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Laboratory and Field Studies to Investigate Isotope Effects During the Formation of Permafrost - Part II

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Earth Physics Branch Open File Number 80-11

Ottawa, Canada, 19 80

139p.

NOT FOR REPRODUCTION

Price/Prix: $39.00

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

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Abstract

Continued studies of the oxygen and hydrogen isotope distribution in permafrost soils have demonstrated the wide natural variations and related such variations to moisture migration and to the freezing process. Measurements at a recently drained lake site in the Mackenzie Delta have demonstrated isotope fractionation as permafrost aggrades. The results are supported by experiments with laboratory freezing columns.

Résumé

Des études continuelles sur la distribution isotopique de l'oxygène et de l'hydrogène dans le pergélisol ont démontré de larges variations naturelles reliées à la migration de l'eau et au processus de gel. Les données d'un lac récemment asséché situé dans le Delta du Mackenzie ont démontré le fractionnement des isotopes lors de la croissance du pergélisol. Les résultats sont supportés par des études en laboratoire utilisant des unités de congélation cylindriques.

Office of Research Administration
University of Waterloo

Incorporating The

Waterloo Research Institute

Project No. 606-12-04

Laboratory and Field Studies To Investigate Isotope Effects Occurring During The Formation of Permafrost

- PART II -

Contract Serial #OSU79-00064

Final Report

Prepared for
Department of Energy, Mines and Resources

F. Michel
P. Fritz

1980

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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 Dr. Jim Hunter for supplying us with the coring equipment and to Mr. Larry Dyke for providing samples from several sites across the Arctic Islands. The help of Mr. Stan Gruszka in extracting waters is greatfully acknowledged. The authors would also like to thank Mr. Robert Drimmie, Mr. Ian Clark and Mr. Bill Clarke for their assistance in the field. Finally, we would like to acknowledge the generous field support provided to us by the staff of the Polar Continental Shelf Project and the Inuvik Research Laboratory.

1. INTRODUCTION

1.1 Previous Studies

Initial investigations into the natural variations of stable isotopes in permafrost waters were undertaken by the authors in 1976 (W.R.I. contract #606-12) through an examination of cores made available by Foothills Pipe Lines Ltd. These cores represented sections from the proposed Mackenzie Valley pipeline route, with depths of up to 20 metres being examined. Additional cores were obtained in the Norman Wells area for detailed examination and several partial cores from the proposed Polar Gas routing through the central Keewatin District were provided by the Polar Gas group (Fritz and Michel, 1977). The results of this study were presented at the 3rd International Permafrost Conference in July of 1978 (Michel and Fritz, 1978b).

During the 1977-79 period, a program was initiated (W.R.I. contracts 606-12-2 and 606-12-3) to perform laboratory experiments in an attempt to simulate the natural variations detected within the original cores. Most of the 1977-78 period was spent designing and constructing the equipment for the experiments (Michel and Fritz, 1978a).

Modifications to the original equipment design and several experimental runs demonstrated that the equipment was capable of generating isotope variations in soil columns (Michel and Fritz, 1979). In an all water column, isotope fractionation occurred in accordance with the Rayleigh distillation model indicating that reservoir effects could account for some of the isotope variations observed in permafrost waters. In addition to the laboratory work, a number of samples from the Mackenzie Valley cores were analysed for their deuterium contents. The results indicated that equilibrium conditions existed during emplacement of these waters.

1.2 Terms of Reference

This study was developed as a continuation of the laboratory experiments initiated during the previous contracts in order to quantify the effects creating the isotope variations in permafrost related waters described previously. In addition to the laboratory work at the University of Waterloo, a study of isotope fractionations in a field laboratory situation employing natural conditions was to be initiated. Correlation of the field laboratory results with the laboratory program at Waterloo would permit a more detailed discussion of the formation and stability of permafrost. The collection of additional field data from the various proposed northern pipeline routes, in order to increase the data base of observed natural conditions, was also to have been attempted.

1.3 Scope of Present Study

This report describes the work completed to date on the field laboratory site at Illisarvik in terms of samples collected during May of 1979 and the progress made in analysing these samples. Preliminary interpretations of the data are discussed in relation to their significance in understanding the history of the waters at Illisarvik and in terms of the problem of isotope variations in permafrost waters described previously.

The results of two experimental runs completed at Waterloo are discussed in relation to the naturally occurring isotope variations.

Several samples from the Arctic Islands portion of the Polar Gas pipeline route were obtained and are described. Samples from the Foothill's Alaska Highway route were not available during the term of this contract, but negotiations for the release of the core material are continuing. Finally, this report suggests a course along which further work should be directed.

2. WORK COMPLETED

2.1 Illisarvik Experimental Lake Site

2.1.1 Other Studies

The study site, located on the northern tip of Richard's Island in the Mackenzie Delta (Figure 1), was officially named Illisarvik (translated: a place of learning) by Dr. J.R. Mackay on March 20th, 1978. During April 1978, a crew from the Geological Survey of Canada conducted a reconnaissance program at Illisarvik to establish a survey grid, measure the lake bed bathymetry, install thermistor cables and obtain geological and geophysical information on the lake bed sediments. On the afternoon of August 13th, 1978, the lake was drained via an artificial channel to the sea, exposing the lake bed. During the late summer of 1978 additional drilling was conducted for the installation of thermistor cables and other instrumentation as well as one core taken by Dr. J. Ritchie of the University of Toronto for pollen and radiocarbon analysis. In addition, several samples were collected from exposed sections by Dr. Mackay for radiocarbon dating. Except for the one hole by Dr. Ritchie, no core was recovered because of the drilling method used. During late April and early May of 1979, Dr. J.A. Hunter of the Geological Survey of Canada carried out a geophysical survey on the lake bed. Temperature measurements have been made at various times by several researchers since the time of their installation. A series of short reports on these studies has been compiled by Dr. Hunter (1979).

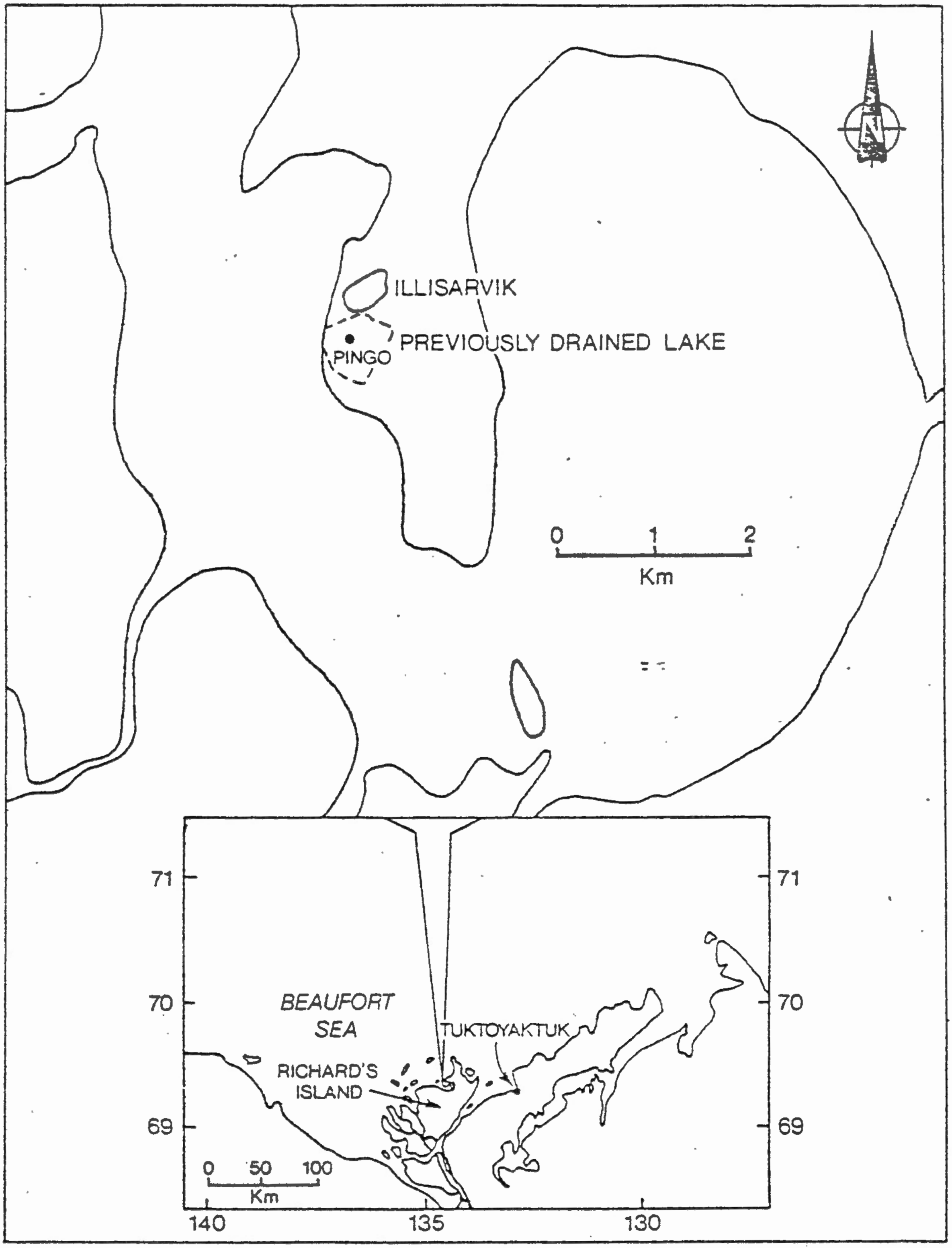

Figure 1 Location map of Illisarvik

In addition to the work described within the present report, a fellow researcher at the University of Waterloo, Dr. P. Fransham, has been measuring various geophysical parameters in the laboratory on material collected through this contract (Fransham, 1980).

2.1.2 May 1979 Coring Expedition

A field party of four, led by Mr. F. Michel from the University of Waterloo, spent the 12 day period from May 6th to May 17, 1979, at Illisarvik. The primary purpose for this program, as stated earlier, was to initiate a study on isotope fractionations by using Illisarvik as a natural field laboratory. During the winter of 1978-79, the lake bed was subjected to extreme sub-zero temperatures for the first time in at least recent history. Throughout the winter, various observations indicated that the lake bed was not snow covered for a variety of reasons. The lack of a snow cover meant that the lake bed was subjected directly to the cold air temperatures throughout the winter.

When our group arrived, the site was bare, whereas the adjacent countryside was snow covered. The weather was overcast about 60% of the time with light flurries during 2 or 3 days. Temperatures never rose above the freezing point, but the lake bed tended to develop a 1 to 2 cm thick muck layer during the afternoons of most days. Near the end of the stay, localized fog developed in the early morning and by late afternoon the air above the lake bed became steamy.

In order to minimize disturbance of the surficial lake bed sediments, drilling and movement on the lake bed was confined to those periods when the surface was solidly frozen.

The study of isotope fractionations created through the one winter of freezing, required the drilling and continuous sampling of a number of holes within and adjacent to the lake bed. In addition to these 13 holes, core samples were collected from holes drilled in the bed of a previously drained extension of Lake Illisarvik, a pingo growing in this same lake bed and two ice wedges exposed by the drainage channel. All borehole locations are shown on Figure 2. Field logs of all the boreholes are reproduced in Appendix A.

As can be seen from Figure 2, the major drilling effort was concentrated on a series of boreholes along a true east-west transverse of the lake. This section begins adjacent to the sea cliff and passes diagonally across the lake to the higher ground in the centre of the peninsula, perpendicular to the coastline. The remainder of the holes drilled off the section were located so as to supplement the boreholes along the section. A hole was not drilled between boreholes 4 and 6 because of the presence of a remnant frozen pond in this area.

Drilling was accomplished using a G.S.C. frozen ground kit (5133-9304) consisting of a Stihl power auger unit (model No. 4308), aluminum drill rods and a CRREL core barrel. The depth to which samples could be collected was restricted to a maximum of 18 feet (f.5 metres) because of the number of drill rods included in the coring kit. Sampling of the unfrozen sediments beneath the upper frozen layer was impossible due to the absence of several pieces of required equipment. After each hole was completed, the core was sectioned either into 2 inch (5 cm) intervals and double sealed in heavy plastic bags or into 4 inch (10 cm) intervals and canned. Those samples that

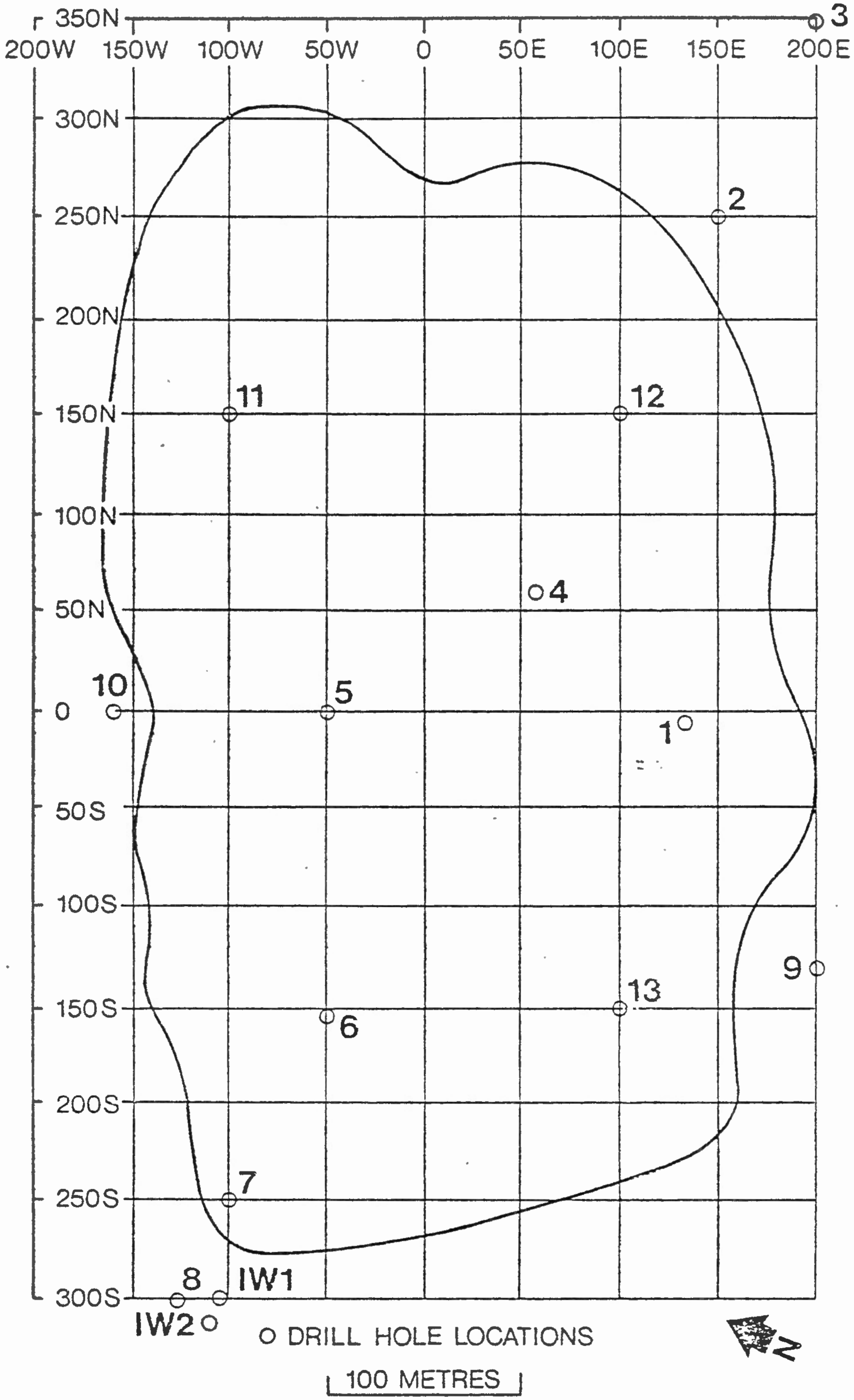

Figure 2 Location map of boreholes drilled at Illisarvik in May 1979

were sectioned into 2 inch intervals were subdivided and bagged as two separate subsamples. Bulk density measurements were made at various intervals along several of the cores before sectioning and are reported by Fransham (1980). By sectioning and packaging each in individual sample in the field, it was unnecessary to maintain the samples in their frozen state during transit to Waterloo for examination of the isotopes and, therefore, no extra precautions were taken during shipping.

2.1.3 Sample Processing

Upon arrival at the university, boxes of samples were placed in a chest freezer for storage. Several of the boxes were kept unfrozen until the water could be extracted from the individual samples.

Various tests were to be conducted on the samples and so that the maximum amount of information could be derived rrom each core, an order of analysis was established. Because of the large number of samples collected and the length of time required for processing each core, the samples are currently at various stages of testing. The first and for this study most important step in the processing of samples involves the analysis of the isotopic contents of the water. In order to extract the water from the soil, the sample must be completely thawed and equilibrated before being squeezed using a process described in an earlier report (Fritz and Michel, 1977). Measurements of the weight of each sample before and after squeezing, as well as the amount of water extracted during squeezing are recorded. Each sample is then resealed in the plastic bags to prevent any additional moisture loss. The water extracted is then used for analysis of their oxygen-18, deuterium and tritium contents.

As will be discussed later in chapter 3, the complexity of the isotopic variations encountered to date has necessitated the analysis of each and every sample interval available. The length of time required to extract and analyse these samples has resulted in only one core being processed beyond this first step at present. That core (79-3) has been analysed for its isotope contents, moisture contents, grain size and various geophysical parameters. Three radiocarbon dates on organic rich units within the core have also been obtained.

Water has been extracted from every sample of cores 1, 3, 4, 6, 7, 8, 14, and I.W. #1. Samples from core 9 are currently being squeezed. Cores 3, 4, 8, 14 and I.W. #1 have been analysed for their oxygen-18 and tritium contents while core 4 has also been analysed for its deuterium contents.

After all of the isotope work on the waters of a core has been completed, that core is then released for the next stage of processing. Moisture contents are measured by drying the squeezed sample material and adding to the weight of water lost, the amount of water extracted during squeezing. This then gives the total moisture content of the sample. For those cores sectioned into 2 inch intervals, comparison checks can be made by using the other unsqueezed subsample. All of the other tests performed are conducted according to standard geotechnical practices. Radiocarbon dating is left to the very end because the sample is destroyed by burning during preparation for analysis.

2.2 Arctic Islands

During the summer of 1979, Mr. Larry Dyke of the Geological Survey of Canada conducted field work along the proposed Polar Gas pipeline route across the Arctic Islands. In addition to his own sample requirements, Mr. Dyke also collected several samples with the following descriptions from four sites across the islands for the authors (Figure 3).

Two samples were collected from a mud boil in bouldery terrain at depths of 0.1 and 0.6 metres near the southwest edge of Fiona Lake (73° 04' N, 95° 07' W) on Somerset Island.

On Bathurst Island, two seperate sites were occupied. Near Freemans Cove (75° 15' N, 98° 06' W) along the southeast edge of the island, three samples were collected at depths of 0.1, 0.6 and 1.2 metres from a pit dug in till. To the northwest, near the head of Bracebridge Inlet (75° 42' N, 99° 30' W) a series of samples from three boreholes were provided. From borehole BHO-25, three samples were taken at depths of 0.5, 1.0 and 1.5 metres. Three samples were also taken in borehole BHO-102, at depths of 0.8, 1.4 and 2.0 metres. From the third hole BHO-182, two samples were collected at depths of 0.8 and 1.0 metres.

The final site (76° 18' N, 108° 33' W) was located north of Sherard Bay on the Sabine Peninsula of Melville Island. At a depth of one metre, a single sample of ice rich shale was obtained.

All of these samples should add to the basic understanding of isotopic contents of waters in the shallow subsurface deposits across the northern islands. To date, only the samples from borehole BHO-102 on Bathurst Island and the sample from the Sabine Peninsula have been analysed for their isotope contents and, therefore, the discussion in section 3.2 is limited to these samples.

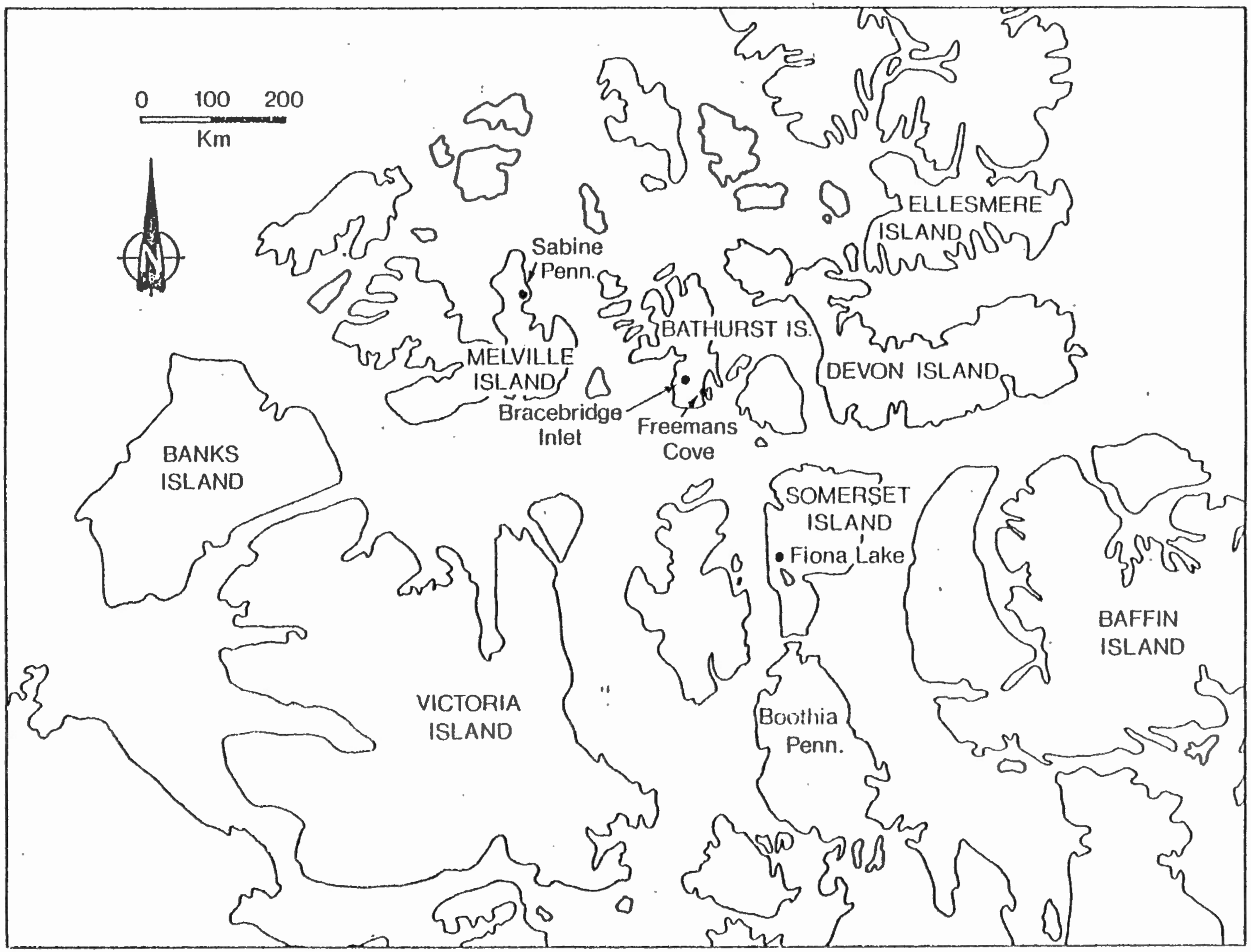

Figure 3 Location map of sample sites across the Arctic Islands

2.2 Laboratory Experiments

As previously stated, samples collected at Illisarvik during May of 1979 were placed in the chest freezer normally used for the column experiments upon our return from the field. Due to the slowness experienced in processing these samples, the samples were transferred to a newly acquired departmental walk-in cold room in the fall of 1979, in order to make available the freezer for additional column experiments. During the latter months of this contract two experimental runs have been completed and are described in detail in section 3.3. The first experiment was conducted over an 1100 hour period, while the second experiment ran for over 350 hours. No problems were experienced with the former experiment with regards to water extraction and analysis of the individual column sections. However, difficulties arose in the extraction of the water from the upper unsaturated sections of the latter column and to date these difficulties have not been overcome. The science machine shop at the university is presently constructing a modified squeezer in an attempt to successfully extract the water from the unsaturated material. For this report, only the isotopic contents of the saturated material are available for presentation. The continuation of the unsaturated column experiments has been temporarily suspended pending the successfull outcome of the modified squeezer extraction method. Until this problem can be resolved only those effects causing isotope fractionation in saturated soils will be examined.

3. DISCUSSION OF RESULTS

3.1 Illisarvik Experimental Lake Site

3.1.1 Stratigraphy

By a quick examination of the field core logs in Appendix A and by noting the observations of other workers (Hunter, 1979), a preliminary, generalized stratigraphy can be established for the Illisarvik site. Each core taken during May 1979 was selected to provide specific information on the stratigraphy.

The lowermost unit encountered by drilling consists of a fine sand, probably of deltic origin, with finely laminated bedding sloping at 10 to 20° in some cores and scattered organic fragments. In several holes, red shale clasts were noted within these lower sands. This sand grades upwards into a series of interbedded sand and clayey silt layers.

Above these layers is a relatively continuous silty clay unit containing small pebbles up to ¼" in diameter, that could be considered as a thin till sheet. Resting on this unit is a sequence of organic rich lake silts that grade laterally into sands near the edges of the local Illisarvik basin. The lake silts are very thick in the central portions of the basin and thin outwards, but are also present at higher elevations as indicated by the core recovered from lLL 79-3. In this borehole, the silts are interlayered with two organic horizons of peaty material.

These two horizons and the surficial organic layer capping the generalized stratigraphic sequence have been dated using the radiocarbon method. The results are listed in Table 1, where the radiocarbon ages given have been adjusted according to their ^{13}C contents. A ^{14}C half-life of 5,730 years was used. The ^{13}C adjustment is only a minor correction that is within the error limits attached to each age. Any detailed interpretation of the history, through the use of these ages, should await further analysis of additional organic horizons encountered in the other boreholes. Within the lowermost sands and the upper lacustrine silts, shell fragments were found. Isotope analysis of these shells are planned for the future.

3.1.2 Moisture Contents

Once the water has been extracted from every sample of a core and satisfactorily analysed for its isotope contents, the samples are then dried and the moisture contents measured. A record of the amount of water originally extracted for isotopes is maintained so that the original moisture content of a sample can be calculated. To date, only core 79-3 has been released for moisture content measurements. These measurements were made by Mr. J. Unrau as part of his B.Sc. thesis work involving velocity measurements on this particular core.

As can be seen in Figure 4, wide variations in the moisture contents with depth are present. If one carefully examines the field log in Appendix A, a good correlation between the moisture content and the visible ice content becomes apparent. The upper one metre of soil contains numerous ice lenses up to 1/8 inch thick. The peaks in

TABLE #1: ^{14}C AGES OF ORGANIC HORIZONS AT ILLISARVIK

CORE NO.	SAMPLE NO.	DEPTH (CM)	δ^{13}C (0/00 POB)	pmC*	^{14}C AGE (YRS.)
1LL79-3	2	5-10	-28.2	98.4	75 ± 65
"	9	40-45	-28.5	52.3	5150 ± 80
"	22	105-110	-26.6	44.9	6400 ± 100

*percent modern Carbon

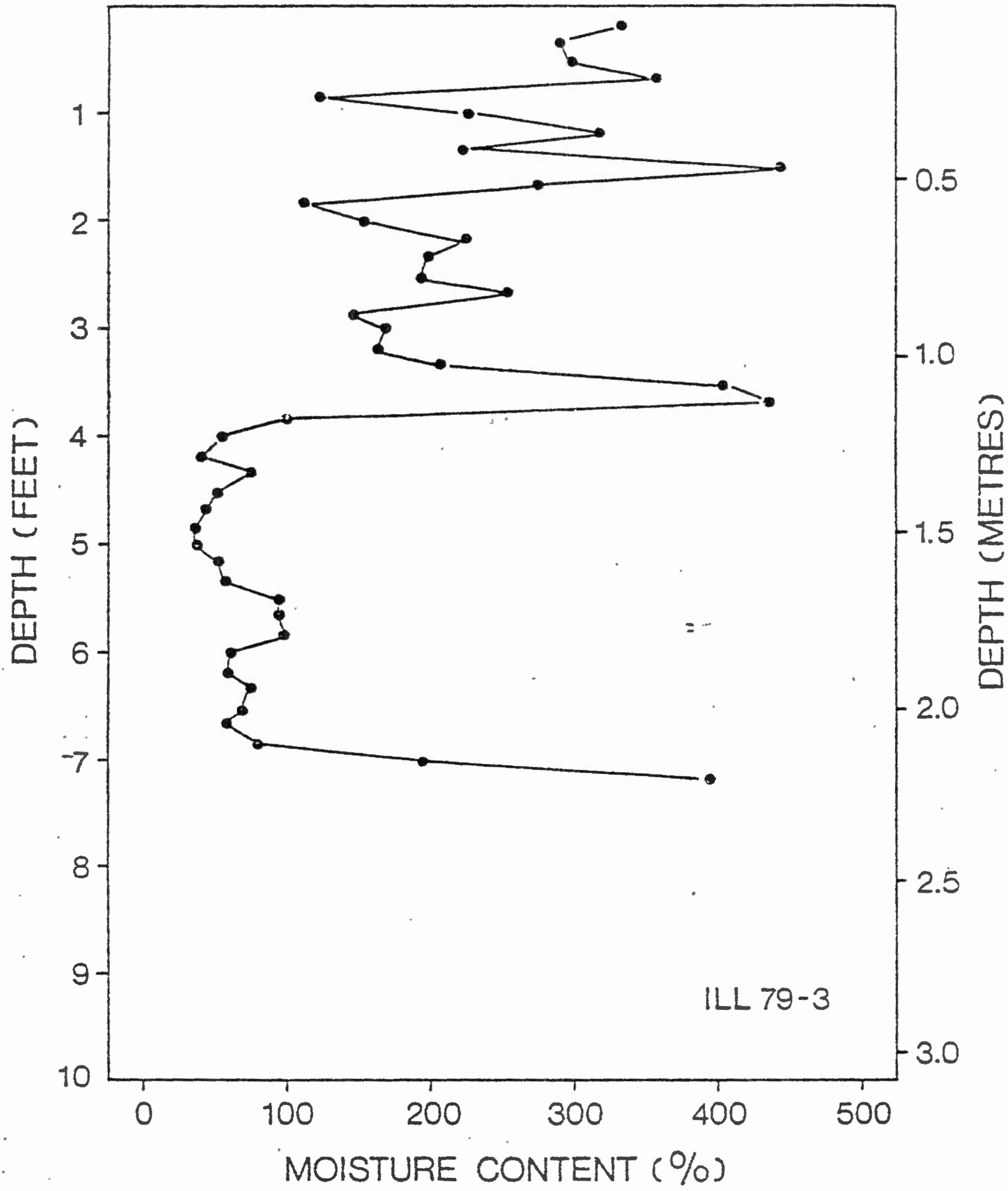

Figure 4 Moisture contents with depth for core 79-3

moisture contents at 0.45 and 1.1 metres are the combined result of high ice contents and the soil type; organic horizons. These organic horizons have been radiocarbon dated and their ages given in section 3.1.1.

The sharp decrease in moisture contents below 1.1 metres corresponds to a decrease in visible ice in the field log and to an increase in the silt and clay contents. At the very bottom of the hole, the field log notes an increase in ice towards the base and this increase can be seen by the dramatic rise in water content in Figure 4.

In the field logs, it is obvious that the ice contents vary widely throughout the basin and to some degree are dependent on the soil type. A general pattern would indicate that ice contents are highest in the organic and lacustrine silt units, extremely variable in the clay till unit and generally lower in the deltaic sands at depth.

