PERMAFROST†*

Louis L. Ray
U.S. Geological Survey

It is reported that approximately one-fifth of the land area of the earth is underlain by ground that remains frozen throughout the year (Muller, 1943 and 1945). Such frozen ground was reported by Frobisher, after his voyages to the New World in the late 16th century (Sumgin, *et al.*, 1940). Similar reports in the mid-17th century were carried to the Western World from Siberia, where remains of frozen "ice age" mammals had been discovered in remarkable states of preservation. These reports of ground frozen throughout the year, even in forested areas, were viewed with scepticism by those whose experience had not taken them from the mid-latitude temperate climates. It was not until the classic studies of Middendorff (1848-75) in Siberia, just over a century ago, that all doubts as to the existence of this seemingly strange phenomenon were dispelled.

Only casual scientific interest was taken in frozen ground until human activities in northern latitudes forced recognition of this phenomenon because of the problems it posed in the effective utilization of the land. The building of the Trans-Siberian Railroad was an important factor in the development of Russian interest in this subject. In Alaska and the Yukon Territory, the discovery of gold at the turn of the century introduced Americans to the problems of frozen ground. In 1910 a marked stimulus to the study of frozen ground and the processes resulting from intensive frost action was provided by the excursion of the 11th International Geological Congress to Spitsbergen. Members of this excursion carried home new ideas, which were used in the interpretation of Pleistocene deposits and geomorphic processes active in the rigorous climates of high altitudes (see Högbom, 1914, and others).

During the first decades of this century, Russia was the leader in the study of frozen ground. Despite the early recognition of frozen ground in Alaska and the well-known studies of Leffingwell (1919) and later Taber (1930, 1943a and b), relatively little organized effort was made toward systematic studies in this discipline. Although many scattered references to frozen ground and to the features developed by frost action can be found in reports on Alaska published during the first three decades of this century, interest was mainly directed to other seemingly more important fields, and detailed examination of frozen ground was at a minimum. With the growth of permanent settlements in Alaska, the establishment of farming communities, and the inevitable acceleration in construction of all types, the necessity for understanding and dealing with frozen ground has become of prime importance

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and concerted efforts have been made in the past ten years toward a scientific understanding and practical evaluation of this phenomenon.

Early in 1943 S. W. Muller (1943, p. 3) proposed the name *Permafrost* for "a thickness of soil or other superficial deposit, or even of bedrock, at a variable depth beneath the surface of the earth in which a temperature below freezing has existed continually for a long time (from two to tens of thousands of years)." He further stated: "Permanently frozen ground is defined exclusively on the basis of temperature, irrespective of texture, degree of induration, water content, or lithologic character." This term, around which there have been controversies, was proposed as an alternative to the expression "permanently frozen ground". However, as the ground is not *permanently* frozen, the term has been generally modified to *perennially* frozen ground. Muller distinguished a dry frozen ground, in which there was no ice as a cementing substance. This he termed "*dry permafrost*". He points out that some have applied the term perennially frozen ground to ground that contains little or no water, whereas frozen ground contains water in the form of ice. Studies have shown, however, that water is not wholly in the form of ice even though the temperature is below 0°C (Tsytovich, 1947), but that frozen and unfrozen water exist in equilibrium, their relative proportions depending on temperature, pressure, impurities, and grain size of the enclosing sediment. For simplicity, the original broad definition of Muller will be used here.

Difficulties in terminology in this field of endeavour are many. Frequently definitions have been poor, spelling casual, and duplication common because of the use of synonyms derived from the various languages in which a tremendous volume of permafrost literature is now accumulating. With this in mind, the late Kirk Bryan (1946) proposed a new terminology for this discipline which he called *Cryopedology*. Although there has been considerable resistance to the use of these new, strange, and seemingly awkward terms, there has been a gradual tendency both in North American and in foreign literature to adopt certain cryopedologic terms as substitutes for the more cumbersome phrases. It appears doubtful, however, that the term "permafrost", now so well established in both scientific and common usage, will be supplanted.

