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BY

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LA GLACE DE SOL ET LA FORMATION DU RELIEF DANS LES REGIONS DE PERGELISOL

SOMMAIRE

Le rôle de la glace de sol dans la formation du relief des régions de pergélisol comprend également les résultats de la fonte de la glace de sol. Plusieurs formes du relief dans les régions de pergélisol doivent leur origine à l'accumulation de glace dans le sol. De nombreuses formes saillantes résultent de l'alluvionnement du pergélisol et des masses de glace de sol de plusieurs mètres qui l'accompagnent. Ces formes comprennent les pingos, les palses et les plateaux tourbeux, les polygones de coins de glace et les glaciers rocheux. Un deuxième groupe de formes associées à la dégradation du pergélisol et à la fonte de la glace de sol englobe les dépressions et creux de thermokarst, les lacs et les affaissements dus au dégel, les élévations de terre dites "cemetery mounds" et les cours d'eau en chapelet. La classification de Mackay de la glace de sol a coordonné dans une large mesure le rapport entre ces formes de relief et les formes de glace de sol dans les régions de pergélisol.

GROUND ICE AS AN INITIATOR OF LANDFORMS IN PERMAFROST REGIONS

R.J.E. BROWN

INTRODUCTION

The role of ground ice as an initiator of landforms in permafrost regions implies also the formation of landforms which result from the melting of ground ice. Many landforms in permafrost regions owe their origin to the build-up of ice in the ground. Several types of prominent features are formed by the aggradation of permafrost and the accompanying formation of large masses of ground ice, many metres in size. Such landforms include pingos, palsas and peat plateaux, ice wedge polygons and rock glaciers. A second group of landforms associated with the degradation of permafrost and melting of ground ice includes thermokarst depressions and hollows, thaw lakes, thaw slumps, cemetery mounds and beaded streams. The Mackay classification of ground ice has systematized to a considerable degree the relationship between these landforms and forms of ground ice in permafrost regions.

FEATURES ASSOCIATED WITH THE AGGRADATION OF PERMAFROST

Pingos

Closed and open system pingos, 20—400 m in diameter and 10—70 m high, are the largest and most spectacular landforms, the former containing the largest bodies of ice of any surface features in the permafrost region (Figure 1). Closed system or Mackenzie type pingos, which occur in the continuous permafrost zone, are thought to form by the so-called cryostatic method in one of two ways (Washburn, 1973) : (1) A lake becomes covered or filled by encroachment of vegetation from the margins and, being in a permafrost environment, this leads to the water becoming entrapped by progressive freezing from the top, bottom and sides. Eventual freezing and expansion of the entrapped water results in heaving and doming of the ground; (2) Draining or diversion of a water body that had insulated the underlying high-moisture sediments from freezing, leading to progressive all-sided freezing of the sediments. This causes a massive ice body to form either by expelling unfrozen water to where it freezes as injection ice, or providing a ready supply of water for development of segregation ice. The pingos in the Mackenzie Delta region of Northern Canada are virtually all located in or marginal to present or former lake basins. The origin of these pingos is becoming better understood through the work of J.R. Mackay (1962, 1963a, 1966, 1968, 1972a, in press; Mackay and Black, 1973).

Open system or East Greenland type pingos are thought to form by the so-called artesian method (Figure 2). Ground water flowing under artesian pressure below thin permafrost or in taliks within the permafrost, forces its way to near the surface where it freezes as injection ice, again forming an ice core that heaves the surface (Washburn, 1973). Such pingos can form in either soil or bedrock. Their origin has been discussed in detail by Müller (1959). Open system pingos are essentially restricted to the discontinuous permafrost zone and generally lie near the base of slopes. Water appears to enter the subsurface system from the surface in the non-perma-

FIGURE 1. Closed system pingo 40 m high near Tuktoyaktuk, N.W.T. in Mackenzie Delta Region.

