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LABORATORY AND FIELD STUDIES TO INVESTIGATE ISOTOPE EFFECTS OCCURRING DURING THE FORMATION OF PERMAFROST - PART IV

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Earth Physics Branch Open File Number 82-5

Ottawa, Canada, 1982

Price/Prix: $26.50

Abstract

Observations on the distribution of oxygen and hydrogen isotopes in permafrost waters have been completed at a drained lake site in the Mackenzie Delta, along the Dempster Highway. Additional laboratory observations of isotope fractionation in phase change were completed. The analyses are used in conjunction with C^{14} dates to delineate the history of the drained lake basin over the past 9000 yrs. and to examine permafrost history and the origin of the waters in the north-eastern Yukon.

Résumé

Des obervations de la répartition des isotopes de l'oxygène et de l'hydrogène dans des eaux de pergélisol ont été réalisées sur l'emplacement d'un lac asséché, dans le delta du Mackenzie, le long de la route de Dempster. Elles ont été suivies d'autres observations en laboratoire sur la séparation isotopique en changement de phase. Ces analyses et la datation au C^{14} permettent de retracer l'histoire du bassin du lac asséché depuis 9000 ans, ainsi que d'étudier l'histoire du pergélisol et l'origine des eaux dans le Nord-est du Yukon.

OFFICE OF RESEARCH ADMINISTRATION

UNIVERSITY OF WATERLOO

INCORPORATING THE

WATERLOO RESEARCH INSTITUTE

Laboratory and Field Studies to Investigate Isotope Effects Occurring During the Formation of Permafrost

- Part IV -

Contract Serial No. OSU81-00076

FINAL REPORT

Prepared for

Department of Energy, Mines and Resources

By

F. Michel
P. Fritz

1982

ACKNOWLEDGEMENTS

The authors would like to express their thanks to Dr. Alan Judge, the scientific authority for this contract, for his support during the past year.

Our thanks are also extended to Foothills Pipe Lines (Yukon) Ltd. for kindly providing the core material. Finally, we would like to thank Mr. Doug Fisher of Foothills for his support of the program and for supplying the location maps, borehole logs and communication link.

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Chapter I

INTRODUCTION

1.1 PREVIOUS STUDIES

Initial investigations into the natural variations of stable isotopes in permafrost waters were undertaken by the authors in 1976 (Fritz and Michel 1977). That study involved an examination of cores made available by Foothills Pipe Lines Ltd. for the Mackenzie Valley, and by Polar Gas Ltd. for their proposed pipeline route through the central Keewatin. The results of this study, which revealed oxygen-18 shifts of 10 to 15 $^0/oo$, were presented at the 3rd International Permafrost Conference (Michel and Fritz 1978b).

During the 1977-79 period, a program was initiated to perform a series of laboratory experiments in an attempt to simulate the natural variations detected within the original field cores. Beginning with those experiments and continuing into the 1979-81 period, the laboratory work has demonstrated that it is possible to generate fractionations on a small scale as a result of freezing.

To supplement the laboratory work and to increase the natural data base, an extensive field program was undertaken in May of 1979 and 1980 at an experimental lake site (named

Illisarvik) in the Mackenzie Delta. A total of 23 continuous cores were collected at this site from within the drained lake bed, the surrounding shore and from a nearby pingo. Interesting variations were found in a number of cores, while other cores displayed an equally interesting lack of variation. A number of small variations similar in magnitude to those generated within the laboratory program were detected while larger shifts ranging from +5 to -15 ^{0}/oo for oxygen-18 were also encountered. Isotope profiling of the pingo has revealed a complex freezing history for the ice core. Through the use of isotopes it has also been possible to determine the thickness of the active layer during the past 30 years, the manner in which the active layer freezes, the age of the waters and the presence of water from different sources. The year by year progress of these investigations has been described in a series of reports (Michel and Fritz 1978a, 1979, 1980, 1981, in press) which have been compiled and summarized by the senior author as a Ph.D. thesis (Michel 1982).

1.2 TERMS OF REFERENCE

As part of the ongoing investigations of groundwater in permafrost regions of Canada, this study was undertaken as a continuation of the previous research program. Specifically, the objectives of this study were:

1. to continue to quantify the mechanisms creating the isotope variations in permafrost waters, in order to permit a more detailed discussion of the formation and stability of permafrost,
2. to continue to study isotope fractionations occurring at Illisarvik,
3. to correlate the field results with the laboratory program, and
4. to expand the data base by examining permafrost waters from the area south of Inuvik (along the Dempster Highway).

1.3 SCOPE OF THIS REPORT

This report describes the work completed and presents the data acquired during the contract period. Preliminary interpretations of the data are discussed in relation to their significance in understanding the history of the permafrost waters at Illisarvik and along the Dempster Highway. The laboratory experiments undertaken using saturated clay columns are discussed in relation to the previous experiments. Finally, the report suggests a course along which further work could be pursued.

Chapter II

WORK COMPLETED

2.1 ILLISARVIK

The work conducted during the period of this contract has involved the radiocarbon dating of a number of organic samples collected during the 1979 and 1980 field programs. These analyses have been performed in order to provide a better understanding of the age of the various sedimentary units, the age of Lake Illisarvik and the maximum age of the permafrost. In addition, selected samples from four cores have been analysed for their deuterium contents in order to examine the relationship of oxygen-18 and deuterium contents in these waters.

2.2 DEMPSTER HIGHWAY

During the past year, Foothills Pipe Lines (Yukon) Ltd. sent to the University of Waterloo all of the available core material collected during their 1978 drilling program along the Dempster and Klondike Highways. Water from a large number of samples representing the entire length of the route has been extracted and analysed for oxygen-18.

2.3 LABORATORY EXPERIMENTS

During the current contract period, two experiments were conducted using saturated kaolinite clay. These experiments were designed to examine fractionations which could occur in fine grained soils as a result of freezing and to compare these fractionations with those developed in coarser silt and sand soils during previous contract periods. Oxygen-18 and deuterium contents were determined in both of the experiments.

Chapter III

DISCUSSION OF RESULTS

3.1 ILLISARVIK

3.1.1 Background

Illisarvik is located on the northern tip of Richards Island in the Mackenzie Delta (Figure 1). It was designated by a group of Canadian researchers as an experimental site for the investigation of permafrost formation and aggradation. The lake was drained via an artificial channel to the coast during August of 1978. This exposed the lake bed to the atmosphere and permitted the upper several metres of the lake bed to freeze for the first time during the winter of 1978.

In May of 1979 and 1980, drilling programs were undertaken in order to collect continuous core material from various locations within the lake bed and from the surrounding basin. A total of 15 boreholes and 2 ice wedges were drilled during the 1979 program, while a total of 8 cores were collected in 1980. Except for the 4 cores taken from the pingo immediately south of Illisarvik, all of the borehole locations are shown in Figures 2 and 3.

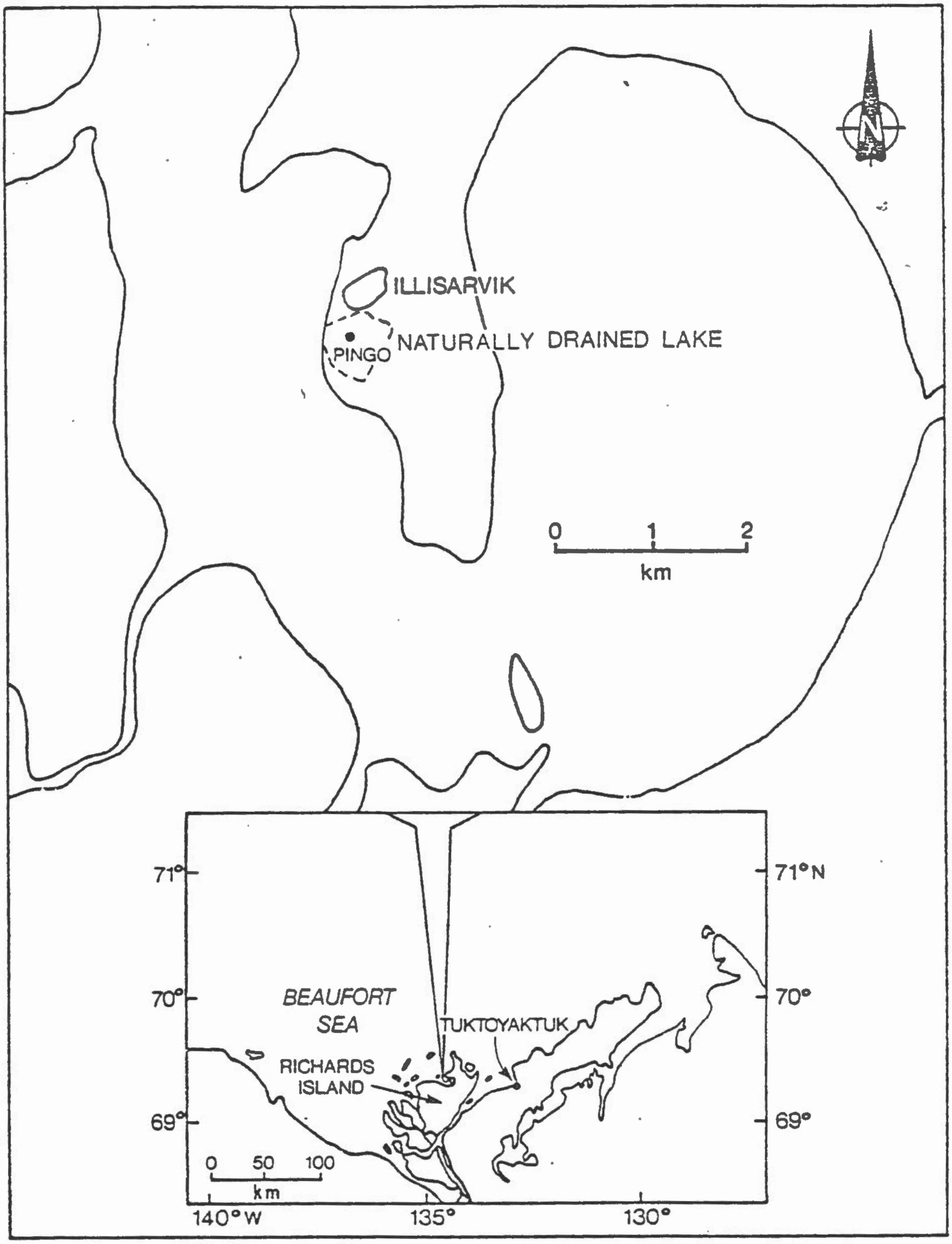

Figure 1 Location of Illisarvik in the Mackenzie Delta.

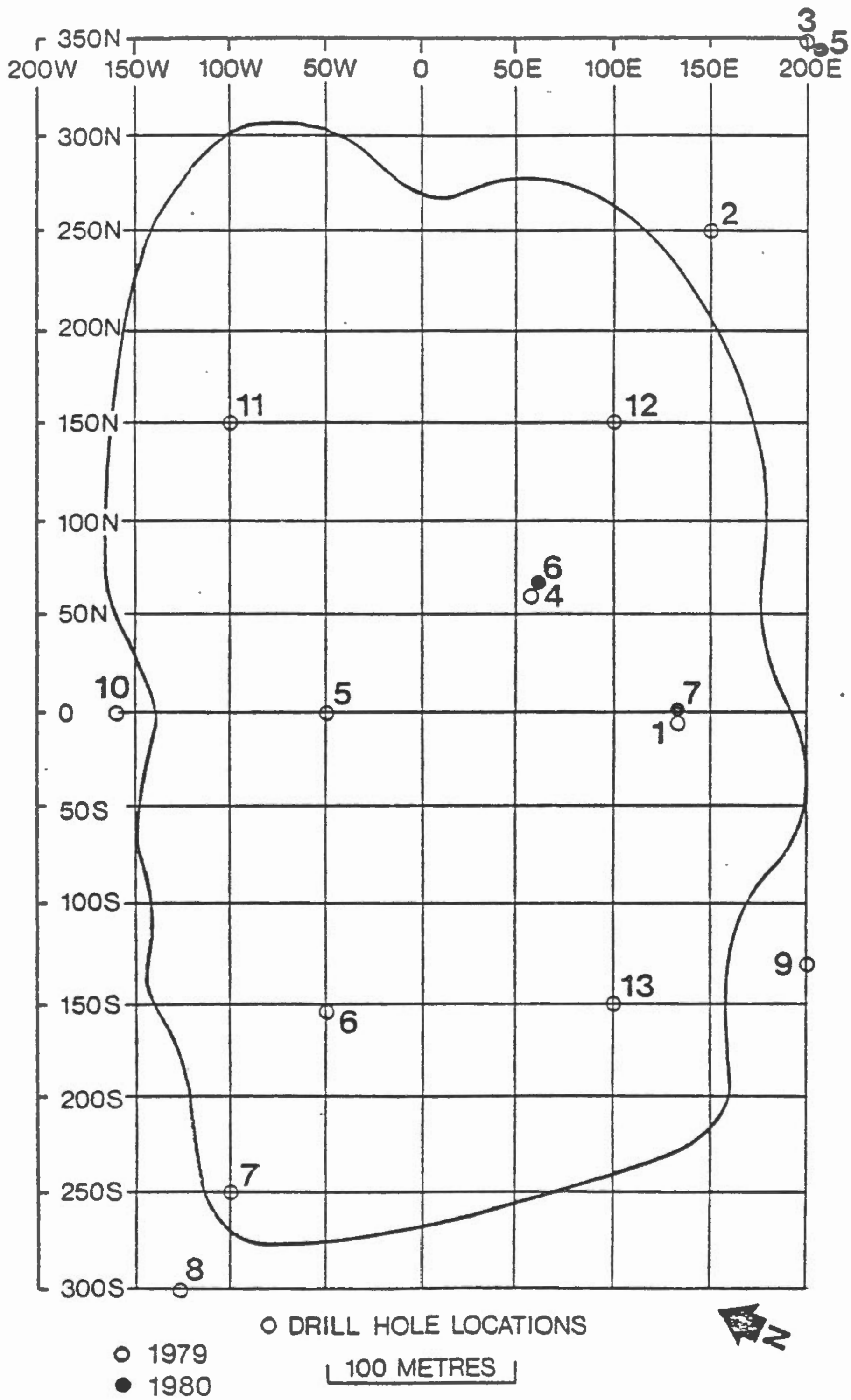

Figure 2 Location of boreholes drilled within the grid area of Illisarvik in May of 1979 and 1980.

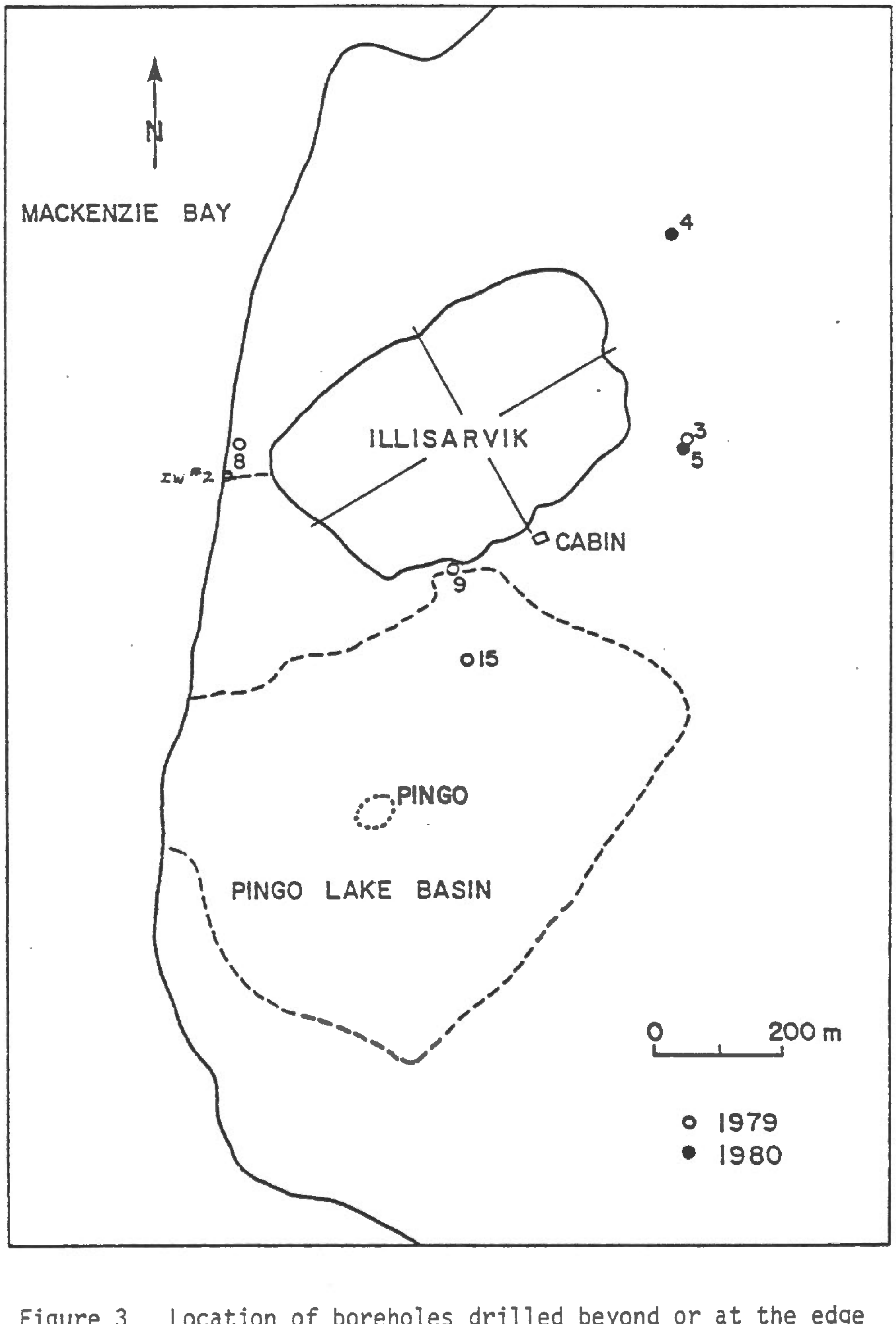

Figure 3 Location of boreholes drilled beyond or at the edge of the grid area at Illisarvik in May of 1979 and 1980.

