Permafrost distribution and ground ice in surficial materials

J.A. Heginbottom[1]

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Abstract: The Mackenzie valley lies within the permafrost region of Canada; in consequence, most moisture in the ground occurs as ground ice. Ground ice commonly forms a significant component of the upper part of the ground and has important implications for economic development in the region. Ice occurs in many forms, most often as fillings in the intergranular pores of soils; however, it can also form much more massive bodies such as ice wedges and layers up to several metres thick.

Climate warming will lead to thawing of ground ice. This will lead to surface subsidence, increases in slope failures, and silt deposition in water bodies. Wildfire reduces the insulating capacity of ground-surface vegetation and will also induce excessive thaw. These outcomes can affect foundations and the stability of structures. Any cooling of the climate would reverse most of these effects, and would have relatively few adverse impacts.

Résumé : La vallée du Mackenzie est située dans la région pergélisolée du Canada. En conséquence, la majeure partie de l'humidité du sol se présente sous forme de glace de sol. La glace de sol constitue généralement une composante importante de la partie supérieure du sol et a, de ce fait, des répercussions de taille sur le développement économique de la région. La forme de la glace est variée, mais le plus souvent, elle remplit les espaces interstitiels. Elle peut également former des amas plus vastes comme des coins de glace et des couches de plusieurs mètres d'épaisseur.

Le réchauffement climatique causera le dégel de la glace de sol. Il s'ensuivra des subsidences de la surface, des glissements de terrain plus nombreux et une sédimentation de silt dans les étendues d'eau. Les feux de forêt, en éliminant la végétation de surface, réduisent l'isolation de la surface et provoquent un dégel excessif, ce qui peut avoir des effets néfastes sur les fondations et la stabilité des structures. Tout refroidissement du climat inverserait la plupart de ces effets et aurait relativement peu de répercussions de sens opposé.

[1] Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8

INTRODUCTION

The Mackenzie valley lies entirely within the permafrost region of northwestern Canada. Within this region, the temperature of the ground is continuously below 0°C over significant proportions of the area. One result of this is that moisture in the ground is commonly frozen, with ice often forming a substantial proportion of the upper part of the ground. The ground surface throughout the area is also subjected annually to deep seasonal thawing and freezing in response to seasonal fluctuations of air temperature. Both the low ground temperatures and the presence of ground ice have major effects on the landscape, on active geomorphic processes, and on construction and development in this region.

The ground ice occurs in two main forms, as structure-forming ice, bonding the enclosing sediments, and, particularly in the northern part of the study area, as large bodies of more or less pure ice. These two groups are discussed separately. The structure-forming ice comprises segregated ice, intrusive ice, reticulate vein ice, ice crystals, and icy coatings on soil particles. The large bodies of more or less pure ice, which exist mainly in the upper part of the ground, occur as pingo cores, massive icy beds, and ice wedges.

The distinction between structure-forming ice and bodies of massive ground ice is important for engineering and construction purposes. The design, construction, and operational plans for engineering works need to accommodate structure-forming ice beneath the foundations, as the presence of such ice is ubiquitous. The larger ground-ice bodies can often be avoided, however, provided their presence can be identified and their location detected. Landform analysis and geophysical exploration techniques can be of great value in addressing this problem.

For nearly all economic or development activity in northern regions, the occurrence of ground ice within the permafrost is of much greater significance than the temperature of the ground. This is because of the ground-stability problems associated with any surface disturbance that may cause subsequent thawing of ice-rich permafrost. Thus sufficient and accurate information on the character, distribution, and form of frozen ground and ground ice, as well as the geographical and geological setting of its existence, is very important for rational planning of economic development in northern Canada. In various ways, permafrost has always had significant effects on the economic development of the North, particularly for the energy and mining industries, but also for the construction of modern settlements and infrastructure elements such as roads, railways, airfields, and utilities.

