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PERMAFROST - DISTRIBUTION AND RELATION TO ENVIRONMENTAL FACTORS IN THE HUDSON BAY LOWLAND

BY

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SOMMAIRE

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PERMAFROST - DISTRIBUTION AND RELATION TO ENVIRONMENTAL FACTORS IN THE HUDSON BAY LOWLAND

R.J.E. Brown[1]

SYNOPSIS

The Hudson Bay Lowland lies mostly in the permafrost region of Canada. The distribution of permafrost varies from discontinuous in the southeast, north of the 30°F mean annual air isotherm, to continuous in the northwest, between the 25°F and 20°F mean annual air isotherms. The active layer varies from 1 to 3 feet, and permafrost ranges in thickness from a few inches at the southern limit to 200 feet in the continuous zone at Churchill. In the discontinuous zone, permafrost is found in peat plateaus and palsas which are prevalent, but it does not occur in intervening wet depressions nor in beach ridges or river banks. Permafrost exists everywhere beneath the land surface in the continuous zone which forms a narrow strip along the Hudson Bay coast. The most distinctive permafrost features are palsas of varying size to elevated peat plateaus exceeding 10 feet in height covering several acres. They form very distinctive air photo patterns and their origin appears related to thin snow cover.

DISTRIBUTION OF PERMAFROST

The Hudson Bay Lowland lies almost entirely within the permafrost region of Canada (Brown, 1968) (Figure 1). The southern boundary of the Lowland extends along the fiftieth parallel and the southern limit of permafrost is located at approximately latitude 51°N. From the southern tip of James Bay the Lowland extends in a northwesterly direction to latitude 58°N. About one-half of the permafrost region of the

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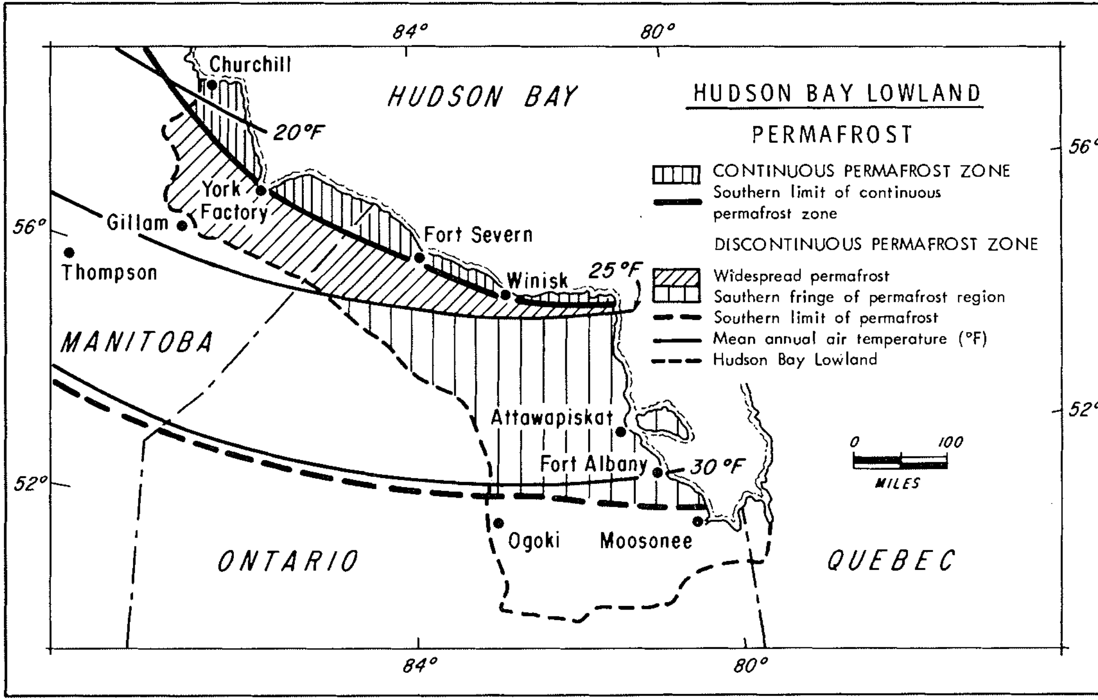

FIGURE I PERMAFROST DISTRIBUTION IN HUDSON BAY LOWLANDS

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Lowland is in the discontinuous zone and one-half in the continuous zone. The distribution of permafrost is notable for several reasons. First, the most southerly limit of permafrost in Canada (excluding the western Cordillera region) is at the south end of James Bay near Moosonee. Second, the discontinuous zone is narrower than anywhere else in Canada, being only about 250 miles wide in contrast to about 500 miles in the Mackenzie River region. Third, the continuous permafrost zone reaches its most southerly extent in Canada at the north end of James Bay (Brown, 1967).

Within the permafrost region of the Lowland, perenially frozen ground varies from scattered islands in the south to continuous in the north. In the southern fringe of the discontinuous zone, permafrost islands vary in extent from less than 50 feet to several acres. The thickness of these patches varies from a few inches to 1 or 2 feet at the southern limit of the permafrost region to tens of feet where the distribution becomes widespread in the northern portion of the discontinuous zone. No information is available on the thickness of permafrost at any stations in Ontario, but thicknesses of 100 feet have been encountered at Gillam in northeastern Manitoba where permafrost is widespread. Northward, the permafrost is continuous reaching depths of 200 feet at Churchill. The continuous zone is generally much thinner in the Lowland than elsewhere in Canada; it is confined to a narrow coastal strip. Because of its proximity to Hudson Bay, the permafrost, although continuous, is probably thin (perhaps only 100 feet or less in Ontario) and wedges out at the shore.

All known occurrences of permafrost in the discontinuous zone occur in peatlands which comprise all of the terrain of the Hudson Bay Lowland except river banks, beach ridges and a few rock outcrops south of Winisk. Several of the major rivers flowing eastward into James Bay - Albany, Attawapiskat and Ekwan - have north- and south-facing banks. It could be expected that permafrost might exist in the north-facing banks of these rivers but none has been reported. In the continuous zone, permafrost occurs everywhere beneath the land surface.

CHARACTERISTICS OF PERMAFROST

Tree growth in the Lowland consists of scattered to dense spruce, varying in height from 2 to 40 feet, and tamarack. Alder and willow provide the under-growth. Areas of burned trees are prevalent especially on well drained peat plateaus and palsas. The ground vegetation is a mosaic of Sphagnum, feather and other mosses, Labrador tea, grass and marsh sedge in various combinations. The micro-relief ranges from flat to very hummocky. Individual hummocks vary in size to a maximum of 3 feet high and 4 feet wide. Variations in elevation from one association to another range through several feet. Peat plateaus rising 3 to 4 feet above the surrounding poorly drained areas are prevalent. Palsas up to 12 feet or more in height occur in large numbers in the Hudson Bay Lowland. Surface and subsurface drainage is variable. Standing water is usually associated with marsh sedge areas and many of the lowest lying Sphagnum areas; individual hummocks, peat plateaus, and palsas are drier. Depth to the mineral soil (thickness of moss/lichen and peat) varies from a minimum of 1 foot to depths exceeding 10 feet. Hustich (1957) has ascribed an average value of annual peat accumulation in the Hudson Bay Lowland of about 1/20 inch based on numerous observations. Mineral soils are predominantly fine-grained silts and clays.

The depth to the permafrost table ranges from an observed minimum of 1 foot to a maximum of about 3 feet. This situation prevails throughout the Lowland from Moosonee in the southeast to Churchill in the northwest. Local differences in moisture content and related thermal conductivity of the peat cause greater variations in the depth of thaw than regional climatic differences. The thickness of permafrost varies from layers a few inches thick at the southern limit to about 200 feet at Churchill. Ground ice occurs mainly in horizontal layers ranging from hairline to about 1 inch in thickness. One exception to this was a layer of ice 3 feet thick encountered in the palsa in Figure 2. Ice is also found in the form of small pellets and other random inclusions.

