Distribution and Thawing of Permafrost in the Southern Part of the Discontinuous Permafrost Zone in Manitoba

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ABSTRACT. This study was carried out to evaluate the environmental factors which influence the distribution and collapse of perennially frozen peats in the southern part of the discontinuous permafrost zone in Manitoba. The changes in permafrost bodies were measured by means of aerial photography carried out over a period of 20 years. About 25 per cent of the once occurring permafrost is still present. Melting appears to have exceeded aggradation of permafrost since about 150 years B.P. Two types of collapse were noticed: peripheral collapse around very small permafrost bodies; and a central collapse for the larger bodies. The amount of collapse has varied from 0 to 30 metres horizontally in a 20 year period.

RÉSUMÉ. *Distribution et fonte du permagel dans la partie sud de la zone de permagel discontinu au Manitoba.* On a mené cette étude dans le but d'évaluer les facteurs d'environnement qui influent sur la distribution et l'affaissement des tourbes gelées dans la partie sud de la zone de permagel discontinu au Manitoba. On a mesuré les changements dans les masses de permagel par des photographies aériennes recueillies sur une période de 20 ans. Environ 25 pourcent du permagel de naguère est encore présent. Depuis environ 150 ans A.P., la fonte du permagel a été plus importante que son extension. On remarque deux types d'affaissement: un affaissement périphérique autour de très petites masses de permagel et l'affaissement par le centre des masses plus grandes. Sur une période de 20 ans, cet affaissement a varié entre 0 et 30 mètres horizontalement.

РЕЗЮМЕ. *Распространение и оттаивание мерзлых грунтов в южной части зоны островного залегания мерзлых грунтов в Манитобе.* Была проведена оценка влияния окружающей среды на распределение и разрушение мерзлых торфяников в южной части зоны островного залегания мерзлых грунтов в провинции Манитоба. Изменения мерзлых толщ измерялись при помощи аэрофотосъемки, проводимой в течение 20 лет. Приблизительно 25% прежде существовавших мерзлых грунтов существует до настоящего времени. Оттаивание, повидимому, начало преобладать над градацией мерзлых грунтов 150 лет тому назад. Были отмечены два типа разрушения: разрушение на периферии для очень малых мерзлых толщ, и разрушение в центре для больших массивов. Горизонтальное разрушение за двадцатилетний период колебалось от 0 до 30 метров.

INTRODUCTION

Permafrost, especially on its sensitive southern fringe has to be studied on an ecosystem basis, for the environmental and biotic factors influencing its ecosystem are so intricately interrelated that only on such a basis can the dynamic aspects of perennial frosts be understood. In an attempt to assess some of these complex ecological relationships, the distribution and thawing of perennially frozen peats in the southern portion of the discontinuous permafrost zone in Manitoba were studied, and the results are presented in this paper.

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Permafrost is defined as earth materials having a temperature below 0° C for two or more years. Various zones of it have been identified in Canada (Brown 1967) on the basis of the distribution and frequency of perennially frozen ground in relation to air temperatures. Zoltai and Tarnocai (1969) have mapped it in Manitoba on the basis of the occurrence of permafrost landforms or remnants in peat. In the southern part of its discontinuous zone, permafrost is generally restricted to peatlands in which palsas, peat plateaus and collapse scars occur in abundance.

Palsas are mounds of peat land and mineral soil with a perennially frozen core. They are generally much less than 100 metres in diameter, and vary in height between 1 and 3 m. (Sjörs 1961) and may reach 5 m. Peat plateaus are elevated, flat peatlands having a perennially frozen core. They are usually low, and seldom exceed 120 m. in height, but may cover areas of over 1 km². In the south, permafrost in peat plateaus does not usually reach underlying mineral soil, as it does in palsas (Zoltai 1971), but in both cases the areas concerned may be heavily wooded with black spruce and white birch. Palsas and peat plateaus are surrounded by unfrozen, water-saturated peatland, commonly with leads of open water.

Palsas and peat plateaus are morphological variations of the same process (Brown 1968). Ice formation in peat during the winter causes uplifting. The peat thus raised, if sufficiently dry, acts as an insulator and may preserve the frozen core throughout the summer. After reaching the maximum degree of development permitted by climatic and local conditions, the permafrost may begin to decay as a result of some disturbance in the balance of the factors of water table, vegetation, insulating cover and climate. The decay or degradation stage for palsas and peat plateaus is marked by a collapse of edges and the presence of thermokarst features (Brown 1968).