The details of the permafrost extent and ground-ice conditions shown in the accompanying figures (Fig. 1a, 1b) have been summarized largely from engineering geology field mapping by the Geological Survey of Canada, as compiled by Heginbottom and Radburn (1992) and Heginbottom and Ruhland (unpub. map manuscript, 1995). Where data from engineering geology field maps were lacking, maps of surficial geology and Quaternary features were relied on. The compilations by Heginbottom and Radburn (1992) and Heginbottom and Ruhland (unpub. map manuscript, 1995) were produced by evaluating all the permafrost- and ground-ice-related information provided by the field geologists and map compilers, developing a common legend for the permafrost and ground-ice conditions, and drafting the maps with a minimum of generalization (Heginbottom, 1983, 1985). The source maps for these compilations were published between 1966 and 1982 — a time span of 17 years. This imposes some limitations on the data for the purposes of evaluating the implications of climate change, in that the climate was not regarded as changing over the period from 1966, when the first source map was published, until the present — a situation that is now known to be unrealistic. Thus the maps by Heginbottom and Radburn (1992) and Heginbottom and Ruhland (unpub. map manuscript, 1995) present a summary of the permafrost and ground-ice conditions as reported, but the data have not been adjusted to a common date.

The Quaternary geology of the region has been described by Hughes (1972), Rampton (1982, 1988), Hughes et al. (1983), Vincent (1989), and Duk-Rodkin and Hughes (1995). Ground ice in the Arctic Lowlands in general was reviewed by Carter et al. (1987). Terminology in this paper generally follows the recommendations of the Permafrost Subcommittee (1988), except for terms and definitions of permafrost zones; these follow Heginbottom and Radburn (1992).

EXTENT OF PERMAFROST

The extent of permafrost increases from sporadic discontinuous permafrost (with <35% of the area underlain by frozen ground), in the southern part of the region, to continuous permafrost (>90% of the area underlain by frozen ground), at the Beaufort Sea coast (Fig. 1b). There are two exceptions to this broad generalization. First, the Mackenzie Delta comprises an area of intermediate discontinuous permafrost (35–65% of the area underlain by frozen ground), well within the zone of continuous permafrost. This is due partly to the large proportion of the delta occupied by lakes with subjacent taliks, but also to warming of the ground by advected heat from the Mackenzie River. Secondly, in the Franklin Mountains, the Canyon Ranges of the northern Mackenzie Mountains, and the Richardson Mountains, altitudinal effects result in more extensive permafrost than would otherwise be expected on the basis of latitude alone. These effects occur both at upper elevations, as a result of normal adiabatic temperature-lapse rates, and also in valley bottoms, caused by ponding of very cold air and severe radiative cooling under conditions of stable temperature inversions in winter.

GROUND-ICE CONTENT OF SURFACE DEPOSITS

The ice content of the upper part of the ground ranges from negligible in consolidated rock and dry, coarse-grained deposits in the southern part of the study area, to high in peatlands and fine-grained deposits, particularly in the central and northern parts of the study area (Fig. 1a). The ice usually occurs as frozen pore water, lenses of segregated ice typically a few millimetres thick, or ice veins. These ice forms, which act to bind the enclosing sediment, lead to the concept of 'ice-bonding'. This provides a practical distinction from the strictly thermal condition of being below 0°C used to define 'permafrost'.

At most locations, the upper few metres of permafrost, immediately below the base of the summer thaw zone (termed the active layer), tend to have a relatively higher ice content than deeper permafrost (Pollard and French, 1980). This has been postulated to have resulted from a general cooling of the climate over recent decades to centuries. The ice-content figure (Fig. 1a) summarizes current knowledge of the general content of ice in the upper 10–20 m of the ground, in six categories.

High ice-content permafrost

High ice-content permafrost comprises ground containing greater than 15% visible ice. Areally, this is the least extensive of all the categories, being essentially confined to an area of peat-covered, glaciolacustrine silts and clays, immediately northwest of Sans Sault Rapids, and to a few small areas of fine-grained deposits to the west of the Richardson Mountains, and in the upper valleys of the Peel and Arctic Red rivers.

Moderate ice-content permafrost

Moderate ice-content ground contains between 5 and 15% visible ground ice in the upper part of the ground. This is the most widespread category of ground ice in the study area, and occurs throughout the region from 60°N to the Arctic coast. It is the most commonly occurring form of ground ice in areas of till plains, including those with extensive peat cover, and the Mackenzie Delta plain. It is also present in the broad valley floors within the western mountains (Mackenzie and Richardson mountain ranges), and in sandy deposits of the Pleistocene Mackenzie Delta of Richards Island, Yukon Territory coastal plain, and parts of Tuktoyaktuk Peninsula.

