INTERACTION OF VEGETATION AND SOIL FROST PHENOMENA†*

William S. Benninghoff
U.S. Geological Survey

In northern lands special problems presented by frost in soils are receiving more and more attention as the pace of construction and settlement increases. Investigations aimed primarily at these problems, notably that of permafrost, have partially revealed the composition and mechanisms of the severe frost climate[1] environment. Parts of this environment owe their nature to the influence of vegetation and soil frost[2] on each other.

In temperate climates the effects of soil frost on plants are so seldom observable that they have been studied in special cases only. In the severe frost climates of high latitudes, and in similar climates at high altitudes, perennially frozen ground and intensive frost action are primary environmental factors in the development and existence of individual plants and of plant communities. Similarly, the fact that penetration of seasonal frost is influenced by vegetation cover is common knowledge in temperate regions but has not required special study. In the severe frost climates, however, plants both individually and collectively strongly modify the occurrence and work of soil frost.

This interaction is the basic mechanism of a dynamic soil–vegetation system in severe frost climates. Undoubtedly these forces are now at work to some degree in the mid-latitudes, but the effects are too slight or too local to have received special attention. Much evidence is being produced to show that intensive frost action exerted strong effects in the mid-latitudes during the Pleistocene glaciations, leaving behind soil features that still have expression in many landscapes (Denny, 1938; Smith, 1949; Raup, 1951). In northern regions, such as Alaska, knowledge of soil frost phenomena and their interaction with vegetation is vital to an understanding of soils, vegetation, and landforms.

Influence of soil frost on plants

The frozen condition of a soil must exert direct effects upon the plant roots contained in it, but the exact effects are little known as most studies

†Publication authorized by the Director, U.S. Geological Survey.
*Presented at Permafrost Symposium, first Alaskan Science Conference, 11 November 1950, Washington, D.C.

[1]"Frost climate" as used here is a climate which includes low temperature periods capable of inducing sub-freezing temperatures in upper soil layers (cf. Troll, 1943 and 1944). A severe frost climate is distinguished by either or both of the following conditions: long periods in which temperatures diurnally cross the freezing point, causing intensive frost disturbance in wet soils, or a mean annual temperature below freezing, inducing development of perennially frozen ground.

[2]The term soil frost is used here because these relationships apply only to frost in the upper layers of the ground; and both seasonal frost and permafrost, in some situations difficult to differentiate, are concerned.