3.1.3 Conductivity Measurements

Conductivity measurements have been made on the extracted water of several cores using a Beckman (model RC-18A) conductivity bridge. This instrument requires only about 2 c.c. of water and is, therefore, capable of measuring even those samples with low water contents. All measurements are listed in Appendix B. As discussed in the previous section, water contents in the soils at Illisarvik are highly variable and somewhat dependent on the type of soil present. It is possible to show that the conductivity of the waters examined is directly related to the moisture content and, to some degree, to the soil type.

Figure 5 is a plot of the conductivity with depth for core 79-3. When one examines Figure 5 with the moisture content plot in Figure 4, it becomes obvious that the two graphs are nearly identical. A high moisture content corresponds to a low conductivity and vice a versa. This would be expected if one considers that, in the extreme case, massive ice without any soil would have a conductivity equal to or lower than the original water. An increase in the soil content would result in a corresponding increase in the dissolved solids content and thus a higher conductivity.

The relationship between conductivity and soil type can be demonstrated by considering a clay rich soil. Because of electrical surface charges on the clay platelets, higher concentrations of ions are found in the pore waters of clay rich soils than in coarser grained soils.

This relationship is clearly demonstrated by the waters in core 79-8. Conductivity values for these waters are plotted in Figure 6. The upper section containing ice rich sediments shows low values in conductivity because of the high water contents. The active layer is clearly marked by higher conductivity values than the underlying ice rich sediments.

At a depth of approximately two metres, the ice contents decrease and the conductivities rise to over 2000 micromhos. This change is related to the clay till unit described previously. The rise in conductivity values cannot be related entirely to changes

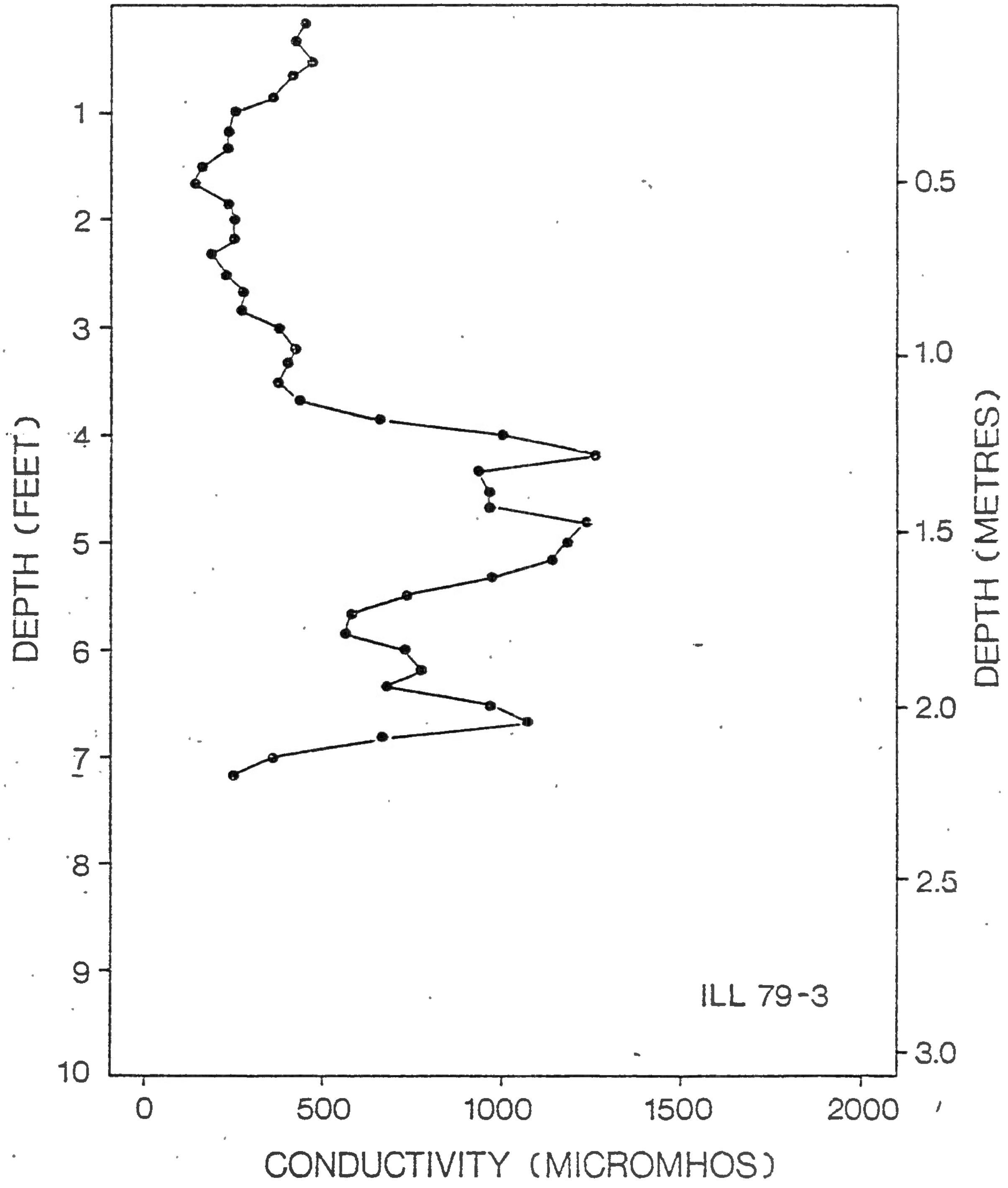

Figure 5 Conductivity with depth for core 79-3

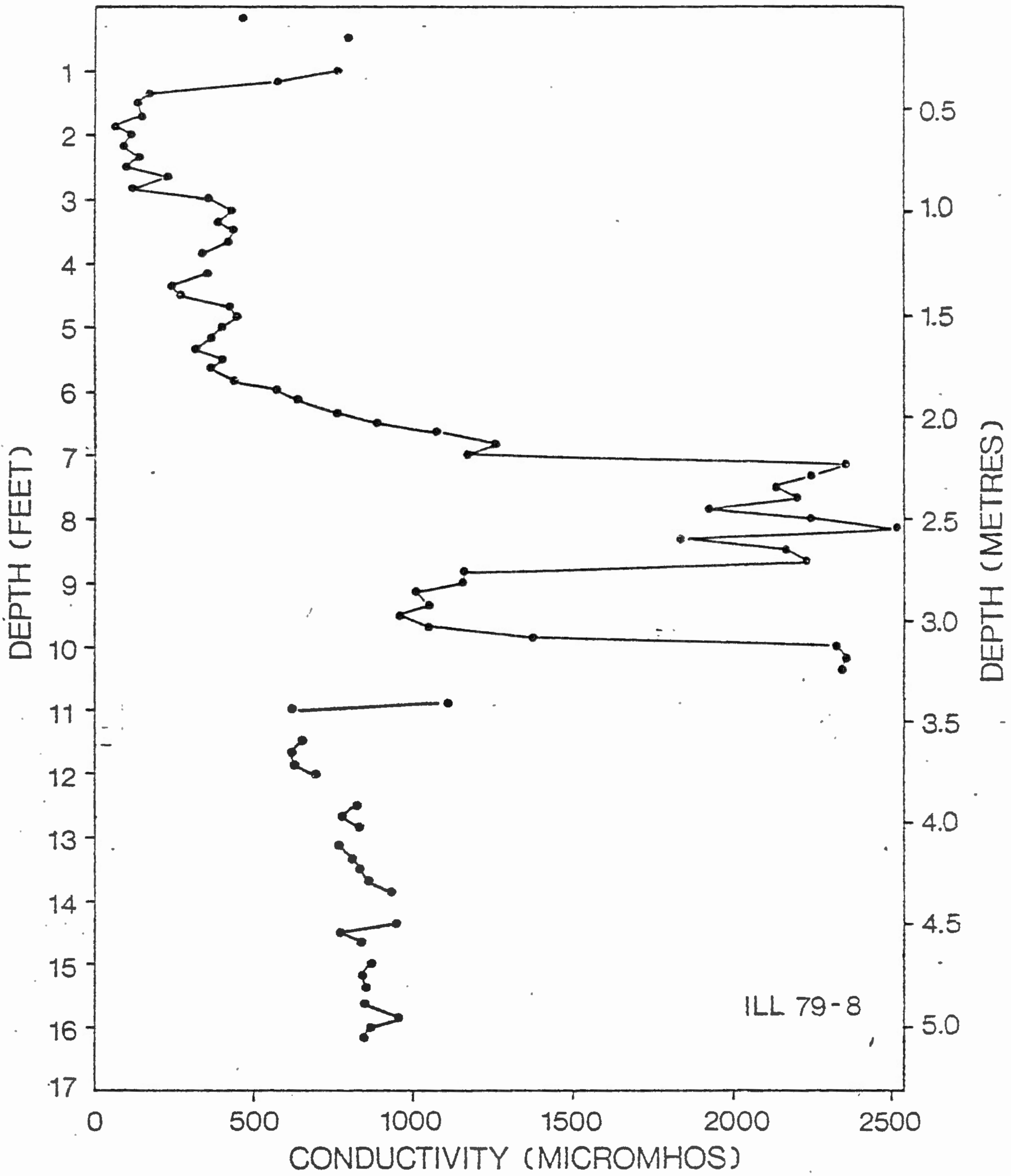

Figure 6 Conductivity with depth for core 79-8

in the moisture content and, therefore, must be in part related to the soil type.

In the lower third of the core, deltaic sands with little or no visible ice are found. Although the ice contents are low, the conductivities decrease to a relatively constant range which is higher than the upper ice rich sediments, but much lower than the clay till unit in which ice lensing was present. Because moisture contents and ice contents may not be exactly comparable between sediment types, any further discussion of these relationships must await the determination of moisture contents for core 79-8.

Within the lake bed, the conductivity values measured for cores 79-4 and 79-6 (Figures 7 and 8 respectively) indicate that large variations in the water contents exist. Since only lacustrine silts and organics were encountered in core 79-4, it would appear that the variations in conductivity represent ice lensing. In core 79-6, the upper sediments show consistently high conductivity values as opposed to the low values measured in the bottom half of the core. Because the field log does not clearly indicate why this pattern exists, discussion of this core will be left until further data are collected.

3.1.4 Isotope Measurements

3.1.4.1 Oxygen-18 and Deuterium

During the early investigations of isotope variations in permafrost related waters (Fritz and Michel, 1977), a core collected from the Norman Wells area was sectioned and analysed in 2.5 cm

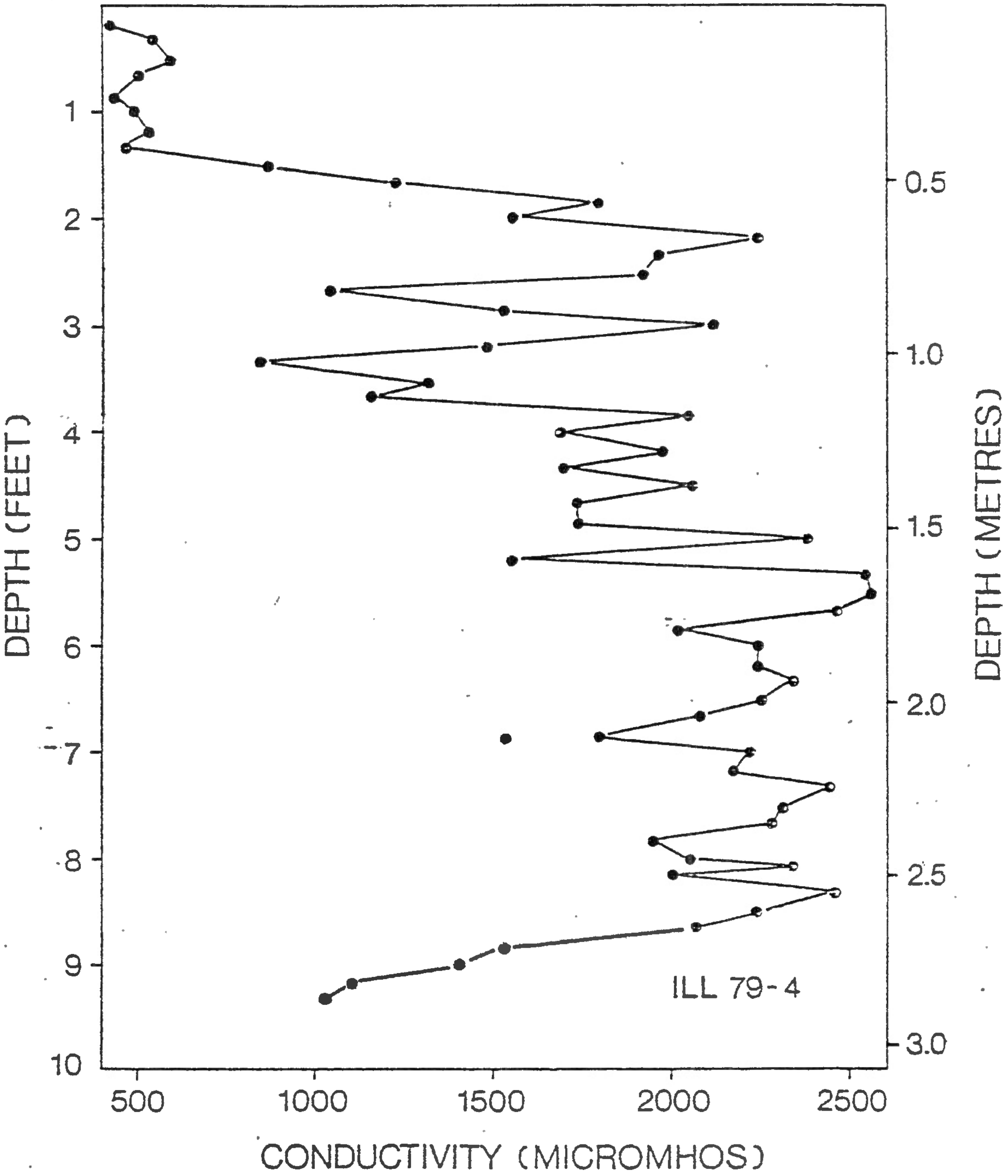

Figure 7 Conductivity with depth for core 79-4

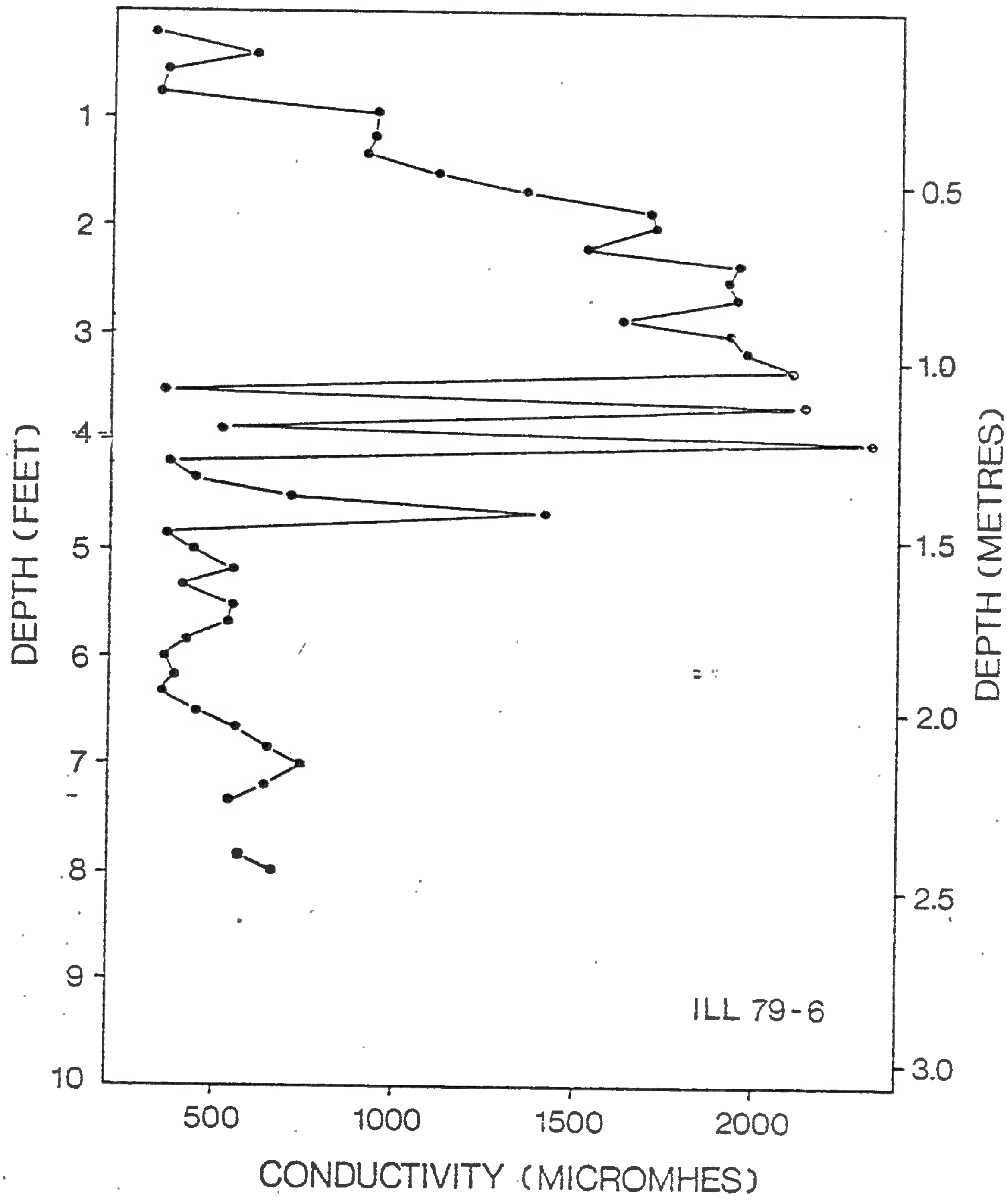

Figure 8 Conductivity with depth for core 79-6

intervals for the oxygen-18 contents of the waters. The amount of water available from a 2.5 cm interval and the number of analyses required to completely study even this short core led to the decision in this study to section the cores obtained into either 5 or 10 cm intervals as stated earlier in section 2.1.2.

Although very time consuming and tedious, it was also decided to start the analytical work by examining completely several cores sectioned in 5 cm intervals. Outside of the lake bed, cores 79-3 and 79-8 have been squeezed and analysed for their oxygen-18 contents while the water in core 79-9 is presently being extracted. Within the lake basin, core 79-4 has been squeezed and analysed for its oxygen-18 and deuterium contents while cores 79-1, 79-6 and 79-7 have been squeezed and are currently being analysed. The cores recovered from the pingo (79-14) and the first ice wedge (79-I.W. #1) have been analysed for their oxygen-18 contents and will be described in sections 3.1.5 and 3.1.6.

Standard error limits that must be considered when examining the results are ± 0.2‰ for oxygen-18 and ± 2‰ for deuterium. Therefore, small random variations in the order of 0.5‰ for oxygen-18 are considered simply as scatter. All isotope analyses are tabulated in Appendix C.

The higher ground surrounding the lake basin, especially to the east and north, has probably been exposed to the extreme negative winter temperatures for some time, although the radiocarbon ages determined for the organic horizons in core 79-3 indicate that lake silts were being deposited on this higher ground around 5,000 radiocarbon years before present. The lack of a detailed stratigraphic and historical record for the area, at this time, makes the interpretation of the isotope contents difficult.

However, it is possible to examine the variations present and to compare these variations between boreholes. The oxygen-18 contents of cores 79-3 and 79-8 are graphically presented in Figures 9 and 10 respectively.

Borehole 79-3 penetrated only two metres of fine grained sediment and was terminated in the till unit. Because of the higher elevation, these sediments have probably been exposed to the winter air temperatures longer than any penetrated by the other boreholes drilled. As such, the waters frozen in the sediments could reflect isotope contents of precipitation at some earlier time. Alternatively, these waters may represent a larger than average component of snow melt infiltration due to the sloping ground on which the hole was drilled.

The young ^{14}C ages for the upper metre of sediment and the isotope contents within the active layer tend to support the latter explanation. All samples examined from the active layer contain tritium (see section 3.1.4.2) and, therefore, must represent young waters.

The active layer in 79-3 appears to be confined to the upper 30 cm of core according to the oxygen-18 record. The negative ^{18}O peak within the active layer suggests that freezing of the active layer occurred from the ground surface downwards and from the permafrost table upwards. A similar, but somewhat more complex

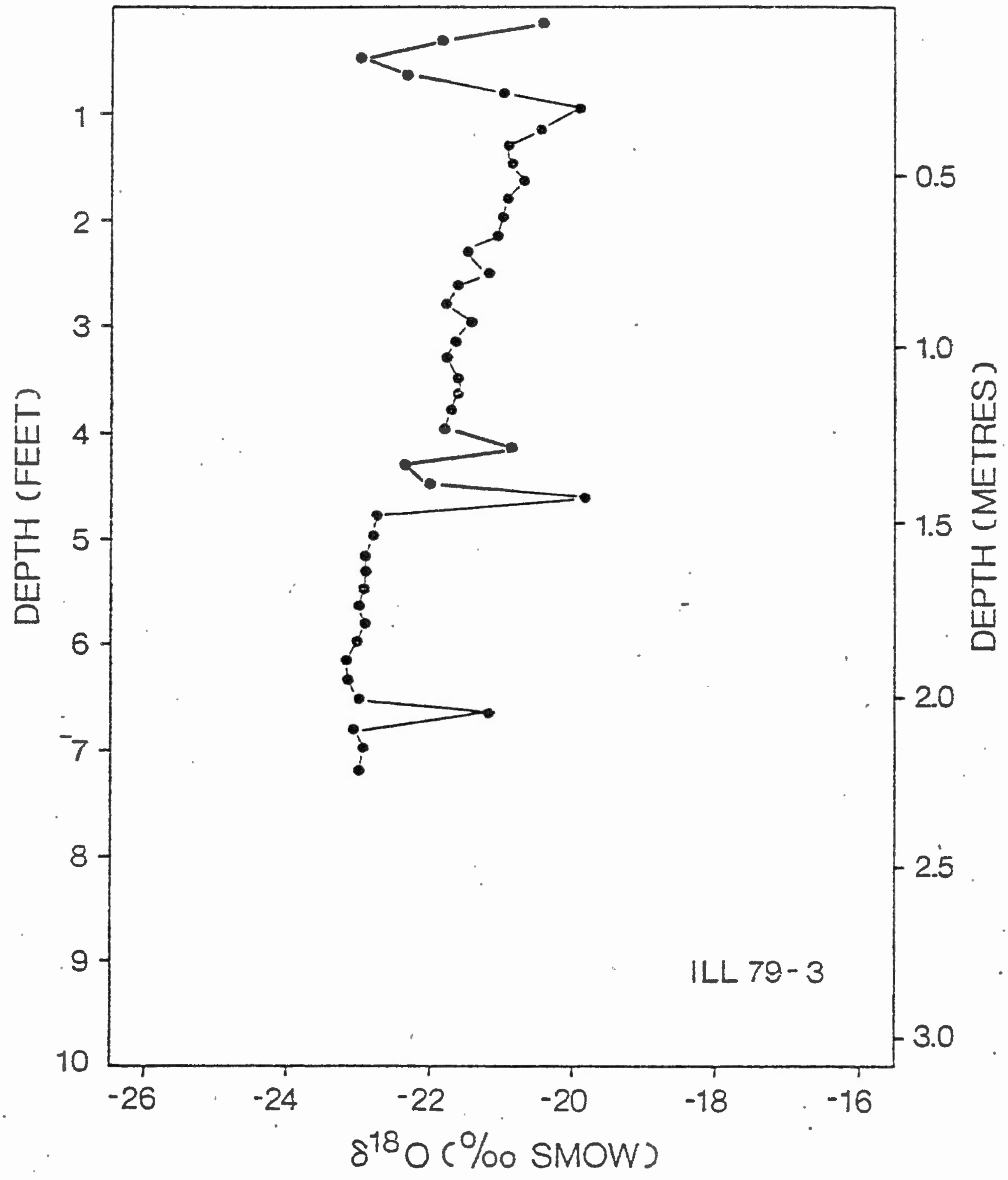

Figure 9 ^{18}O contents with depth for core 79-3

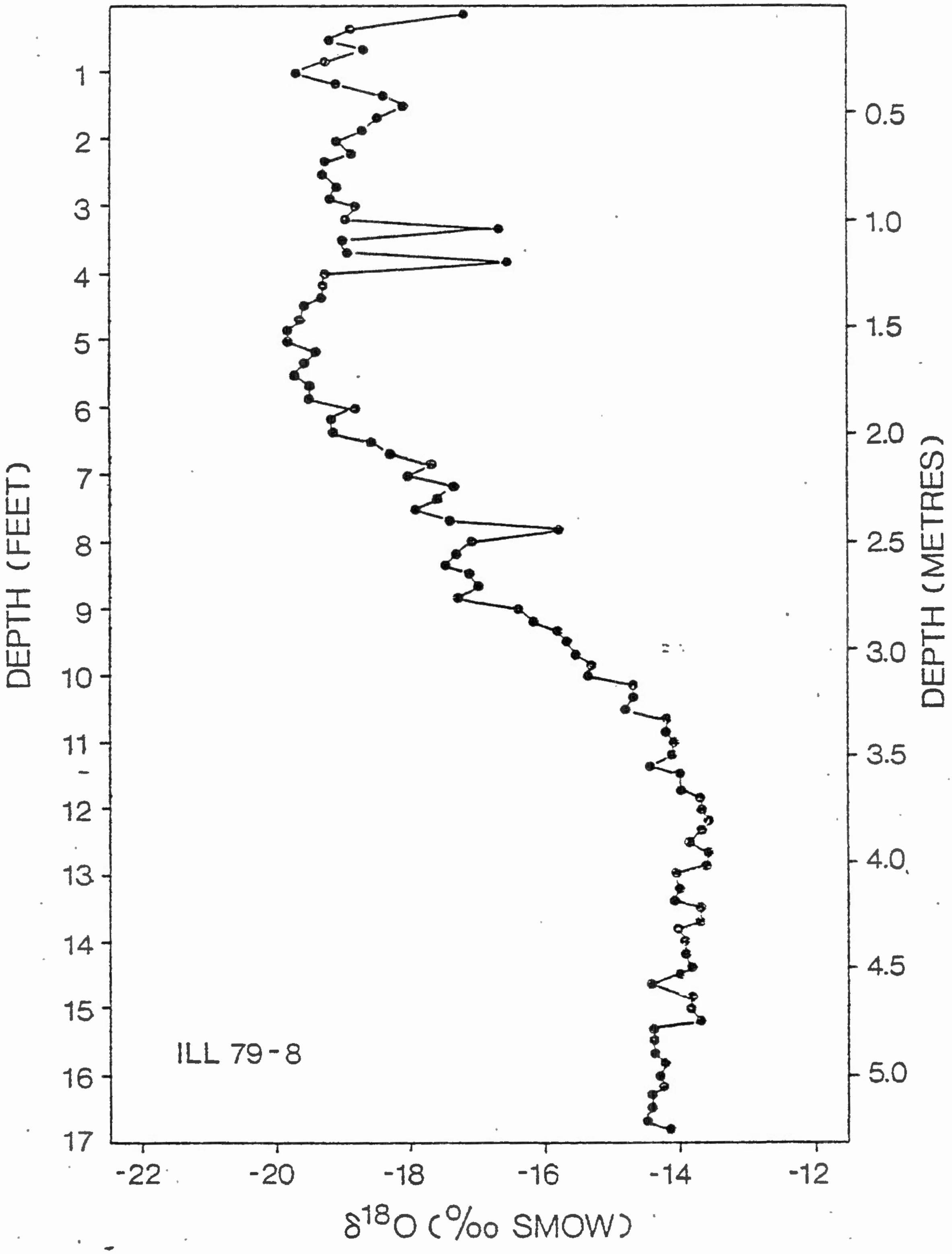

Figure 10 ^{18}O contents with depth for core 79-8 pattern of oxygen-18 distribution is present for core 79-8 in the upper 50 cm. The development of these negative peaks can be explained by equilibrium fractionation of the active layer waters during freezing with ^{18}O depletion proceeding simultaneously with freezing. The lower energy oxygen-18 molecules become concentrated in the frozen material while the higher energy oxygen-16 molecules remain within the unfrozen water thereby causing a relative depletion in oxygen-18.

Above the negative peak, the positive shift reflects the isotopic contents of the final waters to infiltrate the ground surface prior to the commencement of freezing. Below the negative peak, but still within the active layer, a small positive peak of approximately one per mil is found in both cores. These peaks represent enrichment of oxygen-18 at the permafrost table caused by the upward freezing mentioned earlier.

Both cores also exhibit additional positive peaks ranging in size from 1 to 3‰. These peaks are similar in magnitude to peaks in the Norman Wells core. These peaks, positive and negative, must be the result of fractionation processes. Whether or not these processes occurred under equilibrium conditions cannot be stated until the deuterium contents of these waters are determined.

The presence of these peaks at various depths would appear to indicate that the movement of water through these soils must be extremely slow. However, further work is required to determine the rate at which the water might be moving under the natural conditions and gradients that exist. As will be shown in the following section, tritium can be of help in making this determination. Diffusion of the isotopes, down the concentration gradients present, must also be extremely slow unless the peaks were formed recently. The implications arising from these peaks and their ages become important in any examination of water movement through frozen ground.

The more positive isotope contents in the lower portion of core 79-8 are similar to the precipitation and lake water values obtained in this study and the study from last year (Michel and Fritz, 1979). This would appear to indicate that, at some point in time, subsurface drainage of lake water to the ocean has occurred. If the peaks, discussed earlier, are related to freezing mechanisms, then the presence of a peak within the transition zone of isotope contents would indicate that the sands, through which the drainage was occurring, were unfrozen during that time period. Further interpretation and discussion of the isotope variations found in this core must await the compilation of a more complete record of the history and stratigraphic ages of the deposits.

Within the lake bed, a long term natural experiment of isotope fractionations during freezing was initiated by the drainage of the lake and the onset of winter. During the winter of 1978, the lake bottom sediments were subjected to freezing temperatures and the penetration of ground frost to considerable depths. Because of variations in moisture contents and the thermal properties of the sediments, the depth to which frost penetrated varied between holes from approximately 2.2 metres to 4.3 metres. By collecting samples during the early spring of 1979, only one winter of freezing had occurred and the effects of that single cold period on the waters could be determined.

Core 79-4, taken near the centre of the lake, penetrated organic rich lake silts which were frozen to a depth of almost 2.5 metres (sample 49A). The presence of H_2S in the sediments was quite evident below the lower boundary of frost penetration, but no such odour was noted above this boundary. Detailed analysis of the waters in this core for their oxygen-18 and deuterium contents (Figures 11 and 12 respectively) indicate that no major fractionation of either isotope occurred during freezing so as to create a positive or negative peak, however, a gradual depletion of ^{18}O and ^{2}H due to freezing fractionation did occur. The small variations present in both graphs are considered to only represent scatter.

