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LABORATORY AND FIELD STUDIES TO INVESTIGATE ISOTOPE EFFECTS OCCURING DURING THE FORMATION OF PERMAFROST - PHASE III -

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Abstract

Field and laboratory studies of oxygen and hydrogen isotopes were continued. Observations from the Illisarvik drained lake site have yielded important constraints on the lake history and the role of migrating moisture in the underlying permafrost. Laboratory studies of freezing columns have demonstrated fractionation at the freezing front but by only half of that predicted. The implications for isotope profiles with depth are discussed.

Résumé

On a poursuivi les études en laboratoire et sur le terrain des isotopes de l'oxygène et de l'hydrogène. Les résultats au lac drainé, Illisarvik, créent d'importantes contraintes pour l'évolution du lac et pour le rôle que joue la migration de l'eau dans le pergélisol sous-jacent. Les études en laboratoire utilisant des unités de congélation cylindriques ont démontré un fractionnement au front de gel qui n'était que la moitié de ce qui avait été prévu. On discute de ce que cette découverte implique pour les profils des isotopes en fonction de la profondeur.

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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 Rayleight 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.

In 1979-80, the laboratory work at Waterloo continued while a field laboratory program was initiated at Illisarvik in the Mackenzie Delta (W.R.I. contract 606-12-4). A series of 15 cores were obtained from within and surrounding the drained lake at Illisarvik during May of 1979.

The individual core samples were squeezed to extract the water and analysed for their isotope contents. Preliminary interpretations based on the data collected by March 1980 were presented in the final report (Michel and Fritz, 1980). Several shallow samples from across the Arctic Islands were also obtained and analysed.

1.2 Terms of Reference

This study was developed as a continuation of the laboratory experiments at Waterloo in order to qualify the effects creating the isotope variations in permafrost waters described previously, and to continue the field laboratory program at Illisarvik. Continued analytical work on the 1979 cores would provide a better understanding of the formation and stability of permafrost. A second drilling program was to be undertaken in order to supplement the previous data and to examine changes in the growth of the permafrost at Illisarvik after two winters of exposure.

1.3 Scope of Present Study

This report describes the work completed on the field laboratory at Illisarvik since the previous report in the spring of 1980. 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 seven experimental runs completed at Waterloo are discussed in relation to the naturally occurring isotope variations. The relationship of the isotope fractionation with respect to temperature gradients is also briefly examined.

Since the results of all the contract studies will be compiled and discussed in detail this summer as the senior author's Ph.D. thesis, this report serves primarily as a report of activities for the present contract. The thesis will be made available upon its completion later this year. A paper was recently presented at the 4th Canadian Permafrost Conference in Calgary (Michel and Fritz, 1981) on this research.

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 20, 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 13, 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.

During the summer of 1979 and 1980, Dr. J. R. Mackay has been continuing his studies at Illisarvik. Temperature measurements have been made at various times since the time when temperature cables were installed. Dr. P. Fransham of the University of Waterloo undertook some geophysical investigations in conjunction with the authors' work in 1979 and 1980. A series of short reports on those studies up to 1979 has been compiled by Dr. Hunter (1979) and a compilation of recent studies is currently in progress.

2.1.2 May 1980 Coring Expedition

A field party of four, led by F. Michel, spent an eight-day period from May 6th to May 14, 1980, at Illisarvik. Other members assisting in the

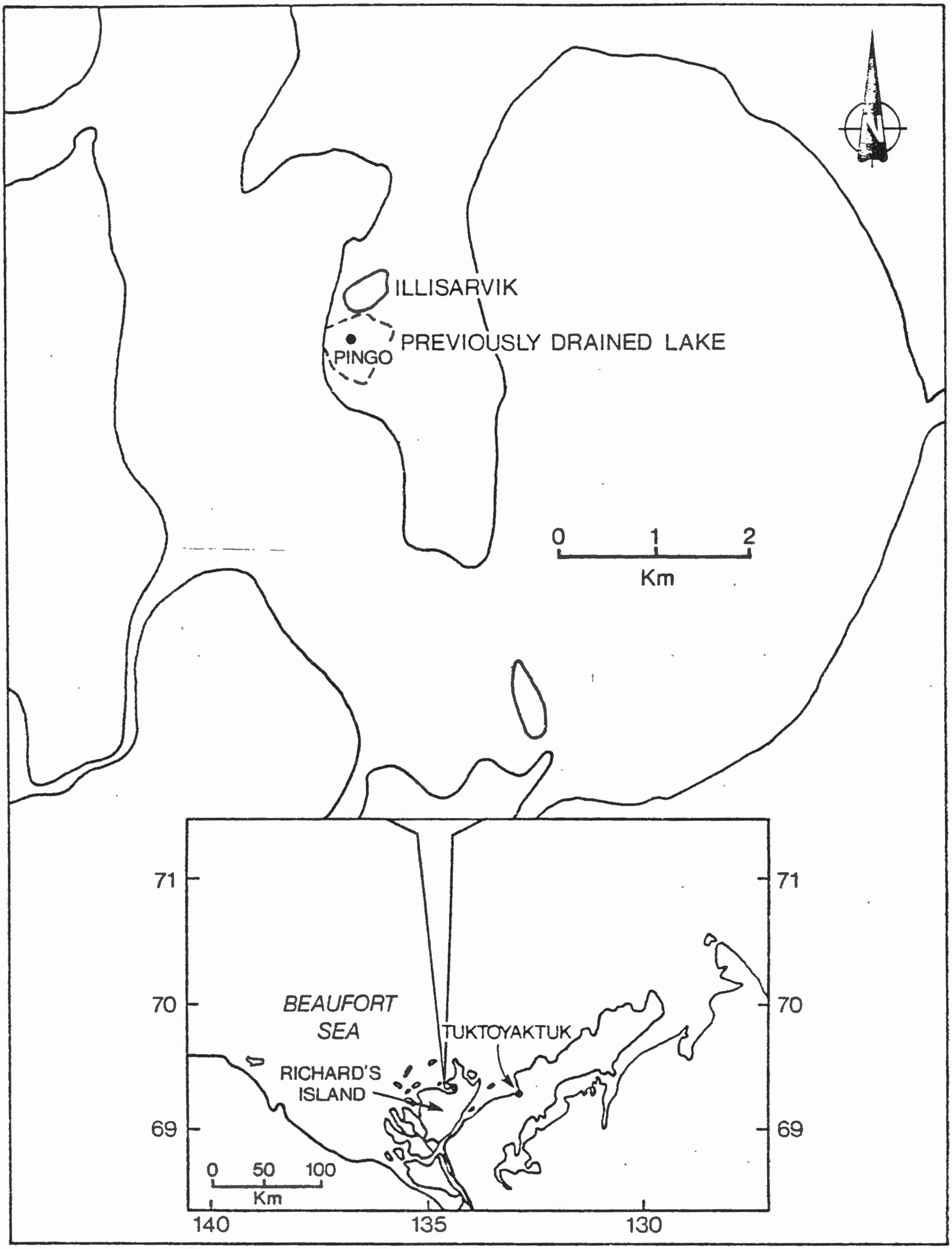

Figure 1. Location map of Illisarvik

field were Mr. S. Gruszka, Mr. A. Scott and Mr. E. Linton; all of which are technical support staff at the University of Waterloo.

Equipment and supplies were flown in during the evening of May 6th from the PCSP base at Tuktoyaktuk using a Bell 206A helicopter supplied by PCSP. After the first load of supplies was dropped off at Illisarvik, a short side trip was taken to Hooper Island in order to examine the possibility of collecting a series of samples down the face of the shore cliffs. Upon arrival on the north side of the island, it was determined that the exposed sediments had suffered moisture loss and would not be suitable for sampling without a drill. Before leaving, six samples were collected of water worn wood chips located at various elevations within the stratified sands.