3.1.2 Stratigraphy

Based on the observations of other workers (Hunter et al. 1979), and an examination of core material collected during the previous studies, the stratigraphy of the basin can be divided into three primary units, capped by modern peat, as shown in Figure 4.

The lowermost unit encountered during drilling consists of a clean, fine to medium sand, probably of deltaic origin, with finely laminated bedding sloping at 10 to 20 degrees in some cores, and containing scattered organic fragments. This sand grades upward into a series of interbedded sand and clay-silt layers.

Above these layers is a continuous clay-silt unit containing varying proportions of sand, minor organics, and numerous stones. These stones are up to 2 cm in diameter and vary in lithology from small red shale clasts (1 to 2 mm thick) to sub-rounded quartz and granite pebbles. Rampton (1971) described "a till-like material up to 15 feet thick" overlying the sand unit on Richards Island, while Mackay (1963, p. 26) reported only "a small percentage of exposures" where a thin till could be found over the sands. Mackay suggested that "where stones are lacking, the field identification of till is hazardous." Although the limit of glaciation in this portion of the Mackenzie Delta is uncertain, it appears that the Illisarvik area was not glaciated

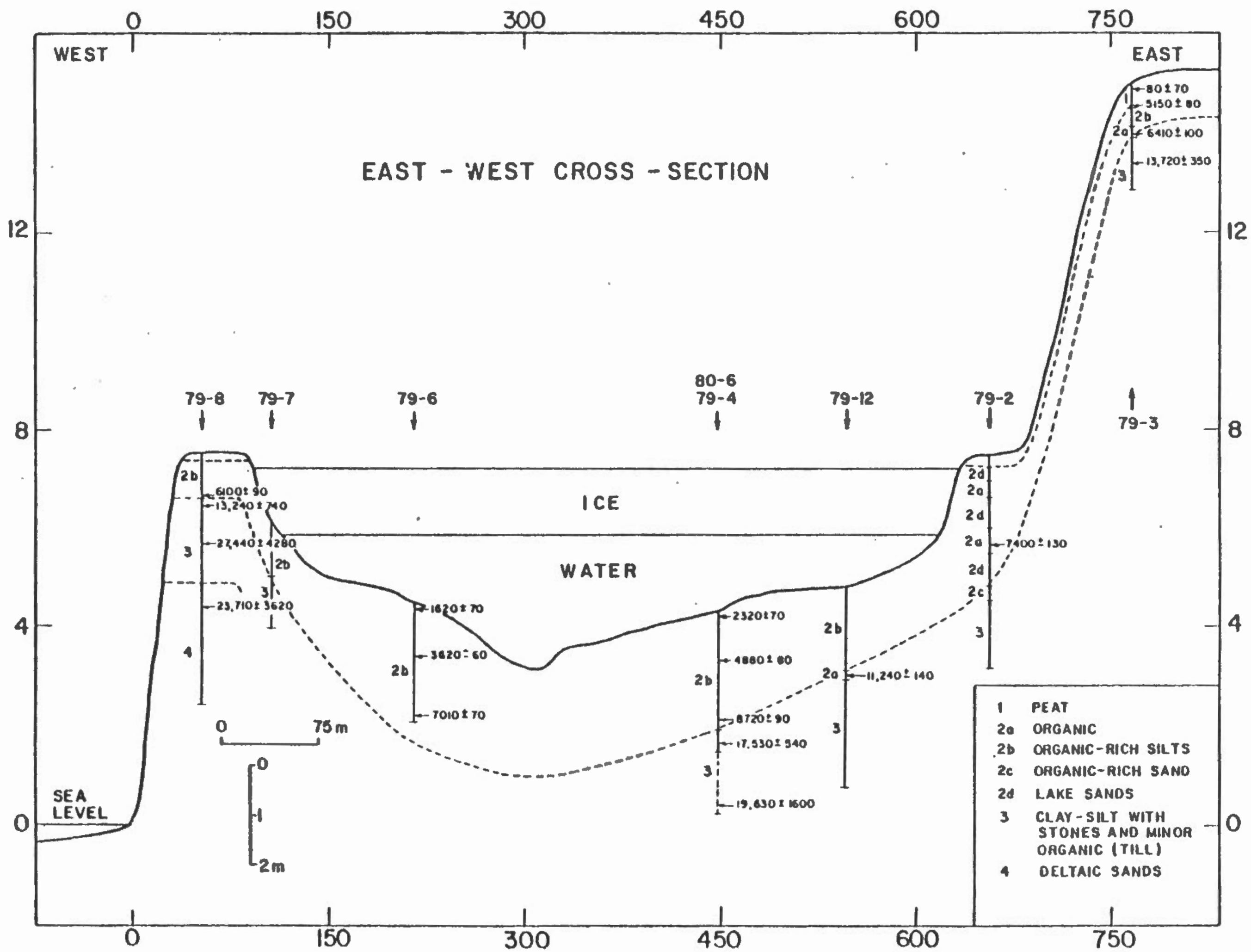

Figure 4 True east-west stratigraphic cross-section of Illisarvik and location of boreholes drilled along the section. Individual radiocarbon dates shown. Vertical exaggeration is 37.5x.

during the Late Wisconsin (Mackay et al. 1972). At Illisarvik, this clay-silt unit locally reaches a thickness of up to approximately 2 metres. This layer may represent solifluction debris, but the widespread nature of the unit and the preponderance of stones within it suggest to the authors that perhaps the unit represents flow till material as described by Boulton (1971).

Resting on this till is a sequence of organic-rich lake silts containing mollusc fragments near the base, that grade laterally into sands near the edges of the local Illisarvik basin. These lake silts are thickest in the central portions of the basin and thin outwards. A similar organic silt soil was found above the till layer in core 79-3 at an elevation of almost 7 metres above lake level.

Radiocarbon dating of organic material was undertaken in order to provide a time frame for the history of the lake and the sediments. A ^{14}C half-life of 5,568 years was used and the radiocarbon ages listed in Table 1 have been adjusted by standardization of their ^{13}C contents to -25 $^{0}/oo$. Some of these data are also plotted on the east-west cross-section shown in Figure 4.

In every study involving radiocarbon dating, it is necessary to examine the validity of the ages determined. Plant materials, and especially wood, are generally considered to yield more realistic ages than shells or other inorganic materials (Karrow, personal communication). Even with plant

Table 1 Radiocarbon data for Illisarvik

Sample #	Depth (cm)	Material Type [1]	$\delta^{13}C$ (‰ PDB)	% Modern (PMC)	^{14}C Age (Yrs B.P.)	WAT #
79-2-19	180-190	BD	-28.2	39.6	7400±130	801
79-3-2	5-10	A	-28.2	98.4	80±70	631
79-3-9	40-45	A	-28.5	52.3	5150±80	632
79-3-22	105-110	A	-26.6	44.9	6410±100	639
79-3-32	155-160	D	-27.1	18.0	13720±350	800
79-4-2	5-10	C	-29.3	74.3	2320±70	746
79-4-20	95-100	C	-28.5	54.1	4880±80	739
79-4-44	215-220	C	-21.8	34.0	8720±90	741
79-4-53	265-270	E	-27.4	11.2	17530±540	740
80-6	360-365	E	-27.4	8.6	19630±1600	742
79-6-3	10-15	C	-29.6	81.0	1620±70	814
79-6-23	110-115	C	-28.2	63.3	3620±60	784
79-6-45	220-225	C	-23.0	42.0	7010±70	782
79-8-17	80-85	B	-27.9	46.6	6100±90	802
79-8-21	100-105	E	-25.5	19.2	13240±740	790
79-8-35	170-175	E	-28.1	3.3	27440±4280	783
79-8-61	300-305	E	-28.4	5.2	23710±3620	761
79-9-11	50-55	B	-29.5	76.6	2070±70	804
79-9-23	110-115	D	-27.7	65.3	3380±60	799
79-9-34	165-170	B	-28.1	39.5	7410±120	791
79-12-18	170-180	BD	-28.5	24.5	11240±140	803
79-15-1	30-40	B	-30.7	78.1	1890±120	805

[1] A Peat
B Fibrous organic
C Organic silt
D Woody fragments and sticks
E Organic fibres and streaks

materials, it is necessary to determine whether the material grew in situ, or whether it was redeposited from another location. If it was redeposited, then one must consider the period of time between growth and deposition or redeposition. Unfortunately, this is often very difficult to determine. The modern date obtained near the top of core 79-3 (WAT 631), indicates that the age determined is the age of the material dated. However, it is still necessary to determine where the material originated. In the case of the modern peat the answer is obvious because the organic (plant) matter grew in situ, but ages determined for other older organics are not as clear. Therefore, for the purpose of this study, it is assumed that the organic material was incorporated into the sediments shortly after the plants died and that the continual supply of new organic debris was always much greater than the supply of reworked older organics.

Only one radiocarbon date of 23,710 years was obtained for organics contained within the lower sand unit encountered in borehole 79-8 (WAT-761). Organic material from the overlying till unit yielded a slightly older radiocarbon age of 27,440 years (WAT-783), although the error limits are sufficiently large that the two samples could be of the same age. This suggests that the organic material in the till unit was not formed in situ. Other organic samples from the till unit yielded ages ranging from 13,000 to almost 20,000 years before present, indicating that this till is from the Late Wisconsin. Since the organics were incorporated into the till, the ice must have been present in the vicinity approximately 13,000 radiocarbon years ago. Mackay (1963) reported that the region was probably deglaciated by 12,000 years B.P. which would permit only a short 1,000 year period for an ice cover in the area. The field work of Mackay (1963, p. 25) indicated that ice flow into the area was from the south-southwest and that "minor differences in relief, of the order of several hundred feet, seem to have played important roles in controlling ice movement, thus suggesting a thin cover". Geothermal data collected by Judge (personal communication) also would suggest a thin or short-lived ice cover.

In borehole 79-12, a 30 cm thick organic unit containing sticks and plant fragments was encountered at the boundary between the till layer and the overlying organic silts. Radiocarbon dating of a portion of this organic mat (WAT-803) provided an age of 11,240 years, which places an upper limit on the age of the till.

An age of 8720 years, determined for sample 44 of core 79-4 (WAT-741) was the oldest date obtained within the lake silts. Since a thin layer of the lake silts occurs below the sample dated, it is possible that the lake, at least in the vicinity of core 79-4, initially formed almost 9,000 radiocarbon years ago. Borehole 79-6 was terminated in the lake silts. An age of 7010 years (WAT-782) from near the bottom of this core and an age of 7410 years from lake silts in core 79-9 (WAT-791) demonstrate that most of the lake basin ws covered by a lake more than 7,000 years ago. Basal dates of 6100 and 6410 years, for cores 79-8 (WAT-802) and 79-3 (WAT-639) respectively, indicate that a lake much larger in extent than the recent Lake Illisarvik existed during the warmer Hypsithermal period. This warmer interval is generally thought to have lasted from 8000 to about 4000 years ago (Dansgaard et al. 1971, Ritche and Hare 1971).

Along the entire length of the cross-section, there is a definite break in the sedimentation record. This break coincides with the transition from organic-rich lake silts to the stony clay-silt till. Although the formation of the early phase of Lake Illisarvik appears to have occurred about 2,000 years after the ice retreated, there is no evidence that a vegetation cover formed on the till surface, except for possibly the thick organic layer noted in core 79-12 at a depth of 1.6 to 1.9 metres.

The dating of lake organics from several intervals in cores 79-4 and 79-6 suggests that the water body has existed continuously since its formation, but the ages for the uppermost dated samples in these two cores (2320 and 1620 years respectively) are somewhat troublesome. In Figure 5, where the sedimentation break is clearly marked, the lake silts of core 79-4 indicate continuous sedimentation at a

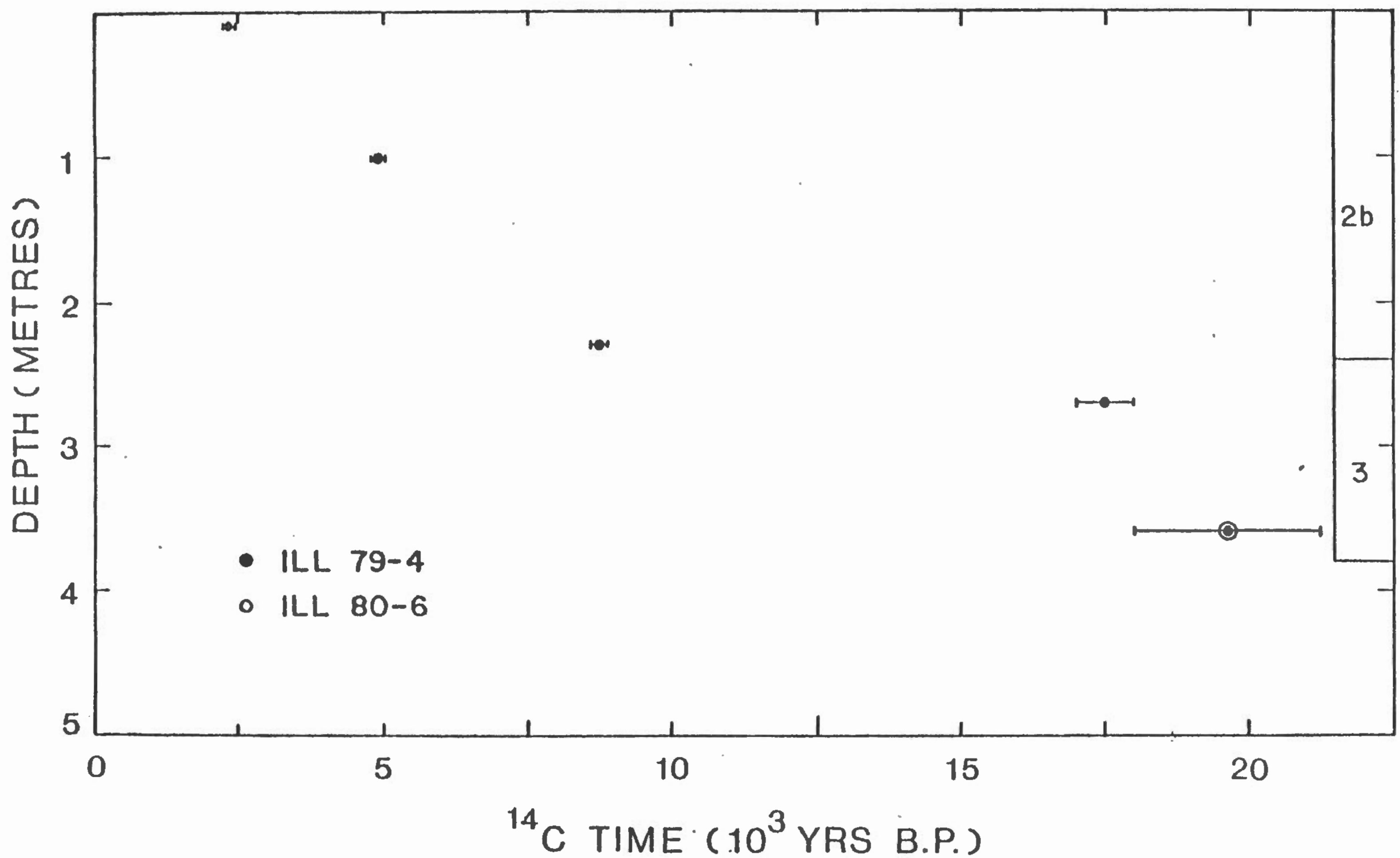

Figure 5 Radiocarbon ages with depth for cores 79-4 and 80-6.

rate of 0.35 mm/year. Core 79-6 yielded a rate of 0.35 mm/year in the lower portion and a rate of 0.53 mm/year for the upper one metre of lake silts. Using the lower sedimentation rate for both cores, the two samples in question should have ages not in excess of 300 to 400 years.

This discrepancy could be the result of an age effect due to the uptake of ^{14}C depleted carbon into the organic matter. Such "hard water" age effects have been noted in many more southerly lakes (Karrow and Anderson 1975), but have not been investigated in these northern environments where the drift contains some carbonate material, even when bedrock is deeply buried. Since the sedimentation rate is constant throughout the lake silt sequence of core 79-4, any age effect must be applicable to some extent for all of the radiocarbon dates. This would not only reduce the age for the formation of the lake, but would also imply age effects for the remaining radiocarbon dates which were determined on organics from a variety of settings.