Micro-relief in the form of hummocks, peat plateaus, and frequently palsas are widespread. The Sphagnum is hummocky regardless of whether or not permafrost is present. Peat plateaus and palsas always indicate the existence of permafrost and both types of features appear to be related in origin and development. In the Hudson Bay Lowland, numerous areas of coalescing palsas exist which are virtually indistinguishable from peat plateaus. West of Winisk, for example, mature peat plateaus with lichen cover (Figure 3) were observed to be similar in origin and appearance of coalescing palsas in Figures 4 and 5.

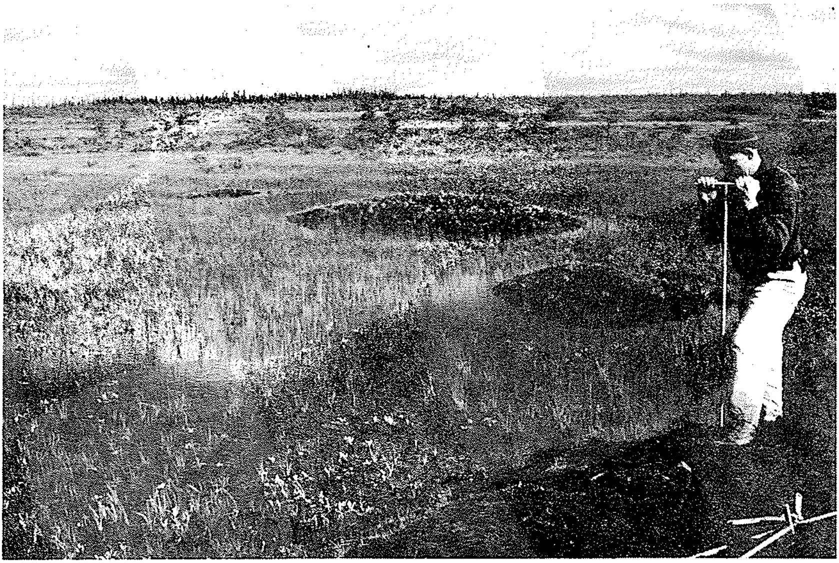

Figure 2 - Stop No. 5 - Small youthful palsas containing permafrost in wet peatland with no permafrost located at the southern limit of discontinuous zone in Hudson Bay Lowland. The peat in the large palsa in the foreground is 5 ft 2 in. thick overlying grey clayey silt with fine sand. The depth to the permafrost table in the centre of this palsa is 1 ft 1 in. and the permafrost layer is 4 ft 2 in. thick. 14 September 1965.

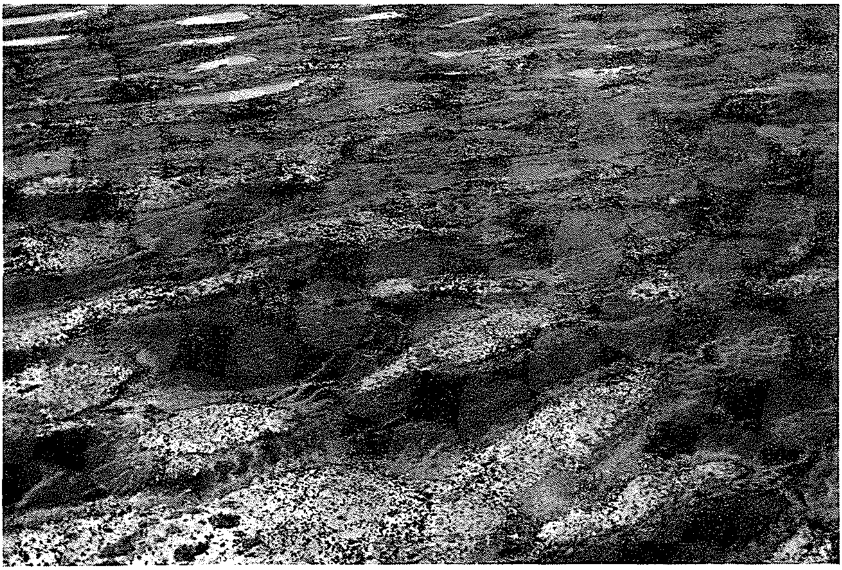

Figure 3 - Aerial view from altitude of 500 ft of mature palsas, coalesced palsas and peat plateaus interspersed with ponds and small shallow lakes in Hudson Bay Lowland 20 miles west of Winisk. 17 September 1965.

Figure 4 - Stop No. 9 - Mature coalesced palsas forming peat plateaus in Hudson Bay Lowland. Note burned spruce trees and dense cover of Labrador tea. Ground surface is very hummocky and covered with Sphagnum and lichen below which is peat to a depth of 4 ft 9 in. overlying grey silty clay with sand and stones. The depth to the permafrost table is 2 ft 8 in. No permafrost occurs in the sedge-covered depression in foreground. 16 September 1965.

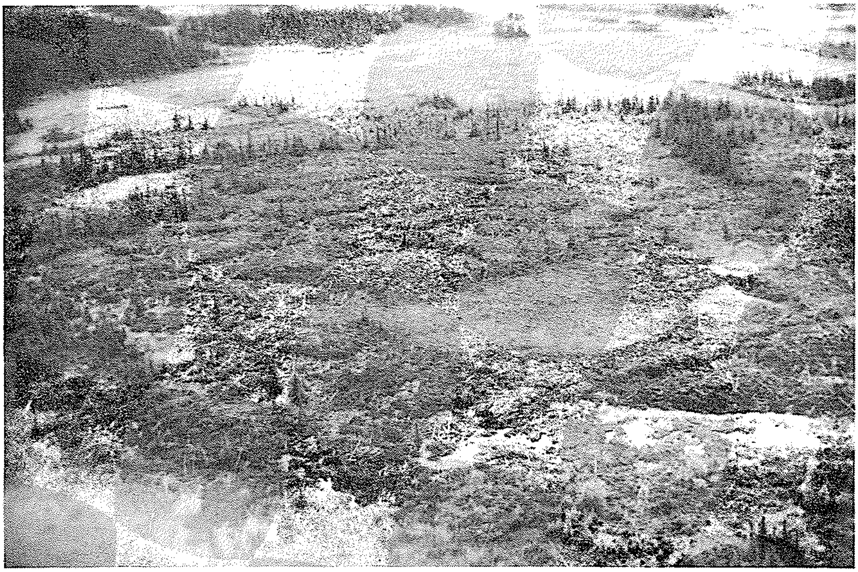

Figure 5 - Aerial view from altitude of 500 ft of palsas and peat plateaus at Stop No. 9. Note wet patterned fen with spruce islands in background. 16 September 1965

The peat plateaus and palsas in the Hudson Bay Lowland are the sites of the worst forest fires because they are the driest areas and support the most vigorous tree and lichen growth. One peat plateau south of Fort Severn which experienced a very recent burn was 3 feet high with recently burned dead spruce up to 15 feet. The ground cover consisted of charred Sphagnum and burned lichen, with a few patches of unburned Sphagnum. The fire had burned the top 1/2 inch of Sphagnum and the top 1 inch of lichen down to the wet basal layer. The depth to the permafrost table in the peat was 1 foot, the same as in the surrounding unburned Sphagnum-covered areas. It appeared that the unburned peat protected the permafrost from the heat of the fire and the increased solar heat input due to the burned black surface.