Prior to our arrival at Illisarvik, the cabin had been visited by a local bear that left most of the windows broken and several claw punctures in the walls. Because of the broken windows, several decimetres of snow had drifted into the cabin, covering the lower bunks, table, counter, shelves and stove. The stove lines were completely frozen with ice and each section had to be individually thawed. Removal of the snow took some four hours with an additional four hours to thaw the stove lines.

In comparison to 1979, the Illisarvik area received considerably more snow during the winter of 1979-80. On May 7th, there was approximately 30 to 40 centimetres in the open flats and 1 to 5 centimetres over most of the lake bed. The lake bed was almost completely exposed by the 11th of May, but the drainage channel remained completely snow plugged throughout the stay. A summary of basic weather conditions is given in Table 1.

A total of eight holes were drilled in various locations throughout the area using drill equipment similar to that of last year's program and a 7.5 cm diameter core barrel. Three holes were drilled across the pingo to the south of the cabin in order to complete the section started last year with hole 79-14. Hole 80-2 penetrated about 9.5 metres of massive ice and ended in ice. A single hole was drilled on the bay some 200 metres west of the drainage channel. This hole penetrated approximately a half metre of ice underlain by frozen silts. A hole drilled on the high ridge running along the centre of the peninsula encountered some five metres of massive ice above sand.

Table 1: Illisarvik Weather Conditions, May 1980

Date	Time	Temperature (^{o}C)	Wind and Direction	Notes
May 6	21:00	cold	light S.W.	clear
May 7	8:00	very cold	moderate N.E.	clear & sunny
	22:30	-10.5	strong N.W.	light snow, overcast
May 8	8:00	-15.0	strong N.W.	light snow, overcast
	23:30	-11.0	light S.W.	overcast
May 9	10:00	-8.0	light E	overcast
	16:00	-5.0	moderate E	partly sunny
May 10	9:00	-5.0	light E-N.E.	sunny
	afternoon	+1.0		sunny
	23:00	-2.0		
May 11	7:30	-8.0	calm	heavy fog (clear at sunrise)
	12:00	-1.5	calm	foggy
	16:00	-1.0		
	24:00	-3.0	calm	overcast
May 12	3:30			light snow
	8:00	-4.0	calm	overcast
	21:00	-3.0		
May 13	9:00	-4.0	moderate-gusting	sunny
May 14	8:00	-5.0	strong E	clear

The remaining three holes were drilled adjacent to the holes drilled during the 1979 program so that changes during the year could be examined. Hole 80-5 was drilled near to 79-3, but the absence of a pipe in 79-3 and the heavy snow cover prevented the relocation of 79-3. Holes 80-6 and 80-7 were drilled adjacent to holes 79-4 and 79-1 respectively. These holes, located in the Illisarvik lake bed, provided samples of organic silts and sands that have been subjected to freezing for two winters. Both holes showed that the freezing front had advanced downwards up to 1 metre more than last winter. A summary of hole locations and depths are provided in Table 2. It should be noted, that the core barrel jammed in hole 80-1 and two pints of methyl alcohol were required to free the drill. All of the holes, with the exception of 80-1 and 80-BAY, were cased with PVC pipe containing a galvanized steel plug in the bottom and a cap on top.

2.1.3 Sample Processing

Since returning from the field, the processing of samples collected during the 1979 and 1980 programs has been underway. 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). The water extracted is then used for analysis of their oxygen-18, deuterium and tritium contents. Due to the large number of samples collected, the analytical work is still in progress, but the amount of work completed far surpasses the contractual requirements.

Water extraction has been completed on cores 79-1, 2, 3, 4, 6, 7, 8, 9, 12, 14, 15, IW#1, IW#2 and 80-2, 4, 5, 6, 7, BAY. The remaining cores are being stored. Oxygen-18 analyses have been completed on all of these cores while deuterium analyses are currently in progress on selected samples from several cores. Tritium determinations have been made on samples from cores 79-3, 4, 6, 8, 14, 15, IW#1, IW#2 and 80-2, 4, 6, BAY.

Those cores for which the isotope work has been completed have been released for measurement of their geotechnical parameters and for radiocarbon dating. Radiocarbon dating has been completed on two samples

Table 2: Illisarvik Borehole Locations and Depths, May 1980

Borehole #	Note	Location	Depth (m)
80-1	Pingo	6 m east of 79-14	2.59
80-2	Pingo	6 m west of 79-14	9.85
80-3	Pingo	6 m west of 80-2	2.93
80.4	Highest ground	4 + 50N, 1 + 00W	7.25
80-5	Same as 79-3	3 + 50N, 2 + 00E	3.09
80-6	same as 79-4	0 + 58N, 0 + 52E	3.22 frozen 3.80 E.O.H.
80-7	Same as 79-1	0 + 00N, 1 + 35.7 E	5.07 frozen 5.60 E.O.H.
80-BAY	200 m west of drainage channel		0.54 ice 1.80 E.O.H.

from Hooper Island, five samples from 79-4, two samples from 79-6 and two samples from 79-8 during the current fiscal contract.

2.2 Arctic Islands

During the summer of 1980, Mr. Larry Dyke of the Geological Survey of Canada, undertook field work on the Sabine Peninsula of Melville Island. To supplement the single ice rich sample collected in 1979 at a site north of Sherard Bay (76^{0} 18^{1}N, 108^{0} 33^{1}W) on the Sabine Peninsula, Mr. Dyke provided a group of eight samples from two sites in the same area. These samples are currently being processed and will be reported at a later date.

2.3 Laboratory Experiments

Simulation of freezing conditions in the laboratory has progressed well during the current year. A total of seven experiments were conducted between May 1980 and February 1981. Run times varied from a minimum of 690 hours to a maximum of just over 1700 hours. A new small diameter squeezer was constructed in an attempt to extract water from the unsaturated materials tested last year in experiment #7. In anticipation of this, a second unsaturated experiment was conducted this year. Unfortunately, the new squeezer did not perform as expected and as a result neither of these experiments have been examined to date for their isotope contents. Preparations are being made to distill the samples in the near future. All other experiments conducted employ the use of saturated materials with one column being filled with water (similar to experiment #4). The experiments concentrated on examining the effects of a stabilized freezing front and the layering of different soil types. Whereas in previous years the columns were frozen completely, many of the experiments this year were terminated with the bottom portion unfrozen.

3. DISCUSSION OF RESULTS

3.1 Illisarvik Experimental Lake Site

3.1.1 Stratigraphy

The generalized stratigraphy for the Illisarvik basin was presented in the report last year (Michel and Fritz, 1980). Since that time, the stratigraphic work has focused on the radiocarbon dating of organic materials in order to provide a time frame for the history of the lake and the sediments. This work is continuing on several cores, with the results of the first two cores presented in Table 3. The ages obtained for core 79-3 were briefly described last year and will be left until all of the dating is complete.

The authors estimated an age for the formation of the lake in their paper at Calgary based on five dates from core 79-4 (Michel and Fritz, 1981).

Within the lake, core 79-4 represents a section through the organic rich lake silts and the upper portion of the stony clay-silt unit. As can be seen from Figure 2, a time break in sedimentation occurs at the boundary between these two units. If the basal layers are indicative of the formation of the present Lake Illisarvik, then the apparent age for the lake, in at least this portion of the basin, is approximately 8700 to 9000 years ago. This age could be reduced by as much as 2000 years if the "age" of the modern sediments is assumed to be about 2000 years, as indicated by extrapolation to the surface. This age effect could be due to the uptake of ^{14}C depleted aqueous carbon into the organic matter. Such "hard water" effects have been noted in many more southerly lakes (Karrow and Anderson, 1975), but have not been investigated in these northern environments.