An alternative explanation for this discrepancy would be erosion, and/or a sharp decrease in the rate of sediment accumulation. Radiocarbon dating of the uppermost lake silts (WAT-805) in the drained lake immediately south of Illisarvik, referred to here as the Pingo Lake basin, and the base of the organic mat on the sill separating the two lake basins (WAT-804), indicates that the Pingo Lake drained approximately 2,000 years ago. Drainage of Pingo Lake probably resulted in an appreciable decrease in the level of Lake Illisarvik. This decrease in turn would create changes in the circulation patterns within the lake which could result in an increase or decrease in the sedimentation rate, and a remobilization of older sediments. Such an hypothesis is favoured by the authors because it does not require the introduction of major adjustments to the radiocarbon data. However, efforts should still be made to investigate the hard water effects in these northern environments.

It should be noted that organic and inorganic sediments have been accumulating in the Illisarvik area since deglaciation. If one assumes that the active layer has had a constant thickness over time, then the accumulation of sediment would result in a rise of the permafrost table. Mackay (1967) reported the existence of lakes which were partially dammed by the accumulation of peat. No doubt the continual growth and accumulation of the peat caused the permafrost table to rise and effectively block the outflow of water. Thus, it appears likely that a similar continued accumulation of peat at Illisarvik has resulted in a rise of the permafrost table and a gradual rise in the lake level during the past 2000 years.

3.1.3 Deuterium Contents

During the past two years, the analytical program has focussed on the determination of the oxygen-18 contents of permafrost waters recovered from many of the 23 cores drilled at Illisarvik. With the exception of core 79-4, which displayed only a minor shift to more negative oxygen-18 values with depth, none of the cores had been examined for their deuterium contents. It is known from theory and from the laboratory experiments that both deuterium and oxygen-18 will be preferentially enriched in the ice phase during freezing. However, since the two isotopes fractionate at slightly different rates it was not known whether additional information could be obtained by determining the concentration of both isotopes. Therefore, during the present contract period the analytical work has been confined to an examination of deuterium in selected samples from four cores with water containing large variations in oxygen-18 content, and which represent different environments or freezing histories. The first two cores (79-2 and 79-9) were taken near the edge of Lake Illisarvik and represent different ages of permafrost. The third core (79-14) was collected from the pingo in the adjacent lake basin, while the fourth core is representative of a cross-section through a relatively young ice wedge. The isotope data for these cores are listed in Appendix A. The soil key for all cores is given in Figure 4.

The deuterium profile of core 79-2 (Figure 6) is identical to the oxygen-18 profile for this core. Clearly visible are the shift within the active layer representing freezing from two directions, the shift to more negative values with depth in the upper two metres of the permafrost, followed by a rapid increase in the deuterium concentration. Only two samples have been analysed from the bottom 1.5 metres of the core, but it would appear that within this zone the deuterium concentration is relatively constant at approximately -140 ⁰/oo.

Core 79-9 (Figure 7) also has a deuterium profile closely resembling its oxygen-18 profile. Within the upper 2.5 metres, the two isotopes have been analysed in sufficient detail to demonstrate that the two profiles are related in almost every detail. Below 2.5 metres only thre samples have been analysed for deuterium. Although these samples indicate a rapid decrease in the deuterium concentration, they are not able to demonstrate the large number of minor fluctuations visible in the oxygen-18 profile (Figure 8). To accomplish this would have required many more deuterium analyses.

Upon examination of the deuterium and oxygen-18 profiles for the pingo core (79-14) shown in Figures 9 and 10 respectively, it can be seen that the two isotopes have behaved in a similar manner during freezing. Within the upper zone of massive ice, both isotopes clearly outline the individual

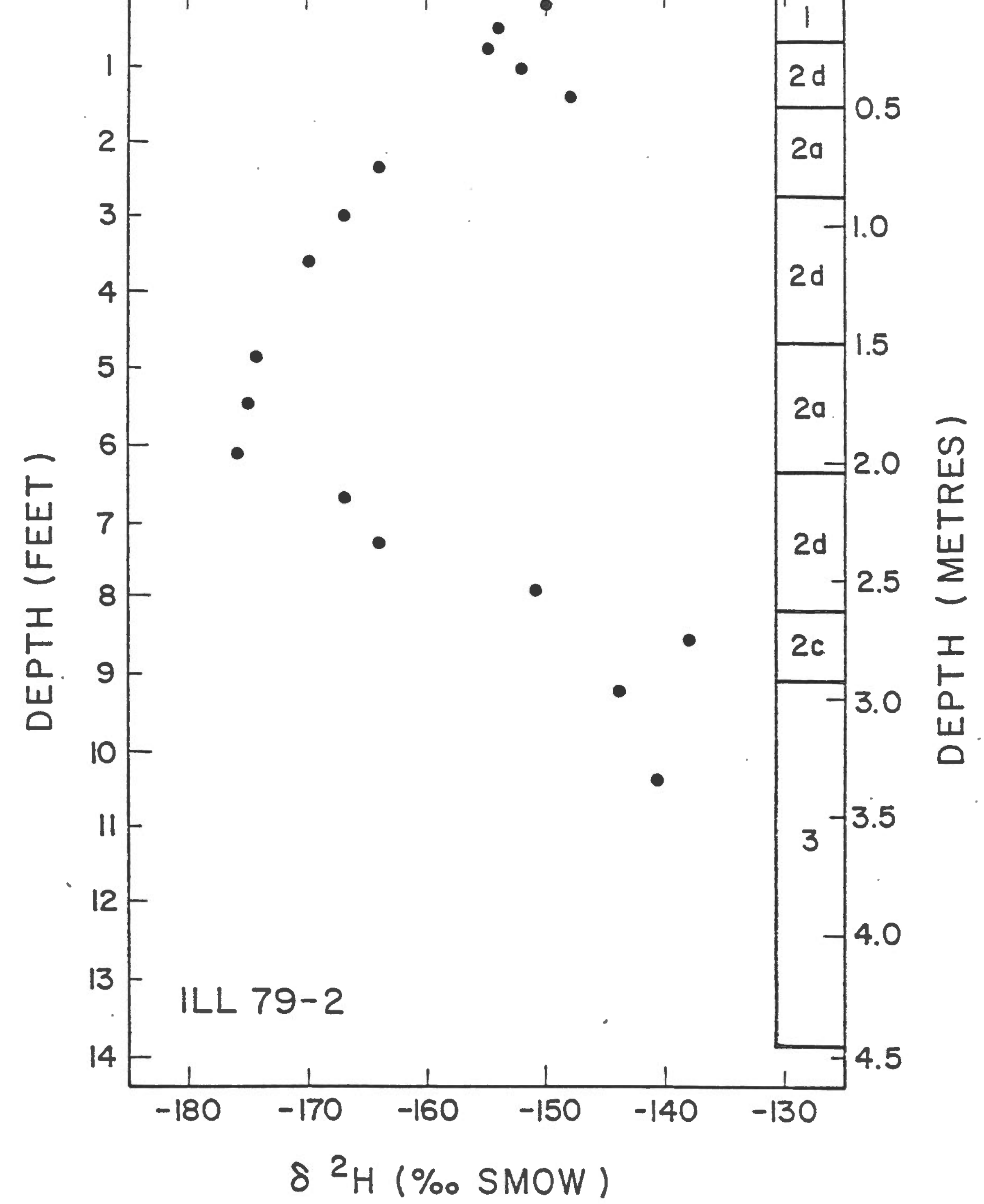

Figure 6 Variation in ^2H content with depth for

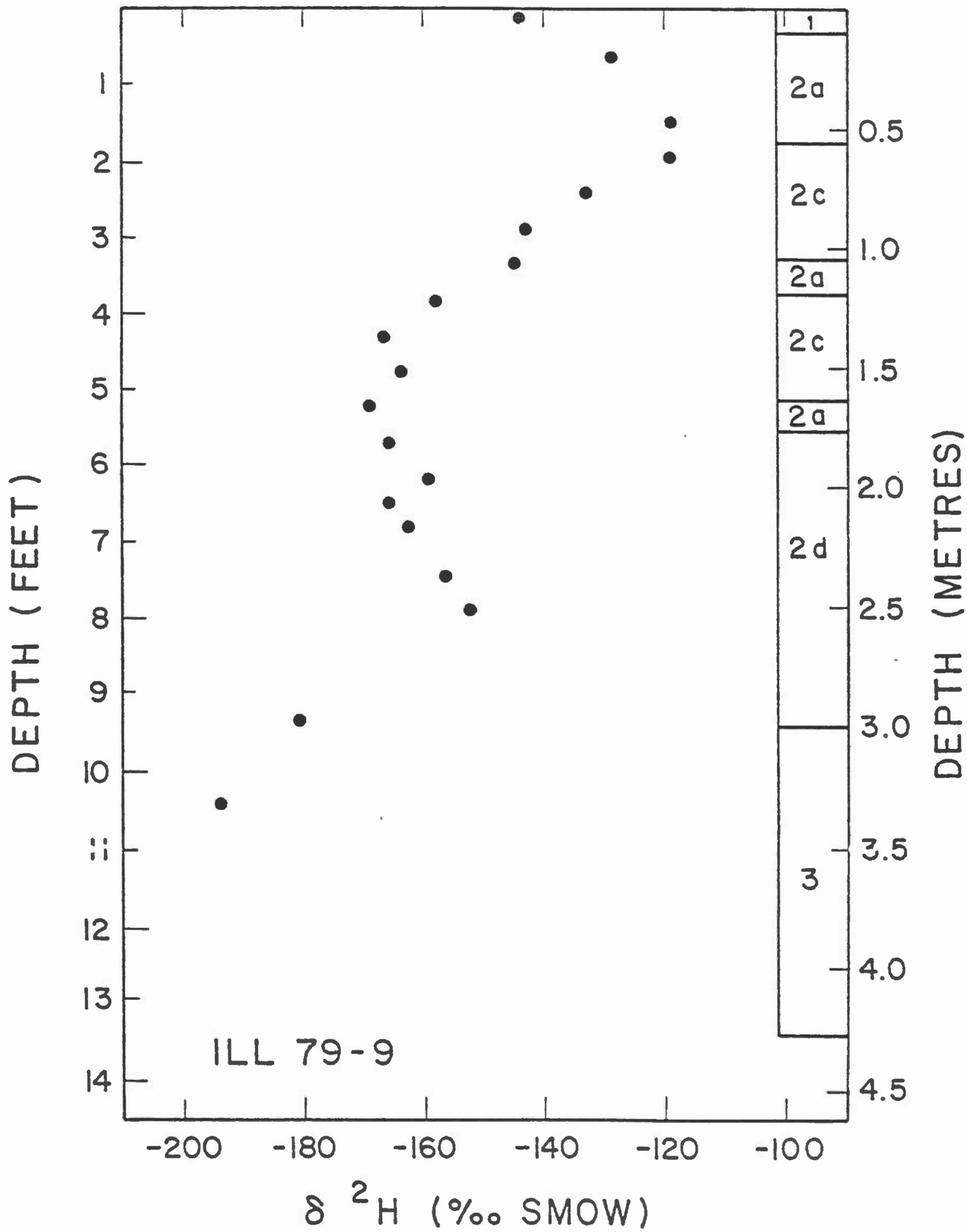

Figure 7 Variation in ^2H content with depth for core 79-9.

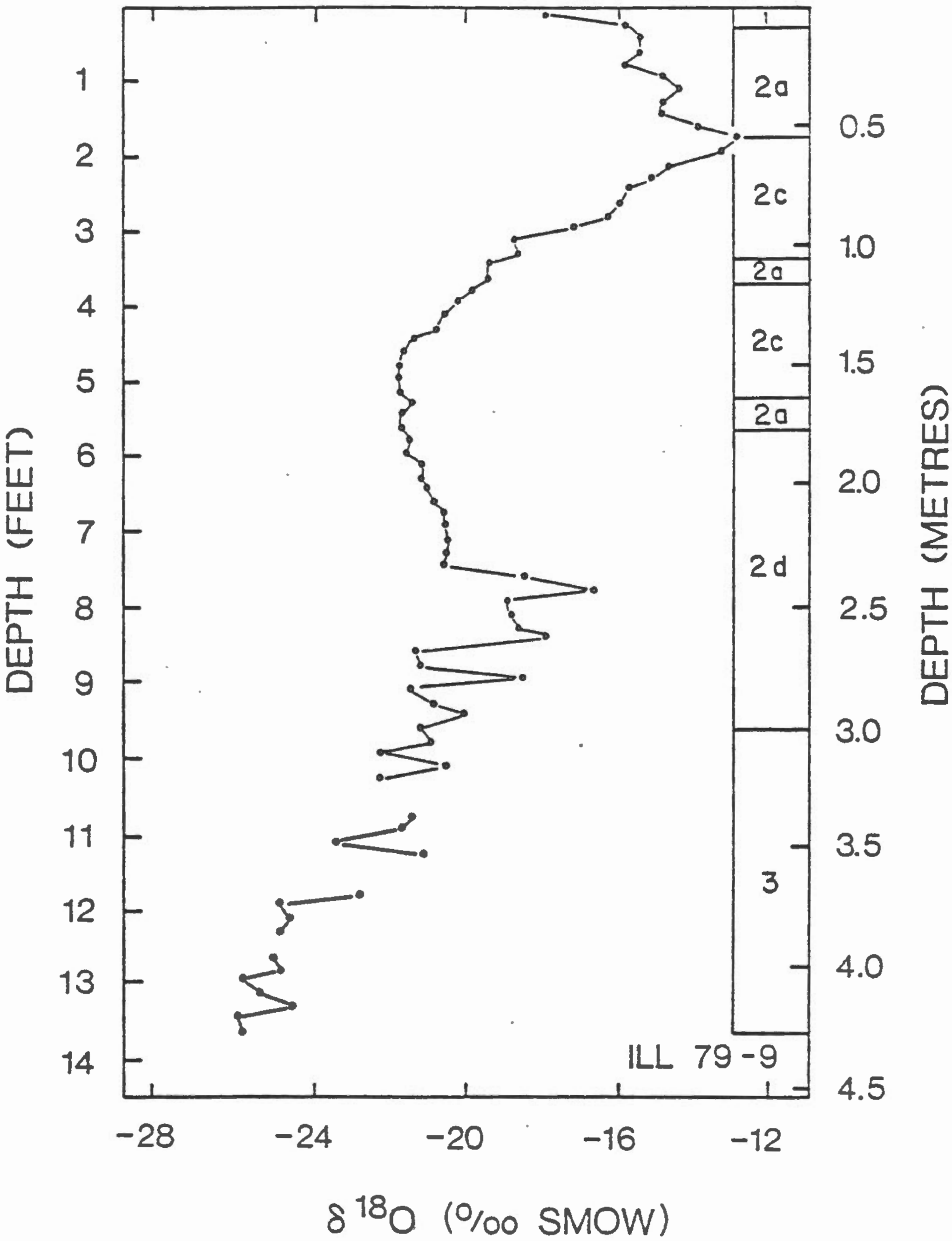

Figure 8 Variation in ^{18}O content with depth for core 79-9.

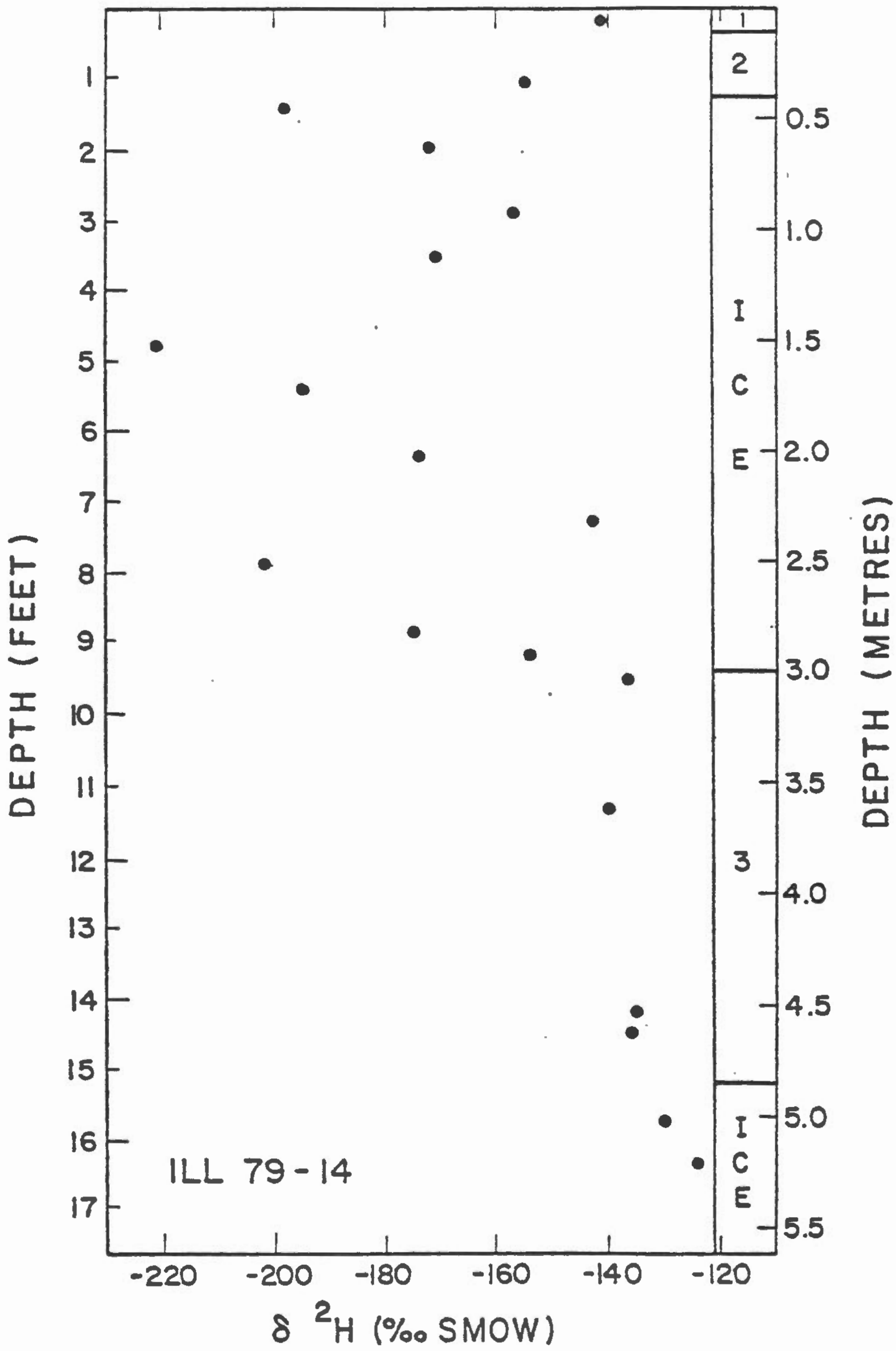

Figure 9 Variation in ^2H content with depth for core 79-14.