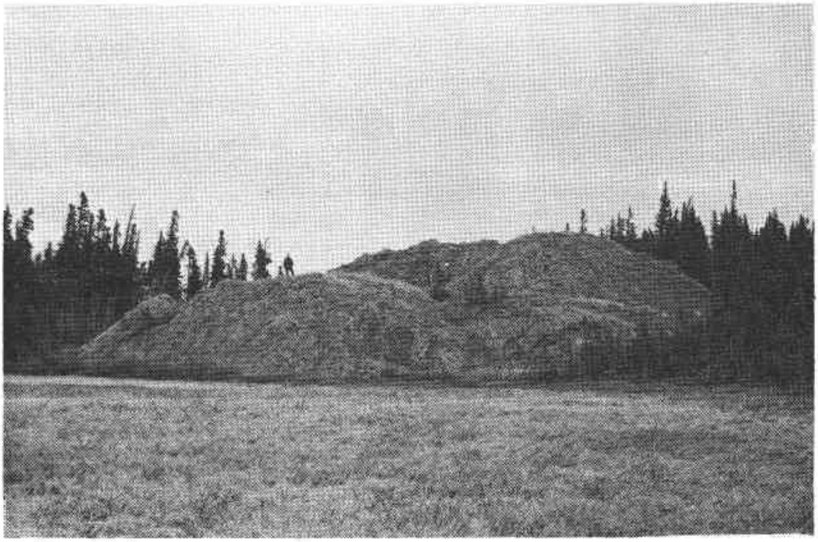

FIGURE 2. Open system pingo about 12 m high at base of Richardson Mountains west of the Mackenzie Delta.

frost areas upslope. Studies in the last decade indicate that almost all open system pingos in northwestern North America lie on the south or southeast facing slopes of alluvium-filled valleys (Holmes *et al.*, 1968; Hughes, 1969). The reason for this is unknown, although perhaps there are more opportunities for surface water to enter the ground in the non-permafrost areas on south facing slopes.

Some observations are available on pingo growth. Rates for closed system pingos up to 25 m in height, in the Mackenzie Delta region, have been determined by precise measurements (over a period of up to 3 years) to average about 15 cm annually (Mackay, 1972a). Extensive faulting also accompanies pingo growth, and a pingo summit has been observed to decrease 7.5 cm in one year, and then increase the next year (Mackay and Black, 1973).

Radiometric dating indicates that most pingos in North America are less than 4,000—7,000 years old. Mackay (in press) shows, by careful field measurements of four pingos over several years, that many are probably less than 1,000 years old and some less than 25 years.

Palsas

Palsas are mounds of peat overlying mineral soil and ice, 1—7 m high and 10—50 m in diameter, that occur in bogs (Figure 3). They protrude prominently above the level of the bog, have a rather hard and dry surface, and are more or less blown clear of snow in winter. The segregation of ice in thin layers and in bodies up to 2 m thick mainly in the mineral soil accounts for their formation. The thickness of the surface peat layer, which may vary from 1—5 m, is generally the same as in the surrounding terrain. Palsas have been traditionally thought to belong to the southern part of the discontinuous permafrost zone but similar features have been observed in the Canadian Arctic Archipelago in the continuous permafrost zone.

Palsas and associated peat plateaux are widespread in the discontinuous permafrost zone of Canada, especially the southern portion where the permafrost is patchy. They are found across Canada in this subzone, having been reported in all physiographic regions from Labrador (Brown, in press) to the Western Cordillera (Brown, R.J.E., 1967; Hughes *et al.*, 1972). They are particularly prevalent in the Hudson Bay Lowland in northern Ontario and northeastern Manitoba (Brown, 1968; Railton and Sparling, 1973) and they have been mapped from aerial photographs at a scale of 6.4 km to 1 cm (Bates and Simkin, 1966). Detailed studies have been carried out at several locations. Hamelin and Cailleux (1969) studied several palsa fields at Great Whale River, P.Q., near the east shore of Hudson Bay, observing their relationship to the local mean annual air temperature of -4°C to -5°C. Their age appears to be less than 4,000 years having formed after the postglacial thermal optimum following postglacial emergence.

