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INFLUENCE OF CLIMATIC AND TERRAIN FACTORS ON GROUND TEMPERATURES AT THREE LOCATIONS IN THE PERMAFROST REGION OF CANADA

BY

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Regular periodic measurements (at least monthly) of ground temperatures are being taken by the Division of Building Research, National Research Council of Canada, at three locations in northern Canada to assess the influence of climatic and terrain factors on permafrost. These are Thompson, Manitoba (55° 48'N, 97° 52'W), situated in the southern part of the discontinuous permafrost zone, Yellowknife, Northwest Territories (62° 28'N, 114° 27'W), in the northern part of the discontinuous permafrost zone, and Devon Island (76°N), located in the Canadian Arctic Archipelago (Queen Elizabeth Islands) in the northern part of the continuous zone. Ground temperature measurements with thermocouple cables down to the 15-m depth in various types of terrain are being taken at these locations and analyzed to determine the range of mean annual ground temperatures that may exist at any one site in the permafrost region.

L'INFLUENCE DES CONDITIONS DU CLIMAT ET DU TERRAIN SUR LA TEMPERATURE DU SOL EN TROIS ENDROITS DE LA REGION DU PERGELISOL AU CANADA

La Division des recherches en bâtiment du Conseil national de recherches du Canada effectue des mesures périodiques (au moins mensuelles) de la température du sol en trois endroits du Nord canadien afin d'évaluer l'influence des conditions du climat et du terrain sur le pergélisol. Ces endroits sont Thompson au Manitoba (55° 48'N, 97° 52'O), dans la partie sud de la zone du pergélisol discontinu; Yellowknife dans les Territoires du Nord-Ouest (62° 28'N, 114° 27'O), dans la partie nord de la zone du pergélisol discontinu; et l'île Devon (76°N), située dans l'Archipel arctique canadien (les îles Queen Elizabeth), dans la partie nord de la zone du pergélisol continu. On effectue en ces endroits des mesures de la température du sol au moyen de câbles à couple thermoélectrique jusqu'à une profondeur de 15 m dans divers genres de terrain; on analyse ensuite ces mesures afin de déterminer l'écart des températures annuelles moyennes du sol pouvant exister en un endroit quelconque de la région du pergélisol.

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INTRODUCTION

Regular periodic measurements (at least monthly) of ground temperatures are being taken by the Division of Building Research, National Research Council of Canada, at three locations in northern Canada to assess the influence of climatic and terrain factors on permafrost. These are Thompson, Manitoba (55°48′N, 97°52′W), situated in the southern part of the discontinuous permafrost zone, Yellowknife, Northwest Territories (62°28′N, 114°27′W), in the northern part of the discontinuous permafrost zone, and Devon Island (76°N), located in the Canadian Arctic Archipelago (Queen Elizabeth Islands) in the northern part of the continuous zone.[1,2] Ground temperature measurements with thermocouple cables down to the 15-m depth in various types of terrain are being taken at these locations and analyzed to determine the range of mean annual ground temperatures that may exist at any one site in the permafrost region.

TERRAIN CONDITIONS AND DESCRIPTION OF SITES

Thompson, Manitoba

Thompson, 200 m above sea level with a mean annual air temperature of −3.3 °C, is located in the Precambrian shield region in northern Manitoba. It is situated near the northern margin of glacial Lake Agassiz where the glaciolacustrine varved silts and clays are about 30 m thick overlying a thin layer of till on bedrock. The generally subdued relief is interrupted only by river valleys, cut into the overburden, scattered rock outcrops, and glaciofluvial deposits.

Permafrost occurs in scattered islands varying in extent from a few tens of square metres to several hectares and in thickness from about 1 to 15 m or greater, averaging between 3 and 5 m.[3] The permafrost table is generally encountered anywhere from about 0.5 to 2 m below the ground surface. Much ice, primarily in the form of horizontal lenses up to 20 cm thick (the average thickness being less than 2.5 cm), is found throughout the frozen glaciolacustrine silts and clays underlying the area. No permafrost occurs in the Precambrian rock outcrops scattered throughout the region.[3]

Five sites were selected for study in a program of investigation of microclimatic and terrain factors affecting the distribution and characteristics of permafrost, which includes measurements of ground temperatures.[4] Four of the sites on the glaciolacustrine soils are located within a distance of a few hundred metres of each other, two with permafrost and two with none. Weekly measurements of ground temperatures have been undertaken since June 1968 on 12-point thermocouple cables installed in augered holes to a depth of 7.5 m. The fifth site is located in a rock (pegmatite) outcrop where weekly measurements of ground temperatures have been undertaken since February 1968 on thermocouple cables installed in drilled holes to a depth of 6 m. Air temperature, ground surface temperature, snow depth, and density measurements also have been taken regularly at all sites.