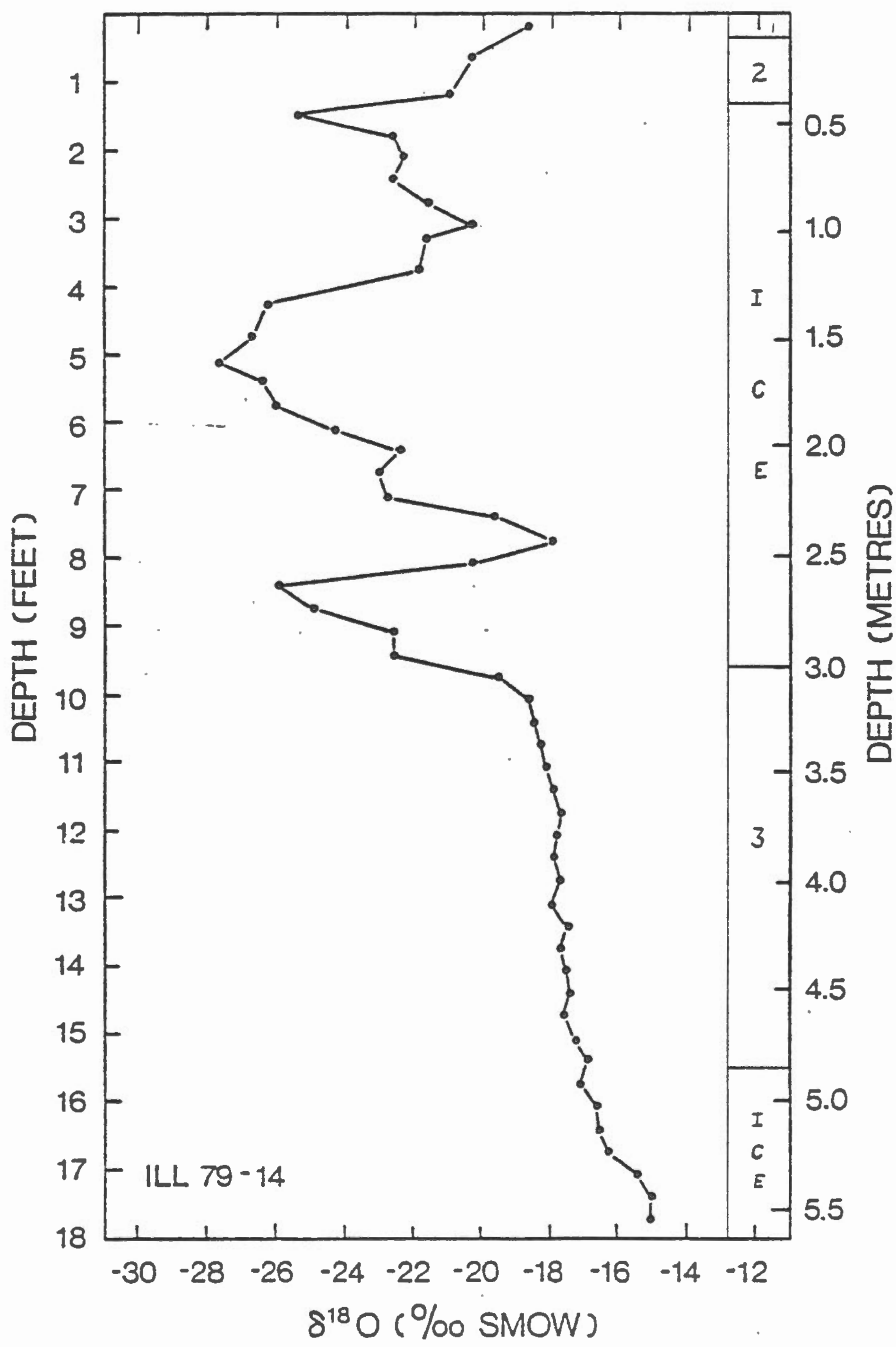

Figure 10 Variation in ^{18}O content with depth for core 79-14.

pulses of water which have frozen during the growth of the pingo. As was shown originally in the oxygen-18 profile, the underlying clay soil and massive ice display relatively little variation in comparison to the upper massive ice zone.

Ice wedge #2, which was cored by horizontally drilling perpendicular to the wedge, also displays a deuterium profile that parallels the original oxygen-18 pattern. The ice wedge is clearly visible in Figure 11 as the group of more negative deuterium values in the interval of 0.8 to 1.15 metres, while the soil on either side of the wedge contains water with relatively positive deuterium values.

Although the four cores examined contain permafrost waters which differ in age and freezing history, the behaviour of both the oxygen and hydrogen isotopes has been shown to be the same. This would appear to indicate that no additional information is acquired by analysing the second isotope, since all of the relative variations can be described by determining the distribution of only one of the two isotopes. However, since the rate of fractionation during freezing differs slightly for the two isotopes, it is possible that a direct comparison of the isotopes would reveal information that could be useful in understanding the development of permafrost or permafrost-related phenomena.

The oxygen-18 and deuterium data for all four cores have been plotted in Figure 12. It is apparent that all of the

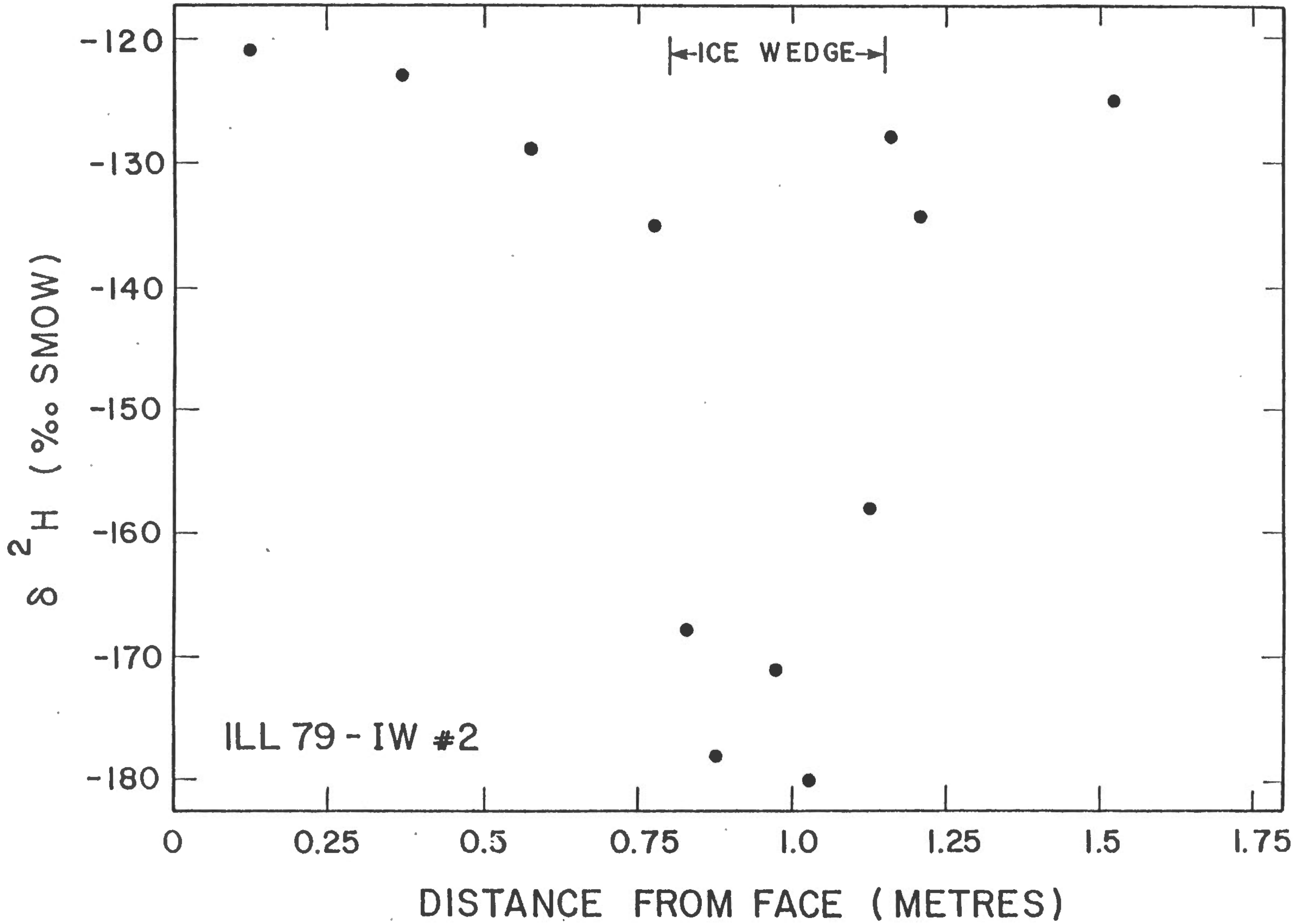

Figure 11 Variation in ^{2}H content across ice wedge 79-IW#2.

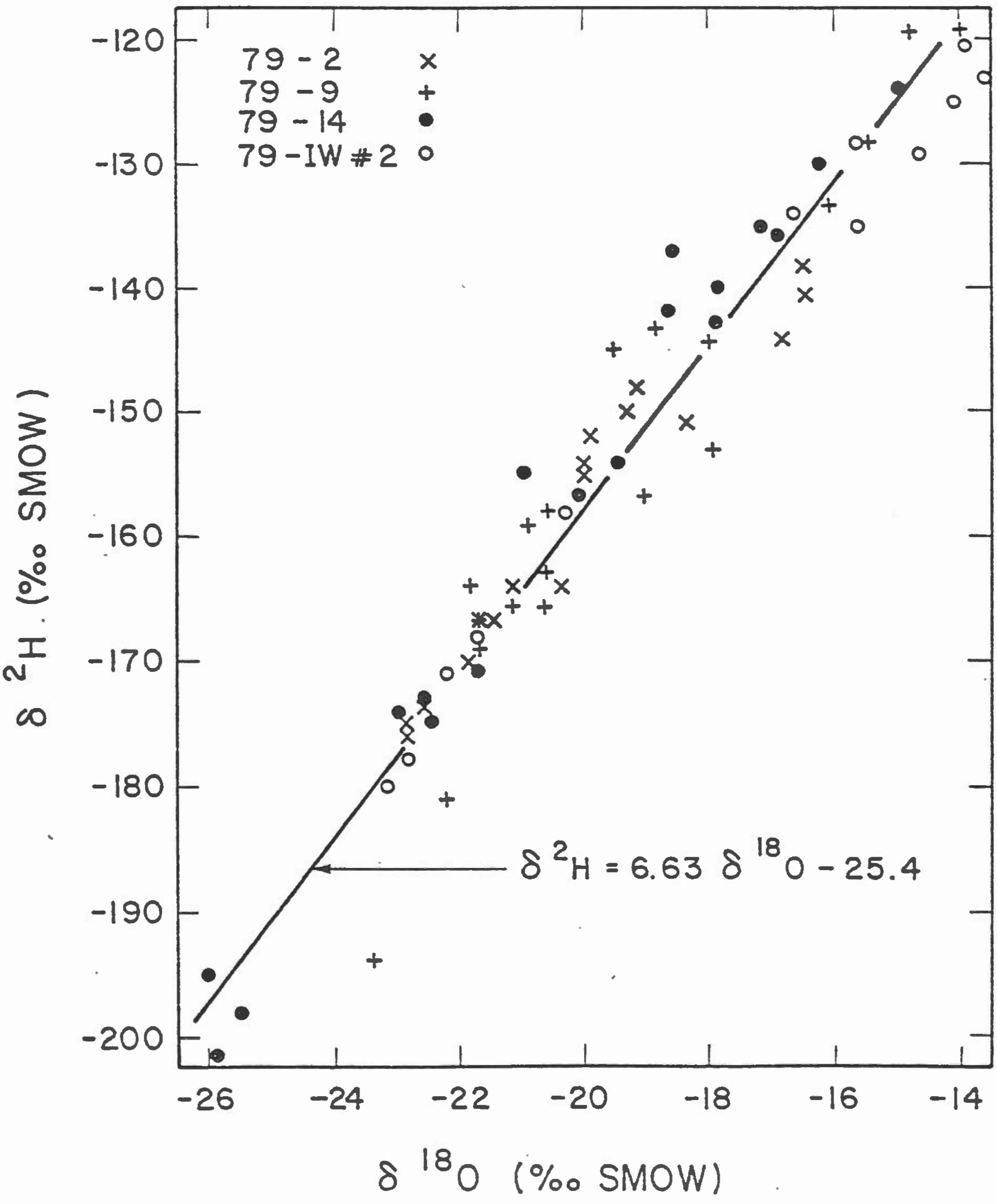

Figure 12 Relationship between ^{2}H and ^{18}O contents for cores 79-2, 79-9, 79-14 and 79-IW#2. Correlation coefficient of 0.97.

data points are part of a single overall trend which can be described by the relationship of $\delta^2H = 6.63 \delta^{18}O - 25.4$ (correlation coefficient of 0.97). Upon closer examination, it can be seen that the data for the individual sections of each core (Table 2) form their own relationship which varies from the overall trend. The cause of these variations and their significance are not fully understood at present.

In theory when a closed body is being frozen, the distribution of the isotopes within the profile will display a gradually accelerating increase in the concentration of the light isotopes within the residual liquid. This distribution of the isotopes can be described by a curve generated from the Rayleigh distillation model using equilibrium fractionation factors. When the relationship of oxygen-18 to deuterium and their respective rates of fractionation are compared, it is found that the slope of the line changes from approximately 7.5 with 20% of the water mass frozen, to 7.0 when 98% of the water mass is frozen. Suzuoki and Kimura (1973) found, from their experimental work on fractionation factors in the ice-water system, that deuterium fractionated at a rate which was 7.4 ± 0.5 times greater than for oxygen-18. Since only a small percentage of the total water mass was frozen during their experiments, it would be expected that their value would be close to the theoretical value of 7.5 for initial freezing.

At Illisarvik, a number of different processes are active and each would appear to affect the ^{18}O - ^{2}H relationship in its own way. The normal pattern of freezing, in which the concentration of the heavy isotopes decreases with depth, is represented in core 79-2 by section 5-20 and in core 79-9 by section 51-67 (see Table 2). In both instances the slope values are in the range of 7.0 to 7.5. This condition can probably be best described as a downward migrating freezing front with a large available supply of water below.

The zone of annual freezing and thawing in core 79-2 (section 1-5) has a slope value of 6.82 which is suggestive of a closed system freezing condition in which none of the water is expelled or escapes from the system. Such a condition would appear reasonable since the relatively dry centre was bounded by ice-rich zones. In the active layer of 79-9 (section 1-10) it was originally suggested on the basis of the isotope profiles that the freezing occurred entirely from the permafrost table upwards. If this were the case, then the similarity in slopes for the active layer relationship and the upper permafrost (section 10-34) could possibly indicate that the upper zone of permafrost has formed by an upward moving permafrost table. The reason for the slope be ing lower than the active layer value of core 79-2 is unclear.

In both cores 79-2 and 79-9, the sections which have been interpreted as zones of isotope diffusion (section 20-28 and 34-51 respectively) have slope values of less than 6.

Table 2 Linear regression analysis of deuterium and oxygen-18 data for Illisarvik samples.

