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BY

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# Permafrost as an ecological factor in the Subarctic

R. J. E. Brown

Permafrost is a natural phenomenon of subarctic regions. Its occurrence and distribution are determined by the close and complex interaction of a large number of climatic and terrain factors. In turn, these factors are influenced by the presence of permafrost.

For this symposium it is useful to describe the distribution and occurrence of permafrost relative to the limits of the Subarctic. These limits are not fixed by a single universally accepted criterion but vary from one scientific discipline to another. The southern limit of the Subarctic is particularly debatable. In the consideration of permafrost, it is convenient to state arbitrarily that the southern limit of the Subarctic coincides with the southern limit of permafrost. A convenient criterion for the northern limit of the Subarctic would be the division between the discontinuous and continuous permafrost zones. Many scientific disciplines, however, accept the tree line, despite its debatable definition and location, as the northern limit of the Subarctic. Consequently, in this paper, the tree line is considered as the northern limit of the subarctic permafrost region although this region includes parts of the continuous permafrost zone.

## DEFINITION OF PERMAFROST

Permafrost is defined exclusively on the basis of temperature, and refers to the thermal condition of earth materials such as soil and rock when their temperature remains below 0° C continuously for a number of years (Muller, 1945; Pihlainen and Johnston, 1963; Shvetsov, 1959; Sumgin *et al.*, 1940). Permafrost includes ground that freezes in one winter, and remains frozen through the following summer and into the next winter. This is the minimum limit for the duration of permafrost; it may be only a few centimetres thick. Thus the English term, climafrost, and the Russian, *pereletok*, are part of permafrost.

At the other end of the scale, in the continuous zone, permafrost is thousands of years old and hundreds of metres thick. The mode of formation of such old and thick permafrost is identical to that of permafrost only one year old and a few centimetres thick. In the case of the former, even a small negative heat imbalance each year results in a thin layer being added annually to the permafrost. After several thousands of years have elapsed, this annually repeated process can produce a layer of permafrost hundreds of metres thick. This process does not cause the permafrost to increase in thickness indefinitely. Rather, a quasi-equilibrium is reached whereby the downward penetration of frozen ground is balanced by heat from the unfrozen ground below.

Permafrost is not permanent. This is particularly true in the Subarctic where changes in climate and terrain can cause the permafrost to thaw and disappear. Thus the English term, perennially frozen ground, and the Russian, *mnogoletnemerzlyi grunt*, are used to denote permafrost.

## NATURE AND DISTRIBUTION OF PERMAFROST IN THE SUBARCTIC

The Subarctic includes all of the discontinuous permafrost zone and the southern part of the continuous zone. The —5° C isotherm of mean annual ground temperature measured just below the zone of seasonal variation was chosen arbitrarily by Russian permafrost investigators as the division between the discontinuous and continuous permafrost zones (Bondarev, 1959). This criterion has been adopted in North America.

### DISCONTINUOUS PERMAFROST ZONE

In the discontinuous permafrost zone, there are areas and layers of unfrozen ground. In the southern fringe of the Subarctic, permafrost occurs in scattered islands a few square metres to several hectares in area, and it is restricted to certain types of terrain, mainly peatlands. Other occurrence sare associated either with the north-facing slopes of east-west oriented valleys, or isolated patches in forested stream banks apparently associated with increased shading from summer thawing and reduced snow cover. Northward it becomes increasingly widespread and is associated with a greater variety of terrain types. It varies in thickness from a few centimetres or metres at the southern limit to several hundred metres at the boundary of the continuous zone—up to 250 m in eastern Siberia. Unfrozen layers or taliks may occur between layers of permafrost. The depth to the permafrost table is extremely variable ranging from about 50 cm to several metres. The active layer, which freezes in winter and thaws in summer, does not always extend to the permafrost table. The temperature of the permafrost at the level of zero annual amplitude ranges from a few tenths of a degree below 0° C at the southern limit to —5° C at the boundary of the continuous zone.

### CONTINUOUS PERMAFROST ZONE

In the continuous zone, permafrost occurs everywhere beneath the ground surface except in newly deposited unconsolidated sediments where the climate has just begun to impose its influence on the ground thermal regime. The thickness of permafrost varies from about 250 m at the southern limit of the continuous zone to 500 m at the tree line in Siberia. In North America the range is probably about 100 to 300 m. The active layer generally varies in thickness from about 50 to 100 cm and usually extends to the permafrost table. The temperature of the permafrost at the level of zero annual amplitude ranges from —5° C in the south to about —10° C at the tree line in Siberia and to about —8° C in North America.

### PERMAFROST DISTRIBUTION IN MOUNTAINOUS REGIONS

Permafrost occurs at high altitudes in mountainous regions south of the subarctic region. It is found in the Western Cordillera in North America, and in the Alps and Himalayas in Eurasia. Its distribution varies with altitude as well as latitude. The lower altitudinal limit of permafrost decreases in elevation progressively from south to north. With increasing elevation the distribution of permafrost changes progressively from scattered islands to widespread and finally continuous. In mountainous regions there is the added problem of the differences between slopes of different orientation. Permafrost is more widespread and thicker on north-facing slopes than on south-facing slopes. Snow cover, which has considerable influence on permafrost, is heavier on windward than leeward slopes. Other terrain factors also vary from one slope to another to complicate the distribution of permafrost.