Little is known about the rate of degradation or collapse of palsas and peat plateaus. Collapse seems to be an integral part of the life cycle of the two landforms and occurs under cool climatic conditions. The presence of peat plateaus during both the aggradation and degradation stages near the southern limit of permafrost (Zoltai 1972) shows that degradation does not necessarily indicate an amelioration in climate — a fact which has been stated by Svensson (1970) with reference to palsas in Scandinavia. It has been suggested that a relationship exists between degrading and aggrading phases and climatic changes; the present prevalence of degradation over aggradation in this area is caused by an overall warming trend in climate (Johnston *et al.* 1963).

METHODS

A study was made of ecosystems over a large area (about 1300 km.²) by surveying and analysing a number of characteristic elements both through the interpretation of aerial photographs and by means of selective field sampling. Elements which can be analysed by these techniques are: relief, drainage, vegetation, landform and parent material, and the importance of environmental changes over periods of time can be assessed when aerial photographic coverage has been repeated periodically.

The results of four different coverages of the study area by aerial photography are available: with oblique photographs in 1926; and with vertical photographs in 1946/47, 1957 and 1967, with scales respectively of 1:15,400, 1:68,000 and 1:15,800. A preliminary photo-interpretation was carried out to select sites for ground truth stations and a representative area for detailed aerial-photographic analysis. After the fieldwork had been completed, the relief, drainage flow, permafrost distribution, vegetation, fire history and surficial geology were studied and mapped from the aerial photographs. A detailed interpretation of sample areas (totalling about 225 $km.^2$) and covering a wide range of different conditions was done on the large-scale photographs. The objective was to identify and measure changes in the size of permafrost bodies and relate these to drainage condition and flow, vegetation, forest fire history, thickness of peat, etc. Changes in the superficial extent of permafrost bodies were marked on the 1967 photographs. Percentage collapse of permafrost was estimated visually and measured in a horizontal line perpendicular to the permafrost edge. A scale with gradations of 0.1 mm. built into a magnifying system was used for the taking of measurements.

DESCRIPTION OF THE AREA

The study area is located in central Manitoba and is bordered by the latitude of 54° N, the longitudes of 99° W and 98° W, and Lake Winnipeg (Fig. 1). The climate is moist subhumid, and characterized by relatively cool short summers, cold long winters and low precipitation. The average air temperature in July is

