Ground temperature studies of permafrost growth at a drained lake site, Mackenzie Delta

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Illisarvik lake on Richards Island, Mackenzie Delta, Canada, was artificially drained in order to investigate the growth of permafrost. Twenty-four boreholes were hydraulically drilled to depths ranging from 15 to 92 m below lake level and were instrumented with temperature cables. Monitoring of ground temperatures beneath the lake and surrounding shore-lines prior to drainage delineated a bow-shaped talik extending up to 32 m below lake bottom. Characteristics of the predrainage temperature profiles in the central lake holes were i) an upper unfrozen horizon in which temperatures reached a maximum of 2.5°C at roughly 5 m below lake bottom, ii) a permafrost table at depths of 20 to 32 m in the central part of the lake with consistently negative temperatures below, and iii) negative temperature gradients below the 5 m maximum temperature, averaging 50 mk/m in the permafrost section. Two years of post-drainage temperature monitoring revealed iv) that the former talik had completely frozen at nearshore sites (10 m thick or less), whereas, v) only 5 to 6 m of new permafrost had formed at central sites, and vi) in the unfrozen sections temperatures were close to 0°C. A two-dimensional finite element computer simulation of the formation and growth of Illisarvik suggests a minimum lake age of 900 to 1000 years. Post-drainage conditions in the first year after drainage were modelled by studying the microclimatic regime together with the ground thermal regime. Although predicted profiles agreed well with measured temperatures, geotechnical and year-round weather gathering programmes are necessary before further post-drainage modelling is warranted.

On a asséché le lac Illisarvik dans l'île Richards du delta du Mackenzie au Canada dans le but d'étudier la croissance du pergélisol. Vingt-quatre trous ont été forés hydrauliquement jusqu'à des profondeurs variant entre 15 et 92 m dans le fond du lac et ont été reliés à un réseau de câbles de mesure de la température. L'observation des températures du sol sous le lac et sur les rives avant l'assèchement a permis de déliminer un talik en forme de croissant qui s'enfonce jusqu'à 32 m sous le lac. Les profils de températures avant l'assèchement, dans les sondages creusés au centre du lac, révèlent (i) un horizon supérieur non gelé dont la température maximale est de 2,5°C à une profondeur d'environ 5 m sous le lac, (ii) un toit de pergélisol dans le centre du lac à des profondeurs de 20 à 32 m au-delà desquelles la température se maintient systématiquement sous 0°C, (iii) des gradients de température négatifs sous le niveau de température maximale de 5 m, avec une moyenne de 50 mk/m dans la zone de pergélisol. Les contrôles de température effectués deux ans après le drainage ont révélé (iv) que l'ancien talik est complètement gelé près des rives (10 m d'épaisseur ou moins), tandis (v) qu'une couche de seulement 5 à 6 m de nouveau pergélisol s'est formé au centre du lac, et (vi) que la température des zones non gelées est voisine de 0°C. Une simulation bidimensionnelle, par éléments finis sur ordinateur, de la formation et de la croissance d'Illisarvik indique que le lac s'est formé il y a au moins 900 à 1 000 ans. Les conditions pendant la première année après l'assèchement ont été modélisées à partir d'une étude du régime microclimatique et du régime des températures du sol. Même si les profils prévus sont en bon accord avec les mesures de température, il faudra mettre sur pied des programmes de collecte de données géotechniques et de données météorologiques d'années complètes pour justifier la modélisation d'une plus longue période postérieure à l'assèchement.

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Introduction

The drainage of lakes by natural processes in the Mackenzie Delta, Canada, has been occurring for several thousand years. Since 1950, at least 29 lakes have drained either partially or completely, an average rate of one lake per year, and permafrost is now aggrading in the former lake bottoms (Mackay 1981). In August 1978, "Illisarvik Lake", an unofficial name literally translated from Inuktituk as "A place of learning", located on northern Richards Island in the Mackenzie Delta (Figure 1) and on the verge of self-drainage by natural shore-line erosion, was artificially drained. The experiment proposed in 1973 by Dr. J.R. Mackay of the University of British Columbia (Mackay 1980) was undertaken to investigate the growth of permafrost in the western Canadian Arctic under naturally occurring field conditions. The overall objectives were to increase the knowledge of permafrost properties and of the processes involved in permafrost growth (for example, redistribution of moisture, ice segregation, rate of frost penetration, and associated heave) and thus lead to a better understanding of both natural permafrost processes and problems relating to northern development. The artificial drainage of a lake permitted a scheduled observation of the predrainage characteristics in order to describe the initial physical conditions.