### RELIC PERMAFROST

Along the southern limit of permafrost the known occurrences seem to be in reasonable equilibrium with the present environment. To date no relic occurrences in North America south of the permafrost region which represent radically different conditions have been described. There are a few random reports, however, of isolated bodies of permafrost lying at depth beneath the ground surface. If such permafrost does exist, it probably formed during a previous period of cooler climate and lies at a depth below that affected by the current climate. There is no evidence on the ground surface of these bodies of permafrost and they would be detected only by mining operations or ground temperature measurements. Relic occurrences have possibly been found and described in the eastern hemisphere but no references have been found in the literature. Occurrences of relic permafrost at depth are known farther north in the permafrost region.

### CIRCUMPOLAR SOUTHERN LIMIT OF PERMAFROST

The most southerly extent of permafrost in the Western Hemisphere, excluding the Western Cordillera, is about 51°-52° N. around and east of James Bay[1] (Fig. 1). West of Hudson Bay it extends north-westwards through the northern parts of the provinces and the south-west corner of Yukon Territory. In Alaska the southern limit forms an arc around the Gulf of Alaska (Ferrians, 1965). Greenland lies entirely within the permafrost region. The existence of permafrost in Iceland is uncertain but probably occurs at high elevations in the interior. In Scandinavia the southern limit of permafrost lies at its most northerly location in the Northern Hemisphere (close to 70° N.). Eastward in the Kola Peninsula it extends south-eastwards. Farther east in the U.S.S.R. a tongue extends southwards in the Ural Mountains beyond which the trend is south-eastwards to the Yenissey River. East of this river the southern limit extends below 50° N, in Manchuria and Outer Mongolia (Zhukov, 1961). Towards the Pacific Ocean it extends north-eastwards to the Sea of Okhotsk and across central Kamchatka (Batanov, 1959).

1. R. J. E. Brown, *Permafrost Map of Canada*, Division of Building Research, National Research Council, Canada and the Geological Survey of Canada. In press.