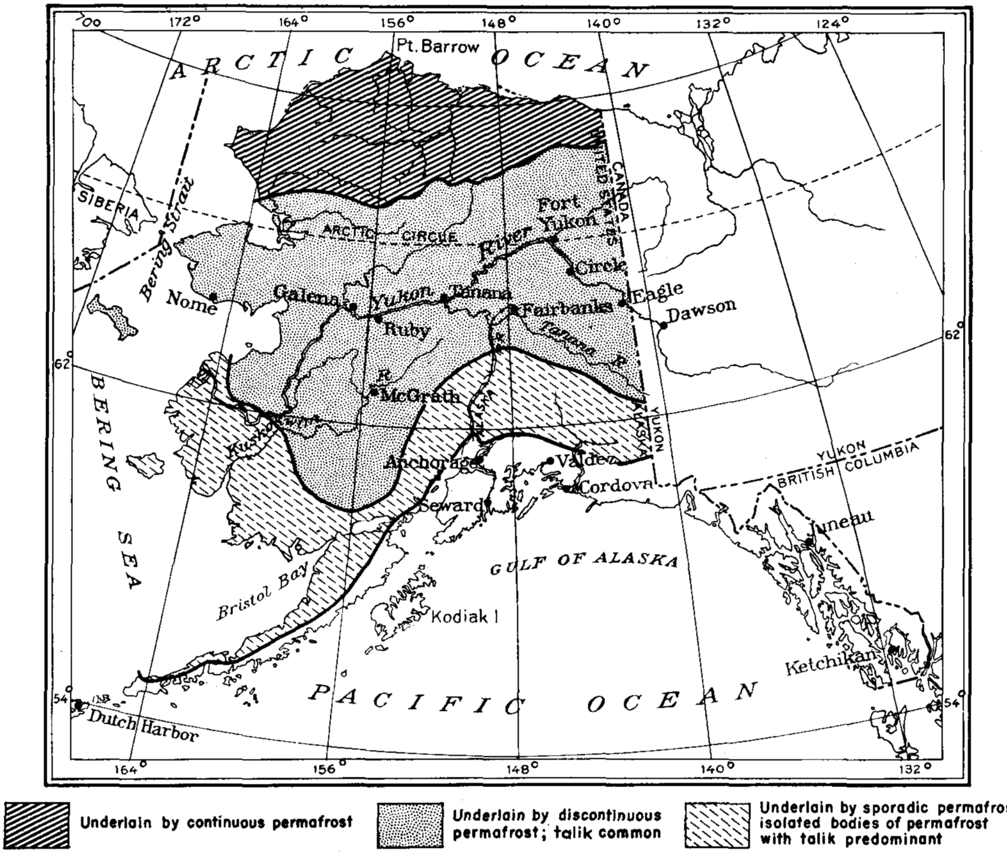

Fig. 1. Generalized map of permafrost distribution in Alaska.

have been confined to frost injury to aerial parts (see titles in Harvey, 1935). In the high latitudes roots are not only encased in frozen material for a great part of the year, but by repeated freezing and thawing, especially during the autumn freeze-up, they are heaved, torn, and split by forces of great strength. In soils unprotected by snow, sudden sharp drops in temperature frequently cause cracks as much as 2 feet wide and 8 feet deep (Zhukov, 1944) with severe damage to intersected roots. In Alaska frost-aided soil movement on slopes and differential frost heaving are intense and occur widely, often radically deforming root systems. By tipping the whole plant, these movements frequently cause deformation of stems of erect perennials as growth of the axial shoot apex is always vertical (Benninghoff, 1950).

Permafrost, or perennially frozen ground, occurs in more than half of Alaska (Fig. 1). In the north, where permafrost is continuous and at shallow depth, the overlying active, or seasonally frozen, layer is generally limited to 8 to 20 inches. Farther south permafrost is discontinuous, as it is interrupted by channels and bodies of thawed ground. Here the depth to permafrost ranges in different places from one to several tens of feet, and the active layer, 4 to 10 feet thick, may or may not reach the top of the permafrost. Near the southern limits of permafrost its occurrence is sporadic, and localities where the active layer extends to the top of permafrost are widely scattered.

Permafrost cannot be occupied or penetrated by living roots, although roots of many native plants are commonly observed close to its upper surface. The shallow, spreading roots of white spruce in soils with permafrost near the surface commonly have ovoid cross sections due to greater annual growth on the upper side. Permafrost at shallow depth in effect creates a shallow soil with a hard impervious substratum. The limitations imposed on the anchoring functions of tree roots in such soils are obvious and are demonstrated by the relative ease with which the trees are overturned. Following a severe storm in 1935, Taber (1943) observed a higher percentage of windfall in the spruce at the tree-line east of Golofnin Sound than among the spruce a few miles away. He cited this as an indication that insufficient depth for the proper functioning of roots limits spruce forest. Pulling (1918), in a study of root habits and plant distribution in the Subarctic, concluded that the success of trees growing on soils with permafrost at shallow depth is related to the flexibility of their root habits. White spruce, with its shallow and flexible root system, was considered best suited. Black spruce, larch, and white birch have shallow but less flexible root systems; and although they have wide ranges on these soils, Pulling believed them to be somewhat less frost-tolerant.

Soil drainage is invariably altered by the presence of frost. Bodies of frozen ground inhibit lateral movement of soil water and prevent downward percolation. Release of water from the thawing of frozen ground may lead to extreme waterlogging of soils. On the other hand, thawing throughout the summer in the upland soils of dry interior Alaska is believed by some observers to provide water for the relatively luxuriant forests. It is probable that frost in the ground, by cooling the upper layers, adds moisture to the soil surface by condensation from the atmosphere.

Plants may be subjected to severe water loss, perhaps to the extent of permanent damage, by exposure to drying winds while the roots are encased in frozen soil and cannot absorb water. Birkengof (1934) concluded that extensive top damage in dahurian larch forests of northeastern Siberia was due to excessive flow of sap to the tops in early summer, when those parts were already thawed out but the lower trunk, roots, and soil were still frozen. Dessicating winds during the long winter have been regarded as limiting to tree growth on frozen ground and this has been cited as an aid to explanation of the fact that the tree-line extends farthest north in sheltered valleys (Taber, 1943).

