Significance of isotope variations in permafrost waters at Illisarvik, N.W.T.

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Analyses for ^{18}O and ^{2}H contents in permafrost cores from the Mackenzie River basin revealed very large depletions in the heavy isotope contents with depth. These shifts could be a reflection of decaying climatic conditions resulting in lower ^{18}O and ^{2}H contents in older ice or, under special circumstances, might be due to isotope fractionation processes occurring during freezing. Thus, as part of a detailed study of permafrost growth at the drained lake site known as Illisarvik on Richards Island in the Mackenzie Delta, a number of continuous cores were collected from within, and adjacent to, the lake bed. Water extracted from the samples by squeezing was analyzed for ^{18}O, ^{2}H, and ^{3}H isotopic contents in addition to conductivity. The soils were examined for grain size and moisture content, while organic-rich horizons were dated using the radiocarbon method. Radiocarbon dating of the lake-bed sediments indicate that the lake initially formed some 6700 to 8700 years ago. The ^{18}O contents from the Illisarvik lake bed are in the range of -15 to -16 per mille near the surface, which are similar to the average lake water prior to drainage. Outside of the lake, ^{18}O contents vary from -14 to -31 per mille. Tritium is confined to the active layer outside of the lake, while within the lake bed tritium occurs to a depth of 2 m. The results of this and other ongoing studies into the distribution of stable and radioactive isotopes occurring naturally in waters related to permafrost indicate that such investigations provide valuable insight into the history and origin of these waters.

Le dosage de l'^{18}O et de l'^{2}H dans des carottes de pergélisol prélevées dans le bassin du fleuve Mackenzie a révélé une diminution marquée de la teneur en isotopes lourds en fonction de la profondeur. Cette diminution pourrait être due à des conditions climatiques de désintégration qui donnent lieu à de faibles teneurs en ^{18}O et en ^{2}H dans la vieille glace ou, dans des circonstances spéciales, à des phénomènes de fractionnement isotopique qui se produisent pendant le gel. Ainsi, dans le cadre d'une étude détaillée sur la croissance du pergélisol à Illisarvik, ancien lac asséché de l'île Richards dans le delta du Mackenzie, on a prélevé un certain nombre de carottes continues dans le lit du lac et dans les environs. On a mesuré la teneur en ^{18}O, en ^{2}H, et en ^{3}H de l'eau extraite des échantillons par compression ainsi que sa conductivité. On a effectué une analyse granulométrique et une analyse hygrométrique des échantillons de sol, puis on a daté des horizons riches en matière organique par la méthode du radiocarbone. La radiodatation des sédiments du lit du lac révèle que ce dernier est apparu il y a quelque 6700 à 8700 ans. Les teneurs du lit en ^{18}O varient entre -15 et -16 pour mille près de la surface, valeurs qui sont voisines de la moyenne de l'eau du lac avant son assèchement. Sur les rives, la teneur en ^{18}O varie entre -14 pour mille et -31 pour mille. La zone de tritium se limite au mollisol sur les rives du lac, tandis que dans le lit du lac, on en trouve jusqu'à une profondeur de deux mètres. Ces résultats et ceux d'autres études en cours sur la répartition d'isotopes stables et radioactifs naturels qu'on trouve dans les eaux du pergélisol indiquent que de telles recherches fournissent des renseignements précieux sur le passé et l'origine de ces eaux.

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Introduction

The planned development of natural resources in the northern regions of Canada has resulted in an increased interest in permafrost: its distribution, physical conditions, and hydrology. One of the aspects of concern is the movement of groundwaters within and through permafrost, since groundwater is important in the formation of almost every permafrost feature described in the literature. To better understand water movement within frozen soils, the authors initiated a study in 1976 employing the use of environmental isotopes (oxygen-18, deuterium, and tritium) which label the individual water molecules.

In the first phase of this project, Michel and Fritz (1978) demonstrated that very large isotope variations are preserved in the permafrost waters and are considered to be the result of changes in climate and/or fractionation during the freezing process. Isotope variations in precipitation which are due to changes in the climate have been well documented by researchers working on the polar ice caps (Dansgaard *et al.* 1971; Paterson *et al.* 1977). Suzuoki and Kimura (1973) have shown that during freezing, under equilibrium conditions, a fractionation of 2 to 3 per mille occurs for ^{18}O between the solid and liquid water phases. Freezing in the subsurface should be an equilibrium process and, therefore, these fractionation effects might be present. They could be considerably enhanced, moreover, if "reservoir effects" caused by the preferential removal of isotopically enriched (^{18}O, ^{2}H) water molecules from the aqueous phase were also important. Laboratory experiments were thus undertaken to simulate freezing fronts in order to investigate the magnitude of nonclimatic variations and were complemented by field studies at Illisarvik. This paper focuses on preliminary data from the latter.

Method

To determine the ^{18}O contents, 8 ml of water were equilibrated for at least four hours with a standard CO_2 gas. The oxygen isotope ratio of the equilibrated gas was measured relative to a laboratory working standard using a Micromass 602D mass spectrometer. To measure the deuterium concentrations, 20 microlitres of water were circulated over hot uranium metal (800 to 850°C) and converted to hydrogen gas for analysis. The $^2H/^1H$ ratio was also measured relative to a laboratory standard using the mass spectrometer.