Low ice-content permafrost

Containing generally less than 5% visible ice, low ice-content permafrost is found primarily in three situations: 1) the foothills of the western mountains, south of 64°N, and including the eastern slopes of McConnell Range; 2) the mountainous terrain of the northern Canyon Ranges and the Richardson Mountains, north of 64°N; and 3) areas of coarse-grained and well drained deposits within the Interior Plains; ridged moraine in the southeast of the study area; rock outcrop in hills; coarse alluvial deposits in river valleys in the central part of the study area; and glaciofluvial deposits in the Tuktoyaktuk coastlands.

Negligible ice-content permafrost

Permafrost which contains no visible ice is described herein as having negligible ice content. This category is present primarily in the southern parts of the Canyon Ranges and Franklin Mountains.

Variable ice-content permafrost

There are also extensive areas of permafrost with widely variable ice contents. These comprise 1) subregions where distinct patches of high, moderate, low, and even negligible ice-content permafrost are intermixed, and 2) areas of primarily hummocky and ridged moraine with low ice-content ground on the tops of hummocks and ridges, and high ice-content ground in the intervening depressions. The former category is widespread in the southern part of the study area, particularly in areas of alluvial and lacustrine deposits associated with glacial Lake McConnell. These areas are found alongside the valley of Mackenzie and Liard rivers, to the south of 64°N. The second category occurs in patches on the plains. It is most common south of 64°N, but smaller areas are found north to the Arctic coast.

Areas free of permafrost

There are also a number of areas that are essentially free of permafrost and so contain no perennial ground ice. Most occur in the area either side of the Mackenzie River, between Mills Lake and the confluence of Liard and Mackenzie rivers.

ICE WEDGES, MASSIVE ICE, AND PINGOS

Large bodies of ice, occurring within ice-bonded permafrost and having major dimensions ranging from a few metres to many hundreds of metres, occur in three main forms: as ice wedges, as massive icy beds, and as the cores of pingos.

Ice wedges

These occur widely throughout the northern part of the area, but only sporadically in the southern part. Active ice wedges (downward tapering bodies of ice which are growing where meltwater fills thermal contraction cracks) are probably confined to the northernmost part of the region, generally north of 68°N. Even in this area, many ice wedges do not crack each year. In the northern part of the study region, the general distribution of active ice wedges can be gauged from the occurrence of intersecting networks of frost polygons or ice-wedge polygons. The distribution of inactive ice wedges is poorly known, however, as most have no surface expression.