Of the four sites, site A supports black spruce up to 6 m high and dense growth, 0.5-1.5 m between trees, growing on a 10-cm-thick layer of feathermoss and forest litter overlying brown clayey soil (grain-size analysis at a depth of 15-23 cm: clay, 59 percent; silt, 39 percent; sand, 2 percent). No permafrost exists at this site.

Site B supports open stunted black spruce up to 4 m high with 1.5-3 m between trees growing on a 10-cm-thick layer of *Sphagnum* over 10 cm of peat, 23 cm of black organic clay (31 percent organic content by weight) overlying brown clayey soil (grain-size analysis at a depth of 30-53 cm: clay, 77 percent; silt, 22 percent; sand, 1 percent). There is no permafrost at this site.

Site C (Figure 1) supports open stunted black spruce similar to that at site B growing on an 18-cm-thick layer of hummocky *Sphagnum* over 18 cm of peat, 10 cm of black organic clay (26 percent organic content by weight) overlying brown clayey soil (grain-size analysis at a depth of 35-60 cm: clay, 85 percent; silt, 14 percent; sand, 1 percent). There is permafrost at this site. The permafrost table in 1968 at the beginning of the observations was at a depth of about 48 cm, almost coincident with the base of the organic soil. The permafrost is about 2.7 m thick.

Site D supports dense black spruce similar to that at site

FIGURE 1 Site C at Thompson, Manitoba, June 1968.

A that grows on a 13-cm-thick layer of *Sphagnum* over 18 cm of black organic silt (77 percent organic content by weight) overlying brown clayey soil (grain-size analysis for the organic silt: clay, 28 percent; silt, 62 percent; sand, 10 percent; in the brown clay at 33-48 cm: clay, 87 percent; silt, 12 percent; sand, 1 percent). The permafrost table is at a depth of about 75 cm and the permafrost exceeds 6 m in thickness.

A thermocouple cable was installed in the fall of 1971 in a peat plateau with permafrost to a depth of 22.5 m. The tree vegetation is similar to that at site A with a ground cover of hummocky *Sphagnum*, lichen, and peat about 0.5 m thick overlying brown clayey soil similar to the other soil sites. Temperature measurements through part of 1 year indicate that the permafrost is 12 m thick and cooler than the permafrost at site D.

Yellowknife, Northwest Territories

Yellowknife, 180 m above sea level with a mean annual air temperature of -5.5 °C, is located in the Precambrian shield on the north shore of Great Slave Lake. The terrain consists mainly of rock outcrops with scattered pockets of till, glaciofluvial deposits including sand and gravel outwash, and beach deposits. Peat bogs and small lakes occupy many of the rock basins.

Permafrost is widespread, but not continuous, and extends to depths exceeding 50 m in some areas.[5] It does not occur in the exposed bedrock, but it is found where the rock is covered with overburden. Its greatest extent is in peatlands supporting spruce and sedge vegetation where the active layer is about 1 m. Little information is available on ground ice. Random bodies of massive ice some tens of centimetres thick have been found in pockets of silt and clay, and thin ice layers have been observed at depth in bedrock fissures.

Eight sites were selected for study in a program of investigation of microclimatic and terrain factors affecting the distribution and characteristics of permafrost, which includes measurements of ground temperatures. A 12-point thermocouple cable was installed at each site to a depth of 15 m, four in September 1969 and the remainder 1 year later. Weekly or monthly measurements of ground temperatures have been undertaken since those dates. Air temperature, ground surface temperature, snow depth, and density measurements also have been taken regularly at all sites.

Three of the sites are situated on exposed bedrock supporting a few scattered stunted black spruce trees. The first (termed "black rock" site) is greenstone having a thermal conductivity [1] (wet) of 2.72 W/mk and porosity by volume of 0.2 percent. The second is a white granite (termed "white rock" site) having a thermal conductivity (wet) of 3.70 W/mk and porosity by volume of 0.8 percent. The third (Figure 2) is a pink granodiorite (termed "red rock" site) having a thermal conductivity (wet) of 2.60 W/mk and porosity by volume of 0.7 percent. No permafrost occurs in these sites.