The gradual depletion in the heavier isotopes with depth indicates that the freezing of these sediments during the winter of 1978-79 was a slow continuous process. The rate at which freezing of the water occurred was slow enough to allow equilibration of the isotopes as shown by the ^{18}O-^{2}H relationship in Figure 13. One of the precipitation samples collected by Dr. J. Anderson for the authors has also been plotted. The ^{18}O-^{2}H relationship can be described in a preliminary fashion by the equation:

$$\delta^{2}H = 8\delta^{18}O - 8.0$$

Although some scatter exists, the clustering of points along the

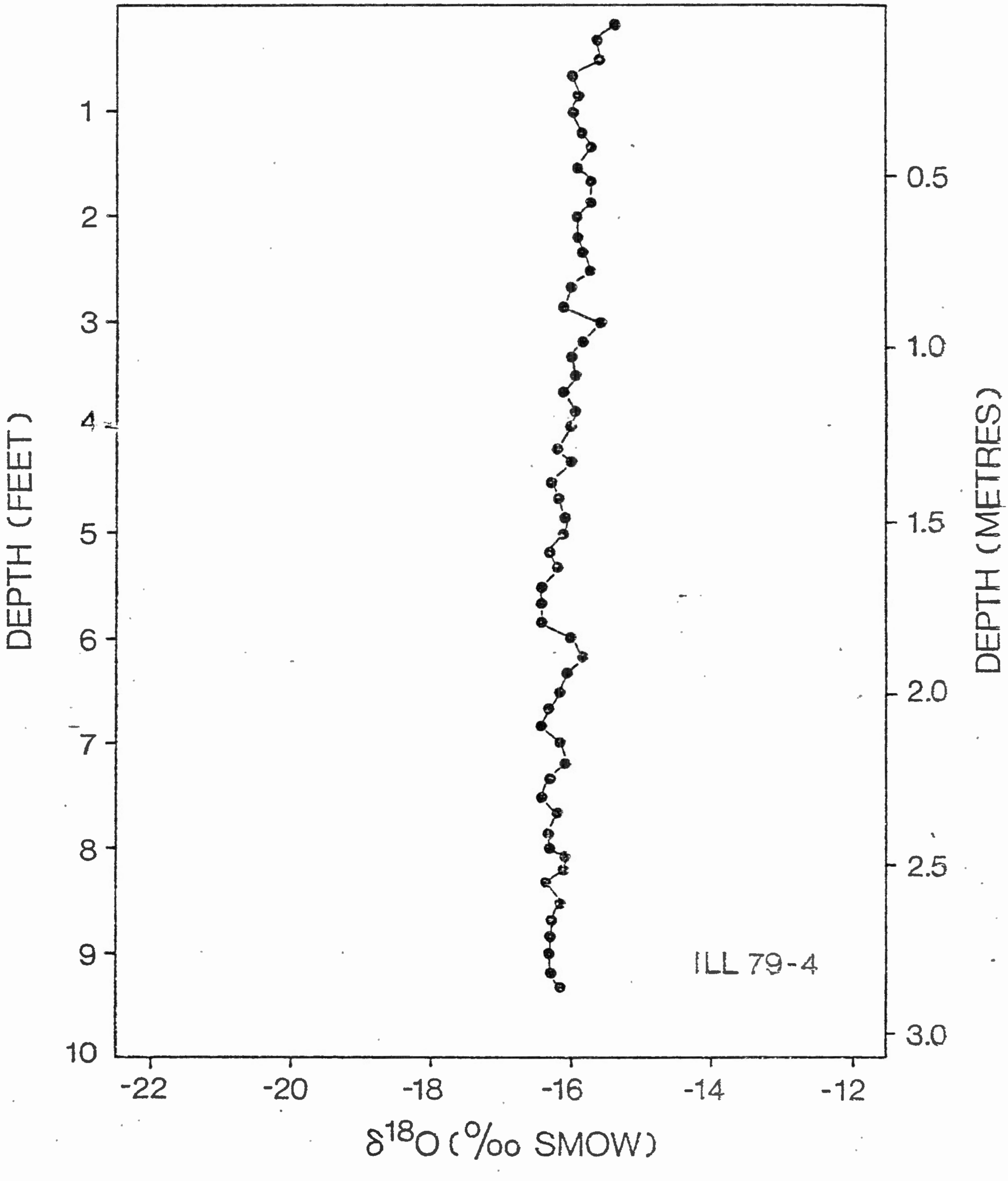

Figure 11 ^{18}O contents with depth for core 79-4

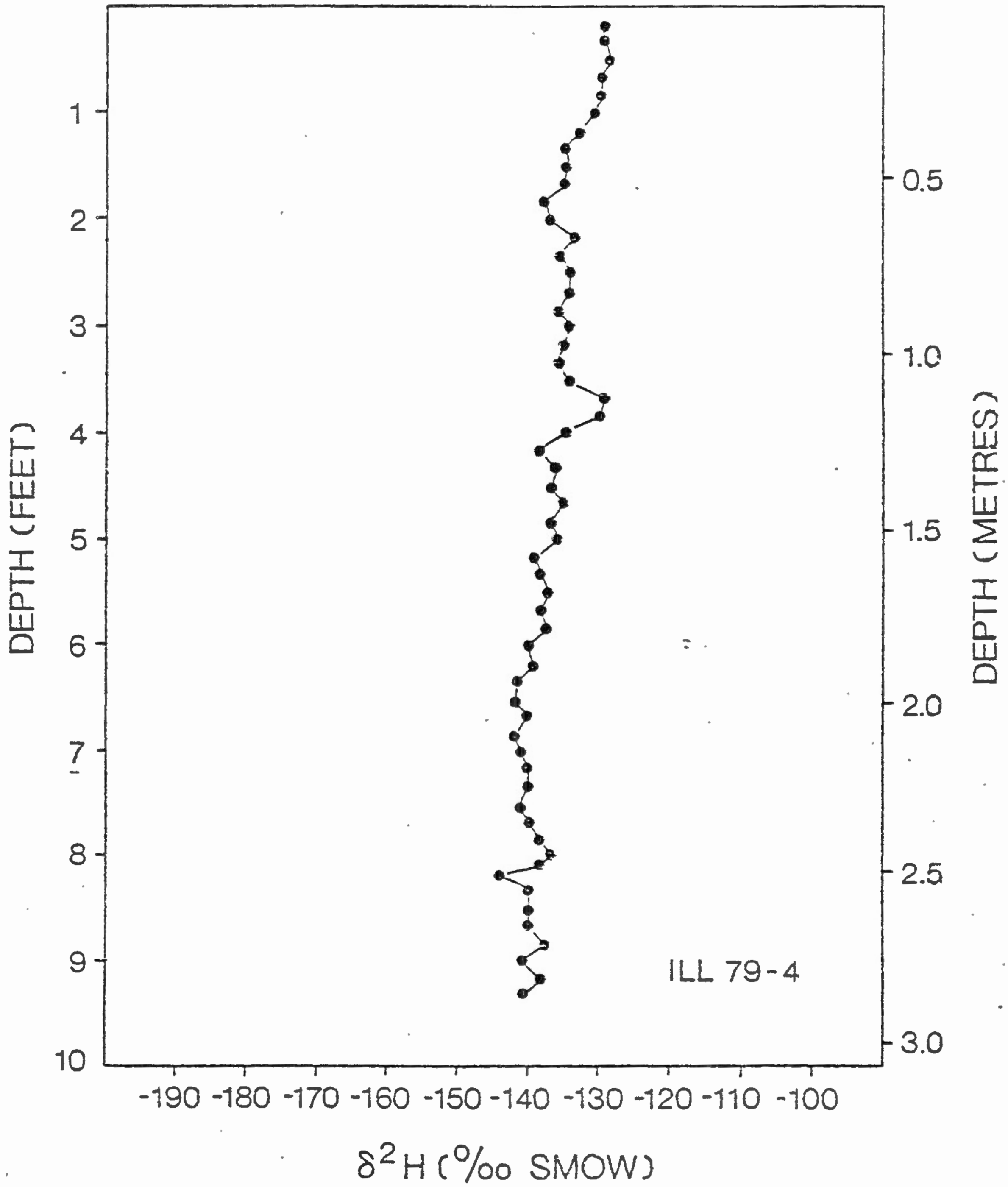

Figure 12 ^{2}H contents with depth for core 79-4

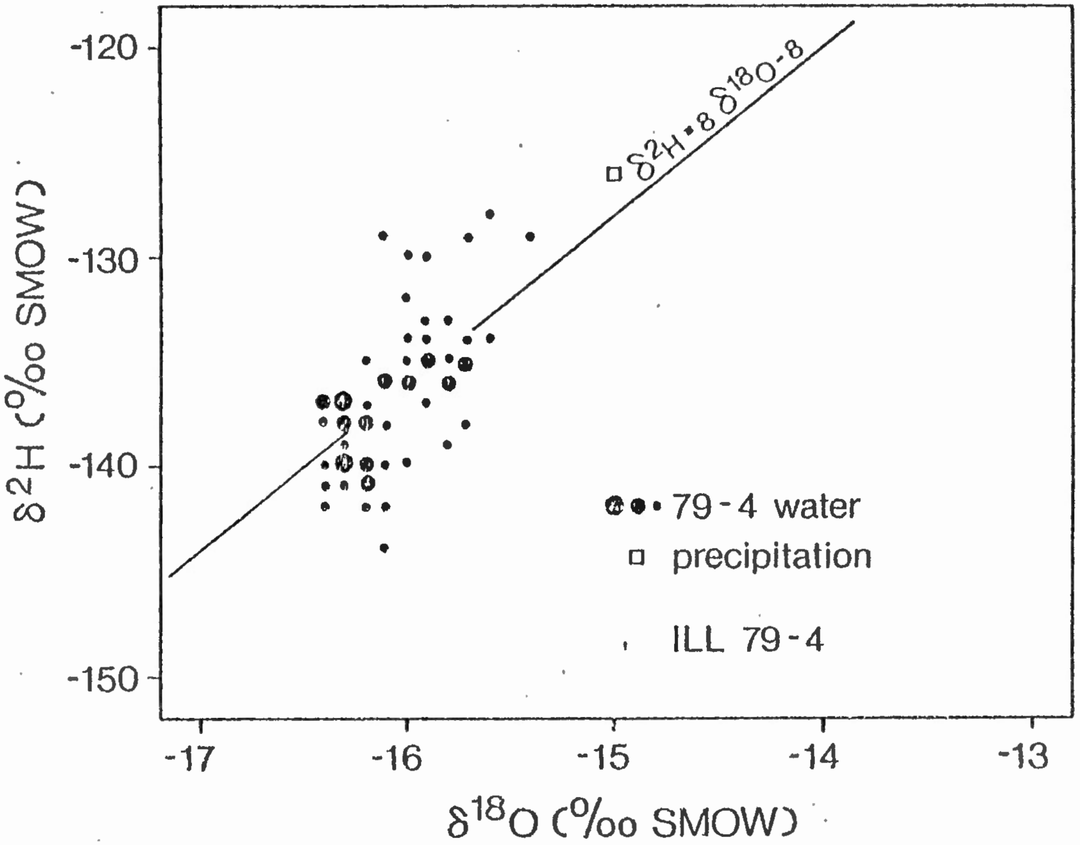

Figure 13 ^{18}O - ^{2}H relationship for core 79-4 meteoric water line indicates that the fractionation did occur under equilibrium conditions. The collection of an additional core adjacent to 79-4, during the upcoming field season, and information on the depth of thaw during the summer of 1979 should make it possible to examine several freezing effects which are related to the presence of a frozen zone at depth.

3.1.4.2 Tritium

The high levels of tritium found in precipitation are the result of an extensive program of nuclear detonations in the atmosphere during the 1950's and early 1960's. In 1963, tritium levels in the northern hemisphere reached a peak and have been declining since.

Tritium data are listed in Appendix C with the oxygen-18 and deuterium contents and are listed in tritium units (T.U.). Samples for which no tritium was detected are noted as n.d. for not detected. Because of background noise, all analyses have an error of ± 10 T.U. and, therefore, any value below 10 T.U. can also be considered as dead. The significance of values in the 10 to 25 T.U. range is uncertain, but probably represents minor random contamination during processing and analysis. Therefore, any sample with less than 25 T.U. will be considered as dead or older than 1952.

In core 79-3 (Figure 14), the 1963 tritium peak is clearly evident at a depth of 25 cm and, with the above assumption, all tritiated water is confined to the active layer or the upper 45 cm.

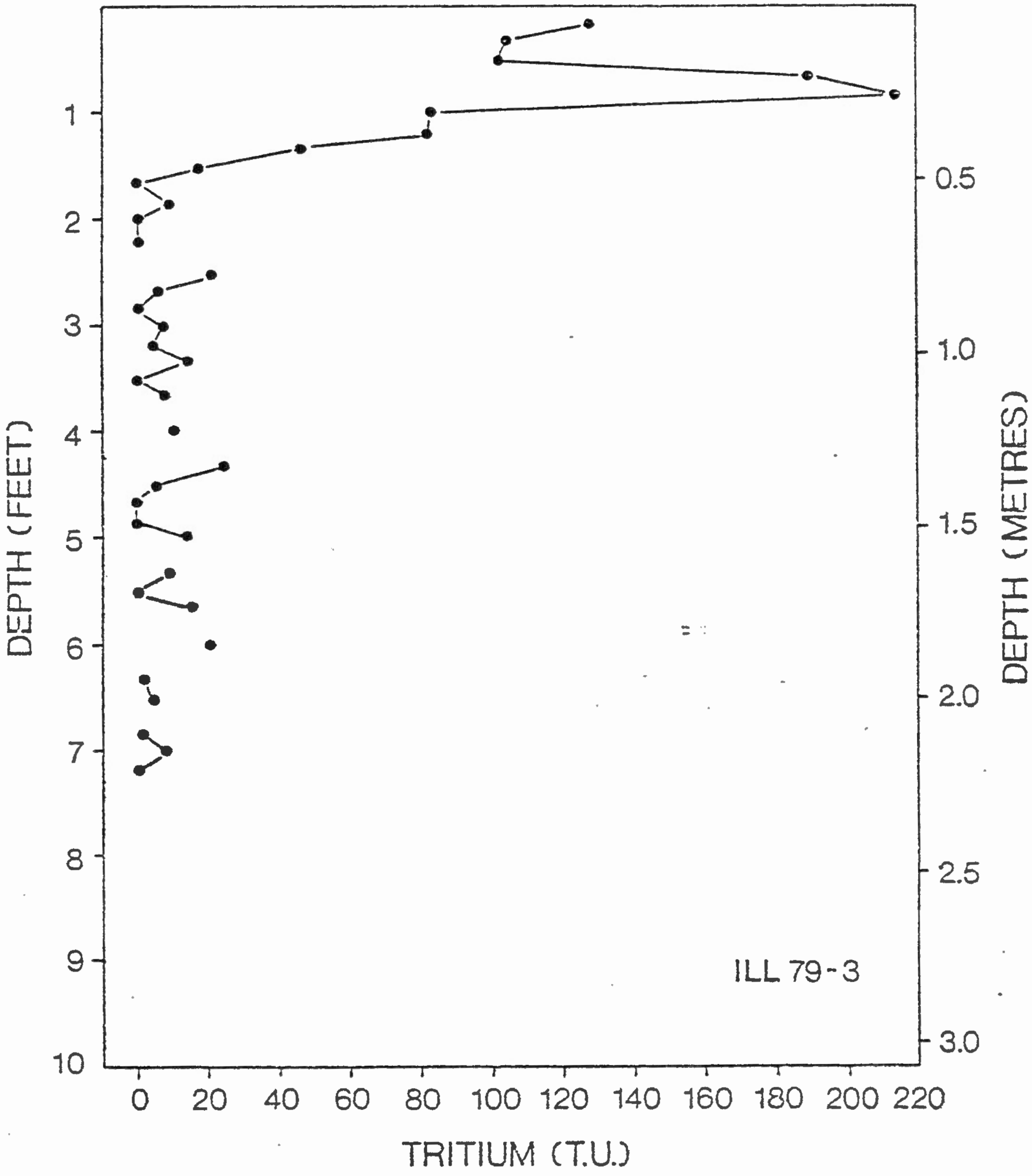

Figure 14 Tritium contents with depth for core 79-3

A similar pattern is displayed in the top half metre of core 79-8 (Figure 15). The lack of sufficient water in several samples from the active layer does not allow for the complete delineation of the tritium profile in this upper zone, but the 1963 peak is still evident. Again, no tritium was detected below the permafrost table indicating that the diffusion of tritium through frozen ground must be very slow. Considering the thickness of the active layer as being approximately half a metre is supported by the depth to the top of local ice wedges and the depth to the upper ice unit in the pingo core.

Within the unfrozen lake bed sediments, the distribution of tritium indicates downward movement at the rate of 2.5 to 5 cm per year (Figure 16). The 1963 level appears to be at a depth of approximately 50 to 60 cm. Values decrease downwards to a depth of almost two metres, where levels are below background.

From all three cores analysed for tritium, the uppermost samples yield tritium contents in the range of 80 to 140 T.U., whereas, the two precipitation samples collected have values of 69 and 93 T.U.

Although the precipitation values do not represent the yearly average tritium contents, as do the soil waters, the agreement between the two groups is still quite good. Even better agreement is found when the top sample from core 79-4 (136 ± 10 T.U.) is compared to the lake water (141 ± 8 T.U.) collected during 1978 before the lake was drained. The use of tritium to delineate the thickness

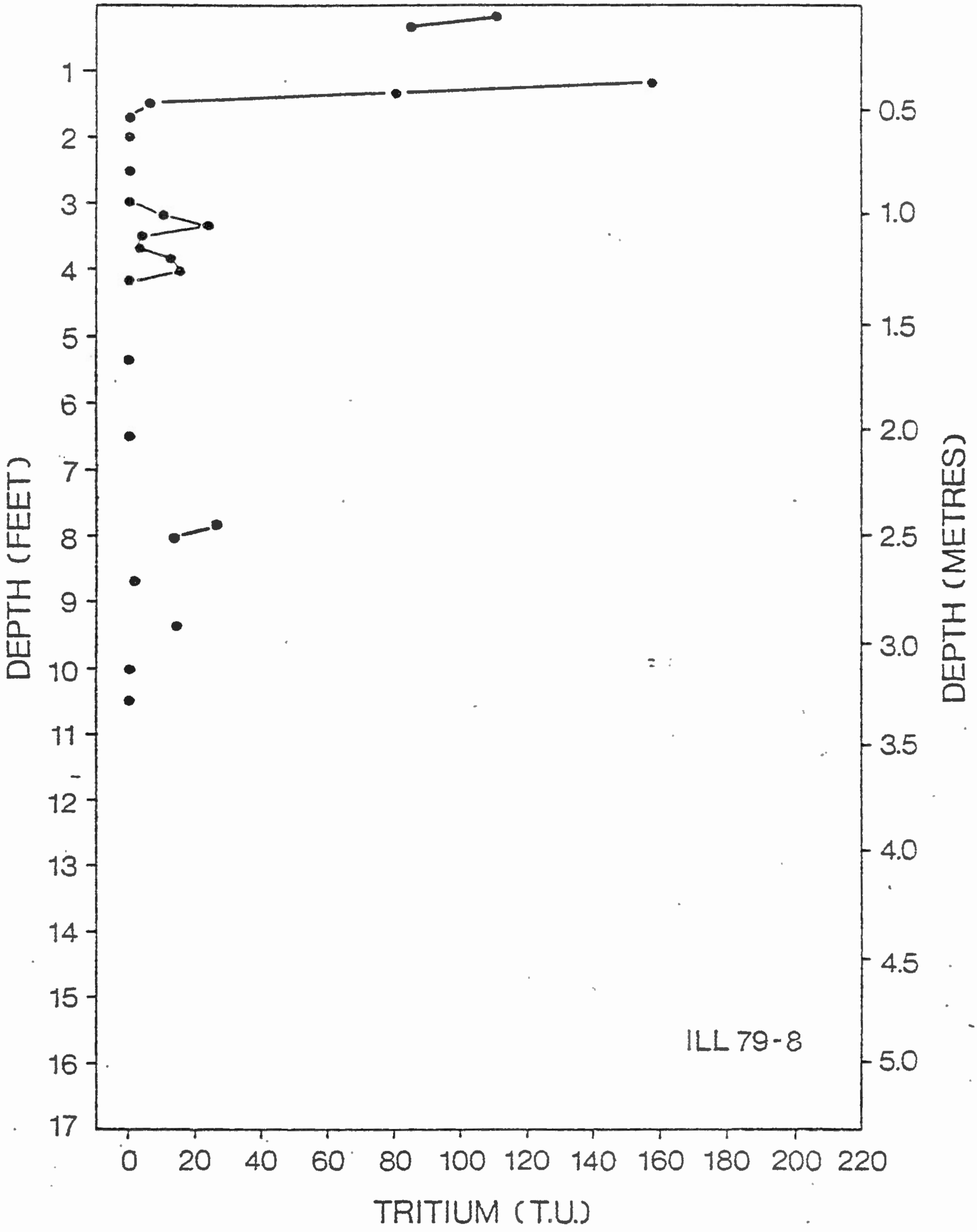

Figure 15 Tritium contents with depth for core 79-8

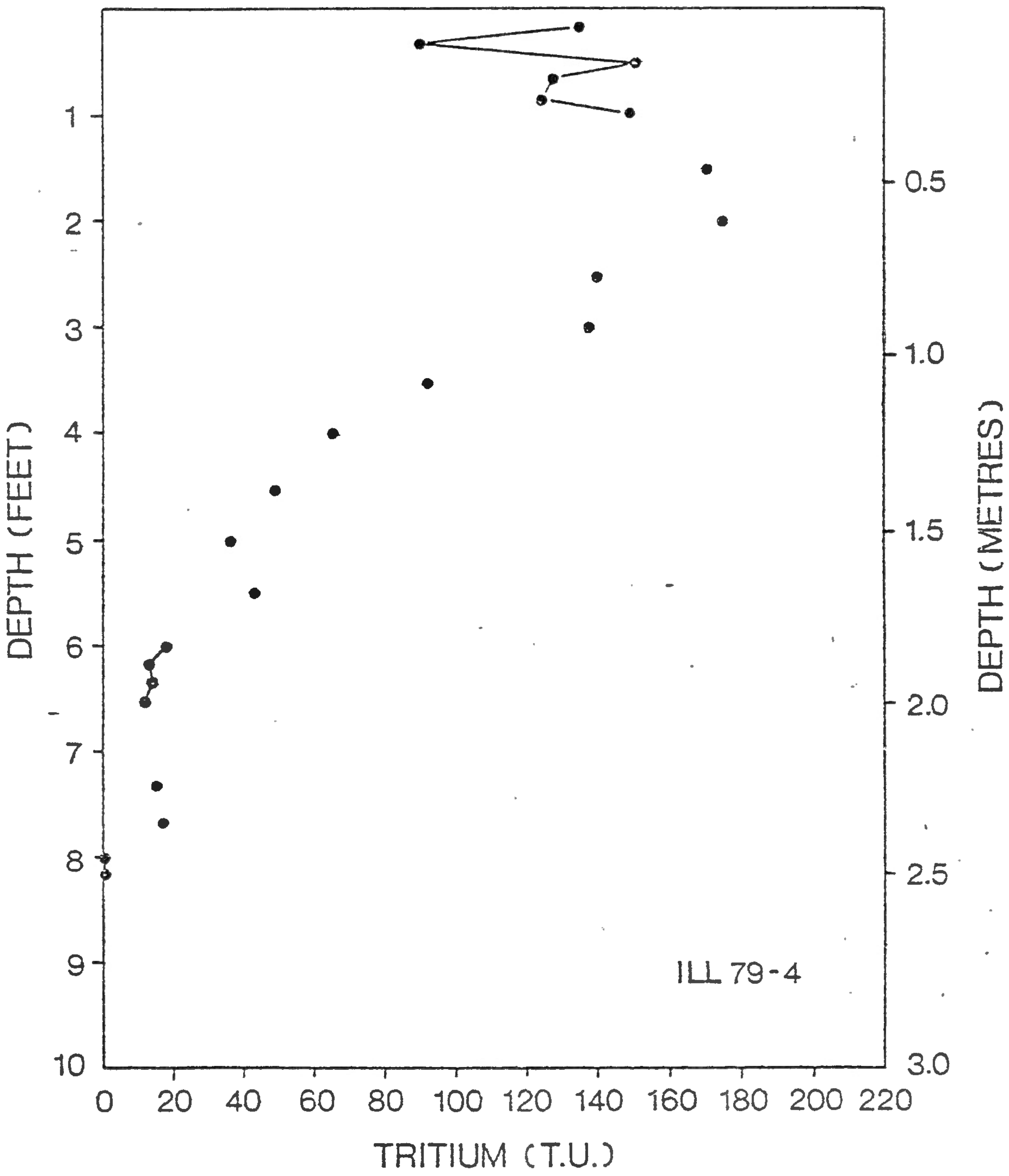

Figure 16 Tritium contents with depth for core 79-4

of the active layer, during the past 30 years, and the rate of downward migration through the lake bed sediments has been clearly demonstrated. Analysis of the tritium contents from additional cores will permit the confirmation of active layer thicknesses around the lake basin, the rate of movement through various types of lake bed sediment and possibly the dating of recent alterations to the lake due to natural processes.

3.1.5 Pingo

At one time, Lake Illisarvik was part of a larger body of water. Coastal erosion finally breached the western edge of this larger lake resulting in drainage of its water. The level of Lake Illisarvik also decreased, but the lake did not completely drain because of a low sill on which drill hole 79-9 was sited. Drainage of the lake resulted in the alteration of the thermal regime of the sediments. Permafrost aggradation and increasing pore water pressures with time prompted the initiation of a pingo in the central portion of the lake bed. During the May 1979 expedition, borehole 79-14 was drilled from the crest of the pingo in order to examine the internal structure and the isotope contents of the ice core. The field log, included in Appendix A, shows that the pingo consists of an upper soil cover; the active layer; an ice core, a lower silty clay unit and a lower ice zone. It should be noted that near the contact between the ice core and the lower silty clay unit is a thin, clean sand layer.

The thickness of the active layer, as determined from the soil cover above the ice core, is approximately 50 cm. The boundary between the soil and ice core is also visible, as a sharp decrease in conductivity values (Figure 17) upon entering the ice. Low conductivities are typical for the main ice core and the lower massive ice zone. The lower clay unit waters display much higher conductivities that are similar in magnitude to the clay till layers of the cores collected around and in Lake Illisarvik. The large variations in conductivity within the clay unit reflects the differences in water content as noted in the field log when zones of high ice content were encountered. The oxygen-18 data, as plotted in Figure 18, indicate that the formation of the ice lenses within the clay unit did not produce isotope fractionation. These data also show that the main ice core and the lower massive ice zone were derived from two completely separate sources.

The main ice core, on the basis of the oxygen-18 data, can be divided into two sections. These divisions are supported by the conductivity and the tritium (Figure 19) profiles. The upper section (0.5 to 1.6 metres) contains very pure ice, except for the lowermost part where the conductivity values increase slightly. A trace of tritium may be present in this lower part, but it is not possible to state one way or the other with any degree of certainty. The oxygen-18 contents vary by almost 8‰ with a positive peak occurring in the pure ice. The ^{18}O contents then decrease towards the bottom of this section to the lowest value determined in the entire core of -27.7‰.