Soil surfaces are in places rendered unavailable to plants or to certain kinds of plants because of soil stirring, sorting, and transport by frost action. Patterned ground, i.e. surfaces with polygons, pitted tundra, soil stripes, and similar features, gives striking demonstrations of these effects (Antevs, 1932; Polunin, 1934–5; Washburn, 1950; Hopkins and Sigafoos, 1951). Thawing of frozen ground containing unevenly distributed ice bodies results in differ-

Fig. 2. Thaw sink in cultivated field near Fairbanks. Subsidence resulted from thawing of buried ground ice mass.

ential settling of the surface (Fig. 2). This imposes on the surface various minor relief forms, such as hummocks or pits, and thus changes the physical environment for the vegetation occupying the site. Elsewhere sites for vegetation are destroyed by progressive thawing of permafrost. Margins of lakes in areas with high permafrost tables are especially subject to this destruction (Fig. 3). Wallace (1948) described caving lake margins in the Nabesna, Chisana, and Tanana river valleys of eastern Alaska. For these he calculated a mean rate of shore retreat of from 2.3 to 7.5 inches a year. Hopkins (1949), in a study of thaw lakes and thaw sinks in the central Seward Peninsula, pointed out the ephemeral nature of such lakes and evidence of cyclical filling and draining. The oriented lakes on the Arctic Coastal Plain in northwestern Alaska have been shown by Black and Barksdale (1949) to be constantly changing owing to caving of shores, draining, filling with peat, and initiation of new thaw cycles. All these frost processes in the soils demonstrate fundamental features of the severe frost climate environment: instability of the surface and consequent transcience of site conditions.

Influence of plants on soil frost

Plants affect soil frost phenomena most significantly through controls exercised on the thermal regime of the soils, and these controls and resultant effects are probably different for all natural sites. The Yukon River section

Fig. 3. Destruction of spruce forest on caving shore of lake near Fairbanks.

shown in Fig. 4 presents typical permafrost conditions on wooded floodplains in northern interior Alaska. Erosion and thawing by a meandering stream cause the permafrost table to retreat far below the stream bottom level, but it rises under deposits on the slip-off side (Péwé, 1947). The permafrost table rises several feet more in the new alluvium during maturation of the initial balsam poplar forest, and rises still more as that forest is replaced by a dense stand of white spruce.

Vegetation shields the soil from maximum penetration of heat by shading, by decreasing air circulation, by retaining moisture in and just above the soil, and by intercepting rain. Another cooling effect, resulting from evaporation of moisture on plant surfaces, may be significant. Russian workers have demonstrated that mosses play an important part in this effect (Sumgin, Kachurin, Tolstikhin, and Tumel, 1940). Mosses have low thermal conductivity, especially when dry, but also have a large water-holding capacity and are strongly hygroscopic. They absorb water not only from precipitation but also from atmospheric vapour, the latter being absorbed in direct proportion to the relative humidity of the air. Yet during a dry period they tend to lose moisture rapidly. This is important because the latent heat of vaporization of water at 0°C is 596 gram cal./gram, whereas the latent heat of fusion of ice is only 79.7 gram cal./gram. For example, at the Bomnak experimental station in eastern Siberia (Sumgin, *et al.*, 1940) one gram of *Sphagnum papillosum*, at a relative humidity of 100 per cent on the surface at night and 42 per cent during the day, evaporated 0.2685 grams of water during the day. In this process each dry-weight gram of *Sphagnum* withdrew 155.79 calories from the surrounding environment during the day. After a night with heavy dew, or after a rain, each dry-weight gram of this species of *Sphagnum* is capable of taking up 14.975 grams of water, the evaporation of which would withdraw from the ground-stratum environment 8643.33 calories. In addition to surface evaporation, the evaporation of moisture from transpiration also withdraws heat energy, but the quantities involved are unknown.

It has been common knowledge in Alaska that thawing of frozen ground is greatly hastened by removal of the "moss", a term loosely used for moss carpets, thick turf, and surface peat. Accumulations of vegetable matter are effective insulators in periods of thaw and good conductors when they are frozen in the water-saturated condition (Sumgin, 1937).