Three sites in overburden where no permafrost was found are located on till, a beach ridge, and burned peatland. The till site supports open groves of birch and alder up to 7 m high with a ground cover of scattered berry plants, mosses, and lichens and an organic layer about 3 cm thick overlying a brown sandy stony till. The beach ridge site supports a dense growth of birch, jackpine, alder, and willow up to 8 m high with ground cover of berry plants, mosses, and lichens and organic layer about 3 cm thick overlying brown sandy

FIGURE 2 Red rock site at Yellowknife, N.W.T., September 1970.

gravel. The burned peatland site supports a dense growth of spindly black spruce up to 8 m high containing many dead and burned trees with ground cover of mosses and Labrador tea and a layer of wet peat 30 cm thick overlying wet fine sand. This material forms a 6-m-thick layer on greenstone bedrock.

The remaining two sites both contain permafrost. One site (termed "sedge peatland" site) is located in a peat bog supporting very scattered and stunted black spruce and tamarack up to 3 m high with willow and alder shrubs and ground cover of sedges, mosses, and peat 1 m thick overlying wet fine to medium sandy soil (Figure 3). The active layer is about 68 cm and the permafrost is about 30 m thick. The other site (termed "spruce peatland" site) is located in a peat bog supporting black spruce and some tamarack up to 7 m high with scattered willow and alder underbrush and ground cover of hummocky *Sphagnum* and lichen and peat 1.3 m thick overlying silty fine sand with stones. Greenstone bedrock occurs at a depth of 3 m. The active layer is 30 cm, and the permafrost is about 50 m thick.

Devon Island, Northwest Territories

The ground temperature observation sites are located on the north coast of Devon Island in a lowland near sea level

FIGURE 3 Sedge peatland site at Yellowknife, N.W.T., September 1970.

measuring about 6 X 8 km. The terrain consists of groups of beach ridges interspersed with lowlying tundra meadows. The northwest corner of the lowland consists of a Palaeozoic limestone bedrock plain, and Precambrian granite outcrops are scattered throughout the eastern portion. The lowland is bounded on the east and south landward margins by 300- to 400-m-high uplands of Cambro-Ordovician interbedded limestones and sandstones and Precambrian granite, respectively.[1]

Permafrost occurs everywhere beneath the ground surface to an estimated thickness of 450–600 m.[2] The active layer varies from a maximum of about 2.2 m in the granite bedrock to a minimum of about 12 cm in wet peaty meadow sites. Surface features, characteristic of high latitude continuous permafrost, abound including tundra ice-wedge polygons, 2-m-high polygonal peat mounds with 1-m-deep trenches, stony earth circles, and stone nets. Little information is available on the occurrence and distribution of ground ice, but it has been observed to exist in layers up to 1 m thick in the peat mounds and in vertical wedges beneath the trenches between these mounds.

Eleven holes were drilled in these major terrain units in June and July 1971 to obtain information on the perennially frozen soils and bedrock and to install thermocouple cables for monitoring ground temperatures in the permafrost. Monthly ground temperature measurements were taken from July to October 1971 inclusive. They were resumed in May 1972 and will be continued until summer of 1973 to furnish one 12-month period. Air temperature, ground surface temperature, snow depth, and density measurements also are being taken regularly at all sites. Data on the depths of the thermocouple cables, thickness of active layer and other information are given in Table I.

TABLE I Terrain Type and Active Layer Thickness at Thermocouple Cable Sites, Devon Island

Terrain Type	Elevation above Sea Level (m)	Depth of Cable (m)	Thickness of Active Layer (m)
Beach ridge			
south slope	38	1.45	1.1
top	38	1.20	0.9
north slope	38	0.75	0.6
Peat mound			
summit	30	1.35	0.3
trench	30	1.65	0.3
trench	30	1.05	0.3
Meadow	52	2.80	0.7
Limestone			
coast	1	8.70	1.2
inland	9	6.90	1.4
Granite-gneiss	75	6.45	2.2
Upland plateau	306	7.90	0.3

Four thermocouple cables, having sensors at intervals from 0.75 to 1.5 m, were installed in bedrock. Two of these are located in the limestone plain in the northwest section of the lowland, one at the coast about 1 m above sea level (Figure 4) and the other 0.5 km inland, 9 m above sea level. The rock down to a depth of about 4.5 m consists of pitted (vesicular) limestone having thermal conductivity values ranging from about 4.62 to 5.04 W/mk and porosity of about 3 percent. Below, the rock is a dolomitic limestone having thermal conductivity values ranging from about 4.20 to 4.62 W/mk and porosity of about 13 to 7 percent, respectively. One hole was drilled in a granite-gneiss outcrop, 75 m above sea level, having a thermal conductivity of 2.52 W/mk

FIGURE 4 Coastal site on limestone plain at Devon Island, N.W.T., July 1971.

