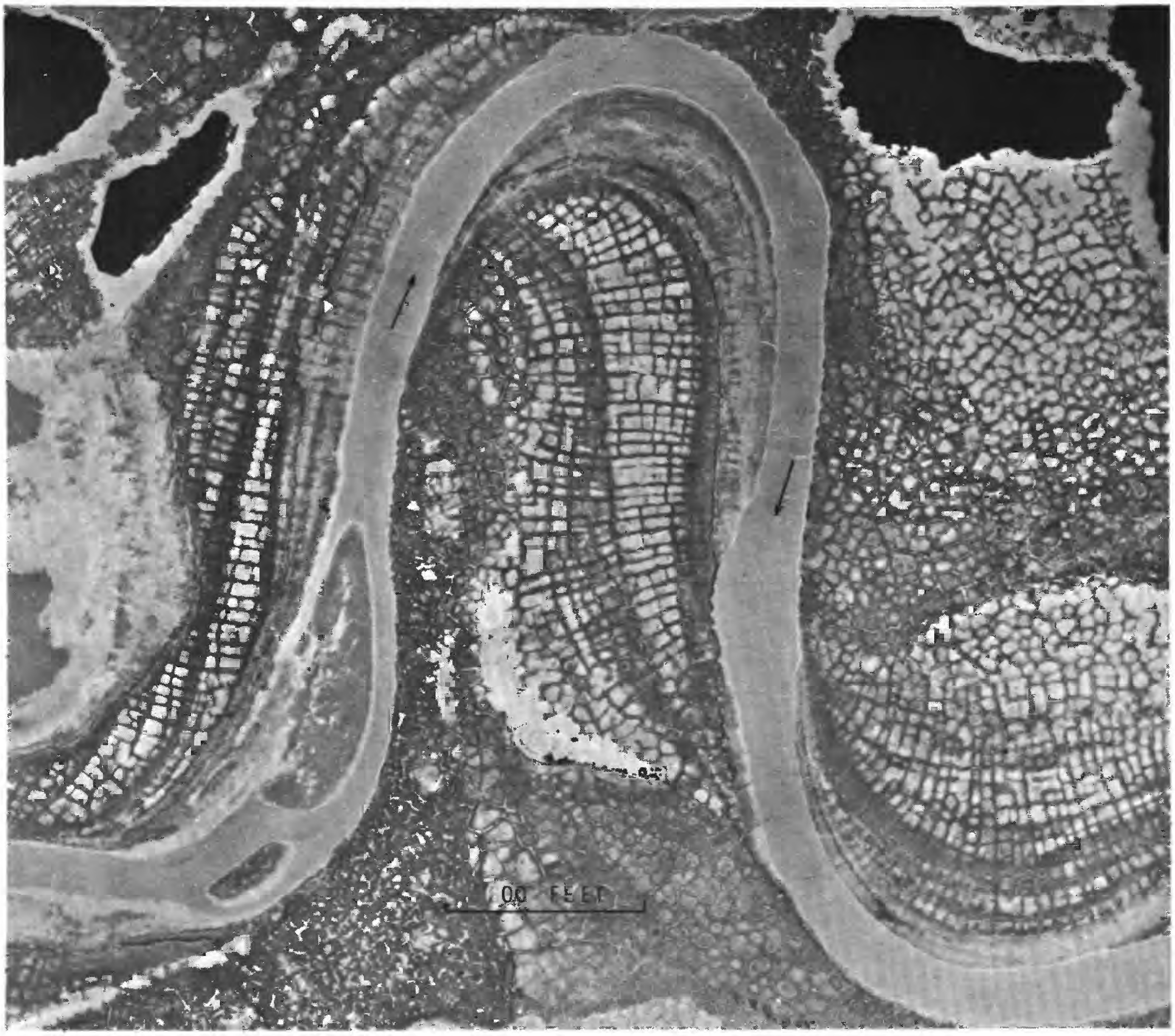


FIGURE 8.—Polygonal markings on ground surface (caused by ice-wedge polygons) in the vicinity of Meade River, about 35 miles southeast of Barrow, in northern Alaska. Photograph by U.S. Navy, July 1949.

steep, the coarse rocks lie in stripes that point downhill. Generally, in garlands and stone stripes the downslope flow pattern is readily apparent. Stone nets, garlands, and stripes indicate strong frost action in moderately well drained granular sediments that vary from silty fine gravel to boulders. These surficial materials are commonly susceptible to flowage.

SOLIFLUCTION

Solifluction sheets and lobes are masses of unconsolidated sediment that range from less than a foot to hundreds of feet in width. These features are extensive in the arctic and may cover entire valley walls. They occur on slopes as low as 3°. Solifluction plays a major role in the formation of patterned ground. This type of patterned ground is formed by the gradual downslope (gravity) movement of water-saturated sediments. The surficial materials are especially mobile in the permafrost region because the active layer commonly is supersaturated with moisture. This condition is caused by the impermeability of the underlying permafrost and by the low evaporation rate. Downslope movements of solifluction features are so rapid that a structure resting upon one will either be subjected to large earth pressures or will move passively downslope.

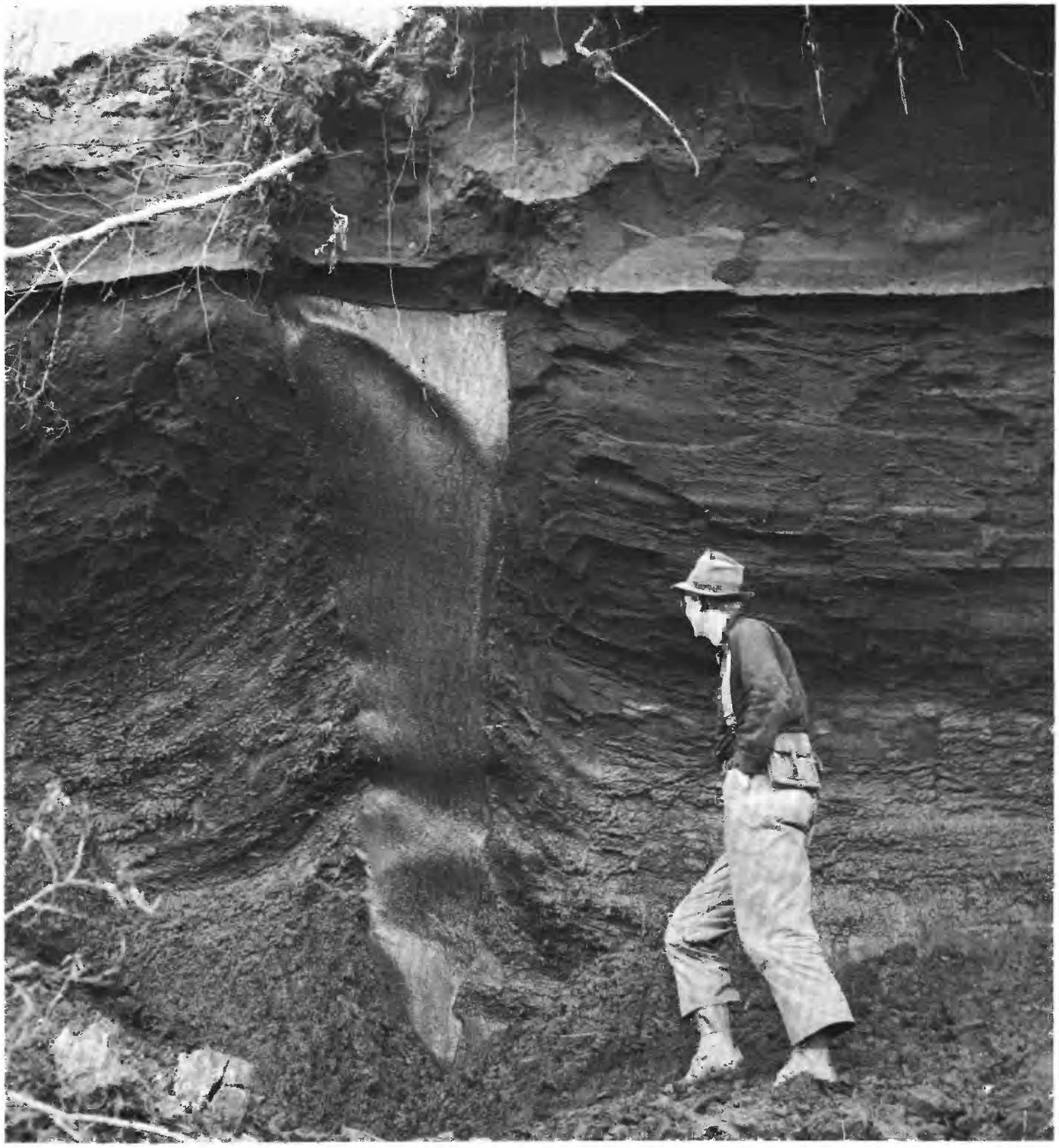


FIGURE 9.—Ice wedge (ground ice) in permafrost exposed by placer mining near Livengood about 50 miles northwest of Fairbanks. Photograph by T. L. Péwé, September 1949.

FIGURE 10.—Thermokarst mounds near Fairbanks. Mounds range from 10 to 30 feet in diameter. See figure 11 for ground view of mounds and explanation. Photograph by R. F. Black and T. L. Péwé, September 1948.

FIGURE 11.—Thermokarst mounds near Fairbanks caused by melting of ice wedges. The resulting ground settlement formed deep trenches in polygonal patterns and left mounds in the intervening areas. The thawing was started after the area was cleared for agricultural purposes. Figure 10 is an aerial view of similar mounds. Photograph taken in June 1955.

FIGURE 12.—Sorted stone circles caused by frost action, in Alaska Range, south-central Alaska. Photograph by T. L. Péwé, June 1968.

THAW OR THERMOKARST PITS

Thaw or thermokarst pits occur in areas underlain by permafrost containing large masses of ground ice (fig. 13). If the ground surface is disturbed above a large ice mass, such as the one shown in figure 13, the resultant change in the thermal regime can cause the ice mass to thaw; this thawing causes a thaw pit to form (fig. 14).

The occurrence of these pits indicates poorly drained, fine-grained sediments with the permafrost table near the surface.

THAW LAKES

Hopkins (1949, p. 119) defines a thaw lake as one which occupies a thaw depression; however, the definition includes lakes that originated in other ways but that have been enlarged considerably by the thawing and caving of their margins. The term "cave-in-lake," (Muller, 1943, p. 214) is used somewhat synonymously with "thaw lake," but the original definition limits its usage to lakes formed in caved-in depressions caused by thawing of ground ice.

Thaw lakes are common throughout the permafrost region and usually indicate poorly drained, fine-grained, unconsolidated sediments with the permafrost table near the surface. These lakes are characterized by undercutting and caving along their margins, caused by the thawing permafrost (fig. 15). Trees along the shorelines that lean toward the lake because their root systems are being undercut are conspicuous indicators of thaw lakes.

Oriented lakes, a very common type of thaw lake in northern Alaska, cover more than 25,000 square miles of the arctic coastal plain (Black and Barksdale, 1949, p. 105). They range in size from small ponds to more than 9 miles long and 3 miles wide. The long axis of these lakes is oriented in a northwesterly direction (ranging from 10° to 15° west of true north). This preferred orientation is strikingly shown on the topographic maps of northern Alaska.

BEADED DRAINAGE

Beaded drainage occurs in areas underlain by systems of ice wedges. The heat in the flowing surface water thaws the underlying ice masses (usually at ice-wedge intersections) forming depressions occupied by pools of water connected by the normally flowing stream. The overall appearance, when viewed from the air, is like a string of beads, hence the name "beaded drainage." Beaded drainage is a surface indicator of the presence of permafrost.

PINGOS

Small ice-cored conical hills called pingos are common in the continuous permafrost zone along the coastal plain of northern Alaska and northwestern Canada (Mackay, 1966, p. 71) and in the discontinuous permafrost zone in central Alaska (Holmes and others, 1968). Figure 16 shows a pingo of the type found in the forested central part of Alaska. Pingos range from 50 to several thousand feet in diameter, and from 10 to several hundred feet in height. Commonly, they have craters on their summits, which are occupied by ponds.

Pingos indicate silty sediments and the presence of ground water (with some hydraulic head) that is confined between the seasonal frost and permafrost table or is flowing in a thawed zone within the permafrost. Those in former lakebeds indicate saturated fine-grained sediments.