S. W. Muller (1943, p. 53) pointed out that dry peat has the heat conductivity coefficient of 0.06 kg. cal./m^2/hr/1°C gradient through one metre thickness. As peat commonly can absorb as much as three times its volume of water, saturated peat can be assumed to have heat conductivity close to that of water, which, in the temperature range 0 to 20°C, is about 0.5 kg. cal., but in the frozen state is about 2.0 kg. cal. Thus during periods of thaw a greater amount of heat is transferred through water-saturated peat into the underlying soil than through dry peat. Furthermore, when water-saturated peat is frozen, heat is transferred from the soil into the air in quantities four times

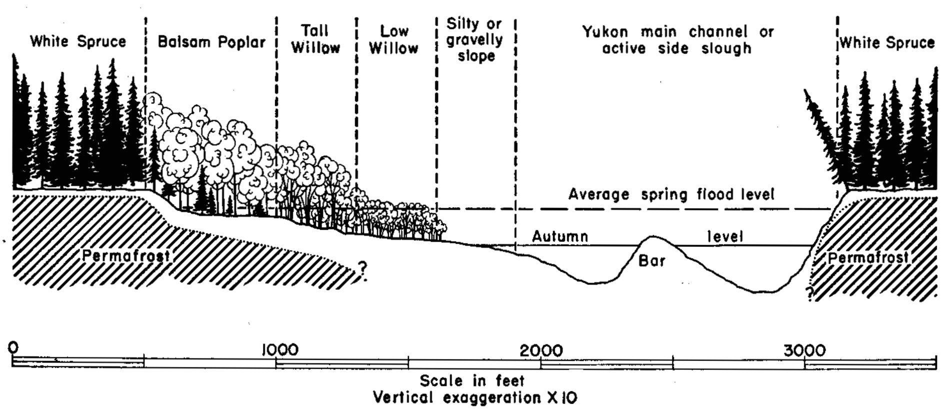

Fig. 4. Diagrammatic section through a main channel and banks of the Yukon River near Fort Yukon, illustrating relationships of permafrost to the river and the floodplain vegetation.

as great as in the thaw periods. Essentially similar properties are recognized in living and dead moss carpets and other accumulations of vegetable matter, although certain factors, such as water-absorbing capacity, vary with different component materials.

Romanov and Rozhanskaya (1946) in studies of seasonally frozen surface peat in a marsh near Leningrad found that the coefficient of heat transmission of frozen samples varied in relation to the amount of air-filled pore space, and that the coefficient of heat transmission of thawed samples changed according to the temperature and to the moisture content. They further determined

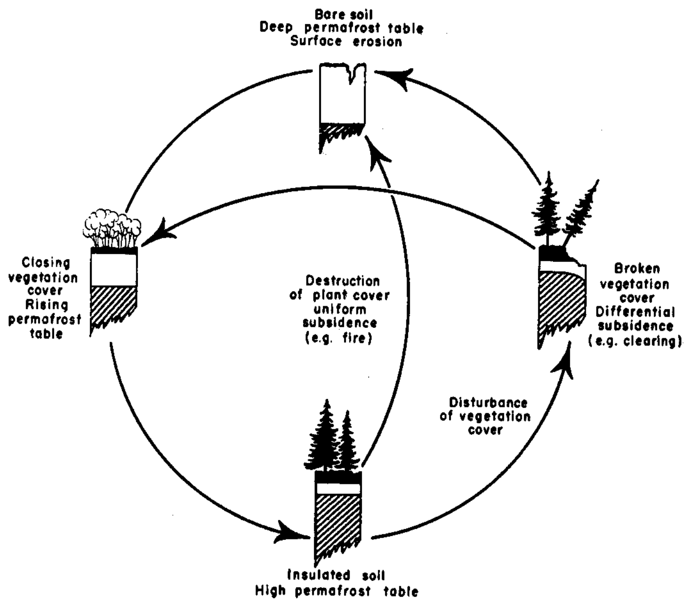

Fig. 5. Outlines of the vegetation–permafrost cycle.

that all physical properties of both frozen and thawed samples depended upon the degree of consolidation and the kinds of vegetable matter constituting the peat.

Although vegetation dominantly favours the accumulation of a cold reserve in the ground, it also contributes to the opposite effect. Vegetation cover decreases air current velocities within its stratum, and thus impedes heat radiation from the soil to the cold air. Tumel (1940) recognized particularly the effect of vegetation cover in impeding ground cooling during the night when air temperatures are lower. The retention of snow by vegetation is important as the thermal conductivity of snow is very low, usually lower than that of dry peat, and the snow cover therefore exerts great influence on the intensity and depth of seasonal freezing of ground.