FIGURE 5 Tundra meadow site on Devon Island, N.W.T., July 1971.

and porosity of 0.3 percent. The fourth thermocouple cable was installed on the 300-m-high upland plateau east of the lowland. Although this site is virtually devoid of vegetation, the ground surface is covered with stone nets. The soil to a depth of 1.5 m is stony silt overlying fissured sandstone and dolomite and has thermal conductivity values ranging from 3.11 to 3.71 W/mk and porosity of 10 to 3 percent, respectively.

Three of the thermocouple cables that had sensors at 15-cm intervals were installed on the south and north slopes and at the top of a gravel beach ridge about 38 m above sea level. This land form, typical of the beach ridges on the lowland, is virtually devoid of vegetation, except for scattered clumps of mosses and small flowering plants.

Another set of three cables, with sensors at 15-cm intervals, was placed in a nearby area of polygonal peat mounds, 30 m above sea level, one on the summit of a mound and two in trenches. The vegetation on the mounds consists of mosses, lichens, and sedges. The mounds consist of peat 2 m thick and contain irregular ice layers up to 1 m thick overlying stony till.

One cable with sensors at 0.75- to 1.5-m intervals was installed in a tundra meadow, 52 m above sea level. The ground vegetation is a continuous carpet of sedges and mosses and 12.5 cm of peat overlying sandy stony till containing granite boulders (Figure 5).

ANALYSIS OF GROUND TEMPERATURE OBSERVATIONS

Mean annual ground temperature values and envelopes for selected years at Thompson and Yellowknife were plotted versus depth to obtain profiles characteristic of the various terrain types (Figures 6-9). At Thompson, Manitoba, mean annual ground temperature values were plotted for 1969 for the four soil sites and for 1969 and 1970 for the pegmatite rock site. Temperature values at Yellowknife were plotted for 1970 for the greenstone rock site, burned peatland, sedge peatland, and spruce peatland sites and for all sites in 1971. At Devon Island, it was not possible to calculate annual means but the available values for July to October 1971 were averaged to obtain characteristics of the summer and fall ground thermal regimes (Figure 10).

Several correlations and generalizations can be made, the principal one being that the mean annual ground temperatures at depths down to 15 m may vary 2 °C among various types of terrain at any one location in the permafrost region.

At Thompson, the mean annual ground temperature profiles vary from the lowest at site D, which has the thickest permafrost, to site C, with thinner permafrost, to the two soil sites, with no permafrost, to the warmest, which is the bedrock site. The temperature differences between adjacent installations at the soil sites range from 0.5 to about 1 °C. The rock site is about 1.5 degrees warmer than the warmest soil site and nearly 3 degrees warmer than the coldest permafrost site. The amplitude of the annual temperature change appears to increase from the coldest hole to the warmest.

At site D, which has the thickest and coldest permafrost, the amplitude from the 2-m depth to the bottom of the hole is about 1 °C and increases to the warmest soil site hole where it is about 2 °C. The amplitude at the bedrock hole is much greater, being about 4.5 °C at the 6-m depth.

The relations of snow depth and density to ground temperatures are not straightforward. The least snow accumulation does occur at site D, but it is almost as low at site A, a nonpermafrost site. Site C, the other permafrost site, is the