The lower section (1.6 to 2.6 metres) shows a similar

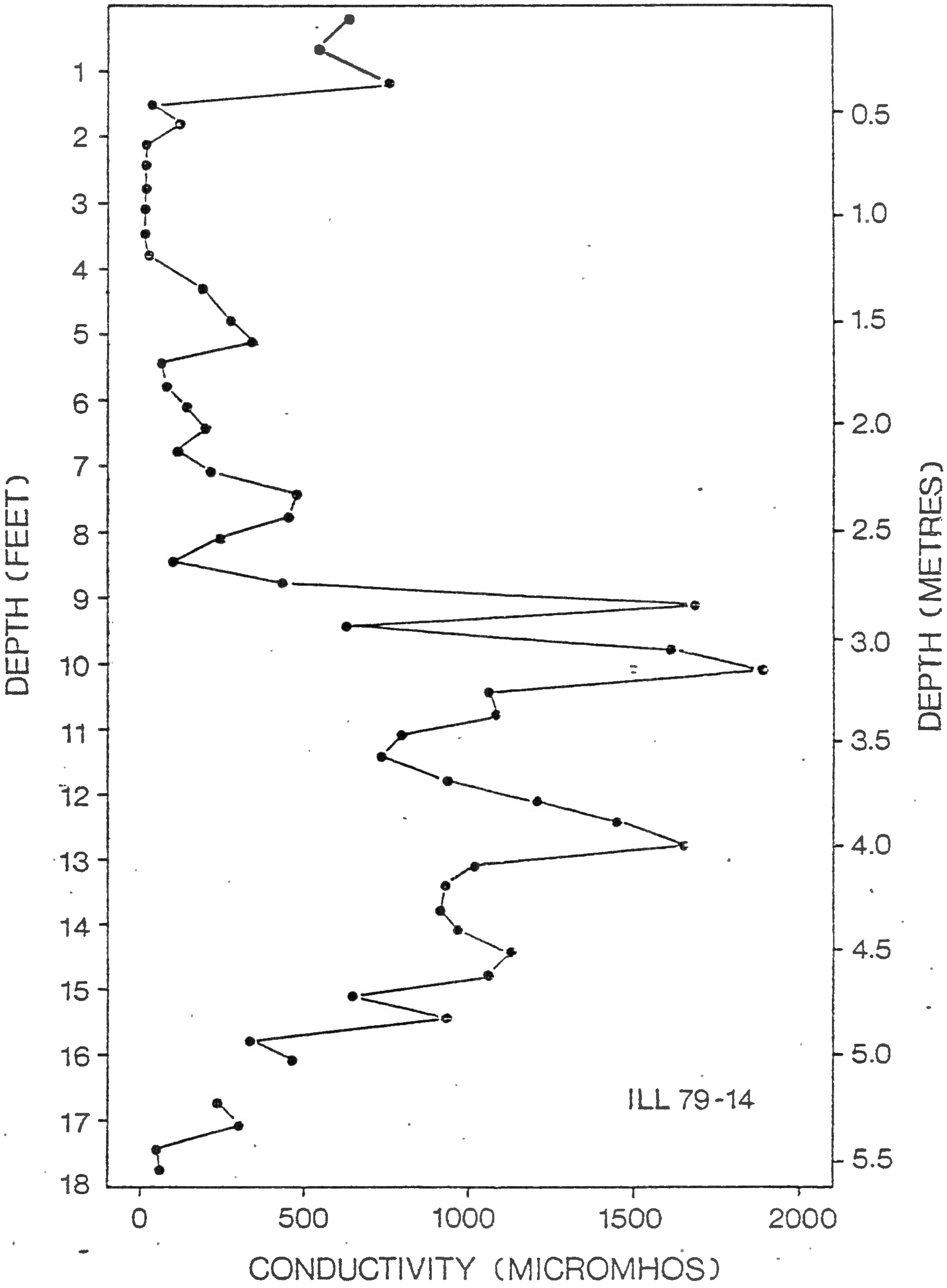

Figure 17 Conductivity with depth for core 79-14

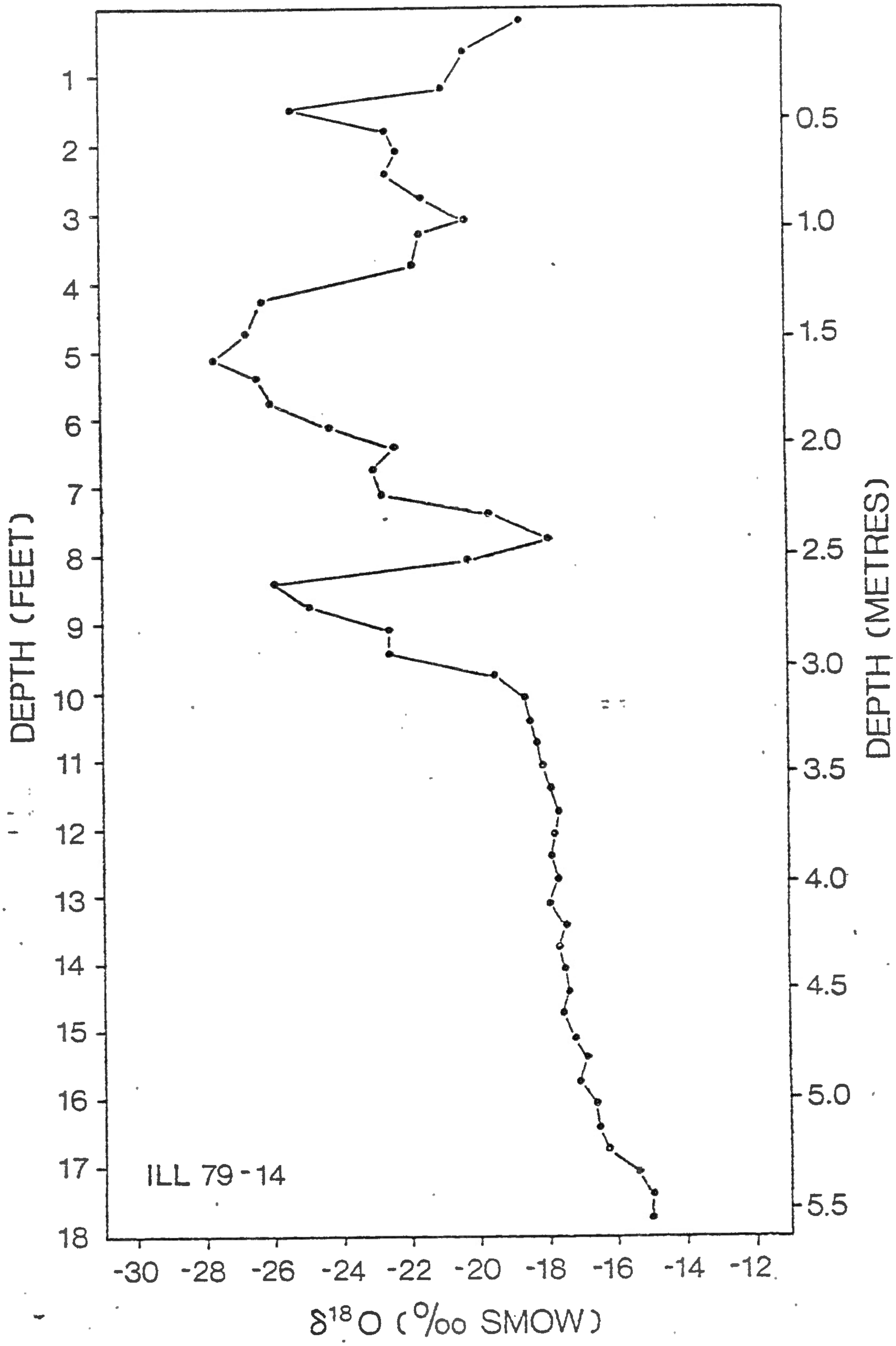

Figure 18 ^{18}O contents with depth for core 79-14

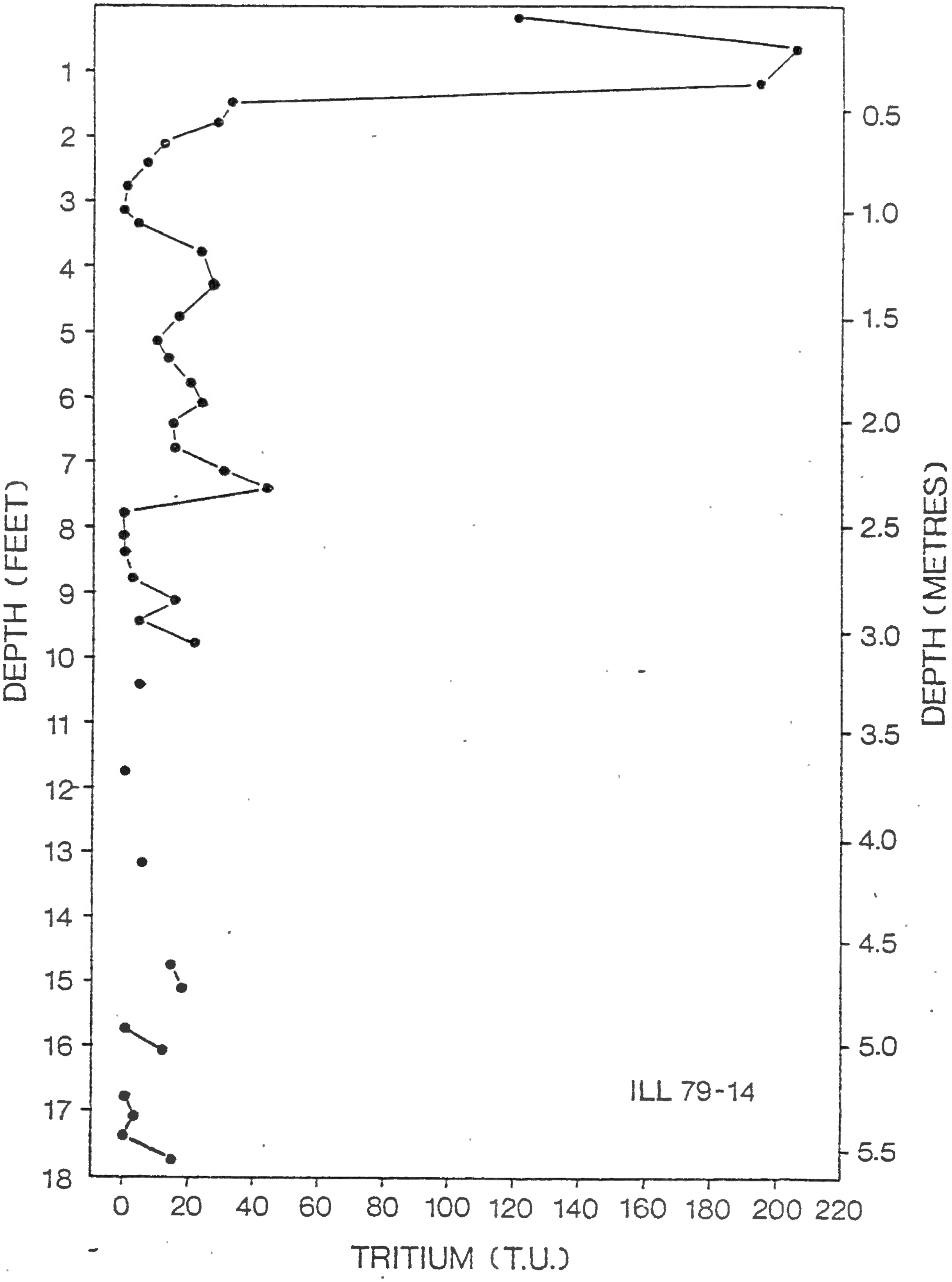

Figure 19 Tritium contents with depth for core 79-14

positive peak in the oxygen-18 data. From the top of this section, the ^{18}O contents gradually increase by almost 10‰ before dropping quickly by 8‰. Both the conductivity values and the tritium contents increase and decrease in unison with the oxygen-18 contents. These large shifts of 8 to 10‰ in the oxygen-18 contents are of the same magnitude as the large shifts noted in the Mackenzie Valley cores (Fritz and Michel, 1977). There is, however, one basic difference. In the Mackenzie Valley cores, once the shift to more negative values occurred, the oxygen-18 contents remained low and did not return to higher values with depth. The two oxygen-18 zones described in the pingo are both approximately one metre in thickness and both a positive and negative peak occur. Such variations would appear to be the result of reservoir effects. A similar variation, but of smaller magnitude, was generated in the laboratory experiments (column 4) conducted at Waterloo last year (Michel and Fritz, 1979). The presence of some tritiated water, in at least the lower half of the ice core, indicates that water which is less than 30 years of age has been incorporated into the core. Continued growth of the pingo and the ice core should result in the possible addition of more tritiated water. Such an addition would allow for a more complete study of this pingo and the mechanisms involved in its growth.

3.1.6 Ice Wedges

During the cutting of the drainage channel, several ice wedges of various sizes were exposed. Two of these ice wedges were sampled for the purpose of studying isotope variations across their width and in the adjacent sediments.

The largest ice wedge (79-I.W. #1) was sampled by drilling a series of short holes parallel to the long axis of the ice wedge. The drill was held horizontally by resting the drill rod on a levelled snow bank in front of the wedge. The width of the ice wedge along the plane of drilling was 102" (2.6 m) and was represented by forty holes in the wedge and two holes to the west of the wedge. Four samples were also collected from a separate ice body situated immediately above the main wedge. The location of each sample is shown in Figure 20. Within the ice wedge, each hole was drilled to a depth of 15 cm. With a few exceptions (see Appendix A), the first 5 cm of material were discarded, while the remaining 10 cm were collected as two samples.

The second ice wedge sampled (79-I.W. #2) was also located on the north channel wall but at the extreme western end. This wedge was sampled by drilling from the sea cliff face across the ice wedge. The core was sectioned into 5 cm intervals and consisted of the ice wedge and the adjacent sediments from both sides. Because this ice wedge was much smaller than the first, the entire core length was only 1.56 metres. Time has not permitted for the examination of this ice wedge during the present contract. Therefore, discussion will be restricted to the first ice wedge described.

Analytical work on ice wedge #1 is still in progress and this discussion will, therefore, be kept brief. The waters from both sets of samples have been examined for their conductivities and these measurements are plotted in Figure 21. Samples 2 through 37 consist

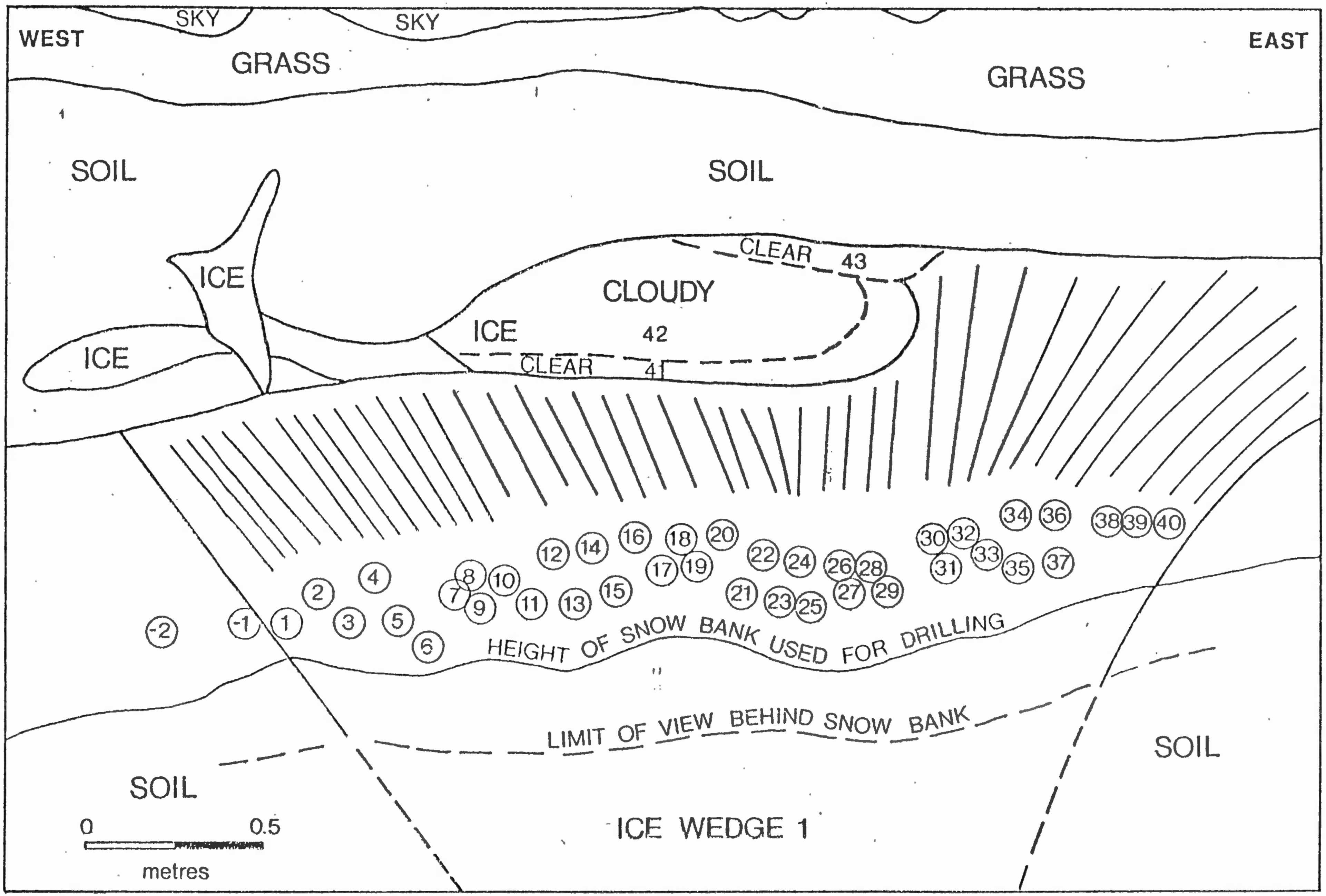

Figure 20 Sketch map of ice wedte #1 showing sampling locations

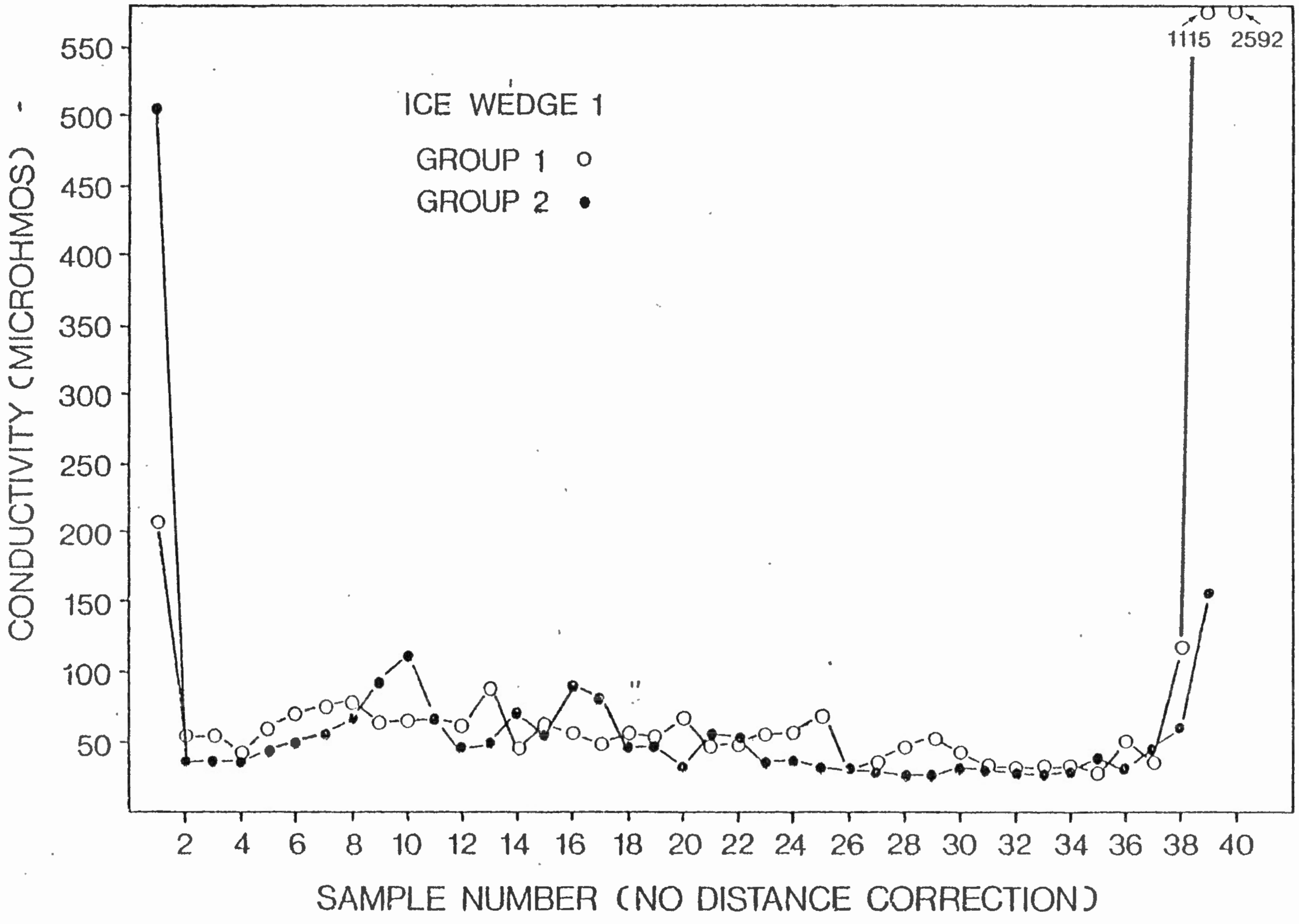

Figure 21 Conductivity profile across 79-I.W. #1

of massive ice with little or no soil present. At the extreme edges of the wedge, soil contents increase as do the conductivities. Because of this relationship, it is possible to see that the ice-soil contact is not perpendicular to the exposed face, but rather angles to the east with depth from the face. The low conductivities measured for this massive ice are similar to those measured for the massive ice core in the pingo.

Oxygen-18 contents have only been measured for the group two samples which were located the furthest from the exposed face. The pattern recorded by the oxygen isotopes (Figure 22) can best be described as a continuous series of peaks and valleys. The maximum difference in oxygen-18 contents is 3.1‰. These variations indicate that the ice wedge is composed of a series of individual layers which grew over a period of years. Each layer is represented by a peak-valley couplet which has formed by isotope fractionation during freezing. The age of the source waters cannot be determined until the tritium contents have been fully determined. Several determinations, which have been made, indicate that low tritium levels are present in sample 10, but none of the other analyses have definitely shown the presence of tritium. The determination of additional tritium and deuterium contents will permit a more complete discussion of the age of the ice wedge and the fractionation processes responsible for the isotope pattern developed.

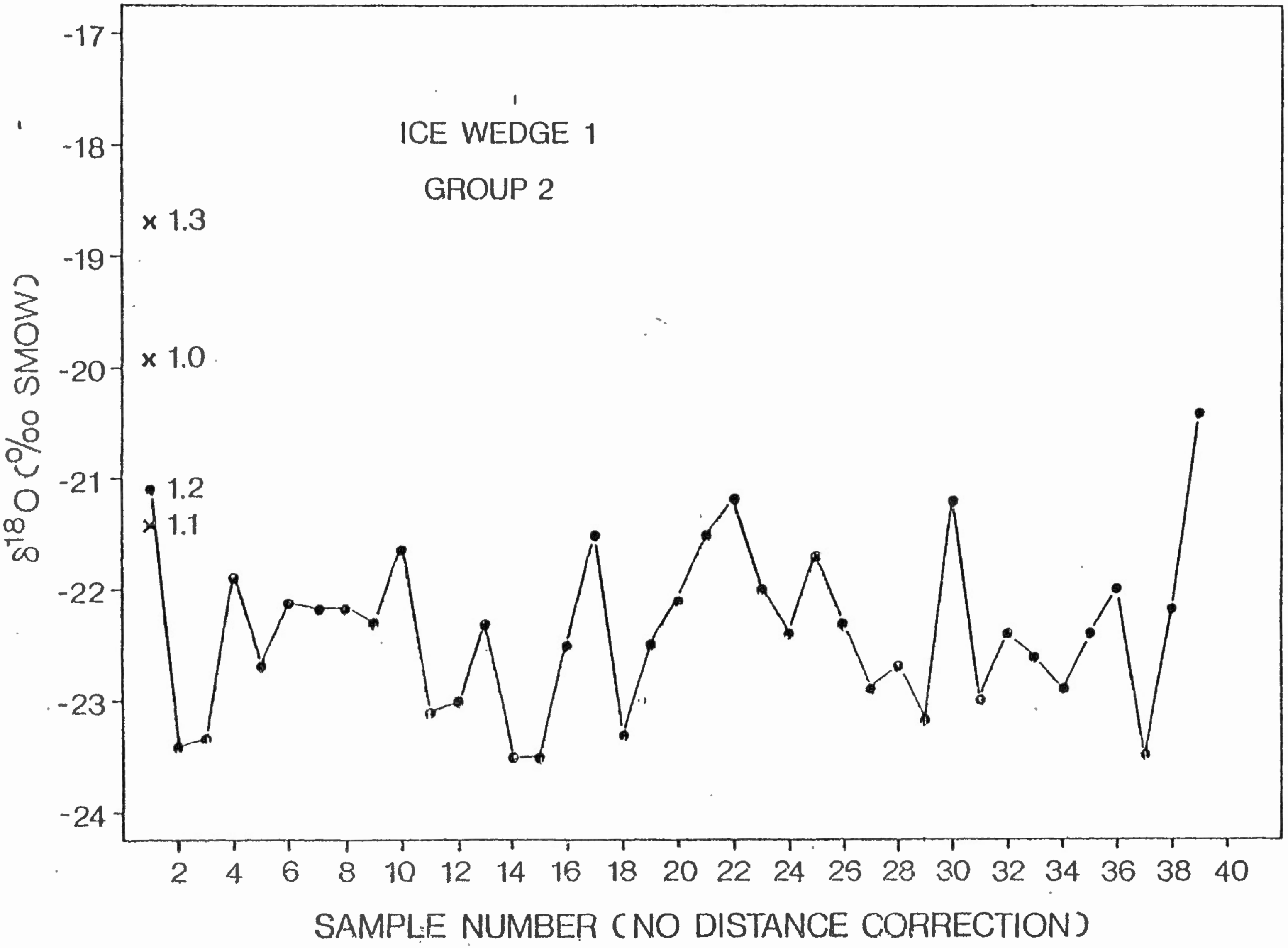

Figure 22 ^{18}O content profile across 79-I.W. #1

3.2 Arctic Islands

To date, only the single sample from the Sabine Peninsula and the three samples from borehole BHO-102 on Bathurst Island have been examined with the data listed in the appropriate appendices.

The isotope data from the borehole samples indicate the presence of a negative shift with depth. Whether or not this shift is similar to those noted in the Mackenzie Valley cores studied in 1977 cannot be ascertained with any certainty. It is possible that these data merely represent reservoir effects as seen in the pingo core at Illisarvik. It must be remembered, however, that these reservoir effects were restricted to the massive ice core. On Bathurst Island, the sediments, from which the waters were extracted, consist of clay till type material. Only small amounts of water were obtained from these samples. It would, therefore, appear likely that the isotope contents of these three samples may represent a major negative shift similar to those seen in the Mackenzie Valley.

The single sample from the Sabine Peninsula produced a large amount of water with a conductivity higher than any other sample analysed. As discussed earlier, in section 3.1.3, high water contents have been related to low conductivities. The Sabine Peninsula water, therefore, poses somewhat of a problem. This high conductance may be the result of either the shale beds within which the ice has formed or, the purification of sea water by salt expulsion during freezing.

The presence of low levels of tritium in this sample indicates that the ice has formed within the last 30 years. A complete discussion of the history and formation of this ice rich section cannot be undertaken without a better understanding of the local geology.

3.3. Laboratory Experiments

3.3.1 Introduction

During this contract period, a total of two experiments were performed and are labelled in sequence with the experiments conducted last year.

Experiment six was run over a period of 1131.5 hours, while experiment seven lasted only 366.75 hours. Both experiments used the medium grained Hawkesville sand described in an earlier report (Michel and Fritz, 1978a). In the following sections, each experiment is described in detail, with all of the temperature data recorded in appendices at the end of this report. Moisture contents are calculated as a percent of the dry weight of the soil. Because of the smaller amount of water required, only deuterium has been analysed on these waters where possible.

3.3.2 Experiment 6

For this experiment, a 45 cm long column was packed with a saturated sand mixture. The excess water was removed after the column had been filled to within 1 cm of the top. The column was fully insulated on the sides with the styrofoam blocks. The heater block on the top of the column was kept in direct contact with the air, while the bottom heater was set on top of 7.5 cm of insulation. Small styrofoam chips were packed around the sides of the top heater to prevent any leakage of cold air down along the sides of the column.

The temperature readings taken over the 1131.5 hours that the experiment was conducted are recorded in Appendix D. Throughout the entire length of the experiment, freezing occurred from the top downwards. Unlike the experiments conducted during the 1978-79 period, relatively high temperature gradients were required to maintain the freezing front at a fixed position.

During the early hours of the experiment (Figure 23), a temperature gradient of 9 to 13°C per metre existed. The gradient gradually decreased to the 9°C per metre level 93.5 hours into the experiment. In an attempt to reduce the gradient further before freezing began, the temperature of the top heater was increased. As is evident from Figure 24, the adjustment resulted in the development of a reversed gradient in the upper 15 cm of the column. Readjustment of the base heater after the 167.5 hour mark caused the temperature within the entire column to rise approximately two degrees.

By the 248 hour mark (Figure 25), the temperature reversal in the upper 15 cm had been eliminated, but the gradient had increased to 15.5°C per metre below the 20 cm depth. Temperature readjustments shifted the temperature throughout the column upwards by half a degree at this point in time.

A final attempt to decrease the temperature gradient at 298.25 hours caused the temperature within the column to rise approximately 1.5°C. Before this rise occurred, the temperature in the top 20 cm of the column had fallen a few tenths of a degree below zero.

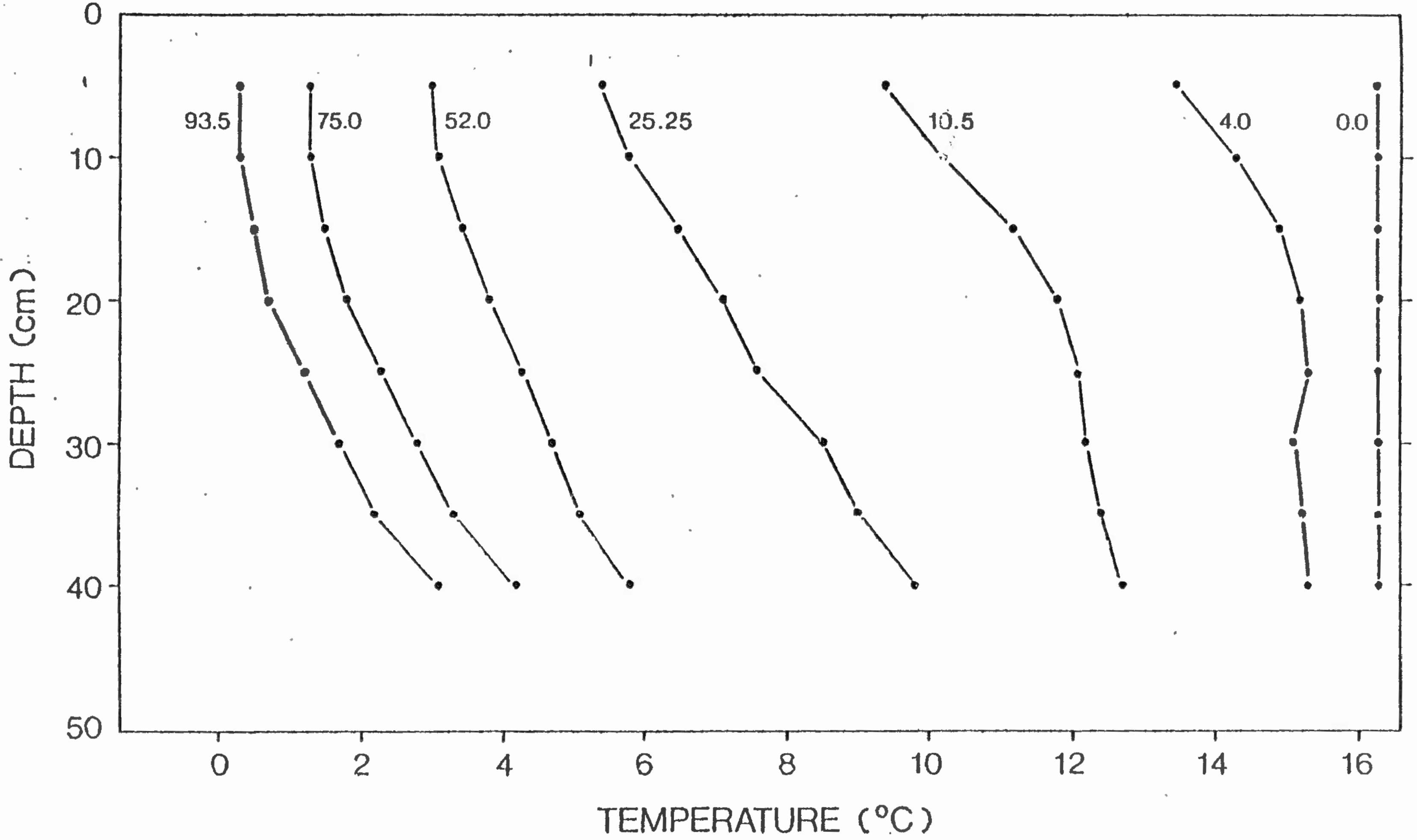

Figure 23 Temperature changes with depth in experiment #6 during the period 0 to 93.5 hours

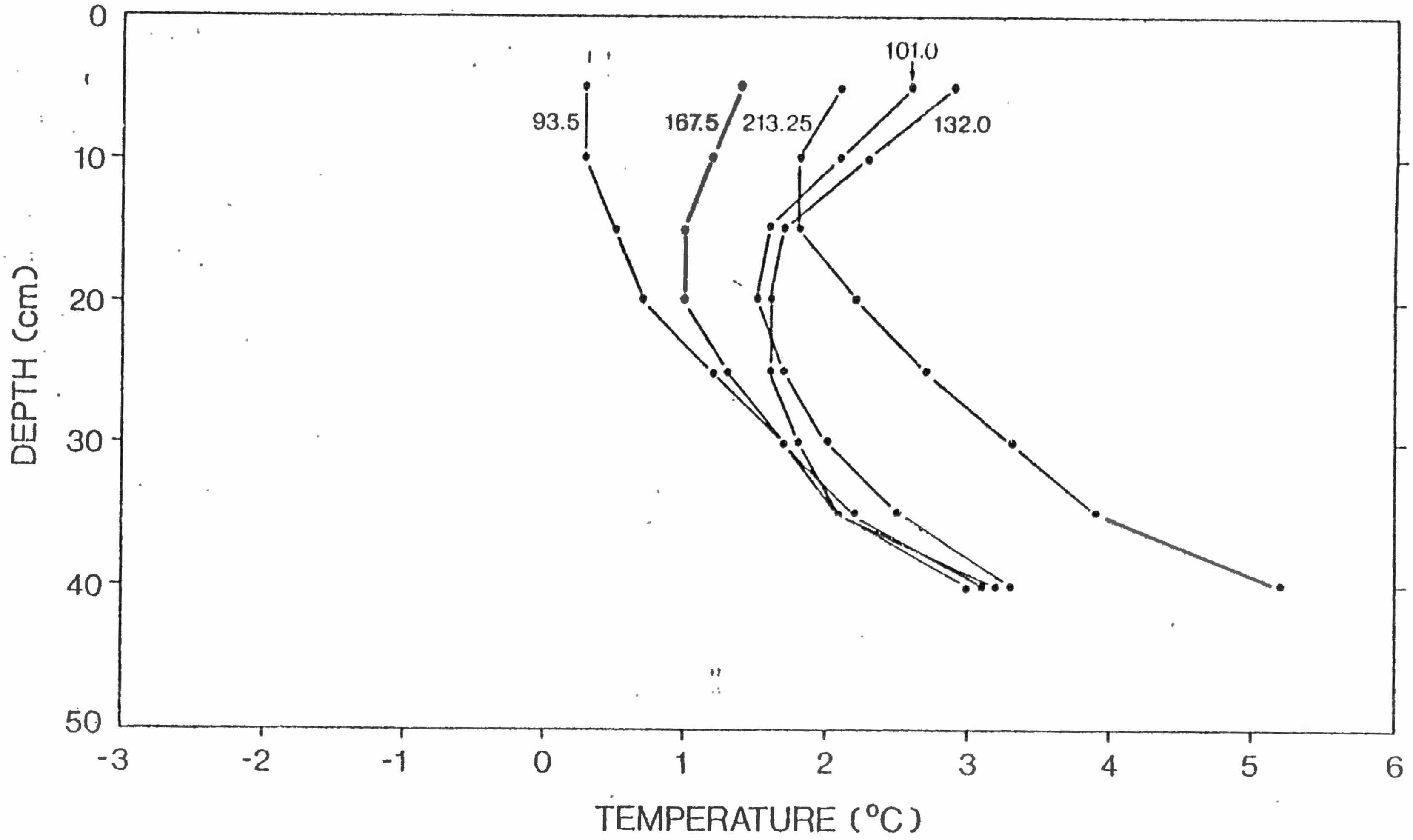

Figure 24 Temperature changes with depth in experiment #6 during the period 93.5 to 213.25 hours

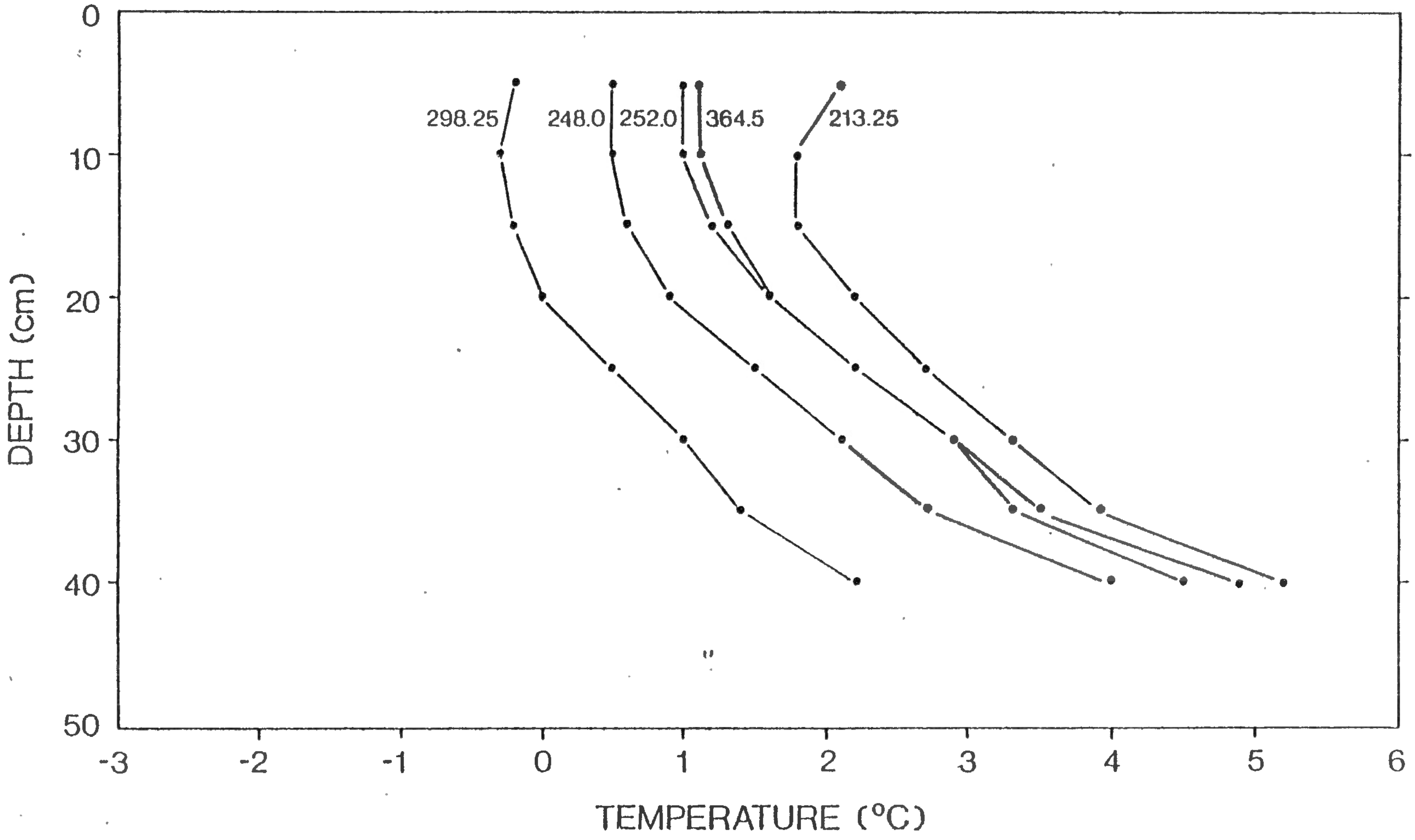

Figure 25 Temperature changes with depth in experiment #6 during the period 213.25 to 364.5 hours

The rise in temperature was halted at the 364.5 hour mark and from this time on the column was allowed to gradually cool. Freezing in the upper 10 cm of the column began by the 390 hour mark (Figure 26) and the freezing front was stabilized at a depth of 20 cm shortly after 400 hours into the experiment.