Plant roots and underground stems have certain mechanical roles in the genesis of soil frost features. These organs serve as binding and anchoring agents in the turf and upper soil layers, and may show remarkable strength and resilience against frost action. Roots and underground stems hold the turf wall together on the front scarp of turf-banked terraces, and anchoring roots hold back great heavy mats of turf and sod on slopes with unstable soils. Hopkins and Sigafoos (1951) observed on the Seward Peninsula that the anchoring effect of roots, along with the insulating effects of plants and their dead parts, decreased frost disturbance in tundra.

The ground which permits the greatest degree of water penetration usually thaws to the greatest depth (Tumel, 1940). Extensive root systems tend to impede downward percolation of water, and thus restrict thaw. On the other hand, roots, especially when dead and decaying, may provide channels for water penetration and sometimes become loci for the growth of granules and small stringers of ice. Uprooting and other disturbances to roots of larger plants over a high permafrost table can initiate thaw sinks.

Frost in the soil and the associated vegetation cover thus exert dynamic influence upon each other. In many situations this interaction engenders cyclic changes, especially prominent in vegetation–permafrost relationships. A much simplified diagram of a basic type of vegetation–permafrost cycle is shown in Fig. 5.

Applications

The degree of accuracy attained in predicting soil frost conditions by ground reconnaissance or from air photographs is proportionate to the degree of understanding of the interactions of vegetation and soil frost. Vegetation can be a valid indicator of many ground conditions if the signs can be identified and evaluated (Benninghoff, 1950; Sigafoos, 1950). The success of Raup and Denny (1950) in relating vegetation types of the southern Alaska Highway district to ground conditions, and then to corresponding vegetation patterns on air photographs, indicates the potentialities of the method when based on sound botanical and geological understanding of at least type localities within the area. Care in observing vegetation, landforms, and micro-relief features will also contribute to knowledge of the history of local areas and their soils—an approach that can add materially to predictions of soil behaviour.

All processes and conditions mentioned above bear on agriculture and forestry in regions of severe frost climates. In many localities the deleterious effects of soil frost are limiting factors in land use, as, for example, on many lower slopes and valley bottoms in the vicinity of Fairbanks (Péwé, 1949).

Development of farming in interior Alaska has brought attention in recent years to the problems of agriculture in permafrost areas. Some writers consider permafrost conditions "a negative factor", while others consider them "a beneficial factor" for agriculture. The point of view is determined by the problems of particular areas or ground conditions (Tsiplenkin, 1944; Gasser, 1948). The effect on agriculture depends primarily on the particular permafrost conditions in the given area and climatological factors relating to heat exchange.

Clearing of land has a beneficial influence on the thermal regime of the upper layers of soil during the warm months of the year. However, changes in the water relations may result, and should be anticipated. Due allowance should be made also for the soil becoming colder during the winter (Sumgin *et al.*, 1940).

There is a popular belief that if the permafrost table is near the surface plants benefit by water released during summer thaw, but suffer from the proximity of the cold layer. According to Gasser (1948) experience indicates that after one or two years of cultivation both deleterious and beneficial effects of permafrost on the growth of annual plants become negligible, because the permafrost table retreats beyond the reach of the roots of most annual plants. Nevertheless, the effects of permafrost on drainage and subsidence of ground persist as long as permafrost is present within a few tens of feet of the surface.

Forestry and range-land practices in Alaska must also be adjusted to certain significant relations resulting from soil frost conditions. Raup (1951) has pointed out that slopes modified by intensive frost processes ("cryoplanation") are remarkable for the lateral and vertical uniformity of the covering vegetation. This feature is in strong contrast to conditions in temperate regions where diversity of soils and sites is well developed and reflected in vegetational differences. In places the influence of soil frost activity on the vegetation is so strong that distinct plant communities are regularly associated with a particular type of frost feature. Plant communities in such places must be described, mapped, and managed on the basis of their physical environment.

Plant succession in temperate regions tends to establish more mesophytic conditions in which drainage relations are less extreme. But in regions of severe frost climate, plants commonly generate conditions of extreme lack of drainage and greatly intensified soil frost; in short, the plants frequently destroy the very environmental conditions that favour their growth. Disturbances to the vegetation such as burning and clearing in severe frost climate regions do much more than initiate plant succession that will culminate in the return of the original type of stand. Because of soil frost changes following disturbance, the affected surface and the local environment may be so greatly modified that entirely different communities occupy the site for unknown periods of time.