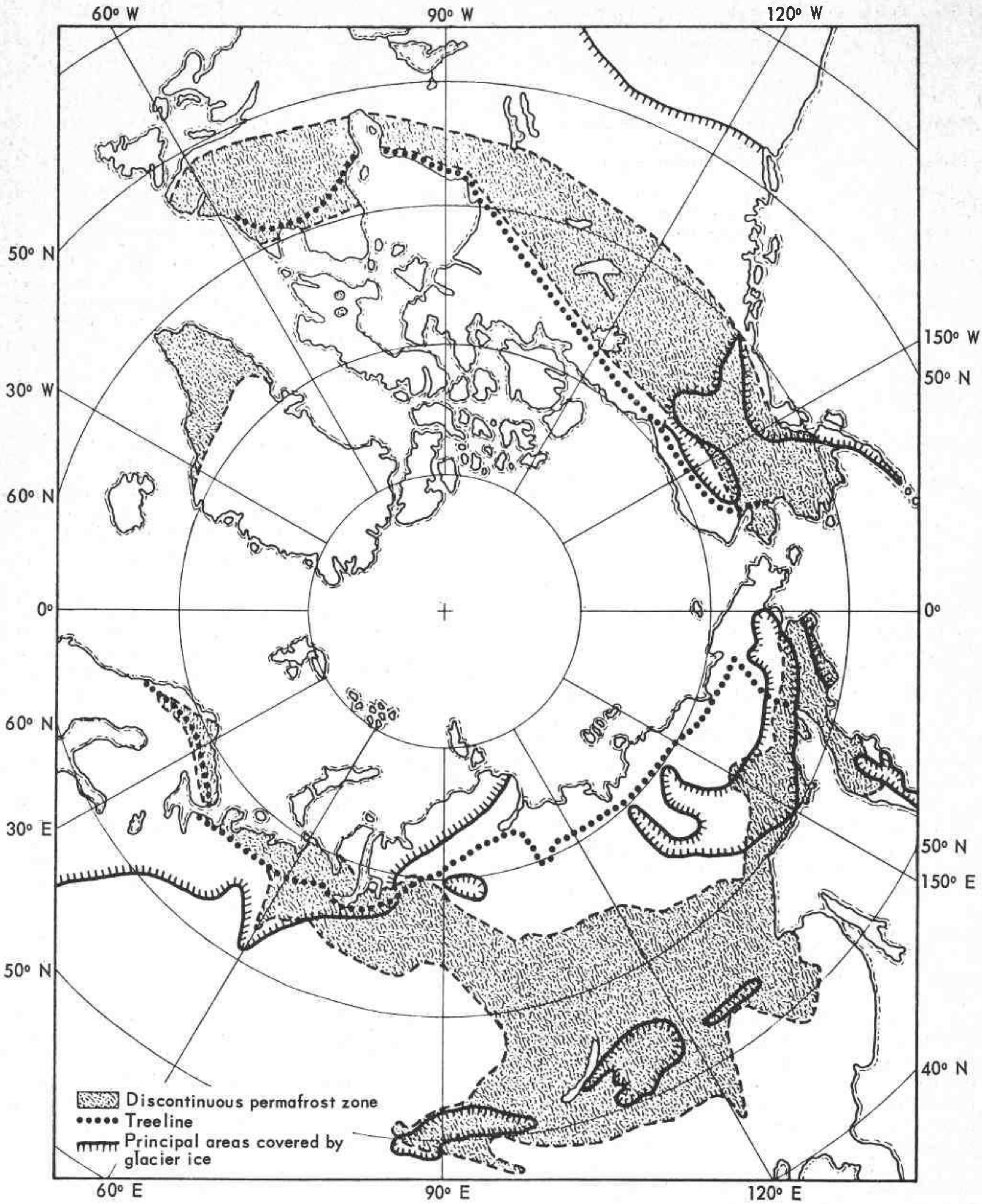


FIG. 1. Northern Hemisphere permafrost distribution.

Table 1. Ecological aspects of permafrost in the Subarctic

| Ecological factor | Influence of ecological factor on permafrost | Influence of permafrost on ecological factor |
|---|---|---|
| Climate | Air temperature and insolation influence ground thermal regime | Frost heaving in active layer, solifluction, and thermokarst change ground surface configuration which influences microclimate |
| Microclimate | Energy-exchange regime at ground surface | |
| Relief<br>Microrelief | Degree and orientation of slope influences amount of insolation received at ground surface, and snowfall | Frost heaving in active layer causes uneven microrelief. Solifluction and thermokarst change ground surface configuration |
| Vegetation | Moss and peat insulate ground. Vegetation influences moisture regime. Variations in albedo control net radiation. Trees shade ground surface and intercept snowfall. Roughness of vegetation influences wind velocities | Impedes warming of soil: low temperatures in root zone impede root growth and cause physiological dryness. Impermeability of permafrost causes poor drainage and swamp conditions |
| Drainage | Standing and moving water thaw underlying permafrost. Moving water thermally erodes permafrost | Impermeable to water |
| Snow cover | Degree of insulation depends on duration, and properties | Retards melting at bottom of snow cover |
| Soil and rock | Influence depends on albedo, moisture content, thermal properties | Alternating freezing and thawing reduce soil particle size in active layer. Frost fissuring and heaving move large rock blocks |

## CIRCUMPOLAR NORTHERN LIMIT OF DISCONTINUOUS PERMAFROST RELATIVE TO TREE LINE

Throughout the Northern Hemisphere, the northern limit of discontinuous permafrost generally lies south of the tree line (Fig. 1). Exceptions to this occur in North America east of Hudson Bay, and in Eurasia from the Atlantic Ocean to the Yenissey River. The northern limit of discontinuous permafrost and the tree line are closer together in the Western Hemisphere than in the Eastern Hemisphere and are approximately parallel to each other. In Canada, the tree line is approximately 300 km south of the continuous permafrost zone east of Hudson Bay and about the same distance north of it in western Canada. In Alaska, the tree line lies about 500 km north of the discontinuous permafrost zone.

In Greenland the division between discontinuous and continuous permafrost varies from about 66° N. to 69° N. in West Greenland and 68° N. to 69° N. in East Greenland.[1] Continuous permafrost has not been reported in northern Scandinavia and the tree line actually lies close to the southern limit of discontinuous permafrost. In the Soviet Union, the northern limit of discontinuous permafrost extends inland from the Arctic coast at Novaya Zemlya, south-eastwards across the Ob Gulf at 70° N., and reaches 60° N. east of Yakutsk, more than 1,000 km south of the tree line. Farther east it trends to the north-east and reaches the Bering Sea at Anadyr. In contrast to the great southward penetration of the northern limit of discontinuous permafrost in Siberia, the tree line extends eastwards at about 70° N. to the far east where it dips southwards to Kamchatka Peninsula.

## INTERACTION OF PERMAFROST AND ENVIRONMENTAL FACTORS

Permafrost in the Subarctic exists in a close and complex interaction with a large number of ecological factors (Table 1). The most important factor is climate which is basic to the formation and existence of permafrost and controls the broad pattern of distribution and occurrence. Terrain conditions are responsible for local variations within this broad pattern.

### *Climate*

The influence of climate on permafrost is most readily expressed by the temperature of the air. This parameter is easily measured and most directly related to ground heat losses and heat gains. The complex energy exchange regime at the ground surface and the snow cover cause the mean annual ground temperature, measured at the level of zero annual amplitude, to be several degrees warmer than the mean annual air temperature. Local microclimates and terrain con-

1. A. Weidick, private communication.

ditions cause minor variations but a value between 3° C and 4° C can be used as an average figure (R. J. E. Brown, 1963*a*).