Having established just what is meant by permafrost, let us examine its character and distribution. As permafrost has a temperature of 0°C or below throughout the year, we must immediately exclude the surface layer, which thaws during the summer season. This important layer, the *active zone*, may be wholly frozen, or it may be partially or wholly thawed, depending on the season. It varies widely both laterally and vertically at any given time, depending on local conditions, and may be readily modified either by natural or by artificial means. It is this zone that is of special importance, because in it all plants are rooted and all churning and soil movements take place; it is the zone in which are developed the geomorphic features that have been considered characteristic of permafrost regions. Intensive frost action in the layer of seasonal freezing is observed outside the permafrost region; however, when this layer of seasonal freezing (the active layer) is underlain by permafrost, frost action is accelerated and intensified.

Permafrost, lying below the unstable active zone, is relatively stable under natural conditions. Its upper surface, known as the *permafrost table*, may or may not coincide with the maximum depth of the active layer. An unfrozen layer existing between the two is called *talik*, a Russian term also applied to unfrozen layers or lenses within or below the permafrost. However, in general, a seasonal decrease in temperature takes place below the active zone so that there are temperature fluctuations in perennially frozen ground below the depth of seasonal thawing (Tumel, 1940). At the borders of an area of permafrost the total thickness of maximum freezing and thawing coincide. Where maximum seasonal thawing penetrates to a depth greater than freezing, permafrost must be "degrading", or depergelating according to Bryan's terminology.

Great thicknesses of perennially frozen ground have been measured or inferred through extrapolation of thermal gradients. Freezing temperatures have been observed to depths of approximately 2,000 feet in Siberia and 1,000 feet in Alaska (Black, 1950). Is this cold reserve the result of the present climate or is it a residuum of a past and colder climate? Justification is found for each theory of origin, for at present permafrost in the Northern Hemisphere appears to be generally depergelating to the south and "aggrading", or pergelating to the north. At intermediate positions it is delicately balanced with present natural conditions, which when disturbed may cause either its disappearance or its development. Bilibin (1937) distinguished two types of permafrost, the active, which reappears when destroyed, and must therefore depend on the present climate, and the passive, which when destroyed does not reappear and thus must be a product of a colder climate. As yet much is to be learned concerning the relationship of permafrost to climate and its fluctuations. Relationship among mean annual temperatures, amount and time of precipitation in the form of rain or snow, cloudiness, evaporation, insolation, and insulation must be more thoroughly understood before they can be definitely correlated with ground conditions. Unfortunately, weather records are scanty for many areas and of too short duration to show definite trends and to permit critical comparisons based on the measured thermal regime of permafrost. At present, margins of permafrost regions are defined only by the most generalized lines on small-scale maps. The extent of permafrost in the temperate zone at high altitudes is almost unknown, especially the extent of dry permafrost. Too few holes have as yet been drilled through permafrost from which careful and detailed measurements of the thermal regime have been taken. Until more quantitative data are available, many questions will remain unsolved.

Commonly, regions of permafrost have been classified as:

1) *Continuous*, where permafrost is of wide and uninterrupted regional extent. This is generally the northernmost zone, the active permafrost of Bilibin.

2) *Discontinuous*, where there are scattered islands of *talik* within the permafrost.

3) *Sporadic*, where small islands of permafrost occur in regions of thawed ground.

Zone 3 falls within the passive permafrost of Bilibin; zone 2 is intermediate. Little is yet known about the depergelation of permafrost at its lower surface, for few observations have been made. It appears reasonable, however, to assume that under present climatic conditions there is a slow depergelation, especially in areas of passive permafrost.

During the general world-wide amelioration of climate within the past century, recorded from many diverse observations, it is probable that permafrost is shrinking in areal extent, the southern boundary moving slowly northward, as reported by Obruchev (1946) in Russia. Climatic fluctuations are known to have occurred in the past, so that features directly related to permafrost are now found far outside the limits of its present occurrence. Colder conditions will extend its occurrence. Until there is better grasp of climatic conditions and their relation to permafrost, areal expansion and contraction cannot be predicted. Such predictions would be of special value in areas of passive permafrost, where slight climatic fluctuations may cause either its complete disappearance or its regeneration.