A detailed ecological study of a palsa bog was carried out in the Hudson Bay Lowland south of Hudson Bay near Winisk, Ontario (Railton, 1968). The palsa bog was found to be ombrotrophic, the frozen cores of the palsas causing damming and perched water levels. Most of the better-developed palsas were found in the drier regions of the bog. Evapotranspiration was the main source of heat loss while exposure (reduced snow cover) and the low thermal conductivity of the peat were the main factors in palsa development. Palsa collapse was attributed to the melting of ground ice following the deterioration of the vegetation cover by rain and wind erosion.

FIGURE 3. Palsa 3 m high with surface layer of peat 1 m thick overlying sandy clay soil near Great Whale River, P.Q. Permafrost is about 6 m thick and none occurs in surrounding terrain.

Two important studies were carried out in Manitoba and Saskatchewan. Zoltai (1971) identified palsas and peat plateaux, indicating permafrost at present or in the recent past, in the field and on aerial photographs and traced them across Manitoba and Saskatchewan. The southern limit of their occurrence coincides with the 0°C mean annual air isotherm; this is south of the -1°C isotherm, designated as the southern limit of permafrost in Canada but coincident with the designated southern limit of permafrost in Alaska. A detailed study of one wooded palsa was conducted in northern Manitoba by Zoltai and Tarnocai, (1971). A cross section through the perennially frozen core, nearly 5 m thick, confirmed that the palsa relief is caused by the build-up of ground ice rather than by an increase in thickness of the surface peat layer.

Mounds resembling palsas have been observed at several locations in the northern part of the continuous zone in the Canadian Arctic Archipelago and may be genetically similar. French (1971) described ice cored hummocks or mounds forming in the centres of ice wedge polygons on Banks Island. Peat mounds, 2–3 m high containing 30-cm thick layers of ice, occur in clusters on the north coast of Devon Island in low-lying tundra meadows (Barr, 1971), the basal peat varying in age from 2,400–7,000 years BP (Figure 4). Similar mounds have been noted also in Bathurst Island (Lowdon *et al.,* 1967). These features may prove to be quite prevalent as more observations are reported.

Ice Wedge Polygons

Ice wedges and the polygonal patterns they reflect on the surface of the ground, are characteristic features of permafrost (Figure 5) (Brown and Péwé, 1973). They occur as wedge-shaped, vertical (or inclined) sheets or dikes 1 cm – 3 m wide and 1–10 m high, where seen in transverse cross section (Figure 6). Some masses, observed on the face of frozen cliffs, may appear as horizontal bodies a few centimetres to 3 m in thickness and 0.5–50 m long. The true shapes of these ice wedges can be seen only in three dimensions. Ice wedges are parts of a polygonal network of ice enclosing polygons or cells of frozen ground 3–30 m or more in diameter.

The network of ice wedges in the ground generally causes a microrelief pattern on the surface called polygonal ground or tundra polygons. Troughs that delineate polygons are generally underlain by ice wedges 1–2 m wide at the top. These polygons are 2–30 m in diameter and should not be confused with small scale polygons or patterned ground produced by frost sorting.

Polygons may be low-centre or high-centre. Upturning of strata adjacent to the ice wedge may make a ridge of ground at the surface on each side of the wedge, thus enclosing the polygons. Such polygons are lower in the centre and are called low-centre polygons or raised-edged polygons and indicate that ice wedges are actually growing and that sediments are actively being upturned. High-centre polygons exist if the material being pushed up cannot maintain itself above ground level or the polygons are not actively growing. Both high-centre and low-centre tundra polygons are widespread in North America, especially in the northwest, and are good indicators of the presence of ice wedges; however, care must be taken to demonstrate that the pattern is not a relic made up of ice wedge casts.

Ice wedges are either active or inactive. Active ice wedges are defined as those which are actively growing. The area of active ice wedges in North America coincides roughly with the continuous permafrost zone; this is

FIGURE 4. Palsa-like polygonal peat mounds on Devon Island N.W.T. in continuous permafrost zone. Peat is 2 m thick containing several layers of ice 30 cm thick overlying till.