CORE #	SECTION (SAMPLE #)	NUMBER OF DATA POINTS	SLOPE	CORRELATION COEFFICIENT (R)
79-2	1-5	5	6.82	0.94
	5-20	7	7.37	0.99
	20-28	5	5.72	0.99
79-9	1-10	3	6.27	1.00
	10-34	9	6.27	0.98
	34-51	7	3.83	0.90
	51-67	3	7.20	0.99
79-14	4-28	11	7.54	0.99
	29-45	4	7.02	0.96
	1-51	19	7.43	0.99
79-IW#2	17-23	5	7.74	0.99
	3-16 24-31	7	4.26	0.89

Whether the low slopes are due to kinetic effects is uncertain, however, if these values are typical for diffusion zones, then rates of migration for each isotope should also be considered during an examination of these slope values.

The ice wedge and pingo cores also contain some interesting slope values. Within the massive ice of the ice wedge, the value of 7.74 is very similar to regional meteoric water lines which lie at a slight angle to, but on the global meteoric water line. Since this line is representative of unaltered precipitation, it would appear that the water contained within the ice wedge has probably not been fractionated during freezing. Furthermore, the more negative isotope values found within the ice as compared to the adjacent soil would suggest that the water forming the ice wedge represents winter precipitation. Mackay (1973) has reported that ground cracking during the late winter (February-March) and infiltration of snow pack waters are responsible for the generation of ice wedges.

The reason for the low slope value of the waters contained within the adjacent soils is unknown, although the value is similar to those discussed previously for zones of isotope diffusion. It should be noted that the oxygen-18 contents are similar to the deeper waters encountered in nearby borehole 79-8. If the waters adjacent to the ice wedge are not related to diffusion, but instead to the deep waters of borehole 79-8, then an analysis of the waters encountered in borehole 79-8 should produce a slope value similar to the soil adjacent to the ice wedge.

Within the upper massive ice core of the pingo which was intersected by borehole 79-14, the individual deuterium and oxygen-18 profiles (Figures 9 and 10 respectively) indicated a series of three discrete ice zones formed by the injection of a water pulse followed by closed system freezing. According to the Rayleigh distillation theory, the complete freezing of a confined water mass should yield a slope value of approximatly 7. From Table 2 it can be seen that the value for the entire massive ice core is 7.54. However, insufficient deuterium analyses have been completed to determine slope values for the individual pulses. It is possible that the more detailed analysis would demonstrate slightly lower slope values.

In summary, it would appear that the determination of both oxygen-18 and deuterium contents for permafrost waters may have the potential to provide additional information concerning the history of these waters and the conditions under which they froze. However, before any definite trends can be described, it is necessary to examine in greater detail the relationship of the two stable isotopes for waters that can be directly related to individual characteristics or phenomena formed as a result of permafrost aggradation.

3.2 DEMPSTER HIGHWAY

3.2.1 Introduction

The proposed route of the Dempster Highway pipeline closely follows the Dempster and Klondike Highways from Inuvik to Whitehorse. The major physiographic regions traversed by the pipeline include the Mackenzie Delta, Mackenzie Valley, Peel Plain, Richardson Mountains, Eagle Plain, Ogilvie Mountains, Tintina Trench and Pelly Mountains. Permafrost has been encountered along the entire route with the the largest ice-rich sections located in the unglaciated Eagle Plain of the northern Yukon (Foothills 1978).

A large number of core samples, from boreholes located along the entire route, were provided by Foothills Pipe Lines (Yukon) Ltd. from their 1978 drilling program. The location of every tenth borehole and those discussed in section 3.2.2 are plotted on Figure 13. In addition to the core samples received from the pipeline route, the second author collected nine groundwater samples from various campgrounds and springs along the route during a visit in July of 1981. The locations of these samples are also shown in Figure 13.

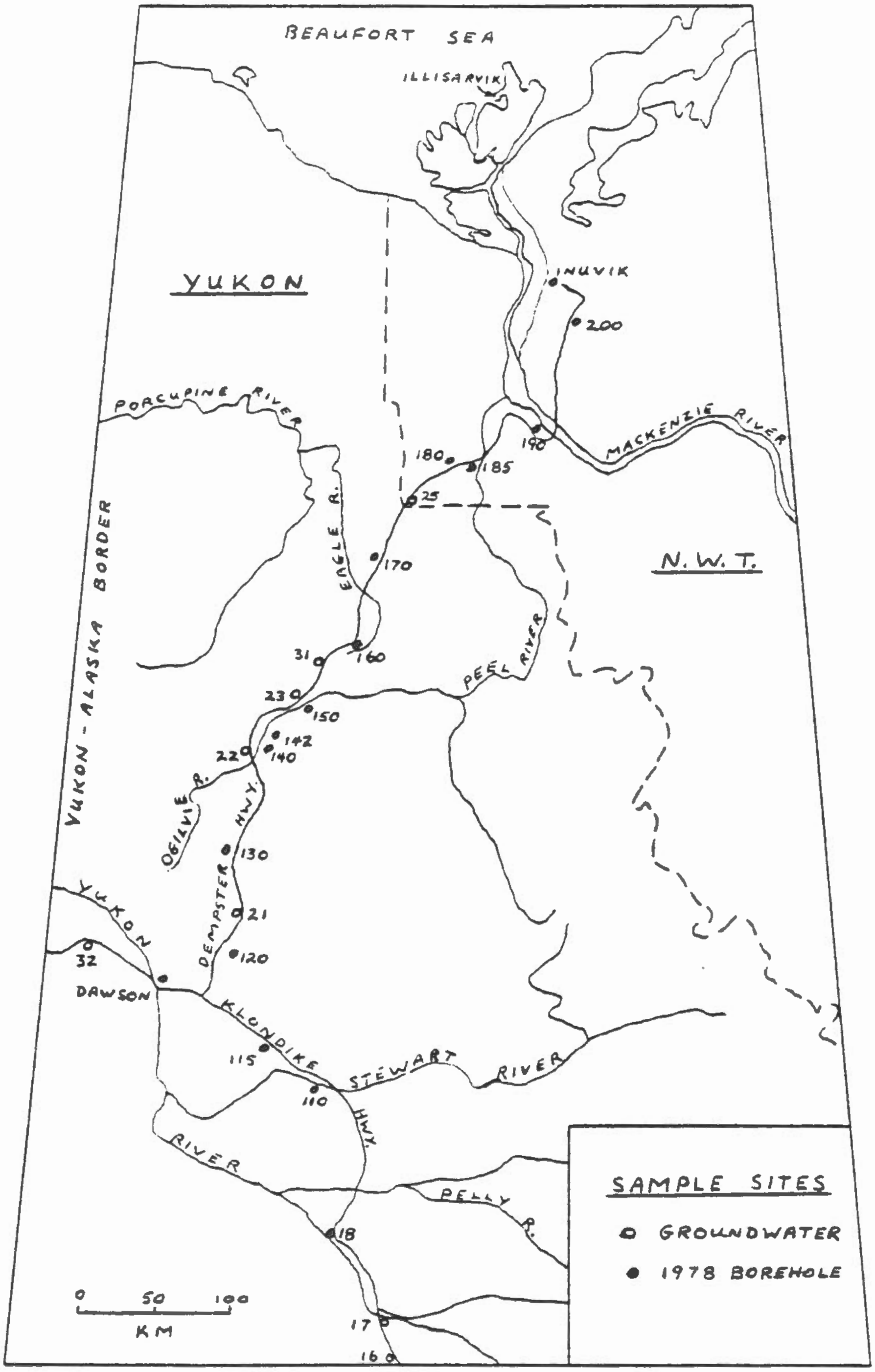

Figure 13 Location map of boreholes and groundwater sampling sites along the Klondike and Dempster Highways.

3.2.2 Isotope Results

During the period of this contract, oxygen-18 contents of permafrost waters have been determined for representative samples from the entire length of the proposed Dempster Highway pipeline. Due to the large number of samples made available for the project by Foothills Pipe Lines (Yukon) Ltd., it was only possible to analyse a few samples from each location. In several instances, samples of the ice (frost) coating the outside of many cores were collected and analysed. Normally this outer layer of ice and soil was removed before the sample was cut in order to remove the possibility of contamination. The preservation of ice lenses within the core are considered to indicate that the cores have not been thawed and subsequently refrozen. All of the isotope data are tabulated in Appendix B. Many of the deeper samples of bedrock or dense till have not yielded sufficient water for analysis.

From the samples collected by the second author, shallow groundwaters appear to generally have oxygen-18 contents in the range of -20 to -23 $^{0}/oo$. The spring discharges, which probably are representative of deeper and more regional flow systems have isotope values in the lower portion of this range. From other work undertaken by the authors, the spring at North Fork Pass is known to flow throughout the year and it has a constant isotope composition. Therefore, it would appear that the isotope contents of the springs can be considered as being representative of the average annual groundwater. Work by Hitchon and Krouse (1972) indicates that the oxygen-18 contents of surface waters in the northern Mackenzie Valley and Peel Plain regions are in the range of -20 to -22 $^{0}/oo$.

Upon examination of the isotope data for the permafrost cores, it can be seen that most of the shallow permafrost waters have oxygen-18 contents in the range of -20 to -22 $^{0}/oo$. Several of the surficial peat samples have values in the range of -14 to -16 $^{0}/oo$ which is considered to indicate partial evaporation of the waters. At depth, the oxygen-18 contents either decrease to values of less than -23 $^{0}/oo$, or they increase to values in the range of -17 to -19 $^{0}/oo$. In those cases where only a few samples from a core have been analysed, it is impossible to determine whether these shifts are related to climatic variations or to freezing fractionations.

All of the available samples for borehole 78-185 have been analysed to a depth in excess of six metres. The isotope profile shown in Figure 14 indicates the presence of both climatic and freezing fractionation variations. The fractionations formed as a result of freezing are well developed 2 to 2.5 $^{0}/oo$ variations. Superimposed on these fractionations is a climatic shift to more negative values with depth. These negative values (-26 $^{0}/oo$) are similar to

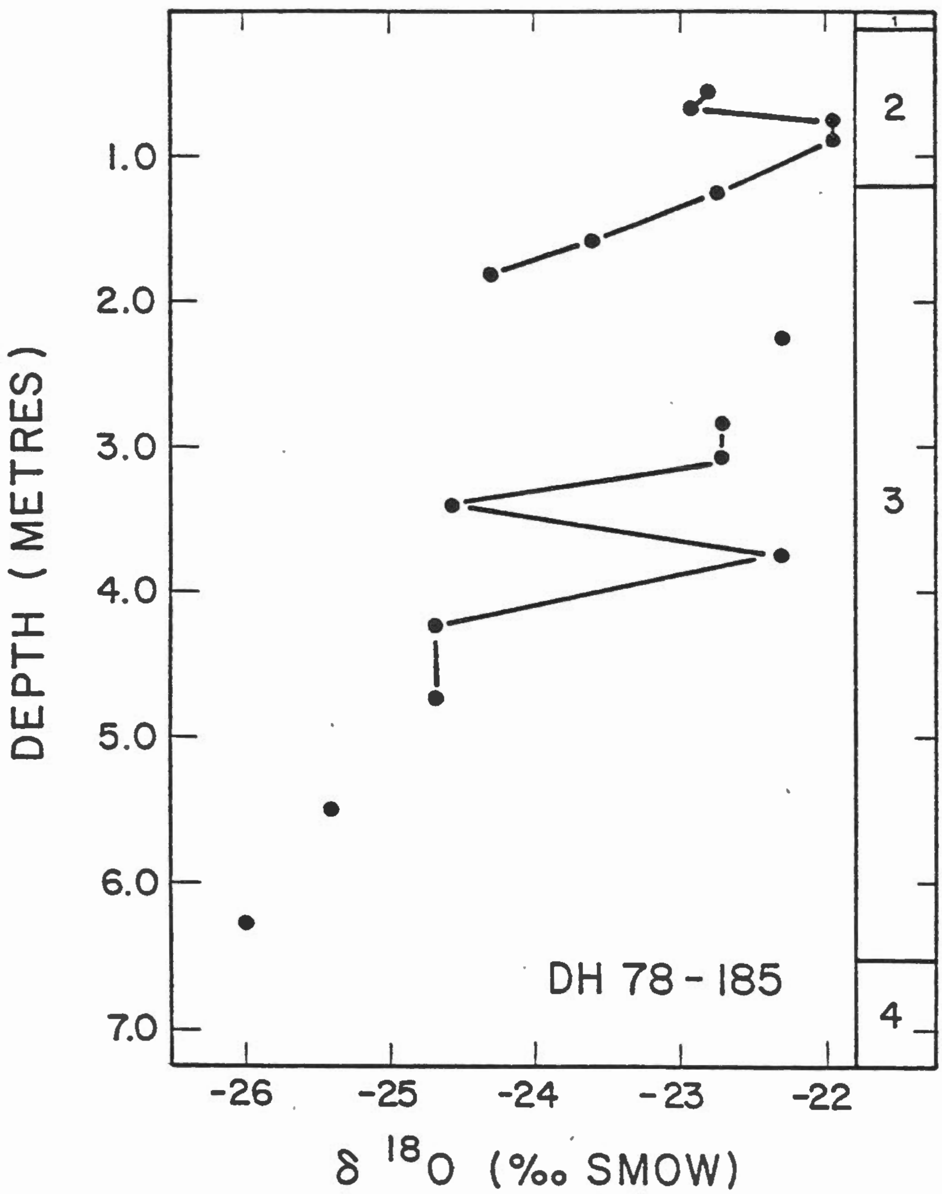

Figure 14 Variation in ^{18}O content with depth for core 78-185. Soil types are: 1 - peat, 2 - organic silt, 3 - clay silt, 4 - ice & clay silt.

those reported by the authors (Fritz and Michel 1977) for permafrost waters contained in fine grained soils of the central Mackenzie Valley. It is possible that deeper samples would have yielded water with isotope contents similar to the -31 ‰ reported for other cores in the northern portion of the Mackenzie Valley and Mackenzie Delta.

In contrast to the isotope profile of borehole 78-185, the oxygen-18 contents of borehole 78-189 display a shift to more positive values with depth (Figure 15). The isotope values of the waters in the lower portion of the core are only slightly more positive than the average shallow groundwater values and the shift is apparent primarily because of the overlying negative trend. If the isotope contents of the waters in the lower portion of the core are related to a climatically warmer period such as the Hypsithermal, then the overlying waters which are isotopically more negative must be related to a post-Hypsithermal event. It could be possible that the lower waters represent part of a young groundwater system which has recently frozen, but this is considered to be unlikely because of the fine grained soil and the location of the borehole on a broad flat plain.

Samples from borehole 78-115, located along the northern section of the Klondike Highway near McQuesten, also yielded waters with oxygen-18 contents higher than the normal range for shallow groundwaters. As shown in Figure 16, the isotopes display a gradual shift to more positive values with

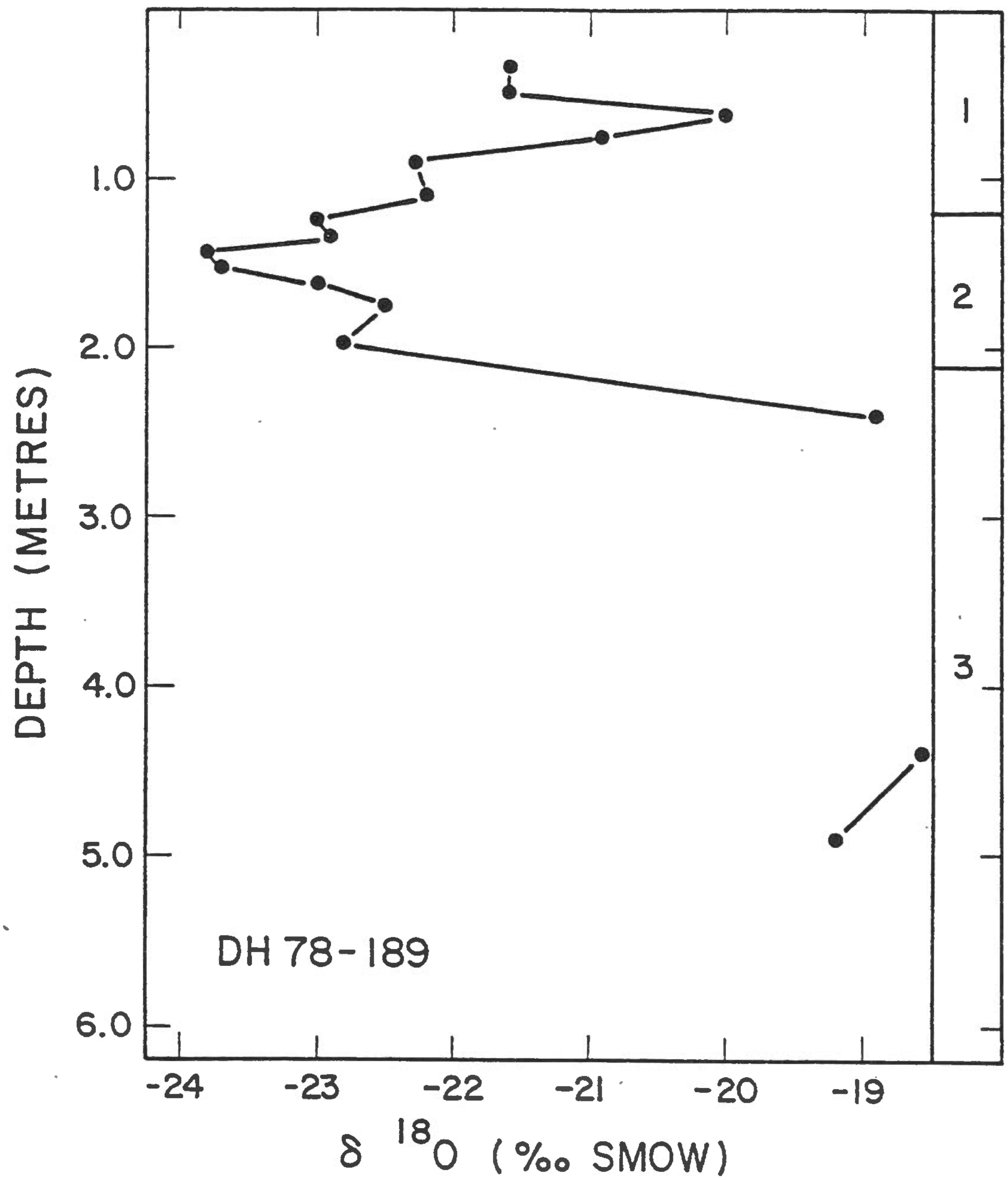

Figure 15 Variation in ^{18}O content with depth for core 78-189. Soil types are: 1 - peat, 2 - organic silt, 3 - clay silt.