The abundances of oxygen and hydrogen isotopes are expressed as parts per thousand (per mille) difference between the sample and the reference, Standard Mean Ocean Water (SMOW), whereby

$$\delta\, ^{18}O \text{ or } \delta\, ^2H = \frac{R \text{ sample} - R \text{ standard}}{R \text{ standard}} \times 1000$$

where R is the isotope ratio $\frac{^{18}O}{^{16}O}$ or $\frac{^2H}{^1H}$

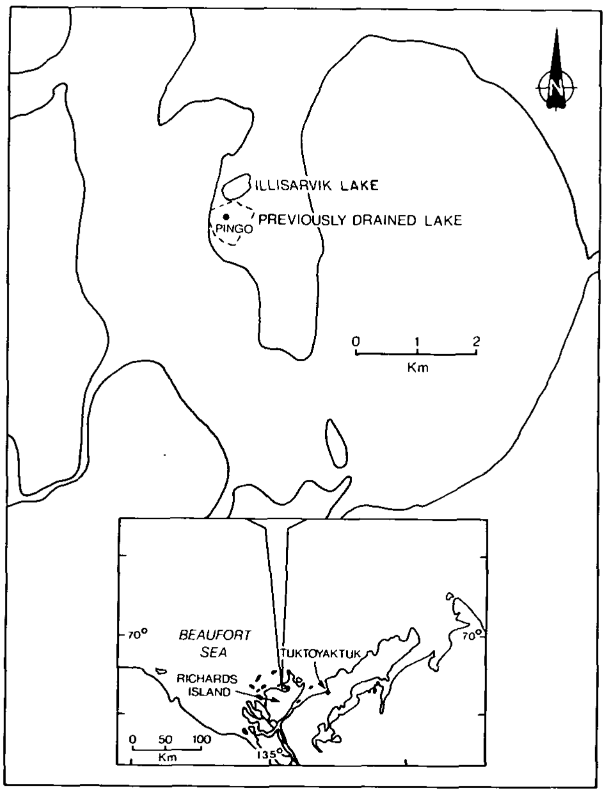

FIGURE 1. Location of the experimental site.

These differences are referred to as delta values (δ) and a negative value describes a concentration less than the standard reference. The overall reproducibility for ^{18}O data is better than ± 0.2 per mille and better than ± 2 per mille for deuterium.

Tritium concentrations are expressed in tritium units (T.U.) where 1 T.U. = $10^{-18}\, ^3H/^1H$. Analyses were done by direct liquid scintillation counting and are accurate to ± 10 T.U.

The Illisarvik Drained Lake Project

Under the direction of Dr. J.R. Mackay (U.B.C.), a multi-disciplinary study of the growth of permafrost was initiated in the summer of 1978 with the drainage of a small lake known as Illisarvik. This lake (Figure 1), located on a peninsula at the northern end of Richards Island in the Mackenzie Delta, is underlain by a bowl-shaped talik (Burgess *et al.* 1982; Mackay 1981). After the draining of the water, the lake-bed sediments began to freeze. Eventually, permafrost aggradation will result in a confined talik with high pore-water pressures and the formation of a closed-system pingo.

The drained lake provides a field laboratory setting where isotope fractionation processes can be studied during natural freezing conditions. The authors undertook the present study of the isotope contents of waters in and around Illisarvik in order to quantify the effects that create the isotope variations in permafrost-related waters. To understand the system completely, it is also necessary to determine the relationships between stratigraphy and age and the physical parameters that may affect the isotope contents of the waters.

Sampling Design

Prior to drainage, a grid was established for the basin, oriented along the major and minor axes of the lake (Figure 2). In May, 1979, a drilling program was undertaken to obtain continuous core samples from within and outside the lake basin. The major drilling effort was concentrated on a series of boreholes along an east–west traverse running perpendicularly from the coast (borehole 79-8) to the height of land along the centre of the peninsula (borehole 79-3). The remainder of the holes drilled were located elsewhere in the basin so as to supplement the data obtained from the boreholes along the section. A series of additional cores were obtained during a second drilling program in May, 1980. The location of those boreholes which were drilled outside the grid area are shown in Figure 3.

Drilling was accomplished using a frozen-ground coring kit consisting of a Stihl power auger unit