It should be noted that the presence of a lake near 79-4 some 6500 to 8500 years ago does not imply that the lake covered all of the present lake bed area at that time. However, preliminary ages for two samples from core 79-6 strongly suggest that this portion of the lake bed was also covered some 7000 to 8000 years ago. Nevertheless, more radiocarbon dating is required before a detailed history of the evolution of the lake can be determined.

Table 3: Radiocarbon data for Illisarvik

Sample #	Depth (CM)	$\delta^{13}C$ ($^{o}/oo$ PDB)	$^{o}/o$ Modern (PMC)	^{14}C AGE (YRS B.P.)	Wat #
79-3-2	5-10	-28.2	98.4	80±70	631
79-3-9	40-45	-28.5	52.3	5150±80	632
79-3-22	105-110	-26.6	44.9	6410±100	639
79-4-2	5-10	-29.3	74.3	2320±70	746
79.4.20	95-100	-28.5	54.1	4880±80	739
79-4-44	215-220	-21.8	34.0	8720±90	741
79.4.53	265-270	-27.4	11.2	17530±540	740
80-6	360-365	-27.4	8.6	19630±1600	742

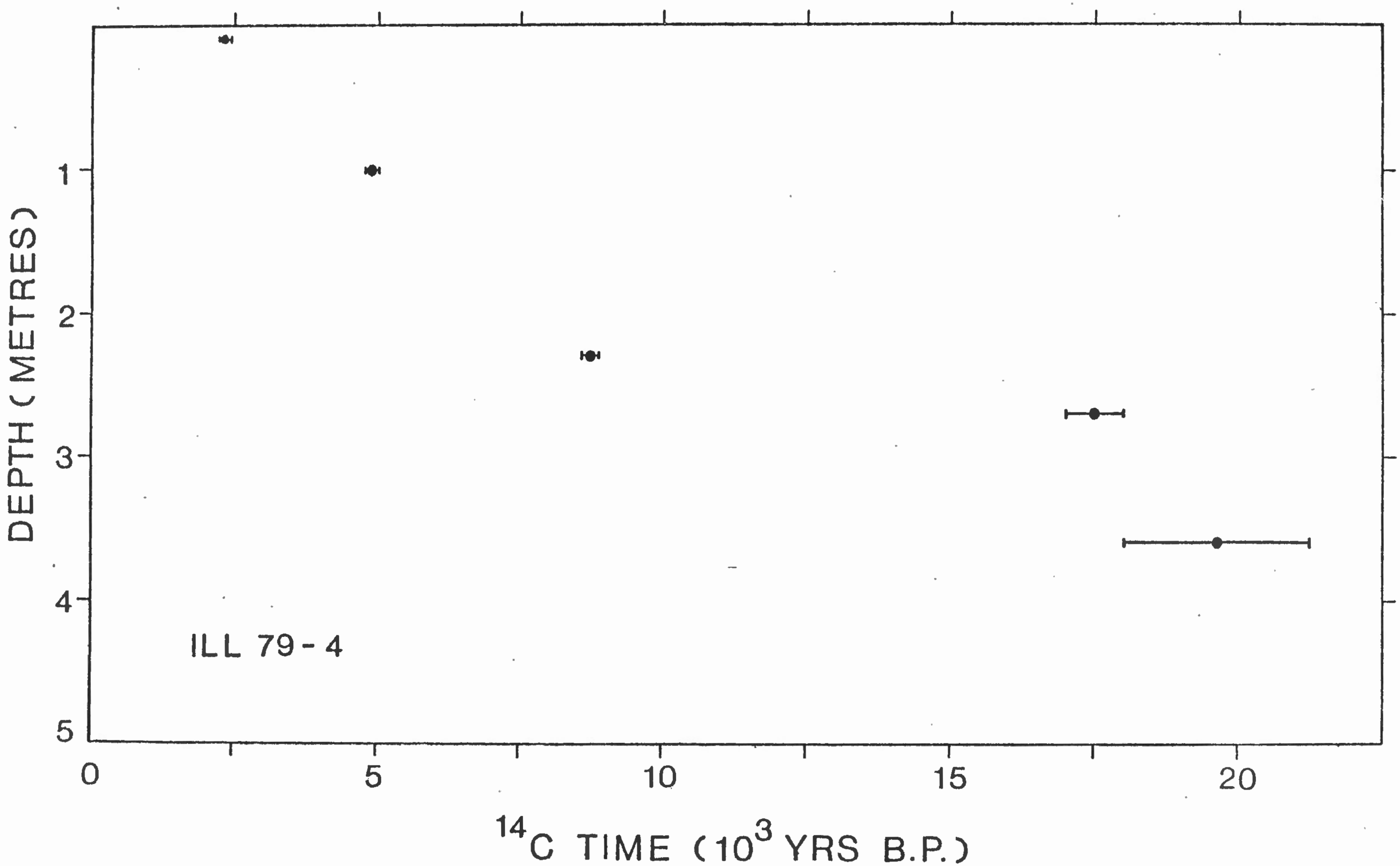

Figure 2. ^{14}C with depth for core 79-4

3.1.2 Moisture Contents

Samples are generally not released for determination of their geotechnical properties until all of the isotope analyses are completed. Because some deuterium and tritium analyses are still in progress, only a select number of samples have been released for moisture content determinations. Some of the samples were released because the isotope work was complete, but most of the samples were organic rich with sufficient water extracted which would enable the isotope analyses to be repeated if required.

The moisture contents for these selected samples are listed in Table 4. Core 80-6 was drilled adjacent to core 79-4 and the results are, therefore, compiled together. It is clearly evident that the organic rich samples contain very large amounts of water. The moisture contents generally decrease with depth to a level of approximately 15 to 20 per cent. This drop is in part due to changes in the soil types, but other factors related to moisture migration are also important. A detailed discussion of these relationships will be left until more complete moisture data are available.

3.1.3 Isotope Measurements

3.1.3.1 Oxygen-18 and Deuterium

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

Stable isotope analyses for the Illisarvik samples are nearing completion. The oxygen-18 content determinations are essentially complete and will be discussed presently, whereas, the deuterium contents are still being analysed and will, therefore, be discussed at a later time. Discussion of the pingo and ice wedge isotope data will be kept separate in sections 3.1.4 and 3.1.5, respectively.

Table 4: Moisture contents for selected Illisarvik samples

Sample #	Depth (CM)	Moisture Content ($^o/o$)
79-4-2	5-10	818
79-4-8	35-40	523
79-4-20	95-100	147
79-4-37	180-185	102
79-4-44	215-220	92
79-4-48	235-240	80
79-4-53	260-265	18
80-6	280-285	20
80-6	360-365	15
79-6-3	10-15	679
79-6-23	110-115	106
79-6-45	220-225	91
79-7-2	5-10	84
79-7-8	35-40	92
79-7-15	70-75	52
79-7-20	95-100	40
79-7-24	115-120	15
79-7-31	150-155	21
79-8-3	10-15	109
79-8-9	40-45	143
79-8-17	80-85	268
79-8-21	100-105	75
79-8-30	145-150	51
79-8-35	170-175	46
79-8-51	250-255	27
79-8-61	300-305	21

As described in the report from the previous contract (Michel and Fritz, 1980), it was decided to examine the oxygen-18 contents of every sample for a number of cores. This amount of detailed work was considered necessary because of the nature of the research being conducted. It is anticipated that once the variations occurring in isotope profiles of permafrost cores are thoroughly understood, the density of samples can be reduced to a more practical level. Several of the profiles were discussed in the paper at Calgary (Michel and Fritz, 1981) and are supplemented by additional data in this report.