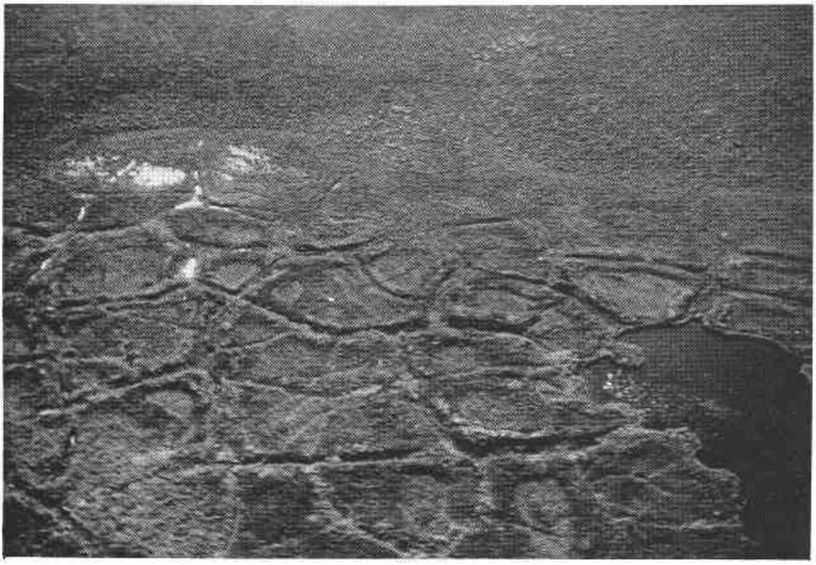

FIGURE 5. Aerial view of ice wedge poylgons about 30 m in diameter near Tuktoyaktuk, N.W.T.