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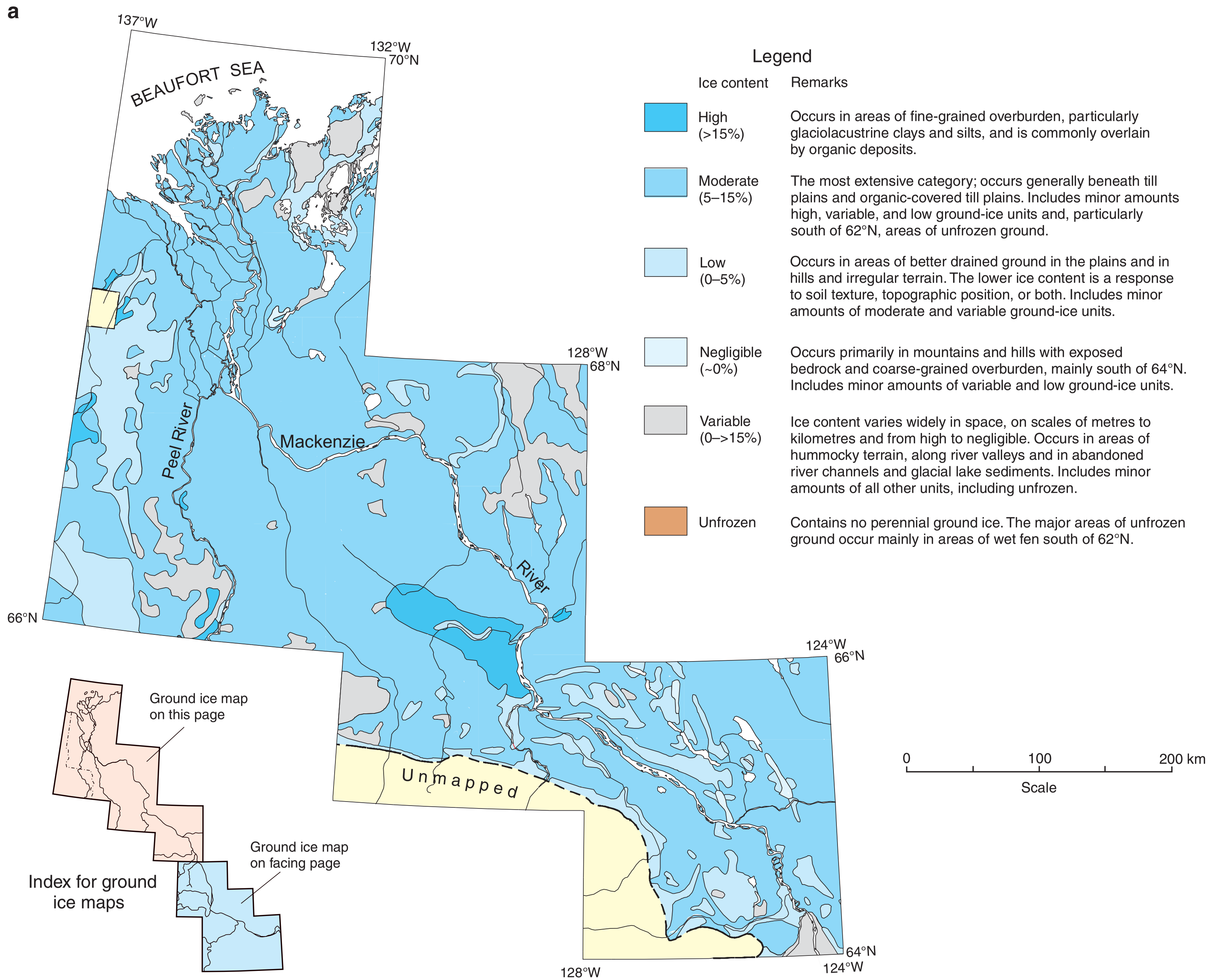

Figure 1. *Maps showing **a**) distribution of ground ice, and **b**) extent of permafrost. Index map shows relationship between the north on south parts of the ground-ice map. The permafrost map covers the same area as the ground-ice map.*