Construction on soils actively disturbed by frost and on soils with permafrost requires special stabilization and drainage measures. Treatment of the vegetation cover requires careful planning. For example, if a foundation site is to be stabilized by the method of preserving the underlying permafrost, then the maximum preservation of the vegetation cover is necessary, particularly on the south side of buildings. Liverovskiy and Morozov (1941), in a discussion of vegetation treatment in Siberian construction areas, pointed out that the preservation of forests helps to prevent the rise of the ground-water table which, when underlain by permafrost, tends to form bogs and marshes. Brush should be cleared from forests, as it retains moisture and hinders drying air from reaching the surface of the ground. Large trees, on the other hand, retain considerable amounts of moisture around their roots and transpire large amounts, thus they are conducive to drying of the soil. Attention to such considerations during planning stages will pay dividends both during construction and throughout the ensuing period of maintenance.

Proposals for future work

Future investigations along the lines mentioned in this paper should continue and extend observations of the occurrence and expression of soil frost phenomena and associated vegetation under natural conditions, as we still have too few adequate descriptions. Little has been accomplished thus far toward measuring these features and processes, and quantitative data are essential before they can be understood and their occurrence predicted.

Some problems that will be met in this general field and have immediate application to Alaskan economy can be indicated here. For example: to what extent does the thawing of soil frost irrigate the soils of the dry interior, and what measures would favour this aid to cultivation? What is the situation with regard to the release of minerals required by plants from native rock materials under a cold climate and in perennially frozen soils? The effects of cold soils on plants need to be investigated in regard to water and mineral uptake under soil temperature conditions both above and below freezing. The relative slowness of organic decay in Alaska has received almost no attention except through studies of phytopathologic fungi (Baxter and Wadsworth, 1939), yet accumulations of peat and organic soils are primary agents in many of the features discussed earlier in this paper. Field study and experimentation are necessary to determine what plants are most effective in stabilizing these varied soils for different purposes.

Investigations such as these benefit from cooperative efforts of workers representing the several disciplines of science that are concerned with the various elements of the problems. Geologists, botanists, and soil scientists are required for the study of almost every one of these problems, while some require in addition physicists, chemists, and climatologists. Training that leads to a wider "awareness" on the part of each specialist in the natural sciences and the combination of specialists from several disciplines in staffing field research projects is particularly desirable.

References

Antevs, E. 1932. 'Alpine zone of Mt. Washington Range'. Auburn, Maine, 118 pp.

Baxter, D. V. and F. H. Wadsworth. 1939. 'Forest and fungus succession in the lower Yukon valley'. *Univ. of Mich. School of Forestry and Conservation Bull.* No. 9, 52 pp.

Benninghoff, W. S. 1950. "Use of aerial photographs in mapping vegetation and surficial geology in subarctic regions". *Photogrammetric Engineering*, Vol. 16, pp. 428–9.

*Birkengof, A. L. 1934. "Za nablyudeniya nad lesnym pokrovom i vechnoy merzloty" (Some observations on the forest cover and permafrost). *Trudy Komiteta po Izucheniyu Vechnoy Merzloty* (Akad. Nauk S.S.S.R.), Tom 3, pp. 41–57.

Black, R. F. and W. L. Barksdale. 1949. "Oriented lakes of northern Alaska". *J. Geol.* Vol. 57, pp. 105–18.

Denny, C. S. 1938. 'Glacial geology of the Black Rock Forest'. *Black Rock Forest Bull.* No. 8, Cornwall-on-the-Hudson, N.Y., 70 pp.

Gasser, G. W. 1948. "Agriculture in Alaska". *Arctic*, Vol. 1, pp. 75–83.

Harvey, R. B. 1935. 'An annotated bibliography of the low temperature relations of plants'. Minneapolis, 223 pp.

Hopkins, D. M. 1949. "Thaw lakes and thaw sinks in the Imuruk Lake area, Seward Peninsula, Alaska". *J. Geol.* Vol. 57, pp. 119–31.

Hopkins, D. M. and R. S. Sigafoos. 1951. 'Frost action and vegetation patterns on Seward Peninsula, Alaska'. *U.S. Geol. Surv. Bull.* 974-C, pp. 51–100.

*Liverovskiy, A. V. and K. D. Morozov. 1941. 'Stroitel'stvo v usloviyakh vechnoy merzloty' (Construction under permafrost conditions). Moscow–Leningrad, 243 pp.