Subfreezing winter temperatures penetrate deeply into permafrost, i.e., below the *permafrost table*, in the zone of active permafrost. Below the maximum depth of seasonal temperature fluctuations within the permafrost, the *level of zero amplitude*, the temperatures range from slightly less than zero to several degrees below zero C. For example, near Barrow, Alaska, a temperature of -9.6°C has been measured at a depth of 100 to 200 feet (Black, 1950). With increasing depth, temperatures slowly rise until 0°C is passed and permafrost disappears. In several measurements from deep wells in permafrost, reversals in temperature gradients have been noted and the conclusion has been reached that such reversals may represent past climatic fluctuations. Caution must be used in reaching such conclusions, for as Birch (1948, p. 760) points out: "The deviations from linearity of temperature–depth curves as a result of climatic fluctuations will be discernible only in unusually favorable circumstances, and it will ordinarily be advisable to examine all other disturbances before adopting a 'climatic' explanation for non-linearity." When more measurements become available, it may be possible to determine the cause of such reversals in temperature gradients, but present data are too limited for satisfactory analysis.

Ice contained in permafrost is probably its most spectacular feature. Where drainage conditions are poor and unconsolidated materials are largely fine-grained, ice masses ranging from small granules, veins, sheets, and ice wedges to large irregular masses may account for more than 50 per cent, sometimes as much as 80 per cent, of the permafrost (Taber, 1943a). This crystalline ice may range from pure to extremely impure ice, filled with air bubbles having a variety of orientations. Studies of the petrography of ground ice, recently completed at the Arctic Research Laboratory at Point Barrow, and as yet unpublished, may provide definite information concerning the origin and age of the ice. Field and laboratory studies have already indicated significant differences in physical properties of ground ice in different localities, presumably with different ages and modes of origin (Black, oral communication).

Briefly, it is apparent that permafrost is only a semi-permanent condition, relatively stable and characterized by temperatures of 0°C or below. In large part it appears to be the result of a climate colder than the present, although in the more rigorous climates it is being generated today. It has a wide areal extent, but at present appears to be depergelating along its southern margin and at an unknown rate along its lower surface. Its thickness ranges up to an observed maximum of approximately 2,000 feet. At present its areal extent, depergelation, and variations in thickness are known only from observations at widely scattered localities. Data on its thermal regime are limited. A large part of its total volume in unconsolidated sediments is of ice, which occurs in many forms, the meaning of which is at present little known. Some evidence suggests the reflection of climatic fluctuations in the thermal gradients of permafrost. It is at once apparent that relatively little is known of permafrost, despite the large volume of scientific literature.

We come to the question of the significance of perennially frozen ground in the understanding and utilization of the land that it underlies. If environmental conditions remained stable, permafrost would be stable. But environmental conditions are not stable, and the constant slight alterations of physical environment bring about changes in permafrost conditions. These changes, whether regional or local, may be produced by natural or artificial means.

One has only to observe the natural terrain in permafrost regions to see that the macro- and micro-relief differ in character from those of mid-latitude temperate climates. In order to explain this difference an entirely new series of concepts is necessary, for the classic geomorphic concepts developed by William Morris Davis and later workers for the temperate climates are not adequate. We are confronted with a terrain in which disintegration is at a maximum and decomposition at a minimum, where the surface of the ground —the active layer—undergoes rhythmic cycles of change in its physical nature. Valleys are clogged with alluvium and the distinctive slopes show a variety of relief features characteristic of mass movement as distinguished from features developed by running water. When thawing or thawed, the active layer is an unstable, water-logged mass resting on a stable permafrost substratum; drainage into the permafrost is not possible, and a complex of factors prevents ready surface drainage. Even on the most gentle slopes, thawed material rests uneasily on the frozen substratum, the contact between the two being *a glide plane* well lubricated by meltwater. Creep and viscous flow appear to be more important than gliding in downslope movement.

Fluctuations in weather conditions during any one year or climatic fluctuations over long periods may have marked significance in disturbing the thermal regime of permafrost and the active layer. With a depression of the permafrost table, for example, better drainage may be allowed the surface of the active layer, thereby changing the character of the vegetative cover and modifying the geomorphic processes that produce the micro-relief forms commonly associated with permafrost. The vegetative cover is of special importance because plants are wholly rooted in the active layer or rest upon it, and are delicate indicators of its physical condition. The vegetation acts as an insulator for the ground, a stabilizing mat, and a trap for the accumulation and protection of snow, which is in turn an insulator of the ground. Any modification of the vegetative cover, whether through destruction by fire, uprooting by wind or frost heaving, clearing of land for cultivation or for other human activities, will directly affect both the active layer and the underlying permafrost.