MUCK DEPOSITS

Although not actually a geomorphic feature, perennially frozen "muck" or organic-rich silt deposits are widespread throughout interior Alaska (figs. 7 and 16) and are important in permafrost areas. In the Fairbanks area, the muck deposits are composed of organic-rich windblown silt (loess) that has been redeposited (Péwé, 1966, p. 14). The tremendous amount of organic material in the deposits presumably was incorporated when the windblown silt was being transported from the hillsides to the valley bottoms by solifluction, sheet wash, and other gravity-type processes. Muck deposits can be thawed in a few months or years when the insulating quality of the surface is modified. This material liquifies when thawed and can create severe engineering problems.

FIGURE 13.—Large mass of ground ice exposed by gold placer mining in silt bluff near Fairbanks. Thawing of a large ice mass causes severe differential settlement of the surface of the ground, as is shown in figure 14. Photograph taken in June 1955.

FIGURE 14.—Thaw or thermokarst pit near Fairbanks formed by the thawing of a large ice mass that caused severe differential settlement of the surface of the ground. Photograph by T. L. Péwé, June 1948.

FIGURE 15.—Shoreline of a thaw lake about 40 miles northwest of Glennallen in south-central Alaska. Shoreline undercut because of thawing of permafrost. Vegetation mat of peat is draped over surface of steep bank (8-12 ft high) and is caving into lake. Trees in foreground are leaning toward lake, and they too will cave into the lake as the undercutting progresses landward. Photograph taken in June 1960.

FIGURE 16.—Pingo in Yukon-Tanana Upland, east-central Alaska. Light birch trees on pingo contrast with dark spruce trees surrounding it. Pingo is about 300 feet in diameter and 50 feet high; water-filled crater on its summit makes it "donut shaped." Photograph by H. L. Foster, August 1960.

SUMMARY OF GEOMORPHIC FEATURES

Table 2 has been prepared as a quick reference to the descriptions and ground conditions associated with these common topographic features in permafrost areas.

ENGINEERING GEOLOGY

Construction and maintenance of structures in the arctic and subarctic regions underlain by permafrost are characterized by a wide range of problems in addition to those experienced elsewhere. Engineers, designers, and construction and maintenance personnel are continuously plagued by extremely severe frost heaving, subsidence caused by thawing permafrost, soil creep or solifluction, landslides, and icings. These processes not only present construction and maintenance problems but in the more severe cases may be a hazard to the users of the structures.

There are two basic methods of constructing on permafrost: (1) the *active method* and (2) the *passive method.*

The active method is used in areas where permafrost is thin and generally discontinuous or where it contains a relatively small amount of ice. The object of this method is to thaw the permafrost, and if the thawed material has a satisfactory bearing strength, then construct in a normal manner. Sometimes the structure itself can be used to thaw the permafrost, and the surface brought back to grade at intervals while the thawing process takes place. Generally, the thawing of the permafrost is accomplished simply by clearing the vegetation, which normally insulates the permafrost from the heat in the air and from solar radiation. Heat from steam and warm water piped into the ground has also been used to thaw permafrost. Naturally, the active method of construction has limited application, because of the great thickness of permafrost throughout most of the region, and because of the time required for thawing the ground.

The passive method, which has broad application throughout most of the permafrost region, is used in areas such as the North Slope, where it is impractical to thaw the permafrost. The object of this method is to minimize disturbance of the permafrost and of the thermal regime. The thermal regime in an area

TABLE 2.—*Common topographic features that indicate ground conditions in arctic and near arctic regions*

Feature and description	Associated ground conditions
Polygonal ground (ice wedges)—Usually indicates the presence of a network of ice wedges—vertical wedge-shaped ice masses that form by the accumulation of snow, hoarfrost, and meltwater in ground cracks that form owing to contraction during the winter. Wedge networks are also common in wet tundra where no surface expression occurs. (Subject to extreme differential settlement when surface disturbed)	Typically indicates relatively fine grained unconsolidated sediments with permafrost table near the ground surface; also known from coarser sediments and gravels where wedge ice is less extensive.
Stone nets, garlands, and stripes—Frost heaving in granular soils produces netlike concentrations of the coarser rocks present. If the area is gently sloped, the net is distorted into garlands by downslope movement. If the slope is steep, the coarse rocks lie in stripes that point down hill.	Indicate strong frost action in moderate well-drained granular sediments that vary from silty fine gravel to boulders. Surficial material commonly susceptible to flowage.
Solifluction sheets and lobes—Sheets or lobe-shaped masses of unconsolidated sediment that range from less than a foot to hundreds of feet in width that may cover entire valley walls; found on slopes that vary from steep to less than 3°.	Indicate an unstable mantle of poorly drained, often saturated sediment that is moving downslope largely by seasonal frost heaving. On steeper slopes they often indicate bedrock near the surface, and on gentle slopes, a shallow permafrost table.
Thaw lakes and thaw pits—Surface depressions form when local melting of permafrost decreases the volume of ice-rich sediments. Water accumulates in the depressions and may accelerate melting of the permafrost. Often form impassible bogs.	Usually indicate poorly drained, fine-grained unconsolidated sediments (fine sand to clay) with permafrost table near the surface.
Beaded drainage—Short, often straight minor streams that join pools or small lakes. Streams follow the tops of melted ice wedges, and pools develop where melting of permafrost has been more extensive.	Indicate a permafrost area with silt-rich sediments or peat overlying buried ice wedges.
Pingos—Small ice-cored circular or elliptical hills that occur in tundra and forested parts of the continuous and discontinuous permafrost areas. They often lie at the juncture of south- and southeast-facing slopes and valley floors, and in former lakebeds.	Indicate silty sediments derived from the slope or valley, and ground water with some hydraulic head that is confined between the seasonal frost and permafrost table or is flowing in a thawed zone within the permafrost. Those in former lakebeds indicate saturated fine-grained sediments.

in a natural undisturbed state is normally in quasi-equilibrium with all the environmental factors, but in many areas this state of equilibrium is very sensitive. The simple passage of a tracked vehicle that destroys the vegetation mat is enough to upset the delicate balance and to cause the top of the permafrost layer to thaw. This thawing can cause differential settlement of the surface of the ground, drainage problems, and severe frost action. Once the equilibrium is upset, the whole process can feed on itself and be practically impossible to reverse. However, if a structure is founded on permafrost that remains frozen, the frozen ground provides rocklike bearing strength. In special cases it may be practical to keep the permafrost intact by using a refrigeration system.

Engineering problems in permafrost nearly always are associated with the active layer (the layer that freezes and thaws annually) and the active layer-permafrost interface (permafrost table). Changes in the surface environment, either natural or man made, produce thermal changes in this zone that can have serious effects upon engineering works and structures.

ENGINEERING PROBLEMS

The engineering problems associated with permafrost are not similar in every type of rock or sediment. For example, bedrock that contains ice in its fractures will present few, if any, construction or maintenance problems. Well-drained coarse-grained sediments such as glacial outwash gravel, although below 0° C, may not contain any ice. Here again few, if any, construction problems will arise. If water is saline, it will remain in the liquid state even if its temperature is below 0° C. The problems associated with this condition are different from those associated with permafrost containing moisture in the frozen state.

Major engineering problems arise where permafrost occurs in poorly drained fine-grained sediments. In such sediments there are generally large amounts of ice, and when the thermal regime is disrupted the ice begins to melt. The thawing produces excessive wetting and undesired plasticity of the fine-grained sediments and renders them unstable. This instability can result in settling, caving, and subsidence of the ground surface, and in many cases, in flowage of the sediments either laterally or downslope.

During the winter months the active layer freezes downward from the ground surface to the permafrost table. In the fine-grained material, formation of this ice results in frost heaving.

Thawing of permafrost and the heaving and subsidence caused by frost action are responsible for the major engineering problems in the subarctic and arctic regions. The following discussion on the thawing of permafrost, the freezing of the active layer, and frost action on ground surface and on piles is presented to prevent repetition of engineering problems. Many of the problems are common to most, if not all, of the structures discussed.

Thawing of Permafrost

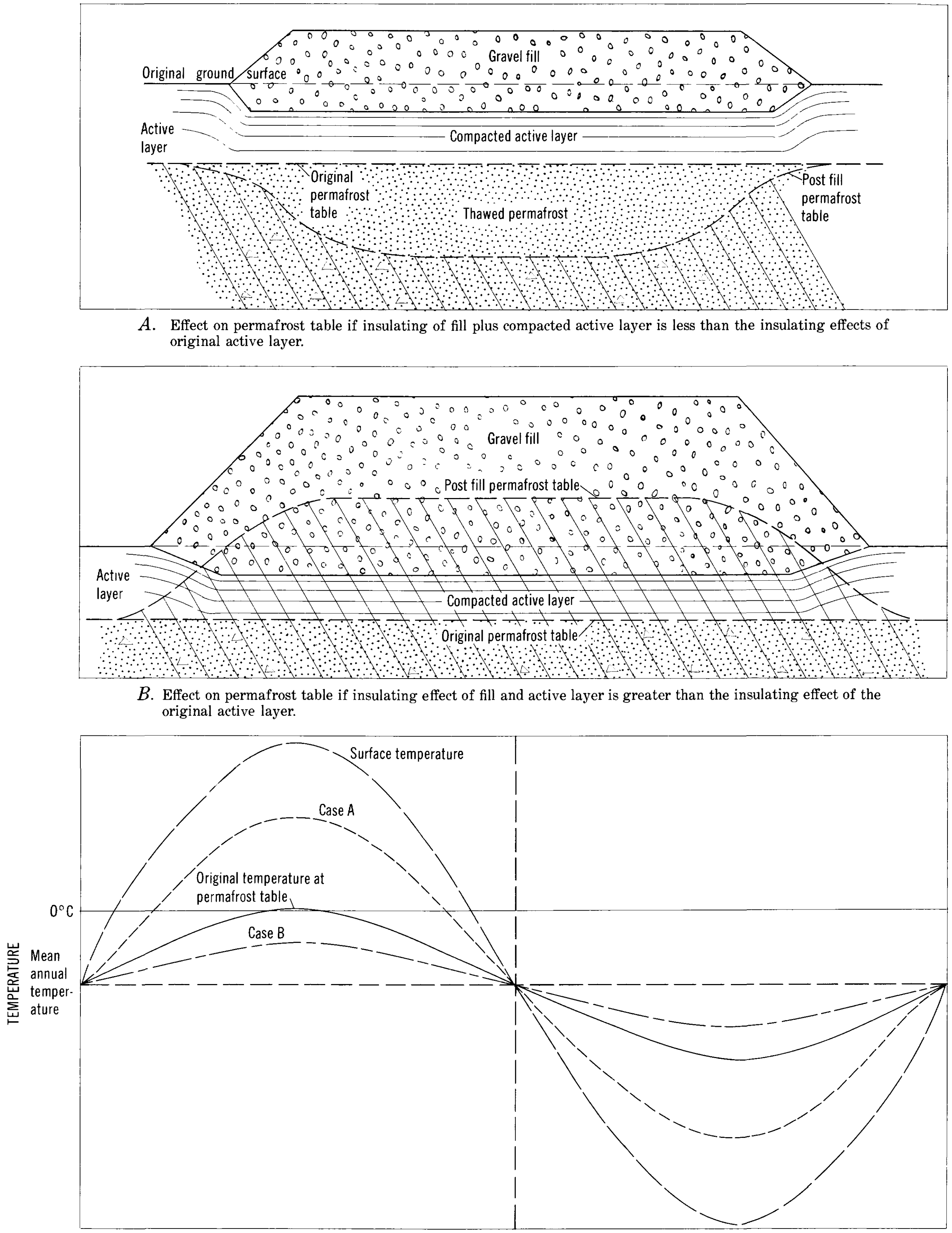
In the past it was engineering practice to remove the protective vegetation cover during construction; thus some of the insulating effect was lost. As soon as the delicate thermal equilibrium is disrupted, permafrost starts to thaw. The result of this thawing is to lower the permafrost table underneath the fill and to make the active layer thicker. The thicker active layer collects larger quantities of moisture, and consequently during the winter greater heaving of the ground surface occurs when the moisture freezes. On the other hand, during the summer, the active layer thaws and the sediments lose their strength causing subsidence, flowage of sediments, and landslides if the structure is on a slope.