PALSAS

Palsas are very prevalent in the Hudson Bay Lowland. The palsas shown in Figure 2 constitute the most southerly occurrence of permafrost. These palsas are small, being in the early stage of development. They vary in size from a few square feet to the largest yet seen measuring 31 feet long by 12 feet wide by 2 feet high and are surrounded by water. Living vegetation is absent except for a few willow shrubs and sedge plants, consisting of bare sedge peat. Subsurface exploration in the largest palsa revealed a layer of peat 5 feet 2 inches thick overlying grey clayey silt with fine sand down to the 7-feet 4-inches depth. Below this depth the soil is stoney. The depth to the permafrost table varied from 1 foot 1 inch in the middle of this palsa to 2 feet 1 inch at the water's edge. The permafrost core varies in thickness from 4 feet 2 inches, including a layer of ice 3 feet thick in the middle of the palsa tapering to 7 inches at the water's edge. The permafrost wedges out a few inches beyond the edge of the palsa under the water. No permafrost occurs in the surrounding areas under water.

Mature palsas (Figures 4 and 5) stand as high as 10 feet above the surrounding peatland surface and support a tree growth of scattered spruce up to 10 feet. The presence of many burned trees both standing and lying on the ground indicated a previous dense growth of mature spruce. The ground cover consists of almost continuous lichen and dense Labrador tea. The lichen has undergone considerable biological oxidation and the ground surface is very hummocky and cracked. The peat varies in thickness from 4 feet 9 inches to 2 feet in local hollows overlying grey silty clay with a mixture of sand and stones. The depth to the permafrost table was observed to be 2 feet 8 inches but no permafrost was found in the local hollows. Ice was found in the peat and mineral soil.

A large 20-feet high mature palsa was examined between the Ekwan and Attawapiskat Rivers about 100 miles west of James Bay. The tree growth, consisting of spruce up to 30 feet high, was the most vigorous of all the palsas examined. The large number of dead mature trees lying on the ground indicated previous dense tall growth. Several depressions up to 20 feet in diameter and about 12 feet deep occurred in the palsa supporting scattered spruce 2 feet high. The ground cover of the palsa consisted of hummocky Sphagnum, scattered lichen and Labrador tea. In the depressions the ground cover was Sphagnum, sedge and ground birch, and the water stood at the ground surface. The peat in the palsa was about 7 feet thick as was that in the depressions overlying grey clayey silt with stones. The depth to the permafrost table was 2 feet 3 inches in the areas of growing trees and 2 feet 9 inches in the burned areas. No permafrost was encountered in the depressions.

In addition to the palsas described above, many others in all stages of development exist in the Hudson Bay Lowland. Near the coast of James Bay, between the Albany and Attawapiskat Rivers, there are many small scattered palsas. Inland from James Bay and south of the Attawapiskat River, several old palsas, partially destroyed by thawing and slumping, were observed. No newly forming ones were seen in this area south to Mississa Lake at the southern limit of the permafrost similar to those described in Figure 2 near Moosonee. North of the Attawapiskat River, palsas seem to exist mostly in the centres of shallow ponds. Many also occur in the vicinity of the rock outcrops at Sutton Lake and Hawley Lake. South of Fort Severn in the northern part of the discontinuous permafrost zone extensive palsas up to 10 feet occur in which the permafrost probably exceeds 30 feet in thickness. Large coalescing ones exist near Fort Severn. Small developing palsas occur in a few lakes in the tundra coastal strip on Hudson Bay between Fort Severn and Winisk. Northward in Manitoba, large coalescing lichen-covered peat plateaus and palsas cover most of the terrain. One unusual feature is the presence of parallel strings of peat plateaus and palsas at York Factory on the peninsula between the mouths of the Nelson and Hayes Rivers. These features develop in concentric rows on strand lines as the peninsula emerges due to isostatic rebound. No permafrost forms in the intervening elongated depressions.

POLYGONS

Polygons and polygonal cracks, another type of feature associated with permafrost, occur widely in the continuous zone. They have been observed from Cape Henrietta Maria in the east to Churchill in the northwest. They are found in beach ridges, and lake bottoms and, near Churchill, they are widespread in peatlands. They appear to be related to thermal contraction of the ground and the development of ice wedges.

AIR PHOTO PATTERNS

The most notable feature of the air photographs is the variety of patterns in the peatlands of the Hudson Bay Lowland. The lack of relief and poor drainage contribute to the jumbled appearance of surface vegetation and other terrain features. Within this broad framework, the recognition of such permafrost features as peat plateaus and palsas is hindered by their small size on the available photographs, and their similarity to other terrain features which have no permafrost. Two photographs show some of the patterns including permafrost features of the Hudson Bay Lowland (Figures 6 and 7).

The first aerial photograph (Figure 6) was taken about 35 miles northwest at Attawapiskat. The entire area is peatland in which three main patterns are evident:

1. Medium grey with smooth texture covering the central and southwest portions of the photograph on both sides of the stream which flows from west to east. This is a low, wet, poorly drained flat sedge-covered area. The black peppery flecks are small pools of water less than 50 feet in diameter. No permafrost occurs in this area.

2. Fine network of closely spaced dark grey to black flecks in a light grey mesh-like matrix covering the northwest and eastern quarter of the photograph. This type of area termed "patterned fen with flarks" by Sjörs (1959b)

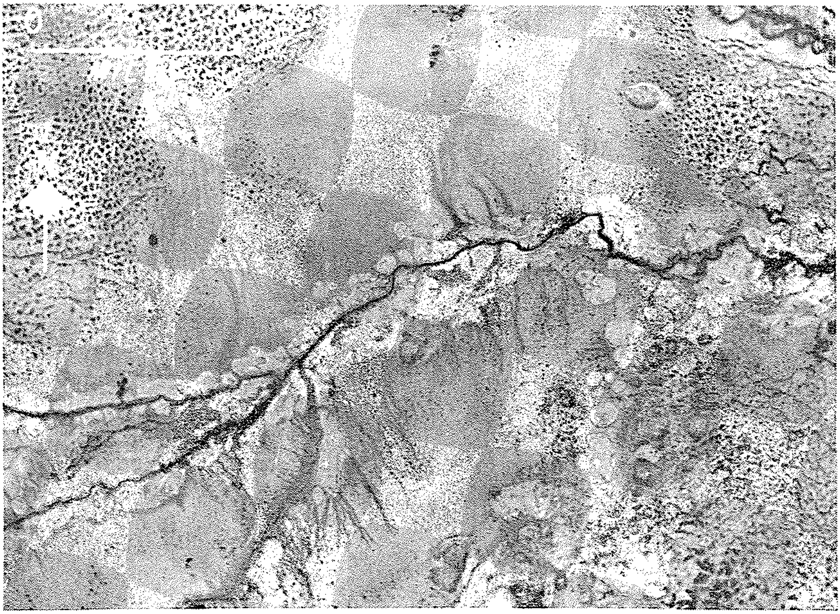

Figure 6 - Section of RCAF air photo A14961-128 at Stop No. 9 in the Hudson Bay Lowland northwest of Attawapiskat.