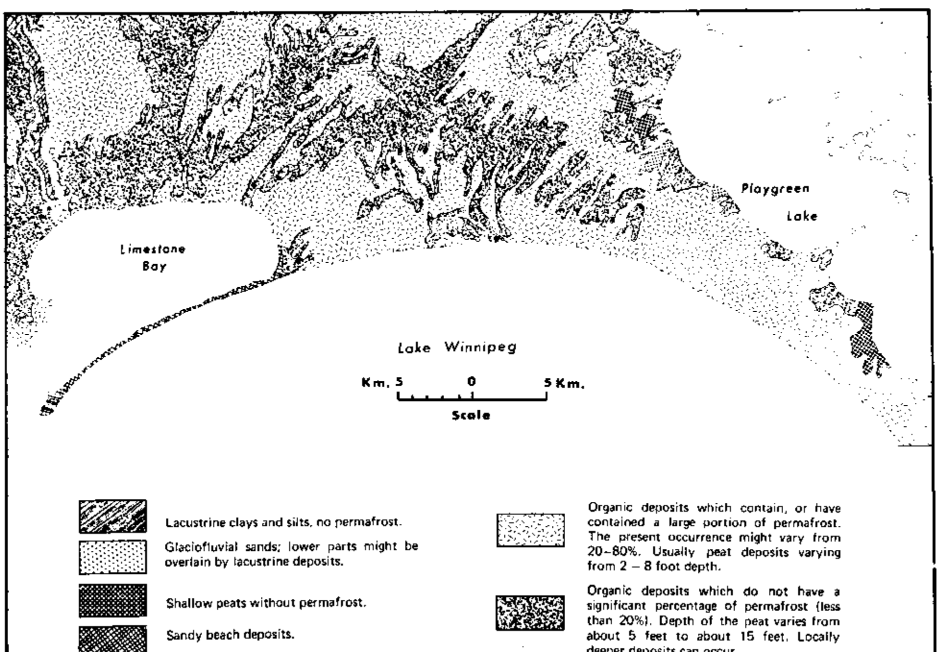

FIG. 1. **Permafrost and surficial deposits.**

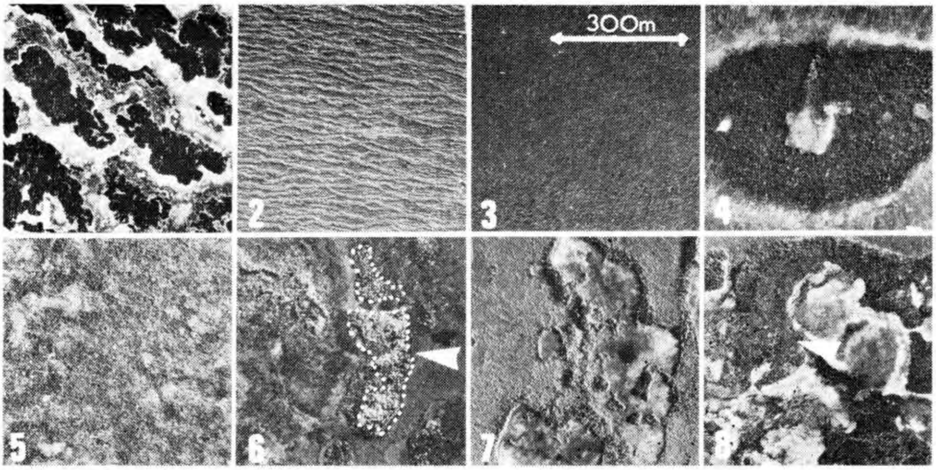

FIG. 2. *Vegetation types:* (1) Sedge fen with open water; (2) Tamarack-sedge patterned fens; (3) Tamarack fens; (4) Black spruce — feathermoss on permafrost; (5) Black spruce — sphagnum, no permafrost; (6) White birch on permafrost; (7) Collapse scars, mainly with sedges — drepanocladus and sphagnum; (8) Regeneration of black spruce on permafrost, 40 years after a fire.

about 18° C, and in January about —22° C. Average annual precipitation is about 38 cm. (Weir 1960).

Topographically the area is very flat, varying between about 218 m. and 228 m. above sea level. During the Wisconsin ice age some large glacio-fluvial landforms were formed in the area. Later, as the glacial Lake Agassiz covered the area, lacustrine clays and silts were deposited and the glacio-fluvial deposits were modified by wave action into sandy plateaus with strand lines. After subsidence of the lake level, peat filled in over most of the area, forming layers up to 5 m. in thickness.

As organic deposits cover 95% of the land area, the vegetation types are mainly ones associated with the different peatlands. They are shown in Fig. 2. Tamarack-sedge patterned fens and tamarack fens are characteristic of saturated minerotrophic to weakly minerotrophic wetlands, and black spruce-sphagnum raised bogs of wet ombrotrophic conditions. On perennially frozen peat, black spruce-feathermoss communities are the most common, the sites usually having a relatively dense cover of black spruce, mixed occasionnally with white birch. The early vegetation in collapse scars is commonly of a Carex-Drepanocladus type. In later stages, hummock-building sphagnum mosses may appear, while tamarack, white birch and black spruce may finally invade the drier parts of the scar. In many parts of the area the vegetation has been disturbed by forest fires which were started by lightning. In order to evaluate the influence of such fires on permafrost, a map was drawn on the basis of a photographic interpretation and other information supplied by the Forest Protection Branch of the Manitoba Department of Mines, Resources and Environmental Management.

Permafrost occurs in both shallow and deep organic deposits (Fig. 1) in peat plateaus and palsas. Thickness of permafrost was not measured, but data from surrounding areas gathered by the author indicated variations of from 0.5 m. to 5 m. Permafrost in peat has a high ice content; and the average moisture content for the frozen peat plateau core is about 80% (Zoltai 1972). Layers of pure ice are rare and quite thin. The peat deposits vary in thickness from 0.5 m. to more than 3 m. and have a sedge, sphagnum, forest and feathermoss origin. The relatively well-drained peat plateaus have forest peat, generally moderately decomposed. Between permafrost landforms moderately decomposed fen peat occurs in weakly minerotrophic areas, and relatively undecomposed sphagnum peat in more ombrotrophic situations.

RESULTS AND DISCUSSION

Distribution and development of permafrost

Permafrost distribution is strongly related to vegetation, drainage and surficial deposits. Most permafrost and collapse scars — indicators of former existence of permafrost — are found in the medium deep (1 m.-2 m.) peat deposits. These peats tend to be ombrotrophic, with a semi-convex relief, and show a radial fen-drainage pattern in between coalescent peat plateaus and palsas (Fig. 6). The deeper, minerotrophic peats with a semi-concave relief, usually found in sedge and tamarack fens, only occasionally contain permafrost; here permafrost islands are seldom greater than 400 m. to 500 m. in length, 50 m. to 200 m. being common. They have a round or tear-drop shape. In the forested shallow peats (less than 1 m. thick) permafrost may occur locally.