With few exceptions, structures in the arctic require some sort of pad or fill. The nature and thickness of the fill—particularly the thickness— are the controlling factors. Figure 17 shows the effects of the pad or fill upon the temperature fluctuations, depth to the permafrost table, and thickness of the active layer. The result of too little fill is shown in figure 17*A*. In this example the insulating effects of the fill plus the compacted active layer is less than the insulating effect before construction. The result is thawing permafrost and an increase in the thickness of the active layer.

Figure 17*B* shows what will happen if the insulating effects of the fill and the compacted layer is greater than the original active layer. In this case, the permafrost table is raised because the amplitude of the seasonal temperature variation is smaller.

The procedures for calculating the appropriate thickness of gravel fill for various climates and materials are explained in detail by Lachenbruch (1959). When the calculated thickness of fill becomes so great as to be impractical, alternative procedures are necessary, such as using insulating materials under the fill.

Although the ice in the sediments is responsible for the heaving, it does give the sediments strength during the winter. However, when the ice melts during the summer, this strength no longer exists and the results may be damaging. If a structure is constructed during the winter, the ice-rich sediments will



A. Effect on permafrost table if insulating of fill plus compacted active layer is less than the insulating effects of original active layer.

B. Effect on permafrost table if insulating effect of fill and active layer is greater than the insulating effect of the original active layer.

C. Effects of cases *A* and *B* on amplitude of seasonal temperature variation at original permafrost table.

FIGURE 17.—Diagram showing effect of gravel fill upon thermal regime.

not fail, but when the ice thaws, the structure will be damaged by subsidence or by flowage of sediments from beneath the structure. Highways become impassable during the summer, whereas during the winter they are considered to be relatively high-speed roads.

Frost Heaving

Frost heaving has long been known as a major destructive factor to structures. Although the frost-heaving mechanism is complex, the major factors controlling it are ground-surface temperatures, surface condition of the soil, and characteristics of the soil. Soil properties include structure, permeability, thermal properties, physical and chemical properties, and moisture content. Of these factors, the most important are the moisture content and texture of the sediments.

The nature of the ice in the active layer, as well as the thickness of the layer, has an important effect on the amount of frost heaving. In relatively coarse grained sediment with a low water content the ice acts as a binder and does not produce much heaving. If coarse sand is interbedded with silt and the water content is not high, ice forms as layers in the silt and as a binder in the coarse sand. In this case, thin ice lenses are formed and moderate heaving results. If the sediments are silt and fine sand and the water content is high, large masses of segregated ice will form and maximum frost heaving will occur.

Frost heaving is a major problem in the arctic and subarctic primarily because most of the low-lying areas are covered by fine-grained surface materials which are poorly drained.

Frost Heaving of Piles

The use of piles for support of structures is as common in the arctic region as it is in the lower latitudes. The problems, however, are quite different. In the warmer climates, the chief problem with the use of piles is to obtain sufficient bearing strength. In arctic regions, the chief problem is to keep the piles in the ground. Frost action heaves them up, and any structure placed upon the piles is also displaced upward, usually differentially.

The force that tends to displace the piles upward is generated in the freezing active layer and is a function of the adfreezing strength between the pile and the active layer, the depth to which the pile has been driven in the active layer, and the perimeter of the pile. The forces acting downward are the load upon the pile, the weight of the pile, and the forces produced in the unfrozen active layer and in the permafrost. The force in the unfrozen active zone is the skin-friction bond between the pile and unfrozen ground over the lateral surface of the pile. The force in permafrost is equal to the tangential adfreezing strength between the pile and the frozen ground distributed over the pile length and the lateral surface of the pile.

The upward-acting forces become greater as the active layer freezes, therefore the thicker the active layer the greater the upward forces. The downward-acting forces in permafrost depend on how deeply the piles penetrate it. If the thermal regime is disrupted and the permafrost starts to thaw, the downward force of the permafrost becomes less and the upward force of the active layer becomes greater. Conversely if the permafrost table rises from its original position, the downward force of permafrost becomes greater after an initial upthrusting.

Péwé and Paige (1963, p. 364) give a hypothetical example of seasonal frost penetration (freezing of active layer) into silt and show the possible upward forces on a 40-inch-perimeter pile. Their data are reproduced in this report as table 3. Note that the upward force becomes greater as the frozen layer becomes thicker at a rate of about 21,600 pounds per foot. It should be stated that Péwé and Paige had to make the assumption that the texture of the silt and the water content was the same throughout the 4½-foot zone. These two factors definitely influence the bond between the frozen active layer and the pile, and therefore the tangential adfreezing strength. The general discussion of thawing permafrost, the freezing active layers, and frost heaving of piles given above applies to all the descriptions of individual structures that follow. The problems are common to all structures in the arctic.

TABLE 3.—*Hypothetical example of seasonal frost penetration into silt in central Alaska and possible upward push on 40-inch-perimeter pile (ground temperature constant)*

[After Péwé and Paige, 1963, p. 364]

Date	Depth of frost penetration (feet)	Maximum force pushing upward (pounds)
November 1	1	21,600
December 1	1½	32,400
January 1	2	43,200
February 1	3	64,800
March 1	4	86,400
April 1	4½	97,200

SPECIFIC STRUCTURES

The problems associated with permafrost and frost action affect structures in numerous ways. Therefore, a brief description of the engineering problems associated with these effects is presented in the following pages.

Railroads

Railroad engineers prefer to keep grades under 2 percent (2 ft of vertical for every 100 ft of horizontal distance). Unfortunately this requires that the roadbed be placed in low-lying terrain which is usually underlain by poorly drained fine-grained sediments containing permafrost. Therefore, construction problems arise, and expensive maintenance problems develop.

The Alaska Railroad, which runs from Seward (mile 0) to Fairbanks at mile 470.3 (fig. 18), was started about 1910 by a private company, The Alaska Central, and was completed in 1923 by The Engineering Commission.

Railroad personnel encountered many construction problems because of thawing permafrost. A minimum of fill and ballast was placed on the right-of-way, causing areas underlain by ice-rich permafrost to thaw. When the thawing occurred the fine-grained sediments lost their strength and the sediments either subsided or flowed from underneath the roadway.

The roadway of The Alaska Railroad is underlain locally by ice-rich permafrost where sediments are fine grained and poorly drained between Broad Pass (mile 304.5) and Dunbar (mile 431.6) and almost continuously from Dunbar to Fairbanks, where the railroad follows the valley of Goldstream. The maintenance from Dunbar to Happy (mile 463.0) amounts to about $200,000 per year (T. C. Fugelstad, The Alaska Railroad, personal commun.) because of the need to install shims beneath the rails and replace ties damaged by frost heaving during the winter. Locally, slower than usual train speeds (slow-orders) are in effect during the winter with a consequent loss to The Alaska Railroad.

When winter has passed and summer arrives, The Alaska Railroad has other permafrost problems. In summer the active layer and eventually the underlying permafrost starts to thaw. When this happens the track subsides, usually differentially (fig. 19).

If the subsidence is not corrected yearly and the track not brought to grade, the track would look like the roadbed shown in figure 20. The railroad which ran from McCarthy to Cordova (fig. 18) was constructed in 1911 to carry copper ore to the port of Cordova. The railroad was abandoned in 1938, and much of its roadbed is now being incorporated into the Copper River Highway.

During the summer The Alaska Railroad places great quantities of gravel in the sink holes caused by thawing permafrost in order to maintain grade. Line changes and ditching are also required in order to control permafrost problems. About $177,500 is spent annually to correct the effect of the thawing.

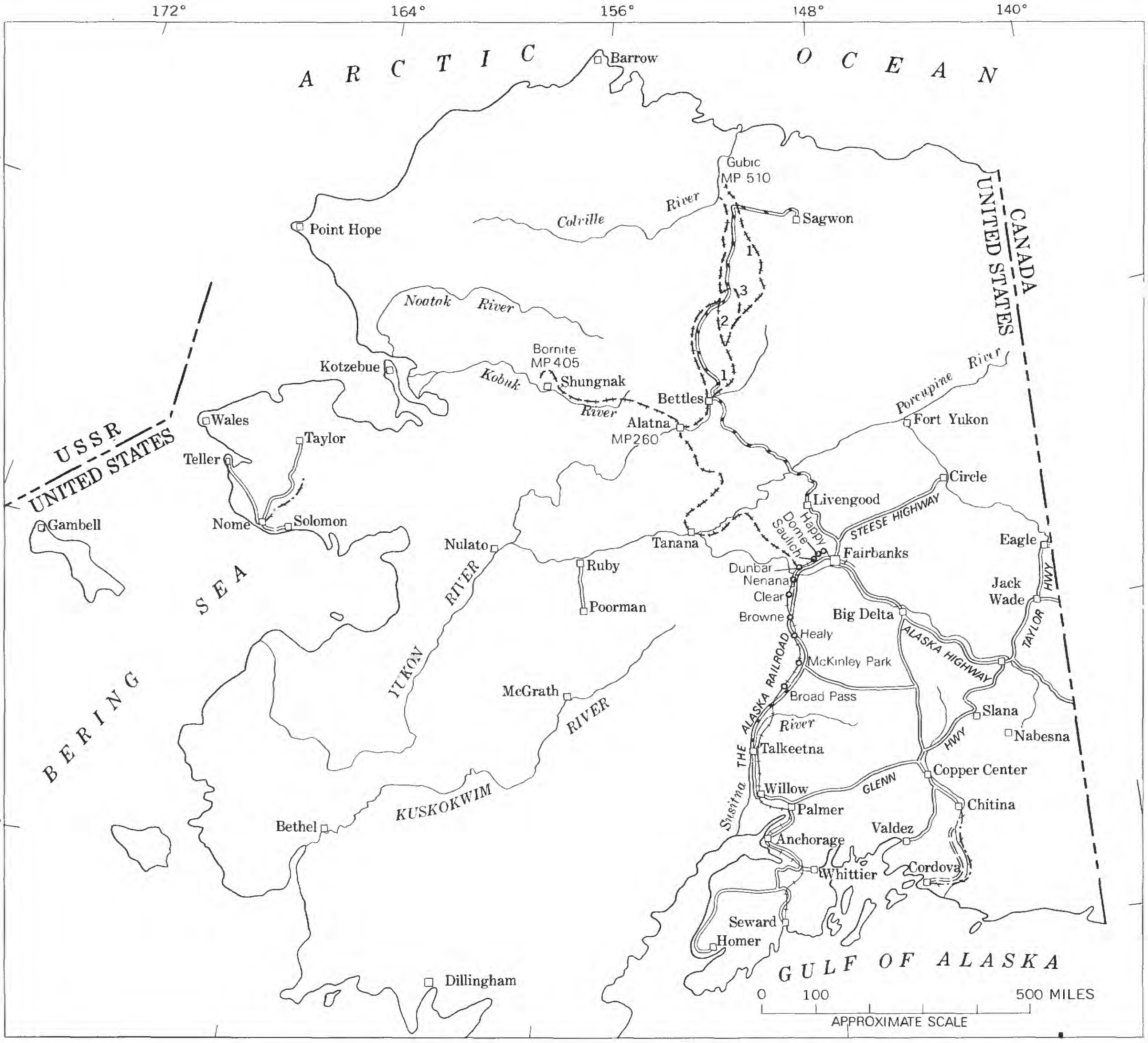
At Moody, a point on The Alaska Railroad where it follows the Nenana Canyon through the Alaska Range toward McKinley Park, the roadbed is underlain by fine silt and clay that was deposited in an ancient glacial lake. The temperature of permafrost here is close to 0° C, and when the railroad was constructed the thermal equilibrium was disrupted and the permafrost started to thaw. Over the years this thawing has required numerous line changes and remedial measures. Figure 21 shows some of the landslides that have occurred. Figure 22 is a photograph of the landslide area near mile 353.5. Piles were driven immediately downslope from the rails in order to prevent the tracks from sliding into the canyon. The pebbles, cobbles, and boulders shown in the photograph are from the gravel which overlies the lake silts and clays. Vertical displacements at the Moody slide have been as much as 4 feet in one day. During the period when landsliding is expected, the track is patrolled in advance of all trains. Remedial measures to combat the landsliding vary from year to year. During the summer of 1967, over $400,000 was spent to realine the track and bring it to grade.