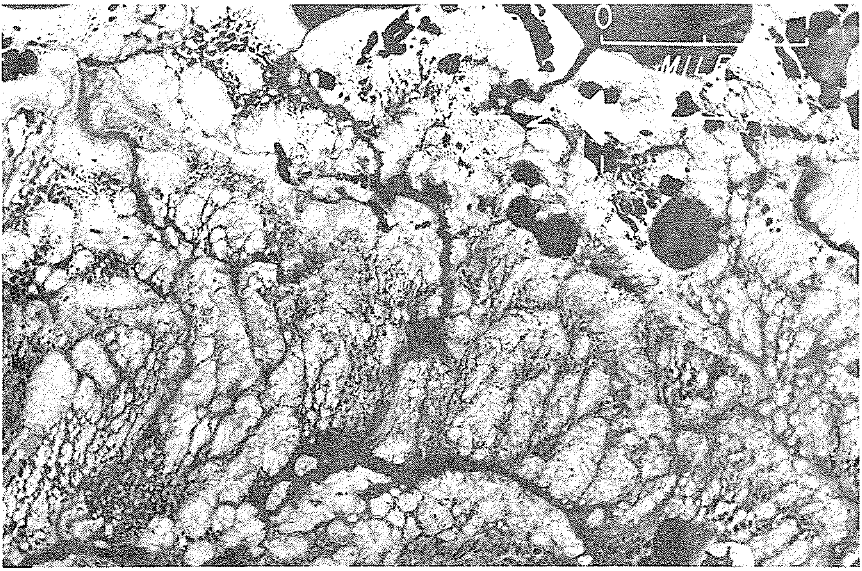

Figure 7 - Section of RCAF air photo A14137-65 west of Winisk in the Hudson Bay Lowland.

is low, wet, poorly drained and flat, and consists of shallow pools up to 100 feet in diameter separated by low narrow sedge-covered peat ridges about 1 foot high. The dark grey circular areas in the southeast corner are spruce islands up to several hundred feet in size. No permafrost was encountered in this type of terrain.

3. Light grey circular and irregularly shaped areas with white patches adjacent to the stream and bordering Pattern 2 in the southeast portion of the photograph. These areas are large mature palsas 15 feet high and high peat plateaus and coalesced palsas (Figures 4 and 5). The light grey tone is caused by the dense cover of Labrador tea growing on the lichen cover of the palsas. Permafrost does occur in these features.

The second aerial photograph (Figure 7) was taken 60 miles west of Winisk near the treeline. The entire area is peatland in which two main patterns are evident:

1. Light grey to white with fine to medium texture. This pattern occurs in irregularly-shaped areas varying greatly in size from several hundred feet to 1/2 mile. These areas are peat plateaus, ridges and mounds rising 5 to 10 feet above the neighbouring ponds and small lakes. The light grey areas support low stunted spruce growing on Sphagnum-lichen, and the white areas are lichen. Permafrost occurs in this pattern (Figure 3).

2. Network of closely spaced dark grey to black irregularly shaped flecks and minute spots in a medium grey mesh-like matrix producing a pattern similar to Pattern 2 of the first aerial photograph (Figure 6). This is also patterned fen with flarks but no spruce islands occur here. This pattern is found mainly along the west edge of the photograph but small areas are scattered throughout. It is unlikely that permafrost exists in this pattern.

RELATION OF PERMAFROST TO ENVIRONMENTAL FACTORS

Climate

The continuous permafrost zone throughout Canada, except in the Hudson Bay Lowland, lies north of the 17°F mean annual air isotherm which corresponds roughly to a mean annual ground termperature of 23°F. In the Lowland, however, the narrow strip along the coast of Hudson Bay appears to lie in the continuous permafrost zone, according to field observations, but in fact it lies south of the 20°F mean annual air isotherm. This discrepancy may be related in some manner to the fact that the area is situated north of the treeline. On the other hand, further field observations may reveal discontinuities in the permafrost placing it in the discontinuous zone.

Terrain

The mechanism of permafrost formation in peat terrain appears to be related to changes in the thermal properties of the peat through the year (Brown, 1966; Tyrtikov, 1959). During the summer the surface layers of peat become dry through evaporation. The thermal conductivity of the peat is low and warming of the underlying soil is impeded. The lower peat layers gradually thaw downward and become wet as the ice layers in the seasonably frozen layer melt. In the autumn there tends to be more moisture in the surface layers of the peat because of a decreased evaporation rate. When it freezes the thermal conductivity of the peat is increased considerably. Thus the peat offers less resistance to the cooling of the underlying soil in winter than to the warming of it in summer. The mean ground temperature under peat will therefore be lower than under adjacent areas without peat. When conditions under the peat are such that the ground temperature remains below 32°F throughout the year, permafrost results and is maintained as long as the thermal conditions leading to this lower temperature persist.

The occurrence of permafrost in the discontinuous zone appears to be closely related to drainage. The importance of water conditions is shown by the absence of permafrost in areas where the water table is at the ground surface, even if the ground cover consists of Sphagnum. Permafrost occurs, however, in the micro-relief peat features such as mounds, ridges, plateaus and palsas which rise above the wet areas. It is suggested that these features are morphological variations of the same process, i.e., the same mechanism is responsible for the formation of peat plateaus and palsas. The European literature appears to support this contention (P'yavchenko, 1955; Svensson, 1961-1962; Tyrtikov, 1966). They appear to pass through a life cycle of development and degradation and all stages occur in the Hudson Bay Lowland.

Initially, these features appear as low mounds of upwarping of peat protruding above water level in the middle of shallow ponds only a few inches deep (Figure 2). The mechanism of their formation and control of their distribution is uncertain, but it is suggested that the pond freezes to the bottom in winter and the underlying saturated peat is domed up at random locations by intensive frost action and ice lens growth. When elevated above the pond level, the dry layer of exposed peat insulates the underlying frozen mass from summer thawing, thus marking the initiation of a perennially frozen or permafrost condition. The elevation of the peat surface above the general level of the surrounding flat level surface devoid of relief exposes it to winter winds which reduce or remove the insulating snow cover. Winter frost penetration is therefore greater than in the surrounding low, flat areas, thus contributing to further permafrost accumulation.

As the peat continues to accumulate year after year accompanied by the increase in permafrost thickness each winter, the mounds grow and coalesce to form plateaus. In the youthful stage, there is little or no living vegetation on the peat surface. During maturity, Sphagnum and other mosses and lichens become established, along with Labrador tea and spruce (Figures 3, 4, 5). Old age and degradation begin when the insulating ground cover ruptures due to biological oxidation and general deterioration, and thawing penetrates into the underlying perennially frozen core. The surface of the palsa or peat plateau becomes very uneven because of differential thawing of the underlying ground ice and large blocks of thawed peat break off the margins. It is not certain whether rejuvenation can occur.

The critical factors in palsa and peat plateau formation are possibly climate, water supply, and snow cover. Little work has been done on the climatic requirements for the formation of these features but some information is available in the Scandinavian literature. It has been recorded in Sweden that palsas occur where the air temperature remains below 32°F during more than 200 days per year. They also appear to be present only where the precipitation - virtually all in the form of snow - during the period of November to April is less than 12 inches (Lundqvist, 1962). It appears from the air temperature and precipitation data for meteorological stations in the Lowland area that these criteria are satisfied.

Drainage conditions and water supply are very important factors in the development of palsas and peat plateaus. The ponds in which they begin to grow probably should be sufficiently shallow to freeze to the bottom in winter so that a frozen zone may develop below. The process of growth is not clear, but the gradual updoming of the peat proceeds possibly because of its high capillarity, which draws considerable quantities of water to the freezing front from the surrounding wet areas. These conditions occur widely in the Hudson Bay Lowland where palsas and coalescing palsas forming peat plateaus grow to heights of 10 to 15 feet.

Snow cover is considered one of the critical factors in palsa development once formation of the feature has begun. According to Lundqvist (37) the amount of snowfall in the region through the winter may not exceed a certain quantity - i.e., 12 inches. In addition, a differentiation occurs in that the snow cover on the palsas is significantly less than on the surrounding terrain. Sjörs' (1959a, 1959b, 1961) studies of the origin and distribution of palsas in the Lowland pointed to the critical role of the snow cover. A detailed ecological study of a palsa bog near Winisk showed that snow cover was thinner on palsas than the surrounding terrain (Railton, 1968). Evapotranspiration was the main source of summer heat loss. Palsa collapse was attributed to deterioration of the vegetation cover by rain and wind erosion causing melting of the ground ice.