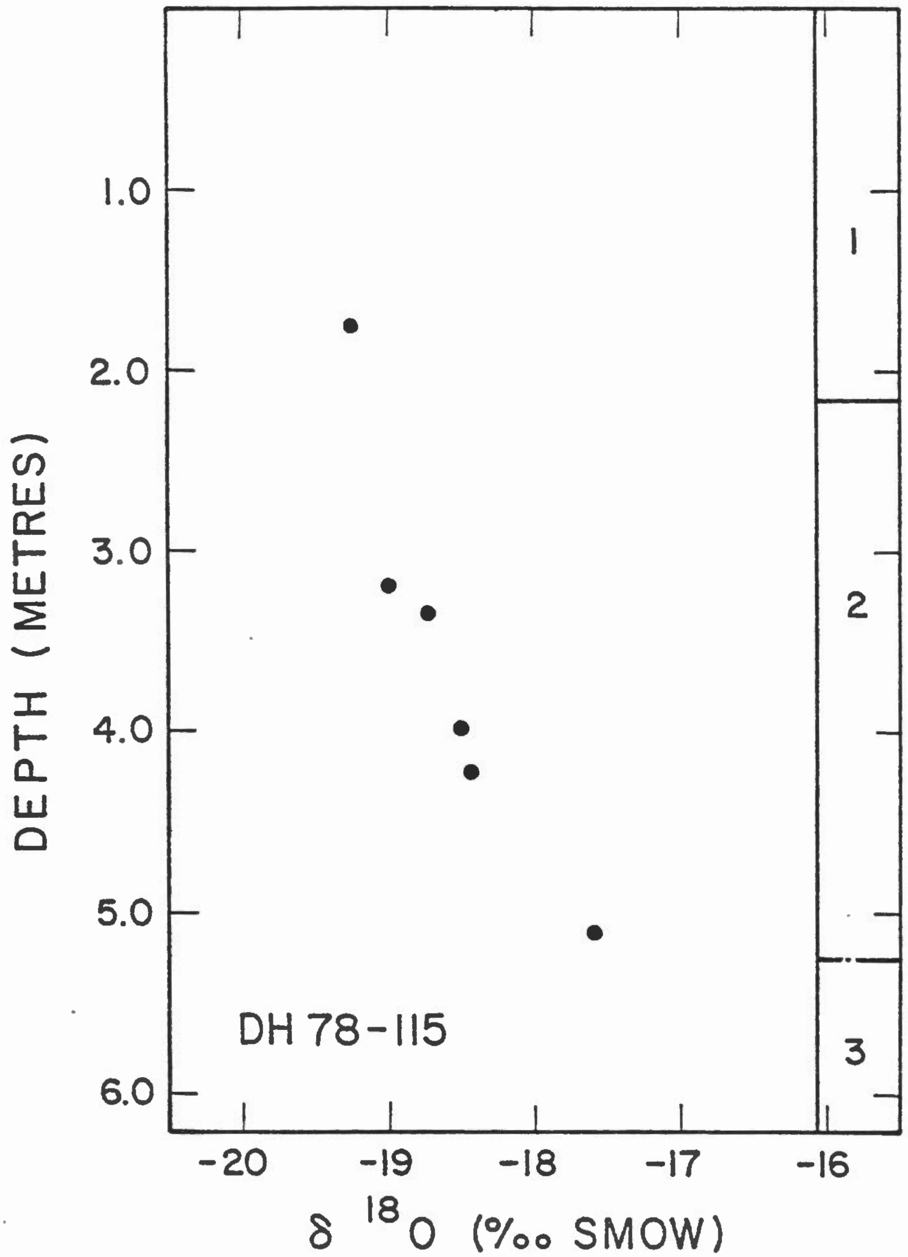

Figure 16 Variation in ^{18}O content with depth for core 78-115. Soil types are: 1 - peat, 2 - silty sand, 3 - gravel.

depth. An examination of the isotope data reveals that other boreholes in this section of the Yukon (for example 78-119) also display slight positive shifts with depth. The two shallow groundwater samples collected in this area have an average oxygen-18 content of -20 $^{0}/oo$. These shifts are relatively small and are still poorly defined at present. Therefore, on the basis of the present data, it is impossible to determine whether these waters are preserved from a warmer climatic period or represent variation within modern groundwaters.

Although incomplete, cores 78-141 and 78-142 have yielded some interesting results for the boundary between the Ogilvie Mountains and the Eagle Plain. Borehole 78-141 was drilled near the Ogilvie River. All of the waters extracted have oxygen-18 contents between -20 and -21 $^{0}/oo$ which is typical of shallow groundwaters. The two springs which were sampled in this area have oxygen-18 contents of -21.2 and -23.0 $^{0}/oo$. Borehole 78-142, which is located on higher ground sloping toward the river, contains waters with oxygen-18 contents of -12.2 $^{0}/oo$ near surface and -14.6 $^{0}/oo$ at depth. The near surface sample could be altered due to evaporation, but the sample at depth (19 to 19.5 metres) is more positive than almost any other sample analysed within the Yukon.

It should be noted that the stratigraphy for borehole 78-142 was reported as:

0 - 1.24 m peat and organic silt

1.25 - 1.5 m ice

1.5 - 1.9 m peat and organic silt

1.9 - 5.2 m ice

5.2 - 6.1 m organic silt

6.1 - 19.0 m ice

19.0 - 19.5 m silt

(Foothills 1978).

The sample collected at depth occurs immediately below almost 13 metres of massive ice. Unfortunately no samples were taken of the ice. However, from theory it is known that as the overlying massive ice formed, the water immediately below the ice would have become depleted in the heavy isotopes or remained the same. Therefore, the water sample collected must represent a water mass with an oxygen-18 content of at least -14.6 $^{0}/oo$. Since the present day waters are considerably depleted relative to this value, the deep water in borehole 78-142 must have infiltrated during a warmer climatic period. Similarly, the relatively positive values determined for waters in core 78-170 must also represent infiltration during a warmer period.

From the samples analysed to date, it is apparent that various ages of permafrost exist along the proposed pipeline routing. Indications of late glacial waters are present within the Mackenzie Valley while within the Yukon the deepest waters analysed appear to correspond to the Hypsithermal interval. Now that isotope contents of permafrost waters are available to serve as background data for the entire length of the Dempster Highway, it is possible to select specific sites fcr detailed coring. Initially the most inexpensive means of undertaking this work would be to analyse selective cores from the Foothills collection which are relatively complete to a depth of at least five metres. Ultimately, a drilling program at several specific sites would yield the greatest amount of informaticn.

3.3 SATURATED CLAY EXPERIMENTS

As part of the ongoing program of laboratory experimentation and investigation, experiment 15 and 16 were designed to examine the development of isotope fractionation effects due to freezing in a saturated pure clay soil. The use of clay in these experiments provides a fine grained end member condition with which to examine the mixed soils normally encountered in the field. The properties of the commercial Georgian kaolinite used are given by Ycng et al. (1979).

3.3.1 Experiment 15

For this experiment, saturated Georgian kaolinite which was allowed to soak for three days was poured into a 45 cm column. The upper 10 cm of the column was left empty to accommodate any expansion of the clay upon freezing. A thin layer of excess water formed on top of the clay prior to the start of the experiment but was not removed. Heaters were placed at both ends of the column.

During the first 75 hours of the experiment the thermal gradient was consistently less than 4°C per metre, even when the temperature dropped below 0°C. While the upper half of the column maintained isothermal conditions at a temperature of -0.6°C for the next 400 hours, the lower half of the column stabilized with a gradient of approximately 28°C per metre. At this point in time, the temperature of the top heater was gradually lowered. This resulted in a decrease in temperature in the upper half of the column with a gradient of 28°C per metre, while the temperature in the bottom half of the column decreased to -0.6°C, where isothermal conditions were formed. Overall, the temperatures within the column were relatively stable for in excess of 700 hours (Figure 17).

When the column was removed from the freezer, expansion of the clay during freezing was evident. Within the column the soil had risen 1 cm into the air space provided. The column rings were also separated by 0.3 cm at a depth of 25 cm, 1.5 cm at the 30 cm level, 0.2 cm at the 35 cm level and 0.1 cm at the 40 cm level. Overall, 8.9% expansion as a result of freezing was measured.

Massive ice formed a 2 cm thick layer on top of the clay. In addition, a thick ring of massive ice had formed around the outer edge of the column while the clay was confined to

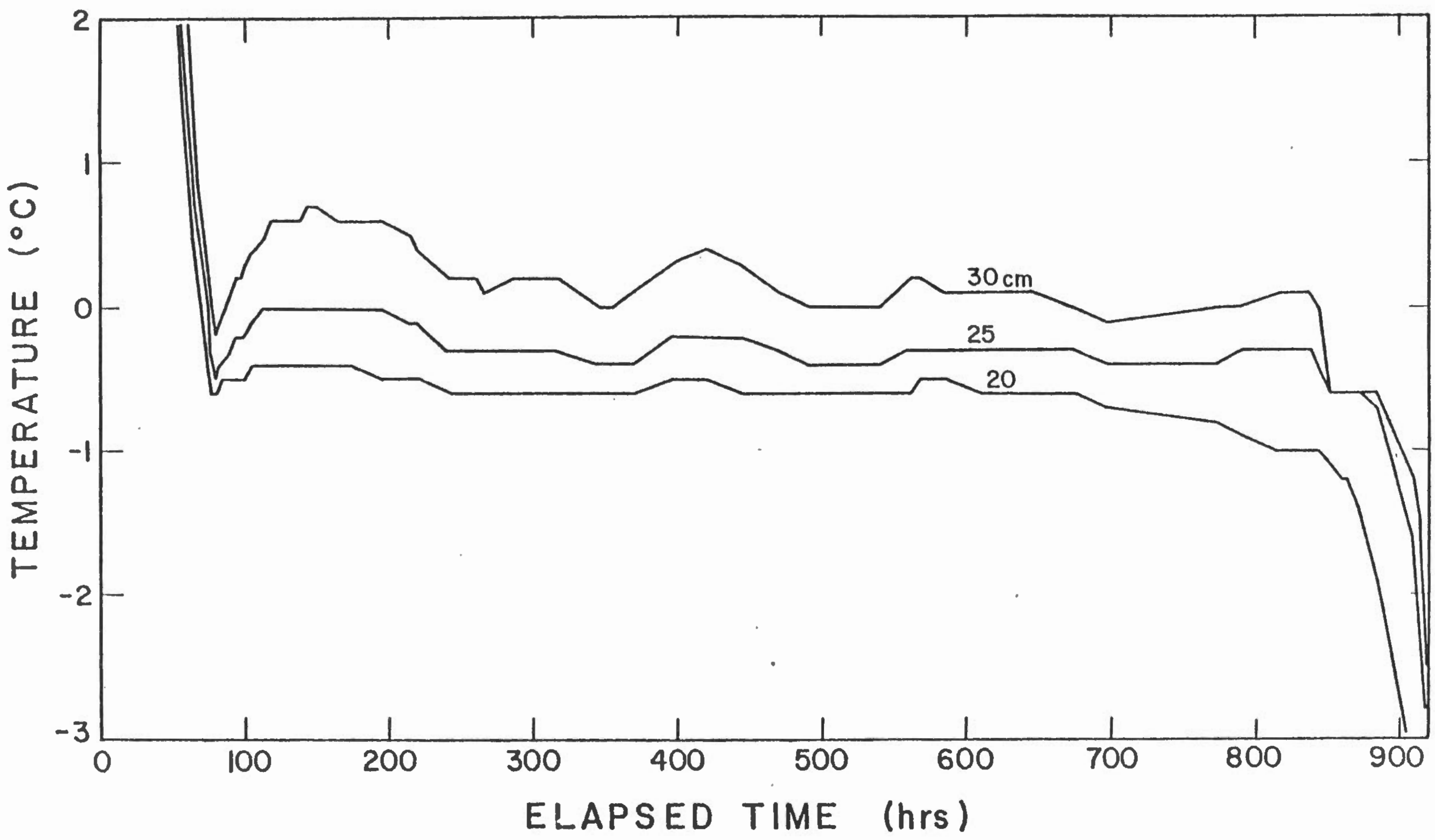

Figure 17 Temperature variations with time for experiment 15 at the 20, 25 and 30 cm levels.

the central core. The thickness of this ring decreased from 2.5 cm at the top of the column to less than 0.2 cm at a depth of 27 cm. In the upper section of this ice, vertical bubble trains curved outward and became horizontal within 0.7 cm of the wall. From this evidence, it was apparent that a significant amount of freezing occurred from the side of the column inward. Within the clay core, ice lenses up to 0.5 cm in thickness were horizontally oriented except near the edges where angles of up to 30° were noted. The size of the ice lenses decreased with depth.

3.3.2 Experiment 16

The setup for this experiment was identical to that of experiment 15. Saturated Georgian clay ws poured into the column with a 10 cm air space kept at the top for expansion. As shown in Figure 18, the temperature was decreased rapidly during the first 75 hours of the experiment and then stabilized for the next 700 hours. During that time, the thermal gradients were similar to those in the previous experiment as were the isothermal conditions at a temperature of -0.6°C. The difference between the two experiments is that experiment 16 was terminated shortly after the zero degree isotherm advanced below a depth of 25 cm.

Dissection of the column revealed 2 cm of clear ice capping the soil and a ring of massive ice around the central core of clay, as described for experiment 15. In this ex-

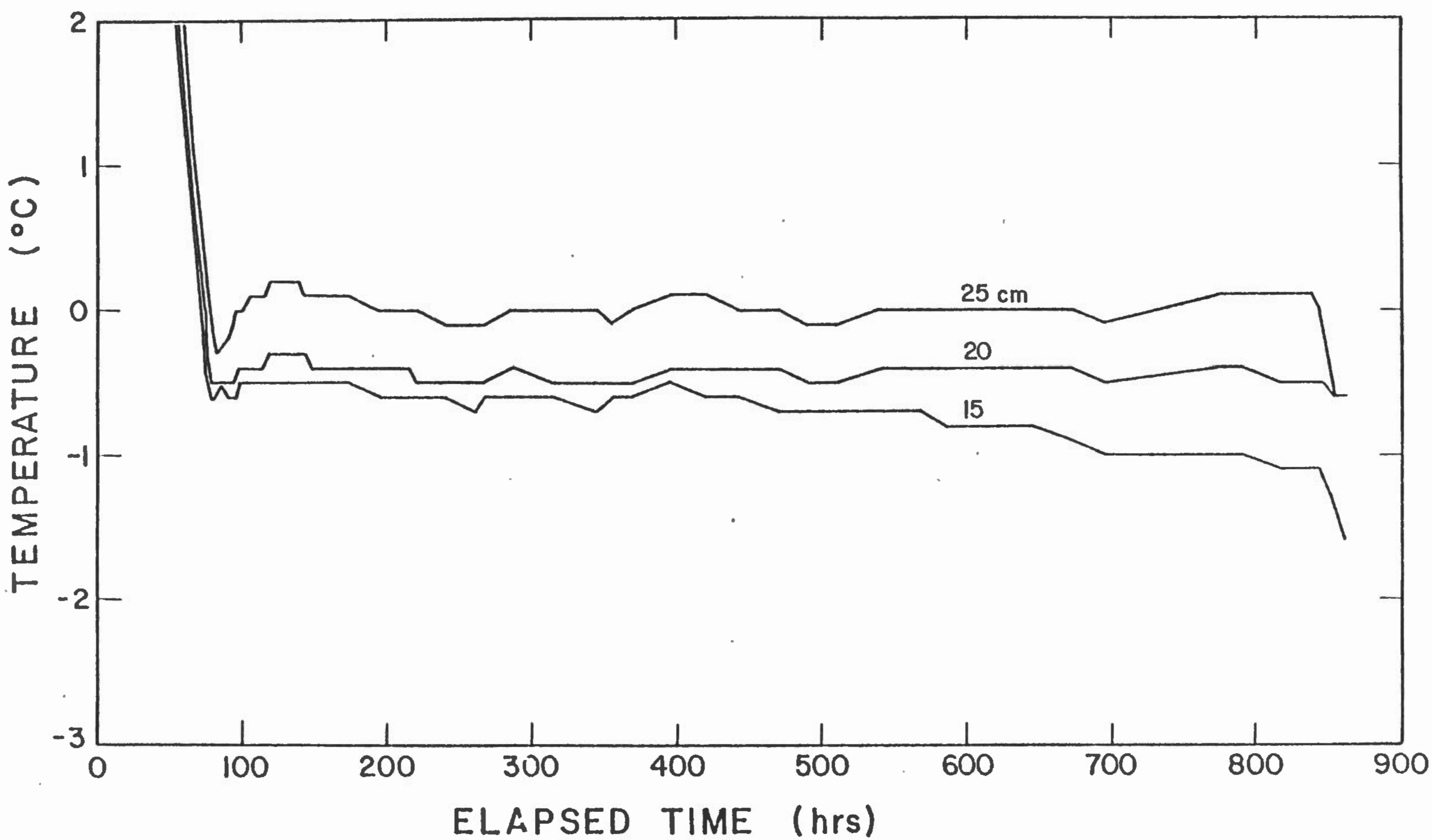

Figure 18 Temperature variations with time for experiment 16 at the 15, 20 and 25 cm levels.

periment, the soil was solidly frozen to a depth of 23 cm. Immediately below the frozen section, small razor blade ice crystals were separated by unfrozen clay. The clay below a depth of 25 cm was cold but unfrozen. In order to examine isotope variability as a result of the downward migration of the freezing front, the massive ice and clay core of each 5 cm interval were sectioned as one sample.