Many bridges on The Alaska Railroad are also affected annually by frost heaving and require maintenance. Time does not permit a discussion of all the structures, and therefore only two bridges are described—one supported by piles and the other by a concrete pier.

The bridge at mile 458.4, in Goldstream valley, is 71 feet long and supported by six bents of wooden piles. Péwé and Paige (1963, p. 380-383) present a detailed description of this structure. A summary of their description of the bridge and its history follows.

The bridge, which was constructed in 1917, is underlain by perennially frozen silt. The permafrost table on September 20, 1954, was 11 or 12 feet below the ground surface at the ends of the bridge and 13 feet deep under the creek.

This wooden-pile bridge has had a continual history of frost heaving and was affected more than any other wood-pile bridge on The Alaska Railroad. The earliest record of pile history was in 1923 at which time all the piles were replaced. The new piles were sunk to depths ranging from 12 to 23 feet, the greatest penetration being at the end bents. During the winter of 1952-53, Péwé and Paige report that the center of the bridge was heaved 14 inches—a dis-



EXPLANATION

Abandoned railroad

Winter road

Highway

Abandoned highway

Clear

Existing route of The Alaska Railroad, showing station house

Proposed route of The Alaska Railroad, showing mile posts. Alternate routes are indicated by numbers

FIGURE 18.—Location of transportation routes in Alaska.

FIGURE 19.—Differential subsidence caused by thawing permafrost along the Murphy Dome Spur of the Alaska Railroad. Roadbed is in Goldstream valley and is underlain by silt. Photograph by T. L. Péwé, June 1954.

placement great enough to decouple railroad cars. The Alaska Railroad cut off the top of the piles and brought the rails back to grade—a common practice in this area.

Frost heaving continued in the winter of 1953-54, and by February 1954 the bridge had heaved 9 inches. In the latter part of February the piles were again replaced, most of the piles being sunk deeply in permafrost. Frost heaving was not evident during the winter of 1954-55. However, during the winter of 1955-56, frost heaving again occurred and by February 3, 1956, the bridge had been heaved 3 inches at bent III, and by the end of the winter it had risen to 5 inches. Péwé and Paige's record stops in 1956. However, Bruce E. Cannon of The Alaska Railroad stated that heaving of the bridge is of only minor consequence at this time (personal commun., 1969).

The explanation for this sequence of events is as follows: The piles were driven into steam-thawed holes and emplaced deep in the thawed permafrost. The permafrost then started to refreeze and must have completely refrozen during the winter of 1955-56. The first winter after the piles were placed (1954-55) the only forces heaving the piles upward were those of the active zone. Apparently these forces were not very strong. The second winter (1955-56), when as much as 5 inches of heaving occurred, the permafrost must have contained more moisture than when the piles were placed. When this additional moisture froze, it expanded and added to the upward force of the active layer. This upward force acted only in the winter of 1955-56, because by the end of that winter the permafrost had refrozen to its original position.

The railroad bridge spanning Riley Creek at mile 347.4 near McKinley Park is a 570-foot steel-viaduct structure supported by concrete piers and concrete abutments. At the request of The Alaska Railroad the bridge site was examined by Reuben Kachadoorian in 1957 to determine the cause of differential heaving of the bridge. In some places the heaving was as much as 5 inches. The piers rest upon sandy stream gravels, which generally are not susceptible to very severe frost action. However, the permafrost table beneath the bridge was irregular and varied from a position lower than the pier bottoms beneath the piers to positions higher than the pier bottoms between the piers. This position varied because the concrete in the piers had a much higher thermal conductivity than the snow or water which surrounded the pier during the winter. Therefore, heat was drawn off from the ground by the piers and ice formed beneath the piers. As the ice grew, additional water was drawn from the unfrozen area around and beneath the piers until a sufficient amount of ice formed to heave the piers. After this explanation was given, The Alaska Railroad took remedial measures, and the effect of frost action upon the Riley Creek bridge was minimized.

Highways and Roads

There are over 2,000 miles of primary and secondary roads in Alaska; the majority are subjected to frost action and are underlain by permafrost. The recent discovery of petroleum north of the Brooks Range at Prudhoe Bay will no doubt stimulate a great deal of highway construction in the area, and all highways will be underlain by permafrost and subject to heaving from frost action. If constructed improperly, the roads will require costly maintenance or even abandonment.

A highway constructed during the winter months may lead the builder into false security. If, for example, the vegetation cover were removed and the roadbed smoothed with heavy equipment, winter use of the highway would not generate any problems of thawing, and any frost heaving of the roadway would be minor.

Bogs, swamps, or other such areas are perfectly capable of supporting traffic during the winter months when they are frozen to a depth of 2 feet or more. Since they are level, they actually invite construction.

In order not to disrupt the thermal equilibrium in permafrost areas, more fill is necessary in the roadbed. The amount of this extra fill is variable under different geological conditions, but it is always a major cost factor. For example, highway contsruction costs in areas underlain by permafrost are substantially higher than in areas free of permafrost.

FIGURE 20.—Differential subsidence of roadbed of Copper River and Northwestern Railway near Strelna, 75 miles northeast of Valdez. The thermal equilibrium of the fine-grained sediments underlying the roadbed was disrupted during construction and the permafrost started to thaw. Maintenance and use of the railroad was discontinued in 1938. Subsidence as well as lateral displacement, however, has continued. Photograph by L. A. Yehle, September 1960.

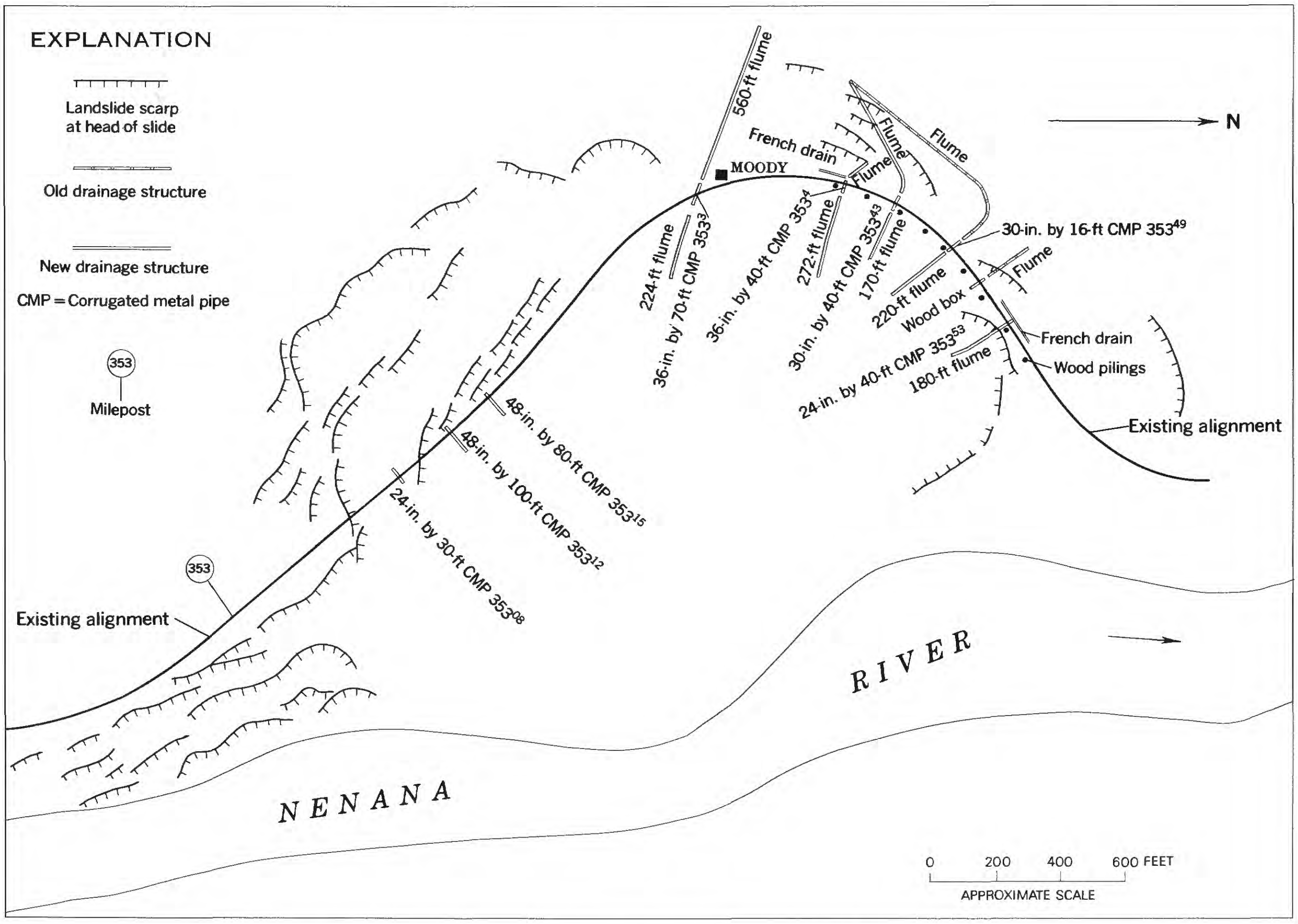


FIGURE 21.—Map of the Moody area on The Alaska Railroad showing landslides and slumps caused by thawing of permafrost and remedial measures taken to combat them. Map prepared by The Alaska Railroad, 1967.

Mr. R. D. Shumway, Alaska Department of Highways, supplied the authors with an analysis of costs of the highway between Rex and Lignite in central Alaska north of the Alaska Range. His results are shown in table 4. One can see that the cost of borrow material in permafrost areas was about 1½ times as much as in permafrost-free areas; the costs of general excavation and of pit stripping were about twice as much.

TABLE 4.—*Comparison of construction costs, per cubic yard, between permafrost and permafrost-free areas of the highway between Rex and Lignite, Alaska*

	Nonpermafrost area	Permafrost area
Borrow material	$0.509	$0.749
General excavation	.464	.967
Pit stripping	.164	.370

Many of the highways in Alaska were originally pioneer or "tote" roads constructed chiefly by removing the vegetation and adding fill. Figure 23 shows the character of the ground surface in July immediately after the removal of the insulating vegetation. The permafrost was exposed in the hope that the sun would thaw it sufficiently by late summer so that fill could be placed upon the thawed sediments. By September the ice in and around the polygons had thawed to a depth of at least 4 feet; this thawing resulted in differential subsidence of the ground surface. In addition, the silt had lost all its bearing strength and was nothing more than a quagmire; consequently, the site was abandoned and the location of the road was moved.

The thermal disturbances created by a roadway have been studied in detail along the Richardson, Glenn, and Tok Highways near Glennallen, Alaska (Greene and others, 1960). Here the permafrost is relatively thin (50–150 ft thick) and mean annual temperatures below the undisturbed ground surface are rarely lower than −2° C. Thus conditions favor extensive thawing when the surface is disturbed. It was found that beneath the roadway the amplitude of seasonal temperature fluctuations was two to three times that found in the nearby undisturbed ground. Furthermore, the ground beneath the roadway was more sensitive to random climatic variations from year to year. A change of only 4° C in the mean annual air temperature over a 2-year period caused a 2.5° C change in the mean annual temperature at depths of 5 to 10 feet beneath the roadway and a change of less than 1° C at similar depths in undisturbed ground nearby. The increased amplitude of seasonal temperature variations together with the greater sensitivity to an increase in the mean surface temperature caused a trough of thawed ground to form beneath the roadway. Water from thawed permafrost drained along the trough until it was trapped in a basin or escaped by exterior drainage. Settling of the roadway followed. Heaving resulted where the melt water was trapped and later refrozen. In subsequent years freezing and thawing of the active layer was accelerated where the melt water had drained away because of the absence of latent heat. Therefore, thawing in colder years reached depths previously attained only in warm years.

During the summer of 1954, the Alaska Road Commission (now Alaska Department of Highways) exposed permafrost in lake silts 2 miles north of Paxson. The ice-rich lake sediments started to thaw and actually flowed (fig. 24).

In many places the thickness of the fill used by the road crews is insufficient to prevent the thawing of the permafrost under the roadbed. An excellent example of one such place is shown in figure 25. The photograph shows the remains of a road from the Umiat Airstrip to several drilling sites in the area; it was constructed about 1950 and abandoned around 1953. The road is underlain by fine-grained sediments containing ice-wedge polygons. The breaks across the roadway are due to the melting of the ice wedges. Such conditions will occur again if the potential effects of thawing permafrost are not considered during highway planning and construction.