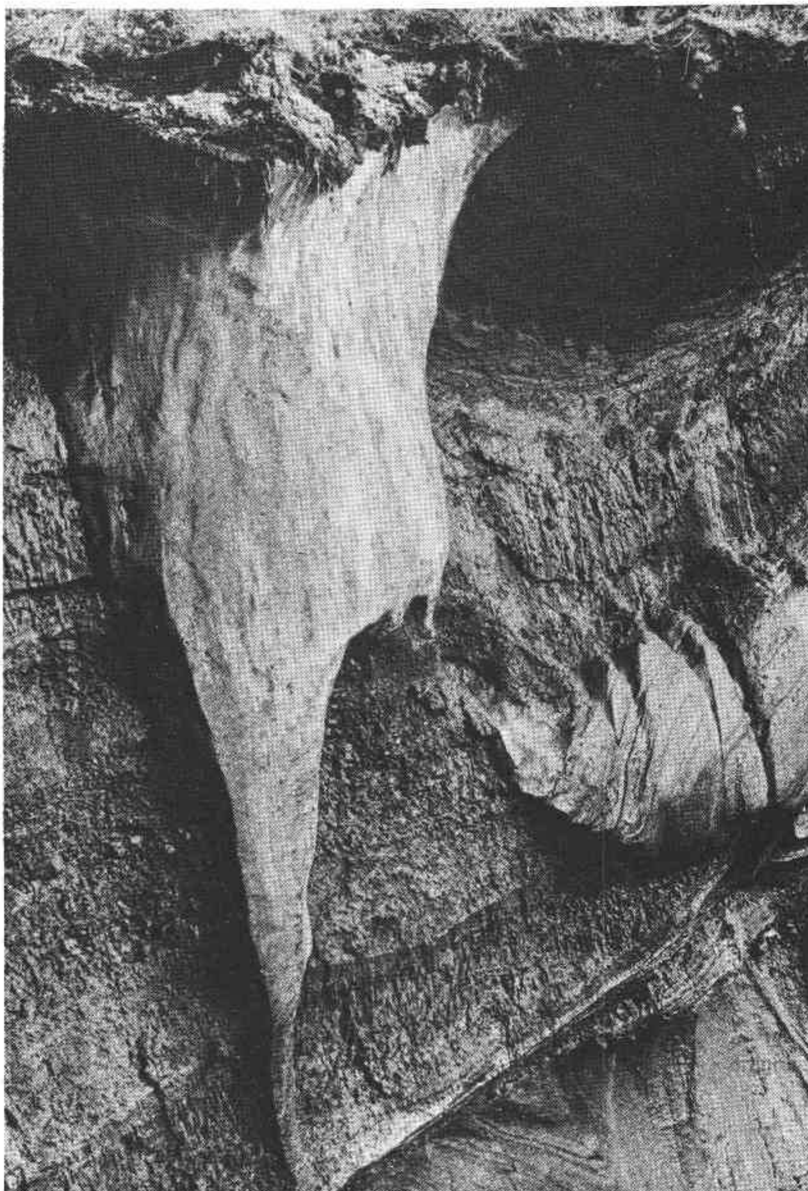

FIGURE 6. Ice wedge about 4.5 m wide at the top on Garry Island N.W.T. in Mackenzie Delta. (Photograph by J.R. Mackay, University of British Columbia).

especially true in Alaska and northwestern Canada. They occur widely in the northern reaches of the Canadian Arctic Archipelago being reported in various areas including Prince Patrick Island (Pissart, 1967, 1968) and as far north as Ellesmere Island (Hodgson, 1972). It appears that the ice wedges will crack and continue to grow where the winter temperature of the ground at the top of the permafrost is about -15°C or colder; this area is limited to the tundra and to the continuous permafrost (Mackay *et al.,* 1972; Mackay, 1972b; Black, 1963, 1969; Jahn, 1972; Pissart, 1967, 1968). Ice wedges in this zone are growing in various types of sediments (silt, sand and gravel) and exhibit a polygonal pattern on the surface of the ground.

In the discontinuous permafrost zone, especially in northwestern North America, the wedges are essentially inactive and the line dividing the zones of active and inactive ice wedges is arbitrarily placed at a position where low-centre or raised-edge polygons are uncommon and where it is thought most wedges do not crack frequently. When more data become available concerning the temperature at the top of the permafrost, this arbitrary line may be more accurately placed.

Inactive ice wedges have no ice seam or crack extending from the wedge upward to the surface in the spring. The top of the wedge may be flat, especially if thawing has lowered the upward surface of the wedge at sometime in the past (Péwé, 1966, in press; Sellmann, 1967, 1972). Ice wedges in the discontinuous permafrost zone, for the most part, are present only in silt; they have thawed and disappeared in many areas where they formerly existed in sand and gravel (Péwé *et al.,* 1969). Large areas of ice wedges in the discontinuous zone of permafrost are covered by Holocene sediments and do not exhibit a polygonal pattern on the surface of the ground.

The age of ice wedges is being studied both from the standpoint of absolute dating and from their geological position. Ice wedges have been radiometrically dated in northern and central Alaska ranging from 14,000–32,000 years old (Brown, J., 1967; Sellmann, 1967, 1972, Péwé, in press). Ice wedges have been investigated in many countries and all wedges seen so far appear to be Wisconsinan or Holocene in age.

In the last decade, a few detailed studies have been made on crystallographic investigations and on the rate of growth and mechanics of cracking of frozen ground. Mackay (1972b) published his observations on 5 years' continuous growth of cracks in the Mackenzie Delta and has now a continuous record for 7 years. He observed annual increments of ice in wedges ranging from 0.04–6.0 mm, with an average of 1–2 mm.

Rock Glaciers

Rock glaciers, tongue-shaped or lobate masses of unsorted, angular frost-rived material with interstitial ice (if active) and with steep fronts 10–100 m high, are one of the most spectacular of deposits in the permafrost environment but are limited in areal extent (Figure 7). They range from 150–3,200 m in width and 300–1,600 m in length, with the majority occurring in cirques. Some rock glaciers are the ablated remains of true ice glaciers while most form independently from pre-existing glaciers (Outcalt and Benedict, 1965; Foster and Holmes, 1965).