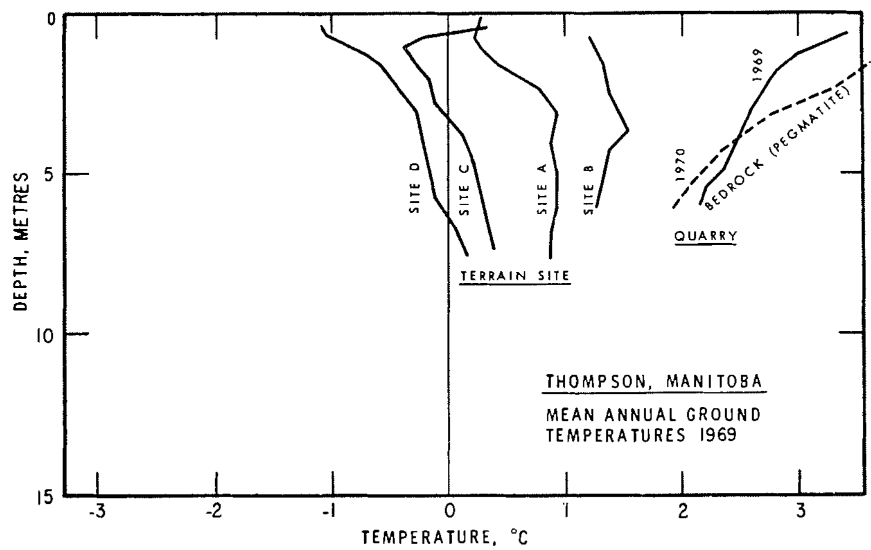

FIGURE 6 Mean annual ground temperatures, Thompson, Manitoba, July 1971.

highest of the four. Sites A and D have denser tree growth than B or C, and snow density values are generally about 10 percent lower at sites B and C. The snowfall in the early winter of 1969–1970 was greater than in 1970–1971, which appears to be reflected in the minimum temperatures at the bedrock site being slightly warmer in 1969 than in 1970.

At Yellowknife, the mean annual ground temperature profiles vary from the lowest at the spruce peatland site, which has the thickest permafrost, to the warmest holes in the bedrock. The temperature differences between adjacent installations average about 0.25 °C; the total range is about 2 °C. This is considerably less than the range between the coldest permafrost hole and bedrock hole at Thompson. The coarse-grained till and beach sites have annual means similar to the bedrock holes. The white rock (granite) has the lowest mean annual temperature (about 0.5 °C) and the highest thermal conductivity (3.68 W/mk); the red rock (granodiorite) has the highest mean annual temperature (about 1.5 °C) and the lowest thermal conductivity (2.59). The black rock (greenstone) has mean annual temperatures of about 1 °C and a thermal conductivity value of about 2.72

The amplitude of the annual temperature change is greatest in the bedrock holes and is similar in the three holes. The difference between maximum and minimum temperatures is much greater than at Thompson, as illustrated by the temperature at the 6-m depth, which is 9.0 °C at Yellowknife and 4.5 °C at Thompson. The amplitude from the 7- to 15-m depth in the till and beach holes is much less, averaging 0.5–1 °C in the former and 1.0–1.5 °C in the

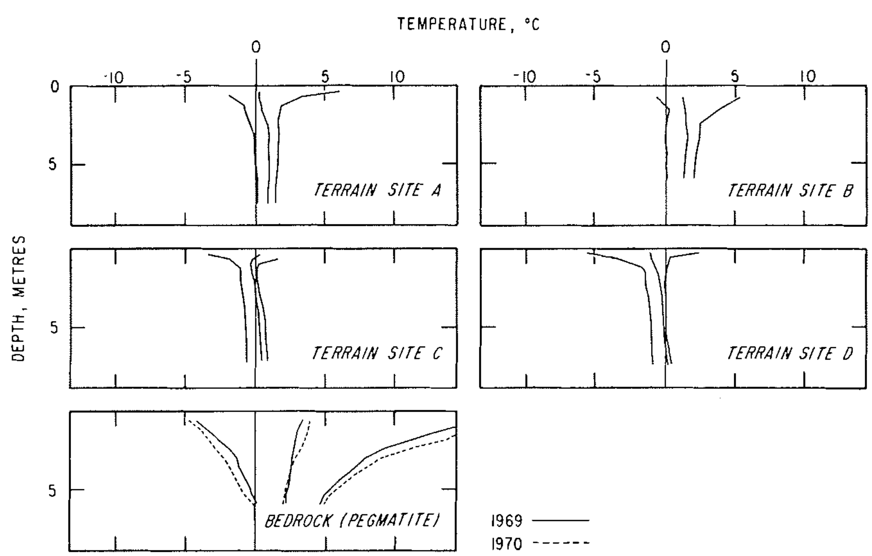

FIGURE 7 Ground temperature envelopes, Thompson, Manitoba, 1969 and 1970.