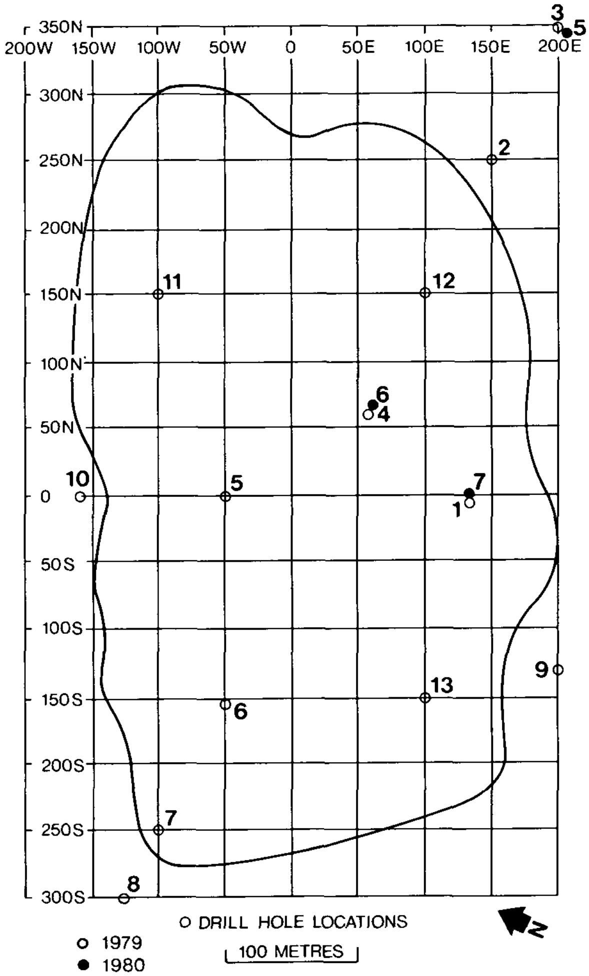

FIGURE 2. Location map of boreholes drilled at Illisarvik in 1979 and 1980.

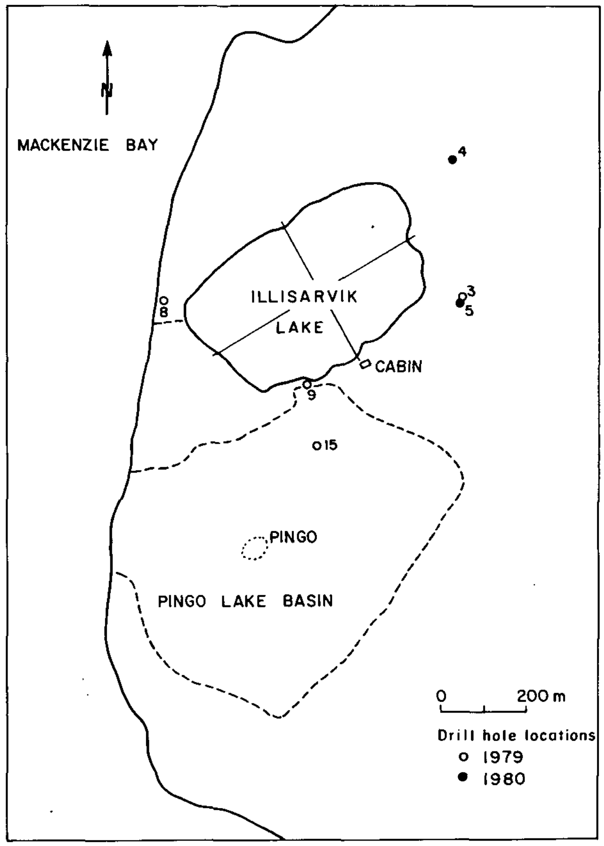

FIGURE 3. Location map of boreholes drilled beyond the base grid at Illisarvik in 1979 and 1980.

(model No. 4308), aluminum rods, and a CRREL core barrel. Sampling of the unfrozen sediments beneath the upper frozen layer within the lake bed was conducted by split spooning. Core recovery of the frozen material was 99 per cent or better, but recovery of the unfrozen sediments was somewhat less successful. During drilling, each section of core was cleaned and described, and representative samples were photographed. After each hole was completed, the core was sectioned either into 5-cm intervals and double-sealed in heavy plastic bags, or into 10-cm intervals and canned. Those samples that were sectioned into 5-cm intervals were subdivided and bagged as two separate subsamples. By sectioning and packaging each individual sample in the field, it was unnecessary to maintain the samples in their frozen state during transit to Waterloo for examination of the isotope contents in the water.

To extract the water from the soil, the samples were first allowed to equilibrate to room temperature in their sealed containers. Each sample was then placed within a steel jacket and subjected to a controlled hydraulic pressure to squeeze the water from the soil, directly into a polypropylene syringe from which the water was then transferred to a polyethylene vial. These procedures were developed by Patterson *et al.* (1978). Water extracted from the samples by squeezing was analysed for ^{18}O, ^{2}H, and ^{3}H isotopic contents in addition to conductivity. The soils were examined for grain size and moisture content while organic-rich horizons were radiocarbon dated by combustion of the entire sample following an acid treatment to remove inorganic carbon. All ^{14}C ages are adjusted to $\delta\,^{13}C = -25$ per mille.

Results and Discussion

The stratigraphy of the basin consists of three primary units. Within the boundary of the lake, a thick sequence of organic-rich lake silts overlie a clay-silt unit containing numerous stones of widely varying lithology. This unit is in turn underlain by a

TABLE 1. Radiocarbon dates from cores 79-4 and 80-6

^{14}C sample No.	Drill core sample No.	Depth (cm)	$\delta^{13}C$ (‰ PDB)[2]	% Modern	^{14}C age (yrs. B.P.)
WAT-746	79-4-2A	5-10	-29.3	74.3	2320 ± 70
WAT-739	79-4-20A	95-100	-28.5	54.1	4880 ± 80
WAT-741	79-4-44A	215-220	-21.8	34.0	8720 ± 540
WAT-740	79-4-53A	260-265	-27.4	11.2	17,530 ± 540
WAT-742	80-6	360-365 (380-385)[1]	-27.4	8.6	19,630 ± 1600

[1] Equivalent sample depth for core 79-4

[2] Carbonate reference standard. *Belemnitella americana* from the Cretaceous Pee Dee formation, South Carolina.

relatively clean, fine- to medium-grained, deltaic sand. Beyond the edge of the lake, a series of organic horizons are interstratified with sandier material.