The drained lake experiment is a multidisciplinary

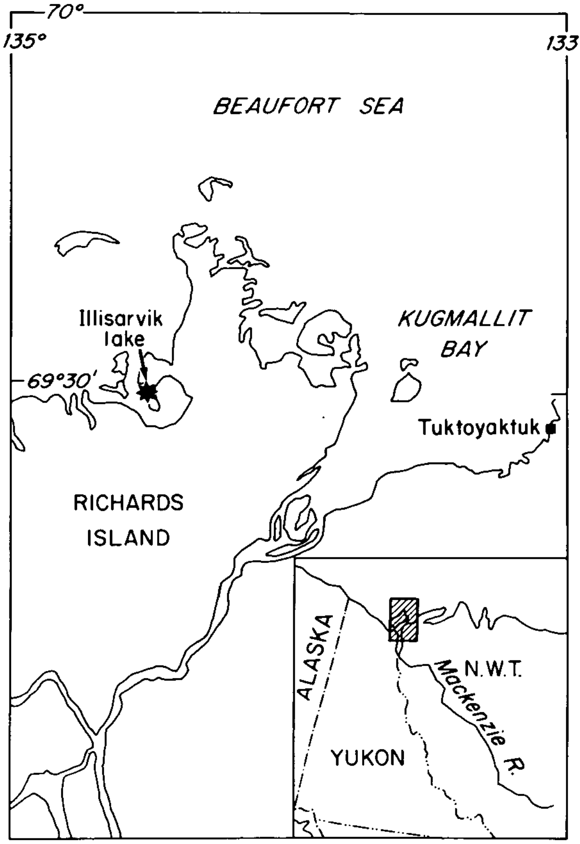

FIGURE 1. Location Map, Illisarvik lake, Mackenzie Delta.

study involving scientists from several institutes; principally the University of British Columbia, the federal departments of Energy, Mines and Resources, Environment, and Indian and Northern Affairs, and the University of Waterloo. The main activities during the predrainage phase consisted of the establishment of a metric grid over the survey area, a bathymetric survey, the drilling of boreholes and their instrumentation with temperature cables, coring for pollen and C-14 analysis, measurements of snow depth and ice thickness, and marine seismic refraction and resistivity surveys to map the top of ice-bonding beneath the lake bed (Hunter 1980; Hunter *et al.* 1980). On August 13, 1978, flow from the lake was diverted to the sea along a prepared 45-m drainage ditch chosen to follow an ice-wedge system and thus to ensure rapid vertical erosion; within eight hours the lake had largely drained (Mackay 1981). Lake bottom features were then marked for observation. After drainage further drilling for ground temperature installations took place and meteorological data collection was begun. The final post-drainage phase involves the long-term monitoring of the ground thermal regime and the microclimatic regime during the freezing of the lake bottom as well as monitoring of geocryologic phenomena.

In this paper, results from predrainage and post-drainage ground temperature monitoring conducted by the Earth Physics Branch of Energy, Mines and Resources are presented. Preliminary results of thermal modelling of the predrainage and post-drainage conditions are also discussed. Thermal conditions in conjunction with climatic and shore-line histories are being analysed to determine the natural predrainage equilibrium permafrost distribution and, hence, the minimum age and thermal history of the lake. The post-drainage ground thermal regime is being analysed using a microclimatic approach to model the freezing of the talik and the formation of permafrost.

Thermal and Geographical Setting

Illisarvik lake is located 60 km due west of Tuktoyaktuk, Northwest Territories, on a peninsula of northern Richards Island, Mackenzie Delta. The predrainage lake measured some 300 × 600 m, was 45 m from the sea coast at its closest point with a mean lake surface 7 m above sea level and maximum water depths of 4.5 m.

The Mackenzie Delta is a low coastal area extending over 15,000 km^2 and covered by unconsolidated Pleistocene fluvial, deltaic, and estuarine sediments up to 100 m thick over much of its area (Mackay 1974). The region is dotted with thousands of lakes and dissected by an anastomotic network of several large channels and numerous smaller winding channels. Active sedimentation, rapid coastal recession (rates as high as 1 m/a have been observed at Tuktoyaktuk), and constantly shifting river channels characterize the delta. Illisarvik lake is situated in an area of older Quaternary sediments east of the present site of major delta aggradation (Rampton 1972). Pleistocene sediments on Richards Island consist of stone-free sands, silts, and clays, with silty clays being more frequent towards the northern end. During the Pleistocene much of the delta was covered by ice sheets; however the northern part of Richards Island is believed to have been unglaciated at least during the late-Wisconsin Glaciation (Forbes 1980; Mackay *et al.* 1972) i.e. for the last 40,000 years. Changes as great as 100 m in eustatic sea level during the glacial epoch resulted in long periods of emergence and submergence. Mid-Wisconsin or earlier transgression brought sea levels to perhaps 50 m higher than present while probable late-Wisconsin marine regression resulted in sea levels 70 m lower than present. If northern Richards Island was unglaciated throughout the late-Wisconsin, it was subjected to low mean air temperatures during periods of emergence, condi-