CONCLUSION

Climate is the most important factor influencing the formation and continued existence of permafrost. This is borne out by the location of the mean annual air isotherms relative to the distribution of permafrost, and indicates the existence of a broad relationship. South of the 30°F isotherm permafrost is not generally found in the Lowland. Between 30°F and 25°F isotherms, permafrost is patchy and restricted to certain types of terrain. North of the 25°F isotherm, permafrost is widespread and in fact is continuous along the Hudson Bay coast.

Permafrost occurs only in the peatlands and peat bogs of the Hudson Bay Lowland. Even in the peat terrain, permafrost does not exist where water lies at or near the ground surface. It is restricted to the positive microrelief peat features - plateaus and palsas which abound in the Lowland. Drainage is therefore one of the main terrain factors influencing the existence of permafrost.

The role of vegetation in the distribution of permafrost is complex. The tree growth, predominantly spruce and tammarack, is not an indicator of permafrost distribution because these trees grow on sites where permafrost is both present and absent. The only direct correlation between tree growth and permafrost occurrence is in the extensive tamarack stands between the major rivers in the Hudson Bay Lowland. The absence of permafrost here is due to the lack of drainage and the tamarack reflect these conditions rather than the absence of permafrost. The Sphagnum and lichen cannot be used as indicators of the existence of permafrost.

One of the most difficult problems is explaining the distribution of permafrost peat features in the peatlands and peat bogs. There does not appear to be any obvious explanation of why these features occur in some peatland areas and not in others with apparently similar conditions. Local small variations in winter winds and snow cover may be sufficient to tip the net effect of all the environmental factors either towards or away from the initiation of these features.

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APPENDIX[1]

Investigations of microclimate and terrain factors affecting the distribution of permafrost in the discontinuous zone have been undertaken at Thompson, Manitoba, since 1968. This community is about 640 km north of Winnipeg in north central Manitoba in the middle of the discontinuous zone. It is about 160 km west of the Hudson Bay Lowland at the northern end of glacial Lake Agassiz. Permafrost occurs in scattered islands varying in extent from a few square metres to several hectares and in thickness from about 1 to 15 m or greater, averaging between 2.4 and 4.5 m (Johnston et al., 1963). 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. Temperatures in the permafrost vary from about -0.5 to 0°C.

Observations at Thompson include air temperature, precipitation, snow depth, density and temperatures, wind speeds at the 1.8 m level, net radiation, evapotranspiration, ground heat flow at the 30 cm depth, ground temperatures to 7.5 m, and annual depth of ground freezing and thawing. These measurements are being carried out at four sites located within a distance of a few hundred metres of each other, two with permafrost and two with none.

Soil profiles of the four sites are shown in Figure A-1. Site A supports dense spruce growing on a 10-cm thick layer of feather moss and forest litter overlying brown clayey soil (grain size analysis at a depth of 15 to 23 cm: clay - 59 per cent, silt - 39 per cent, sand - 2 per cent). There is no peat at this site and no permafrost.

Site B supports open stunted spruce growing on a 10-cm thick layer of Sphagnum over 10 cm of peat, 23 cm of black organic clay (31 per cent organic content by weight) overlying brown clayey soil (grain size analysis at a depth of 30 to 53 cm: clay - 77 per cent, silt - 22 per cent, sand - 1 per cent). There is no permafrost at this site.

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[1] This material is extracted from: Brown, R.J.E. and G.P. Williams, 1972. The Freezing of Peatland. National Research Council of Canada, Division of Building Research, NRCC 12881, 24 p.

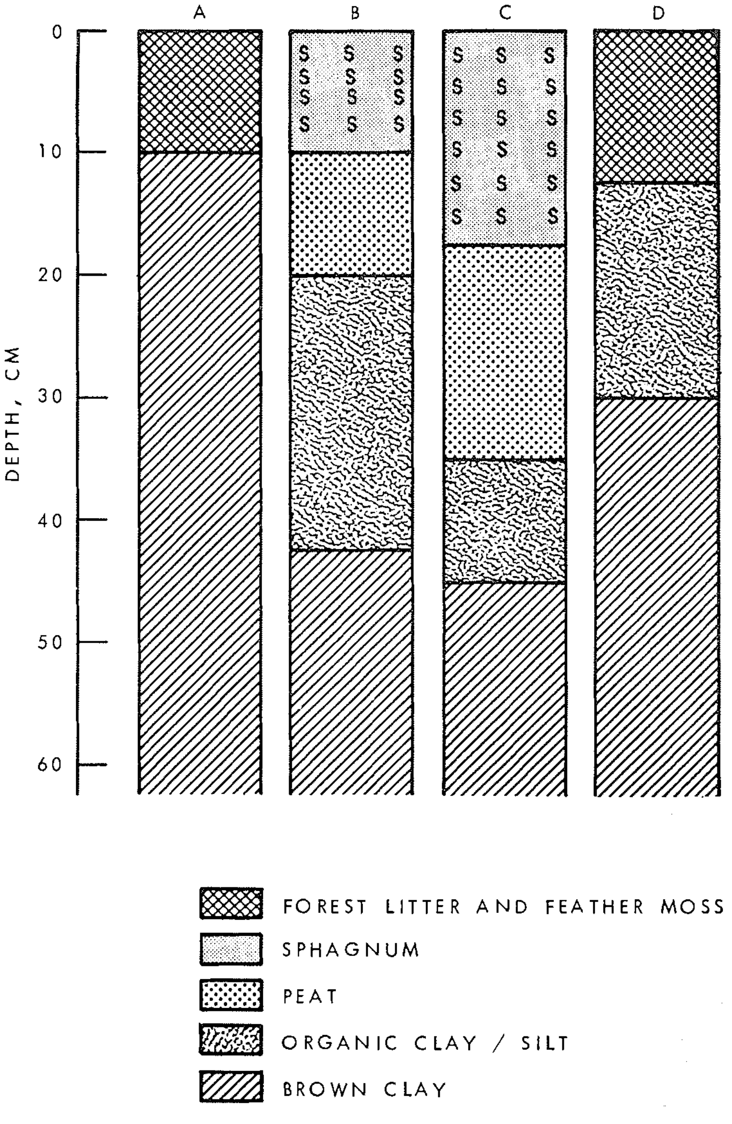

FIGURE A-1
SOIL PROFILES OF SITES AT THOMPSON, MANITOBA

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

Site D supports dense spruce, similar to that at Site A growing on a 13-cm thick layer of Sphagnum over 18 cm of black organic silt (77 per cent organic content by weight) overlying brown clayey soil. Grain size analysis of the organic silt is: clay - 28 per cent, silt - 62 per cent, sand - 10 per cent; in the brown clay at 33 to 48 cm it is: clay - 87 per cent, silt - 12 per cent, sand - 1 per cent. There is no peat at this site similar to that at Sites B and C, but the organic silt has a very high organic content. The permafrost table is at a depth of about 75 cm and the permafrost exceeds 6 m in thickness.

GROUND FREEZING REGIME

Frost depth-time graphs are shown for each site for three complete freezing seasons (1968-69, 1969-70, 1970-71) in Figure A-2. At the two sites with no permafrost seasonal frost penetrates to its maximum depth in late winter, followed by thawing from the surface downward in spring. At the sites with permafrost seasonal thawing progresses downward each summer, reaching the permafrost table in the early autumn. This is followed by seasonal freezing from the surface downward to the permafrost table.