Radiocarbon

Radiocarbon dating permits one to estimate the probable age of this lake, at a "sedimentation break" recorded in the samples from core 79-4 (Table 1) obtained near the centre of the lake. This break coincides with a transition from organic-rich lake silts to the stony clay-silt unit. The apparent age for this transition is about 8720 years B.P. (WAT-741), but could be reduced by as much as 2000 years if the apparent age of the modern sediments, indicated as 2000 years by extrapolation to the surface, is assumed to represent an actual age of zero years. This age effect may be due to uptake of ^{14}C-depleted aqueous carbon into the organic matter. Such "hard water" effects have been noted in many more southerly lakes (Karrow and Anderson 1975), but have not been investigated in these northern environments.

The presence of a lake near 79-4 some 6700 to 8700 years ago does not imply that the lake covered all of the present lake bed area at that time. More radiocarbon dating is required before a detailed history of the evolution of the lake can be described. However, it is possible to determine at least a generalized history for the Illisarvik lake basin by examining the isotope content of the waters extracted from several cores collected at various locations within the area.

Stable Isotopes

The ^{18}O and ^{2}H contents determined in water or ice relate directly to the history of the waters and not of the associated sediments, although the two may be related in some instances. Both isotopes are conservative and thus their abundance reflects on the origin of the water, the degree of evaporation from the lake, climatic conditions, and, under favourable circumstances, the freezing history.

Borehole 80-4 (*see* Figure 3) was drilled on the top of the high ridge running along the centre of the peninsula. A zone of massive ice was encountered from approximately 0.45 to 5.5 m which contained some soil and numerous vertically oriented bubbles. Near the base of the ice zone, one side of the core was ice while the other half was soil, which suggests that an ice wedge had been cored.

From the ^{18}O profile (Figure 4), it is possible to define the depth of the active layer as 0.45 m which

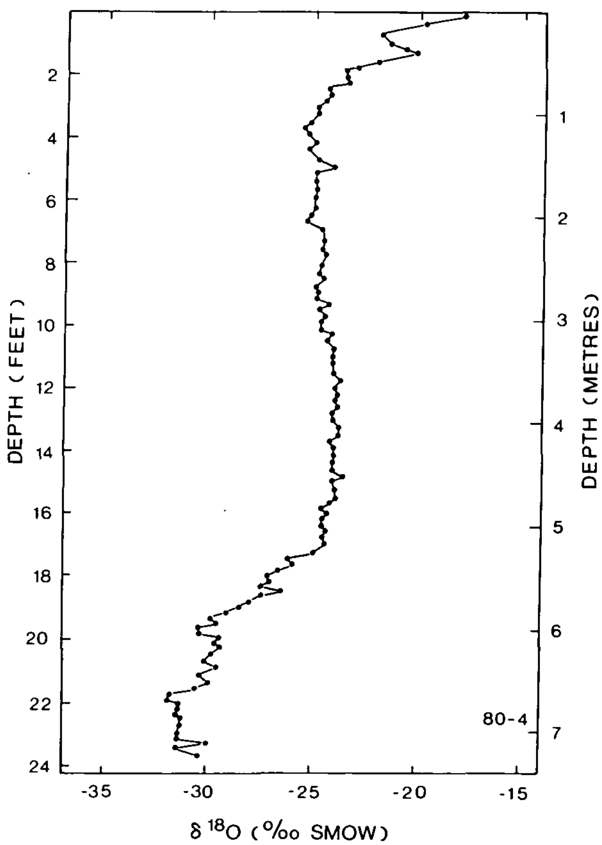

FIGURE 4. ^{18}O profile for core 80-4. Note the massive wedge ice from 0.45 to 5.5 m.

coincides with the soil–ice interface. The δ ^{18}O values of -18 to -20 per mille found in the active layer are representative for modern groundwaters in the area. The large negative shift within the active layer and the small positive shift near the active layer - permafrost boundary indicate that freezing of the active layer occurred from the ground surface downwards and from the permafrost table upwards. Within the ice wedge, the ^{18}O contents are extremely uniform at -24 to -25 per mille. Below the ice wedge, the δ ^{18}O values decrease to around -31 per mille. These low values are similar to values obtained for cores taken within the northern part of the Mackenzie Valley (Michel and Fritz 1978). This shift from present precipitation values is the same as the 11 per mille shift found by Dansgaard *et al.* (1971) in the Greenland ice cap, suggesting that the highly negative waters were recharged during the late-glacial period.

Proceeding from the top of the ridge and onto the slope, borehole 79-3 was drilled at the east end of the east–west section. The depth of penetration was only slightly over 2 m due to blockage by a stone.

The isotope profile (Figure 5) displays the negative shift within the active layer noted for 80-4. Again the active layer profile indicates freezing from above and below. Within the permafrost, the ^{18}O profile depicts several small, single sample, positive shifts in the order of 2 to 3 per mille. These are similar to small shifts produced in the laboratory which were the result of isotope fractionation during periods when the freezing front was stabilized. The ^{18}O contents found in this core gradually decrease with depth, but it is unkown whether the -31 per mille values would have been found if deeper samples had been available.