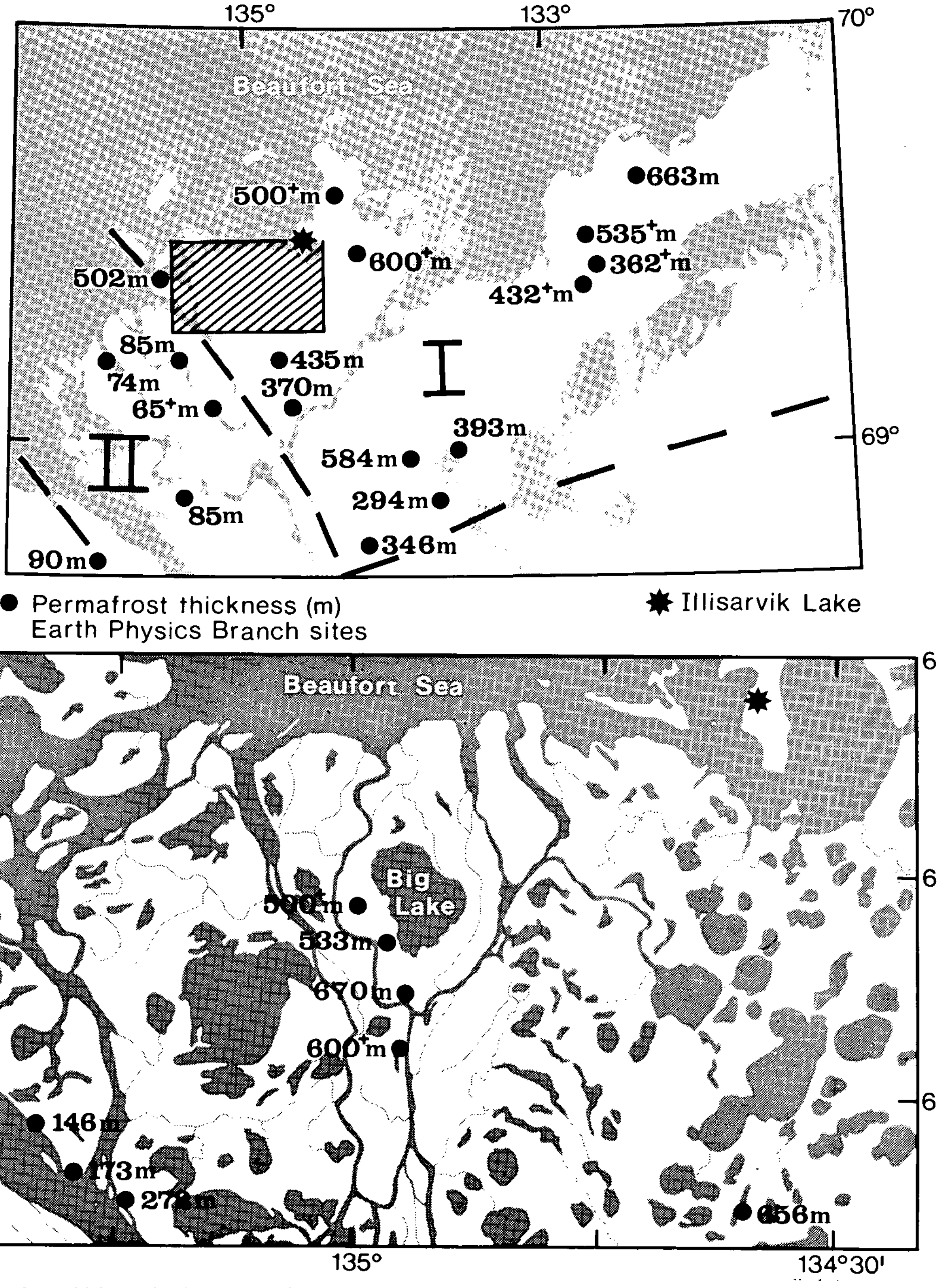

FIGURE 2. Permafrost thickness in the Mackenzie Delta (*top map*) and, in particular, in the vicinity of Illisarvik lake (*bottom map*).

tions conducive to the formation of thick permafrost. Such conditions have existed in the delta since deglaciation over 10,000 years ago.

The glacial history and geographical setting have resulted in a complex picture of permafrost distribution. In Figure 2 (top), the Mackenzie Delta has been divided into two thermal zones (Judge 1975): the older Delta (I) where surface temperatures range from −4 to −9°C and permafrost thicknesses lie between 90 and 700 m, and the younger (modern) Delta (II) of active sedimentation and spring flooding where surface temperatures are slightly below 0°C and permafrost is marginal (0 to 80 m thick). These thermal zones correspond to Mackay's (1974) geomorphic subdivisions of the delta; zone I being Mackay's Pleistocene Coastlands Region III and zone II, his Mackenzie Delta Region II (excluding the Taglu area, now known to be underlain by older delta and consequently thick permafrost).

Permafrost thickness in the vicinity of Illisarvik lake is generally greater than 450 m (Figure 2, bottom) and at several sites exceeds 600 m, generally thickening towards the present Arctic coast. These thicknesses have been determined from long-term monitoring of exploration wells by the Earth Physics Branch (Judge *et al.* 1981*b*). Mean annual ground temperatures determined from the well sites are in the range − 8 to − 10°C.

Ground Temperature Installations

During the spring of 1978, ten holes were drilled to depths of 15 to 87 m below the ice-surface of the lake using a practical low-cost hydraulic drilling technique (Judge *et al.* 1976; MacAulay *et al.* 1977). An additional four holes were drilled during the summer of 1978, three on the shore-line to 60 m depths and one to 92 m located on the hilltop 250 m from the lakeshore. Multisensor cables containing thermistors with an individual precision of ± 0.1 K were installed in each of the drillholes.