Borehole 80-4 was drilled on the top of the high ridge running along the centre of the peninsula. The area was covered with 10 to 20 cm of snow which made the siting of the hole somewhat difficult. A zone of massive ice was encountered from approximately 0.45 metres to 5.5 metres which contained some soil and numerous vertically oriented bubbles. Near the base of the ice zone, one side of the core was ice while the other half was soil. This evidence would suggest that an ice wedge had been cored.

From the oxygen-18 profile (Figure 3), it is possible to define the active layer depth at 45 cm which coincides with the soil-ice interface. The $\delta^{18}o$ values of -18 to $-20^{o}/oo$ found in the active layer are representative of shallow modern groundwaters in the area. The large negative shift within the active layer and the small positive shift near the active layer-permafrost boundary indicates that freezing of the active layer occurred from the ground surface downward, and from the permafrost table upwards. Within the ice wedge, the oxygen-18 contents are extremely uniform at -24 to - $25^{o}/oo$. These are very similar to the ^{18}o contents of the ice wedges examined near the drainage channel.

Below the ice wedge, the $\delta^{18}o$ values decrease to around $-31^{o}/oo$. These low values resemble the values obtained for the deep core samples taken within the northern part of the Mackenzie Valley (Michel and Fritz, 1978). This shift from present precipitation values is the same as the $11^{o}/oo$ shift found by Dansgaard et al. (1971) in the Greenland ice cap, suggesting that the highly negative waters were recharged during the late glacial period.

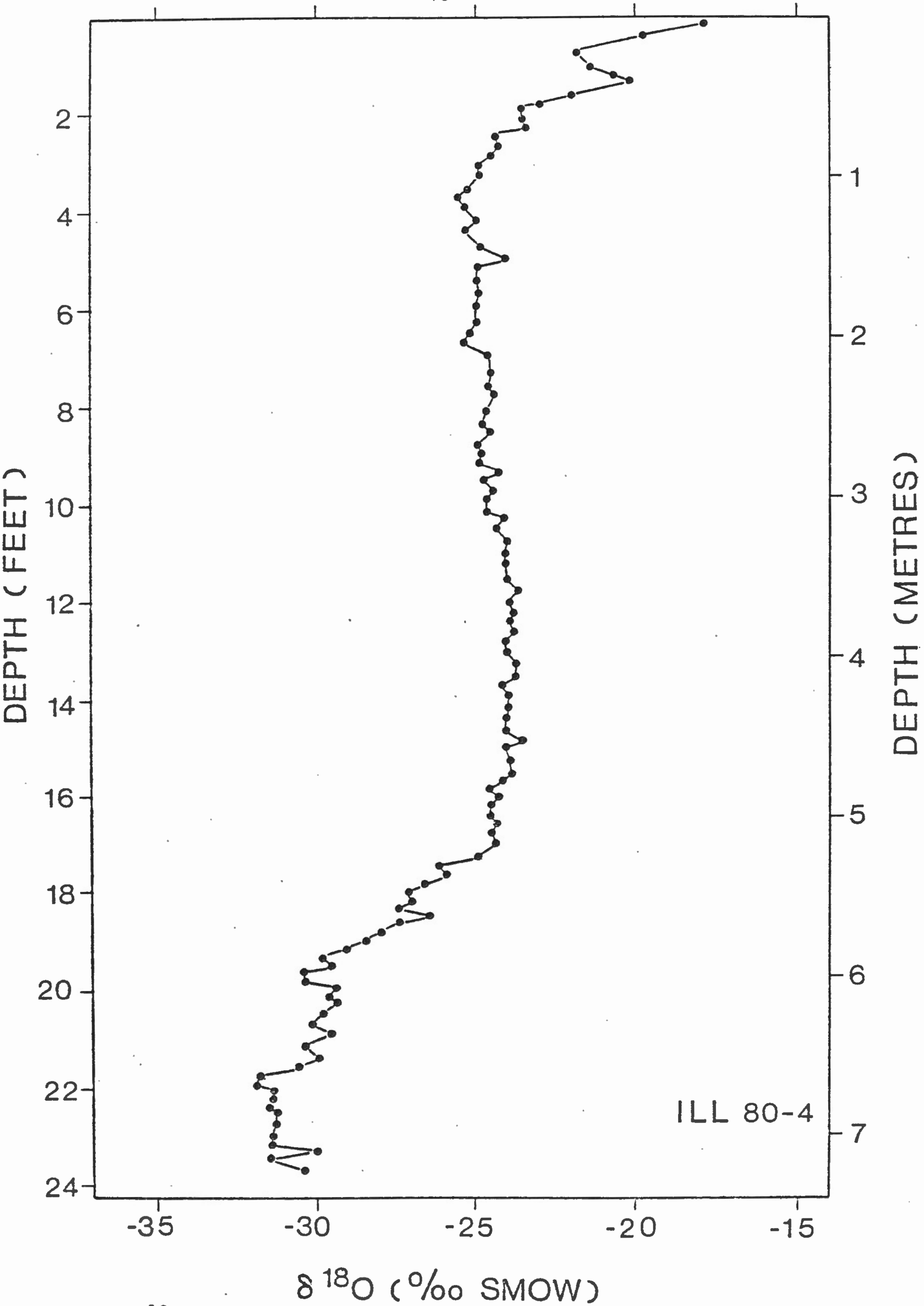

Figure 3. ^{18}O with depth for core 80-4

Moving off the top of the ridge and onto the slope, boreholes 79-3 and 80-5 were drilled at the east end of the main east-west section. The depths of penetration were slightly over 2 metres and 3 metres respectively. Both holes were terminated because of stone blockages. The depth of snow in 1980 and the lack of a marker for 79-3 prevented an exact positioning of the two holes adjacent to one another. It is believed that although close, hole 80-5 was located slightly downslope of 79-3. The major difference in the field logs for these two holes is the presence of an additional 60 cm thickness for the upper organic-silt strata.

In comparing the oxygen-18 profiles of cores 79-3 and 80-5, Figures 4 and 5 respectively, the general trends can be seen to be the same. The lack of an active layer shift for 80-5 is due to the gross sampling of this layer from 0 to 33 cm as one sample. The active layer shift in core 79-3 indicates freezing from above and below as described for core 80-4 on top of the ridge.

Both profiles gradually shift to increasingly negative values with depth in the upper organic-silt unit while only a very small shift occurs below. The break between these two sections contains a double peak shift in both cores. These single sample, positive shifts in the order of 2 to $3^{0}/oo$ are similar to small shifts produced in the laboratory (see section 3.2) which were the result of isotope fractionation during periods when the freezing front was stabilized. The profiles indicate a very slow shift below these fractionation spikes. Whether the oxygen-18 contents would continue to decrease towards the $-31^{0}/oo$ values of core 80-4 is unknown.