The present and past distributions of permafrost give rise to the suggestion that formation of permafrost started in the areas where black spruce-sphagnum communities were likely to exist, and confirmation of it is provided by the fact that young (incipient) peat plateaus generally occur under dense (more than 4 per $m.^{-2}$) black spruce in a fen, or nutrient-poor fen (Zoltai 1972). Such nutrient-poor conditions are predominant in such parts as have a convex relief which in the study area is usually caused by mineral substrata that form slight domes or else escarpments. Permafrost occurrence is a reflection of the presence of buried strandlines, glacio-fluvial landforms, bedrock escarpments, etc.

All peat plateaus and palsas exhibit a distinct pattern of drainage flow. Their smooth forms are moulded by slow flows of ground water (Fig. 3), the tails of the teardrop shapes pointing in the downflow direction. As permafrost tends to develop first of all in areas where clumps of black spruce occur, permafrost bodies may be expected to have a dominant growth vector in a downflow direction, and new permafrost tends to develop in the tail area where the fen type of vegetation is gradually colonized by sphagnum and black spruce. When black spruce trees are established, seasonal frost can penetrate deeper in winter, as the snow cover near the stem and under the branches is then considerably thinner than in the surrounding area. The shade of the branches in summer provides better protection against heat inflow (Zoltai and Tarnocai 1971). Only relatively "young" permafrost bodies in fens with a poorly defined and slow groundwater flow tend to have circular shapes.