Within the lake, the upper sediments were subjected to freezing for one winter prior to the drilling in 1979. Borehole 79-4, intersected approximately 2.4 m of frozen ground that changed gradually to unfrozen material at a depth of 2.5 m. Temperature measurements by Burgess *et al.* (1982) indicate that permafrost ($T<0°C$) extended to depths well in excess of 2.5 m, which suggests that freezing of the pore water did not occur until the temperature had dropped at least several tenths of a degree below zero.

The ^{18}O profile for 79-4 (Figure 6) is extremely uniform throughout. The lack of any shift at the frozen–unfrozen boundary indicates that the freezing front was still migrating downwards at the time of drilling. The δ ^{18}O values of -15 to -16 per mille near the surface are representative of the average lake water prior to drainage. Similar ^{18}O

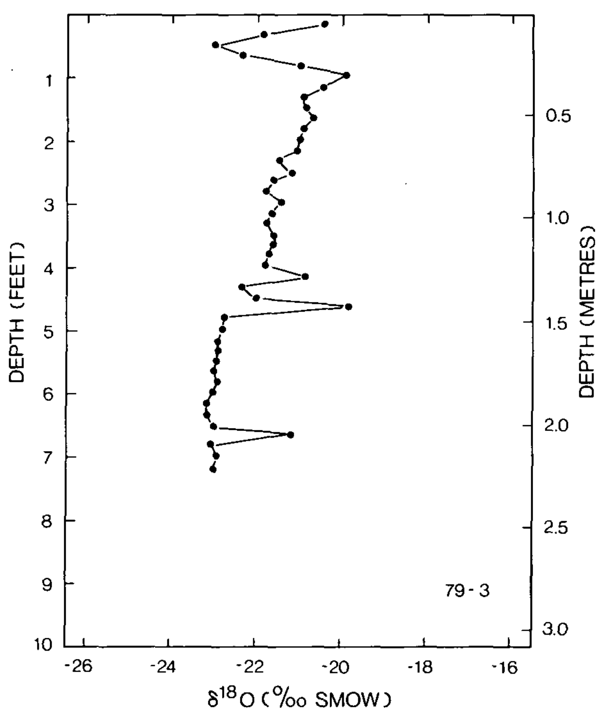

FIGURE 5. ^{18}O profile for core 79-3 drilled on slope outside the lake bed.

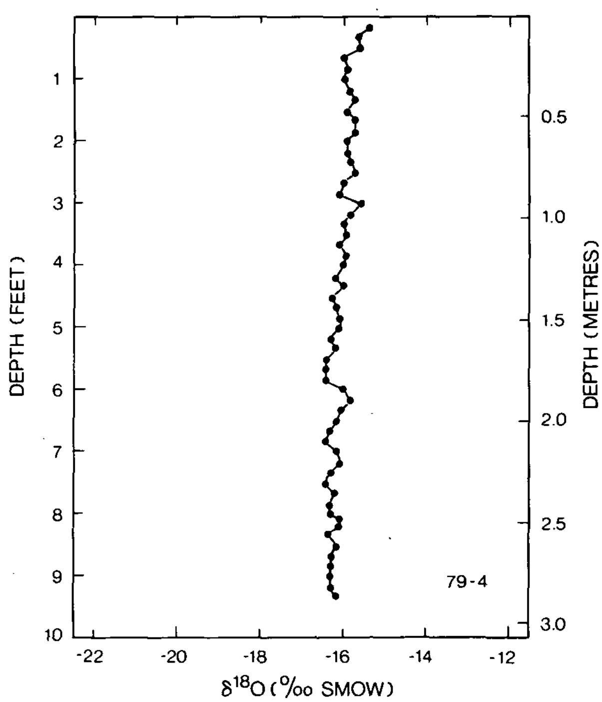

FIGURE 6. ^{18}O profile for core 79-4 drilled within the lake bed.

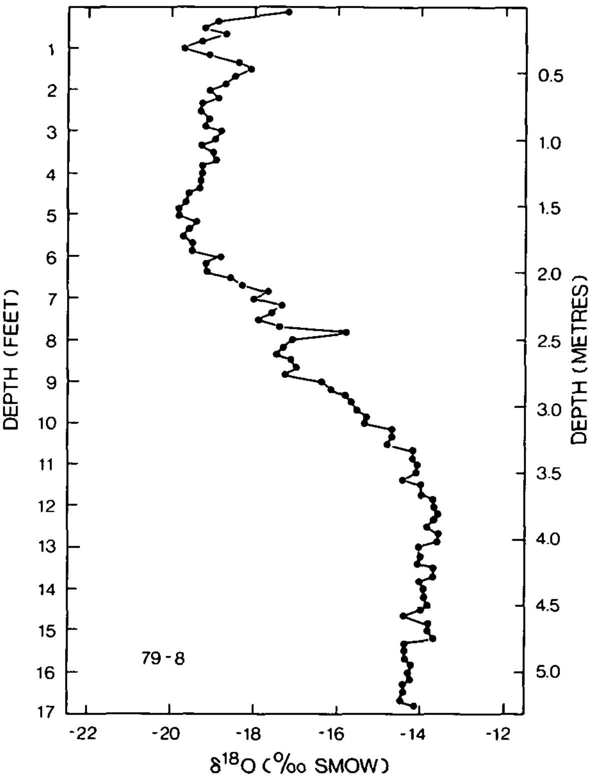

FIGURE 7. [18]O profile for core 79-8 drilled adjacent to the sea coast.