FIGURE 22.—Landslide area at mile 353.5, The Alaska Railroad. Note the tops of piles immediately downslope from the rails to prevent displacement of the tracks.

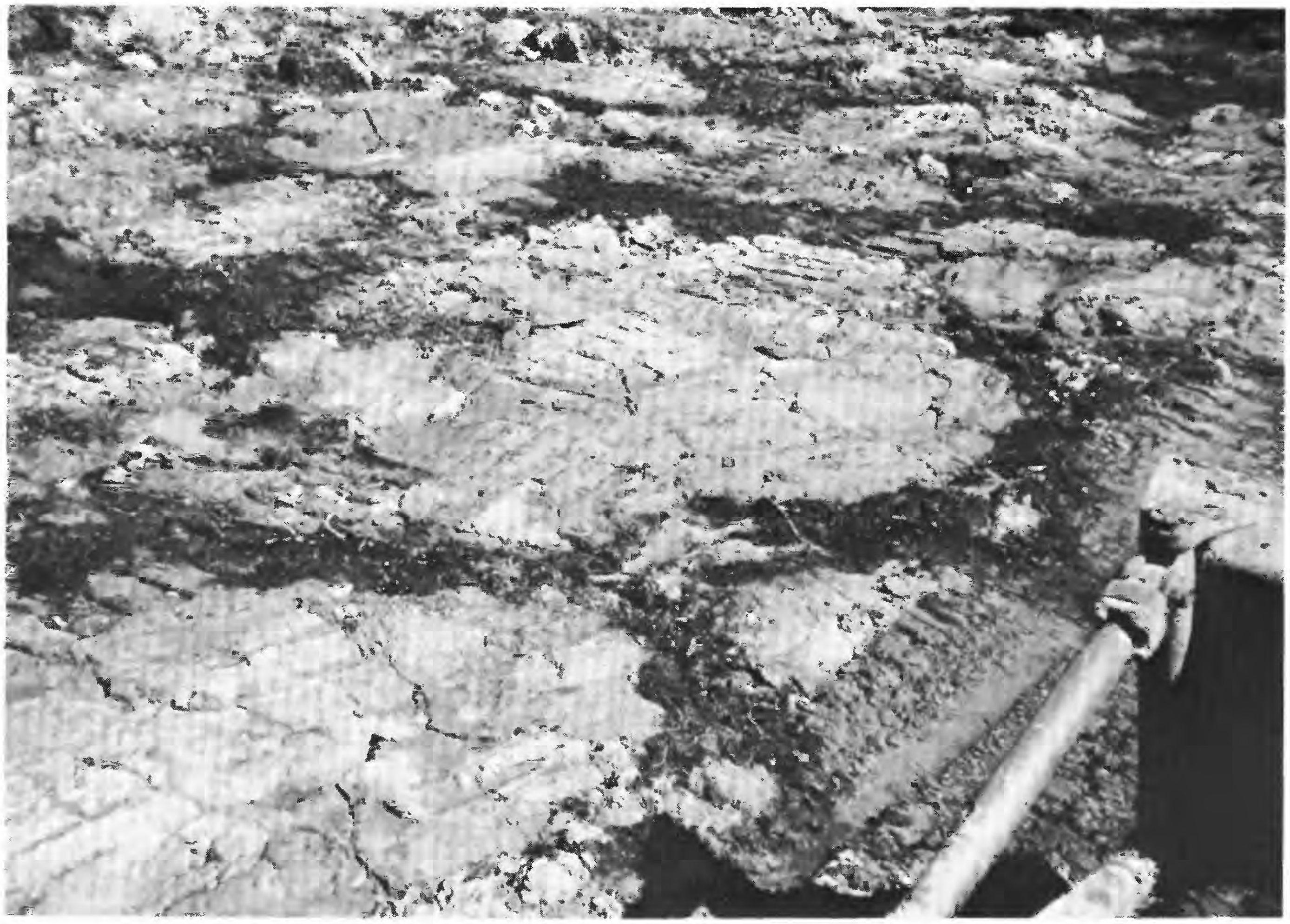


FIGURE 23.—Initial location of part of the Denali Highway near the Susitna River, interior Alaska. Construction crew is removing the insulating vegetation to expose polygonal ground in permafrost. Sediments are windblown sand and silt overlying silty glacial till. The dark areas outlining the polygons overlie ice wedges as much as 12 inches wide. Photograph taken in July 1953.

The location of a highway on a slope underlain by unconsolidated materials always presents problems. One must bear in mind that the highway is in a delistate of equilibrium, and that any change, not necessarily to the highway itself, may generate a slump or landslide in the structure.

Nichols and Yehle (1961, p. 25) describe such a slump and slide in the Richardson Highway roadbed at Simpson Hill near mile 113. This particular section of the highway crosses a small gully in a long sidehill cut. A thick fill was used to cross the gully. In the spring of 1954, a new telephone line upslope from, and parallel to, the road was constructed. During the construction, a wide swath of the insulating vegetation cover was stripped off. Rapid thawing of the permafrost during the summer resulted, releasing moisture to saturate the fill downslope. This increased moisture caused some small slumps in the fill. Early in September 1954, in order to bring the road back to grade, fill material was obtained from upslope and downslope of the roadway. Overnight, a 15-foot-wide section of the road slid downslope 10 feet (fig. 26). The slide was repaired with large amounts of silt excavated along the cut. Almost a year later, the same part of the road again slid 10 feet after attempts had been made to level minor slumps by the addition of a small amount of fill. Black layers above the culvert in the scarp of the landslide (fig. 26) are asphalt, representing layers of paving laid during the settlement or subsidence of the fill.

In nonpermafrost areas any fill or pad, whether it be for a railroad, highway, airstrip, or any other structure, requires adequate drainage along its margins. Improper drainage may saturate the fill and cause slumping or water may flow along the margins of the fill and cause erosion. In permafrost areas improper drainage causes additional problems. If the fill is allowed to saturate, it is much more susceptible to frost heaving and solifluction. In addition, water flowing alongside the fill may melt the permafrost and cause thawing and subsequent collapse. The results of inadequate drainage along the Sheep Creek road northwest of Fairbanks are shown in figure 27. Rainwater runoff, which should have been channeled away from the highway, was allowed to flow along the side. The water thawed the permafrost and the edge of the roadway collapsed as much as 8 feet. Thawing by flowing water does not occur only at the edge of the road but may also develop on the roadway itself.

Roads in permafrost areas that are built on the vegetation, without fill, quickly become useless. In addition they may do irreparable damage to the environment. For example, at a camp in northwestern Alaska (fig. 28) trails over the tundra were made by a tracked vehicle called a "weasel." The trail from the camp to the upper right of figure 28 climbs to the top of a ridge. The constant use of weasels on this trail compacted and destroyed the protective vegetation, causing the underlying permafrost (about 1 ft below the surface) to thaw. This thawing was accelerated by runoff from rainfall, and by 1962 the gullies in the road were as much as 15 feet deep. In the area adjacent to the campsite the vegetation cover was completely destroyed, the underlying permafrost thawed, and quagmire areas formed.

The removal of the vegetation cover during winter highway construction will eventually create problems.

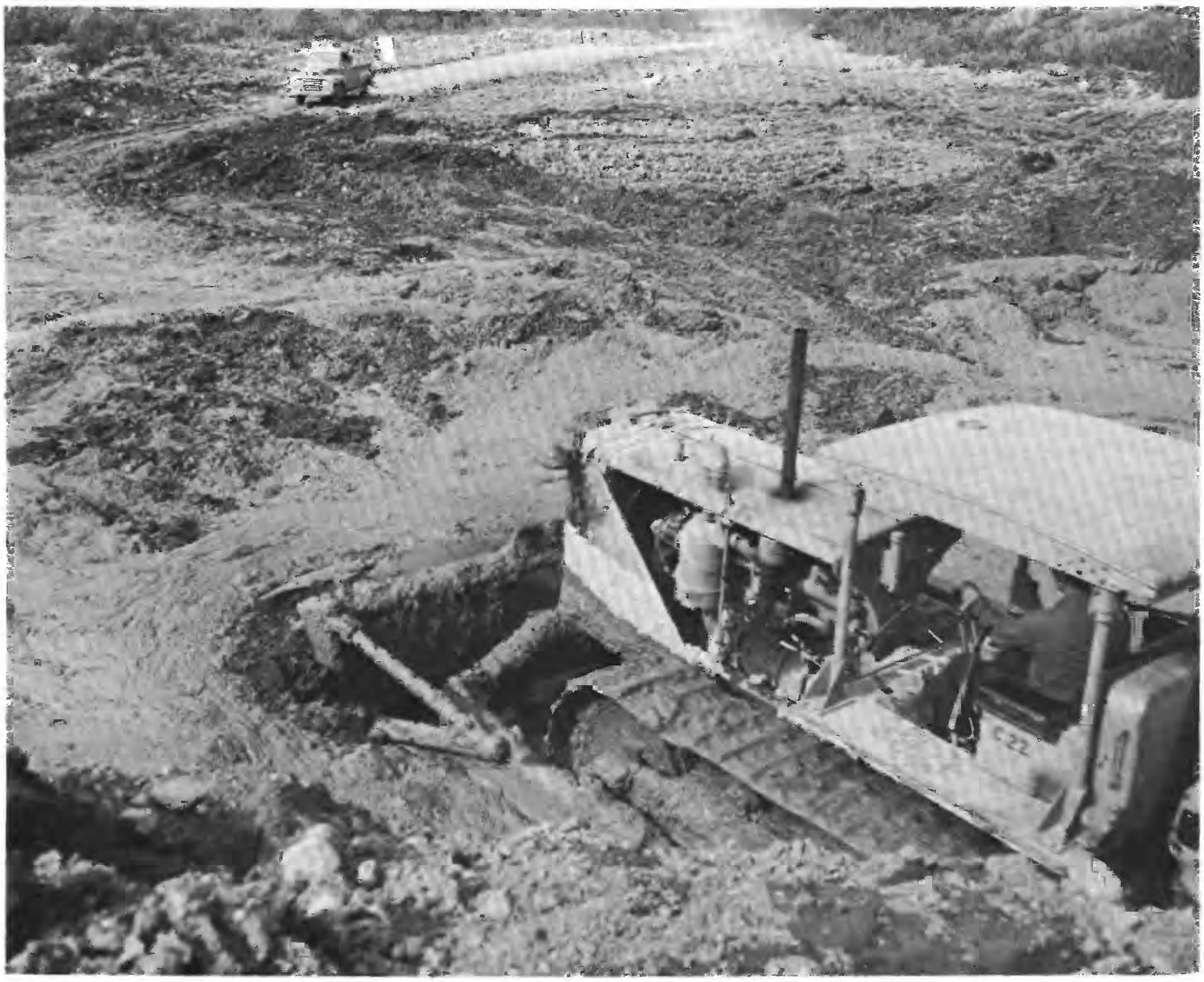


FIGURE 24.—Thawed lake sediments flowing around blade of bulldozer. Ice-rich permafrost in the lake silts was exposed in a cut during the construction of the Richardson Highway 2 miles north of Paxson. Photograph by T. L. Péwé, June 1954.

FIGURE 25.—Gravel road near the Umiat showing severe differential subsidence caused by thawing of ice-wedge polygons in permafrost. Photograph taken in August 1958.

The winter road from Livengood on the Yukon River to Sagwon on the Arctic North Slope was constructed in the winter of 1968-69. By the end of the summer, it is almost certain that thawing will have advanced to the extent that the once high-speed road will be impassable in places. It will either require fill to bring the road up to grade or rerouting for use during the coming winter.

Figure 29 is a photograph of a tractor trail constructed on the north slope near Canning River during the winter of 1967-68. The trail was built by bulldozing off the vegetation cover. The small ponds in the abandoned trail formed during the summer of 1968. These ponds will continue to grow deeper and wider as the permafrost thaws.