Drilling times usually ranged from 30 minutes to 3 hours depending on the total length of the drillhole. The period of time required for the holes to stabilize after drilling depends on the drilling fluid temperature, the time of drilling and also upon the water content of the soil and the amount of latent heat that needs to be released upon freezeback (Lachenbruch and Brewer 1959). In general, where equilibrium temperatures are positive or very little water is in the soil, temperatures return to within 0.1°C of equilibrium several days after jet-drilling; where water contents are high and equilibrium temperatures are below 0°C, up to a month may be necessary.

Since the drilling process disturbed the natural ground temperatures the cables installed in the spring were read as frequently as possible until ice break-up. The measurement technique and equipment are described by Judge (1973). Only two of the ten sites on the lake bottom survived the break-up in early June. In order to monitor the gross characteristics of the freezing lake bed, further hydraulic drilling was undertaken at Illisarvik on the drained lake bottom in the summer of 1979. An additional ten holes were jet-drilled to depths of 30 m and were instrumented with

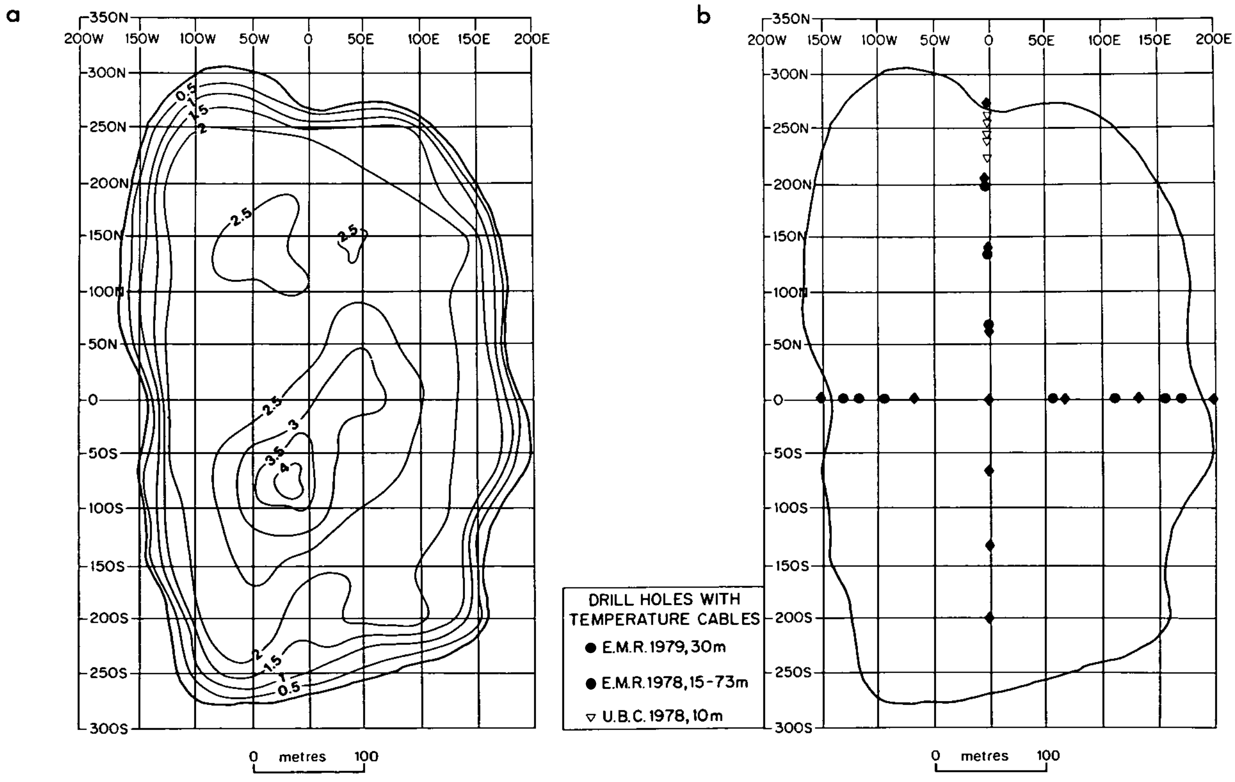

FIGURE 3. a Illisarvik lake bathymetry (m) and measurement grid; b Illisarvik lake ground-temperature installations.