3.3.3 Discussion

A major achievement of experiments 15 and 16 was the extensive formation of segregated ice throughout the frozen clay. Due to a problem with freezing from the sides of the columns, most of the massive ice formed as an outer ring, while the clay was concentrated within the central core. This segregation demonstrates that the water migrated toward the colder walls during freezing.

To examine the isotope distribution in both the clay and the segregated ice ring, separate samples were collected in experiment 15. The isotope contents listed in Table 3 clearly demonstrate preferential enrichment of the heavy isotopes in the ice, while the residual water within the clay became depleted. As shown in Figure 19, the heavy isotope content of the clay core gradually increases with depth as the amount of massive ice decreases. The largest fractionation detected occurs at the top of the column where the amount of ice is greatest. Both the oxygen-18 and deuterium

Table 3 : Isotope and moisture data for experiment 15.

Sample	Depth (cm)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	M.C. (%)
Tap Water	-	-11.1	-72	-
Coln #15	-	-11.3	-76	-
15-1I	9-10	-10.8	-75	-
15-2 upper	10-12.5	-10.5	-72	-
15-2c	11-15	-13.1	-87	69
15-2 lower	12.5-15	-10.5	-70	-
15-3I	15-20	-10.4	-67	-
15-3c	15-20	-12.0	-81	137
15-4I	20-25	-10.2	-70	-
15-4c	20-25	-12.1	-80	203
15-5I	25-30	-10.5	-72	-
15-5c	25-30	-11.7	-80	217
15-6	30-35	-11.7	-77	56
15-7	35-40	-11.2	-75	63
15-8	40-45	-11.4	-78	116
15-9w	45	-11.3	-77	-

I represents massive ice usually around the edge

c indicates central core of column

w indicates excess liquid water

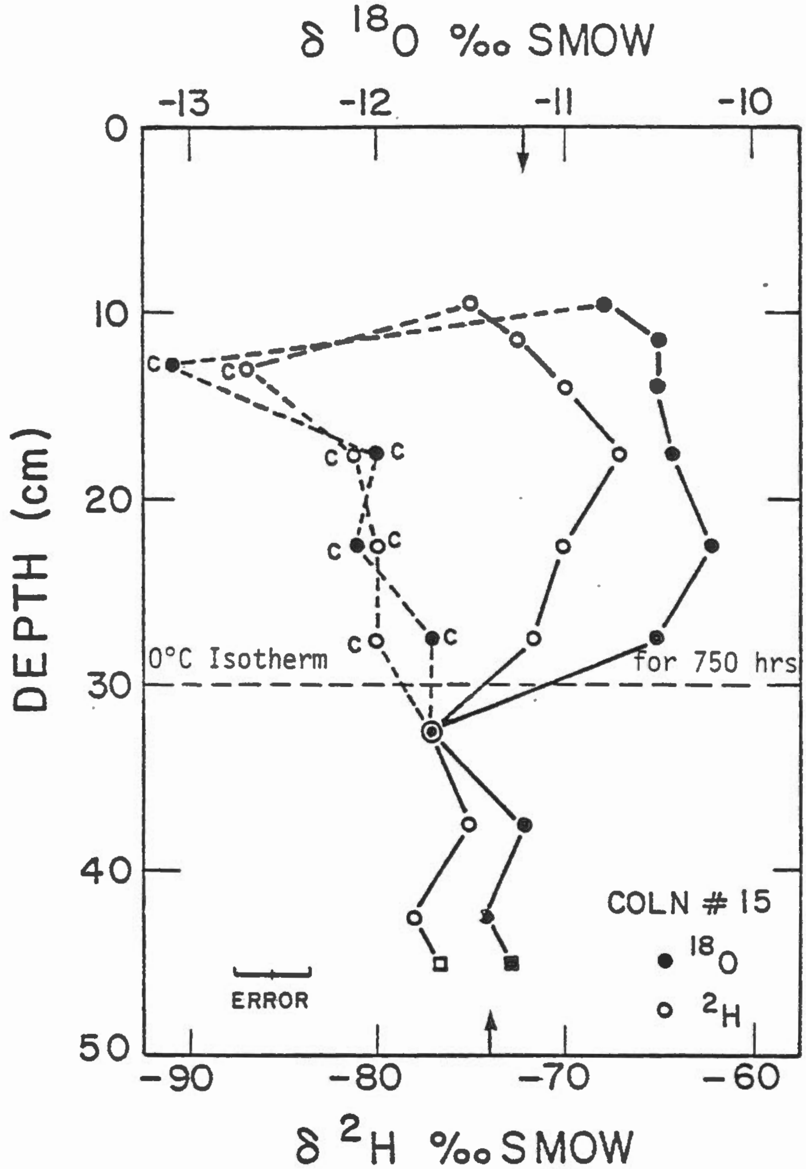

Figure 19 Variation in ^{18}O and ^{2}H contents with depth in column 15. Arrows indicate initial isotope contents of the water. Square symbols represent isotope contents of excess water. 'C' represents material from the central core of the column.

isotopes display similar trends and neither of the isotopes produced fractionations greater than those predicted by theory for the pure ice-water system.

Separation of the massive ice and clay into individual samples makes it difficult to detect overall variations with depth as a result of the stabilization of the freezing front. There appears to be a depletion of the heavy isotopes in the first interval that does not contain the ice ring (30-35 cm) which would correspond to the zone immediately beneath the freezing front where such a depletion would be expected.

In experiment 16, the massive ice and clay core of each 5 cm interval was sectioned as one sample, so that variations in the isotope contents as a result of the downward migration of the freezing front could be studied. Examination of the isotope data, listed in Table 4 and plotted in Figure 20, reveals a systematic pattern of variations that are recorded by both of the stable isotopes. The top layer of ice is enriched in the heavy isotopes relative to that of the underlying soil. No major accumulation peak is visible within the frozen section of the column. However, a large negative peak immediately beneath the frozen zone is clearly visible. The remainder of the column, which was unfrozen, displays a gradual but continuous shift to more negative values with depth.

Table 4: Isotope and moisture data for experiment 16.

Sample	Depth (cm)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	M.C. (%)
Tap Water	-	-11.1	-72	-
Coln #16	-	-11.3	-76	-
16-1I	9-11	-9.9	-70	-
16-2	11-15	-11.7	-76	80
16-3	15-20	-10.9	-77	183
16-4 F1	20-21.5	-11.0	-79	385
16-4 F2	21.5-23	-11.0	-80	481
16-4u	23-25	-12.0	-85	77
16-5u	25-30	-11.1	-78	69
16-6u	30-35	-11.3	-79	90
16-7u	35-40	-11.6	-80	97
16-8u	40-45	-11.6	-84	84
16-9w	45	-	-82	-

I represents massive ice

c indicates central core of column

w indicates excess liquid water

u represents unfrozen material

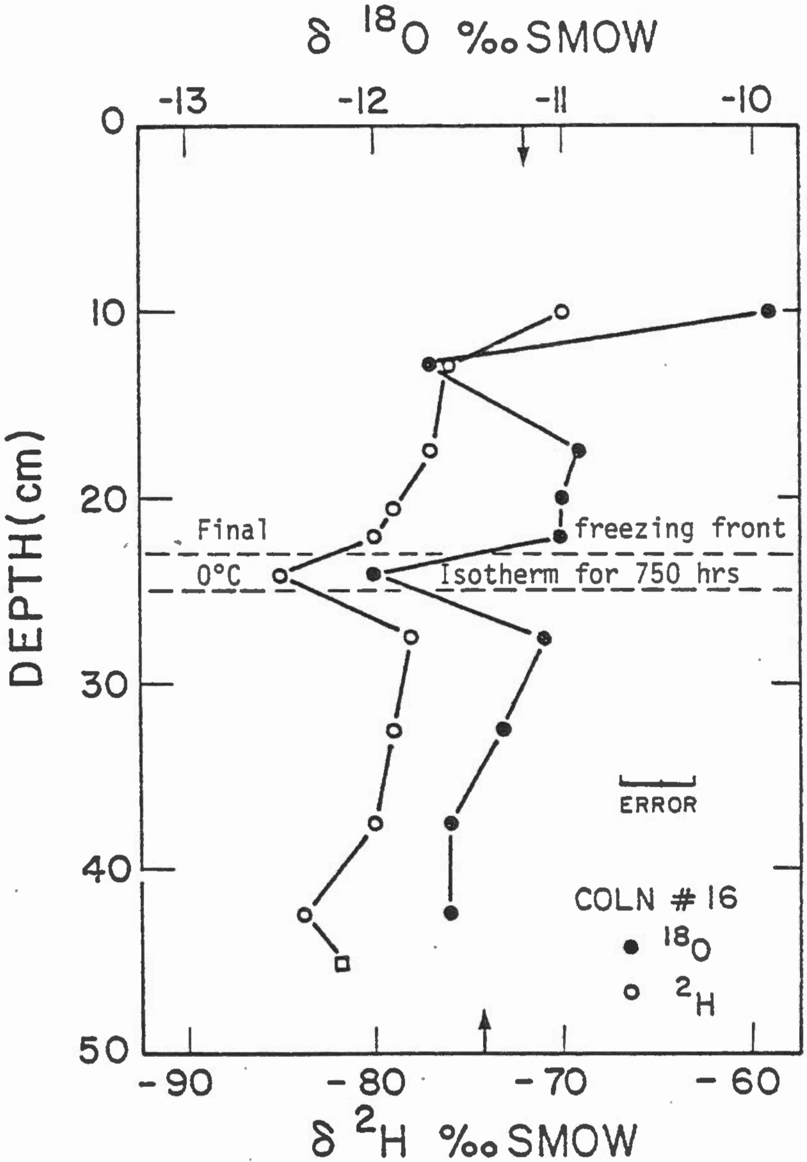

Figure 20 Variation in ^{18}O and ^{2}H contents with depth in column 16. Arrows indicate initial isotope contents of the water. Square symbol represents isotope content of excess water.

From these two experiments, it is evident that extensive ice segregation can occur in saturated clay-rich soils. As this segregation developed, oxygen-18 and deuterium were preferentially incorporated into the ice structure, while oxygen-16 and hydrogen remained in the residual liquid. Although the amount of massive ice formed around the edge of the columns was large, fractionation of the isotopes between the massive ice and the ice in the clay core did not exceed that predicted by theory for the ice-water system. Furthermore, when sampling was conducted on a regular interval basis, regardless of soil composition or ice content, the isotope profiles displayed only small, single-sample variations. These variations are similar in character to those developed in the silt experiments (Michel and Fritz 1980) in which the freezing front was stabilized for a considerable period of time.

Throughout the experimental program, fractionations have been developed as a result of freezing. These fractionations were most easily formed in fine grained soils, but some variations were generated in the sands. All of the isotope fractionations generated in saturated soils were confined to small, single-sample intervals. The fractionations developed in the unsaturated soils and the confined water columns, although sizeable, cannot be sustained for large depth intervals. Therefore, it would appear to be impossible to generate major isotope shifts that can be maintained with depth, through the fractionation of isotopes during freezing.

Chapter IV

SUMMARY AND CONCLUSICNS

4.1 ILLISARVIK

During the current contract period the work at Illisarvik has focussed on determining in detail the stratigraphy and age of sediments in the lake basin, and on the distribution of deuterium in the pore waters.

The stratigraphy of the lake basin can be subdivided into three main units. The lowest unit encountered during drilling is a clean fine to medium grained deltaic sand. Overlying this sand is a 1 to 2 metre thick widespread stony clay-silt unit occasionally containing trace amounts of organic fragments. This unit was deposited during the Late Wisconsin and is described by the authors as a till. The till layer is overlain by up to 3 metres of organic-rich silt. Beyond the edge of the lake, the organic silts are covered by modern peat. Radiocarbon dating of the lake silts indicate that the lake originally formed approximately 9,000 years ago and flooded most of the present lake basin by at least 7,000 years ago. The lake has existed continuously since it originally formed, but has varied in size and extent. During the warmer period of the Hypsithermal, it is believed that the lake was part of a much larger lake which also encompassed the lake basin to the south of Illisarvik.

This larger lake was drained approximately 2000 years ago when coastal erosion breached the western edge of the southern basin.

Deuterium profiles for various permafrost conditions are very similar to the oxygen-18 profiles and by themselves do not yield additional information concerning the history of the permafrost waters. However, when deuterium and oxygen-18 are plotted against one another, it appears that characteristic slope values can be determined for various permafrost conditions.

4.2 DEMPSTER HIGHWAY

Water extracted from core samples collected along the entire length of the Dempster and Klondike Highways have been analysed for their oxygen-18 contents. Many of the samples appear to contain relatively young water with isotope contents similar to modern shallow groundwaters throughout the region. These waters generally have oxygen-18 contents in the range of -20 to -23 $^{0}/_{00}$. At depth, several cores contained waters with decreasing concentrations of oxygen-18 in comparison to the shallower waters. This shift to more negative values with depth was best defined in core 78-185 from the northern Mackenzie Valley and is comparable to previously described shifts within the Mackenzie Valley.

Close to core 78-185, core 78-189 displayed a slight positive shift which was characteristic of most cores at depth. Several samples from the Eagle Plain - Ogilvie Mountains area yielded waters from depth with oxygen-18 contents in the -12 to -15 $^{0}/oo$ range. These waters are definitely representative of warmer climatic conditions and have been preserved in a variety of settings. Unfortunately, the wide scattering of the samples analysed have not permitted a detailed examination of permafrost histories along the proposed pipeline routing.

4.3 COLUMN EXPERIMENTS

In order to examine fractionations as a result of freezing in pure clay soils, two experiments were undertaken using saturated kaolinite. Extensive ice segregation occurred in the columns but the isotope fractionations did not attain the equilibrium values determined for the pure ice-water system. When the massive ice and soil from each layer were considered as one combined sample, only single-sample variations were detected.

Throughout the experimental program, fractionations have been developed as a result of freezing. These fractionations, which were most easily developed in fine grained soils, never attained the equilibrium ice-water values and it would appear that the presence of soil in the system effectively reduces the degree to which the fractionations can develop. It would also appear to be impossible to generate major isotope shifts that can be maintained with depth, through the fractionation of isotopes during freezing in the soil-ice-water system.

4.4 SUGGESTIONS FOR CONTINUED WORK

The initial investigations at Illisarvik of deuterium-oxygen-18 relationships has indicated that it may be possible to differentiate between various permafrost processes on the basis of different slope values. To determine whether characteristic slopes values do exist for various permafrost conditions, it is suggested that research be undertaken to examine permafrost and permafrost-related phenomena which are well defined in terms of their formation and growth.

The reconnaissance isotope survey undertaken of permafrost along the Dempster and Klondike Highways indicates that various ages of permafrost have been preserved. Selection of deep well-sampled cores from the material provided by Foothills Pipe Lines (Yukon) Ltd. would permit an initial investigation of specific sites along various sections of the highways. Ultimately, a separate detailed drilling program of interesting sections should be undertaken to provide continuous core material from depth. This program should probably be concentrated on the Eagle Plain region as part of an examination of permafrost waters in a non-glaciated area. Any shift in isotope abundance within such an area must be due to changes in climate (temperature) and would eliminate glacial meltwater as a possible source for the very negative waters found at depth in the Mackenzie Delta.

In addition, the following specific areas of research would be beneficial in developing a fuller understanding of the permafrost waters and could lead tc a better understanding of other permafrost-related phenomena:

1. A study of a continuously sampled core through the full thickness of old stable permafrost.
2. A study of permafrost, precipitation, groundwater and glacial meltwater immediately downslope from a present-day glacier.
3. A detailed study of shallow permafrost waters and average annual isotope contents in precipitation at several Arctic localities.
4. A comparison study of sub-sea permafrost waters and land-based permafrost waters.
5. An isotope study of permafrost-related features such as massive buried ice, pingos, frost blisters and ice wedges.
6. A continuation of the laboratory studies, but with better experimental control than was attained in this program.