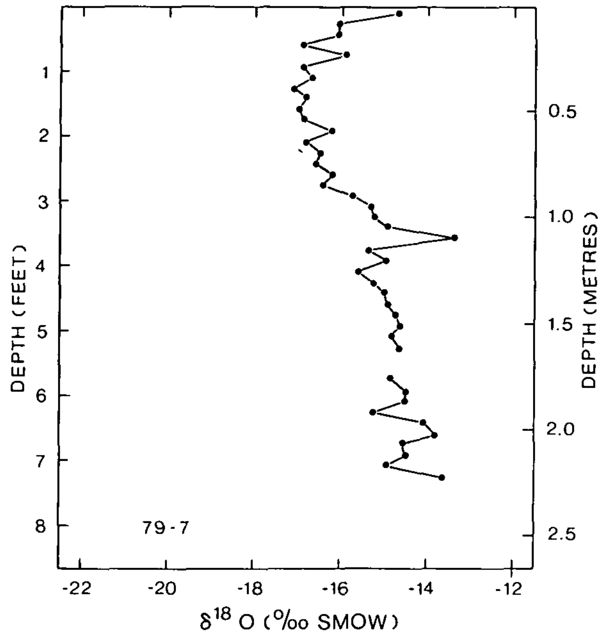

FIGURE 8. [18]O profile for core 79-7 drilled within the nearshore area of the lake.

contents have been found in other cores collected within the lake bed; analysis of the deuterium contents of these waters shows that evaporation has been insignificant.

Near the drainage channel, borehole 79-7 was drilled in the lake within a few metres of the shoreline, while 79-8 was drilled on shore within five metres of the coast. Borehole 79-8 is located on a low, level area criss-crossed by numerous ice wedges. Mackay (1981) described these wedges and pseudo-wedges within the lake bottom. In 1979, this area was bare of any snow cover so that the ice wedges could be located as linear depressions in the ground surface and avoided.

Figure 7, the [18]O profile for 79-8, displays the characteristic active-layer shift within the upper half metre. Within the permafrost, the δ [18]O values are initially relatively consistent between -18 and -20 per mille. Between a depth of 2 to 3 m, the profile shifts continuously toward the more positive value of approximately -14 per mille. Below 3 m, the profile is again relatively uniform to the bottom of the core.

The [18]O profile of core 79-7 (Figure 8) also shifts from near-surface values of -16 per mille (recent lake water) to more positive values around -14 per mille. Such values are not generated in this area under today's climatic conditions and the maintenance of this value with depth suggests that these waters originated from a lake existing in the Illisarvik basin during a warmer climatic period, possibly the Hypsithermal, which is generally thought to have lasted from 8000 to about 4000 years B.P. (Dansgaard *et al.* 1971).

The [18]O contents of waters from core 79-15 (*see* Figure 3) reveal a rapid positive shift towards a value of -14 to -15 per mille (Figure 9). Borehole 79-15 is located in the "Pingo Lake" basin immediately to the south of Illisarvik lake, approximately half way between Illisarvik and the pingo. The similarity in [18]O contents, in addition to other evidence, suggests that the two lake basins were at one time part of one larger lake.

When the Pingo lake waters drained, due to breaching of the western flank of the lake by coastal erosion, the water level in the Illisarvik basin decreased to a new, lower level that was controlled by a shoal which separated the two basins. Mackay (1981) noted that, although Illisarvik lake lacked a regular drainage channel, overflow across this sill to the Pingo lake basin occurred during June of 1978. Borehole 79-9 was positioned along this intermittent drainage route so as to examine the history of the sill.

From the [18]O data (Figure 10), the active layer

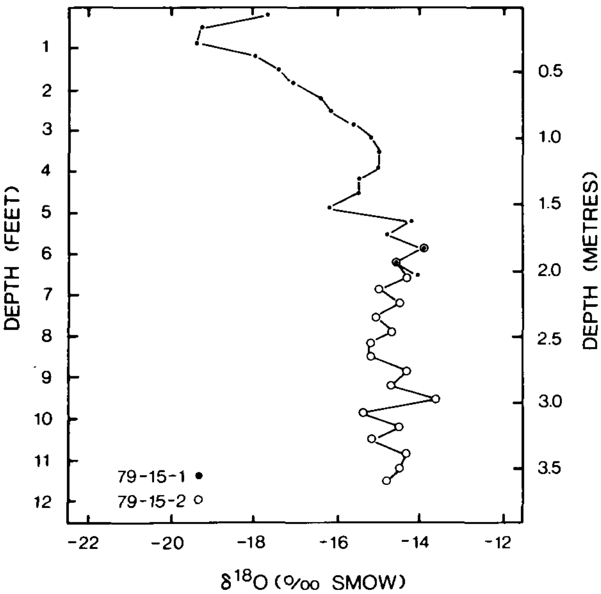

FIGURE 9. ^{18}O profile for core 79-15 drilled in the Pingo lake basin.