The freezing front was maintained at this depth for approximately 150 hours (Figure 27). During the next 200 hours, the temperature gradually decreased to $-0.2^{\circ}C$ at this 20 cm depth. It then was allowed to decrease more rapidly until the end of the experiment. Throughout the period during which the freezing front was relatively stable, a temperature gradient of approximately $10^{\circ}C$ per metre existed. As can be seen from Figure 27, the column temperatures fluctuated over a wide range during the first 400 hours of continuous readjusting but was remarkably constant afterwards. Once the column was dismantled, the frozen-unforzen interface was clearly visible at a depth of 37 cm as a change from ice bonded to soft, unfrozen sand. Moisture content determinations as listed in Table 2, indicate that the average water content in the column was 18.2%. A comparison of the deuterium contents (Table 3) with the water contents in Figure 28 shows that variations in both parameters were created during freezing.

In the top 20 cm of the column, decreases in the water content correlate with increases in the deuterium concentration and vice a versa. The lower 25 cm of the column does not show this trend however. The two sections, where the water contents are the lowest, correspond to those zones immediately above the positions of the freezing fronts during the stable 350 hour period and at the end of the experiment.

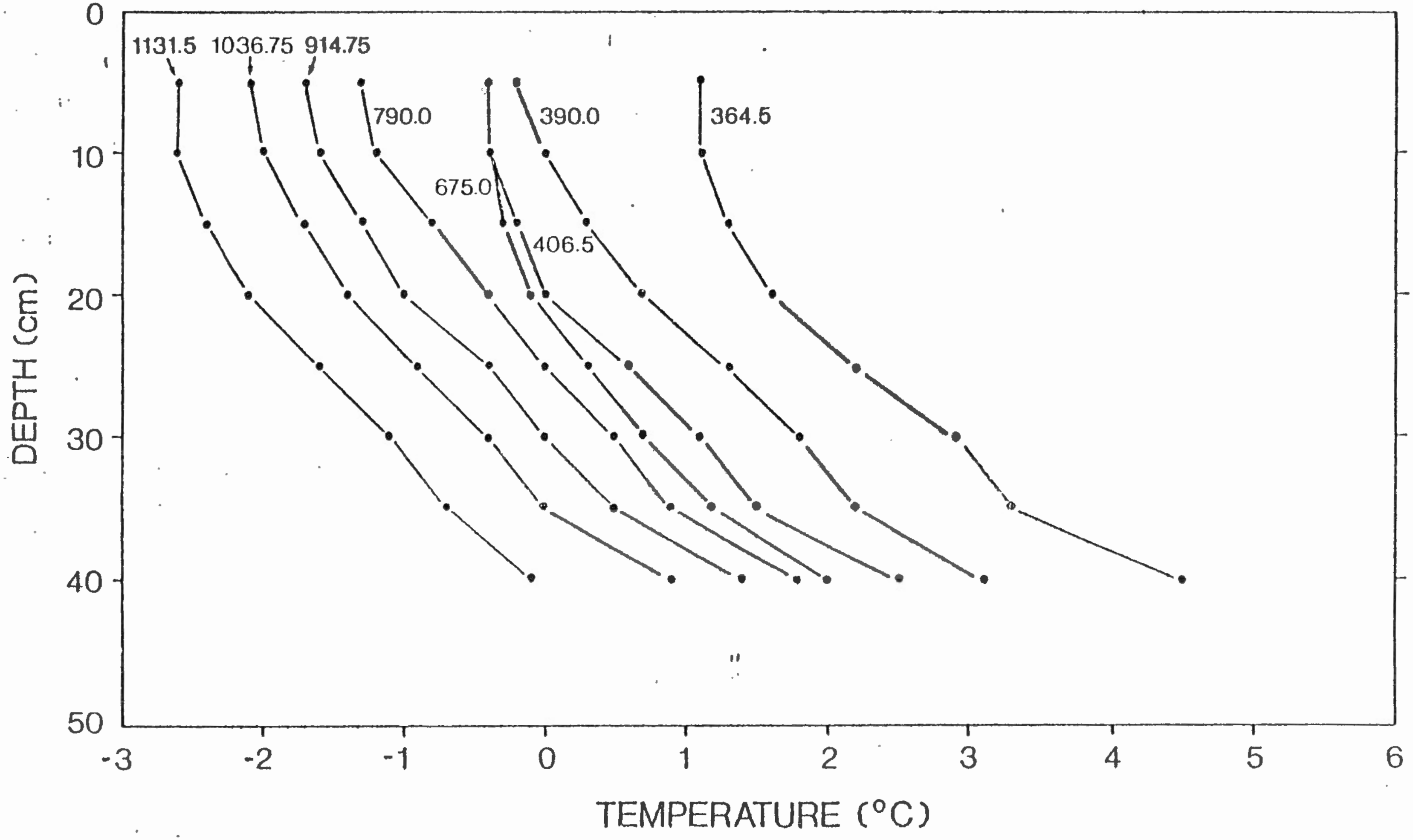

Figure 26 Temperature changes with depth in experiment #6 during the period 364.5 to 1131.5 hours

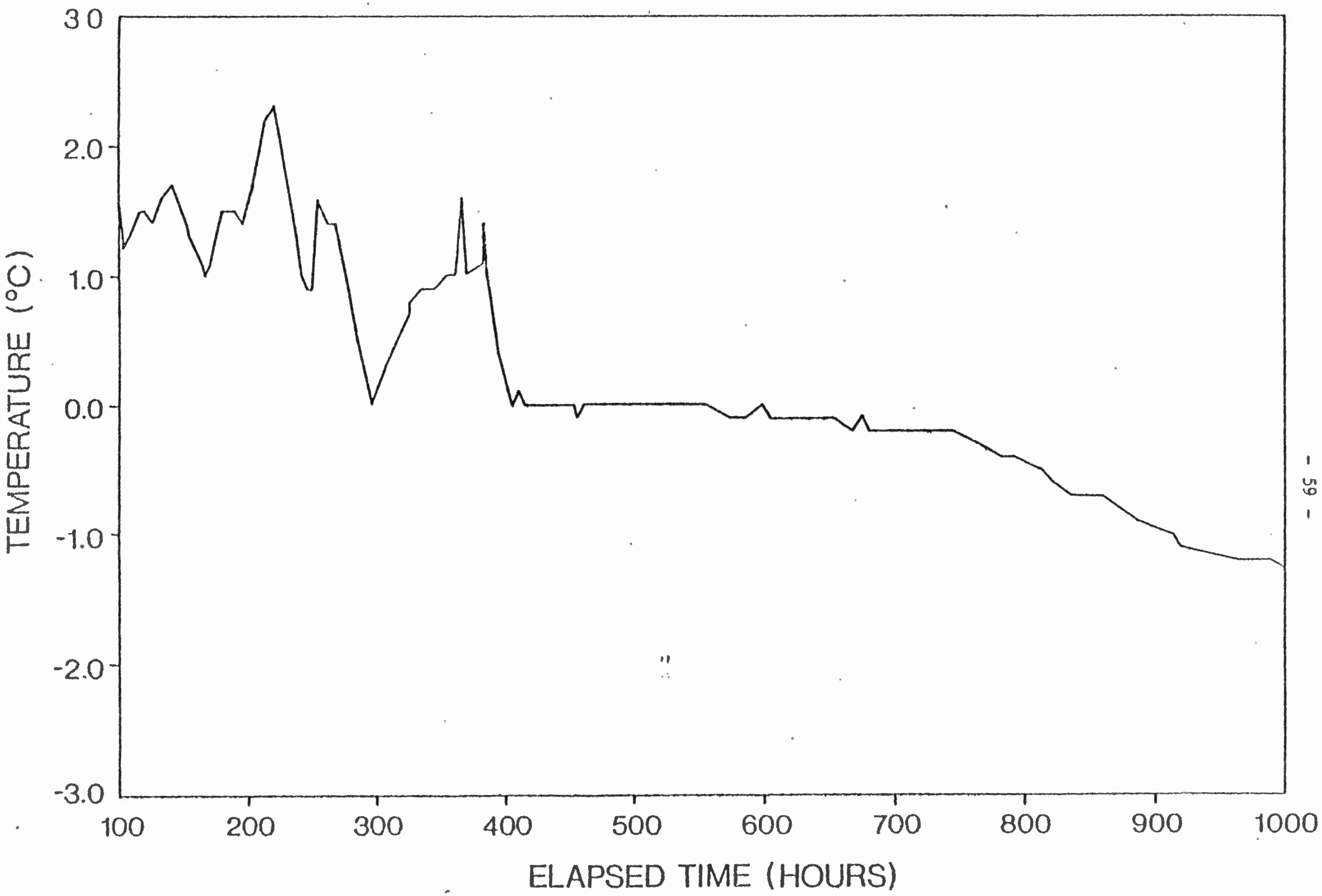

Figure 27. Temperature variations with time for experiment #6 at the 20 cm level

TABLE #2: MOISTURE CONTENTS WITH DEPTH IN EXPERIMENT #6.

LISTED AS % OF DRY SOIL WEIGHT.

SAMPLE	DEPTH (CM)	MOISTURE CONTENT (%)
6-1	0-5	18.0
6-2	5-10	17.3
6-3	10-15	19.2
6-4 UPPER	15-17.5	14.7
6-4 LOWER	17.5-20	18.5
6-5	20-25	20.5
6-6	25-30	19.6
6-7	30-35	18.9
6-8	35-37	14.9
6-8 u	37-40	20.0
6-9 u	40-45	16.2

u = UNFROZEN SECTION

AVERAGE WATER CONTENT

(WEIGHTED ACCORDING TO THICKNESS) 18.2

TABLE #3: DEUTERIUM CONTENTS WITH DEPTH IN EXPERIMENT #6

SAMPLE	DEPTH (CM)	δ^2H (0/00 SNOW)
Std. Water	-	-76
Initial Water	-	-76
6-1	0-5	-78
6-2	5-10	-75
6-3	10-15	-77
6-4 UPPER	15-17.5	-74
6-4 LOWER	17.5-20	-74
6-5	20-25	-75
6-6	25-30	-77
6-7	30-35	-77
6-8	35-37	-78
6-8 u	37-40	-78
6-9 u	40-45	-76

u = UNFROZEN SECTION

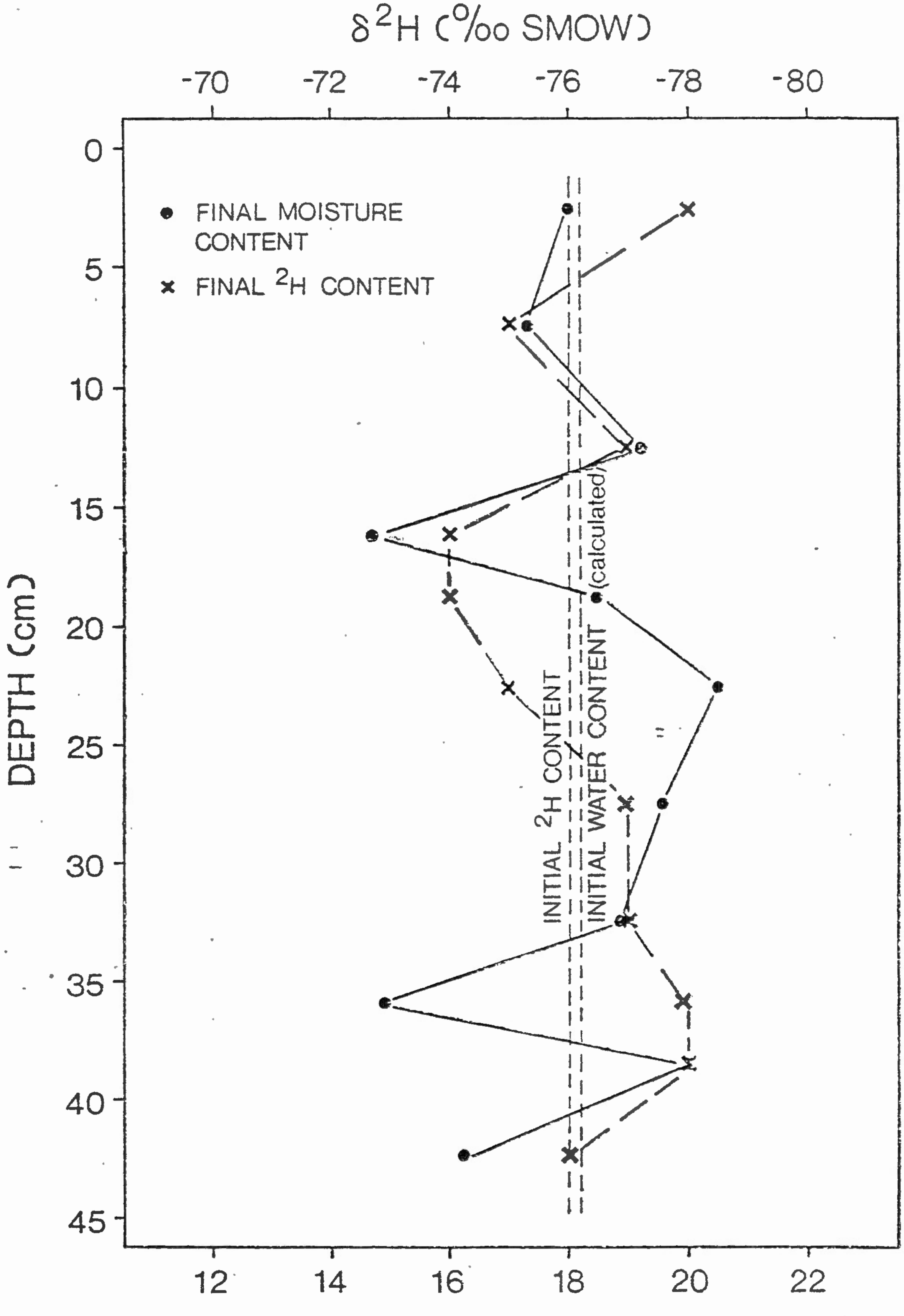

Figure 28 Moisture content and deuterium variations with depth in experiment #6

The major enrichment of deuterium, above the column average, also occurs at the position of the stable freezing front. It would, therefore, appear that migration of water and fractionation of the deuterium isotope occurred as a consequence of the stable freezing front even though the sand soil was saturated. The depletion of deuterium in the water of the lower column would then explain the poor relationship between the two parameters at the 36 cm level.

From this experiment, it is evident that when conditions permit the stabilization of a freezing front, it is possible to generate zones of isotope enrichment and depletion and moisture migration even in saturated, coarse grained materials. The effect of a decreased temperature gradient or an increased period of stabilization on the magnitude of these variations is unknown at this time.

3.3.3 Experiment 7

In this experiment, a 45 cm long column was packed with saturated sand for the bottom 10 cm and air dried sand for the remaining 35 cm. The air dried sand had a moisture content of less than 0.1%. Compaction of the lower saturated sand by the overlying dry sand resulted in the excess water moving upwards into the adjacent 2 or 3 cm of dry material. The heater blocks and insulation were assembled in the same manner as described for experiment six. All of the temperature readings taken over the entire 366.75 hour period are recorded in Appendix E.

Prior to the initiation of this experiment, it was decided to attempt to stabilize the freezing front in a much shorter period of time than taken in experiment six and thereby reduce the overall time required to conduct the experiment. It was also decided to terminate this experiment without allowing the freezing front to progress downwards after the main period of stabilization.

With these thoughts in mind, the temperature was decreased quickly towards the freezing point. As can be seen from Figure 29, the saturated zone initially had a higher temperature than the overlying dry material, but within the first five hours, these relative temperatures were reversed. The rapid decrease in the temperature of the top heater resulted in the gradient increasing from nearly isothermal conditions at the 14 hour mark to 12°C per metre at the 26 hour mark. By the time the experiment had run for 48 hours, the top 10 cm of the column were experiencing negative temperatures and the gradient had increased to 21°C per metre. At this point, the temperature of the top heater was increased in an attempt to decrease the gradient. As can be seen in Figure 30, the gradient was reduced slightly to 18°C per metre and was then maintained until the experiment was terminated.

The tight clustering of the temperature gradients in Figure 30 after the 125 hour mark indicates that the freezing front remained relatively stable throughout the remainder of the experiment. Figure 31, which plots the temperature with time for the thermocouples at depths of 10 and 15 cm, indicates that although small temperature fluctuations were present, the freezing front was stabilized at a depth of approximately 12 cm for in excess of 200 hours.

When the experiment was terminated, the column was maintained

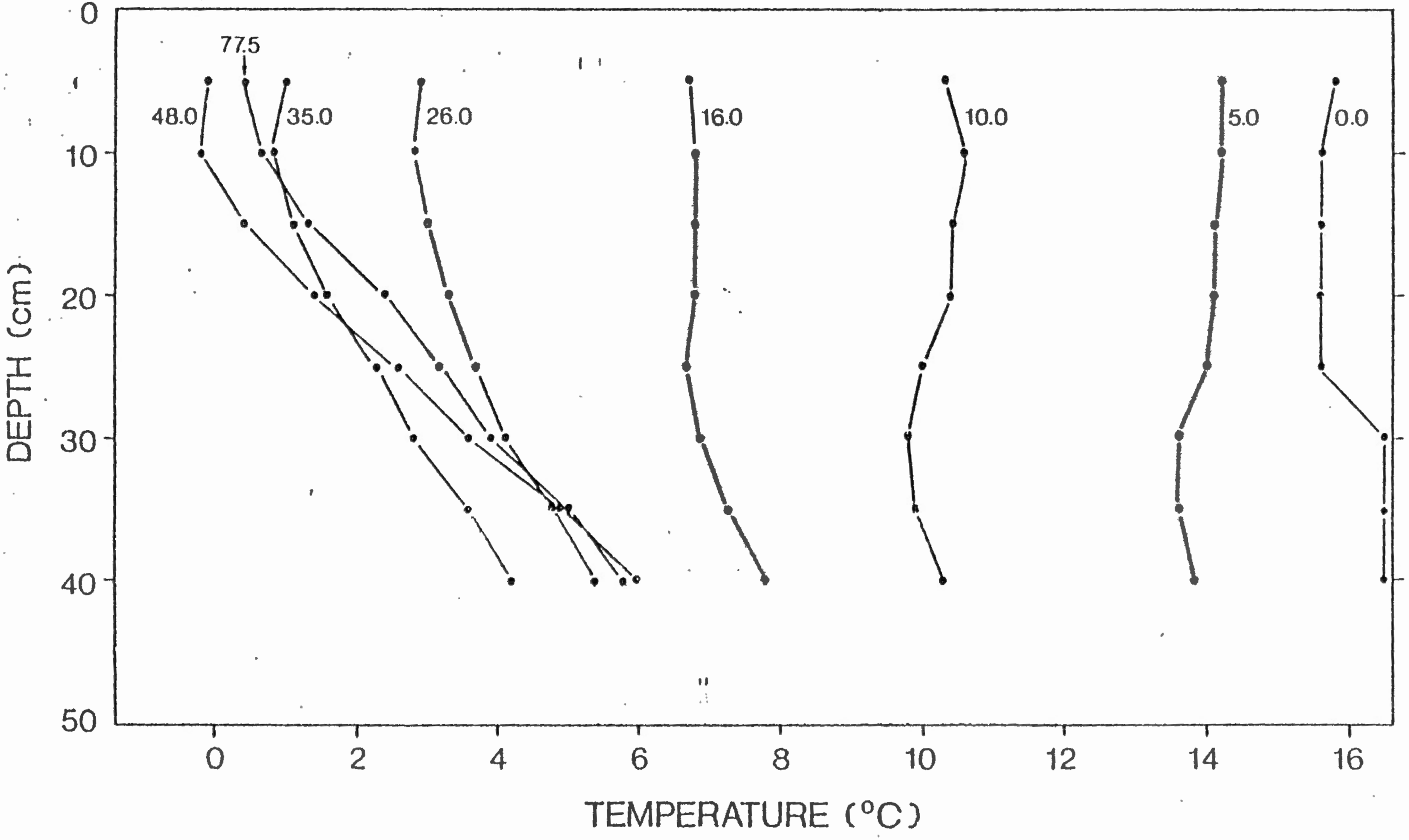

Figure 29 Temperature changes with depth in experiment #7 during the period 0 to 77.5 hours

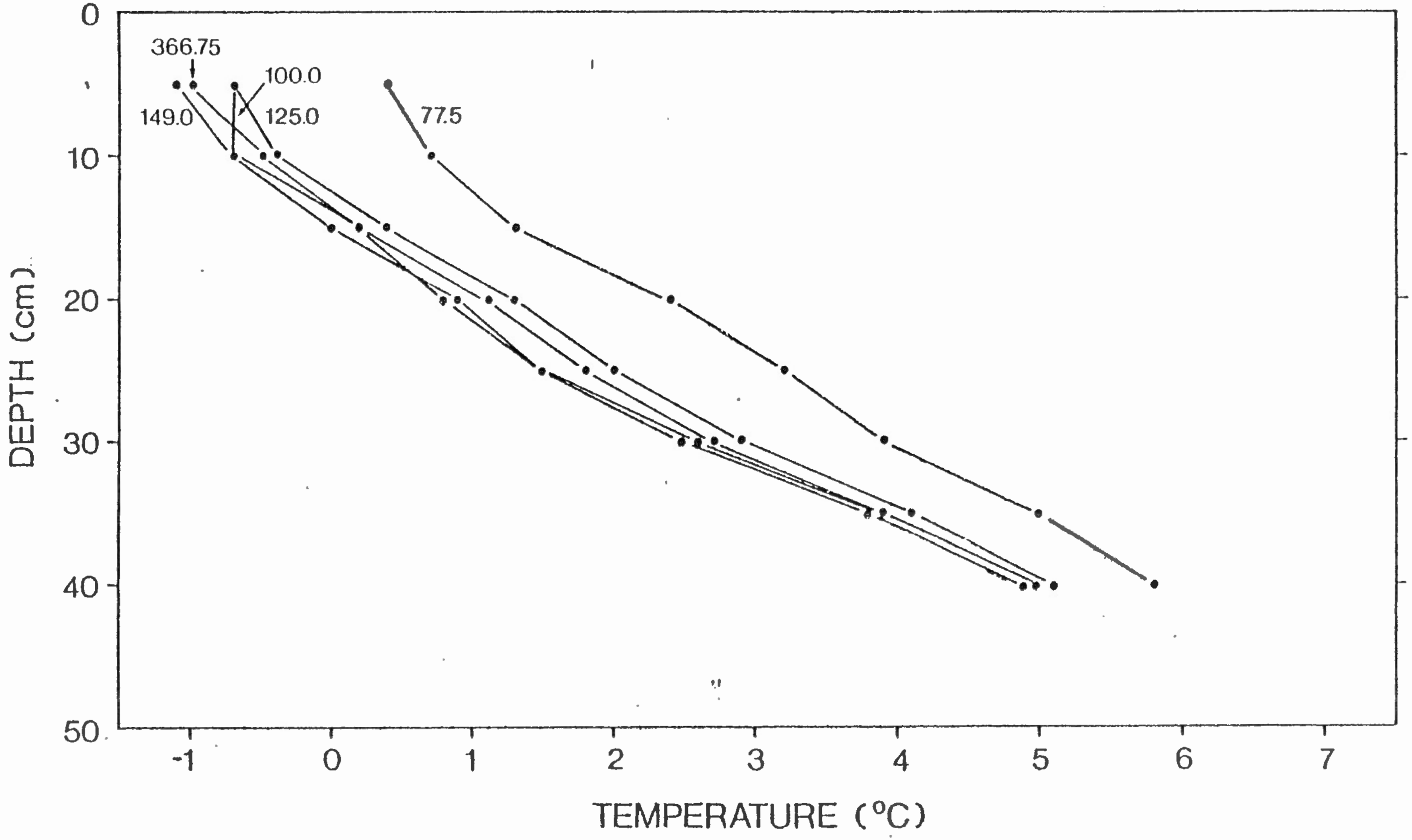

Figure 30 Temperature changes with depth in experiment #7 during the period 77.5 to 366.75 hours

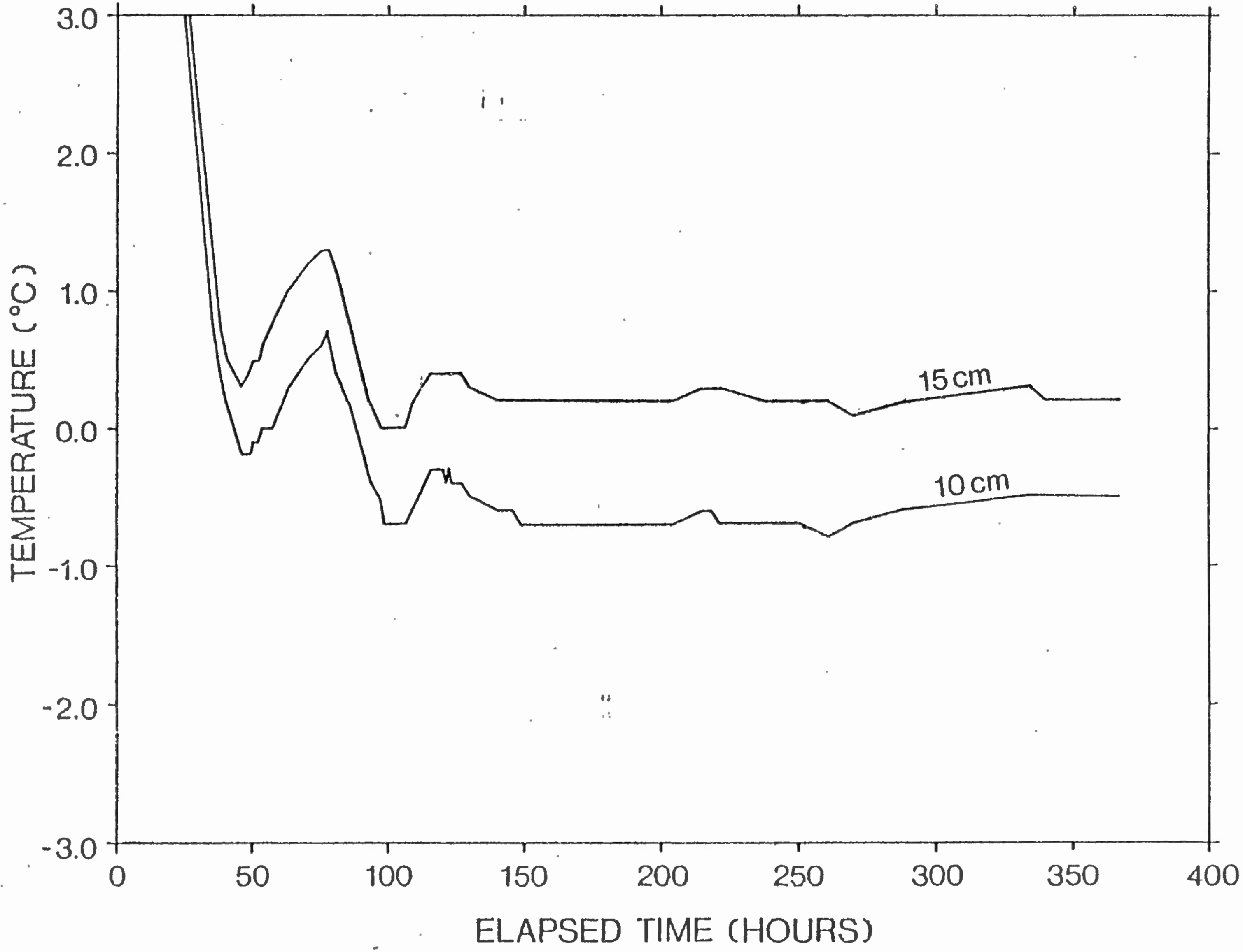

Figure 31 Temperature variations with time for experiment #7 at the 10 and 15 cm levels

in an upright position and the heater removed. Since no ice bonding occurred in even the frozen section, it was possible to scoop the individual samples from their respective sections by hand. Once a section had been sampled, the column ring was dismantled and the remainder of the soil material was removed. Each section was sampled following this same procedure.

During sampling and dismantling, changes in the sediments were recorded. The upper 10 cm were dry but very cold. Moisture was first noted at a depth of 13 cm or just below the freezing front. With depth, the moisture contents gradually increased to a depth of 33 cm where the soil appeared to be nearly saturated. This was approximately the depth at which the original boundary between the dry and saturated material occurred. Only the bottom 5 cm of soil were described as definitely being saturated.

Moisture content determinations (Table 4) indicate that the visual descriptions recorded at the time of dismantling were accurate. As shown in Figure 32, the upper 15 cm contained less than 1% water, but every interval was higher than the dry sand originally placed in the solumn. The moisture contents continued to increase to the basal section where a water content of 15.6% was measured. Even this highest water content was less than the average value for the saturated sand in experiment six. By estimating the original moisture content profile and by assuming that all of the water in the column was originally contained in the lower 12 cm, an average value for the lower saturated sands of just over 18% is attained. This is in excellent agreement with the previous experiment.