Muller, S. W. 1945. 'Permafrost or permanently frozen ground and related engineering problems'. Strategic Enginering Study 62, U.S. Army Engineers, second printing with corrections, 231 pp. (Litho-printed, Ann Arbor, Mich., 1947).

Péwé, T. L. 1947. "Permafrost and geomorphology in the lower Yukon River valley". (Abstract of paper presented at Cordilleran section of the Geological Society). *Geol. Soc. Amer. Bull.* Vol. 58, p. 1256.

1949. "Preliminary report of permafrost investigations in the Dunbar area, Alaska". *U.S. Geol. Surv. Circular* 42, 3 pp.

Polunin, N. 1934–5. "The vegetation of Akpatok Island: Parts 1 and 2". *J. Ecology,* Vol. 22, pp. 338–95; Vol. 23, pp. 161–209.

Pulling, H. E. 1918. "Root habit and plant distribution in the far north". *Plant World,* Vol. 21, pp. 223–33.

Raup, H. M. 1951. "Vegetation and cryoplanation". *Ohio J. Sci.* Vol. 51, pp. 105–16.

Raup, H. M. and C. S. Denny. 1950. 'Photo interpretation of the terrain along the southern part of the Alaska Highway'. *U.S. Geol. Surv. Bull.* 963-D, pp. 95–135.

*Romanov, V. V. and O. D. Rozhanskaya. 1946. "Fizicheskiye svoystva promerzshego sloya bolot" (Physical properties of the seasonally frozen layer in marshes). *Priroda* (Akad. Nauk S.S.S.R.), Tom 35, No. 3, p. 57.

Sigafoos, R. S. 1950. "Some botanical problems in the interpretation of aerial photographs of tundra areas". *Photogrammetric Engineering,* Vol. 16, pp. 429–31.

Smith, H. T. U. 1949. "Physical effects of Pleistocene climatic changes in nonglaciated areas: eolian phenomena, frost action, and stream terracing". *Geol. Soc. Amer. Bull.* Vol. 60, pp. 1485–515.

*Sumgin, M. I. 1937. 'Vechnaya merzlota pochvy v predelakh S.S.S.R.' (Permafrost in the soil of the U.S.S.R.). Akad. Nauk S.S.S.R., Moscow–Leningrad, 2nd ed., 379 pp.

*Sumgin, M. I., S. P. Kachurin, N. I. Tolstikhin, and V. F. Tumel. 1940. 'Obshcheye merzlotovedeniye' (Ground frost studies). Akad. Nauk S.S.S.R., Moscow, 340 pp.

Taber, S. 1943. "Perennially frozen ground in Alaska: its origin and history". *Geol. Soc. Amer. Bull.* Vol. 54, pp. 1433–548.

Troll, C. 1943. "Die Frostwechselhaufigkeit in den Luft- und Bodenklimate der Erde". *Meteorologischen Zeitschr.,* Bd. 60, pp. 161–71.

1944. "Strukturböden, Solifluktion und Frostklimate der Erde". *Geol. Rundsch.* Bd. 34, pp. 545–694.

*Tsiplenkin, E. I. 1944. "Vechnaya merzlota i ee agronomicheskoe znacheniye" (Permafrost and its influence on agriculture). *Trudy Instituta Merzlotovedeniya im. V. A. Obrucheva* (Akad. Nauk S.S.S.R.), Tom 4, pp. 230–55.

*Tumel, V. F. 1940. "Sezonnoe promerzaniye i sezonnoe protayvaniye gruntov v oblasti rasprostraneniya vechnoy merzloty" (Seasonal freezing and thawing of the ground in the permafrost area): in Sumgin, M. I., and others 'Obshcheye merzlotovedeniye', Akad. Nauk S.S.S.R., Moscow, pp. 53–90.

Wallace, R. E. 1948. "Cave-in lakes in the Nabesna, Chisana, and Tanana river valleys, eastern Alaska". *J. Geol.* Vol. 56, pp. 171–81.

Washburn, A. L. 1950. "Patterned ground". *Rev. Can. de Géographie,* Vol. 4, pp. 5–54.

*Zhukov, V. F. 1944. "Morozoboinyye treshchiny v rayonakh vechnoy merzloty" (Fissures caused by frost cracking in the permafrost region). *Trudy Instituta Merzlotovedeniya im. V. A. Obrucheva* (Akad. Nauk S.S.S.R.), Tom 4, pp. 226–30.

---

*The original Russian publications were not examined. The information was taken from translations and abstracts derived from various sources.