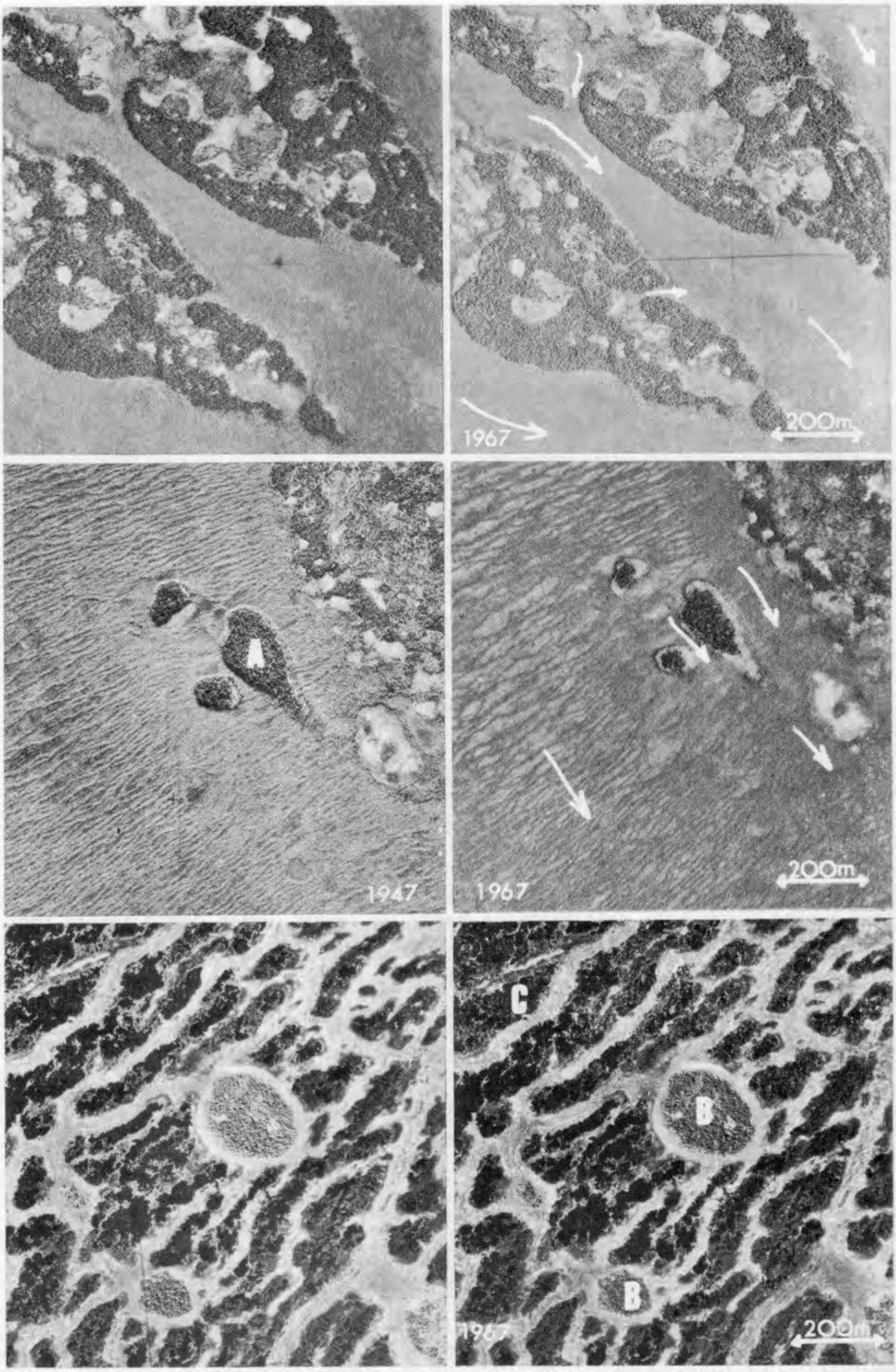

FIG. 3. *Permafrost occurrence:* TOP stereopair show the size and shape of most of the larger peat plateaus. (Note the light-toned collapse holes.) MIDDLE LEFT picture shows a palsa (A) in a large ribbed tamarack fen area in 1947; MIDDLE RIGHT picture shows the same area in 1967. (Note the peripheral collapse; drainage flow is indicated by arrows.) BOTTOM stereopair shows an area with many flarks (C).

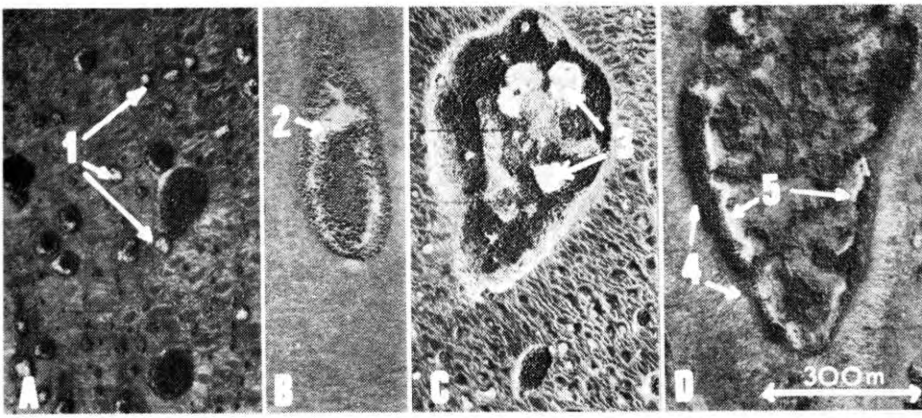

FIG. 4. *Relation of melting to size of permafrost landform:* (A) shows complete collapse of small palsas (1); some larger ones have undergone peripheral collapse. (B) shows peripheral collapse (2) of a small peat plateau, all the melting having occurred over a period of 20 years. (C) shows central collapses (3) of a medium-size peat plateau. (D) shows a large peat plateau in which most of the permafrost did thaw; only a small fringe of permafrost (4) remains facing the fen, and the collapsing (5) is proceeding from the inside. (Scales of pictures A-D are the same.)

Rate of melting of permafrost

From aerial photographs it can be seen that a considerable amount of thawing occurred throughout the study area over the period from 1947 to 1967, and also from 1926 to 1947. No measurable aggradation of permafrost occurred over the aggregate period of about 40 years.

Retreat by edge collapse of permafrost landforms of less than 100 m. in diameter was in the range of 15 m. to 20 m. over a period of 20 years. Nearly all small peat plateaus showed active collapse. Most permafrost bodies having a diameter of 50 m. or less totally disappeared over a period of 20 years (Fig. 4), collapse being generally peripheral.

In fens medium-sized peat plateaus (i.e., ones with a diameter of about 100 m. to 750 m.) melt at relatively slow rates. The process of collapse starts in the middle — probably first in the form of a thermokarst hole in a mature or overmature body. After a hole is formed, a slow collapse from the inside follows, the rates of horizontal retreat being of less than 5 m. in 20 years. Retreat of the edges by collapse can be from 10 m. to 20 m. over a 20-year period. The amount of melting tends to be high in areas where small fringes of permafrost areas are left. Usually the outer edges start to collapse only after the inner core has largely, or partially, collapsed. In exceptional cases the existence of a drainage channel from the inside melting area to the lower fen area seems to have given rise to outer-edge melting.

In large peat plateaus (over 750 m. in diameter) the collapsing process also tends to start in the centre core, but closest to the headward part of the landform. The edge facing large fen areas shows less tendency to collapse than do the edges facing the other permafrost bodies, though the latter are separated by small fen-type drainage channels. The rate of retreat by collapse of distinct edge is of the order of 10-20 m. per 20 years. Other parts melted at rates of between 1 m. and

5 m. per 20 year period. Old collapsed parts of large peat plateaus frequently showed signs of transformation into a raised bog.