Frost heaving of highway bridges is as severe as that of bridges on The Alaska Railroad. The same mechanism applies to both, whether the piles are of wood or of steel. Two examples of frost action on bridges—one with wood piles whose ends were heaved

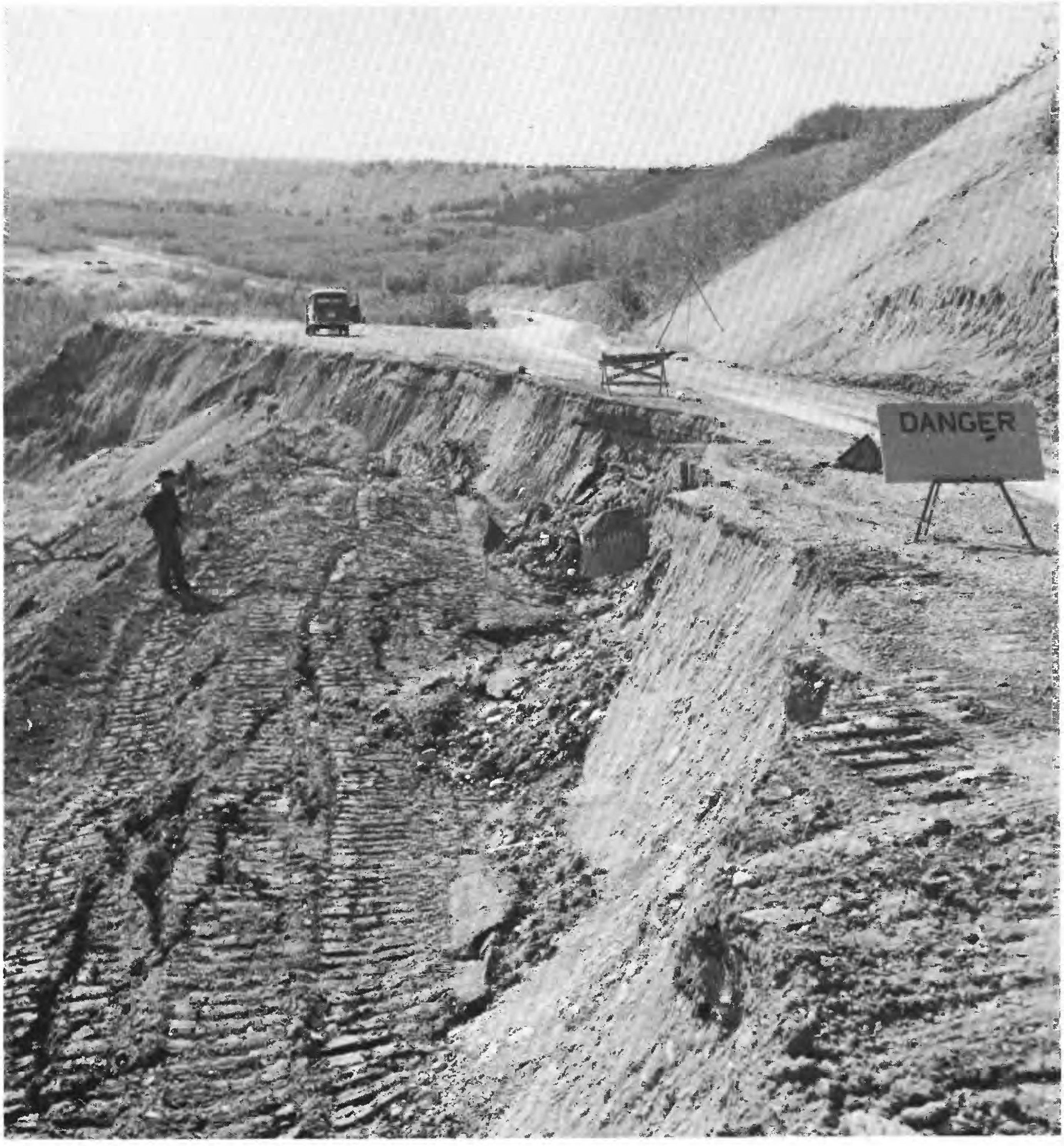


FIGURE 26.—Slump block of fine-grained highway fill material at Simpson Hill, near mile 113 on the Richardson Highway. Centerline of road formerly lay over exposed part of sheared culvert. Note bulldozer tracks on slump block surface, which are a continuation of those at road level on right side of photograph. Photograph by D. R. Nichols, September 1955.

and the other with steel piles whose center was heaved—are shown in figures 30 and 31. The pattern of heaving damage depends largely upon the amount and distribution of water in the foundation material. Péwé and Paige (1963) present an explanation for the heaving of the ends of the bridge shown in figure 31.

Figure 32 is a photograph of a steel-pile bridge on the Kougarok Highway in the Seward Peninsula. This highway extended from Nome to the mining camp of Taylor, but is now maintained only to about mile 84. The steel piles driven into fine-grained saturated sediment heaved because of frost action. Yearly frost heaving of the piles has completely destroyed the structure. Center heaving of this bridge, in contrast to the end heaving of the bridges shown in figures 30 and 31, was caused by the complete freezing of the flowing water and the underlying sediments during the winter. The underlying sediments at the point of maximum heaving of the piles contain a much higher moisture content than those elsewhere underneath the structure. The bridge at the outlet of Clearwater Lake (fig. 30) did not heave near the center of the structure because the flowing water and underlying sediments did not freeze.

Airfields

The gravel pad on an airstrip has the same effect on permafrost as the gravels fills on railroad and highway beds. Frost action or heaving also occurs on

FIGURE 27.—Old Sheep Creek Road northwest of Fairbanks. Gully along edge of road was caused when the surface drainage thawed the permafrost in the underlying loess deposits. Photograph by T. L. Péwé, summer 1955.

FIGURE 28.—Oblique aerial photograph of Chariot Site, northwestern Alaska. Dark area to the left of camp was caused by the heavy equipment that moved over the terrain while the barges were being unloaded. Trails were caused by tracked vehicles. Photograph by R. H. Campbell, summer 1960.

airstrips, but generally does not present a major engineering problem. However, this does not necessarily mean that frost heaving should be ignored; it should be taken into consideration in determining the location of the airstrip and the design of the drainage system around the airfield.

For years the paved runways at Northway, Alaska, have been affected by thawing permafrost. The runways are underlain by fine silts and sand with local areas of ice-rich permafrost. At Gulkana, Alaska, where the airstrip also is paved, the runways are underlain by ice-rich clayey lacustrine silts. Because of differential subsidence the east-west runway at Gulkana has been condemned. At Umiat, the airstrip was constructed by placing a small gravel pad upon fine-grained sediments containing ice-rich permafrost. The runway was not paved. By 1952 the runway had subsided differentially to the extent that it had to be resurfaced with additional gravel (J. C. Reed, personal commun., 1969).

Buildings

A building has a different effect on the thermal regime of the underlying permafrost than does a road, a runway, or an open storage area. There have been many studies made of the influence of a building on the thermal regime of permafrost, including one by Lachenbruch (1957a). Lachenbruch's paper presents a basic formula for determining the thermal disturbance caused by a heated building as well as other important thermal problems caused by permafrost. For example, the geothermal disturbance caused by bodies of water and by highway and railroad fills can be analyzed by his theory. Brewer (1958) collected data beneath a heated building 40 feet by 100 feet at Barrow, Alaska, which showed that the temperature rose about 5½° C at a depth of 20 feet. Based on Lachenbruch's formula, the temperature would rise about 6° C.

Some of the heated buildings at Barrow settled differentially as much as 20 inches in 3 to 4 years

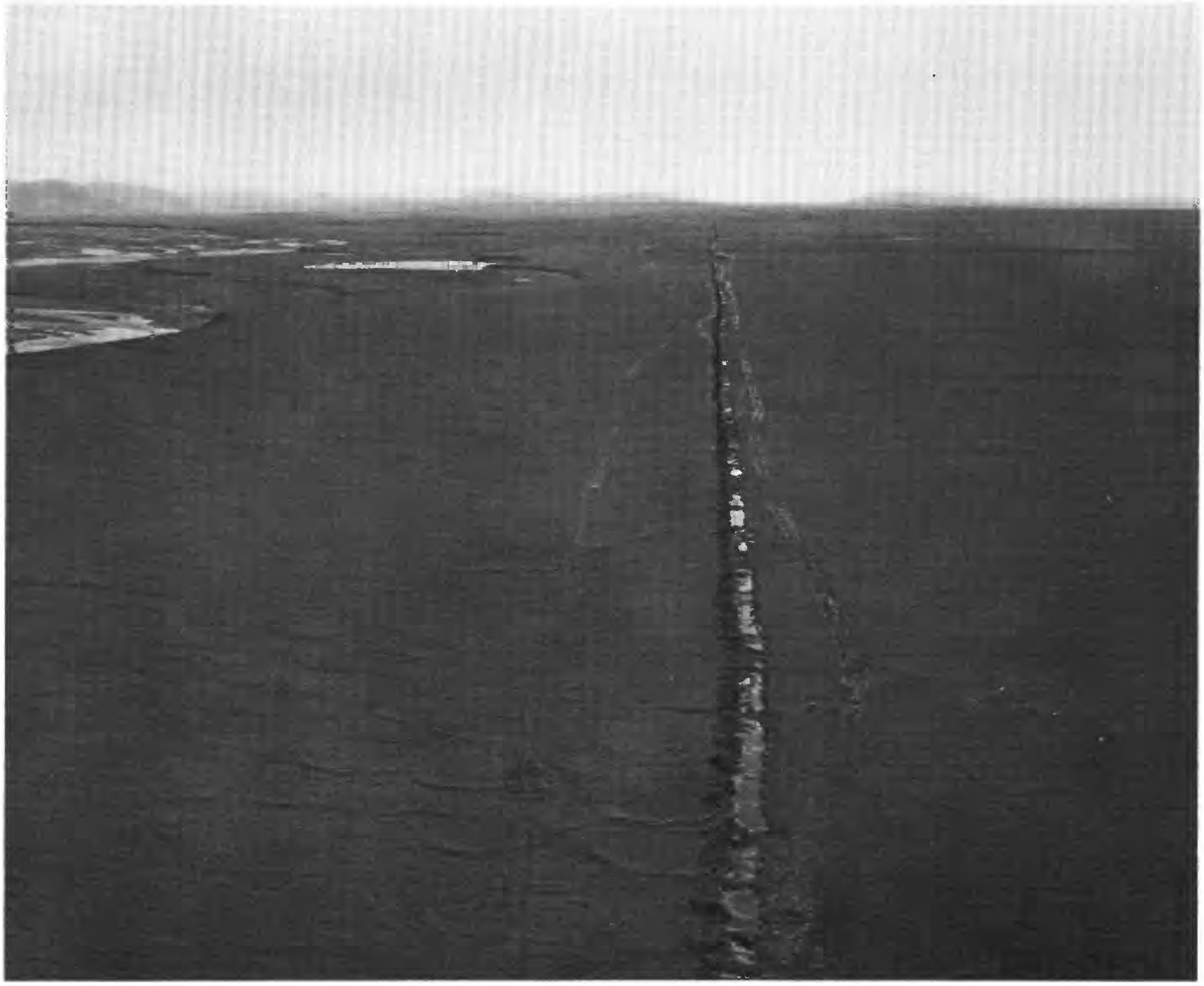


FIGURE 29.—Oblique photograph of tractor trail near Canning River, North Slope. Note small ponds due to thawing permafrost in roadway. Photograph by Averill Thayer, Bureau of Sport Fisheries and Wildlife, August 1968.

(Brewer, 1958). When the buildings were no longer heated the thawed ground beneath the structures refroze, and in some instances as much as 1 foot of frost heaving occurred within a year.

Figure 33 is a view of a roadhouse on the Richardson Highway. The building, constructed in 1951, subsided the most near the front of the center section where the furnace was located. The porch did not subside as much as the center of the building because it was unheated. The building had to be razed in 1965.

The problem of averting settlement of heated buildings in permafrost areas has received a great deal of attention. The most promising method of solving the problem is to build the structure above ground with large air holes in the foundation. This allows the cold winter air to circulate beneath the floor of the building, counteracting the effects of the heat. Figure 34 is a photograph of a schoolhouse on a concrete foundation at Glennallen, Alaska. The air vents through the foundation are opened during the winter and closed during the summer. The jacks are used to keep the structure level because of differential subsidence in the ice-rich sediments that underlie the building.

Frost heaving of buildings is a common occurrence in arctic and subarctic environments. If piles are

FIGURE 30.—Frost-heaved piling of bridge spanning outlet of Clearwater Lake, 8 miles southeast of Big Delta. Piles are of wood. Photograph by M. F. Meiser, August 1951.