Present knowledge of the southern limit of permafrost indicates that it coincides roughly with the —1° C mean annual air isotherm. Southward, permafrost occurrences are rare and small in size because the climate is too warm. They are related to unusual insulation conditions caused by thick dry peat or low insolation where summer cloud cover is unusually heavy such as around the Gulf of Alaska. Between the —1° C and —3.5° C mean annual air isotherms, permafrost is restricted mainly to the drier portions of peatlands because of the low thermal conductivity of the peat. Scattered bodies of permafrost occur also on some north-facing slopes and in some heavily shaded areas. In the vicinity of the —3.5° C mean annual air isotherm, the difference of 3.5° C between the mean annual air and ground temperatures produces a mean annual ground temperature of a fraction of a degree below 0° C in most types of terrain. Northward to the boundary of the continuous zone, permafrost becomes increasingly widespread and thicker and the mean annual ground temperature at the level of zero annual amplitude decreases to —5° C. This corresponds to a mean annual air temperature of about —8.5° C. Northward to the tree line, permafrost is continuous and increases in thickness in response to the progressive reduction in the mean annual air temperature.

Over a long period of time, a change in the mean annual air temperature can result in a significant change in the extent and thickness of permafrost. Geothermal gradients in permafrost ranging from about 1° C/20 m to 1° C/160 m—depending to some degree on the type of soil or rock—have been observed in Canada, Alaska, and the U.S.S.R. (Brewer, 1958; W. G. Brown *et al.*, 1964; Melnikov, 1959). A change of 1° C in the mean annual air temperature can result, over a long period of time, in a change of 1° C in the mean annual ground temperature. This would cause a change in permafrost thickness of approximately 20-160 m.

Microclimatic factors are also important in influencing the distribution of permafrost. Net radiation, evaporation (including evapotranspiration), condensation, and conduction-convection are all elements of the energy-exchange regime at the ground surface (R. J. E. Brown, 1965). Although they are climatic in origin, their contribution to the ground thermal regime is determined by the nature of the ground surface and thus can be considered as terrain factors.

Although climate has a profund influence on permafrost, there is little or no direct influence exerted by permafrost on the climate. Indirectly, permafrost may influence the microclimate by modifying the ground surface configuration. Frost action in the active layer can produce microrelief features 1 m or more in height which affect air movement at the ground surface. Resulting variations in degree and orientation of slope are small but may be sufficient to cause variations in the quantities of insolation received at the ground surface. The depth to the permafrost table influences the types of plants that can grow which thus affect the climate near the ground—air movement, net radiation, and other energy components.

### Terrain

In the discontinuous zone, variations in terrain conditions are responsible for the patchy occurrence of permafrost, size of permafrost islands, depth to the permafrost table, and thickness of permafrost (Legget *et al.*, 1961) (Fig. 2 to 7). In the continuous zone, the thermal properties of the peat and other terrain factors assume a relatively minor role and the thermal properties of the ground as a whole, together with the climate, become dominant. Terrain factors that affect permafrost conditions include relief, vegetation, drainage, snow cover, soil type, and glacier ice. In its turn, permafrost influences these features in the subarctic environment.

*Relief.* Relief influences the amount of solar radiation received by the ground surface. The influence of orientation and degree of slope on permafrost distribution is particularly evident in mountainous regions but smaller scale variations cause similar situations elsewhere in the Subarctic. Permafrost may occur, for example, in the north-facing bank of even a small stream but not in the opposite south-facing bank. Similar differences between north- and south-facing slopes can occur even in areas of intensive microrelief such as peat mounds, ridges and plateaux.

Permafrost affects the relief or ground surface configuration. Solifluction and other down-slope mass movements of earth material over permafrost surfaces alter the ground surface configuration. Thermokarst is frequently an active process in areas where large masses of ground ice exist. The melting of this ice and resulting subsidence of the ground produce undulations and hollows which considerably alter the relief.

*Vegetation.* Vegetation and permafrost are closely related in the subarctic environment and exert considerable influence on each other (R. J. E. Brown, 1963*b*; Tyrtikov, 1959). The most obvious effect of vegetation is its role of shielding the permafrost from solar heat. This protection is provided mainly by the insulating properties of the widespread moss and peat cover. Removal or even disturbance of this surface cover causes degradation of the underlying permafrost. In the discontinuous zone, this may result in the disappearance of bodies of permafrost. In the continuous zone, the permafrost table will be lowered. The predominance of the moss and peat in protecting the permafrost