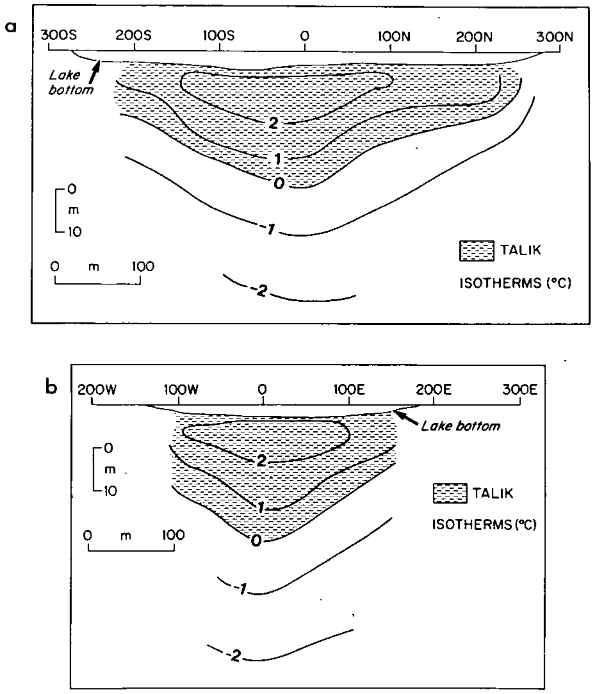

FIGURE 4. Isothermal cross-sections prior to drainage of Illisarvik lake: **a** North–South section; **b** East–West section.

ten sensor multithermistor cables with a precision of ± 0.1 K or better. Higher precision sensors were used to determine more accurately the pore-water freezing temperatures. The lake bathymetry, surveyed in the spring before drainage, is outlined in Figure 3**a**, while the locations of all the jet-drill holes (except the hilltop site) are shown in Figure 3**b**.

Temperature Results

Predrainage Ground Temperatures

Mean annual ground temperatures determined from the temperature profiles at Illisarvik ranged from −3°C at the lake shore-line to −7°C 250 m inland from the shore. In April 1978, the average ice thickness at the jet-drill sites was 1.2 m, over water ranging in depth from 2 to 3.5 m; temperatures in the bottom sediments ranged from 1.0 to 1.8°C and rose to a maximum of 2.8°C at a depth of 5 m sub-bottom. Sediment temperatures, remeasured in August 1978 prior to drainage with a small probe penetrating 5 cm, ranged from 9.3 to 10.3°C. These measurements indicate a minimum amplitude of 7.5 to 9.3 K for the annual lake-bottom temperature variation.

Two temperature cross-sections along the zero gridlines have been compiled from predrainage information in Figure 4. The lake bottom is underlain by an unfrozen bow-shaped horizon, the talik, which ranges from 15 m thick 200 m north of the gridline intersection to 32 m slightly south of the intersection at the centre of the lake. The upper permafrost surface plunged steeply lakewards at both ends of the lake where water depths had exceeded 1.5 m (Mackay 1981). Temperature characteristics of the deeper central holes, illustrated in Figure 5 by the profile at site 78-10 (0.0N, 67E), can be summarized as follows:

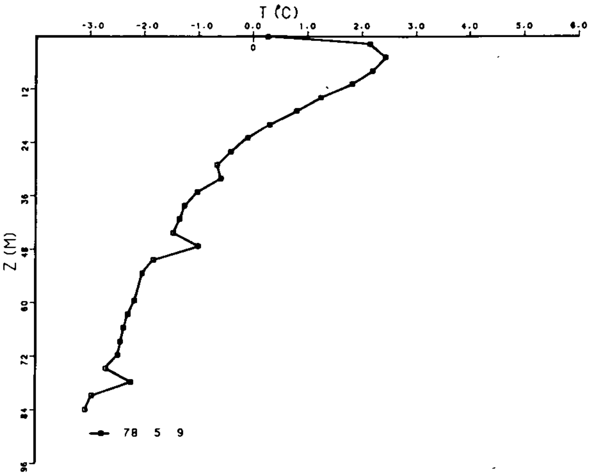

FIGURE 5. Ground-temperature profile, predrainage, at site 78-10 (0.0N, 67E).

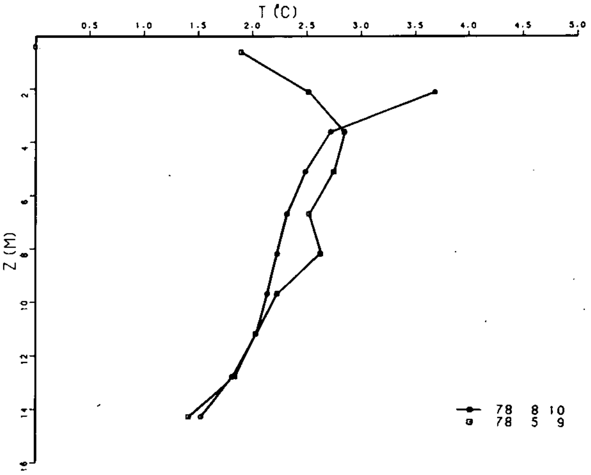

FIGURE 6. Ground-temperature profile at site 78-2 (67S, 0.0E) illustrating the extent of summer heating of the unfrozen horizon prior to drainage.

(i) an upper unfrozen horizon in which temperatures reach a maximum of 2.5°C at roughly 5 m below lake bottom.

(ii) a permafrost table at depths of 20 to 32 m below which temperatures are consistently negative.

(iii) negative temperature gradients beneath the 5 m temperature maximum, averaging − 50 mK/m within the permafrost section.

(iv) temperatures still decreasing at the bottom of the drillholes, reaching − 3°C at 90 m beneath lake bottom.