Several patterns are evident on the basis of observations over three freezing seasons, for there are significant differences in the freezing and thawing regimes at the four sites. Site A experiences considerably deeper frost penetration and a longer period of seasonal freezing each year than Site B. Both sites are without permafrost and only Site B can be considered a peatland site. Both Sites C and D are in permafrost areas and seasonal frost penetrates to the permafrost table each year. The active layer is significantly thicker at Site C and changes from year to year. It appears to remain constant at Site D.

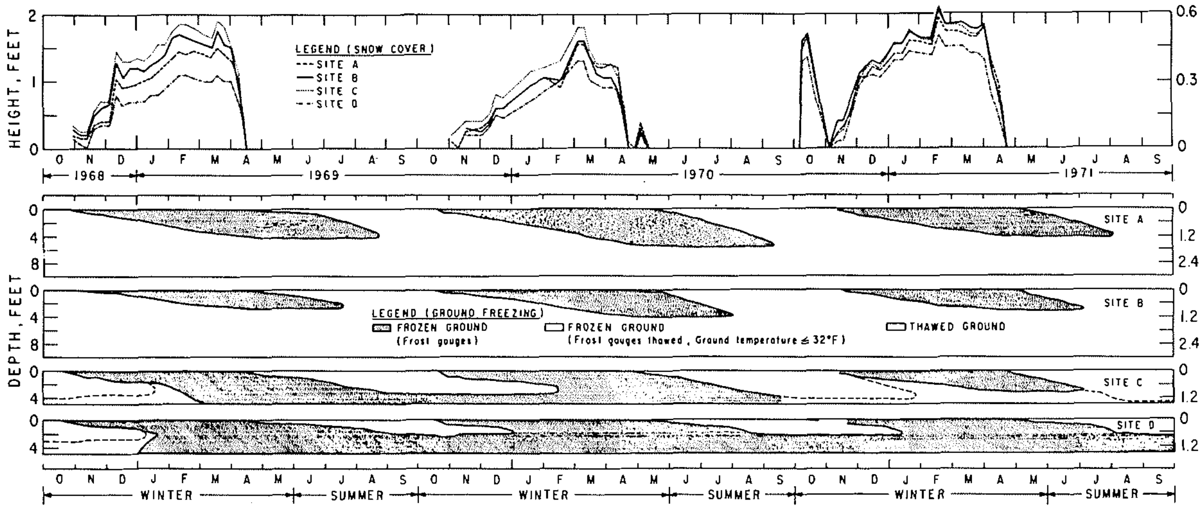

FIGURE A-2

SNOW COVER AND GROUND FREEZING REGIMES AT THOMPSON MANITOBA

The rate of frost penetration is more uniform at Sites A and B where there is no permafrost than at Sites C and D where permafrost complicates the seasonal freezing of the ground. Frost penetration for all four sites in Table A-I is presented for the three freezing seasons. Depths and penetration rates are greater at Site A than at Site B; penetration rates at both sites are generally two to three times greater in the first part of the winter than in the latter part, although brief periods at lower rates occur at the very beginning. Thawing of the ground begins in the early spring at about the time the frost penetrates almost to its maximum depth. Further ground freezing of a few centimetres at most does occur during the following two- to eight-week period but its effect in the total freezing regime is minimal. The last remnant of frozen ground disappears in late summer about one month later at Site A than at Site B. At both sites it was located at the bottom of the frozen layer, indicating little or no thawing from beneath.

The situation is somewhat different at Sites C and D where permafrost exists, although that at Site C is more marginal than that at Site D. At Site C the temperature of the permafrost is about -0.1°C and thus is very sensitive to any disturbance. Three years of weekly observations have resulted in a drop in the permafrost table from the original level of 48 cm to 1.35 to 1.5 m. At Site D, where the temperature of the permafrost is slightly colder at about -0.5°C, the permafrost table has remained steady at a depth of about 0.75 m. Although the frost gauges at both sites were installed in the fall of 1968 the methylene blue liquid in the bottom few decimetres of the gauges in the permafrost did not freeze until mid-winter.

Frost penetration rates are generally more uneven at Sites C and D than at the sites with no permafrost. This was particularly true in 1968-69 and 1969-70 when penetration rates were rapid during the first two or three weeks, levelled off in the late fall, and then increased as the seasonal freezing plane approached the permafrost table. At Site D the seasonal frost reached the permafrost table at the end of December 1969-70, the most severe of the three freezing seasons. This season produced the deepest frost penetration at the non-permafrost sites. At Site C seasonal frost reached the permafrost table in mid-February 1969-70. Ground thawing of the active layer begins at about the same time as for the two sites with no permafrost.

TABLE A-I

FROST PENETRATION, THOMPSON, MANITOBA

	No Permafrost		Permafrost	
	Site A	Site B	Site C	Site D
Rate of Penetration, (cm/week)				
1968 - 69	5.3 (29 Oct - 28 Feb) 3.0 (1 Mar - 20 May)	2.0 (29 Oct - 10 Dec) 4.3 (10 Dec - 25 Feb) 3.0 (25 Feb - 1 Apr)	8.8 (19 Oct - 12 Nov) 1.8 (3 Dec - 15 Jan)	6.8 (15 Oct - 12 Nov) 0.8 (12 Nov - 31 Dec)
1969 - 70	5.5 (10 Nov - 28 Apr) 1.8 (28 Apr - 12 June)	5.0 (17 Nov - 23 Mar) 1.8 (23 Mar - 12 May)	27.0 (20 Oct - 27 Oct) 3.3 (27 Oct - 12 Feb)	14.5 (14 Oct - 27 Oct) 1.3 (27 Oct - 16 Dec)
1970 - 71	5.5 (12 Nov - 26 Feb) 2.5 (26 Feb - 21 May)	4.5 (18 Nov - 26 Feb) 2.0 (26 Feb - 7 May)	11.0 (12 Nov - 23 Jan)	2.5 (18 Nov - 23 Dec) 9.0 (23 Dec - 6 Jan)
Deepest Frost Penetration, cm (Date First Attained)				
1968 - 69	110 (20 May 1969)	68 (15 Apr 1969)	Seasonal frost penetrated to permafrost table at 53-cm depth.	Seasonal frost penetrated to permafrost table at 75-cm depth.
1969 - 70	143 (12 June 1970)	104 (12 June 1970)	Seasonal frost penetrated to permafrost table at 105-cm depth.	Seasonal frost penetrated to permafrost table at 75-cm depth.
1970 - 71	110 (23 July 1971)	80 (7 May 1971)	Seasonal frost penetrated to permafrost table at 123-cm depth.	Seasonal frost penetrated to permafrost table at 75-cm depth.
Beginning of Ground Thawing				
1968 - 69	21 Apr 1969	17 Apr 1969	18 Apr 1969	18 Apr 1969
1969 - 70	9 May 1970	2 May 1970	1 May 1970	28 Apr 1970
1970 - 71	22 Apr 1971	27 Apr 1971	22 Apr 1971	26 Apr 1971
Thawing of Last Frozen Ground				
1968 - 69	23 Aug 1969	18 July 1969	about 15 Jan 1969	about 15 Jan 1969
1969 - 70	12 Sept 1970	2 Aug 1970	14 Feb 1970	31 Dec 1969
1970 - 71	3 Aug 1971	4 July 1971	about 23 Jan 1971	9 Jan 1971

OBSERVATIONS ON CLIMATE AND TERRAIN FACTORS

Observations of climatic and terrain factors are tabulated in Table A-II. Net radiation observations are not tabulated. They were commenced on a continuing basis during the summer of 1971.[2] Wind velocities were measured at the four sites through the freezing seasons of 1969-70 and 1790-71. Average wind speeds are very low, less than 1.6 km/hr compared with an average of approximately 16 km/hr at the standard meteorological installation 12 m above ground level at the Thompson airport.