The difference in type of collapse as between small bodies and large ones may be related to age or stage of development. Small bodies, especially in fens where permafrost development is likely to have started later, may be expected to be younger than the medium and large-sized ones.

By comparing the 1926, 1946/47 and 1967 photographs, in particular noting the tones resulting from invading vegetation it was possible to estimate the age of collapse scars. By applying this technique to the 1946/47 photographs, scars up to 60 years old could be mapped. Analysis of the superficial extent of collapse scars showed that at one time about 60% of the total land area may have been permafrost. Of this maximum about 25% is still present — i.e. about 15% of the total land area (Fig. 5). On the basis of a measurement of the amount of thawing in relation to the former extent of permafrost, it appears that degradation

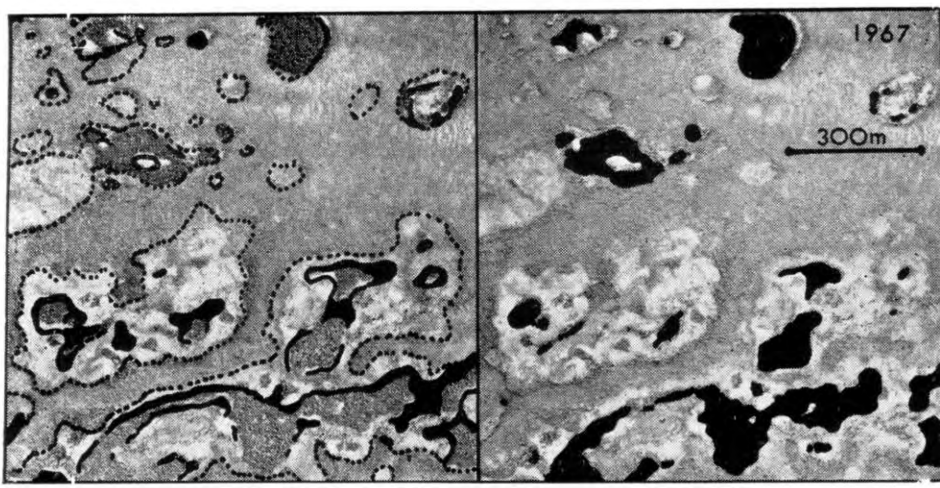

FIG. 5. *Melting of permafrost:* The stereopair indicate permafrost distribution at different times; the dotted line shows maximum distribution at any one time; the dark areas (RIGHT) still have permafrost (1967), while in the dark areas (LEFT) it melted between 1946 and 1967.

has been outpacing aggradation of new permafrost in this area for a considerable time. Most collapse scars were found to be rather young; they were usually filled with sedges, drepanocladus and some sphagnum. The slightly older scars contained more of the hummock-forming sphagnum, dwarf birch, bog laurel, leather leaf, etc. On the basis of the age dominance of the young and medium-aged scars and an extrapolation of the present rate of melting, it was estimated that extensive melting started between 100 and 200 years ago, and has progressed most rapidly over about 120 years ago till the present — a period during which more than half the total amount of melting has taken place.

Forest fires have not had a measurable influence on the rate of collapse of permafrost. For areas burned between 1900 and the present no change was noticed in rate of melting compared with that for the non-burned areas in the immediate vicinity (Fig. 6). Many of the mature black spruce stands covering the