Within the lake, the upper sediments were subjected to freezing for one winter prior to the drilling in 1979. Borehole 79-4 intersected approximately 2.4 metres of frozen ground that changed gradually to unfrozen material at a depth of 2.5 metres. Temperature measurements by Judge et al. (1981) indicate that permafrost formed to depths well in excess of 2.5 metres which would suggest that freezing of the pore water did not occur until the temperature had dropped at least several tenths of a degree below zero. Borehole 80-6 was drilled approximately 3 metres from 79-4 in 1980. It encoutered frozen ground to a depth of 3.1 metres which was still

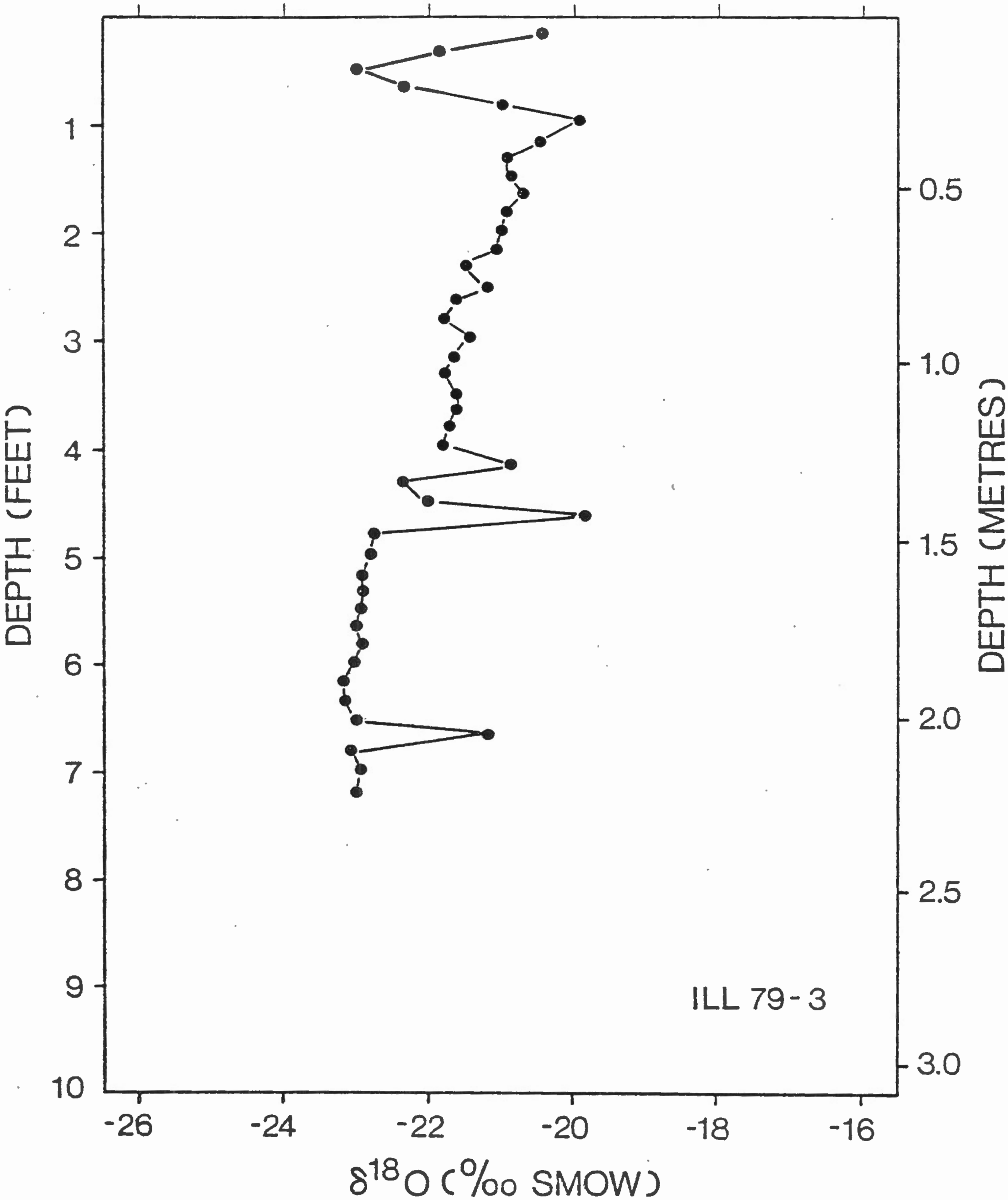

Figure 4. ^{18}O with depth for core 79-3

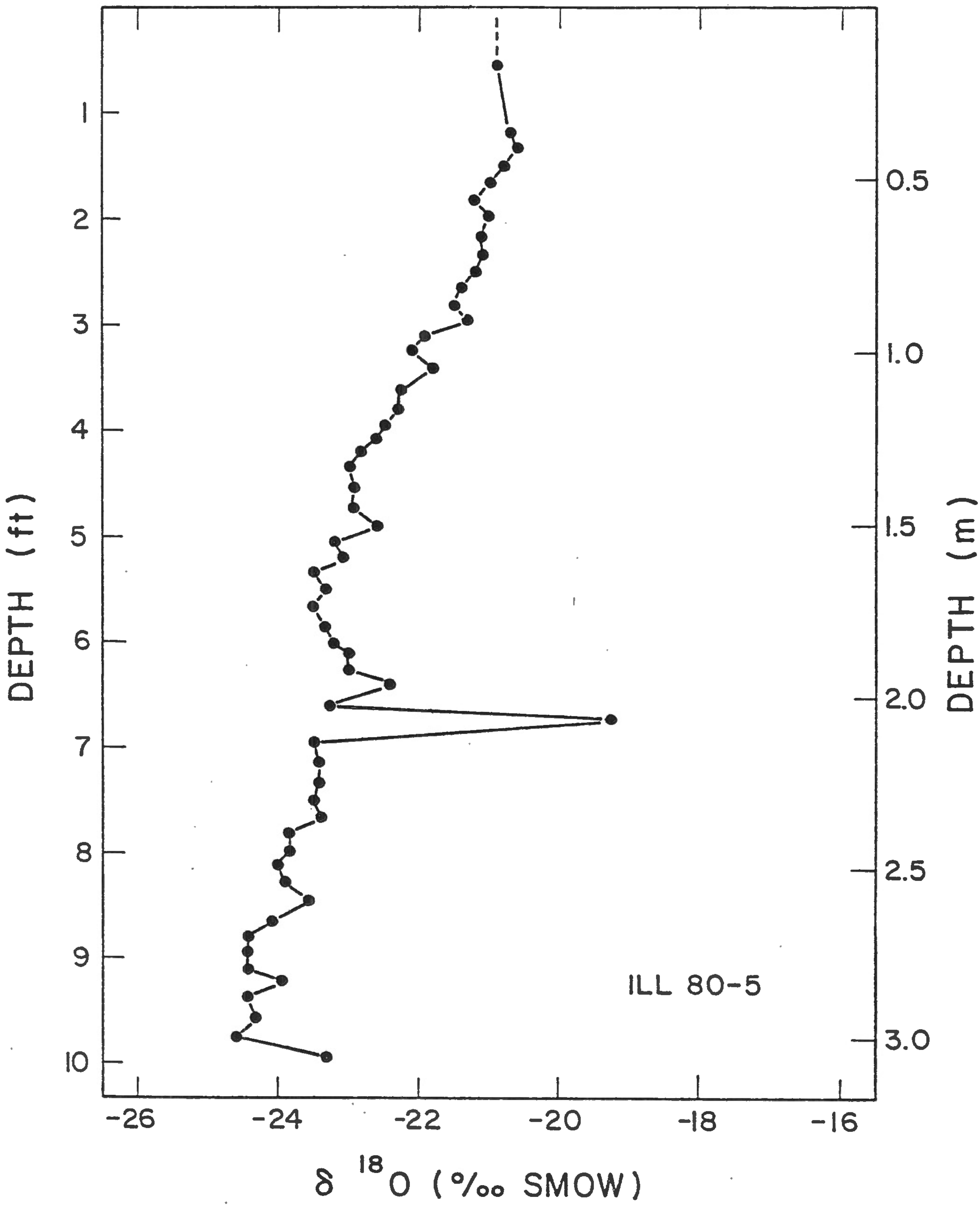

Figure 5. ^{18}O with depth for core 80-5

less than indicated by the temperature measurements.