The penetration of the annual temperature variation below lake bottom is illustrated in Figure 6 by the profile at site 78-2 (67S, 0.0E). The general extent of summer heating of the unfrozen horizon can be seen; below 3 m, summer heating has not yet been felt, the lag due to heat diffusion in the sediments causing summer temperatures to be lower than those of spring.

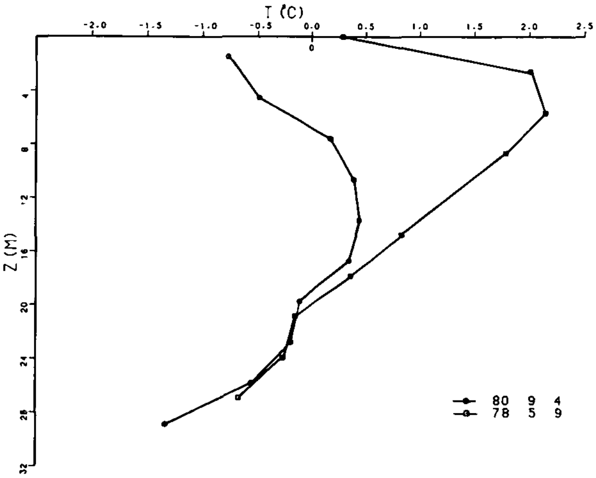

FIGURE 7. Post-drainage ground temperatures (1980) and predrainage profile at 67N, 0.0E.

Post-drainage Ground Temperatures

Since drainage, ground temperature measurements have been acquired whenever practicable and have been compiled into a continually updated file on ground temperature data (Judge *et al.* 1981*a*). The temperature profiles at location 67N, 0.0E prior to drainage and two years after are plotted in Figure 7. Temperatures are close to 0°C and the talik has begun to freeze; the temperature profile in the talik is nearly isothermal and temperatures below the talik, as well as temperature gradients, remain negative as before drainage. Temperatures in the centre of the lake, 10 m below bottom, were around 2°C before drainage; two years after, they have cooled to 0.5 to 1°C (Figure 8).

Observations by Mackay (1981) of permafrost growth at nearshore sites, where permafrost was at a depth of 10 m or less prior to drainage, have indicated complete freezeback of the talik within one summer and two winters after drainage. In contrast at more distant and central lake sites, freezing, which is primarily downwards here as opposed to downwards, upwards, and horizontally near shore, had reached 5 to 6 m by August 1980.

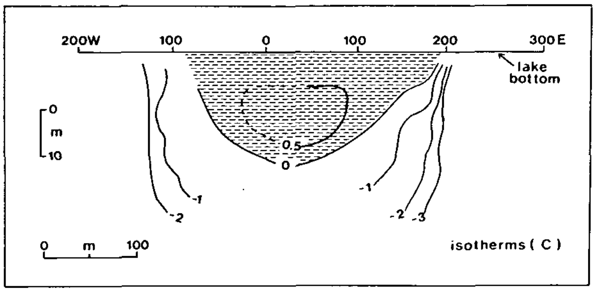

FIGURE 8. Isothermal cross-section of summer 1980 post-drainage temperatures on the East–West zero grid line.

A rough calculation of the height of the potential Illisarvik pingo may be made using the predrainage characteristics. The volume of water in the talik is first estimated, supposing the talik to be saturated and composed of 25 per cent organic material and clay, and 75 per cent sand. Complete freezing of the talik would result in a 9 per cent volume expansion providing there are no additional sources of water. Should this expansion be concentrated at the lake centre, a four-metre high pingo would form assuming the shape to be that of a circular cone with a base 60 m in radius. Its formation would involve the liberation of 1.7×10^{14} Joules of latent heat.

Thermal Analyses

The impact of a northern lake upon the surrounding permafrost terrain has been reported previously by Brewer (1958) and Brown *et al.* (1964).

Brown *et al.* studied the thermal regime under and surrounding an inland arctic lake at a modern delta site near Inuvik, N.W.T. Ground temperature observations were compared to a computer-modelled ground temperature regime, with good agreement. The lake, although half the size of Illisarvik, was not underlain by permafrost.

Brewer conducted a detailed study of the thermal regime of a lake Imukpuk on the Alaskan arctic coastal plain. Measurements were made of temporal, vertical, and lateral water temperature variations. Conditions at Imikpuk resemble those at Illisarvik: the lake is close to the coast (120 m), water depths reach 3 m and ground temperature profiles under the lake have negative gradients. However, Imikpuk is twice as large and its talik extends to 58 m below lake bottom as compared to 32 m at Illisarvik. Mean annual bottom temperatures for that part of the lake which does not freeze to bottom were 1.2 to 1.8°C; at Illisarvik they were slightly higher, around 2.5°C.

Predrainage Modelling

The thermal impact of the formation of Illisarvik has been simulated using a two-dimensional computer model. The program uses a finite element formulation of the transient heat conduction equation incorporating latent heat effects and is based upon a model designed to study river channel shifting in the Mackenzie Delta (Smith and Hwang 1973).