When the insulating mat of vegetation is removed during the clearing of land for agricultural purposes, summer warmth penetrating the soil may depress the permafrost table, with frequently deleterious results. Ice masses in permafrost may thaw, producing a variety of topographic forms through subsidence. These range from thermokarst pits or thaw sinks (Hopkins, 1949), resulting from the thawing of large ice masses, to a hummocky micro-relief. Where wedges of ground ice arranged in polygonal patterns thaw, the enclosed ground remains as a hummock surrounded by thaw depressions. If the permafrost lacks ice masses or the ice is scattered homogeneously throughout, uniform settlement, often scarcely noticeable, takes place. Gasser (1948) states that growing tests indicate that permafrost is neither stimulating nor dwarfing to plants. Gasser (1948) and Tsiplenkin (1944) report that if the active layer is sufficiently thin, plants absorb the moisture produced by thawing of the ice at the permafrost table, obtaining necessary water where rainfall is deficient. As thawing proceeds to greater depth, drainage is increased by sinking of free water within the soil, and the surface layers in which plants are rooted may become dry so that plants will suffer if precipitation is low.

Where permafrost is continuous, supplies of ground water are difficult to obtain, for free circulating water cannot exist within it, and supplies available during thawing periods in the overlying active layer are generally unreliable. Commonly, surface water of streams and lakes is the only available supply; in winter these also may be unreliable for large and permanent supplies. However, where permafrost is discontinuous, steady supplies are frequently available from *talik* either below or within permafrost. Water derived from such thawed zones may be highly mineralized. Wells drilled through permafrost in unconsolidated material are difficult to maintain, especially where there is a high content of ice. Equally difficult is the distribution through pipes to consumers. If laid in the active layer, the pipes are subject to damage through heaving and freezing; if pipes are laid in permafrost, they are subject to freezing unless a large volume of water is kept in constant motion. Specially constructed conduits, or utilidors, and insulated pipes have been used to prevent freezing. It is readily seen that permafrost adds a difficult and complicating factor to the problems of ground-water hydrology.

The necessary disturbance of natural conditions during the construction of roads, railroads, airfields, and buildings causes a myriad of special problems. The difficulties are well known, and spectacular examples are described in the literature. Organized study of these problems has been carried on in the field and laboratory for a period of years. Whenever the natural conditions are disturbed by construction, a new set of environmental conditions is established, generally with an acceleration of frost processes that tend to establish an equilibrium with the artificially introduced conditions. In order to adopt suitable construction methods, it is necessary to understand thoroughly the natural conditions, predict what changes will take place when they are disturbed, provide for the frost effects developed during changing of the environment, and assure a satisfactory equilibrium of the construction in the new environment that has been established. Generalizations are difficult, and it is necessary that each construction site be individually examined and interpretation made in the light of the basic data available and past experience. This is a large order, difficult to fulfil in the present state of knowledge.

The complexities of permafrost and some of its interrelations to the many facets of the environment have been briefly mentioned. Other factors are as yet little known. For example, relationship between ground ice and grain size has received attention but little has been done to indicate relationship of ground ice to shape of particles, especially as it affects the strength of the frozen material and amount of compaction when thawed and drained. Although many investigators are now engaged in research that will provide a wealth of quantitative data for the development of basic principles, the field is open to many new lines of study that will complement those of the present. Continued efforts are needed to provide the necessary data from field studies for critical analysis and prediction. The origin, extent, and physical-mechanical properties of permafrost, and its pergelation, depergelation, and relation to climate and vegetation are still only partially known. The geomorphic processes, especially those related to the active layer, deserve continuing study because of their practical significance. Only through an understanding of the basic principles can proper planning and adequate use be made of the vast areas underlain by permafrost. Man has adapted himself to a mode of life above the ground in permafrost regions, but he must adapt his activities to conditions of the ground if he is to utilize fully these northern lands.

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