The oxygen-18 profiles for cores 79-4 (Figure 6), 80-6 (Figure 7) and 79-12 (Figure 8) are extremely uniform throughout with only a minor negative shift with depth. The lack of any shift at the frozen-unfrozen boundary indicates that at the time of drilling, the freezing front was still migrating downwards. An absence of any shift in core 80-6 would further suggest that none of the sediments remained frozen throughout the summer of 1979. If they had, an impermeable layer would have existed which would generate an isotope fractionation shift as the freezing front progressed downwards towards the permafrost table as noted for the active layer. The $\delta^{18}o$ values of -15 to -16^{o}/oo are representative of the average lake water prior to drainage. Analysis of the deuterium contents of the waters from core 79-4 shows that evaporation has been insignificant.

The oxygen-18 profile for core 79-6 (Figure 9) is similar to the other cores collected within the lake bed, but there are slightly greater oscillations between individual samples. It is not entirely clear at this time why the oscillations occur but they must be the result of minor isotope fractionations during freezing.

Borehole 79-2 was drilled just beyond the edge of the lake. The oxygen-18 profile (Figure 10) again displays the typical active layer negative shift. Within the permafrost the oxygen-18 contents begin to gradually decrease as did the profiles for cores 79-3 and 80-5 further along the main section line. At a depth of approximately 2 metres, the oxygen-18 contents suddenly begin to increase towards a $\delta^{18}o$ value of approximately -16.5^{o}/oo. The stability with depth of the oxygen-18 contents signifies that a different water mass has been encountered. Whether this water was connected to the lake water or whether it represents an earlier body of water is not known, however, work by Mackay (1981) would suggest that the former hypothesis is unlikely.

Near the drainage channel, borehole 79-7 was drilled in the lake within a few metres of the shoreline. while 79-8 was drilled on shore within five metres of the coast. Borehole 79-8 is located on a low, level area criss-crossed by numerous ice wedges. Mackay (1981) described these wedges