Rock glaciers form under the influence of a periglacial climate in an area lacking the net accumulation of snow required for the formation of a conventional glacier. A permafrost environment must be present (mean

FIGURE 7. Rock glacier south of Fairbanks, Alaska.

annual air temperature lower than 0°C) to enable the snow and water, which trickles down into the interstices between the rock, to remain as ice. Rock glaciers are indeed permafrost and move slowly downslope. They are probably more widely distributed, best developed, and more intensely studied in Alaska than anywhere else in North America but in the last 10 years, most work on rock glaciers appears to have been done in the Rocky Mountains of the contiguous United States, Alaska and in Canada. Rate of movement studies in the last 10 years include those by White (1971a, b) in the Colorado Front Range, where he indicates that rock glaciers move 5–10 cm/yr; Potter and Moss (1968) in the Absaroka Mountains of Wyoming indicate movement of 1–83 cm/yr. In Yukon Territory, measurements on some rock glaciers show movement of 50 cm/yr (Price, 1972).

An active rock glacier must be in equilibrium with a permafrost climate in order to produce frost-rived debris and to permit interstitial ice to exist. The rock glacier becomes inactive when these climatic conditions are no longer met, and thus loses its steep front, interstitial ice and forward motion. In North America inactive rock glaciers can be found at lower elevations than presently active ones, and no doubt they represent the lowering of snowline and changing of other climatic parameters in the past. There are both active and inactive rock glaciers in Alaska and it is thought that all of them were formed in post-Wisconsin time. Inactive rock glaciers, at an elevation of 1,200 m, occur along the Denali Highway in Alaska (Péwé, 1965) and at an elevation of 1,200–1,500 m in Anaktuvuk Pass in the Brooks Range (Porter, 1966). Two ages of rock glaciers also exist in the St. Elias Mountains of Yukon Territory (Price, 1972).

FEATURES ASSOCIATED WITH THE DEGRADATION OF PERMAFROST

The thawing of ice-rich permafrost creates an uneven topography, termed *thermokarst,* which consists of mounds, sink holes, tunnels, caverns, short ravines, lake basins, circular lowlands and beaded streams caused by melting of the ground ice. (Figures 8, 9, 10, 11) (Brown and Péwé, 1973). These features are the result of disturbance or removal of the vegetation or from a warming of the climate.

Thermokarst topography is most commonly formed where massive ice exists in the ground such as ice wedges, or thick layers of segregated ice. Only in the last decade has information become available in North America concerning quantitative measurements of the amount of ice in the ground. J. Brown (1967) made the first approximation of ground ice inventory for the arctic coastal plain of Alaska. Based on examination of ice in the ground from many boreholes in the Barrow area, and extrapolation from boreholes to the rest of the coastal plain by use of aerial photographs, he estimated that 10% of the volume of the upper 3.5 m of permafrost in the coastal plain is composed of ice wedges. Segregated ice is the most extensive type of ground ice — in places representing 75% of the ground by volume (Sellmann and Brown, 1973).

Mackay (1971) has demonstrated that, for the large area of thermokarst lakes in the Mackenzie Delta, the permafrost has a great amount of ice. There are widespread masses of ice associated with pingos and ice wedge polygons; in addition there are hundreds of square kilometres of thick, massive icy beds. In terms of weight of ice to dry soil, the icy beds are more than 200% ice. Recent quantitative measurements of ice in permafrost also have been made by Hussey and Michelson (1966) and by Williams