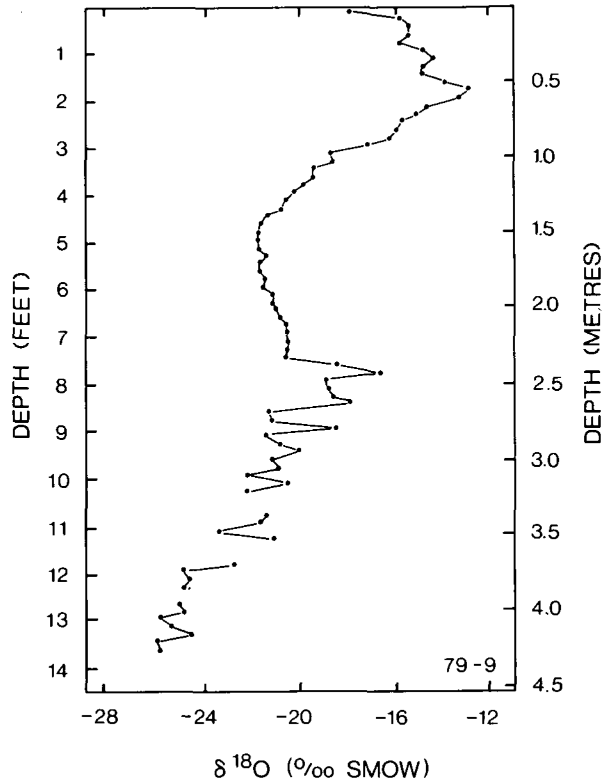

FIGURE 10. ^{18}O profile for core 79-9 drilled on the control sill.

has been determined to be approximately 60 cm deep in borehole 79-9. The upper section of permafrost contains water with ^{18}O contents similar to those in the upper sections of cores such as 79-3. Starting at a depth of 2.5 m, the profile shifts steadily from -18 to -26 per mille at the bottom of the core. The importance of this profile is that there is no indication of the warmer (-14 per mille) waters within this sill. To preserve the permafrost and the negative ^{18}O contents in this sill, the lake must have been sufficiently shallow to permit freezing to penetrate into the bottom sediments during winter. Based on ice thicknesses formed under the present climatic conditions, this would place an upper limit of 1 to 1.5 m on the water depth. If recent sedimentation is neglected, this would mean that the level of the previous (Hypsithermal?) lake could not have been more than 1 to 1.5 m above the level of Illisarvik lake prior to drainage, and that it possibly was much below this maximum.

Tritium

The radiocarbon data indicate that the basin contained some water throughout this period. By examining the tritium concentrations of the permafrost waters, it is possible to describe moisture migration during the past 30 years, since the tritium present in the water is the result of thermonuclear testing in the atmosphere during the 1950's and early 1960's. The tritium profiles would reflect the validity of the conclusions based on stable isotopes because if tritium were found at depth, then some of the interpretations made above for cores outside of the actual lake bed could not be sustained.

Beyond the shoreline of Illisarvik lake, tritium is confined to the active layer where it reaches a peak concentration of just under 220 T.U. (79-3) and then decreases rapidly to background levels (Figure 11). The Pingo lake core (79-15) yielded the highest tritium levels to date, 269 T.U.; most cores, however, have a maximum concentration of between 200 and 220 T.U. The relationship between tritium and the active layer indicates that the active layer is as thick today as it was 30 years ago, and that no tritium-labelled water has migrated downwards into the permafrost more than a few centimetres.

In sharp contrast, the tritiated lake waters have migrated almost 2 m downwards through the sediments (Figure 12). The tritium profile for these unfrozen sediments is much broader in comparison to the compressed active layer profile (*see* Figure 11). The shape of the curve with its gradual depletion of tritium would appear to indicate that diffusion is the major process involved in the downward migration of the moisture. A second core collected in 1980 from a location adjacent to 79-4 yielded a tritium profile identical to the one in Figure 12. This documents that the profile was not significantly affected by the freezing of these sediments after drainage of the lake.

Summary and Conclusions

The detailed multi-disciplinary study being conducted at Illisarvik is revealing a complex history for the area. By supplementing the stratigraphic work on the sediments with an isotopic study of the pore waters within the lake talik and the permafrost, it is possible to begin to unravel this history. From the work completed to date, the following can be stated for the Illisarvik area.

1. The central ridge of the peninsula contains relict permafrost waters with ^{18}O contents of close to −31 per mille.
2. A larger body of water, encompassing the Illisarvik and Pingo lake basins, existed during a period of warmer climatic conditions (Hypsithermal?). The waters from this lake had ^{18}O contents of approximately −14 per mille.
3. The isotope data obtained from a sill separating the two basins indicate that the level of this lake was at most 1.0 to 1.5 m above the level of Illisarvik lake. Most likely it was well below this maximum.
4. Groundwater movement has occurred only within the top 2 to 3 m of permafrost which has formed in the last few thousand years since the higher level lake disappeared.
5. Outside the lake basin, tritium is confined to the top 0.5 m corresponding to the average thickness of the active layer, whereas tritium has migrated downwards through the unfrozen lake sediments to a depth of about 2 m.
6. Detailed isotope profiling of the active layer has shown that freezing of this zone occurs from above and below.
7. Radiocarbon dating of the basal organic silts from near the centre of the basin indicates that the "original" lake formed between 6700 and 8700 years ago.