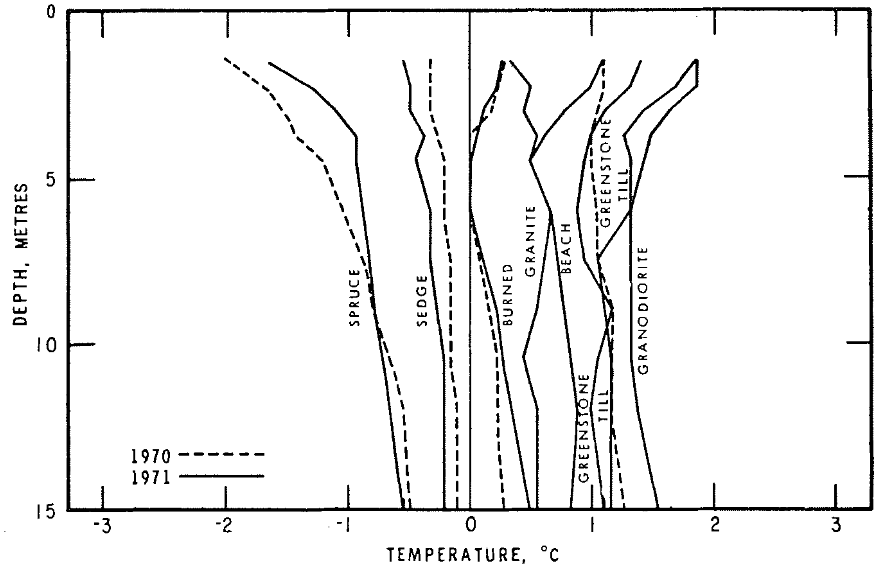

FIGURE 8 Mean annual ground temperatures, Yellowknife, N.W.T., 1970 and 1971.

latter. It is even smaller in the burned sedge and spruce peatland sites that range from 0.25 to 0.5 °C. The amplitudes in the last three holes decrease abruptly in the 1- to 3-m depth and to a lesser extent in the till and beach holes in contrast to the bedrock holes where the amplitudes decrease smoothly with depth. In all of the holes, there is a noticeable fluctuation of temperature through the year at the 15-m depth that ranges from 2 °C at the black rock site to 0.25 °C in the sedge peatland.

The relation of snow depth and density to ground temperatures is again not straightforward. The maximum snowcover in the winter of 1970-1971 ranged from 33 cm at the black rock site to 45 cm in the burned and sedge peatland sites. The rock sites generally had slightly less accumulation than the other sites and densities about 5 percent higher.

Snowfall was greater in 1970-1971 than in 1969-1970 which appeared to be reflected in the ground temperature regimes. For example, the annual mean and minimum temperatures were slightly warmer in the second year at the black rock and spruce peatland sites.

At Devon Island, ground temperature observations are available only for July to October 1971. Nevertheless, some characteristics of the summer and fall ground thermal regime are evident. Significant variations occurred in the thickness of the active layer in different types of terrain ranging from the deepest (2.2 m) in granite-gneiss to the shallowest (0.3 m) in the peat mounds and the upland plateau. Variations due to slope orientation are very evident in the beach ridge. There did not appear to be significant variation in the peat mounds between the mound summit and the trenches. The

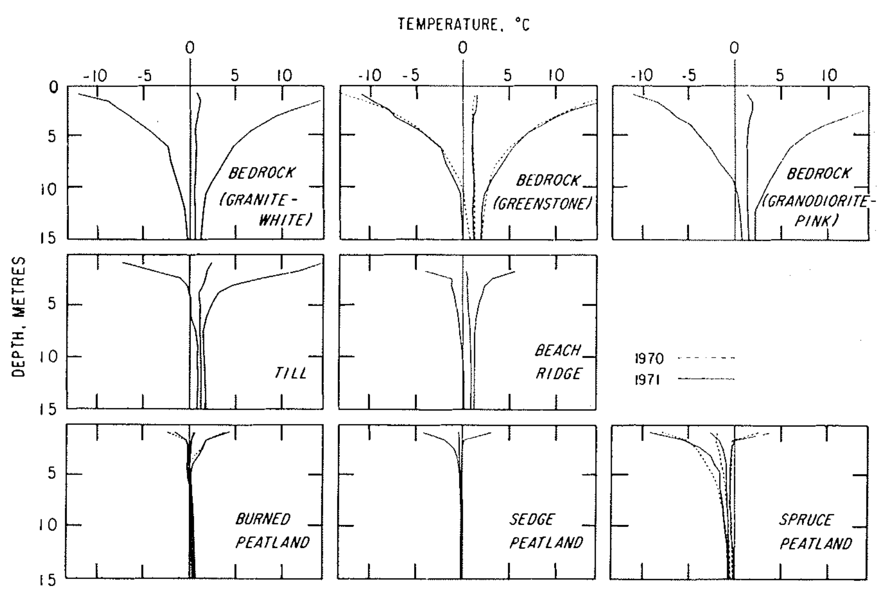

FIGURE 9 Ground temperature envelopes, Yellowknife, N.W.T., 1970 and 1971.