The mean air temperature for the eight-month winter period of each of the three freezing seasons was slightly higher at Site A than at Site B, both sites with no permafrost. The same was true for the four summer months. At the permafrost sites the mean winter air temperature was generally lower at Site C than at Site D. The mean summer temperature was consistently lower at Site D, the lowest of the four. The three-year average encompassing the three freezing seasons, October 1968 to September 1971, was highest at Site A and -0.3 C deg less at the other three sites, which were virtually the same. These values are similar to the value of -3.6°C for the same period at the meteorological station at Thompson.

Mean ground surface temperatures followed somewhat the same pattern during the winter. Site A had generally the highest values of the four sites and Site D the lowest. During the summer Site A was consistently low and Site B, the other site with no permafrost, high. The three-year average encompassing the three freezing seasons, October 1968 to September 1971, was highest at Site B and lowest at Site D.

Ground heat flow measurements are available through the two freezing seasons 1969-70 and 1970-71. There is consider-

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[2] Analysis of net radiation is not yet completed. Preliminary examination of the data indicates that values are highest at Sites B and C (sparse tree growth), somewhat less at Site A (dense tree growth - no permafrost) and lowest at Site D (dense tree growth - permafrost).

TABLE A-II

CLIMATIC AND TERRAIN DATA
THOMPSON, MANITOBA

	Site A	Site B	Site C	Site D
Air Temperature, °C				
Winter - mean				
Oct. 1968 - May 1969	-12.1	-12.4	-12.6	-12.3
Oct. 1969 - May 1970	-11.3	-11.4	-11.7	-11.6
Oct. 1970 - May 1971	-11.6	-11.7	-11.9	-11.3
Summer - mean				
June - Sept 1969	13.1	12.7	13.2	12.3
June - Sept 1970	13.6	13.3	13.1	13.0
June - Sept 1971	13.6	13.0	13.4	12.6
Average Annual				
Oct 1968 - Sept 1971	-3.3	-3.6	-3.6	-3.6
Ground Surface Temperature, °C				
Winter - mean				
Oct 1968 - May 1969	-4.3	-4.1	-4.5	-6.4
Oct 1969 - May 1970	-4.9	-6.1	-4.4	-6.6
Oct 1970 - May 1971	-2.5	-4.4	-4.2	-5.8
Summer - mean				
June - Sept 1969	5.8	11.9	9.5	8.8
June - Sept 1970	8.2	11.6	8.9	10.6
June - Sept 1971	9.2	11.9	10.3	10.2
Average Annual				
Oct 1968 - Sept 1971	-0.1	0.7	-1.4	-0.9
Wind Speed, km/hr				
Winter - mean				
Oct 1969 - May 1970	0.40	0.34	0.43	0.50
Oct 1970 - May 1971	0.61	0.37	0.90	0.67
Summer - mean				
June - Sept 1970	0.77	0.51	1.30	0.94
June - Sept 1971	1.31	0.22	0.54	0.77
Ground Heat Flow, $cal/cm^2/hr$				
Winter - mean				
Oct 1969 - May 1970	-0.16	-0.18	-0.23	-0.11
Oct 1970 - May 1971	-0.22	-0.14	-0.13	-0.10
Summer - mean				
June - Sept 1970	0.53	0.48	0.66	0.44
June - Sept 1971	0.53	0.62	0.74	0.58
Surface Organic Layer, (cm)				
Moss/forest litter	10	10	17.5	12.5
Peat	0	10	17.5	0
Organic clay/silt (per cent organic content by weight)	0	23 (31)	10 (26)	17.5 (77)
Total thickness (cm)	10	43	45	30
Snow on Ground				
Thickness - cm - mean				
Oct 1968 - May 1969	29	35	38	21
Oct 1969 - May 1970	28	26	29	23
Oct 1970 - May 1971	39	42	41	33
Density - gm/cc - mean				
Oct 1968 - May 1969	0.198	0.206	0.213	0.186
Oct 1969 - May 1970	0.211	0.197	0.174	0.183
Oct 1970 - May 1971	0.179	0.174	0.180	0.173

able difference in average values for heat flow for the two years of observations. During both winter seasons Site D had the lowest value (less heat lost to the atmosphere). During both summers Site C had the highest positive values (heat flow from the atmosphere to the ground).

The surface organic layer is an important factor in the freezing regime of the ground. The organic profile at each site has been described and is tabulated in Table A-II. The organic layer is thicker at Sites B and C, 43 and 45 cm respectively, and thinner at Sites A and D, 10 and 30 cm respectively.

Snow cover is one of the most important factors influencing the freezing of the ground. The mean thickness of the snow layer has been consistently highest at Sites B and C, where tree growth is sparse. Site D has the lowest snow accumulation and the densest, tallest tree growth. The pattern of snow density was less consistent, although values tended to be slightly lower at Site D than at the other sites.

DISCUSSION OF RESULTS

The three major factors determining the freezing and thawing pattern at a site are:

(1) heat exchange at the surface by radiation, convection and evaporation,

(2) depth and density of snow cover, and

(3) thermal properties of the soil.

The assessment of the relative influence of these factors is complicated by their close interrelationship. Often virtually unmeasureable changes in one of the factors or in the weather and soil properties upon which they depend can cause significant differences in soil freezing or thawing. A discussion of the observations can, therefore, only illustrate in a qualitative way the importance of various variables, particularly that of the surface organic layers, in the freezing and thawing of ground at these four sites.

There are not sufficient data on radiation, wind velocity and surface moisture to allow discussion of the observed freezing and thawing patterns from a surface energy exchange point of view. In winter, differences in evaporative and convective heat losses at the four sites tend to be undetectable; wind velocities are extremely low and all sites have generally the same surface conditions. Differences in net radiation may not be very great because the greater amount of solar radiation received at exposed sites could well be offset by higher long-wave radiation losses to the atmosphere. The fact that average air temperatures during the winter are almost identical at all sites tends to support this conclusion. In summer, differences in surface heat balance depend to a great extent on surface moisture conditions which control evaporation. The relative importance of evaporation and other components of surface energy exchange during the thaw period will become clearer with continuing measurements over periods of several years.

During the winter, snow cover largely controls the amount of heat lost from the ground and subsequent ground freezing at the four sites. Figure A-3 shows average calculated heat flow for each site for each snow session (1 November to 30 April). These calculations were made by assuming steady-state conditions, and an average snow surface temperature equal to the average air temperature. The average temperature gradient through the snow cover was assumed to be equal to the difference between average air and ground temperatures divided by the average depth of the snow. The thermal conductivity of the snow was calculated from snow density values (Williams and Gold, 1958).

The results of the calculations shown in Figure A-3 indicate that there was considerable variation in heat loss through the snow cover from year to year. Heat loss was highest at all sites during 1968-69 and lowest during 1970-71. On the average, Site A showed the largest heat loss; Sites B and C showed almost identical heat losses; and Site D showed the lowest average heat loss.

The calculated values for heat loss through the snow cover were checked by comparing them with heat loss measured at the 30-cm depth. The total heat loss for two winter seasons (1969-70, 1970-71), measured with the heat meters, is about 15 per cent higher than the estimated heat loss through the snow cover at Sites A, B and C (Figure A-3). Measured heat loss at Site D is slightly lower than calculated heat loss through the snow cover. Considering the uncertainties associated with measurement of heat flow by means of soil heat meters and the fact that the heat meters were not placed at the surface, the agreement is quite good.