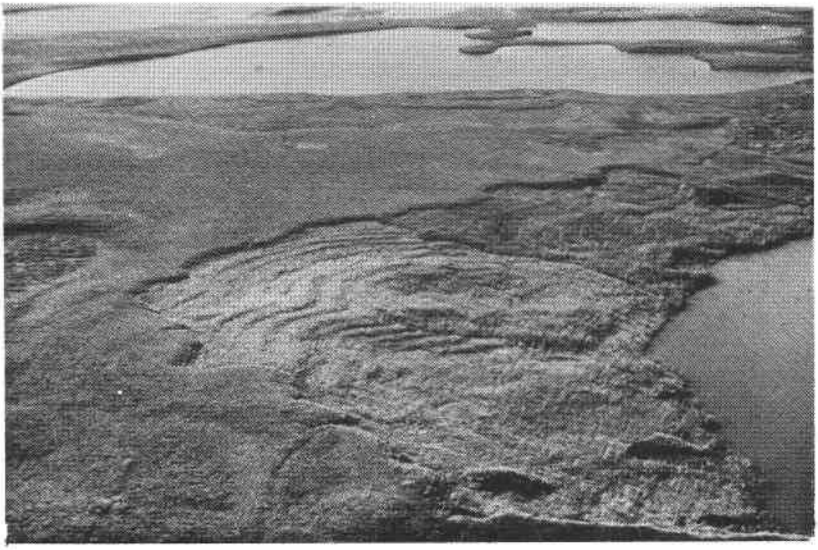

FIGURE 8. Slumped hills caused by melting of ice-rich permafrost near Tuktoyaktuk, N.W.T.

FIGURE 9. Cemetery mounds resulting from the melting of ice wedges near Yakutsk, U.S.S.R.

FIGURE 10. Thermokarst depression (alas) with cemetery mounds in background near Yakutsk, U.S.S.R.

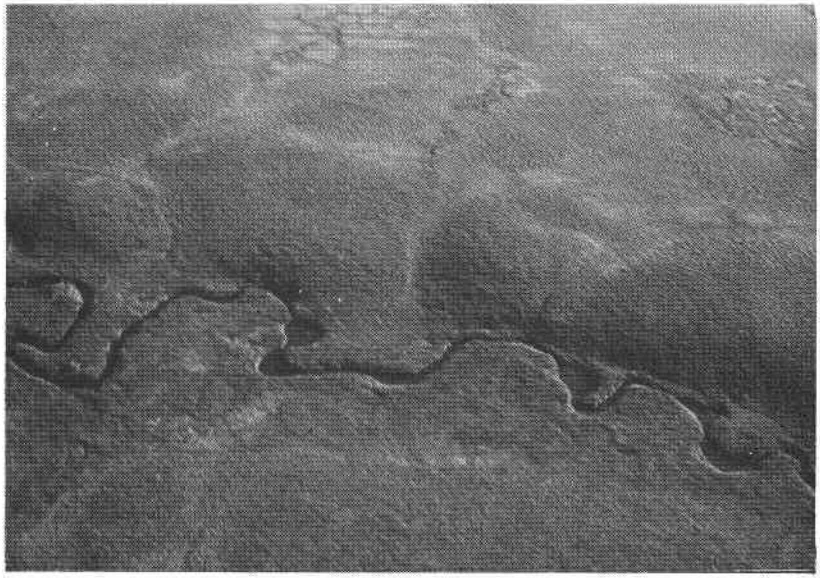

FIGURE 11. Beaded stream near Tuktoyaktuk, N.W.T. The enlargements in the stream are caused by the melting of blocks of ground ice in the stream bed.