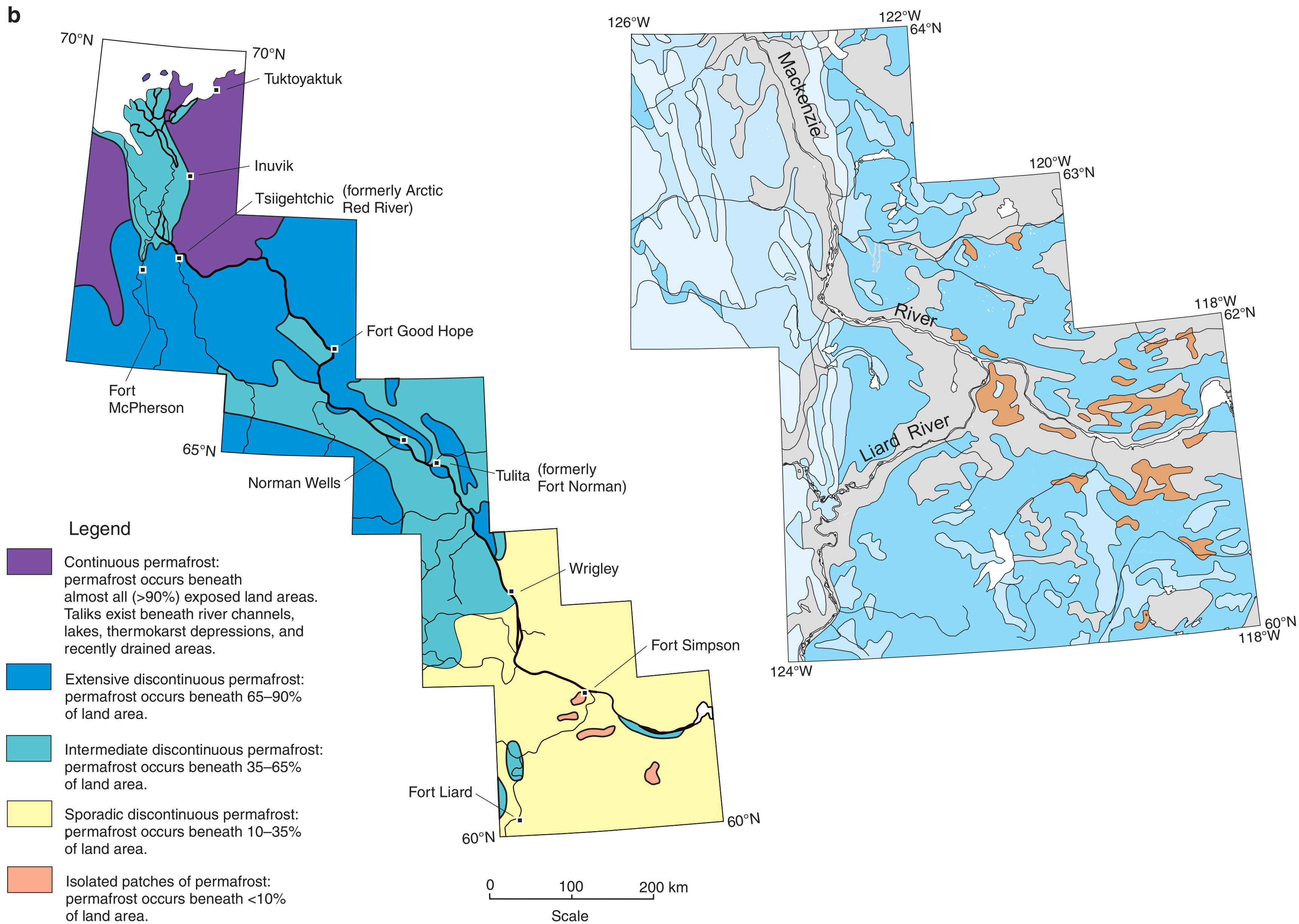

Figure 1 *(cont.)*

Massive icy beds

Massive beds of ground ice are found exclusively in the northernmost part of the region. They are well exposed in coastal sections of the Yukon Territory coastal plain, the islands off the Mackenzie Delta, and the Tuktoyaktuk Peninsula, including the Eskimo Lakes. Their origin and distribution have been discussed by Mackay (1963, 1971, 1973), Rampton and Mackay (1971), and Mackay and Dallimore (1992). It is believed that much of the higher ground of the Pleistocene Mackenzie Delta, particularly Richards Island and the Tuktoyaktuk Peninsula, owes its elevation to thick, extensive, tabular sheets of ground ice (Rampton and Mackay, 1971; Rampton and Walcott, 1974). Mackay (1963, Fig. 21) included a map of 'ground ice slumps' (now also referred to as 'retrogressive thaw slumps', or 'bimodal flows'); as many of these exposed massive ground ice, Mackay's map gives some indication of the wide extent of massive ice deposits in the area east of the Mackenzie Delta. It is possible that some of these ice masses are relict glacial ice; others may be buried deposits of other surface ice, such as river icings, snowbanks, or lake ice. Mackay's map of ground-ice slumps is reproduced as Figure 2.

Pingo cores

Pingos, large conical to hemispherical mounds or small hills with icy cores, also occur exclusively in the northernmost part of the region. Their distribution was also mapped by Mackay (1962, Fig. 1). Mackay's map of pingo distribution in the Tuktoyaktuk coastlands is reproduced as Figure 3. The Tuktoyaktuk Peninsula and adjacent areas include the world's largest concentration of pingos — over 1450 in an area 120 km long by 50 km wide. Their distribution and origin have been reported on extensively by Mackay (1962, 1963, 1979).