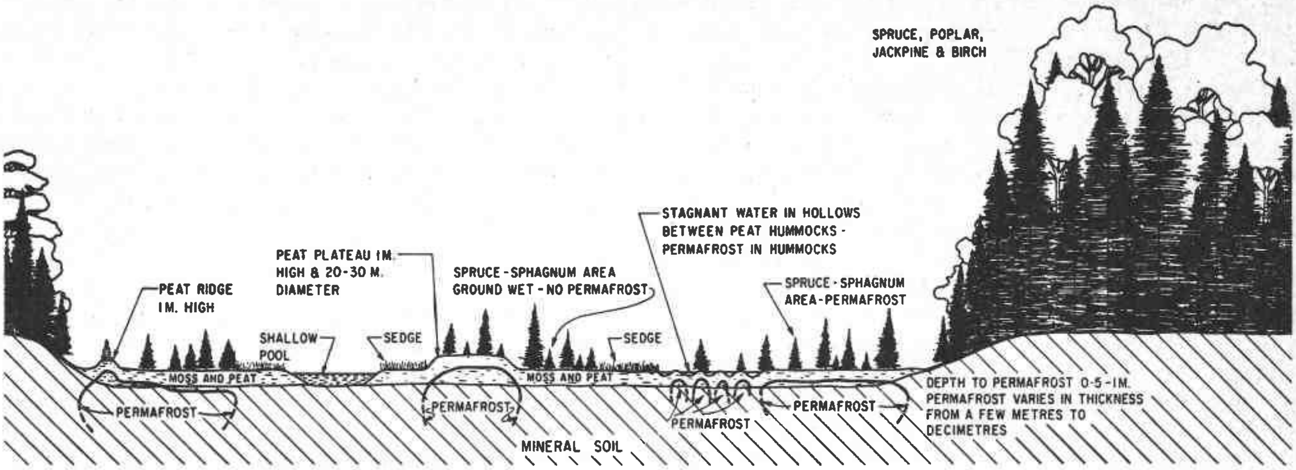


**FIG. 2. Profile through typical peatland in southern fringe of discontinous zone showing interaction of permafrost and terrain factors.**

from atmospheric heat is demonstrated by the fact that little change occurs in the depth of the permafrost table when trees and brush are removed provided that the moss and peat are not disturbed. A fire may burn trees, brush, and even the surface of the moss without altering the underlying permafrost.

The mechanism that causes permafrost to form in peatlands in the southern fringe of the permafrost region south of the —3.5° C mean annual air isotherm appears to be associated with variations through the year of the insulating properties of the moss and peat (Tyrtikov, 1959). During the warm season a thin surface layer of peat becomes dry. Its thermal conductivity is low and warming of the underlying soil is impeded. During the cold part of the year the peat becomes saturated from the surface and then freezes, greatly increasing its thermal conductivity. Consequently, the amount of heat transferred in winter from the ground to the atmosphere through the frozen ice-saturated peat is greater than the amount transmitted in summer in the opposite direction through the surface layer of dry peat. A considerable amount of heat is also required during the warm season to melt the ice and to warm and evaporate the water. The net result is a negative imbalance of heat and conditions conducive to the formation and preservation of permafrost.

Although the influence of the ground vegetation on permafrost is dominant, trees are of some importance. They shade the ground from solar radiation and intercept some of the snowfall in winter. The effect of even a single tree in shading the ground in summer and reducing the snow cover at its base in winter appears to influence the heat exchange at the ground surface sufficiently to produce a lens of permafrost beneath the tree (Viereck, 1965). The density and height of trees influence the microclimatic effects of ground-surface wind velocities. Wind speeds are lower in areas of dense growth than in areas where trees are sparse or absent. The movement of air represents the transfer of heat from one area to another. In peatlands the trees are generally stunted and scattered, and there are numerous open areas that permit higher wind speeds and the removal of heat per unit time. Therefore, the possibility of slightly lower air temperatures and ground temperatures, because of higher wind speeds is greater than in areas of dense tree growth (Johnston *et al.*, 1963).

Permafrost exerts considerable influence on the environment in which the subsurface organs of plants have developed (Tyrtikov, 1959). The effects of permafrost are mostly detrimental to plant development because of its cold temperatures and impermeability to moisture. Permafrost impedes warming of the soil during the growing season and the temperature of the root zone is considerably below the optimum. Absorption of water by the roots is reduced which leads to physiological dryness of the plants. On the other hand, water is gradually released to the root zone through the summer as the active layer thaws. Root development is retarded and roots are forced to grow laterally because downward penetration is prevented by the permafrost. Large trees cannot be supported by these shallow root systems and a "drunken" forest results.

Permafrost forms an impermeable layer which impedes drainage leading to a decline in aeration and impoverishment of nutritive substances because of the weakening of the activity of micro-organisms. Soil movement in the active layer also influences the vegetation. Frost action causes unevenness in the ground surface, solifluction and other down-slope mass movements of earth material disturb the vegetation, and thermokarst changes the surface configuration of

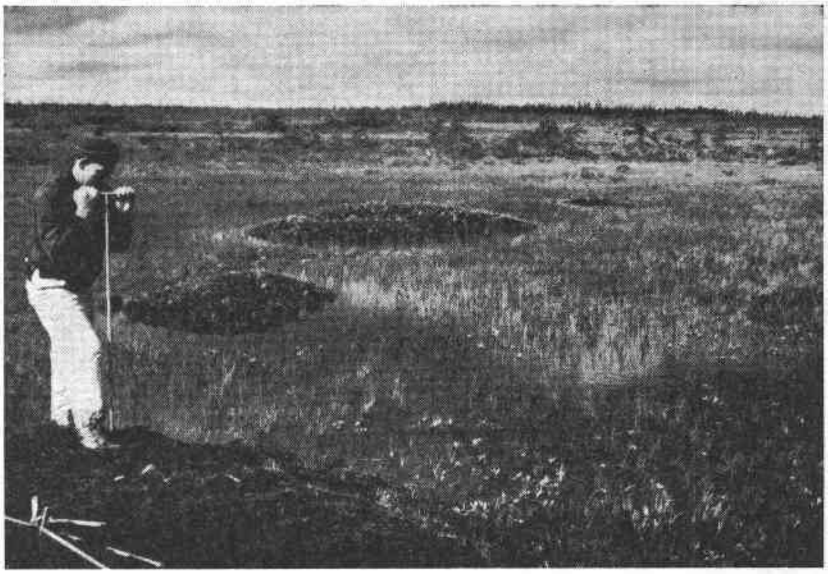

FIG. 3. Palsas containing permafrost in wet peatland with no permafrost, located at southern limit of discontinuous zone near south end of James Bay, Canada.

the ground, all producing detrimental influences on the vegetation. These various influences of permafrost on vegetation increase northwards as permafrost becomes increasingly widespread and the active layer becomes thinner.