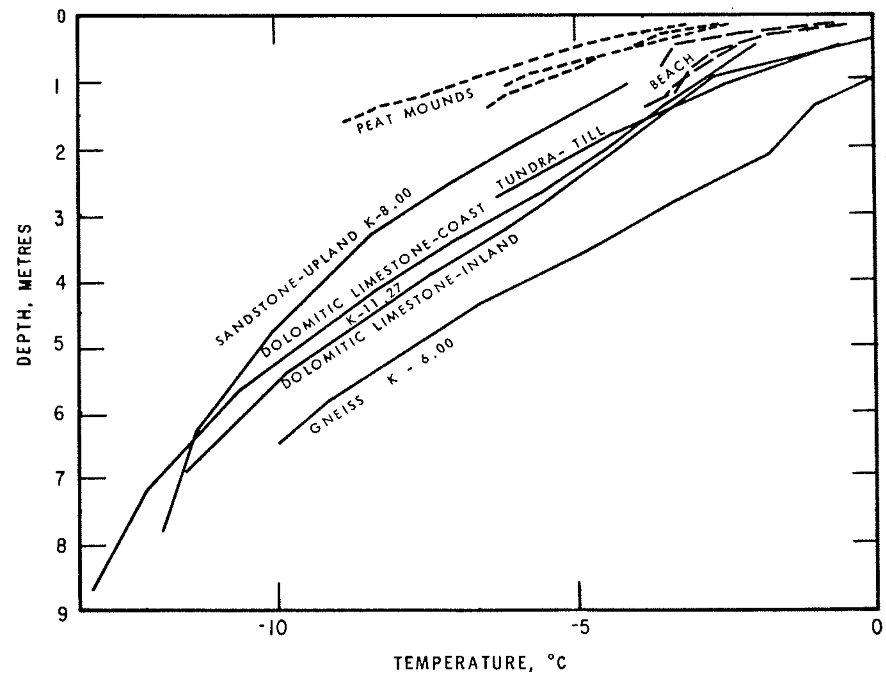

FIGURE 10 Average of mean monthly ground temperatures, Devon Island, N.W.T., July to October 1971 (inclusive).

active layer in the meadow was less than in the beach ridges (except the steep north slope) and rock outcrops because of the surface vegetation. The active layer in the limestone (especially at the coast) was considerably less than in the granite-gneiss possibly because of the former area's proximity to the cold ocean water.

These variations in depth of active layer are reflected in the ground temperature averages for the summer months. In the peat mounds, these values were nearly 3 °C lower than in the beach ridges in the active layer and top metre of the permafrost. Further down, the upland was coldest, probably because of its high elevation relative to the other stations, the tundra meadow was colder than the limestone, and the granite-gneiss was considerably warmer. The relative effect of variations in thermal conductivity for the rock is not clear nor is the influence of snow depth and density.

All sites experienced a marked drop in ground temperature near the surface from August to September, and freeze-back of the active layer was completed during this period. At the bottom of the holes, the warmest temperatures were experienced in October as the effect of summer atmospheric heating penetrated downward.

CONCLUSION

These observations at Thompson, Yellowknife, and Devon Island indicate that mean annual ground temperatures at depths down to 15 m may differ over a 2 °C range among various types of terrain at any one location in the permafrost region. These variations are reflected in different depths of active layer that may range from less than 0.5 m to more than 2 m, even in the northern part of the continuous zone. Variations greater than 1 °C may occur even between sites only a few tens of metres apart. These local differences can reflect significant differences in the extent and thickness of permafrost and the susceptibility to thawing. Many more observations are required from other parts of the permafrost region to correlate terrain type and ground temperature conditions.

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NOTE

[1] All thermal conductivity determinations in this paper were made by the Geothermal Studies Section, Seismology Division, Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa, Canada.

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