GEOTECHNICAL CONSIDERATIONS

Throughout the region, ground ice is generally within a few degrees of its melting point, often within a fraction of a degree of 0°C, and is susceptible to surface disturbance and slope failure. On level ground, in fine-grained, high ice-content deposits, surface disturbance commonly leads to the development of thermokarst, extensive subsidence of the ground surface and the growth of thaw lakes. On slopes, deeper thawing leads to slope failure, initially in the form of skin flows or

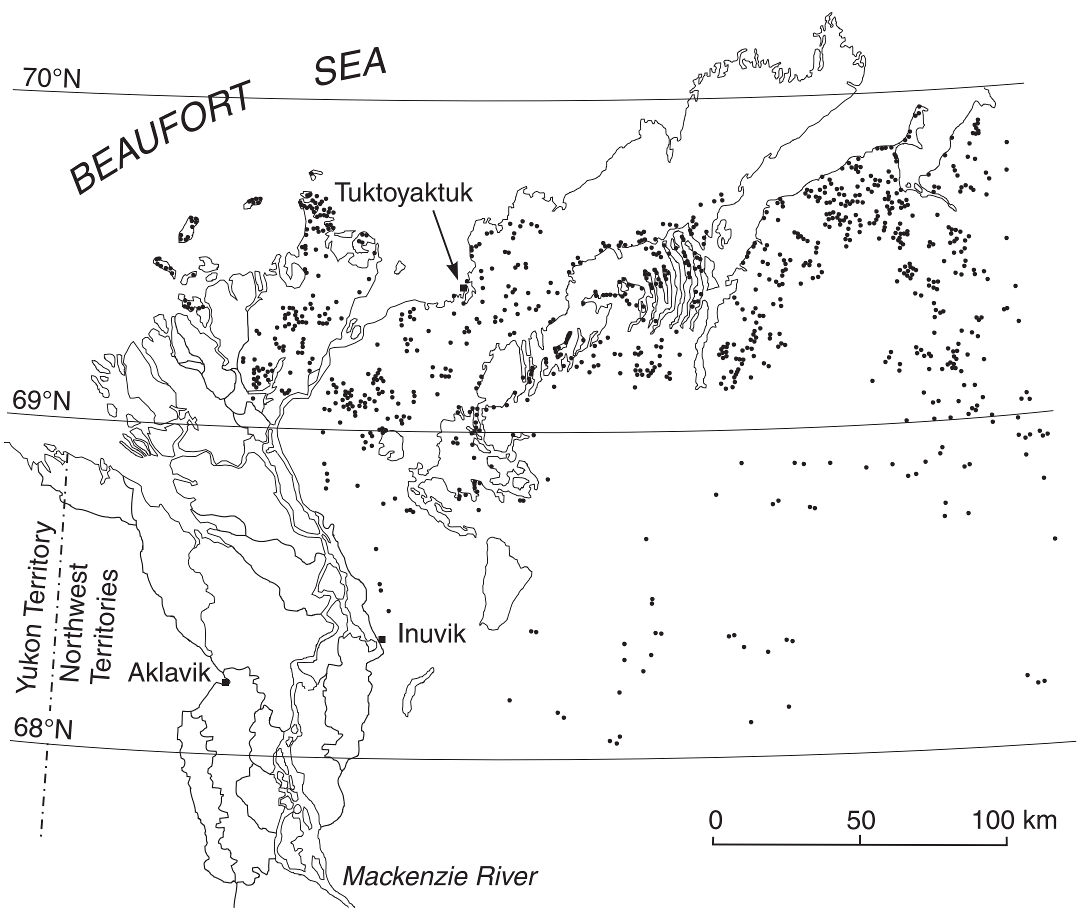

Figure 2. *Location where massive ground ice has been exposed in slumps. Where dots are clustered, they represent one or more slumps. Where dots are dispersed, they usually represent only one slump (*after *Mackay, 1963).*