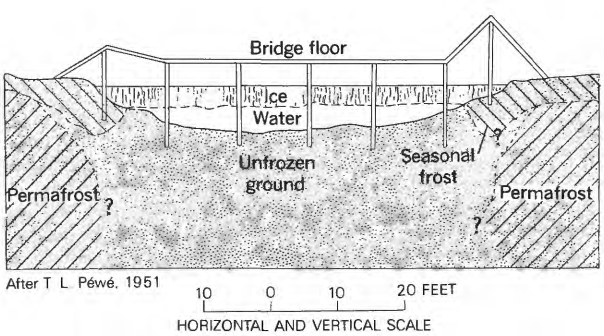


FIGURE 31.—Geologic sketch of foundation conditions of frost-heaved bridge, 8 miles southeast of Big Delta. Compare with figure 30. After Péwé and Paige (1963, p. 349).

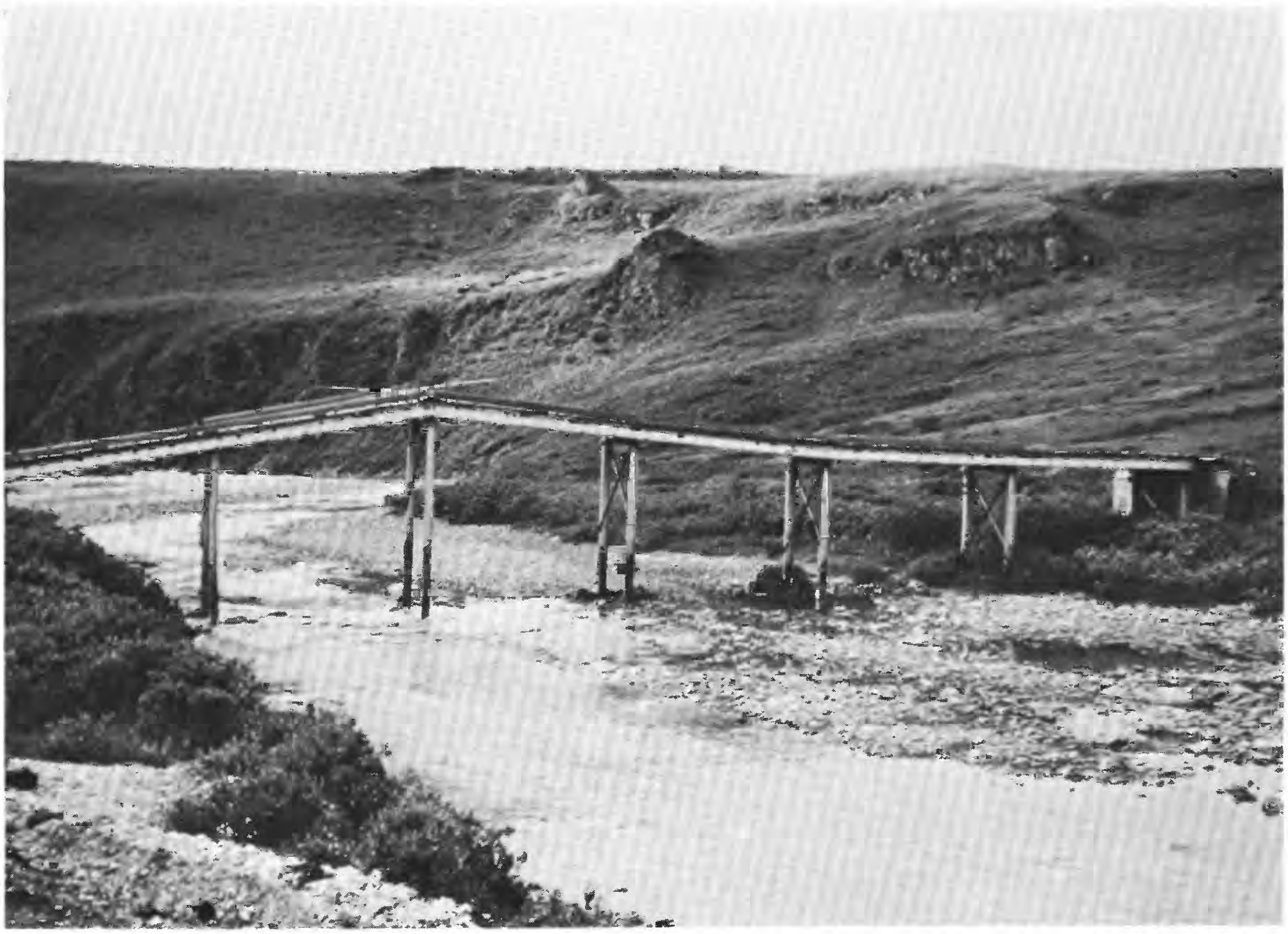


FIGURE 32.—Frost-heaved steel-pile bridge spanning North Fork at about mile 120 on the Kougarok Highway, Seward Peninsula. Photograph by G. D. Eberlein, summer 1955.

improperly emplaced, frost heaving is as damaging to buildings as it is to highway and railroad bridges. Buildings resting upon concrete foundations may be heaved beyond the yielding point of the concrete. Figure 35 shows the results of frost action upon the foundation for an apartment house in Fairbanks. The foundation was laid during the late summer of 1953 and left exposed during the winter of 1953-54. The underlying flood-plain silts were saturated and during the winter sufficient ice formed to heave and rupture the structure.

Power and heating plants produce large amounts of heat which, if improperly insulated, may thaw the underlying permafrost. Therefore, these structures require special attention in location, design, and construction.

Aircraft hangers usually cover a large ground area and require heating. Because the underlying sediments vary, permafrost will thaw differentially, causing an uneven settlement of the floor.

Dams

Dams constructed on bedrock present no major permafrost or frost-heaving problems. However, if the structure is placed on sediments containing ice-rich permafrost, the impounded water will initiate thawing of the underlying permafrost. The dam will then settle differentially and will crack. Also, water may seep or be piped beneath the dam, eventually eroding the support for the structure; thus, a careful study of the nature of the reservoir section of the damsite should be made to determine whether the dam is founded in bedrock or sediments. Any frozen sediments under the impounded body of water will thaw, and will result in slumping and landsliding.

Telephone and Power Transmission Lines

Telephone lines and powerlines carried on wood poles present major problems, because of frost heaving. Telephone and power poles are much more severely heaved than the bridge piles because the poles have a much less load and usually are not deeply emplaced in permafrost. Service and construction roads along the telephone lines and powerlines cause additional problems by melting the underlying permafrost. Eventually the roads become impassable and rerouting is necessary.

Large steel transmission lines requiring more than one foundation may heave differentially during the winter and settle differentially during the summer. These massive, usually high, structures are sensitive to differential displacement and may require continued maintenance in permafrost regions.

Pipelines

The construction of pipelines in an arctic environment is, at best, a major undertaking. If the pipeline is placed underground, the vegetation cover overlying the permafrost is destroyed, disrupting the thermal regime. This disruption can cause differential settlement of the pipeline, and, since it is underground, the settlement may not be noticed until the pipeline has been ruptured. If the line carries a warm fluid, it will thaw the permafrost and cause differential subsidence which could cause the structure to lose support.

Pipelines on the surface or on a supporting structure are subjected to frost heaving during the winter and subsidence during the summer. This action will be especially strong if the line passes over fine-grained sediment or over a bog or swamp. Other areas to be avoided are solifluction lobes where slow gravitational flowage of masses of surficial material occurs. These masses move downslope during the summer months after the active layer is thawed. If a pipeline were placed in or on these solifluction lobes, it probably would be damaged by the downslope movement. Therefore, such areas should be recognized and avoided. Another place to be avoided is the bottom of a stream channel, where winter ice on the stream might damage the pipeline.

In areas where the permafrost contains ice wedges, severe damage to an above-ground pipeline will occur if the ice wedges are allowed to thaw. The effects of

FIGURE 33.—Roadhouse, mile 278.5, Richardson Highway. The structure is distorted because of thawing of the underlying ice-rich permafrost in fine-grained silts and sands. Photograph by T. L. Péwé, May 29, 1962.

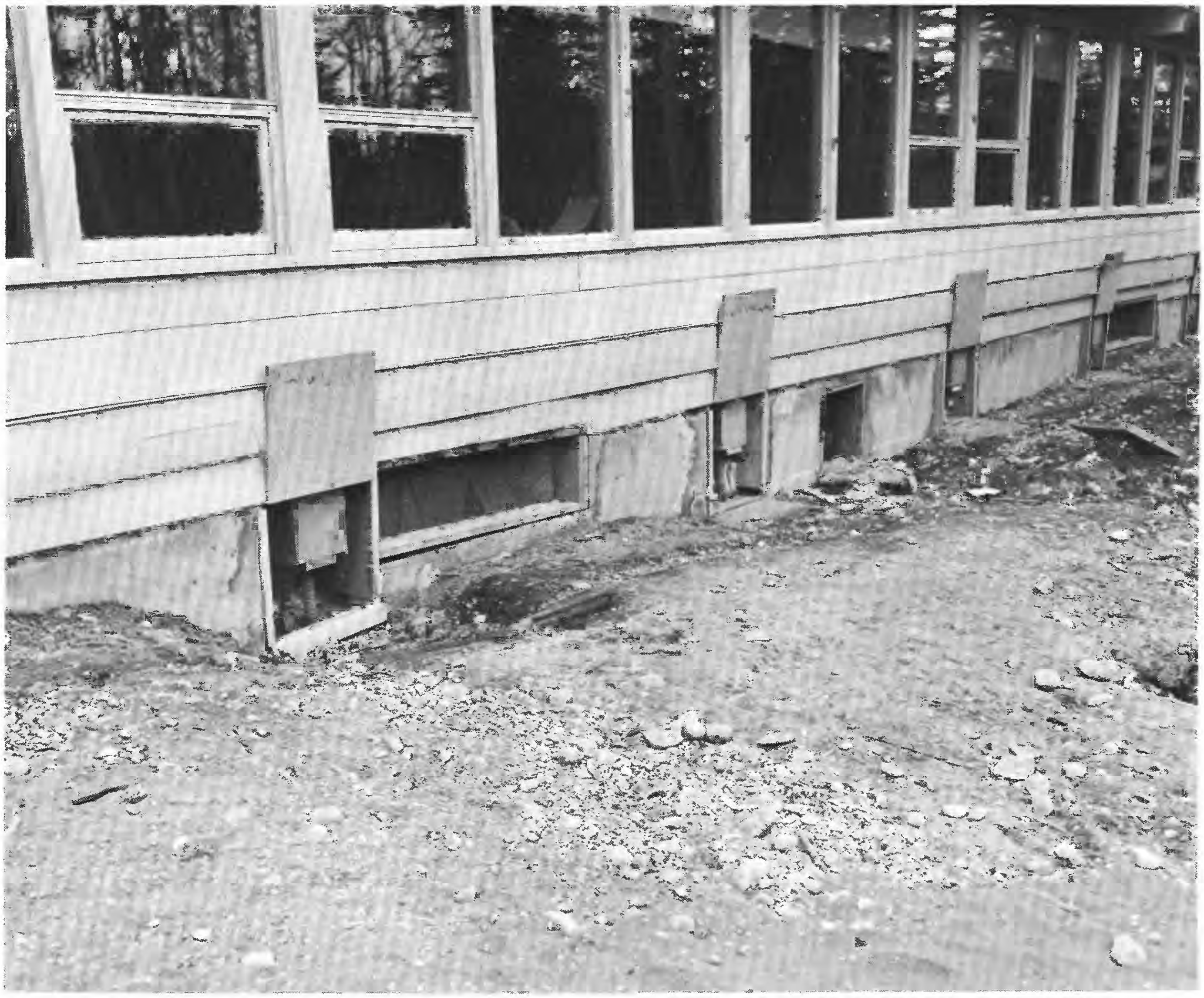


FIGURE 34.—View of the schoolhouse at Glennallen. Air vents, which are open, allow cold air to enter crawlway in winter to counteract heat from building. The vents are closed during the summer. Jacks are used to counteract any differential settlement. Photograph by T. L. Péwé, May 1954.

thawing ice wedges has already been described in the the discussion of highways.

Construction and service roads for pipelines present the same problems as those built along powerlines and telephone lines.