*Drainage.* Water greatly influences the distribution and thermal regime of permafrost. In the discontinuous zone, the existence of permafrost is inhibited in poorly drained areas. Precipitation influences the depth of thaw and soil temperatures (Shvetsov and Zaporozhtseva, 1963). First, the amount of moisture in the soil immediately before it freezes in the autumn determines the ice content and depth of thaw the following summer. Second, the moisture content of the soil surface and the infiltration of atmospheric water influence the heat transfer to the frozen soil during the thaw period. Moving water is an effective erosive agent of perennially frozen soils. There is almost always an unfrozen zone beneath water bodies that do not freeze to the bottom. The extent of this thawed zone varies with a large number of factors—area and depth of the water body, water temperature, thickness of winter ice and snow cover, general hydrology, and composition and history of accumulation of bottom sediments (Johnston and Brown, 1964). The ocean has an important thermal influence on permafrost causing it to be thinner at the shore than inland (Lachenbruch, 1957).

Permafrost greatly influences the hydrological regime, Its impermeability to water is responsible for the existence of many small shallow lakes and ponds in the continuous zone and in the northern part of the discontinuous zone where permafrost is widespread. Beaded streams are another indication of the influence of permafrost. Irregular enlargements of stream channels result from the melting of masses of ground ice beneath streams.

FIG. 4. Section of Royal Canadian Air Force aerial photograph A 14975-31 of terrain in Figure 3.

**Fig. 5. Permafrost exists in forested peat plateau in background but not in low wet area in foreground. Location in discontinuous permafrost zone near Nelson River, northern Manitoba (Canada).**

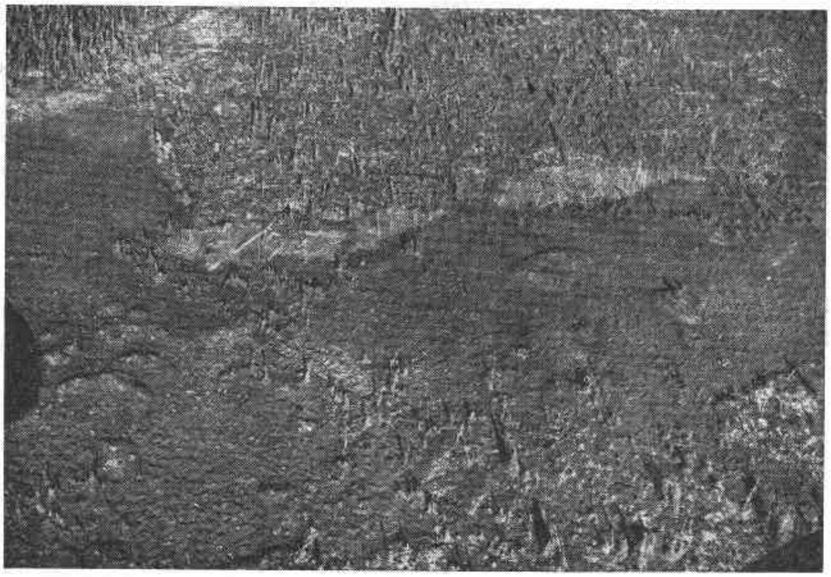

**Fig 6. Aerial view from altitude of 150 m of terrain in Figure 5 showing forested peat plateaux with permafrost and low wet treeless areas without permafrost.**