TABLE #4: MOISTURE CONTENTS WITH DEPTH IN EXPERIMENT #7

LISTED AS % OF DRY SOIL WEIGHT

SAMPLE	DEPTH (CM)	MOISTURE CONTENT (%)
7-1	0-5	0.2
7-2	5-10	0.3
7-3	10-15	0.8
7-4	15-20	3.6
7-5	20-25	4.7
7-6	25-30	5.3
7-7	30-35	6.4
7-8	35-40	8.9
7-9	40-45	15.6

It is obvious from this experiment that water migrated towards the freezing front through unsaturated, coarse grained material. Because of the coarseness of the sand, this migration must have occurred in the form of vapour transport. To see the effect that vapour transport through unsaturated sands has on the isotope contents of the water, an attempt was made to extract water from the sediment. As stated earlier, only the two lowermost samples yielded any water and as a result, new extraction equipment is under construction.

The two deuterium measurements made on these lower waters (Table 5 and Figure 32) indicate that these waters became depleted in deuterium relative to the initial concentrations. Although the deuterium concentrations have not been measured for the upper sections of the column, it is possible to estimate the contents by using a simple mass balance equation. By knowing the initial deuterium concentration of the waters and the final deuterium contents of the lower waters, the undertermined concentrations can be estimated based on an assumption of whether these concentrations are constant or vary throughout the upper column. By assuming that they are constant, a minimum value of -74‰ is obtained. Since a continuous variation is likely, the deuterium contents of the uppermost waters can be expected to be much more positive. The simple calculation used in estimating even the minimum deuterium concentration shows an enrichment of about 8‰ in the upper waters. The importance ov vapour transport mechanisms in generating the isotope variations found in permafrost related waters requires additional attention. The effects of an increased time period and thus a larger transport of water to

TABLE #5: DEUTERIUM CONTENTS WITH DEPTH IN EXPERIMENT #7

SAMPLE	DEPTH (CM)	8 ^{2}H (0/00 SNOW)
Std. Water	-	-77
Initial Water	-	-78
Tap Water	-	-77
7-1	0-5	
7-2	0-10	
7-3	10-15	
7-4	15-20	
7-5	20-25	
7-6	25-30	
7-7	30-35	
7-8	35-40	-82
7-9	40-45	-81

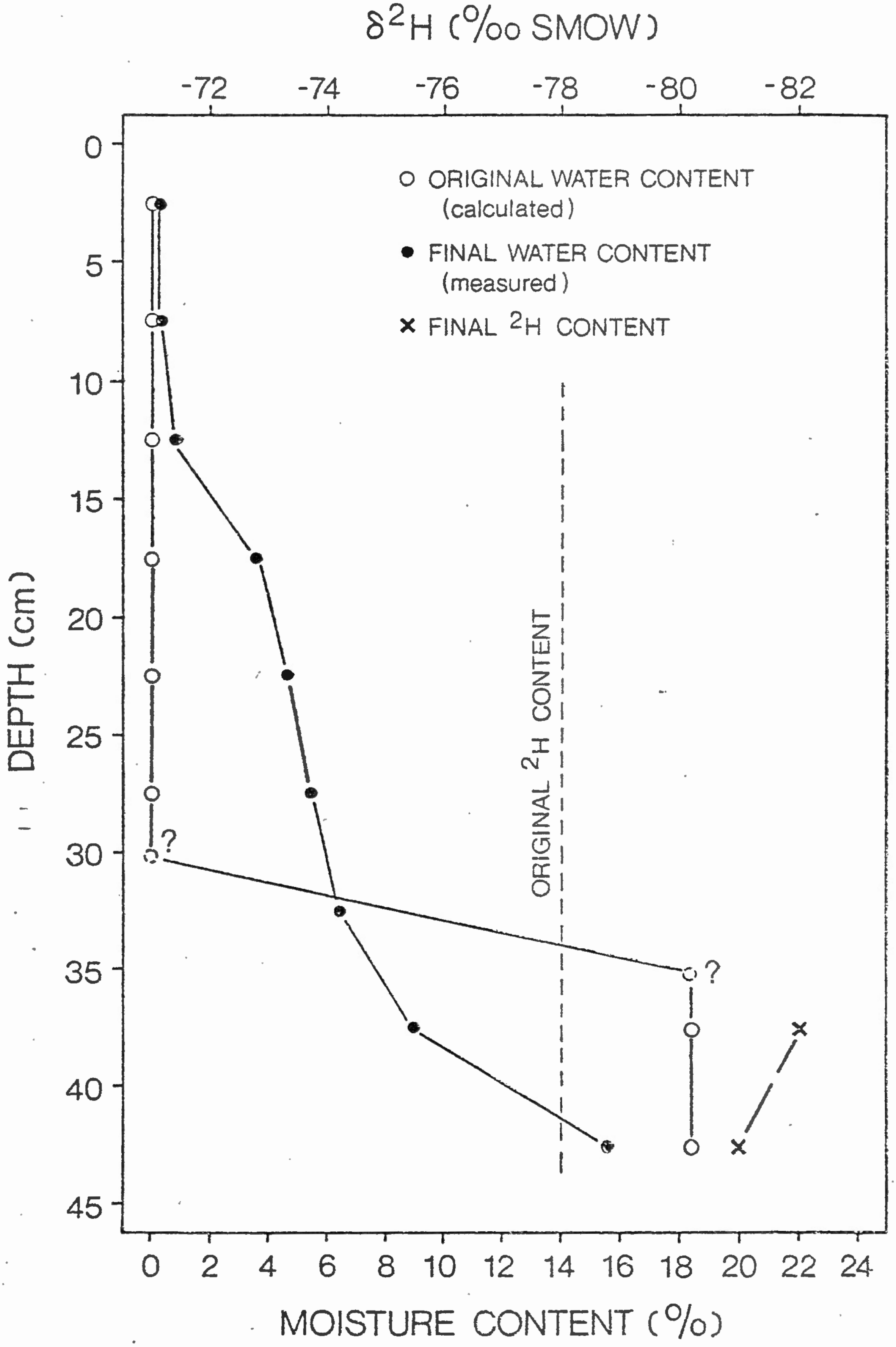

Figure 32 Moisture content and deuterium variations with depth in experiment #7

the upper sediments must also be examined. The major discrepancy between experiment seven and the field observations are the water contents. Many of the soils investigated, which show the large negative isotope shift, contained water contents in excess of 20%. Only continued experimentation will ultimately solve this problem.

4. Summary and Conclusions

4.1 Illisarvik

During May of 1979, a number of cores were collected from Illisarvik, all of which are still in the process of being analysed. The complexity and size of variations being examined has resulted in requiring the detailed analysis of each and every sample collected. Although tedious and time consuming, the understanding of freezing processes that will be gained by completing this work in detail should be of benefit to anyone working on moisture migration in frozen soils.

At present, a number of preliminary observations can be stated. The conductivity of the soil water is directly related to the moisture content of the soil and to the type of soil itself.

Within the older permafrost surrounding the lake, a number of positive ^{18}O peaks were described from various depths. These peaks are in the order of 1 to 3‰ and are believed to be the result of fractionation processes occurring during freezing. If they are, the presence of these peaks would indicate that moisture migration is a very slow precess under the existing conditions. Variations in the ^{18}O contents and the presence of high tritium concentrations can clearly define the lower boundary of the active layer during the past 30 years.

During examination of the lake bed sediments, that were frozen during the winter of 1978-79 for the first time, a gradual depletion in the heavy isotopes was noted with depth. This fractionation of the isotopes occurred under equilibrium conditions. The relationship between ^{18}O and ^{2}H for these waters indicates that the meteoric water line for this area can be described by the equation: $\delta^{2}H = 8\ \delta^{18}O - 8.0$.

Reservoir effects are considered to be responsible for the large variations of up to 10‰ seen for oxygen-18 contents in the ice core of the pingo. The generation of both a positive and negative peak, within a thickness of approximately one metre, would suggest that the large negative shifts seen in the Mackenzie Valley cores are the result of some other process. However, until all of the analytical work is completed, the possibility of large reservoir induced variations cannot be totally ignored.

4.2 Arctic Islands

Although only a few samples have been analysed, preliminary conclusions can be drawn about the waters at the two sites examined. The ice rich shales of the Sabine Peninsula contain water that is less than 30 years of age. This water had the highest conductance of any waters examined and, although still relatively low; the combined high conductance and high water content might indicate that this water may have originally been sea water. The three samples examined for their ^{18}O contents from Bathurst Island show a major shift to more negative values with depth. This shift could very well be similar to the shifts observed in the Mackenzie Valley cores, but due to the small number of points examined it is not possible to say with any degree of certainty.

4.3 Laboratory Experiments

Two column experiments were conducted during the present contract period. The first experiment demonstrated that movement of water and isotopes in a saturated sand soil towards a stable freezing front can occur. The magnitude of the isotope variation generated was increased significantly during the second experiment. In this experiment, the freezing front was stabilized within an upper unsaturated zone overlying saturated sands. Movement of water towards the freezing front by vapour transport was also clearly documented in this experiment. Because of difficulties in extracting the water from the upper unsaturated sand, only a minimum deuterium shift of 8‰ could be estimated.

4.4 Suggestions for Continued Work

The successful demonstration during the present contract of both water and isotope movement in saturated and unsaturated sands makes the continuation of this experimental work imperative. The excellent performance of the control apparatus should permit the expansion of this work to several columns operating simultaneously. The collection of additional samples from Illisarvik, during the spring of 1980, would supplement the data obtained during the present contract and would permit the examination of the affects that a second winter of freezing has had on the lake bed sediments. The processing of samples could be sped up by overcoming the extraction bottleneck.

A final attempt should also be made to obtain samples from the Alaska Highway route. Although the age of these samples may have resulted in contamination during storage, it is felt that an attempt should be made to examine the waters from this region.

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APPENDIX A

ILLISARVIK

FIELD LOGS

MAY 1979 EXPEDITION

ILL 79-1 (33)

Grid Location:	0+03S, 1+35E	Date:	May 7, 1979
Hole Length:	167" (4.24 m)	Core Length:	164" (4.16 m)
Sample Thickness:	2" (5 cm)	Core Diameter:	3" (7.5 cm)

0-2" (0-5 cm)	Sandy organic, minor Vx ice
2-14" (5-35.5 cm)	Sand, Vx ice in vugs
14-18" (35.5-45.7 cm)	Silty Clay, ice lenses up to 1/16" thick
18-164" (45.7-416.5 cm)	Uniform sand throughout remainder of core after ice lenses. Top intervals show horizontal banding at approx. 68", slight angle develops at 148", angle of bedding is 20°, frozen to 164"
164-167" (416.5-424.2 cm)	Soupy sand, material lost (unfrozen)
167" (424.2 cm)	End of hole

ILL 79-2 (34)

Grid Location: 2 + 50 N, 1 + 50 E
Date: May 7, 1979
Hole Length: 172" (4.37 m)
Core Length: 172" (4.37 m)
Sample Thickness: 4" (10 cm)
Core Diameter: 3" (7.5 cm)

0-10" (0-25.4 cm)	Peat
10-22" (25.4-55.9 cm)	Sand
22-33" (55.9-83.8 cm)	Peat + massive ice
33-60.5" (83.8-153.7 cm)	Sand
60.5-70.5" (153.7-179.1 cm)	Organic + massive ice, wood (root?) Fragments 65-70.5"
70.5-80" (179.1-203.2 cm)	Organic + massive ice with wood fragments
80-84" (203.2-213.4 cm)	Sand, with Vx ice
84-92" (213.4-233.7 cm)	Sand, with thin (1/32") ice lenses throughout. Minor organics 88-92"
92-99" (233.7-251.5 cm)	Sand, minor organics + some wood
99-103" (251.5-261.6 cm)	Medium to coarse sand
103-108" (261.6-274.3 cm)	Layered sand + organic + wood
108-115.5" (274.3-293.4 cm)	Same. Occasional pebbles near base. Sand is brown starting at 112"; previously grey in holes 1 and 2
115.5-117" (293.4-297.2 cm)	Sand
117-132.5" (297.2-336.6 cm)	Silty clay, small pebbles at base of overlying sand layer. Thin ice lenses. Core is breaking along thicker(1/16") ice lenses
132.5-137.5" (336.6-349.3 cm)	Silty clay, minor organics. Thin Vs ice seams
137.5-172" (349.3-436.9 cm)	Same + occasional pebbles. Thin ice seams are approx. 1/4" apart
172" (436.9 cm)	End of hole

ILL 79-3 (35)

Grid Location:	3 + 50 N, 2 + 00 E	Date:	May 8, 1979
Hole Length:	86.75" (2.20 m)	Core Length:	85" (2.16 m)
Sample Thickness:	2" (5 cm)	Core Diameter:	3" (7.5 cm)

0-1" (0-2.5 cm)	Woody
1-11" (2.5-27.9 cm)	Peat + Vs ice
11-21" (27.9-53.3 cm)	Organic + Vs ice
21-25" (53.3-63.5 cm)	Grey clay + massive ice lenses
25-30" (63.5-76.2 cm)	Grey clay + minor organic, Vc, Vs ice
30-34" (76.2-86.4 cm)	Brown silty clay + minor organic, Vs ice up to 1/8" thick
34-44.5" (86.4-113.0 cm)	Organic, Vs ice
44.5-47" (113.0-119.4 cm)	Greyer silty clay + minor organic, Vs ice
47-55.5" (119.4-141.0 cm)	Brown silty clay, Vx, Vc and Vs ice, not all Vs is horizontally oriented
55.5-60.5" (141.0-153.7 cm)	Same. Vs is horizontally oriented Some woody material @ 59"
60.5-66" (153.7-167.6 cm)	Same. Some Vx at 65"
66-70" (167.6-177.8 cm)	Grey-brown silty clay. Some massive Vx ice. Vs ice nearly vertical in orientation. 1/16" thickness
70-76" (177.8-193.0 cm)	Grey silty clay. Vx ice
76-78.5" (193.0-199.4 cm)	Same. Finely laminated ice seams at approx. 5°.
78.5-85" (199.4-215.9 cm)	Increasing Vs towards base. Base is almost ice with soil inclusions
85" (215.9 cm)	End of hole. (Pebble blockage)

ILL 79-4 (36)

Grid Location:	0 + 60 N, 0 + 55 E	Date:	May 9, 1979
Hole Length:	112" (2.85 m)	Core Length:	112" (2.85 m)
Sample Thickness:	2" (5 cm)	Core Diameter:	3" (7.5 cm)

0-6" (0-15.2 cm)	Organic + Vs ice
6-12" (15.2-30.5 cm)	Same. + minor Vc ice
12-44" (30.5-111.8 cm)	Same. Vs is poorly defined
44-59" (111.8-149.9 cm)	Dark grey silty clay + minor organic + poor Vs
59-71.5" (149.9-181.6 cm)	Same but lighter grey + Vx, Vc
71.5-76.5" (181.6-194.3 cm)	Same. Higher organic content
76.5-94.5" (194.3-240.0 cm)	Black organic + Vc + minor silty clay
94.5-97" (240.0-246.4 cm)	Black organic + shells + Vr, Vs. Organic is melting and wrapping around core barrel
97-112" (246.4-284.5 cm)	Unfrozen black organic. The black organic zone has strong H_2S odour
112" (284.5 cm)	End of hole

ILL 79-5 (37)

Grid Location: 0 + 01 S, 0 + 50 W

Date: May 9, 1979

Hole Length: 123" (3.12 m)

Core Length: 123" (3.12 m)

Sample Thickness: 4" (10 cm)

Core Diameter: 3" (7.5 cm)

0-1" (0-2.5 cm)	Dry organic
1-15" (2.5-38.1 cm)	Organic + Vc ice
15-32.5" (38.1-82.6 cm)	Organic + silty clay. Almost massive ice. Clay lenses separated by Vc and Vs ice in lower portion Nbe through 30-32.5"
32.5-48" (82.6-121.9 cm)	Silty clay + Vx ice
48-57.5" (121.9-146.1 cm)	Same + Vc, Vr and minor organic
57.5-65" (146.1-165.1 cm)	Silty clay + organic + Vc
65-73.5" (165.1-186.7 cm)	Same + shells
73.5-81.5" (186.7-207.0 cm)	Same. Nbe replaces Vc
81.5-87" (207.0-221.0 cm)	Silty clay + organic bands + shell throughout. Some Vc, Vr
87-89" (221.0-226.1 cm)	Fine sand + minor organic + Nbe
89-90" (226.1-228.6 cm)	Same + Vx
90-97" (228.6-246.4 cm)	Grey-brown silty clay with black organic streaks + Vx, Vr
97-103.5" (246.4-262.9 cm)	Same + small stones + wood
103.5-119" (262.9-302.3 cm)	Same but unfrozen
119-123" (302.3-312.4 cm)	Same, pebbles to 1/2" diameter
123" (312.4 cm)	End of hole. This hole very similar to #4.

ILL 79-6 (38)

Grid Location:	1 + 50 S, 0 + 52 W	Date:	May 10, 1979
Hole Length:	96" (2.44 m)	Core Length:	96" (2.44 m)
Sample Thickness:	2" (5 cm)	Core Diameter:	3" (7.5 cm)

0-1" (0-2.5 cm)	Dry organic
1-22.5" (2.5-57.2 cm)	Organic + silty clay + Vc + Vs. Ice lenses are numerous enough to cause soil chunks to be broken and set within an ice matrix. Minor vertical ice
22.5-26.5" (57.2-67.3 cm)	Same but less organic
26.5-30.5" (67.3-77.5 cm)	Same but more ice
30.5-31.5" (77.5-80.0 cm)	Same but very little ice visible
31.5-38" (80.0-96.5 cm)	Same. Large vertical ice lenses
38-45" (96.5-114.3 cm)	Grey-brown silty clay. Minor ice
45-68.5" (114.3-174.0 cm)	Brown silty clay. Nbe 1/2" stones 66-68.5"
68.5-88" (174.0-223.5 cm)	Brown silty clay + organic + small wood fragments. No visible ice in this organic material
88-96" (223.5-243.8 cm)	Same material--unfrozen. 88-92" was badly broken, discarded. 92-96" recovered
96" (243.8 cm)	End of hole

NOTE: 1) Water level measured at 93".

2) Samples 1 to 7 constitute top 16". Therefore, there is no sample 8.

ILL 79-7 (39)

Grid Location:	2 + 50 S, 1 + 00 W	Date:	May 10, 1979
Hole Length:	85" (2.16 m)	Core Length:	85" (2.16 m)
Sample Thickness:	2" (5 cm)	Core Diameter:	3" (7.5 cm)

0-3" (0-7.5 cm)	Organic + silty clay + Vc, Vs ice
3-6" (7.5-15.2 cm)	Organic + Vs
6-12" (15.2-30.5 cm)	Organic + increasing silty clay + Nbe
12-14.5" (30.5-36.8 cm)	Silty clay + Nbe
14.5-23" (36.8-58.4 cm)	Silty clay + minor organic + Vs, Vc
23-29.5" (58.4-74.9 cm)	Same. Vs up to 1/8"
29.5-31" (74.9-78.7 cm)	Brown sand + occasional pebbles + Vc
31-38" (78.7-96.5 cm)	Same + trace organic
38-43" (96.5-109.2 cm)	Black organic + Vs. Badly broken.
43-47" (109.2-119.4 cm)	Brown silty clay (till?) clasts up to 1.5". Little ice
47-53" (119.4-134.6 cm)	Same + Vr, Vc, Vs. Lenses up to 1/8"
53-57" (134.6-144.8 cm)	Organic + silty clay (till?) + occasional pebbles. Vs up to 1/8" thick causing frequent breakage.
57-64" (144.8-162.6 cm)	Same. Pebbles up to 1/8" diameter. Lots of Vs ice, 1/8" thick and 1-2" apart
64-65" (162.6-165.1 cm)	Core lost
65-79" (165.1-200.7 cm)	Silty clay (till?) breakage along ice. Vs to Vr decreasing near base
79-85" (200.7-215.9 cm)	Same. Vr ice
85" (215.9 cm)	End of hole. Drill stuck. Antifreeze required to free

ILL 79-8 (40)

Grid Location: 3 + 00 S, 1 + 25 W

Date: May 10, 1979

Hole Length: 201" (5.11 m)

Core Length: 201" (5.11 m)

Sample Thickness: 2" (5 cm)

Core Diameter: 3" (7.5 cm)

0-6" (0-15.2 cm)	Peat (roots)
6-10" (15.2-25.4 cm)	Grey-brown silty clay + organic Vx top 1". Vs ice thick lenses 1/4". Bottom 1" (9-10) large rounded pebble 1" x 3/4" x 1/4" with vertical orientation
10-16" (25.4-40.6 cm)	Peat + silty clay + Vx
16-17" (40.6-43.2 cm)	Ice + minor soil
17-34" (43.2-86.4 cm)	Brown silty clay + organic + Vs ice 50% soil/50% ice
34-36.5 (86.4-92.7 cm)	Grey-brown fine sand. Vx, Vc
36.5-39" (92.7-99.1 cm)	Same. Some massive ice
39-50" (99.1-127.0 cm)	Same. Some massive ice + Vs, Vr
50-53" (127.0-134.6 cm)	Massive ice + fine sand
53-55" (134.6-139.7 cm)	Fine sand. Less ice. Vs, Vr. Note: occasional pebbles throughout all of the core
55-56" (139.7-142.2 cm)	Vs ice (6%) + grey-brown silty clay
56-63" (142.2-160.0 cm)	Same. Ice is 50-60%
63-67" (160.0-170.2 cm)	Grey-brown silty clay. Fine ice laminations. Vs 10%
67-69.5" (170.2-176.5 cm)	Same. Vs coarser & white (25%)
69.5-70.5" (176.5-179.1 cm)	Same. Fine ice laminations. Vs 10%
70.5-78.5" (179.1-199.4 cm)	Same. Vs 1/16" thick, 1/8" spacing
78.5-84.5" (199.4-214.6 cm)	Same. Fine Vs laminations
84.5-88" (214.6-223.5 cm)	Same. Nbe

88-93.5" (223.5-237.5 cm)	Same. Thin Vs laminae
93.5-94.5" (237.5-240.0 cm)	Same. 1/8" Vs
94.5-98.5" (240.0-250.2 cm)	Same. Thin Vs laminae. Note: From 20" to 98.5" the core split across perfectly indicating Vs horizontal. Unable to cut vertically. The horizontal breaks as a result are approx. 1/4" apart
98,5-105.5" (250.2-268.0 cm)	Same. Thin ice Vs laminae at top grading to 1/16" white ice near bottom. 10-20% ice
105.5-107" (268.0-271.8 cm)	Same. Thin Vs laminae
107-115.5" (271.8-293.4 cm)	Grey-brown silty clay. Trace black organic throughout. Very tiny Vs ice 5%
115.5-118" (293.4-299.7 cm)	Fine Sand. Nbe
118-119" (299.7-302.3 cm)	Same. 1/16" white Vs ice
119-120" (302.3-304.8 cm)	Same. Nbe
120-121" (304.8-307.3 cm)	Same. 1/16" white Vs ice
121-124" (307.3-315.0 cm)	Same. Nbe. Occasional pebbles 1/4"
124-125" (315.0-317.5 cm)	Grey-brown fine sand. Nbe
125-127" (317.5-322.6 cm)	Same. 1/16" white Vs
127-147" (322.6-373.4 cm)	Same. Nbe. A thin Vs ice lenses at 147" level
147-153" (373.4-388.6 cm)	Fine sand + occasional shells. Nbe except Vs at 153"
153-201" (388.6-510.5 cm)	Grey fine sand + occasional shells. Nbe
201" (510.5 cm)	End of hole. Depth capacity reached.

ILL 79-9 (41)

Grid Location:	1 + 25 S, 2 + 00 E	Date:	May 11, 1979
Hole Length:	165" (4.19 m)	Core Length:	165" (4.19 m)
Sample Thickness:	2" (5 cm)	Core Diameter:	3" (7.5 cm)

0-22.5" (0-57.2 cm)	Dark Brown peat + Vc ice. Zone 1-2.5" is oxidized orange-red
22.5-28" (57.2-71.1 cm)	Rapid change to medium-coarse sand. Vc and some Vs to 1/8"
28-36.5" (71.1-92.7 cm)	Same. Vx, Vc. Some organic at 29" and at 31.5"
36.5-43.5" (92.7-110.5 cm)	Same. With thin organic. Vs to 1/4"
43.5-45.5" (110.5-115.6 cm)	Peat + minor sand
45.5-46" (115.6-116.8 cm)	Peat. Vc, Vr
46-48" (116.8-121.9 cm)	Silty clay + some organic + Vs up to 1/4" 40%
48-53" (121.9-134.6 cm)	Same + massive ice 80%. Vs, Vr organic is black and brown. Silty clay is grey
53-57.5" (134.6-146.1 cm)	Silty clay + Vs 60-70%. Ice is clear to white. Trace organic?
57.5-60" (146.1-152.4 cm)	Grey to brown silty clay. Vs 30%
60-66.5" (152.4-168.9 cm)	Same. Vs 30-50% trace organic
66.5-71.5" (168.9-181.6 cm)	Brown silty clay. 1/16" Vs white 50% Two brown organic zones 1/2" thick and sloping 5 to 10° . Lower pod at 71".
71.5-78" (181.6-198.1 cm)	Same + brown organic pods. Ice 50%
78-82" (198.1-208.3 cm)	Brown silty clay. Vs clear 20-30%
82-83.5" (208.3-212.1 cm)	Same + fine sand + Vr 70-80%
83.5-86" (212.1-218.4 cm)	Mixed fine sand + silty clay. Vs 20%
86-91" (218.4-231.1 cm)	Grey silty clay + 1/4" Vs at approx. 1/2" spacing, white. Dark brown organic from 89.5-90"

91-101.5" (231.1-257.8 cm)	Brown silty clay + fine sand. Scattered organic. Vs 1/16", clear to white. Stones in lower 2".
101.5-104" (257.8-264.2 cm)	Brown fine sand + silty clay. Vr 20%
104-105.5" (264.2-268.0 cm)	Same. Vs white 1/8"
105.5-108" (268.0-274.3 cm)	Same + black-brown organic interlayered 1/2" thick
108-112" (274.3-284.5 cm)	50/50 organic + fine sand in thin bands 1/8" thick. Nbe.
112-117.5" (284.5-298.5 cm)	Same, but less organic. Nbe.
117.5-125" (298.5-317.5 cm)	Fine-medium sand + some organic. 10% Vr But generally Nbe.
125-128" (317.5-325.1 cm)	Dark grey silty clay. Nbe.
128-131" (325.1-332.7 cm)	Same. Vr up to 1/4". Occasional small pebbles 125-131"
131-133" (332.7-337.8 cm)	Silty clay. Nbe.
133-135.5" (337.8-344.2 cm)	Massive ice
135.5-136.5" (344.2-346.7 cm)	Large pebbles (beach?)
136.5-141" (346.7-358.1 cm)	Silty clay + minor black organic pockets. 139-141" has white Vs, Vr up to 1/8" thick.
141-145" (358.1-368.3 cm)	Silty clay + fine sand. Vr & Vs up to 1/8". Can see individual ice grains.
145-148.5" (368.3-377.2 cm)	Silty clay + fine sand + occasional pebbles. Scattered fine black organic. Some Vr. Ice lenses oriented at 32°.
148.5-156" (377.2-396.2 cm)	Dark grey silty clay. Vr 1/8-1/4" seams Coarse grained.
156-164" (396.2-416.6 cm)	Same. Individual ice grains up to 1/16"
164-165" (416.6-419.1 cm)	Grey silty clay + pebbles. (60%) + massive ice (40%). Taken with 2" core barrel.
165" (419.1 cm)	End of hole. Unable to penetrate layer of pebbles. Probably coarse gravel.

ILL 79-10A

Grid Location:	0 + 00 N, 1 + 60 W	Date:	May 12, 1979
Hole Length:	13.5" (0.34 m)	Core Length:	13.5" (0.34 m)
Sample Thickness:	4" (10 cm)	Core Diameter:	3" (7.5 cm)

0-4.5" (0-11.4 cm)	Dark Brown Peat, 0.2" is 50-60% Vr, Vc, white
4.5-5" (11.4-12.7 cm)	Peat + silty fine sand (brown)
5-6" (12.7-15.2 cm)	Organic, roots?
6-10" (15.2-25.4 cm)	Brown silty fine sand. Some small pebbles. Minor Vr
10-13.5" (25.4-34.3 cm)	Same. 1/8" Vr 20-30%
13.5" (34.3 cm)	End of hole. Hit large stone. Have moved 6" west (10B)

ILL 79-10B

Grid Location:	0 + 00 N, 1 + 60 W	Date:	May 12, 1979
Hole Length:	49.5" (1.26 m)	Core Length:	49.5" (1.26 m)
Sample Thickness:	4" (10 cm)	Core Diameter:	3" (7.5 cm)

0-13.5" (0-34.3 cm)	See 10A; same
13.5-21" (34.3-53.3 cm)	Grey brown silty fine sand. 50-60% Vs. Vr up to 1/4". Ice is coarse grained. Occasional pebbles.
21-25" (53.3-63.5 cm)	Brown silty fine sand + some dark brown organic. Occasional 1/8" pebbles. Vr, Vc 20%
25-29.5" (63.5-74.9 cm)	Brown silty fine sand. Vs clear 70-80% ice. A large 1/2" pebble
29.5-37.5" (74.9-95.3 cm)	Same. Vs, Vc up to 1/2" diameter Ice 70-80% no pebbles
37.5-40.5" (95.3-102.9 cm)	Same. Vs, Vc up to 3/4" diameter. Ice 50-60%
40.5-42" (102.9-106.7 cm)	Fine-medium sand. Nbe
42-45.5" (106.7-115.6 cm)	Silty fine sand + Vr ice up to 1/4" 70-80%
45.5-49.5" (115.6-125.7 cm)	Brown silty fine sand. Vr up to 1/8" near top. Lower portions (47.5-49.5") See Vs as thin 1/32" laminae. Occasional small pebbles
49.5" (125.7 cm)	End of hole. Stopped at pebble.

ILL 79-10C (42)

Grid Location:	0 + 00 N, 1 + 61.5 W	Date:	May 12, 1979
Hole Length:	196.5" (4.99 m)	Core Length:	195" (4.95 m)
Sample Thickness:	4" (10 cm)	Core Diameter:	3" (7.5 cm)

FROZEN PUDDLE 2" DEEP OVERLIES HOLE LOCATION.

NOT INCLUDED IN CORE LENGTH.

0-4" (0-10.2 cm)	Peat
4-7.5" (10.2-19.1 cm)	Organic + rootlets?
7.5-10" (19.1-25.4 cm)	Silty fine sand. Little ice
10-16.5" (25.4-41.9 cm)	Same. Vr, Vc up to 1/2" thick. Small organic bleb.
16.5-19" (41.9-48.3 cm)	Same. Vs 3/8" + Vr
19-21.5" (48.3-54.6 cm)	Organic + ice 50%
21.5-27" (54.6-68.6 cm)	Silty fine sand + ice 60-70% Vs, Vr
27-33" (68.6-83.8 cm)	Brown silty fine sand + Vs, Vc up to 1/2". 70-80% ice
33-35.5" (83.8-90.2 cm)	Silty fine sand + thin Vs laminae, 30%
35.5-39" (90.2-99.1 cm)	Same as 27-33"
39-49.5" (99.1-125.7 cm)	Grey clay silty fine sand. Tiny grains like coarse sand. Vs 50%
49.5-57.5" (125.7-146.1 cm)	Grey clay silt + some fine sand. Occasional 1/8" pebbles (49.5-55.5") Vs near horizontal 50-60%. (55.5-57.5") Vs near horizontal + Vr oriented at 45° Ice 70%
57.5-67.5" (146.1-171.5 cm)	Grey silty clay + Vs + some Vr. (57.5-59.5") Vs, Vr up to 1/8" 50% (59.5-67.5") laminae thinning toward base. Vs 20-30%
67.5-77.5" (171.5-196.9 cm)	Same. Vs up to 1/16" near horizontal 20-40%
77.5-81" (196.9-205.7 cm)	Same. Vs up to 1/16" laminae. 20%

81-84.5" (205.7-214.6 cm)	Same. Vs, Vr up to 1/8" + large pebbles 1.5" long, 3/4" wide. Ice 20-40
84.5-93.5" (214.6-237.5 cm)	Same as 81-84.5". Vs, some Vr oriented up to 45°
93.5-103.5" (237.5-262.9 cm)	Grey silty clay. Vs 1/16" thick 1/4" spacing. 20-30%
103.5-108" (262.9-274.3 cm)	Same + some fine sand. Ice 20-30%
108-111" (274.3-281.9 cm)	Fine sand. Minor Vs 5-10%
111-117" (281.9-297.2 cm)	Clay silt + minor fine sand. Vs 1/16" spaced 1/2" apart. 10-15% trace organic
117-122" (297.2-309.9 cm)	Grey silty clay. Minor thin Vs 10-15%
122-128" (309.9-325.1 cm)	Same. More Vs up to 1/2". 25-30%
128-133.5" (325.1-339.1 cm)	Browner clay silt + fine sand. Vs lenses up to 3/16"
133.5-141" (339.1-358.1 cm)	Same. Vs lenses very thin 10-15%
141-144" (358.1-365.8 cm)	Same. Thin ice lenses. < 5%
144-147" (365.8-373.4 cm)	Clay silt + fine sand + black organic pods. Nbe.
147-196.5" (373.4-499.1 cm)	Fine sand. Nbe.
196.5" (499.1 cm)	End of hole. Depth capacity reached. Final sample was badly splintered and part was lost.