REFERENCES

Boulton, G.S., 1971. Till genesis and fabric in Svalbard, Spitsbergen. In: Till: A Symposium (R.P. Goldthwait, ed.), Ohio State University Press, pp. 41-72.

Dansgaard, W., Johnsen, S.J., Clausen, H.B. and Langway, Jr., C.C. 1971. Climatic record revealed by the Camp Century ice core. In: Late Cenozoic Glacial Ages (K.T. Turekian, ed.), Yale University Press, pp. 37-56.

Foothills Pipe Lines (Yukon) Ltd., 1978. Dempster lateral drilling program. Prepared by Klohn Leonoff Consultants Ltd., 2 volumes.

Fritz, P. and Michel, F.A., 1977. Environmental isotopes in permafrost related waters along two proposed pipeline routes. Report on Project No. 606-12 for Canada Department of Energy, Mines and Resources, File No. 05SU.23235-6-0681, Waterloo Research Institute, University of Waterloo, 51 p.

Hitchon, B. and Krouse, H.R., 1972. Hydrogeochemistry of the surface waters of the Mackenzie River drainage basin, Canada - III. Stable isotopes of oxygen, carbon and sulphur. Geochim. Cosmochim. Acta, Vol. 36, pp. 1337-1357.

Hunter, J.A., MacAulay, H.A., Gagne, R.M., Burns, R.A., Harrison, T.E. and Hawkins, J.P., 1978. Hydraulic jet drilling operations at Illisarvik-Geological and geophysical logs. In: Drained Lake Experiments for Investigation of the Growth of Permafrost in the Western Arctic-A Progress Report (J.A. Hunter, ed.), Permafrost Subcommittee, Associate Committee on Geotechnical Research, National Research Council of Canada, pp. 7-21.

Karrow, P.F. and Anderson, T.W., 1975. Palynological study of lake sediment profiles from southwestern New Brunswick: Discussion. Can. J. Earth Sci., Vol. 12, pp. 1808-1812.

Mackay, J.R., 1963. The Mackenzie Delta area, N.W.T., Dept. Mines Tech. Survey, Geogr. Branch, Ottawa, Memoir 8, 202 p.

Mackay, J.R., 1967. Underwater patterned ground in artificially drained lakes, Garry Island, N.W.T. Geogr. Bull., Vol. 9, pp. 33-44.

Mackay, J.R., 1973. Winter cracking (1967-1973) of ice-wedges, Garry Island, N.W.T. Geol. Surv. Can., Paper 73-1B, pp. 161-163.

Mackay, J.R., Rampton, V.N. and Fyles, J.G., 1972. Relic Pleistocene permafrost, western arctic, Canada. Science, Vol. 176, pp. 1321-1323.

Michel, F.A., 1982. Isotope investigations of permafrost waters in northern Canada. Unpublished Ph.D. thesis, University of Waterloo.

Michel, F.A. and Fritz, P., 1978a. Laboratory studies to investigate isotope effects occurring during the formation of permafrost. Report on Project No. 606-12-02 for Canada Department of Energy, Mines and Resources, File No. 02SU.23235-70768, Waterloo Research Institute, University of Waterloo, 43 p.

Michel, F.A. and Fritz, P., 1978b. Environmental isotopes in permafrost related waters along the Mackenzie Valley corridor. Proc. Third International Conference on Permafrost, Edmonton, Alta., Canada, National Research Council, Vol. 1, pp. 207-211.

Michel, F.A. and Fritz, P., 1979. Laboratory and field studies to investigage isotope effects occurring during the formation of permafrost. Report on Project No. 606-12-03 for Canada Department of Energy, Mines and Resources, Serial No. OST78-00092, Waterloo Research Institute, University of Waterloo, 65 p.

Michel, F.A. and Fritz, P., 1980. Laboratory and field studies to investigage isotope effects occurring during the formation of permafrost, Part 2. Report on Project No. 606-12-04 for Canada Department of Energy, Mines and Resources, Serial No. OSU79-00064, Waterloo Research Institute, University of Waterloo, 139 p.

Michel, F.A. and Fritz, P., 1981. Laboratory and field studies to investigate isotope effects occurring during the formation of permafrost, Phase 3. Report on Project No. 606-12-05 for Canada Department of Energy, Mines and Resources, Serial No. OSU80-00079, Waterloo Research Institute, University of Waterloo, 57 p.

Michel, F.A. and Fritz, P., in press. Significance of isotope variations in permafrost waters at Illisarvik, N.W.T. Proc. Fourth Canadian Permafrost Conference, Calgary, Alta.

Rampton, V.N., 1971. Quaternary geology, Mackenzie Delta and Arctic Coastal Plain, District of Mackenzie. Geol. Surv. Can., Paper 71-1A, pp. 173-177.

Ritchie, J.C. and Hare, F.K., 1971. Late-Quaternary vegetation and climate near the arctic tree line of northwestern North America. Quat. Res., Vol. 1, pp. 331-342.

Suzuoki, T. and Kimura, T., 1973. D/H and $^{18}O/^{16}O$ fractionation in ice-water system. Mass Spectroscopy, Vol. 21, pp. 229-233.

Yong, R.N., Cheung, C.H. and Sheeran, D.E., 1979. Prediction of salt influence on unfrozen water content in frozen soils. Engineering Geology, Vol. 13, pp. 137-155.

Appendix A

STABLE ISOTOPE DATA FOR CORES FROM ILLISARVIK, N.W.T.

79-2

SAMPLE NO.	DEPTH (CM)	$\delta^{18}O$ (°/₀₀ SMOW)	$\delta^{2}H$ (°/₀₀ SMOW)
1	0-10	-19.3	-150
2	10-20	-20.0	-154
3	20-30	-20.0	-155
4	30-40	-19.9	-152
5	40-50	-19.2	-148
8	70-80	-21.1	-164
10	90-100	-21.5	-167
12	110-120	-21.8	-170
16	150-160	-22.6	-174
18	170-180	-22.9	-175
20	190-200	-22.9	-176
22	210-220	-21.7	-167
24	230-240	-20.4	-164
26	250-260	-18.3	-151
28	270-280	-16.5	-138
30	290-300	-16.8	-144
34	330-340	-16.5	-141

79-9

SAMPLE NO.	DEPTH (CM)	$\delta^{18}O$ (°/oo SMOW)	$\delta^{2}H$ (°/oo SMOW)
1	0-5	-18.0	-144
4	15-20	-15.5	-128
10	45-50	-14.0	-119
13	60-65	-14.8	-119
16	75-80	-16.1	-133
19	90-95	-18.8	-143
22	105-110	-19.5	-145
25	120-125	-20.6	-158
28	135-140	-21.7	-167
31	150-155	-21.8	-164
34	165-170	-21.7	-169
37	180-185	-21.2	-166
40	195-200	-20.9	-159
42	205-210	-20.6	-166
44	215-220	-20.6	-163
48	235-240	-19.0	-157
51	250-255	-17.9	-153
60	295-300	-22.2	-181
67	330-335	-23.4	-194

79-14

SAMPLE NO.	DEPTH (CM)	$\delta^{18}O$ (‰ SMOW)	$\delta^{2}H$ (‰ SMOW)
1	0-10	-18.7	-142
3	30-40	-20.9	-155
4	40-47.5	-25.3	-198
7	57.5-67.5	-22.6	-173
9	87.5-97.5	-20.2	-157
11	107.5-117.5	-21.8	-171
14	147.5-157.5	-27.7	-221
16	167.5-177.5	-26.0	-195
19	197.5-207.5	-23.0	-174
22	227.5-237.5	-17.9	-143
24	247.5-257.5	-25.9	-202
27	277.5-287.5	-22.5	-175
28	287.5-297.5	-19.4	-154
29	297.5-307.5	-18.6	-147
35	357.5-367.5	-17.8	-140
44	447.5-457.5	-17.2	-135
45	457.5-467.5	-16.9	-136
49	497.5-507.5	-16.2	-130
51	517.5-527.5	-15.0	-124

79-IW#2

SAMPLE NO.	DEPTH (CM)	$\delta^{18}O$ (°/₀₀ SMOW)	$\delta^{2}H$ (°/₀₀ SMOW)
3	10-15	-13.9	-121
8	35-40	-13.6	-123
12	55-60	-14.7	-129
16	75-80	-15.7	-135
17	80-85	-21.7	-168
18	85-90	-22.8	-178
20	95-100	-22.2	-171
21	100-105	-23.2	-180
23	110-115	-20.3	-158
24	115-116.5	-15.6	-128
25	116.5-125	-16.6	-134
31	150-154	-14.1	-125

Appendix B

STABLE ISOTOPE DATA FOR CORES AND GROUNDWATERS FROM THE PROPOSED DEMPSTER HIGHWAY PIPELINE

GROUNDWATER SAMPLES

SAMPLE NO.	LOCATION	TYPE	$\delta^{18}O$ (°/°° SMOW)
16	Twin Lake Campground (30 m from lake)	Handpump	-18.1/-18.2
17	Carmacks Campground (50 m from Yukon River)	Handpump	-20.2
18	Minto Landing Campground	Handpump	-19.9
21	Dempster Hwy. KM 86 (North Fork Pass)	Spring	-22.1
22	Dempster Hwy. KM 171	Sulphur Spring	-23.0
23	Dempster Hwy. KM 271 (El. 800 m)	Spring	-21.2
25	Dempster Hwy. KM 461 (N.W.T.)	Spring	-21.4
31	Eagle Plains Hotel	Tap	-21.5
32	Top of the World Hwy. KM 52	Spring	-20.4/-20.3

PIPE LINE CORES

CORE NO.	SAMPLE NO.	DEPTH (M)	$\delta^{18}O$ (°/°° SMOW)
78-1	0	0.0-0.1	-14.4
	7A	2.0-2.5	-22.7
78-14	17	11.5-12.0	-20.0
78-63	4	1.5-2.0	-22.7
78-107	2A	0.25-0.4	-19.9
	2B	0.4-0.6	-19.1
78-109	7	1.8-2.05	-21.3
	16	4.75-5.0	-19.4
78-113	10	2.7-2.85	-20.5
78-115	6	1.65-1.85	-19.3/-19.2
	11A	3.15-3.25	-19.0
	11B	3.25-3.35	-18.7
	14	3.9-4.05	-18.5
	15	4.2-4.25	-18.4
	18	5.0-5.25	-17.6
78-116	6	1.45-1.6	-16.2
78-119	8A	2.0-2.15	-19.4
	8B	2.15-2.3	-19.3
	18A	5.2-5.35	-18.7
	18B	5.35-5.5	-18.9
	18C	5.5-5.65	-18.6/-18.4
	22	6.85-7.05	-18.4
78-122	14	4.5-4.75	-15.2
78-127	4	0.8-1.1	-20.9
	8A	2.0-2.15	-20.9
	8B	2.15-2.3	-21.0
	9	2.3-2.6	-20.3
	14	5.7-6.0	-21.2/-21.2
78-128	16A	4.75-4.95	-20.8
	16B	4.95-5.15	-21.3
78-129	3	0.85-1.1	-20.2
78-131	13	3.4-3.65	-20.5
	15A	3.9-4.05	-19.4
	15B	4.05-4.2	-19.2
78-134	5A	1.65-1.75	-20.1
	5B	1.75-1.85	-20.7
	5C	1.85-1.95	-19.5
	5 Frost	--	(-16.2)
78-135	2A	0.2-0.3	-22.7
	2B	0.3-0.4	-22.1
	2C	0.4-0.55	-20.0
78-139	1	0.0-0.2	-16.6
	5A	1.3-1.45	-19.5/-19.5
	5B	1.45-1.6	-19.0
78-141	5A	1.35-1.5	-20.9
	5B	1.5-1.65	-20.3
	12A	3.3-3.4	-20.0
	12B	3.4-3.5	-20.1
	13	3.5-3.65	-20.5

PIPE LINE CORES (continued)

CORE NO.	SAMPLE NO.	DEPTH (M)	$\delta^{18}O$(°/₀₀SMOW)
78-142	1	0.5-1.0	-12.2
	7(6)	19-19.5	-14.5/-14.7
78-147	5A	2.2-2.3	-24.0
	5B	2.3-2.4	-24.1
	5C	2.4-2.55	-24.4
78-148	1	0.0-0.2	-16.5
	4A	1.2-1.35	-20.7
	4B	1.35-1.5	-21.4
	8	2.35-2.55	-20.0
	11	3.05-3.4	-24.8
	16	6.0	-16.6
78-151	9	3.85-4.1	-22.4
78-153	2A	0.35-0.55	-20.5
	2B	0.55-0.7	-21.1
	2 Frost	--	(-18.4)
78-154	5A	1.45-1.6	-21.6
	5B	1.6-1.7	-22.3
	5C	1.7-1.8	-21.1/-21.4
	5 Frost	--	(-20.1)
78-155	3	1.2-1.55	-20.8
78-156	6	1.75-2.1	-22.2
	8A	2.6-2.8	-21.6
	8B	2.8-2.95	-21.4
	8 Frost	--	(-18.3)
	10A	3.9-4.0	-20.5
	10B	4.0-4.15	-21.2
	10 Frost	--	(-18.9)
	12	4.85-5.15	-18.7
	16	6.75-7.05	-19.8
	16 Frost	--	(-19.0)
78-158	2A	0.5-0.65	-22.8
	2B	0.65-0.8	-23.0/-22.6
	8	3.85-4.1	-21.2
78-159	3A	1.0-1.2	-23.0
	3B	1.2-1.35	-22.3/-22.1
	3 Frost	--	(-22.2)
78-160	7A	5.1-5.3	-19.9
	7B	5.3-5.45	-19.1
78-162	3	1.0-1.2	-21.2
	8	3.3-3.65	-20.1
78-166	7A	4.8-4.9	-19.7/-20.0
	7B	4.9-5.0	-21.4
	7C	5.0-5.1	-20.0
78-168	2A	0.6-0.7	-21.4
	2B	0.7-0.8	-21.6
	2C	0.8-0.95	-21.8
	7	3.55-3.9	-23.0

PIPE LINE CORES (continued)

CORE NO.	SAMPLE NO.	DEPTH (M)	$\delta^{18}O$(°/oo SMOW)
78-169	8	3.8-3.9	-18.5
78-170	1	0.0-0.2	-15.2
	2	0.25	-13.6
	9	4.0-4.5	-12.1
78-172	5A	1.8-1.95	-20.3
	5B	1.95-2.1	-19.7
78-173	8	5.7-6.0	-23.1
78-177	3	1.2-1.5	-22.2
78-178	3	0.65-1.0	-21.0/-20.7
	4	1.4-1.7	-19.8
	5	2.1-2.3	-20.6
	7	2.8-3.1	-20.0
78-180	6A	2.15-2.25	-20.4/-20.3
	6B	2.25-2.35	-20.9/-20.9
	6C	2.35-2.5	-20.4
78-184	4	1.2-1.55	-23.8
	7	2.7-2.95	-20.7
78-185	3A	0.5-0.6	-22.8
	3B	0.6-0.7	-22.9
	3C	0.7-0.8	-21.9
	3D	0.8-0.9	-21.9
	4	1.0-1.5	-22.5
	4 Frost	--	(-21.9)
	5A	1.5-1.7	-23.6
	5B	1.7-1.9	-24.3
	6	2.15-2.35	-22.3
	7	2.7-3.0	-22.7
	8	3.0-3.2	-22.7
	9	3.2-3.6	-24.6
	10	3.6-3.9	-22.3
	11	4.0-4.5	-24.7
	12	4.6-4.9	-24.7
	13	5.35-5.7	-25.4
	15	6.2-6.4	-26.0
78-186	4A	0.8-0.9	-22.8
	4B	0.9-1.0	-23.1/-23.2
	4C	1.0-1.2	-22.2
78-187	3A	0.5-0.75	-20.8
	3B	0.75-1.0	-21.8
	4	0.5-1.0	-23.7/-23.5
	10A	2.85-3.0	-22.9
	10B	3.0-3.3	-22.9/-22.8
	12	3.8-4.15	-23.0

PIPE LINE CORES (continued)

CORE NO.	SAMPLE NO.	DEPTH (M)	$\delta^{18}O$(°/oo SMOW)
78-189	2A	0.3-0.4	-21.6
	2B	0.4-0.5	-21.6
	2C	0.5-0.7	-20.0
	3A	0.7-0.9	-20.9
	3B	0.9-1.1	-22.3
	3C	1.1-1.2	-22.2
	4A	1.2-1.3	-23.0/-22.9
	4B	1.3-1.4	-22.9
	4C	1.4-1.5	-23.8
	4D	1.5-1.6	-23.7/-23.7
	4E	1.6-1.65	-23.0
	4 Frost	--	(-22.8)
	5A	1.65-1.9	-22.5
	5B	1.9-2.1	-22.8
	5 Frost	--	(-21.7)
	6	2.2-2.65	-18.9
	9	4.1-4.7	-18.3
	10	4.7-5.1	-19.2
	10 Frost	--	(-17.9)
78-191	2	0.3-0.8	-20.8/-20.5
78-193	3	0.7-1.0	-22.6
78-194	9	3.7-4.0	-20.2
	9 Frost	--	(-20.3)
78-197	7	1.95-2.55	-17.2
	8	2.55-2.85	-20.3
	8 Frost	--	(-19.3)