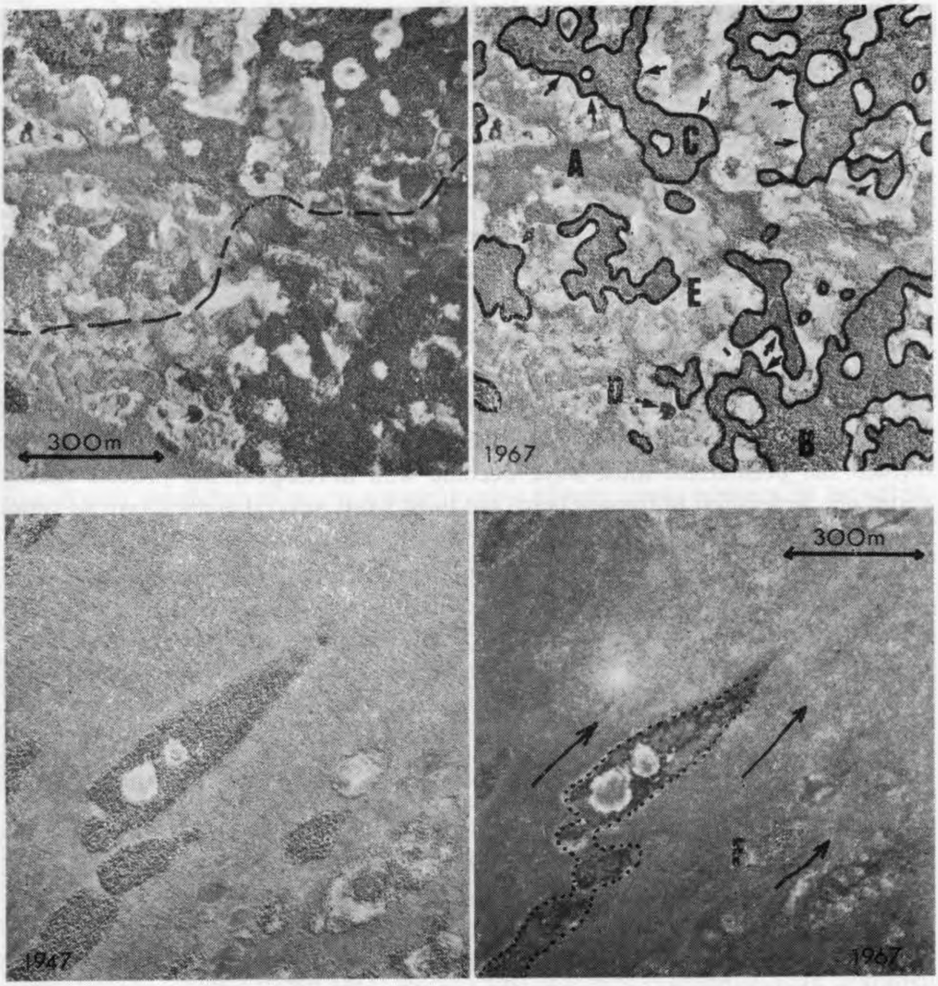

FIG. 6. *Effect of forest fires:* TOP LEFT indicates no significant increase in thawing after forest fire — the area to the north of the broken line was burned about 40 years ago, while the area to the south has not been burned. TOP RIGHT — some active collapse edges are indicated by arrows: (A) — tamarack; (B) — mature black spruce on permafrost; (C) — black spruce regeneration; (D) — pond remaining after complete collapse of permafrost; (E) — young collapse scar overgrown by vegetation. BOTTOM shows sudden collapse caused by a burn [comparison of 1947 (LEFT) and 1967 (RIGHT) photographs]; the burned and collapsed area is indicated by a dotted line.

permafrost are frequently of fire origin, a fact which indicates that, even in this southern discontinuous zone, permafrost persists for about 150 to 160 years after the occurrence of fires. It is possible that a fire destroys the forest cover without affecting the peat very much. The dried peat is a good insulator which prevents heat influx and thawing. Usually a regeneration of dense black spruce or white birch (Fig. 2) occurs early enough to ensure continuity of protection. Some exceptions were however found: for example a 1963 fire brought in its train a collapse of a peat plateau about 700 m. long (Fig. 6).

Permafrost was found to within 20 m. of the shoreline of Lake Winnipeg, and the rate of thawing was not measurably influenced by the modifying influence of the lake on microclimatic conditions.

Collapse and climate

The amount of collapsing that has occurred in the past, and is still occurring, in this area is significant. A large proportion of the original permafrost has disappeared and little, if any, has formed over the same period. Of course, collapsing did not start at 200 B.P.; it always formed a part of the development cycle of palsas and peat plateaus. Also, permafrost may still be formed in this area, but only on specific sites and under suitable climatic conditions.

An approximation of the age of permafrost in this area can be obtained by means of inference and deduction. On permafrost landforms black spruce stands which date from a fire are as old as 150 years. Before such stands could have formed the permafrost must have become well developed, the process taking about one generation of trees at least, but most likely several generations, as small clumps of black spruce trees are needed to initiate perennial ice-lens formations, which may develop slowly into palsas or peat plateaus, as described by Zoltai (1972). From these estimates we can infer that densely wooded permafrost in this area is at least 180-300 years old. The permafrost in the area was formed sometime after deglaciation. As Lake Agassiz covered the area for a long period of time, permafrost could not have developed until the lake level subsided and peat formed. On the basis of evidence which includes the radiocarbon dating of a bog just south of the area (Klassen 1966) it is likely that peat formation started well after about 4,500 B.P. Two alternative eras of origin are: the cold period between 2500 B.P. and 1500 B.P. (Nichols 1967; Bryson and Wendland 1967; Bray 1971); or the cold period after 600 B.P. The first alternative seems somewhat unlikely, as during the warm period of about 1000 years which followed it, permafrost would have collapsed and most collapse scars would most probably have become overgrown. The second alternative is therefore a distinct possibility: most of the permafrost in the study area is probably not much older than about 600 years and not younger than about 150 years. The southern limit of collapse scars as mapped by Zoltai (Zoltai and Tarnocai 1969) must have had permafrost dating from between 600 B.P. and 120 B.P. Possibly this limit was reached during the "Little Ice Age" which started around 550 B.P. and ended about 1850 (Lamb 1963) — most likely between about 400 B.P. and 200 B.P.