To simplify initial thermal analyses, the presence of nearby water bodies was neglected, climatic changes were not taken into account, and the soil was considered to be a uniform saturated sand of 30 per cent porosity. The surface temperature was fixed at −8.5°C and a ground temperature gradient of 15 mK/m was selected (based on borehole temperature logs by the Earth Physics Branch on Richards Island, *see* Judge *et al.* 1981*b*). Geothermal simulation assuming instantaneous formation of Illisarvik with a mean annual lake temperature of 3°C indicates that the gross characteristics of the talik could be achieved in less than 500 years.

However, comparison of the observed predrainage temperature profiles with those predicted by this simple model reveals higher temperatures below the talik in the model. Thus the model was refined to simulate a growing lake (assuming an arbitrary initial radius and constant rate of growth of 0.15 m/a). Wallace (1948) calculated rates of recession of thermokarst lakes in eastern Alaska which varied from 0.05 to 0.19 m/a. Rates observed at Lake Syrdakh in Yakutia over the past 75 years range from 0.5 to 1.0 m/a (Are 1973). The geometry of the half space (symmetrical) model and finite element layout for the lake growth are shown in Figure 9. Profiles predicted by the instantaneous formation model are plotted in Figure 10**a**. The lake growth simulation predicts a ground temperature profile which, after 900 to 1000 years, compares well with the observed predrainage profile (Figure 10**b**).

The model could perhaps be refined to simulate more realistically the lake temperature during its growth, in light of climatic changes and changes in lake water depth. Further refinements, however, such

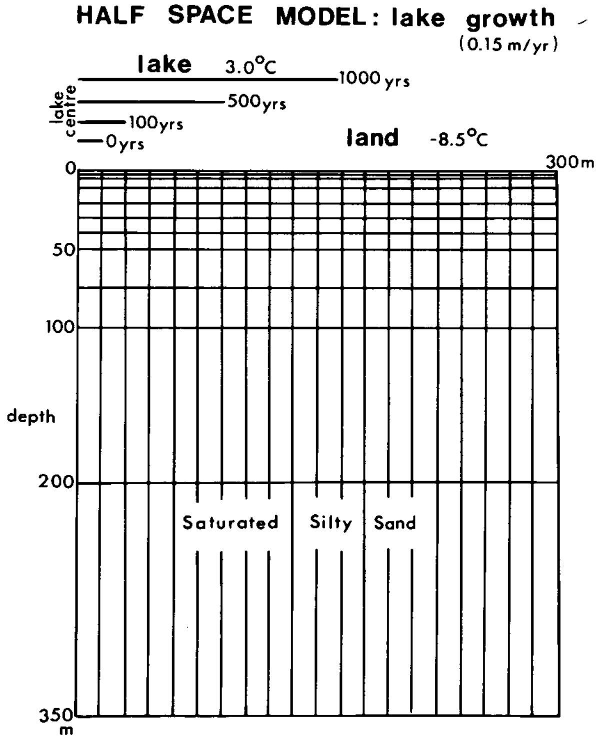

FIGURE 9. Input conditions and geometry of the finite element grid layout for simulation of constant lake growth.

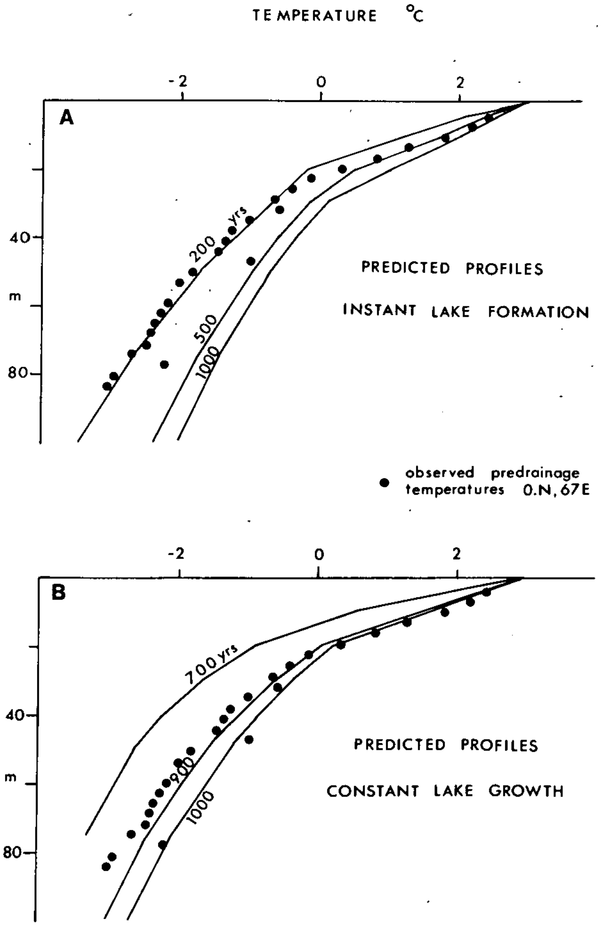

FIGURE 10. Observed predrainage temperature profile at 78-10 (in black dots) and profiles predicted from the simulation of **a** an instantaneous lake formation and **b** a constant lake growth.

as to initial lake size and rate of growth, await corroborative geological evidence.