Utilidors

Utilidors are used extensively in arctic and subarctic regions to carry utilities such as water, steam, gas, sewerlines, powerlines, and telephone lines. Figure 36 is a picture of a utilidor under construction near Fairbanks. An ideal location for an underground utilidor is an area underlain by well-drained ice-free materials that extend to depths of at least 15 feet. However, ideal locations are not always available, and, therefore, many utilidors are damaged by subsidence and frost heaving.

Above-ground utilidors are constructed in areas where the active layer normally freezes down to the permafrost table. These above-ground structures will be subjected to the same engineering problems as above-ground pipelines.

ICINGS

In arctic and subarctic regions, water which reaches the surface in the winter from a river or spring may freeze in successive sheets, until the ice covers a large area. These sheetlike masses are termed "icings." Icings are usually small—seldom larger than a few acres. However, some as large as 48,000 to 54,000

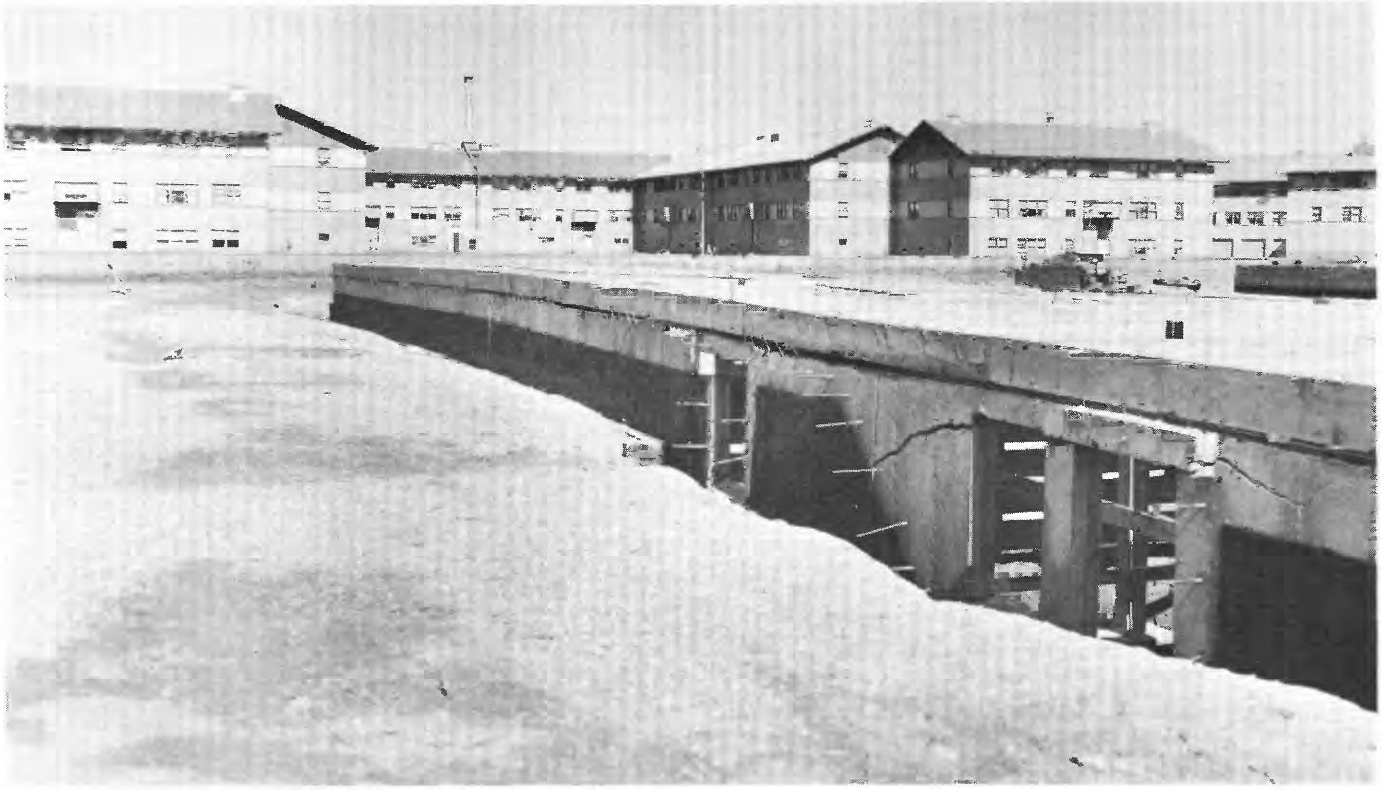


FIGURE 35.—Fracture due to frost heaving of 4-inch concrete foundation of an apartment house in Fairbanks. Photograph by T. L. Péwé, June 1954.

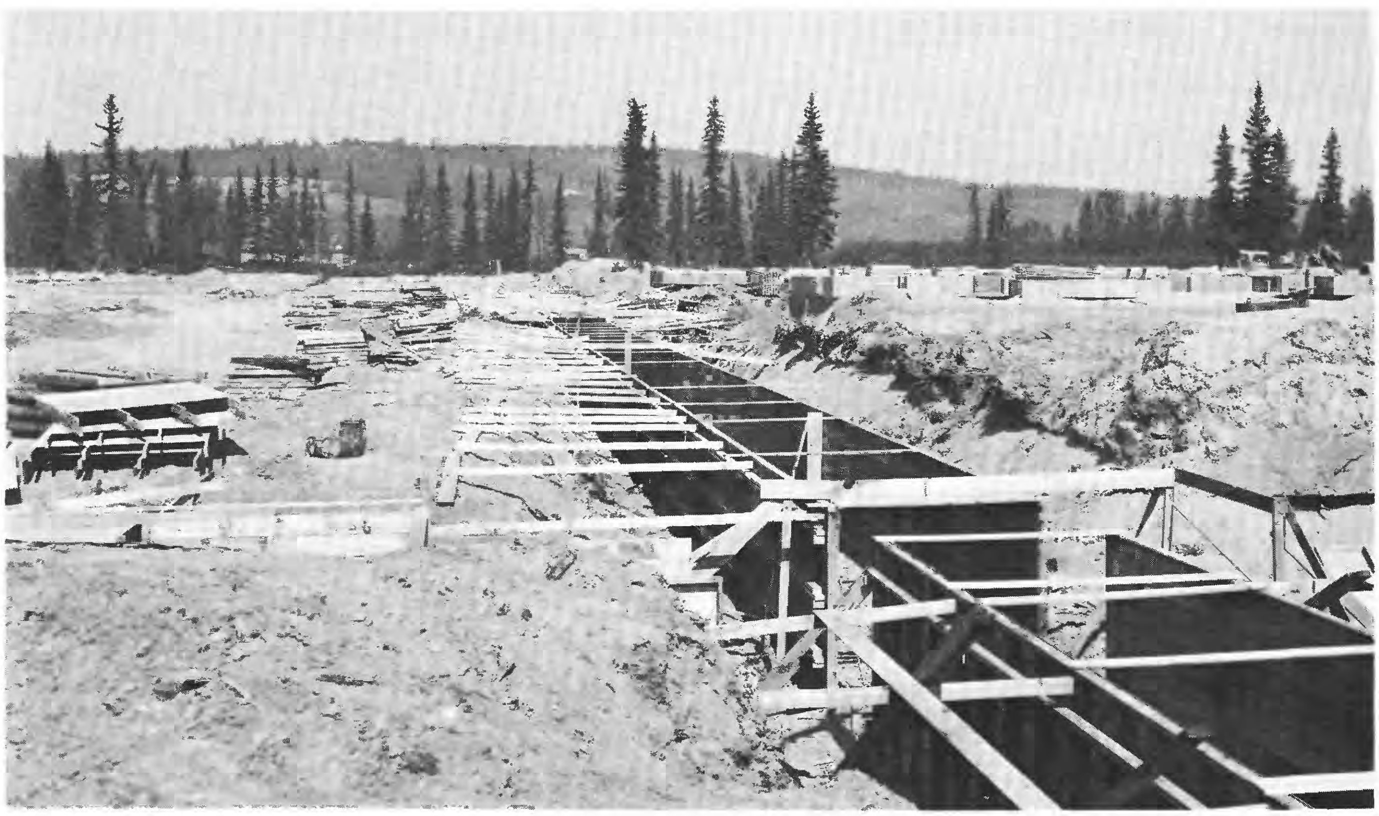


FIGURE 36.—Utilidor under construction at Fort Wainwright near Fairbanks, Alaska. Photograph by T. L. Péwé, July 1947.

acres are found on the Mony River valley in Siberia. Icings as much as 30 feet deep, ½ mile wide, and 1 mile long were noted in the John River valley south of Anaktuvuk Pass by T. C. Fugelstad of The Alaska Railroad during early 1969.

A study of icings on the Glenn, Richardson, and Alaska Highways of the Alaska Highway system indicated that they were quite extensive and usually occurred at road cuts (Williams, 1953). The maximum icings were about 5 feet thick and originated at seeps or springs. The Alaska Railroad is also plagued with winter icings. These are more damaging and require more maintenance than those on highways; the ice on the railroads has to be removed to expose the rails, whereas on highways icings need only to be leveled. Winter icing increases the maintenance costs, for it necessitates extra labor, special equipment, and special techniques to combat the growing ice mass. Countermeasures to reduce icing, such as the construction of larger culverts to divert the source of the icings, also increase construction costs.

Icings cause extensive damage to bridges through diversion of streamflow and burial of the structure. For example, river icings engulfed the bridge spanning the Chistochina River 26 miles west of Slana, Alaska. On February 15, 1950, the ice was 6 feet below the bridge deck but had overflowed the west approach; it was necessary to reroute the traffic across the river ice (Williams, 1953).

Structures built on slopes may be filled with ice during the winter if icing conditions are suitable. Poorly insulated, heated buildings keep the underlying ground from freezing. If water with a hydraulic head is trapped between the frozen ground and the permafrost table, it may flow upward into the house. In some places, houses have been filled very rapidly by water that froze and filled the house with ice.

CONCLUSIONS

Construction and maintenance of structures underlain by permafrost pose a wide range of problems. Engineers, designers, and construction and maintenance personnel are continuously plagued by severe frost heaving of structures, subsidence due to melting ground ice, soil creep or solifluction, landslides, and icings related to the presence of permafrost.

Some guidelines that can be followed to minimize the adverse effects of permafrost and frost action upon structures are summarized below.

1. Wherever possible, locate structures on coarse-grained materials. Avoid fine-grained, poorly drained, ice-rich sediments, since they are subject to much greater frost-heaving and, if the permafrost is thawed, to greater differential settlement.

2. Insofar as possible, make any gravel pad—whether it be for a roadway, railroad grade, building site, airstrip, or drilling site—sufficiently thick to prevent permafrost from thawing.

3. Provide ample and proper drainage around any structure to prevent the thawing of permafrost and to minimize frost action and icings.

4. For heated buildings, whenever possible provide space for circulating air between the surface of the ground and the floor to minimize the transfer of heat into the ground.

5. Avoid the disruption or destruction of the vegetation overlying permafrost by using such techniques as end-dumping. Restrict tracked vehicles, trucks, and other heavy equipment to roads and do not permit them on the tundra or vegetation where they will destroy its insulating quality and cause the permafrost to thaw.

6. Minimize frost heaving of supporting piles by providing the best possible drainage or by anchoring them securely in permafrost if feasible.

7. Avoid borrow sits upslope or downslope from structures. Thawing of the sites may cause drainage problems or damaging slumps and land slides.

8. Where parallel linear structures—such as pipelines, roads, or telephone lines—follow the contours of the slope, minimize disruption of the vegetation so that slumping along one structure will not damage the other.

9. Consider the following problems when pipelines are laid across creeks or rivers: a) If the pipeline crosses the creek or river underground, it may be damaged by the slumping of huge blocks of permafrost undercut at the banks, or it may be exposed by erosion and damaged by boulders, ice, or other debris during flood stage. b) Pipelines placed on the surface of a flood plain may be subject to inundation and possible damage by ice and floating debris.

10. Avoid construction in areas with natural icings whenever possible, or if such areas must be utilized, provide diversionary drainage.

The guidelines given above cannot be successfully applied without a thorough understanding of the thermal and mechanical problems unique to permafrost regions. Engineering procedures based on such an understanding should permit optimum utilization of the resources in the far north at a minimum overall cost and with a minimum disruption of the natural environment.

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