The large increase in the rate of collapse of permafrost in the study area seems to be closely related to the climatic amelioration which occurred around 1850, or about 120 B.P. As the climate became gradually warmer the aggradation of permafrost probably diminished. Permafrost might even now accumulate under certain favourable conditions (such as perhaps a succession of relatively snow-free cold winters) on certain sites. Especially with the trend of cooling of the past 20 years, new permafrost might develop again in some area.

It is inadequate to suggest that a single meteorological parameter, such as temperature, controls permafrost development and collapse. Vegetation is the other important factor, which is itself dependent upon a number of climatic variables.

The distribution of the hummock-building sphagnum, which seems to be essential for the development of wooded palsas or peat plateaus, is strongly related to changes in conditions of moisture, temperature and evapotranspiration, which could well mean that within the general pattern of climatic changes, degradation and aggradation as phases in permafrost formations have alternated with each other.

Zoltai and Tarnocai (1971) found that the depth to which seasonal frost penetrates on wooded palsas and peat plateaus is closely related to thickness of snow layer. Under dense black spruce stands the thin snow allowed deeper penetration of seasonal frost than in the open where the snow formed a thicker and better insulating cover, often preventing the seasonal frost from reaching the permafrost.

In years of relatively heavy snowfall, seasonal frost might not reach the permafrost table, even under a dense black spruce stand. Therefore, in such years (especially when the heavy snow falls early in winter) the rate of collapse might increase at the same time as the rate of accumulation decreases. If such a situation continued over a number of years, a considerable change could perhaps be expected. The contrary might be the case if years of little snowfall occurred.

During the last 100-150 years the southern limit of localized and discontinuous permafrost has moved northward, perhaps from the southernmost occurrences of collapse scars on peatlands. If the present trend of cooling of the climate does not continue, the slow northerly movement will continue; and if the same trend is significant, and continues for a prolonged period of time, this probable movement to the north might well be stopped, and eventually reversed.

SUMMARY AND CONCLUSIONS

The present and former distributions of permafrost in the study area are closely related to the thickness of the peat layer, types of peatland and vegetation, and the relief of underlying mineral substrata, as caused by buried strandlines and glacio-fluvial deposits. Permafrost occurs most abundantly in medium-deep peats, and in bog-type peatlands, in the form of coalescent peat plateaus. The smaller permafrost landforms in fen areas tend to have a teardrop shape and are aggraded according to drainage in downflow direction. Large peat plateaus also have smooth forms, streamlined by drainage-water flow, but are not usually of a teardrop shape. At one time 60% of the land portion of the study area contained permafrost; at present the proportion is down to about 15% of the land area.

Permafrost bodies (in fens) smaller than 50 m. in diameter have in general completely collapsed over the 20-year period 1947-1967. Bodies smaller than 100 m. in diameter (in fens) collapsed peripherally. The amount of horizontal retreat of the permafrost edge was in the range of 15 m. to 30 m. over a 20-year period. Bodies of about 100-500 m. (in fens) had a low rate of collapse. Collapse started generally in the middle — probably the oldest part — in thermokarst sinks. Rates varied usually between 5 m. and 20 m. over the 20-year interval. Distinct collapse edges had rates of about 10-20 m. per 20 years. Some parts had melting rates of about 0-5 m. per 20 years. Larger peat plateaus manifested the same type of collapse — one starting in the inner core. The permafrost edges facing large fens were found to collapse later than edges facing other nearby permafrost bodies.

Downstream edges tend to collapse later than upstream edges. After collapse of the larger permafrost there is a noticeable trend towards the development of raised bogs. These bogs do not have permafrost, but are suitable sites for new permafrost formations. Forest fires do not seem to influence the rate of collapse in the study area. In a few cases, however, total collapse of permafrost has been set in train by fires.

Collapse prevailed over aggradation of permafrost in the study area for some time — that is for about 100-200 years B.P. — and therefore coincided with a climatic amelioration which began at about 120 years B.P. The author suggests that most permafrost in this area may have been formed between 600 B.P. and 200 B.P., and that the southern limit of collapse scars as mapped by Zoltai (1971) may have had permafrost between 400 B.P. and 200 B.P.

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