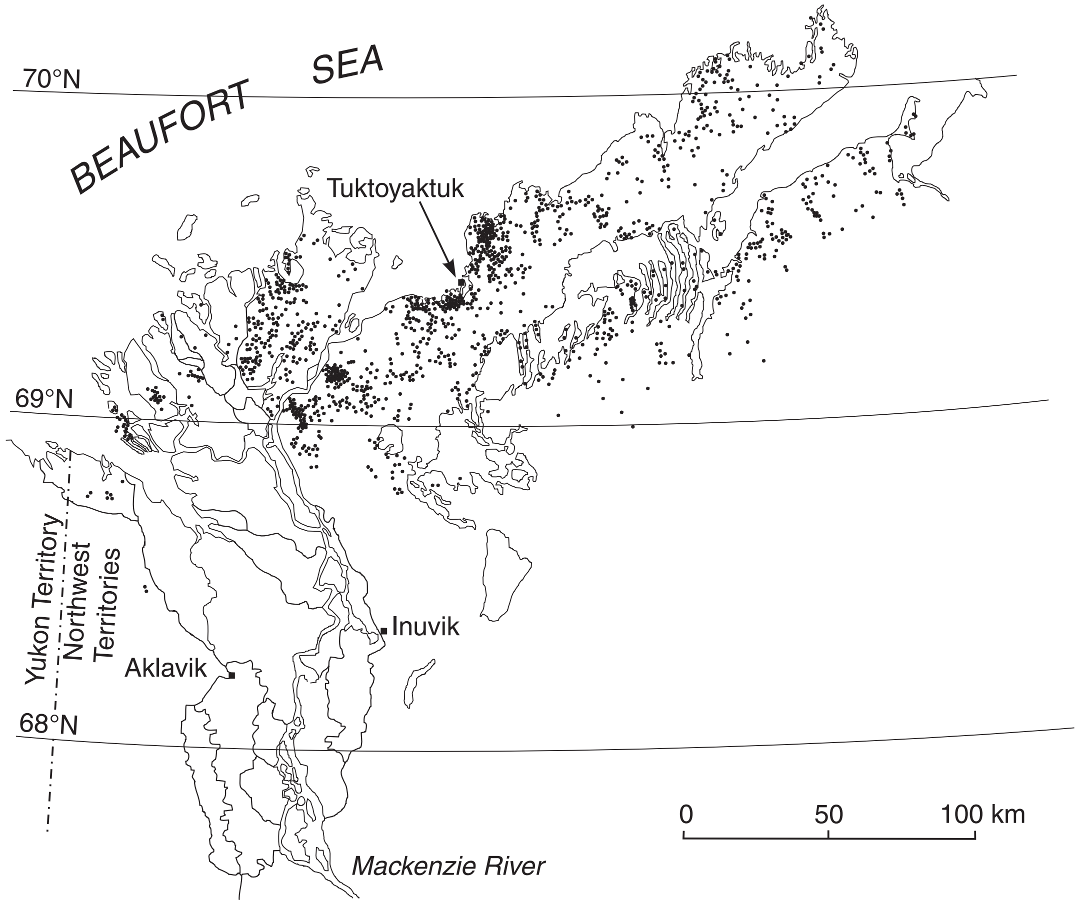

***Figure 3.** Distribution of pingos as mapped from airphotos (*after *Mackay, 1963).*

active-layer failures. If such shallow slope failures expose massive ground ice, retrogressive thaw slumps can develop. Along the Beaufort Sea coast are sections of cliff coastline cut in frozen, unconsolidated sediments. Such materials are susceptible to thermal-niche development and failure as thermoerosional falls. Thermal niches can develop very rapidly under storm conditions in the late summer.

Saline permafrost is known to exist at the Tuktoyaktuk, Inuvik, Tsiigehtchic, and Fort McPherson settlements, and also at sites on Richards Island (Hivon et al., 1989; Hivon, 1991), all in the northernmost parts of the region. It may be assumed that saline permafrost underlies other parts of the area. The origin of this salinity has not been determined conclusively. In part it may result from the dissolution of saline rocks; elsewhere, particularly in the northern part of the region, it may result from the incorporation of seawater into the permafrost body. The salinity of the ground is important because high salinities have negative effects on the mechanical properties (strength, creep, etc.) of soils, and so may necessitate modifications to engineering designs.