The history of Illisarvik lake may in fact have been multiphase and this simulation may represent only the most recent phase. There is some evidence (Mackay 1981; Michel and Fritz 1982) that the lake existed during the hypsithermal at which time it would have been larger and warmer, perhaps coalescing with a currently drained lake to the south. Examination of the ground ice at the drainage outlet (Mackay 1981) suggests that Illisarvik lake drained almost completely once before by natural means.

Post-drainage Modelling

The freezing of the talik in the first year after drainage has been modelled by studying the microclimatic regime together with the ground thermal regime (Burgess 1981). The computer simulation based on a program developed by Smith (1977) models the ground thermal regime using an approach that treats the ground heat flux as a component of the surface energy balance. A simplified flow chart is shown in Figure 11.

Weather data and microclimatic site-specific characteristics (albedo, aerodynamic roughness, wetness) are used as input to constrain the surface energy balance at a specified site. The components of the energy balance (*RN* = net radiation, *LE* = evaporation, *H* = convective transfer of heat into the air, and *S* = soil heat flux) are expressed as a function of the surface temperature. An iterative solution of this equation gives the equilibrium surface temperature from which the individual energy balance components are calculated. The surface temperature is used as a boundary condition together with the ground thermal properties to predict ground temperature distribution. An implicit finite difference form of the heat conduction equation in one dimension is used. Complex stratigraphy and latent heat effects are accommodated.

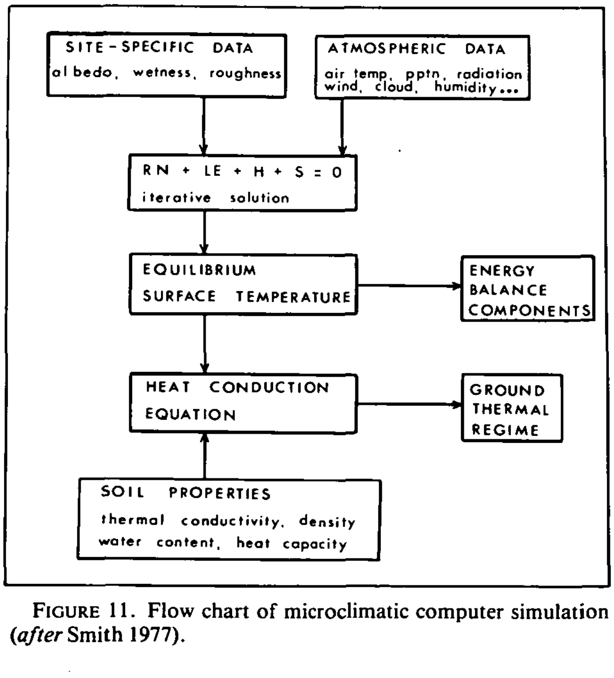

FIGURE 11. Flow chart of microclimatic computer simulation (*after* Smith 1977).

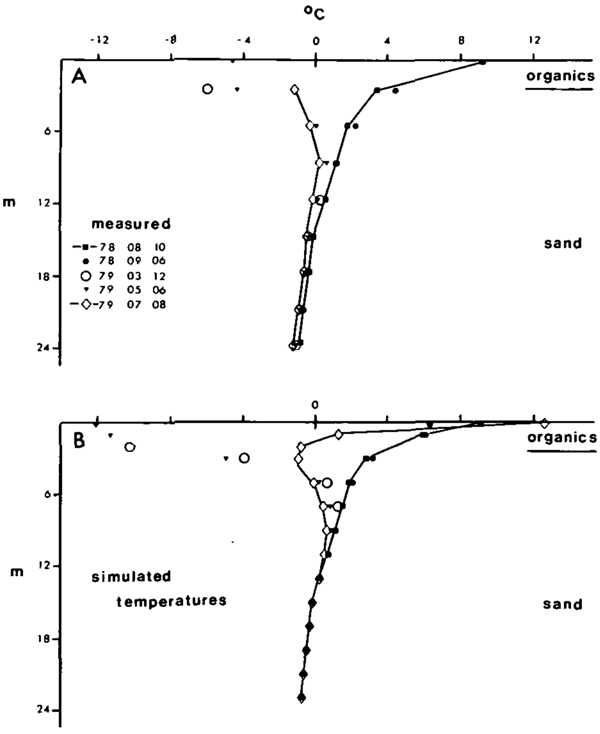

FIGURE 12. **a** Measured temperature logs at borehole 78-9 (0.0N, 135E), first year after drainage. **b** Simulated logs for the same days.

Ground temperatures were predicted for a single site, borehole 78-9 (0.0N, 135E), which was drilled prior to drainage and monitored during the first year afterwards. Agreement between the simulated and observed ground temperatures is good (Figure 12) despite the many necessary assumptions in the input parameters. In order to pursue further the microclimatic modelling, extensive geotechnical and year-round weather-gathering programmes are necessary. These microclimatic simulation tests will, combined with field observations, be important in understanding the active physical processes in the formation of permafrost. Successive microclimatic monitoring and modelling at five-year intervals as the lake bottom becomes revegetated could prove one of the most effective means of studying the impact of the biosphere on the surface energy balance of northern terrains.

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