ILL 79-11A

Grid Location:	1 + 50 N, 1 + 00 W	Date:	May 13, 1979
Hole Length:	78" (1.98 m)	Core Length:	78" (1.98 m)
Sample Thickness:	4" (10 cm)	Core Diameter:	3" (7.5 cm)

0-1" (0-2.5 cm)	Dry organic
1-13.5" (2.5-34.3 cm)	Peat. Ice up to 60-70%. Some banding. Predominantly soil at 5, 7, 11 & 13". Minor soil concentration at 9". (1-3.5") 30% ice
13.5-21.5" (34.3-54.6 cm)	Peat. Soil concentration at 18". Ice 50-70%
21.5-35.5" (54.6-90.2 cm)	Peat. Vc + Vs. < 10%
35.5-42" (90.2-106.7 cm)	Grey silty clay + organic. Nbe.
42-43.5" (106.7-110.5 cm)	Grey silty clay. Occasional pebbles
43.5-52" (110.5-132.1 cm)	Grey silty clay. Nbe.
52-78" (132.1-198.1 cm)	Grey silty clay + minor organic. Stony. Nbe.
78" (198.1 cm)	End of hole. Drilled jammed. Gasoline poured in hole to free rods.

ILL 79-11B (43)

Grid Location:	1 + 51 N, 1 + 00 W	Date:	May 13, 1979
Hole Length:	156" (3.96 m)	Core Length:	156" (3.96 m)
Sample Thickness:	4" (10 cm)	Core Diameter:	2" (5 cm)

0-29" (0-73.7 cm)	Same as 11A
29-34" (73.7-86.7 cm)	Peat
34-37" (86.7-94 cm)	Dark grey silty clay + minor organic. Minor Vr 5-10%
37-43.5" (94-110.5 cm)	Grey silty clay. Minor organic? Nbe.
43.5-48.5" (110.5-123.2 cm)	Grey silty clay. Nbe. Thin Vs at 48" 5%
48.5-75" (123.2-190.5 cm)	Grey-brown clay silt-fine sand. Stony. (Till?) occasional Vr < 5%. Minor organic, stones up to 1" diameter
75-92" (190.5-233.7 cm)	Same with more organic
92-94" (233.7-238.8 cm)	Fine sand with organic. No visible ice
94-100" (238.8-254 cm)	Medium sand with occasional small pebbles. Minor Vr < 5%
100-101" (254-256.5 cm)	Same Nbe.
101-102" (256.5-259.1 cm)	Peat Nbe.
102-105" (259.1-266.7 cm)	Fine sand + minor organic. Nbe.
105-106" (266.7-269.2 cm)	Peat Nbe.
106-109" (269.2-276.9 cm)	Peat. Wood fragments
109-126" (276.9-320 cm)	Sand + some organic. Occasional stones. Minor Vs < 5%. Large stone at 126"
126-131.5" (320-334 cm)	Fine sand + organic + some pebbles. Including 2 small red shale clasts
131.5-137.5" (334-349.3 cm)	Same + occasional Vs 5-10%
137.5-147.5" (349.3-374.7 cm)	Same. 6 small red shale clasts in this section. Semi-frozen at 147.5"

147.5-150.5" (374.7-382.3 cm)	Soft, unfrozen. Fine sand with more clay silt. No stones. Some organic
150.5-154" (382.3-391.2 cm)	Poor recovery of thawed material
154-156" (391.2-396 cm)	Same as 147.5-150.5". Good recovery
156" (396 cm)	End of hole.

ILL 79-12 (44)

Grid Location: 1 + 50 N, 1 + 00 E

Date: May 13, 1979

Hole Length: 160" (4.06 m)

Core Length: 160" (4.06 m)

Sample Thickness: 4" (10 cm)

Core Diameter: 2" (5 cm)

0-2.5" (0-6.4 cm)	Sand + organic. Nbe. Top 1/2" is thawed
2.5-8" (6.4-20.3 cm)	Peat. No visible ice
8-14" (20.3-35.6 cm)	Fine sand + minor organic. Occasional pebbles. Nbe.
14-15" (35.6-38.1 cm)	Peat
15-24.5" (38.1-62.2 cm)	Organic + some fine sand. No visible ice
24.5-29" (62.2-73.7 cm)	Organic + brown clay silt. Thin Vs, 10-15%
29-38.5" (73.7-97.8 cm)	Same. Ice content decreases to not visible by 34"
38.5-45.5" (97.8-115.6 cm)	Grey-brown clay silt + organic + some fine sand. Occasional shells. No visible ice
45.5-78.5" (115.6-199.4 cm)	Grey fine sand with organic. Occasional small pebbles. Nbe. More organic than sand (68.5-70.5")
78.5-89.5" (199.4-227.3 cm)	Grey-brown fine sand + some organic. Vr 5%
89.5-97" (227.3-246.4 cm)	Same. Vr 5%. Red shale clasts at 94 & 95"
97-105" (246.4-266.7 cm)	Same. Vr < 5%. Another red clast at 99.5". Pebbles increasing in size
105-111" (266.7-281.9 cm)	Same. Vr approx. 5%
111-126" (281.9-320 cm)	Same. Vr < 5%. 3 red clasts
126-138" (320-350.5 cm)	Same. Vr < 5% 4 red clasts. Organic pods near bottom
138-150.5" (350.5-382.3 cm)	Same. Vr < 5%. Red clast at 145". Becomes soft (unfrozen) at 150.5"
150.5-151.5" (382.3-384.8 cm)	Same. Unfrozen. Increasing clay-silt content

151.5-157" (384.8-398.8 cm)	Unfrozen clay silt with fine sand Material discarded. Not sure if contaminated from above
157-160" (398.8-406.4 cm)	Same. Sample taken
160" (406.4 cm)	End of hole

ILL 79-13 (45)

Grid Location:	1 + 50 S, 1 + 00 E	Date:	May 14, 1979
Hole Length:	160" (4.06 m)	Core Length:	160" (4.06 m)
Sample Thickness:	4" (10 cm)	Core Diameter:	2" (5 cm)

0-2.5" (0-6.4 cm)	Brown silty sand + minor organic
2.5-13.5" (6.4-34.3 cm)	Peat. Vx
13.5-24" (34.3-61 cm)	Grey clay silt + fine sand & some organic. 15-20% Vr, Vc
24-36" (61-91.4 cm)	Grey-brown clay silt. Occasional pebbles. Vr 15-20%
36-38.5" (91.4-97.8 cm)	Brown clay silt. Vr 5-10%, lower 1" contains organic (roots?)
38.5-40" (97.8-101.6 cm)	Peat
40-43" (101.6-109.2 cm)	Yellow-brown silty fine sand. Occasiona organic and pebbles. Nbe.
43-46" (109.2-116.8 cm)	Yellow-brown fine sand. Occasional organic and pebbles. Nbe.
46-57" (116.8-144.8 cm)	Same. Minor clay silt + organic at 49.5'
57-59.5" (144.8-151.1 cm)	Fine sand + more organic. Occasional pebbles
59.5-70" (151.1-177.8 cm)	Grey-brown silty fine sand with organic blebs. Pebbles up to 3/4". Red shale clasts at 66.5". Vs 5 -10%
70-81" (177.8-205.7 cm)	Grey-brown silty fine sand with minor organic. Occasional pebbles. Vs 5%
81-94" (205.7-238.8 cm)	Grey-brown fine sand with minor organic. Some silt. Occasional pebbles.
94-98" (238.8-248.9 cm)	Grey-brown fine-medium sand. Clean
98-109" (248.9-276.9 cm)	Grey brown clean fine-medium sand. Occasional organic Nbe. Vs < 5% in organic

109-132" (276.9-335.3 cm)	Clean fine-medium sand. Trace organic. Nbe.
132-140.5" (335.3-356.9 cm)	Same. Slightly more organic
140.5-143" (356.9-363.2 cm)	Same. Semi frozen
143-150" (363.2-381 cm)	Same. Unfrozen, moist
150-160" (381-406.4 cm)	Same. Unfrozen, saturated
160" (406.4 cm)	End of hole.

ILL 79-14 (46) PINGO

Grid Location: 580M true S of 79-6

Date: May 16, 1979

Hole Length: 216" (5.49 m)

Core Length: 214" (5.45 m)

Sample Thickness: 4" (10 cm)

Core Diameter: 2" (5 cm)

0-4" (0-10.2 cm)	Peat + chips of ice
4-12" (10.2-30.5 cm)	Brown clay silt. Dry, badly broken
12-16" (30.5-40.6 cm)	Silty clay with thin Vs 50-60% ice. Massive ice at base
16-83" (40.6-210.8 cm)	Massive ice
83-87" (210.8-221 cm)	Massive ice + trace soil
87-95" (221-241.3 cm)	Massive ice + minor fine-medium sand
95-99" (241.3-251.5 cm)	Massive ice + trace soil
99-107" (251.5-271.8 cm)	Massive ice
107-115" (271.8-292.1 cm)	Massive ice + minor silty clay
115-119" (292.1-302.3 cm)	Grey silty clay with Vr 50-60%
119-123" (302.3-312.4 cm)	Silty sand with Vr & Vc 20-30%
123-131" (312.4-332.7 cm)	Grey silty clay with Vr 20-40%
131-135" (332.7-342.9 cm)	Grey silty clay. Vs, Vr 40-50%
135-139" (342.9-353.1 cm)	Massive ice 70% + silty clay
139-143" (353.1-363.2 cm)	Massive ice 50-60% + silty clay
143-147" (363.2-373.4 cm)	Same ice 40-50%
147-151" (373.4-383.5 cm)	Clay silt + some fine sand and occasional pebbles. Vr 20-30%
151-159" (383.5-403.9 cm)	Silty clay + Vr, Vs 20-30%. Ice lenses 1/16" thick on 15° angle
159-163" (403.9-414 cm)	Clay silt + some brown fine sand. Vr, Vx 20-30%
163-179" (414-454.7 cm)	Silty clay. Vs 25-35%

179-183"	(454.7-464.8 cm)	Silty clay + occasional pebbles up to 1/2" diameter. Vs 30-40%. Ice lense angle 15°
183-187"	(464.8-475 cm)	Massive ice 80-90% + minor silty clay
187-191"	(475-485.1 cm)	Massive ice. Trace soil
191-195"	(485.1-495.3 cm)	Massive ice
195-199"	(495.3-505.5 cm)	Massive ice + minor silty clay. Only about 2" recovered
199-203"	(505.5-515.6 cm)	Massive ice 70-80% + some clay silt. Large sample
203-207"	(515.6-525.8 cm)	Massive ice, clear. Trace silty clay
207-211"	(525.8-535.9 cm)	Massive ice, snow white and granular
211-216"	(535.9-548.6 cm)	Massive ice, snow white + clear crystals. Bottom 2" lost
216"	(548.6 cm)	End of hole. Depth capacity reached.

ILL 79-15A PINGO LAKE BED

Grid Location:	300M true S of 79-13	Date:	May 16, 1979
Hole Length:	92" (2.34 m)	Core Length:	92" (2.34m)
Sample Thickness:	4" (10 cm)	Core Diameter:	2" (5 cm)

0-7.5" (0-19.1 cm)	Peat
7.5-11.5" (19.1-29.2 cm)	Grey silty clay. Vr 30%
11.5-14" (29.2-35.6 cm)	Peat. Vx, Vc 15%
14-30" (35.6-76.2 cm)	Grey silty clay. Vs, Vc, Vx. Thin ice laminae 30-40% minor organic
30-51" (76.2-129.5 cm)	Same, Vx, Vc 5-10%
51-55.5" (129.5-141.0 cm)	Same, less organic. Vx, Vc 15-20%
55.5-65.5" (141.0-166.4 cm)	Same. Vx, Vc 20%. Not getting full recovery
65.5-78.5" (166.4-199.4 cm)	Brown clay silt. Some fine sand. Vx, Vc 10%
78.5-92" (199.4-233.7 cm)	Black organic + silty clay. Occasional pebbles to 1/4". Vx, Vc 10-15%
92" (233.7 cm)	End of hole. Unable to penetrate stone blockage

ILL 79-15B (47) PINGO LAKE BED

Grid Location:	0.6 M West of 79-15A	Date:	May 16, 1979
Hole Length:	140" (3.56 m)	Core Length:	140" (3.56 m)
Sample Thickness:	4" (10 cm)	Core diameter:	2" (5 cm)

0-84" (0-213.4 cm)	No samples collected. Same as 79-15A (0-78.5")
84-88" (213.4-223.5 cm)	Black organic
88-92" (223.5-233.7 cm)	Black silty clay. Pebbles up to 1/2". Vs, Vx, Vc 10-15%
92-96" (233.7-243.8 cm)	Dark brown-black silty clay. Vx, Vx, Vc 10-20%
96-100" (243.8-254.0 cm)	Same. Vs, Vx, Vc 20-30%
100-112" (254.0-284.5 cm)	Same. Vs, Vx, Vc 40-50%
112-120" (284.5-304.8 cm)	Grey-brown silty clay. Several small 1/4" pebbles. Vs, Vc 50%
120-140" (304.8-355.6 cm)	Same. Almost looks like a clay silt. Vs, Vc 30%
140" (355.6 cm)	End of hole. Drill stuck. Recovered following morning by pouring antifreeze down hole and jacking drill out

ILL 79-I.W. #1

Grid Location:	3+00S 1+08W	Date:	May 14,15, 1979
Hole Length:	---	Core Length:	---
Sample Thickness:	2" (5 cm)	Core Diameter:	3" (7.5 cm)

SEE ENCLOSED SKETCH FOR SAMPLE HOLE LOCATIONS

1.	4 Subsamples.	1-0	0-2"	From Surface
	Ice-Soil Contact	1-1	2-4"	
		1-2	4-6"	
		1-3	6-8"	
2 to 39	2 Subsamples			0-2" Discarded
		X-1	2-4"	From Surface
		X-2	4-6"	
40	5 - 2" Subsamples			0-10" Ice-soil Contact
-1	2" Left of Sample 1.			Soil
	7 2" Subsamples			0.5-14.5"
-2	10" Left of Sample 1			Soil
	3 2" Subsamples			0-6"
	2 2.5" Subsamples			6-11"
41 to 44	Massive ice lense at top of ice wedge cleared 1-2" off surface before collecting chip samples.			

ILL 79-I.W. #2

Grid Location:	3+20S, 1+20W	Date:	May 15, 1979
Hole Length:	61.5" (1.56 m)	Core Length:	61.5" (1.56 m)
Sample Thickness:	2" (5 cm)	Core Diameter:	2" (5 cm)

DRILLING HORIZONTAL, PERPENDICULAR TO ICE WEDGE

0-11" (0-27.9 cm)	Clay silt + organic (?) Vx, Vc
11-31.5" (27.9-80.0 cm)	Clay silt + organic. Vx, Vc
31.5-44" (80.0-111.8 cm)	Ice from ice wedge. Bubble streams
44-46" (111.8-116.8 cm)	Clay silt + ice. Other side of wedge
46-46.5" (116.8-118.1 cm)	Clay silt. Drilled 2", but only recovered 0.5"
46.5-61.5" (118.1-156.2 cm)	Same. Full recovery. Vr
61.5" (156.2 cm)	End of hole.

APPENDIX B

CONDUCTIVITY MEASUREMENTS

ILLISARVIK

CORE NO.	SAMPLE NO.	CONDUCTIVITY (MICROMHOS)
79-3	1	451
	2	420
	3	470
	4	412
	5	362
	6	250
	7	243
	8	235
	9	170
	10	137
	11	230
	12	249
	13	258
	14	192
	15	217
	16	286
	17	277
	18	392
	19	415
	20	401
	21	373
	22	433
	23	677
	24	1004
79-3	25	1276
	26	932
	27	967
	28	966
	29	1236
	30	1187
	31	1153
	32	975
	33	719
	34	586
	35	568
	36	726
	37	778
	38	686
	39	980
	40	1082
	41	667
	42	353
	43	249

ILLISARVIK

CORE NO.	SAMPLE NO.	CONDUCTIVITY (MICROMHOS)	CORE NO.	SAMPLE NO.	CONDUCTIVITY (MICROMHOS)
79-4	1	429	79-4	26	1705
	2	554		27	2074
	3	597		28	1732
	4	503		29	1747
	5	443		30	2390
	6	496		31	1563
	7	539		32	2543
	8	475		33	2567
	9	878		34	2476
	10	1228		35	2014
	11	1797		36	2241
	12	1563		37	2239
	13	2254		38	2336
	14	1975		39	2254
	15	1928		40	2088
	16	1055		41	1802
	17	1530		42	2213
	18	2117		43	2181
	19	1494		44	2442
	20	842		45	2307
	21	1318		46	2289
	22	1166		47	1953
	23	2063		48	2060
	24	1694		49A	2346
	25	1985		49B	1997

ILLISARVIK

CORE NO.	SAMPLE NO.	CONDUCTIVITY (MICROMHOS)
79-4	50	2461
	51	2238
	52	2083
	53	1526
	54	1409
	55	1103
	56	1023

ILLISARVIK

CORE NO.	SAMPLE NO.	CONDUCTIVITY (MICROMHOS)
79-6	1	315
	2	598
	3	354
	4	333
	5	937
	6	928
	7	904
	9	1105
	10	1367
	11	1704
	12	1710
	13	1518
	14	1946
	15	1912
	16	1949
	17	1623
	18	1918
	19	1973
	20	2100
	21	356
	22	2132
	23	508
	24	2321
	25	376
	26	435
	27	702
79-6	28	1410
	29	363
	30	429
	31	551
	32	404
	33	547
	34	532
	35	409
	36	365
	37	390
	38	348
	39	447
	40	570
	41	648
	42	737
	43	633
	44	540
	45	575
	46	668

ILLISARVIK

CORE NO.	SAMPLE NO.	CONDUCTIVITY (MICROMHOS)
79-8	1	469
	2	
	3	793
	4	
	5	
	6	760
	7	588
	8	185
	9	130
	10	144
	11	82
	12	110
	13	93
	14	127
	15	100
	16	219
	17	115
	18	369
	19	425
	20	392
	21	427
	22	415
	23	332
	24	
	25	359
	26	236
79-8	27	275
	28	420
	29	440
	30	396
	31	372
	32	312
	33	399
	34	374
	35	433
	36	584
	37	629
	38	772
	39	893
	40	1079
	41	1272
	42	1180
	43	2369
	44	2246
	45	2127
	46	2203
	47	1920
	48	2249
	49	2522
	50	1849
	51	2177
	52	2230

ILLISARVIK

CORE NO.	SAMPLE NO.	CONDUCTIVITY (MICROMHOS)
79-8	53	1169
	54	1172
	55	1007
	56	1051
	57	959
	58	1057
	59	1386
	60	2330
	61	2356
	62	2353
	63	
	64	
	65	1105
	66	620
	67	
	68	
	69	657
	70	611
	71	628
	72	697
	73	
	74	
	75	816
	76	786
	77	833
	78	
	79	663
79-8	80	809
	81	831
	82	863
	83	929
	84	
	85	
	86	950
	87	778
	88	832
	89	
	90	876
	91	842
	92	848
	93	
	94	844
	95	960
	96	865
	97	852
	98	
	99	
	100	
	101	

ILLISARVIK

CORE NO.	SAMPLE DEPTH	CONDUCTIVITY (MICROMHOS)
79-14	0-4	627
(Pingo)	4-12	552
	12-16	771
	16-19	35
	19-23	116
	23-27	21
	27-31	21
	31-35	21
	35-39	19
	39-43	16
	43-47	26
	47-55	193
	55-59	288
	59-63	344
	63-67	68
	67-71	88
	71-75	141
	75-79	201
	79-83	113
	83-87	216
	87-91	486
	91-95	452
	95-99	244
	99-103	99
	103-107	425
79-14	107-111	1687
(Pingo)	111-115	625
	115-119	1607
	119-123	1894
	123-127	1071
	127-131	1092
	131-135	798
	135-139	732
	139-143	934
	143-147	1208
	147-151	1466
	151-155	1669
	155-159	1021
	159-163	922
	163-167	913
	167-171	974
	171-175	1124
	175-179	1069
	179-183	650
	183-187	924
	187-191	334
	191-195	472
	195-199	
	199-203	226
	203-207	300
	207-211	47
	211-214	61

ILLISARVIK

CORE NO.	SAMPLE NO.	CONDUCTIVITY (MICROMHOS)	CORE NO.	SAMPLE NO.	CONDUCTIVITY (MICROMHOS)
79-I.W.#1	1.1	210	79-I.W.#1	26.1	30
	2.1	54		27.1	36
	3.1	55		28.1	46
	4.1	42		29.1	53
	5.1	60		30.1	41
	6.1	72		31.1	32
	7.1	75		32.1	28
	8.1	79		33.1	29
	9.1	63		34.1	30
	10.1	66		35.1	27
	11.1	66		36.1	49
	12.1	61		37.1	36
	13.1	88		38.1	116
	14.1	45		39.1	1115
	15.1	61		40.1	2592
	16.1	57			
	17.1	50		41	111
	18.1	57		42	48
	19.1	55		43	33
	20.1	66		44	44
	21.1	45			
	22.1	48		39.0	2533
	23.1	56		1.0	1502
	24.1	56		1.3	1920
	25.1	66			

ILLISARVIK

CORE NO.	SAMPLE NO.	CONDUCTIVITY (MICROMHOS)
79-I.W.#1	1.2	505
	2.2	38
	3.2	36
	4.2	37
	5.2	43
	6.2	50
	7.2	56
	8.2	68
	9.2	92
	10.2	111
	11.2	67
	12.2	47
	13.2	49
	14.2	71
	15.2	55
	16.2	88
	17.2	80
	18.2	44
	19.2	47
	20.2	33
	21.2	56
	22.2	53
	23.2	37
	24.2	38
	25.2	32
79-I.W.#1	26.2	29
	27.2	28
	28.2	23
	29.2	25
	30.2	31
	31.2	28
	32.2	26
	33.2	24
	34.2	26
	35.2	38
	36.2	27
	37.2	43
	38.2	59
	39.2	154

ARCTIC ISLANDS

CORE NO.	SAMPLE NO.	CONDUCTIVITY (MICROMHOS)
BHO-102	0.8 M	---
	1.4 M	223
	2.0 M	186
Sabine Peninsula	1.0 M	6046

APPENDIX C

STABLE ISOTOPE AND

TRITIUM CONTENTS

ILLISARVIK

CORE NO.	SAMPLE NO.	$\delta^{18}O$ (0/00 Smow)	$\delta^{2}H$ (0/00 Smow)	^{3}H (T.U.)
Precip.	1	-15.0	-126	69
	2	-12.5	-113	93
79-3	1	-20.4		128
	2	-21.8		104
	3	-23.0		102
	4	-22.3		189
	5	-21.0		214
	6	-19.9		83
	7	-20.5		82
	8	-20.9		46
	9	-20.8		18
	10	-20.7		n.d.
	11	-20.9		9
	12	-21.0		n.d.
	13	-21.1		1
	14	-21.5		
	15	-21.2		21
	16	-21.7		6
	17	-21.9		n.d.
	18	-21.4		8
	19	-21.7		5
	20	-21.8		14
	21	-21.6		n.d.

ILLISARVIK

CORE NO.	SAMPLE NO.	$\delta^{18}O$ (0/00 Smow)	$\delta^{2}H$ (0/00 Smow)	^{3}H (T.U.)
79-3	22	-21.6		8
	23	-21.8		
	24	-21.7		11
	25	-20.8		
	26	-22.4		24
	27	-22.0		5
	28	-19.8		n.d.
	29	-22.8		n.d.
	30	-22.7		14
	31	-22.9		
	32	-22.9		9
	33	-22.9		n.d.
	34	-23.0		17
	35	-22.9		
	36	-23.0		20
	37	-23.2		
	38	-23.2		2
	39	-23.0		n.d.
	40	-21.2		
	41	-23.1		2
	42	-22.9		8
	43	-23.0		n.d.

ILLISARVIK

CORE NO.	SAMPLE NO.	$\delta^{18}O$ (0/00 Smow)	$\delta^{2}H$ (0/00 Smow)	^{3}H (T.U.)
79-4	1	-15.4	-129	136
	2	-15.7	-129	90
	3	-15.6	-128	151
	4	-16.0	-130	128
	5	-15.9	-135	125
	6	-16.0	-132	149
	7	-15.8	-133	
	8	-15.7	-135	
	9	-15.9	-135	170
	10	-15.7	-135	
	11	-15.7	-138	
	12	-15.9	-137	174
	13	-15.9	-133	
	14	-15.8	-136	
	15	-15.7	-134	140
	16	-16.0	-134	
	17	-16.1	-136	
	18	-15.6	-134	138
	19	-15.8	-135	
	20	-16.0	-136	
	21	-15.9	-134	92
	22	-16.1	-129	
	23	-15.9	-130	
	24	-16.0	-135	65
	25	-16.2	-138	
	26	-16.0	-136	

ILLISARVIK

CORE NO.	SAMPLE NO.	$\delta^{18}O$ (0/00 Smow)	$\delta^{2}H$ (0/00 Smow)	^{3}H (T.U.)
79-4	27	-16.3	-137	49
	28	-16.2	-135	
	29	-16.2	-137	
	30	-16.1	-136	37
	31	-16.3	-139	
	32	-16.2	-138	
	33	-16.4	-137	43
	34	-16.4	-138	
	35	-16.4	-137	
	36	-16.0	-140	18
	37	-15.8	-139	13
	38	-16.1	-142	14
	39	-16.2	-142	12
	40	-16.3	-140	
	41	-16.4	-142	
	42	-16.2	-141	n.d.
	43	-16.1	-140	
	44	-16.3	-140	17
	45	-16.4	-141	
	46	-16.2	-140	18
	47	-16.3	-138	
	48	-16.3	-137	n.d.
	49A	-16.1	-138	n.d.
	49B	-16.1	-144	
	50	-16.4	-140	
	51	-16.2	-140	

ILLISARVIK

CORE NO.	SAMPLE NO.	$\delta^{18}O$ (0/00 Smow)	$\delta^{2}H$ (0/00 Smow)	^{3}H (T.U.)
79-4	52	-16.3	-140	
	53	-16.3	-137	
	54	-16.3	-141	
	55	-16.3	-138	
	56	-16.2	-141	

ILLISARVIK

CORE NO.	SAMPLE NO.	$\delta^{18}O$ (0/00 Smow)	$\delta^{2}H$ (0/00 Smow)	^{3}H (T.U.)
79-8	1	-17.2		111
	2	-18.9		86
	3	-19.2		
	4	-18.7		
	5	-19.3		
	6	-19.7		
	7	-19.1		158
	8	-18.4		80
	9	-18.1		6
	10	-18.5		n.d.
	11	-18.7		
	12	-19.1		n.d.
	13	-18.9		
	14	-19.3		
	15	-19.3		n.d.
	16	-19.1		
	17	-19.2		
	18	-18.8		n.d.
	19	-19.0		10
	20	-16.7		24
	21	-19.0		4
	22	-18.9		3
	23	-16.6		13
	24	-19.3		16

ILLISARVIK

CORE NO.	SAMPLE NO.	$\delta^{18}O$ (0/00 Smow)	$\delta^{2}H$ (0/00 Smow)	^{3}H (T.U.)
79-8	25	-19.3		n.d.
	25	-19.3		
	27	-19.6		
	28	-19.6		
	29	-19.8		
	30	-19.8		
	31	-19.4		
	32	-19.6		n.d.
	33	-19.7		
	34	-19.5		
	35	-19.5		
	36	-18.8		
	37	-19.2		
	38	-19.0		
	39	-18.6		n.d.
	40	-18.3		
	41	-17.7		
	42	-18.1		
	43	-17.4		
	44	-17.6		
	45	-17.9		
	46	-17.4		
	47	-15.8		27
	48	-17.1		13
	49	-17.3		
	50	-17.5		

ILLISARVIK

CORE NO.	SAMPLE NO.	$\delta^{18}O$ (0/00 Smow)	$\delta^{2}H$ (0/00 Smow)	^{3}H (T.U.)
79-8	51	-17.1		
	52	-17.0		2
	53	-17.3		
	54	-16.4		
	55	-16.2		
	56	-15.8		15
	57	-15.7		
	58	-15.6		
	59	-15.3		
	60	-15.4		n.d.
	61	-14.7		
	62	-14.7		
	63	-14.8		n.d.
	64	-14.2		
	65	-14.2		
	66	-14.1		
	67	-14.1		
	68	-14.4		
	69	-14.0		
	70	-14.0		
	71	-13.7		
	72	-13.7		
	73	-13.6		
	74	-13.7		
	75	-13.8		
	76	-13.6		

ILLISARVIK

CORE NO.	SAMPLE NO.	$\delta^{18}O$ (0/00 Smow)	$\delta^{2}H$ (0/00 Smow)	^{3}H (T.U.)
79-8	77	-13.6		
	78	-14.1		
	79	-14.0		
	80	-14.1		
	81	-13.7		
	82	-13.7		
	83	-14.1		
	84	-13.9		
	85	-13.9		
	86	-13.8		
	87	-14.0		
	88	-14.4		
	89	-13.8		
	90	-13.8		
	91	-13.7		
	92	-14.4		
	93	-14.4		
	94	-14.4		
	95	-14.2		
	96	-14.3		
	97	-14.2		
	98	-14.4		
	99	-14.4		
	100	-14.5		
	101	-14.1		

ILLISARVIK

CORE NO.	SAMPLE NO.	$\delta^{18}O$ (0/00 Smow)	$\delta^{2}H$ (0/00 Smow)	^{3}H (T.U.)
79-14	0-4	-18.7		121
	4-12	-20.2		207
	12-16	-20.9		196
	16-19	-25.3		32
	19-23	-22.6		29
	23-27	-22.2		12
	27-31	-22.6		8
	31-35	-21.5		1
	35-39	-20.2		n.d.
	39-43	-21.6		4
	43-47	-21.8		23
	47-55	-26.2		28
	55-59	-26.7		17
	59-63	-27.7		10
	63-67	-26.3		13
	67-71	-26.0		21
	71-75	-24.1		24
	75-79	-22.3		15
	79-83	-23.0		17
	88-87	-22.8		31
	87-91	-19.7		44
	91-95	-17.9		n.d.
	95-99	-20.2		n.d.
	99-103	-25.9		n.d.
	103-107	-24.9		3
	107-111	-22.5		17

ILLISARVIK

CORE NO.	SAMPLE NO.	$\delta^{18}O$ (0/00 Smow)	$\delta^{2}H$ (0/00 Smow)	^{3}H (T.U.)
79-14	111-115	-22.5		5
	115-119	-19.4		22
	119-123	-18.6		
	123-127	-18.4		5
	127-131	-18.2		
	131-135	-18.1		
	135-139	-17.9		
	139-143	-17.7		n.d
	143-147	-17.8		
	147-151	-17.9		
	151-155	-17.7		
	155-159	-17.9		6
	159-163	-17.4		
	163-167	-17.7		
	167-171	-17.5		
	171-175	-17.3		
	175-179	-17.3		15
	179-183	-17.2		18
	183-187	-16.9		
	187-191	-17.1		n.d.
	191-195	-16.7		12
	195-199	-16.5		
	199-203	-16.2		n.d
	203-207	-15.3		3
	207-211	-15.0		n.d.
	211-214	-15.1		16