IMPLICATIONS OF CLIMATE CHANGE

Under conditions of global climatic change, permafrost and ground-ice conditions will change. Climate warming will lead to an overall reduction in the extent of permafrost and a melting of ground ice, with a general northward shift in the southern limits of the permafrost zones. A cooling climate will cause an increase in the extent of permafrost and, with time, an increase in the amount of ground ice, particularly structure-forming ice. As discussed in Dyke and Brooks (2000), there is evidence that the climate of the Mackenzie valley has warmed in recent decades. Currently, global circulation models (GCMs) predict a general warming of climate worldwide by several degrees Celsius. Most GCMs also predict that this warming will occur first and to a greater than average degree in arctic and subarctic regions — the very areas encompassed by the Mackenzie valley. Thus, climatic warming of the past century in this area is anticipated to continue.

The implications of a warming scenario will therefore be discussed in more detail than those associated with climate cooling. It should be noted, however, that even under a general warming of the climate, there will be localities where the ground-surface temperature becomes cooler and permafrost therefore cools and thickens.

A general warming of the climate will have a significant effect on the extent and distribution of permafrost and ground ice, and on permafrost-related geomorphic processes within this region. In general, as the ground warms, the active layer will increase in depth and the icy permafrost immediately below the active layer will thaw. On level to gently sloping sites, thermokarst pits and ponds will develop in areas of poor soil drainage. On slopes, the incidence of shallow slope failures will increase in extent and frequency. Where such active-layer failures (also referred to as skin flows) expose massive ground ice, retrogressive thaw slumps will develop. Ice wedges pose a special difficulty in that inactive wedges often have no surface expression; this can lead to problems for the construction and maintenance of roads, airstrips, and pipelines. As the number of active wedges decreases and more of the inactive ones begin to thaw, these problems are likely to increase significantly. In areas near coasts and rivers, deepening of the active layer and thaw of ice wedges will lead to the drainage of small lakes and ponds. As long as the local air climate is conducive to the continued existence of permafrost, permafrost will begin to develop in these newly exposed areas of land.

Climate warming will gradually lead to changes in vegetation and probably in the incidence of wildfire. Both of these changes will have effects on permafrost conditions, in the long term, where vegetation changes lead to further changes in the relationship between air climate and soil climate, and in the short term, when wildfire further accelerates the incidence of slope failure and the rate of vegetation change locally.

On a site-by-site basis, the effects of climate warming can be assessed qualitatively with a fair degree of accuracy. The general low thermal conductivity and diffusivity of earth materials, coupled with the high latent heat required to melt ice, lead to a lag in time between warming of the air and ground surface and effects on permafrost actually developing. For deep permafrost, this lag time can amount to many thousands of years; deep relict permafrost, which developed during the Pleistocene glacial periods, still exists beneath the Beaufort Sea continental shelf, immediately to the north of the study area. All this shows that while the effects of climate warming on permafrost conditions may be predictable, the timing is quite uncertain; it is amenable to modelling, but only on either a detailed site-by-site basis or in a very general way.

These changes have clear implications for the infrastructure, settlements, and economic activities of the population of the region. Increases in the incidence of slope failures, particularly along river banks, are likely to increase the silt load in rivers, and so affect domestic and commercial fisheries. A deepening of the active layer may negatively affect the stability of roads, airstrips, pipelines, and the foundations of buildings and other structures. Of particular concern will be the stability of tailings-pond dams, water reservoirs, oil tanks, etc., where catastrophic structural failure could lead to other, serious environmental problems.

Finally, there is concern that thawing of permafrost could result in the release to the atmosphere of large quantities of carbon dioxide and methane, which would accelerate the greenhouse effect and increase the rate of future climate warming. These gases would come from the decay of organic material, currently preserved by being frozen, and from the release of gas hydrate presently trapped beneath permafrost.

Any general cooling of the climate would be expected to reverse most of the effects already discussed. Permafrost would increase in extent and, eventually, in thickness. The active layer would be thinner and high moisture-content soils at its base would be incorporated into the permafrost, increasing the iciness of the uppermost part of the permafrost. Slopes would be come generally more stable; ice wedges would be rejuvenated; and thermokarst development would be retarded. Most of these effects would have only limited implications for settlements or infrastructure.

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