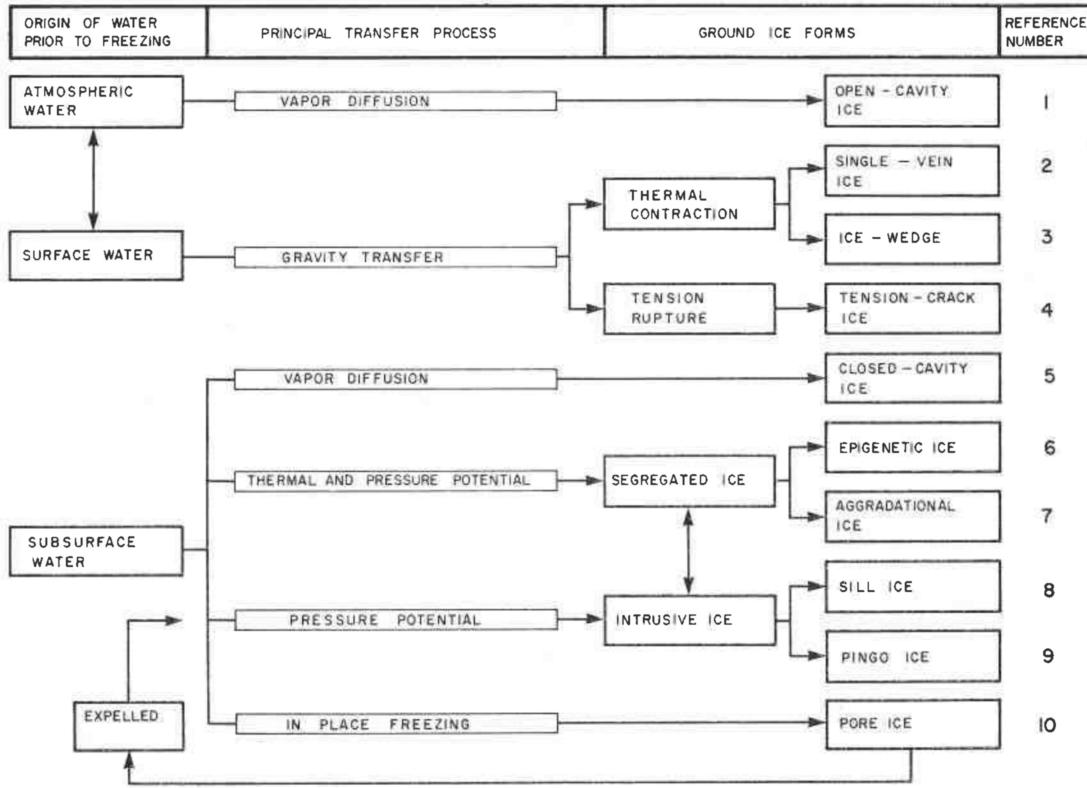

FIGURE 12. Classification of ground ice by J.R. Mackay.

(1968).

The most common thermokarst features are lakes, variously known as thaw lakes, thermokarst lakes, or cave-ins. Lakes occupying thaw basins are exceedingly abundant and widespread in the Arctic and Subarctic of North America. They occur in the lowlands and lower slopes throughout the valleys of central and northern Alaska and the northern part of Canada (French and Egginton, 1973), especially in the Mackenzie Delta area (Mackay, 1971) and elsewhere (Cailleux, 1971). Such lakes are referred to in literature from various parts of the North (Wahrhaftig, 1965; Tedrow, 1969).

Perhaps the most outstanding of the thermokarst lakes are the oriented lakes, widespread on the north slope of Alaska and east of the Mackenzie Delta on the Tuktoyaktuk Peninsula east to Cape Bathurst (Mackay, 1963b). A large area occurs on the west coast of Baffin Island (Bird, 1967) and near Old Crow in Yukon Territory. In the 1950's and earlier, there was much discussion concerning the origin and age of these lakes in northern Alaska; however, little work has been done since that time (Price, 1963, 1968; Black 1969). A summary of investigation of thermokarst development on the North Slope was made by Anderson and Hussey (1963).

Apart from these observations on thaw lakes, investigations of thermokarst phenomena in North America have only recently been initiated. The first study in the Canadian Arctic Archipelago was recently completed on Banks Island (French and Egginton, 1973). In the regions immediately east of the Mackenzie Delta, Rampton (1973) reported on thermokarst basins and deepened trenches in areas of ice wedge polygons resulting from the melting of excess ice. Most of this thermokarst activity postdates 11,500 BP.

CONCLUSION

Ground ice displays a complex variety of forms. J.R. Mackay has developed a classification system of ground ice forms based on two criteria — the first upon the source of water immediately prior to freezing, and the second is based upon the principal transfer processes which move water to the freezing plane (Figure 12). The associated surface features all contain ice of one form or another in the classification system.

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