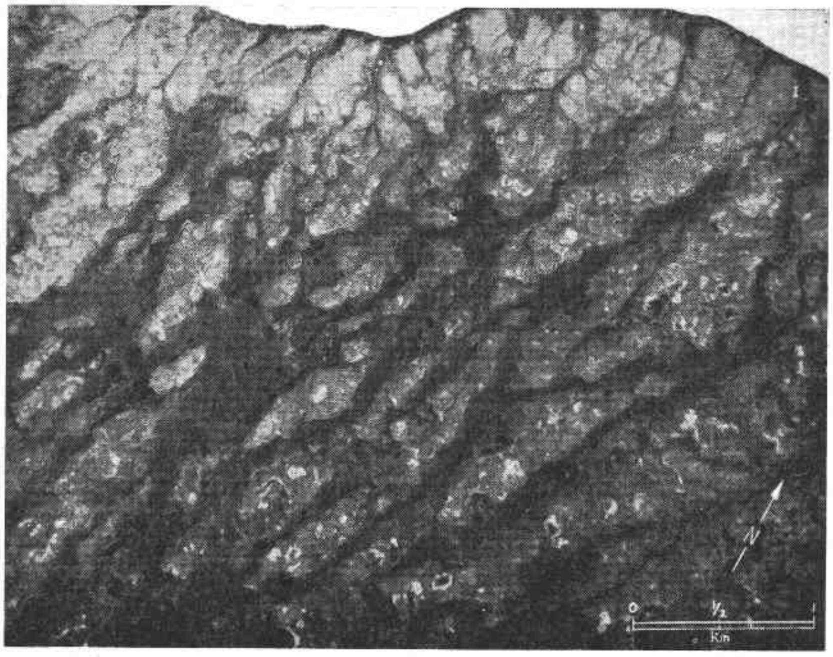


**Fig. 7. Section of Royal Canadian Air force aerial photograph A 14188-119 of terrain in Figure 5. Light grey rough pattern denotes forested peat plateaux with permafrost. Medium to dark grey smoother pattern denotes low wet areas without permafrost.**

*Snow cover.* Snow cover influences the heat transfer between the air and the ground and hence affects the distribution of permafrost. The snowfall regime and the length of time that snow lies on the ground are critical factors. A heavy fall of snow in the autumn and early winter inhibits winter frost penetration. On the other hand, a thick snow cover that persists on the ground in the spring delays thawing of the underlying ground. The relation between these two situations determines the net effect of snow cover on the ground thermal regime. In the discontinuous zone, particularly in the southern fringe, it can be a critical factor in the formation and existence of permafrost. In both Western and Eastern Hemispheres, the thickest permafrost in the southern fringe of the permafrost region occurs in palsas on which snow cover is thin because of their exposure to wind (Lindqvist and Mattsson, 1965; Sjörs, 1959). In the continuous zone, snow cover influences the thickness of the active layer.

The considerable influence of snow cover on the ground thermal regime can best be illustrated by several quantitative examples. At Norilsk, U.S.S.R. (mean annual air temperature —8.4° C), it was shown that a snow cover exceeding 1.5 m completely damped out air temperature influences on heat emission from the ground (Shamshura, 1959). Studies at Schefferville, Canada (mean annual air temperature about —5° C), showed that snow cover is a dominant factor in controlling permafrost distribution at that site. Variations in snow cover cause temperature variations greater than those resulting from vegetation cover. It has been postulated that a snow depth of about 40 cm can be regarded as the critical snow depth for permafrost to survive. Beneath a greater depth either there is no permafrost or a degrading condition prevails (Annersten, 1964).

There is little if any significant effect of permafrost on the snow cover. The low ground temperatures may retard melting at the bottom of the snow cover but this possibility does not appear to exert much influence.

*Bare soil and rock.* Bare soil and rock have considerable influence on the temperature of the ground because of their ability to reflect solar radiation. Reflectivity values in the range of 12-15 per cent for rock and 15-30 per cent for tilled soil have been observed. There will also be different evaporation rates and intakes of precipitation. Variations in thermal properties such as conductivity, diffusivity, and specific heat affect the rate of permafrost accumulation. The thermal conductivity of silt, for example, is about one-half that of coarse-grained soils and several times less than that of rock. These factors assume their greatest significance in the northern part of the Subarctic where the climate is sufficiently cool to produce permafrost regardless of the type of terrain (Brown and Johnston, 1964).

The influence of permafrost on soil and rock is manifested by such phenomena as clay boils, solifluction, and other down-slope mass movements of earth material. These movements and frost action in the active layer tend to break down coarse soil particles and rock fragments into fine-grained material. Intensive frost action is also responsible for the heaving of massive blocks of fractured bed-rock.

*Glacier ice.* The growth and regime of glaciers and ice caps is determined by climate but ice is considered as a terrain factor in this paper because like vegetation, water, and snow, it forms a layer on the ground surface between the permafrost and the atmosphere which affects the heat exchange between them. It has been postulated that the bottom temperature beneath much of a continental ice sheet is below 0° C. In temperate glacier conditions, the ice bottom temperature is at the pressure melting point. Beneath an ice sheet 2,000 m thick, for example, the temperature of the water film at the bottom of the ice would be about —1° C. In polar glacier conditions, the bottom of the ice is frozen to the underlying ground and the temperature at the ice-ground interface is below 0° C. Both of these glacier conditions probably occur extensively throughout an ice sheet. Consequently, beneath continental ice sheets in the Northern Hemisphere permafrost was probably widespread but thin because of the proximity of bottom temperatures to 0° C. Permafrost may have been somewhat thicker beneath the margins of ice masses where the effect of cold air temperatures can penetrate to the underlying ground (Shumskiy, 1964). After the ice retreated, permafrost in areas covered by post-glacial inundations was probably dissipated and would not have re-formed until these bodies of water receded several thousand years later. In contrast to areas covered by ice sheets, much colder temperatures were imposed by the periglacial climate on ice-free areas producing thicker and colder permafrost.