ILLISARVIK

CORE NO.	SAMPLE NO.	$\delta^{18}O$ (0/00 Smow)	$\delta^{2}H$ (0/00 Smow)	^{3}H (T.U.)
79 -	1.2	-21.1		n.d.
IW #1	2.2	-23.4		
	3.2	-23.3		
	4.2	-21.9		
	5.2	-22.7		
	6.2	-22.1		n.d.
	7.2	-22.2		
	8.2	-22.2		
	9.2	-22.3		
	10.2	-21.6		30
	11.2	-23.1		
	12.2	-23.0		
	13.2	-22.3		
	14.2	-23.5		13
	15.2	-23.5		
	16.2	-22.5		
	17.2	-21.5		n.d.
	18.2	-23.3		
	19.2	-22.5		
	20.2	-22.1		7
	1-0	-19.9		
	1-1	-21.4		
	1-3	-18.7		

ILLISARVIK

CORE NO.	SAMPLE NO.	$\delta^{18}O$ (0/00 Smow)	$\delta^{2}H$ (0/00 Smow)	^{3}H (T.U.)
79 -	21.2	-21.5		
IW #1	22.2	-21.2		17
	23.2	-22.0		
	24.2	-22.4		
	25.2	-21.7		n.d.
	26.2	-22.3		
	27.2	-22.9		
	28.2	-22.7		
	29.2	-23.1		
	30.2	-21.2		9
	31.2	-23.0		
	32.2	-22.4		
	33.2	-22.6		
	34.2	-22.9		
	35.2	-22.4		n.d.
	36-2	-22.0		9
	37.2	-23.5		
	38.2	-22.2		n.d.
	39.2	-20.4		

ILLISARVIK

CORE NO.	SAMPLE NO.	$\delta^{18}O$ (0/00 Smow)	$\delta^{2}H$ (0/00 Smow)	^{3}H (T.U.)
BHO- 102	0.8M	-19.0	-143	
	1.4M	-20.0	-157	
	2.0M	-24.0	-176	
SABINE PENN.	1.0M	-23.3	-175	30

APPENDIX D

TEMPERATURE DATA
FOR EXPERIMENT #6

TEMPERATURE DATA FOR EXPERIMENT #6

Temperature (^{o}C) / Thermocouple Depth (CM)

Time (Hrs)	Freezer	Top Heater	5	10	15	20	25	30	35	40	Bottom Heater
0	16.3	16.8	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3	16.3
0.5	- 0.2	17.4	16.6	16.3	16.3	16.3	16.3	16.3	16.3	16.4	17.9
1.0	- 9.5	16.4	16.6	16.3	16.3	16.3	16.3	16.3	16.3	16.5	18.8
1.5	-14.6	14.9	16.4	16.3	16.2	16.2	16.2	16.2	16.3	16.5	19.0
2.0	-12.3	13.5	15.8	16.1	16.1	16.1	16.1	16.1	16.1	16.4	18.8
2.5	-13.1	12.5	15.1	15.6	15.9	15.9	15.9	15.8	15.9	16.2	18.4
3.0	-14.4	11.6	14.5	15.2	15.6	15.7	15.7	15.7	15.7	15.9	18.0
4.0	-17.1	10.4	13.5	14.3	14.9	15.2	15.3	15.1	15.2	15.3	17.4
6.0	-12.4	8.8	11.8	12.7	13.7	14.1	14.3	14.2	14.2	14.2	16.2
8.0	-17.2	7.7	10.6	11.5	12.5	13.1	13.3	13.3	13.3	13.4	15.7
10.5	-13.3	6.9	9.4	10.2	11.2	11.8	12.1	12.2	12.4	12.7	15.5
15.0	-16.1	5.5	7.8	8.3	9.3	9.9	10.4	10.7	11.0	11.7	14.9
20.0	-15.1	4.4	6.5	7.0	7.8	8.3	9.1	9.5	9.9	10.7	14.2
22.5	-14.8	4.0	6.0	6.4	7.2	7.8	8.5	9.0	9.5	10.3	14.0
25.25	-14.0	3.6	5.4	5.8	6.5	7.1	7.6	8.5	9.0	9.8	13.5
28.0	-17.1	3.3	4.8	5.3	6.0	6.6	7.3	8.0	8.4	9.5	13.3
32.0	-17.4	2.9	4.2	4.7	5.3	5.9	6.7	7.4	7.9	9.0	12.8
36.0	-17.1	4.6	4.5	4.6	5.0	5.6	6.3	6.9	7.3	8.4	11.7
38.0	-15.3	4.7	4.3	4.4	4.7	5.1	5.9	6.4	6.9	7.9	11.5
40.0	-13.5	3.4	4.1	4.2	4.5	5.0	5.7	6.2	6.7	7.5	10.4
42.0	-16.9	2.9	3.7	3.9	4.3	4.7	5.4	5.9	6.3	7.0	9.8
44.0	-13.1	2.8	3.5	3.7	4.1	4.5	5.1	5.6	5.9	6.7	9.4
48.0	-16.9	2.7	3.2	3.5	3.8	4.2	4.8	5.2	5.5	6.3	9.1
52.0	-15.3	2.5	3.0	3.1	3.4	3.8	4.3	4.7	5.1	5.8	8.7
56.0	-15.7	2.3	2.5	2.7	3.0	3.4	3.8	4.2	4.5	5.3	8.2
60.0	-16.4	2.1	2.1	2.1	2.4	2.7	3.2	3.6	4.0	4.8	7.9
68.25	-15.8	1.4	1.3	1.3	1.6	1.8	2.3	2.8	3.2	4.1	7.1
71.5	-16.9	1.8	1.5	1.5	1.7	2.0	2.5	2.9	3.4	4.3	7.4

Temperature (°C) / Thermocouple Depth (CM)

Time (Hrs)	Freezer	Top Heater	5	10	15	20	25	30	35	40	Bottom Heater
75.0	-14.2	1.7	1.3	1.3	1.5	1.8	2.3	2.8	3.3	4.2	7.3
84.0	-14.7	1.6	0.7	0.7	0.8	1.2	1.6	2.1	2.6	3.6	6.9
93.5	-15.7	1.0	0.3	0.3	0.5	0.7	1.2	1.7	2.2	3.1	6.2
95.0	-16.6	5.0	0.8	0.5	0.5	0.8	1.3	1.8	2.3	3.2	6.3
97.5	-14.8	7.1	1.7	1.1	0.7	0.9	1.2	1.7	2.1	3.0	6.2
101.0	-16.6	6.7	2.6	2.1	1.6	1.5	1.7	2.0	2.5	3.3	6.5
104.5	-14.7	6.3	2.4	1.8	1.4	1.2	1.5	1.7	2.1	2.9	6.0
108.0	-12.5	6.6	2.5	1.9	1.5	1.3	1.5	1.8	2.1	2.9	6.1
116.5	-14.5	6.1	2.7	2.1	1.7	1.5	1.6	1.8	2.1	2.8	5.6
120.5	-15.1	6.2	2.7	2.1	1.6	1.5	1.6	1.8	2.1	2.7	5.6
125.0	-13.7	6.4	2.7	2.1	1.6	1.4	1.5	1.7	2.0	2.8	5.8
132.0	-15.2	6.6	2.9	2.3	1.7	1.6	1.6	1.8	2.1	3.0	6.1
140.5	-13.2	6.5	2.8	2.2	1.8	1.7	1.7	1.9	2.3	3.0	6.0
144.0	-15.8	4.7	2.4	2.0	1.7	1.6	1.7	1.9	2.2	3.0	5.9
148.0	-12.9	4.3	2.1	1.8	1.6	1.5	1.7	1.9	2.2	3.0	5.9
152.0	-16.7	4.0	1.8	1.6	1.4	1.4	1.6	1.9	2.2	2.9	5.8
155.5	-15.1	4.1	1.7	1.5	1.3	1.3	1.5	1.8	2.1	2.9	6.0
164.5	-16.1	3.8	1.5	1.2	1.1	1.1	1.3	1.7	2.0	2.8	5.9
167.5	-14.5	3.5	1.4	1.2	1.0	1.0	1.3	1.7	2.1	3.2	7.1
171.5	-15.7	3.2	1.4	1.2	1.1	1.1	1.6	2.0	2.5	3.6	7.5
176.5	-14.1	3.3	1.3	1.2	1.2	1.3	1.8	2.4	2.9	4.1	8.1
179.5	-12.6	3.8	1.6	1.3	1.3	1.5	2.0	2.5	3.2	4.4	8.7
188.75	-15.0	4.0	1.8	1.5	1.4	1.5	1.8	2.2	2.6	3.3	6.4
192.5	-13.5	3.9	1.8	1.5	1.3	1.5	1.7	2.1	2.4	3.2	6.0
196.75	-14.7	3.9	1.6	1.5	1.3	1.4	1.7	2.1	2.6	3.7	7.9
203.5	-17.0	4.0	1.8	1.6	1.5	1.7	2.2	2.8	3.4	4.7	9.0
213.25	-14.5	4.1	2.1	1.8	1.8	2.2	2.7	3.3	3.9	5.2	9.3
219.5	-15.3	2.2	1.7	1.7	2.0	2.3	2.9	3.5	4.1	5.3	9.4

Temperature (^{o}C) / Thermocouple Depth (CM)

Time (Hrs)	Freezer	Top Heater	5	10	15	20	25	30	35	40	Bottom Heater
223.5	-13.7	2.0	1.6	1.6	1.8	2.1	2.8	3.3	3.8	4.7	7.6
227.75	-12.7	2.0	1.5	1.5	1.7	2.0	2.5	2.9	3.3	4.1	7.0
237.25	-12.8	1.6	0.9	0.9	1.0	1.3	1.7	2.1	2.4	3.3	6.2
240.5	-13.3	1.4	0.7	0.7	0.9	1.0	1.5	1.8	2.2	2.9	5.9
245.0	-16.5	1.2	0.5	0.5	0.6	0.9	1.4	1.9	2.5	3.7	7.8
247.0	-16.3	1.2	0.5	0.5	0.5	0.9	1.4	2.0	2.6	3.9	8.1
248.0	-15.0	1.2	0.5	0.5	0.6	0.9	1.5	2.1	2.7	4.0	8.3
250.0	-14.4	1.2	0.5	0.5	0.6	1.0	1.6	2.3	2.9	4.2	8.4
252.0	-13.2	1.9	1.0	1.0	1.2	1.6	2.2	2.9	3.5	4.9	9.4
261.75	-12.6	1.2	0.6	0.7	0.9	1.4	2.1	2.9	3.5	4.8	9.0
266.5	-13.6	1.3	0.6	0.7	0.9	1.4	2.0	2.6	3.1	3.9	6.8
269.0	-13.3	1.3	0.6	0.7	0.9	1.3	1.8	2.3	2.7	3.6	6.5
278.75	013.1	1.4	0.5	0.5	0.7	0.9	1.3	1.8	2.2	3.0	6.0
285.5	-14.7	0.9	0.3	0.2	0.3	0.5	0.9	1.4	1.7	2.5	5.4
290.75	-16.1	0.9	0.0	-0.1	0.0	0.3	0.7	1.1	1.5	2.3	5.3
298.25	=15.9	1.0	-0.2	-0.3	-0.2	0.0	0.5	1.0	1.4	2.2	5.5
307.5	-14.2	0.7	-0.2	-0.3	-0.1	0.3	0.9	1.5	2.1	3.4	7.6
311.0	-13.4	0.8	-0.2	-0.2	0.0	0.4	1.1	1.7	2.4	3.6	7.5
317.25	-16.1	0.9	-0.1	-0.1	0.1	0.5	0.3	1.9	2.5	3.8	7.7
323.0	-12.8	1.3	0.1	0.1	0.3	0.7	1.4	2.0	2.6	3.8	7.5
325.5	-14.1	1.2	0.2	0.2	0.5	0.8	1.5	2.1	2.7	3.8	7.6
333.5	-13.3	1.3	0.3	0.3	0.5	0.9	1.5	2.1	2.7	3.8	7.6
337.5	-15.3	1.2	0.3	0.4	0.5	0.9	1.5	2.1	2.7	3.8	7.5
343.0	-15.7	1.2	0.3	0.3	0.5	0.9	1.5	2.0	2.7	3.8	7.6
344.5	-16.8	1.2	0.3	0.3	0.5	0.9	1.5	2.1	2.7	3.8	7.5
357.5	-17.3	1.3	0.5	0.4	0.6	1.0	1.6	2.2	2.8	3.9	7.6
361.0	-17.3	1.2	0.5	0.5	0.6	1.0	1.6	2.2	2.8	3.9	7.5
364.5	-14.4	1.8	1.1	1.1	1.3	1.6	2.2	2.9	3.3	4.5	8.3

Temperature (°C) / Thermocouple Depth (CM)

Time (Hrs)	Freezer	Top Heater	5	10	15	20	25	30	35	40	Bottom Heater
368.0	-17.4	1.1	0.4	0.4	0.6	1.0	1.6	2.2	2.7	3.8	7.6
381.5	-15.0	1.4	0.5	0.5	0.7	1.1	1.7	2.3	2.9	4.0	7.9
382.0	-15.3	1.7	0.9	0.9	1.1	1.4	2.0	2.6	3.2	4.3	7.9
385.25	-14.5	0.0	0.2	0.3	0.6	1.0	1.6	2.1	2.6	3.6	6.7
390.0	-14.2	- 0.6	-0.2	-0.0	0.3	0.7	1.3	1.8	2.2	3.1	6.2
392.0	-14.7	-0.7	-0.3	-0.2	0.2	0.6	1.1	1.6	2.0	3.0	6.1
395.0	-15.6	0.3	-0.3	-0.2	0.0	0.4	0.9	1.4	1.9	2.8	6.1
406.5	-17.5	-0.1	-0.4	-0.4	-0.2	0.0	0.6	1.1	1.5	2.5	5.8
409.5	-12.8	0.3	-0.3	-0.3	-0.1	0.1	0.6	1.1	1.5	2.4	5.6
413.0	-14.8	0.1	-0.3	-0.3	-0.2	0.0	0.5	1.0	1.4	2.4	5.6
417.0	-15.8	0.2	-0.3	-0.3	-0.2	0.0	0.5	1.0	1.4	2.3	5.6
418.5	-13.2	0.2	-0.4	-0.4	-0.3	-0.0	0.4	0.8	1.2	2.2	5.6
433.5	-16.7	0.0	-0.3	-0.3	-0.2	-0.0	0.4	0.8	1.2	2.1	5.2
437.0	-15.4	0.1	-0.3	-0.3	-0.2	-0.0	0.3	0.8	1.2	2.0	5.3
443.0	-15.2	0.2	-0.3	-0.3	-0.2	-0.0	0.4	0.8	1.2	2.2	5.4
453.25	-15.1	0.0	-0.3	-0.3	-0.2	-0.0	0.3	0.7	1.1	1.9	5.1
456.5	-16.8	-0.0	-0.4	-0.4	-0.3	-0.1	0.2	0.7	1.0	1.9	5.0
460.25	-16.1	0.0	-0.3	-0.3	-0.2	-0.0	0.3	0.7	1.1	1.9	5.1
466.75	-15.3	0.3	-0.3	-0.3	-0.2	-0.0	0.3	0.8	1.2	2.1	5.6
477.5	-13.1	0.1	-0.3	-0.3	-0.2	-0.0	0.3	0.8	1.2	2.1	5.4
481.0	-13.1	0.0	-0.3	-0.3	-0.2	-0.0	0.3	0.7	1.1	2.0	5.2
484.75	-15.6	0.0	-0.3	-0.3	-0.2	-0.0	0.3	0.7	1.1	2.0	5.3
488.5	-17.1	0.1	-0.3	-0.3	-0.2	-0.0	0.3	0.8	1.2	2.0	5.3
501.25	-13.0	0.2	-0.3	-0.3	-0.2	-0.0	0.4	0.8	1.2	2.2	5.6
505.25	-17.2	0.0	-0.3	-0.3	-0.2	-0.0	0.4	0.8	1.2	2.2	5.4
513.25	-15.0	0.1	-0.3	-0.3	-0.2	-0.0	0.3	0.8	1.2	2.1	5.4
525.75	-12.6	0.2	-0.3	-0.3	-0.2	-0.0	0.4	0.8	1.2	2.2	5.5
536.0	-14.3	0.1	-0.3	-0.3	-0.2	-0.0	0.4	0.8	1.2	2.2	5.4

Temperature (^{o}C) / Thermocouple Depth (CM)

Time (Hrs)	Freezer	Top Heater	5	10	15	20	25	30	35	40	Bottom Heater
553.75	-14.4	0.0	-0.3	-0.3	-0.2	-0.0	0.4	0.8	1.2	2.2	5.4
573.5	-16.9	-0.0	-0.3	-0.3	-0.3	-0.1	0.3	0.7	1.1	2.0	5.4
580.75	-14.2	-0.1	-0.3	-0.3	-0.2	-0.1	0.3	0.7	1.1	1.9	5.2
585.5	-13.2	0.0	-0.3	-0.3	-0.3	-0.1	0.2	0.7	1.1	2.0	5.4
597.5	-17.5	-0.2	-0.3	-0.3	-0.2	-0.0	0.3	0.7	1.2	2.0	5.2
603.5	-13.8	-0.2	-0.3	-0.3	-0.2	-0.1	0.3	0.7	1.1	2.0	5.2
624.75	-17.2	-0.3	-0.4	-0.4	-0.3	-0.1	0.2	0.6	1.0	1.9	5.1
635.0	-12.6	-0.0	-0.4	-0.4	-0.3	-0.1	0.3	0.7	1.2	2.1	5.6
645.0	-16.8	-0.1	-0.3	-0.3	-0.3	-0.1	0.3	0.7	1.1	2.0	5.4
652.75	-15.8	-0.2	-0.4	-0.4	-0.3	-0.1	0.2	0.7	1.1	1.9	5.2
669.5	-13.9	-0.2	-0.4	-0.4	-0.3	-0.2	0.2	0.7	1.1	2.0	5.4
675.0	-13.7	-0.3	-0.4	-0.4	-0.3	-0.1	-0.3	0.7	1.2	2.0	5.3
680.5	-16.3	-0.3	-0.4	-0.4	-0.3	-0.2	0.2	0.7	1.1	2.0	5.3
693.5	-17.2	-0.3	-0.4	-0.4	-0.4	-0.2	0.2	0.7	1.1	2.0	5.4
699.75	-17.3	-0.6	-0.4	-0.4	-0.4	-0.2	0.2	0.6	1.1	1.9	5.2
704.25	-14.3	-0.6	-0.4	-0.4	-0.3	-0.2	0.2	0.6	1.0	1.9	5.2
718.25	-16.5	-0.7	-0.4	-0.4	-0.3	-0.2	0.2	0.7	1.1	2.0	5.3
731.0	-12.8	-1.1	-0.8	-0.7	-0.4	-0.2	0.1	0.5	1.0	1.8	5.2
744.75	-17.2	-1.4	-1.1	-0.9	-0.5	-0.2	0.1	0.5	1.0	1.8	5.2
766.5	-14.4	-1.5	-1.2	-1.1	-0.7	-0.3	0.1	0.5	1.0	1.9	5.2
782.25	-15.8	-1.5	-1.2	-1.1	-0.7	-0.4	0.1	0.6	1.0	1.9	5.2
790.0	-16.9	-1.6	-1.3	-1.2	-0.8	-0.4	0.0	0.5	0.9	1.8	5.2
813.5	-17.2	-1.6	-1.4	-1.3	-0.9	-0.5	-0.0	0.4	0.8	1.7	5.2
821.5	-12.8	-1.7	-1.5	-1.3	-1.0	-0.6	-0.0	0.4	0.7	1.6	5.0
837.0	-14.9	-1.6	-1.5	-1.4	-1.0	-0.7	-0.1	0.4	0.8	1.7	5.2
847.25	-16.6	-1.7	-1.5	-1.4	-1.1	-0.7	-0.2	0.3	0.7	1.6	5.1
860.5	-16.5	-1.8	-1.6	-1.4	-1.1	-0.7	-0.2	0.3	0.7	1.6	5.1
888.0	-16.5	-1.9	-1.6	-1.5	-1.2	-0.9	-0.3	0.1	0.6	1.5	4.9

Temperature (°C) / Thermocouple Depth (CM)

Time (Hrs)	Freezer	Top Heater	5	10	15	20	25	30	35	40	Bottom Heater
914.75	-16.8	-2.0	-1.7	-1.6	-1.3	-1.0	-0.4	0.0	0.5	1.4	4.8
920.5	-14.6	-2.0	-1.8	-1.7	-1.4	-1.1	-0.5	-0.0	0.4	1.2	4.7
968.75	-17.2	-1.9	-1.8	-1.8	-1.4	-1.2	-0.7	-0.2	0.3	1.2	4.9
988.5	-17.0	-2.0	-1.9	-1.8	-1.5	-1.2	-0.7	-0.2	0.2	1.2	4.7
1013.5	-16.4	-2.1	-1.9	-1.9	-1.6	-1.3	-0.8	-0.3	0.2	1.0	4.4
1036.75	-12.9	-2.2	-2.1	-2.0	-1.7	-1.4	-0.9	-0.4	0.0	0.9	4.3
1061.25	-16.0	-2.5	-2.2	-2.1	-1.8	-1.5	-1.0	-0.6	-0.1	0.7	3.9
1082.0	-16.1	-2.5	-2.3	-2.2	-2.0	1.6	-1.2	-0.7	-0.2	0.7	3.9
1107.0	-14.4	-2.6	-2.4	-2.4	-2.1	-1.8	-1.3	-0.8	-0.4	0.6	3.9
1109.25	-15.0	-2.6	-2.4	-2.4	-2.1	-1.8	-1.3	-0.8	-0.4	0.3	2.9
1131.5	-13.7	-2.8	-2.6	-2.6	-2.4	-2.1	-1.6	-1.1	-0.7		
1131.5	EXPERIMENT TERMINATED										

NOTE: Frozen - unfrozen interface occurred at a depth of 37 CM as a sharp boundary.

APPENDIX E

TEMPERATURE DATA

FOR EXPERIMENT #7

TEMPERATURE DATA FOR EXPERIMENT # 7

Temperature (°C) / Thermocouple Depth (CM)

Time (Hrs)	Freezer	Top Heater	5	10	15	20	25	30	35	40	Bottom Heater
0	14.8	16.4	15.8	15.6	15.6	15.6	15.6	16.5	16.5	16.5	15.1
0.5	4.0	17.7	15.8	15.7	15.6	15.6	15.8	16.3	16.4	16.4	16.6
1.5	-13.6	18.0	16.0	15.6	15.8	15.8	16.1	16.2	16.2	16.4	18.9
2.5	-12.9	15.9	15.9	15.5	15.5	15.6	15.8	15.6	15.7	15.9	18.3
4.0	-13.6	14.0	14.9	14.7	14.7	14.8	14.8	14.4	14.4	14.7	17.2
5.0	-15.0	13.2	14.2	14.2	14.1	14.1	14.0	13.6	13.6	13.8	16.5
8.0	-14.0	10.0	11.8	11.9	11.8	11.8	11.5	11.0	11.2	11.5	14.4
10.0	-12.0	8.7	10.3	10.6	10.4	10.4	10.0	9.8	9.9	10.3	13.2
12.0	-12.7	7.8	9.0	9.2	9.1	9.0	8.8	8.6	8.8	9.3	12.4
14.0	-15.6	7.0	7.8	8.0	8.1	7.9	7.8	7.6	8.1	8.5	11.7
16.0	-15.2	6.2	6.7	6.8	6.8	6.8	6.7	6.9	7.3	7.8	10.9
18.0	-14.9	5.4	5.8	5.8	5.8	5.9	5.9	6.1	6.6	7.1	10.3
23.5	-14.8	4.1	3.7	3.7	3.8	4.0	4.3	4.6	5.3	5.8	9.2
26.0	-15.3	3.5	2.9	2.8	3.0	3.3	3.7	4.1	4.8	5.4	8.8
28.0	-15.5	3.1	2.4	2.2	2.4	2.8	3.3	3.7	4.4	5.0	8.4
31.5	-14.0	2.7	1.7	1.5	1.7	2.2	2.7	3.3	3.9	4.7	8.2
35.0	-12.8	2.3	1.0	0.8	1.1	1.6	2.3	2.8	3.6	4.2	7.9
38.0	-13.9	2.0	0.6	0.4	0.7	1.2	2.0	2.7	3.7	4.7	9.4
40.0	-13.2	1.9	0.4	0.2	0.5	1.2	2.0	2.8	4.0	5.0	10.0
46.0	-12.4	1.6	0.0	-0.2	0.3	1.3	2.4	3.4	4.8	5.9	10.8
48.0	-12.2	1.4	-0.1	-0.2	0.4	1.4	2.6	3.6	4.9	6.0	10.8
49.5	-15.0	1.3	-0.1	-0.1	0.5	1.5	2.7	3.7	5.0	6.1	10.9
51.0	-15.4	1.3	-0.1	-0.1	0.5	1.6	2.8	3.8	5.1	6.2	11.0
53.5	-13.9	1.3	-0.1	-0.0	0.6	1.7	2.9	3.9	5.2	6.4	11.2
57.5	-14.6	1.3	-0.0	0.0	0.8	1.9	3.1	4.0	5.4	6.4	11.2
63.0	-15.4	1.6	0.1	0.3	1.0	2.2	3.3	4.3	5.6	6.7	11.6
70.5	-12.4	1.8	0.3	0.5	1.2	2.4	3.5	4.5	5.9	7.0	12.0

Temperature (°C) / Thermocouple Depth (CM)

Time (Hrs)	Freezer	Top Heater	5	10	15	20	25	30	35	40	Bottom Heater
75.5	-12.2	1.8	0.4	0.6	1.3	2.5	3.4	4.2	5.3	6.2	9.8
77.5	-13.7	1.2	0.4	0.7	1.3	2.4	3.2	3.9	5.0	5.8	9.4
81.0	-15.5	1.0	0.2	0.4	1.1	2.0	2.8	3.5	4.5	5.2	8.8
84.5	-14.1	1.0	0.0	0.2	0.8	1.7	2.4	3.1	4.0	4.9	8.6
93.5	-15.3	0.8	-0.4	-0.4	0.2	1.1	1.7	2.4	3.5	4.3	8.0
97.0	-14.3	0.6	-0.6	-0.5	0.0	0.9	1.5	2.3	3.4	4.4	9.5
99.0	-12.4	0.6	-0.7	-0.7	0.0	0.9	1.5	2.4	3.6	4.7	9.5
100.0	-12.4	0.6	-0.7	-0.7	-0.0	0.9	1.5	2.5	3.8	4.9	9.7
101.0	-12.9	0.6	-0.8	-0.7	-0.0	0.9	1.6	2.6	3.9	5.0	9.9
104.0	-14.0	0.5	-0.8	-0.7	-0.0	1.0	1.8	2.8	4.2	5.4	10.2
105.0	-14.1	0.5	-0.8	-0.7	0.0	1.1	1.9	2.9	4.4	5.5	10.3
106.0	-14.2	0.5	-0.8	-0.7	0.0	1.2	1.9	3.0	4.4	5.6	10.4
108.25	-14.8	0.7	-0.8	-0.6	0.2	1.3	2.1	3.1	4.5	5.6	10.5
116.5	-12.1	0.7	-0.5	-0.3	0.4	1.5	2.1	3.1	4.2	5.2	9.4
120.0	-12.9	0.2	-0.6	-0.3	0.4	1.4	2.0	3.0	4.1	5.0	9.2
121.0	-12.9	0.2	-0.7	-0.4	0.4	1.4	2.0	2.9	4.1	5.0	9.3
122.0	-13.9	0.2	-0.7	-0.3	0.4	1.4	2.0	3.0	4.1	5.1	9.3
123.0	-14.0	0.2	-0.7	-0.4	0.4	1.4	2.0	2.9	4.1	5.1	9.3
124.0	-14.4	0.2	-0.7	-0.4	0.4	1.4	2.0	2.9	4.0	5.1	9.3
125.0	-15.2	0.2	-0.7	-0.4	0.4	1.3	2.0	2.9	4.1	5.1	9.3
126.0	-14.4	0.1	-0.7	-0.4	0.4	1.3	2.0	2.9	4.1	5.1	9.3
129.5	-13.0	-0.0	-0.8	-0.5	0.3	1.3	1.9	2.8	4.0	5.0	9.2
140.75	-13.7	-0.2	-1.0	-0.6	0.2	1.2	1.9	2.8	4.0	5.0	9.3
145.25	-14.8	-0.3	-1.0	-0.6	0.2	1.2	1.8	2.8	4.0	5.0	9.2
149.0	-14.4	-0.9	-1.1	-0.7	0.2	1.1	1.8	2.7	3.9	5.0	9.2
150.75	-12.2	-0.4	-1.1	-0.7	0.2	1.1	1.8	2.8	4.0	5.0	9.3
153.5	-14.3	-0.1	-1.1	-0.7	0.2	1.1	1.8	2.8	4.0	5.1	9.4
156.25	-15.0	-0.1	-1.0	-0.7	0.2	1.1	1.8	2.8	4.0	5.0	9.4

Temperature (°C) / Thermocouple Depth (CM)

Time (Hrs)	Freezer	Top Heater	5	10	15	20	25	30	35	40	Bottom Heater
166.0	-12.0	-0.2	-1.0	-0.7	0.2	1.1	1.8	2.8	4.0	5.1	9.3
169.5	-14.7	-0.2	-1.1	-0.7	0.2	1.1	1.8	2.8	4.0	5.0	9.3
173.75	-15.2	-0.4	-1.1	-0.7	0.2	1.1	1.8	2.7	4.0	5.0	9.2
177.0	-14.8	-0.4	-1.1	-0.7	0.2	1.1	1.7	2.7	3.9	5.0	9.2
179.0	-15.3	-0.4	-1.1	-0.7	0.2	1.1	1.7	2.7	3.9	5.0	9.2
190.5	-13.5	-0.4	-1.1	-0.7	0.2	1.0	1.7	2.7	4.0	5.0	9.3
197.5	-14.1	-0.5	-1.2	-0.7	0.2	1.0	1.7	2.7	3.9	5.0	9.2
204.0	-15.7	0.2	-1.0	-0.7	0.2	1.0	1.7	2.7	3.9	5.0	9.3
214.5	-13.9	-0.2	-1.0	-0.6	0.3	1.0	1.7	2.7	3.9	5.0	9.2
218.5	-12.2	-0.3	-1.0	-0.6	0.3	1.0	1.6	2.7	3.9	4.9	9.1
221.5	-15.7	-0.4	-1.1	-0.7	0.3	1.0	1.6	2.7	3.8	4.9	9.1
238.0	-15.5	-0.3	-1.1	-0.7	0.2	0.9	1.6	2.6	3.9	4.9	9.2
249.5	-16.1	-0.4	-1.1	-0.7	0.2	0.8	1.5	2.5	3.8	4.8	9.0
262.25	-15.4	-0.4	-1.2	-0.8	0.2	0.8	1.5	2.5	3.8	4.9	9.2
269.75	-12.7	-0.4	-1.2	-0.7	0.1	0.8	1.4	2.5	3.8	4.9	9.1
288.5	-12.3	-0.3	-1.1	-0.6	0.2	0.8	1.6	2.6	3.9	5.0	9.2
334.5	-13.4	-0.0	-0.9	-0.5	0.3	0.9	1.6	2.6	3.9	5.1	9.4
341.5	-13.5	-0.3	-0.9	-0.5	0.2	0.8	1.5	2.6	3.9	5.0	9.3
358.25	-15.5	-0.2	-0.9	-0.5	0.2	0.8	1.5	2.6	3.9	5.0	9.3
366.75	-15.3	-0.2	-1.0	-0.5	0.2	0.8	1.5	2.6	3.9	5.0	9.2
366.75	EXPERIMENT TERMINATED										

NOTE: 1. First visual evidence of moisture in sand occurs at a depth of 13 cm.

2. No ice bonded material.