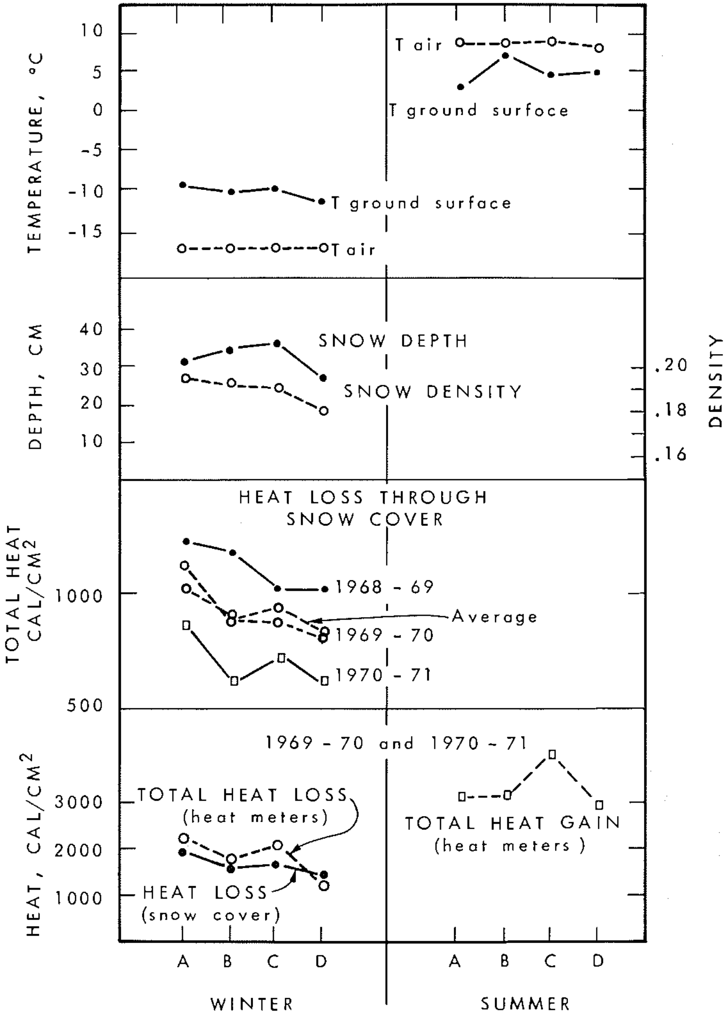

FIGURE A-3

SUMMARY OF AIR TEMPERATURE, GROUND TEMPERATURE AND HEAT LOSSES AND GAINS FOR WINTER AND SUMMER PERIODS

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Differences in heat loss through the snow cover for the four sites are explained by differences in snow depth and density. Sites B and C have comparable average snow depths and densities. Site A has a greater snow depth than Site D, but higher snow density offsets to some extent the greater snow depth. If ground temperature had been the same at both sites, heat loss from Site D would have been only slightly higher than heat loss from Site A. The difference in heat flow between Sites A and D is thus primarily caused by differences in ground surface temperature.

The thermal properties of the surface soil layer have a significant influence on heat transfer to the surface. Frozen peat and Sphagnum in the upper 30-cm layer at Sites B and C should have thermal conductivities ranging from 0.003 to 0.005 cal/cm/sec°C at high moisture contents. These values compare with the range for frozen silt clay at average moisture content, the most likely conditions at Site A. Consequently, average ground temperatures at the three sites are quite similar. Deviations from assumed thermal conductivities and differences in thermal gradient and snow depth and density probably account for differences in average heat loss during the winter. Site D is a drier site than Sites B and C and if the organic layer at Site D has a markedly lower moisture content the thermal conductivity of the frozen surface organic layer would presumably be lower. This combined with the lower subsurface ground temperatures associated with this permafrost site may account for the lower ground temperatures and total heat loss.

The heat loss from the ground surface in winter results in the cooling and freezing of the soil. As large amounts of heat must be extracted to freeze water in soil, the depth and rate of frost penetration depend largely on the amount of moisture present. Site A, the driest site, has a greater depth of frost penetration than Site B, which is poorly drained. The seasonal fluctuations in the rate of freezing of the first few centimeters of soil at Sites C and D (Table A-I) are probably caused by variations in the moisture content of the surface organic layers just prior to ground freezing.

The amount of thawing during the summer determines not only the rate at which seasonal frozen ground melts but also possible degradation of permafrost. If the heat gained by the ground in summer exceeds the heat lost in winter, the surplus heat will warm the ground at non-permafrost sites and melt permafrost at permafrost sites. The only quantitative information on the heat gained by the ground during the summer is the measurement of heat flow at the 30-cm depth at each site.

These values for summer heat gain must be treated with caution. There is no way of checking their reliabilty as there is for the winter period when ground heat losses can be compared with heat flow through the snow cover. The heat flow meters may be less satisfactory in unfrozen soil because they cannot measure any transfer of heat by vapour or ground water movement. Even greater errors can also be expected because the thermal conductivity of the unfrozen soil may be much less than that of the heat meters themselves. Philips (1961) shows theoretically that errors of up to +24 per cent can occur if the thermal conductivity of the surrounding medium is considerably lower than that of the heat meters. Although the absolute values of heat measured by the meters may be uncertain, they should be representative of the relative heat gained by the ground at the four sites.

Figure A-3 shows that the measured heat flow into the ground (total for two summers, 1970 and 1971) was appreciably greater than the heat lost from the ground during corresponding winter periods (1969-70 and 1970-71). The heat gained at Sites A, B and D was about the same; that gained at Site C exceeded it by about 1,000 calories. This much surplus heat would melt about 35 cm of permafrost (at a volumetric moisture content of 35 per cent), roughly the amount of permafrost thawing that took place over the two-year period.

What would cause Site C to have such a large surplus of heat compared with the other sites? Although the answer to this question must be speculative because of lack of data, an explanation can be attempted by comparing the surface heat balance at Site C with that at Site B, which has similar exposure and soil conditions. Let us assume in making this comparison that surface disturbance resulted in ponding of water at Site C so that the surface organic layers were completely saturated, whereas at Site B the surface layers of Sphagnum remained unsaturated. The surface heat balance during the summer period can be represented by the following simple equation:

$$Q_s = Q_{sw} - Q_e + Q_c - Q_{\ell w}$$

where

Q_s = heat flow into ground

Q_{sw} = heat gained from solar radiation

Q_e = heat lost by evaporation

Q_c = heat gained by convection

$Q_{\ell w}$ = heat lost by long-wave radiation.

The heat gained by short-wave radiation would probably be about the same at both sites since they have similar exposure and surface conditions. The heat used in evaporation should also be nearly the same. Although the Sphagnum at Site B is assumed to be unsaturated, evaporation will not be limited by the supply of water because Sphagnum acts as a wick, providing ample surface water. Both Q_c and $Q_{\ell w}$ depend on air surface temperature differences; as air temperatures are about equal at the two sites the surface temperature should be significantly different if there is to be a difference in the amount of heat gained by the ground (Q_s) over the three summer periods 1969, 1970, 1971. Figure A-3 shows that the average surface ground temperature for these three periods was significantly lower at Site C than at Site B. This much difference in surface temperature is sufficient to change $Q_{\ell w}$ and Q_c appreciably (Geiger 1965). As the heat gained by convection would be greater and the heat lost by long-wave radiation less at Site C than at Site B, because of the lower surface temperature, the net heat available for warming the ground would be appreciably greater over the three-year period. This additional heat can be transferred more readily into the ground at Site C, even with lower surface temperatures, because the thermal conductivity of saturated Sphagnum is considerably higher than that of unsaturated Sphagnum. The foregoing analysis suggests that ponding of water at Site C affected the surface heat balance sufficiently to cause significant changes in the total heat gained at the site over the three-year summer period. Other factors such as the lateral inflow of heat by movement of surface water and man-made disturbance affecting surface heat balance may be important.

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