Thus, continental glaciation has undoubtedly exerted great influence on permafrost conditions from one region of the Subarctic to another. It is notable that ice sheets were much more extensive in the Western Hemisphere than the Eestern Hemisphere (see Figure 1). All of subarctic North America, excluding western Yukon Territory and central Alaska, were covered with ice sheets during the Pleistocene (Flint, 1957). In contrast, a large part of central and eastern Siberia was not covered and here continuous permafrost now extends more than 1,000 km south of the tree line, and the thickest permafrost in the Northern Hemisphere has been recorded.

## CONCLUSION

Many fluctuations have occurred through time in the extent, thickness, and temperature of the permafrost in response to changes in climate and terrain. Since its initial formation, the permafrost in any area may have dissipated and re-formed several times during periods of climatic warming and cooling. Glacial history has had a marked effect. Changes in vegetation caused by fire, climatic succession, encroachment in water basins, or by the permafrost itself all have pronounced local effects. The regime of the fall and accumulation of snow influences the ground thermal regime. The geothermal gradient also affects the ground thermal regime. It varies in different types of soil and rock, with changes in geological structure and with time.

Thus the environment in which permafrost exists is a complex dynamic system, the product of past and present climate and terrain features, which are in turn influenced by the permafrost. The thermal sensitivity of permafrost is such that even small changes in climate and/or terrain will produce changes in the extent, thickness, and temperature of the permafrost. The interactions of permafrost and other factors in the Subarctic are varied and very complex. Even a slight change in one factor produces a change in one or several other factors.

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# Résumé

*Le pergélisol, facteur écologique de la région subarctique* (R. J. E. Brown)

Dans la région subarctique, le pergélisol est en corrélation étroite et complexe avec de nombreux facteurs climatiques et morphologiques. La région subarctique est considérée comme comprenant toute la zone discontinue de pergélisol et la partie de la zone continue située au sud de la limite de la forêt. On admet arbitrairement que les deux zones de pergélisol sont séparées par l'isotherme —5° C de la température moyenne annuelle du sol mesurée immédiatement au-dessous de la profondeur où se font sentir les variations saisonnières. L'extension du pergélisol augmente progressivement du sud au nord de la région subarctique, ainsi qu'avec l'altitude dans les secteurs montagneux. On a constaté l'existence de zones fossiles de pergélisol en profondeur dans la région du pergélisol ; il est possible qu'il en existe également au sud de cette région. Dans l'hémisphère nord, le pergélisol s'étend plus au sud et les conditions qui y règnent sont plus rigoureuses en Eurasie qu'en Amérique du Nord. Le climat est le plus important des facteurs qui influent sur la formation et l'existence du pergélisol et qui déterminent les formes générales de son apparition et de sa répartition. Les conditions du terrain, comme le relief, la végétation, l'écoulement des eaux, l'enneigement, le type de sol et la glaciation déterminent les variations locales dans ce cadre général. Le pergélisol influe de son côté sur ces facteurs en milieu subarctique. Ce système dynamique peut évoluer avec le temps, une légère modification de l'un des facteurs entraînant une modification d'un ou de plusieurs autres facteurs.

# Discussion

F. E. Eckardt. Vous avez montré un nombre impressionnant d'exemples de permagel dans des paysages extrêmement variés, et il semble à première vue très difficile d'établir des corrélations entre l'existence de ce phenomène et l'action des facteurs physiques et biologiques qui en sont la cause, le nombre de ces facteurs étant très élevé. Pourriez-vous me dire si l'on a déjà essayé d'établir de telles corrélations au moyen de techniques de calcul modernes ?

R. J. E. Brown. Yes, there are correlations between climatic and terrain factors on the one hand, and permafrost on the other hand, which can be used to predict with considerable confidence the existence and distribution of permafrost. Many of these correlations are discussed in my paper. However, much work remains to be done. There is a great need for conducting detailed and complete energy balance measurements in permafrost areas. In the discontinuous zone, it is important to know why permafrost occurs in one area and not in an adjacent area. This situation is due to variations in the thermal contributions of the various environmental components to the permafrost. The problem then arises of precisely what measurements to make and what instrumentation to use. Some studies of this nature have been carried out in North America and the Soviet Union.

A. Jahn. The problem of thickness of permafrost: both Dr. Brown and Dr. Péwé called the very shallow, very thin

(20-30 cm) layer of frozen ground "permafrost". Is it right to call such a layer permafrost? This may be seasonal frozen ground, rather than permafrost.

R. J. E. Brown. In my paper I defined "permafrost" and stated the minimum and maximum lengths of time involved. The minimum length of time required for frozen ground to persist in order that we may call it permafrost is one year. That is to say, let us consider a situation where seasonal frost begins to form in the late autumn and penetrates to a depth of, say, 1 m through the winter. During the following summer, thawing of the ground proceeds from the surface and extends downward. Let us suppose now that thawing continues into the autumn and stops without thawing a few centimetres (perhaps 5 or 10) at the bottom of the frozen layer. At this time, the seasonal frost begins again to penetrate downward from the surface of the ground. The thin layer which persisted through the summer is permafrost, or perennially frozen ground, because it persisted through one year. Perhaps it will thaw during the next summer but while it existed, it was considered as permafrost. At the other extreme, there is the permafrost which persists through thousands of consecutive summers.

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