When combined, these results describe a peninsula with a central ridge that has been stable for several thousands of years flanked by a lower plain which has been constantly evolving. A series of lakes, with oscillating water levels, has continuously occupied at least portions of the Illisarvik and Pingo lake basins for the past 6700 to 8700 years. Coastal erosion resulted in drainage of the Pingo lake basin and a lowering of the water level in the Illisarvik lake basin. A shoal dividing the two basins became the controlling sill for the Illisarvik lake

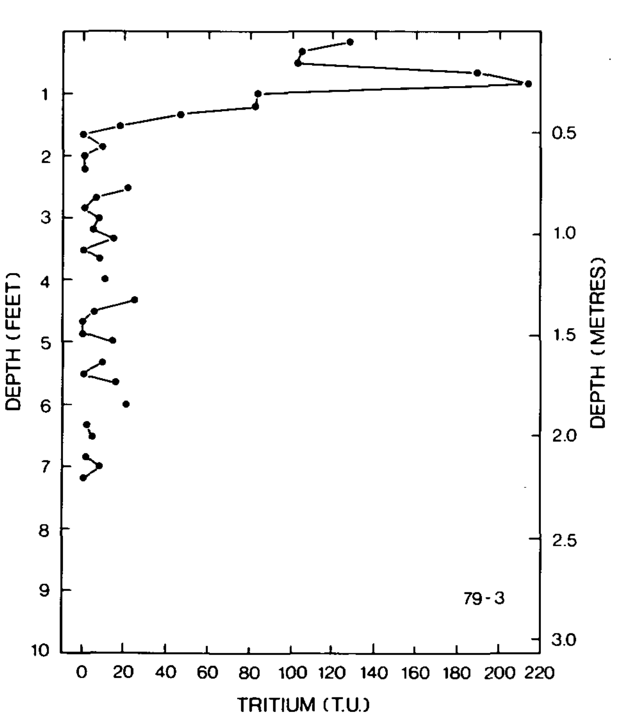

FIGURE 11. Tritium profile for core 79-3 drilled on slope outside the lake bed.

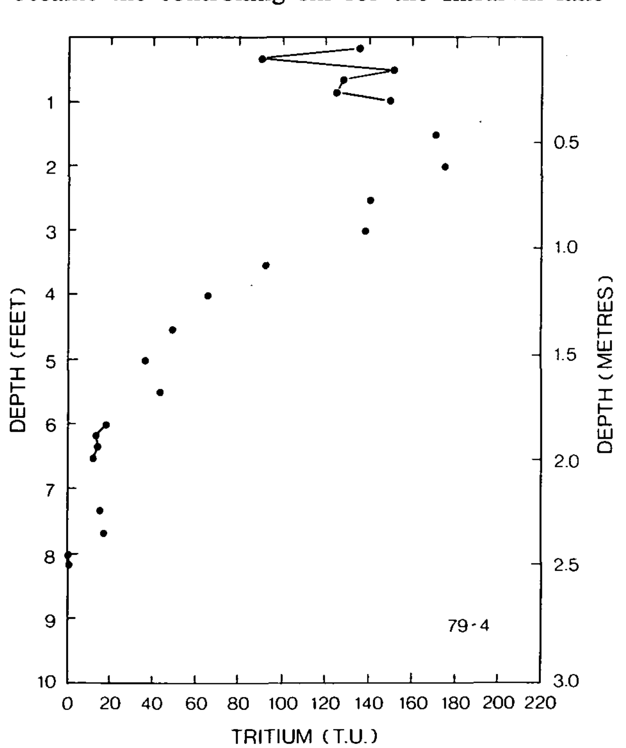

FIGURE 12. Tritium profile for core 79-4 drilled within the lake bed.

level which persisted until the time of drainage in 1978.

Several more general statements can be made regarding the usefulness of isotope studies and the significance of isotope variations in permafrost waters.

1. Isotope studies of waters within the permafrost provide insight into the history and stability of the permafrost.

2. Isotope studies permit the delineation of groundwater movement through the recognition of different water masses.

3. Stable permafrost conditions have persisted in some areas since the end of the Wisconsin with no appreciable groundwater movement since that time.

4. Shifts in the isotope profile, that are maintained for some interval of depth, are the result of climatic change.

5. Small-scale shifts, that do not continue with depth, are the result of fractionation processes during freezing. To generate these shifts of 2 to 3 per mille (for ^{18}O), the freezing front must either be advancing very slowly or be stabilized for a period of time.

In future investigations, the sampling interval should be selected on the basis of the information required. Long-term variations or the migration of water through the ground can be detected using a sampling interval of a metre or more, while the determination of a stabilized freezing front would require detailed sampling at intervals of 5 to 10 cm throughout the section of interest. If considered as part of a normal program of geotechnical investigations, the collection of these isotope data requires no additional field work. Subsampling of the core would permit both the standard geotechnical and the analytical work on isotopes to be conducted simultaneously. By including the isotope data, a considerable amount of additional information is available to aid in the interpretation of the geotechnical data and the groundwater movement.

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