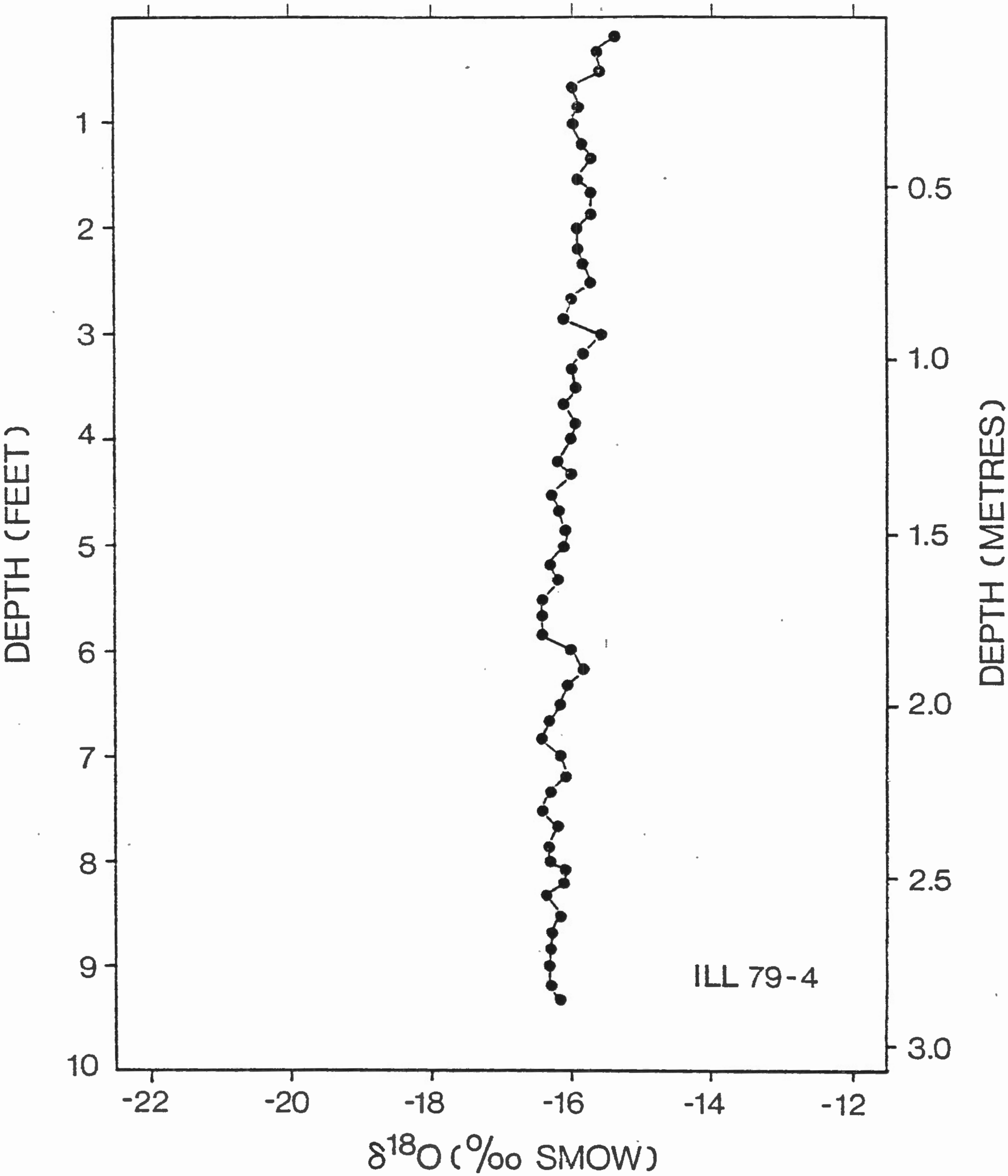

Figure 6. ^{18}O with depth for core 79-4

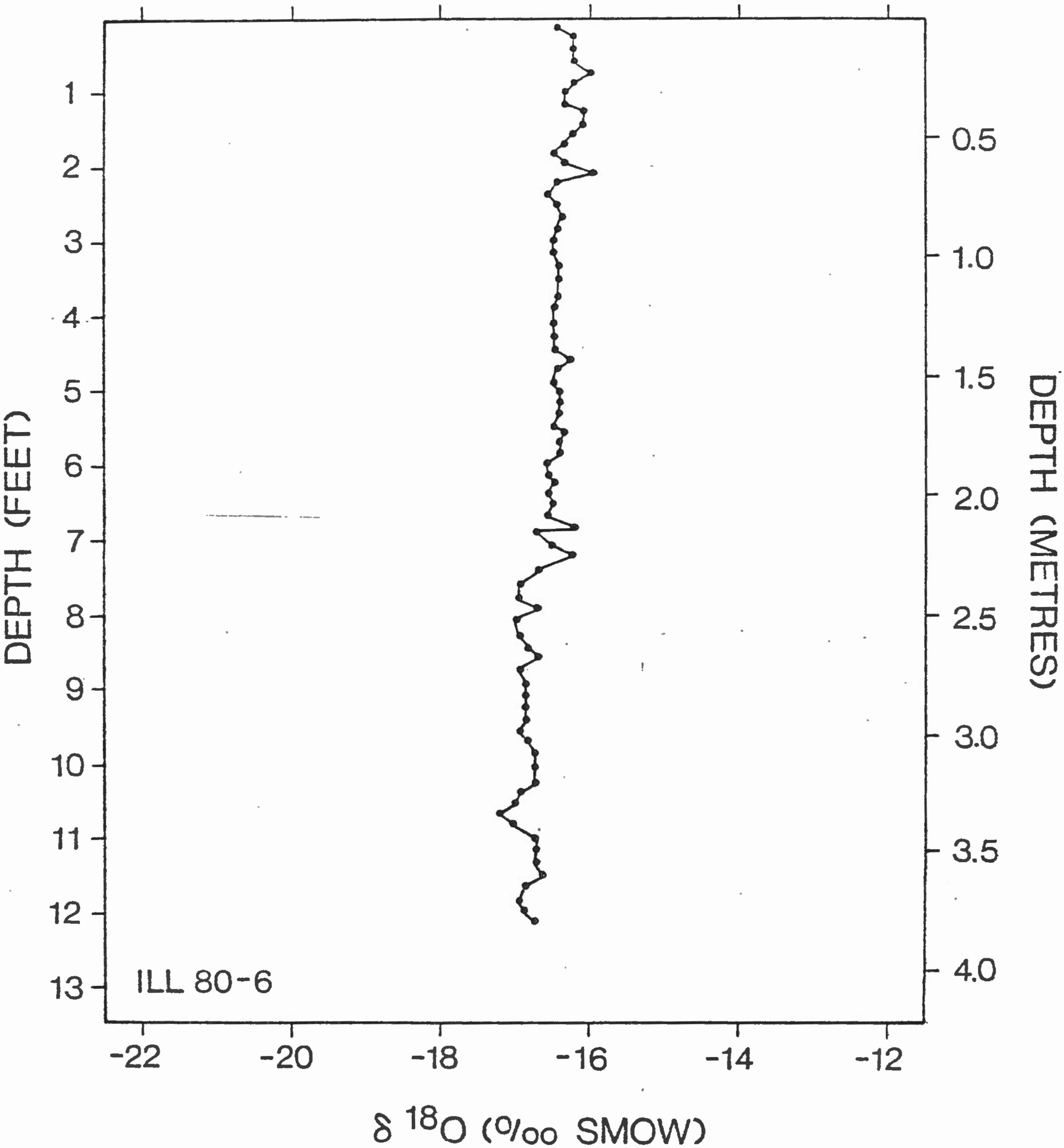

Figure 7. ^{18}O with depth for core 80-6

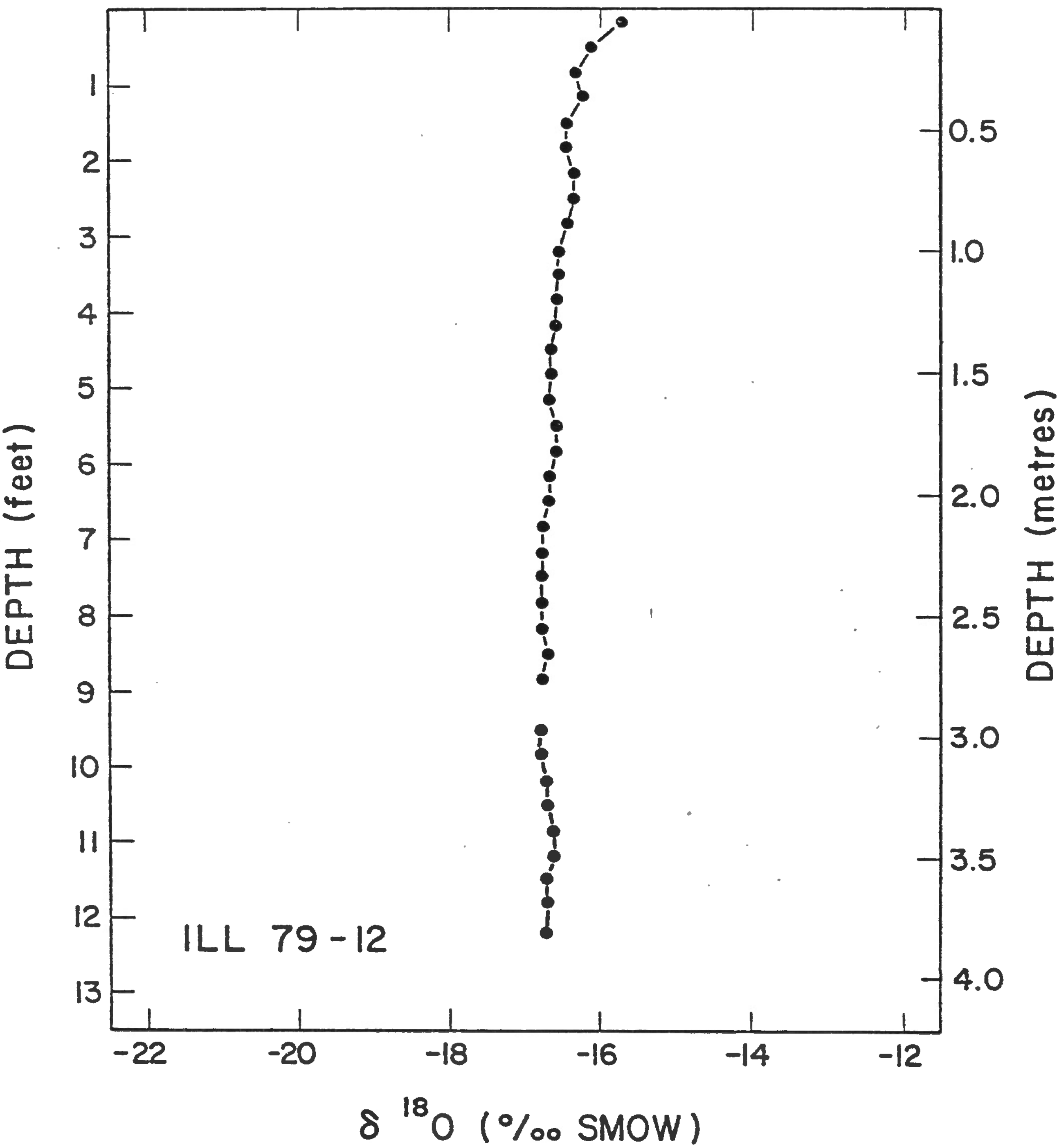

Figure 8. ^{18}O with depth for core 79-12

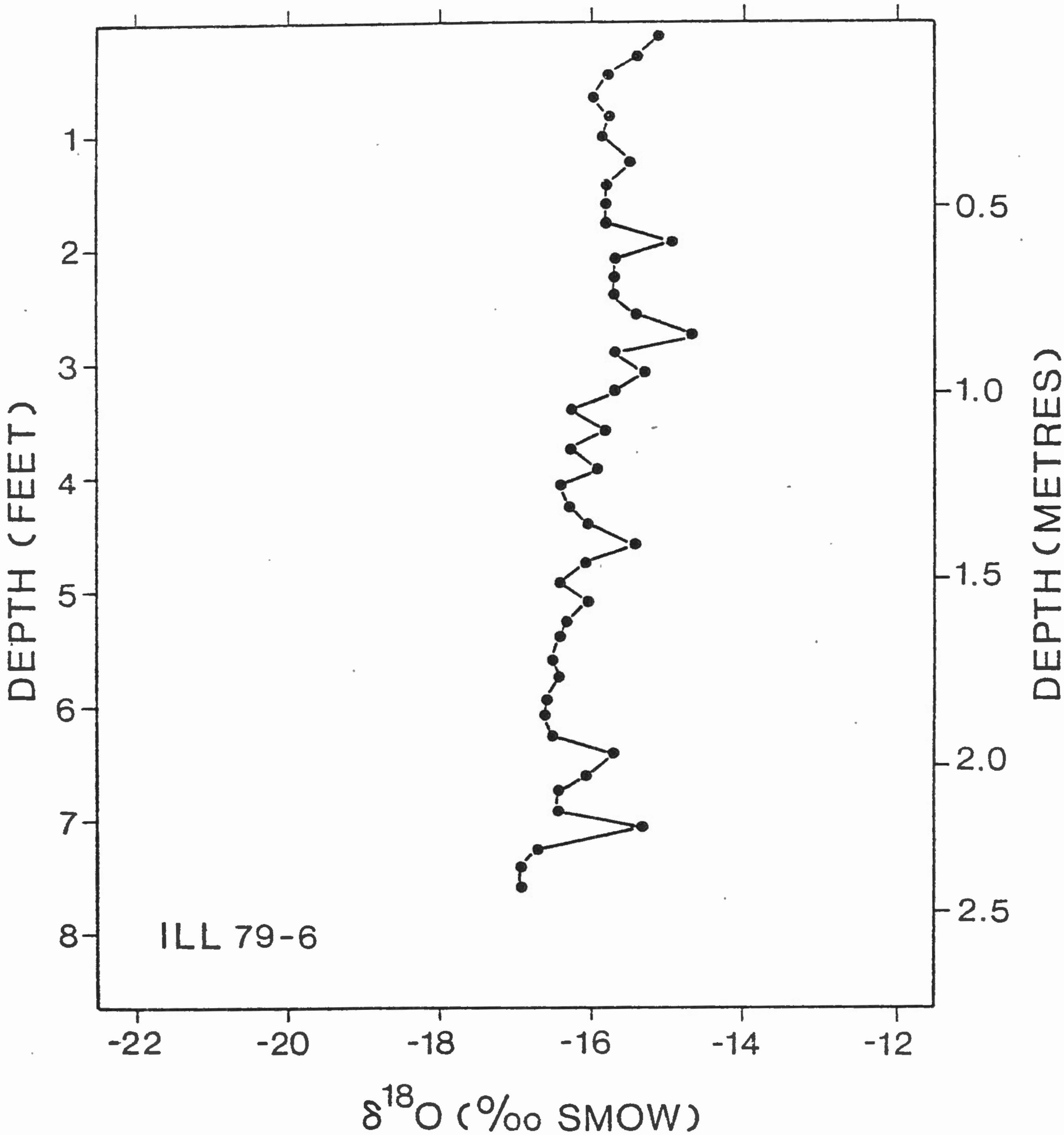

Figure 9. ^{18}O with depth for core 79-6

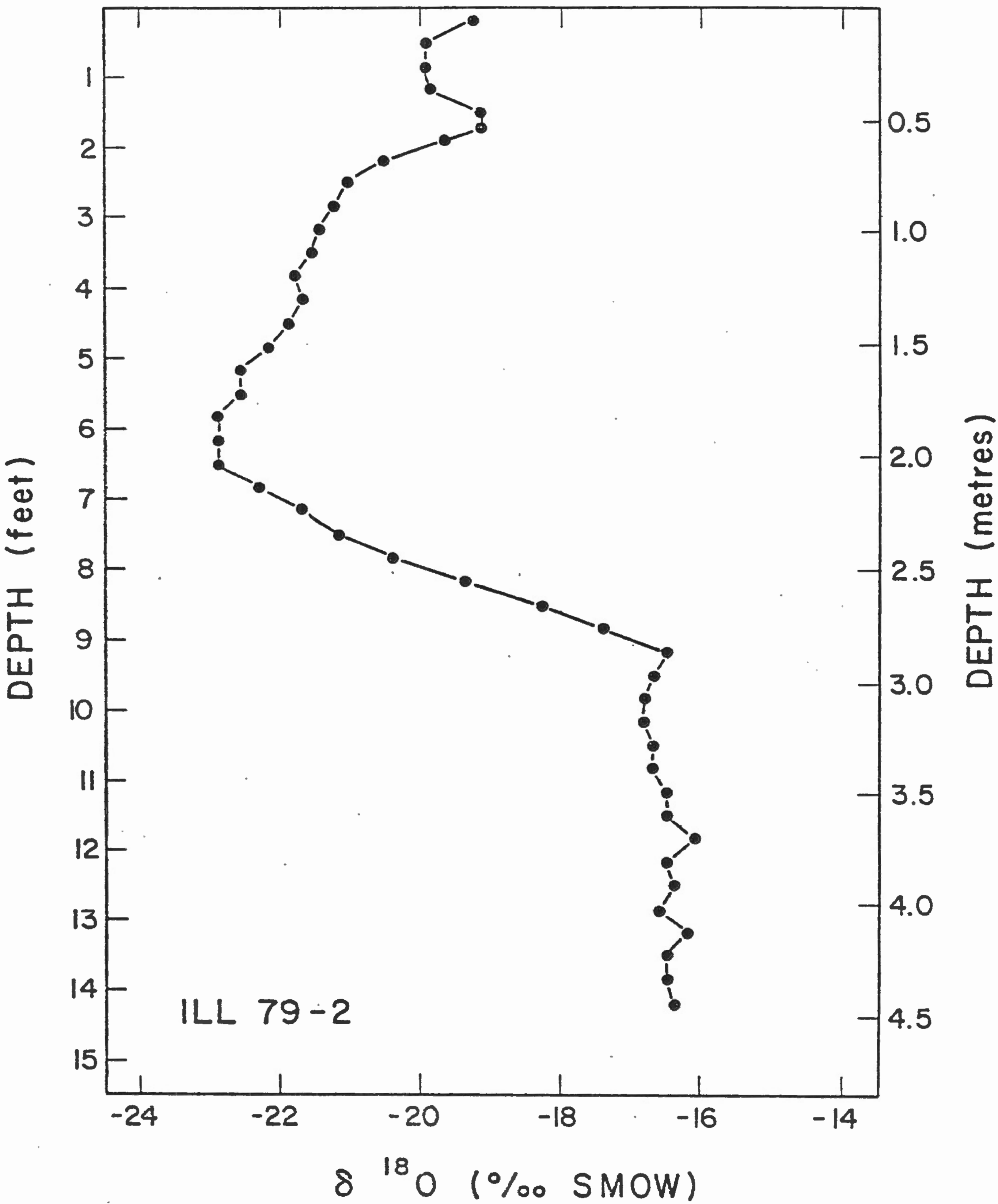

Figure 10. ^{18}O with depth for core 79-2

and pseudowedges within the lake bottom. In 1979, this area was bare of any snow cover so that the ice wedges could be located as linear depressions on the ground surface and avoided.

Figure 11, the oxygen-18 profile for 79-8, displays the characteristic active layer shift within the upper half metre. Within the permafrost the δ^{18}o values are initially relatively consistent between -18 and -20^{0}/oo. Between a depth of 2 to 3 metres the profile shifts continuously toward the more positive value of approximately -14^{0}/oo. Below 3 metres, the profile is again relatively uniform to the bottom of the core. Except for the actual δ^{18}o values at depth, the form of this profile is nearly identical to that of core 79-2.

The oxygen-18 profile of core 79-7 (Figure 12) also shifts from near surface values of -16^{0}/oo (recent lake water) to more positive values around -14^{0}/oo. Such a value cannot be generated in this area under today's climatic conditions and the maintenance of this value with depth could suggest that these waters originated from a lake existing in the Illisarvik basin during a warmer climatic period, possibly the Hypsithermal, which is generally thought to have lasted from 4000 to about 8000 B.P. (Dansgaard et al. 1971).

When the oxygen-18 contents of waters from core 79-15 are examined in Figure 13, a rapid positive shift towards a value of -14 to -15^{0}/oo is found. Borehole 79-15 is located in the Pingo Lake basin immediately to the south of Illisarvik, approximately half way between Illisarvik and the pingo. The similarity in oxygen-18 contents, in addition to other evidence, suggests that the two lake basins were at one time part of the larger lake.

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

From Figure 14, the active layer is seen to be approximately 60 cm deep. The upper section of permafrost contains water with oxygen-18 contents

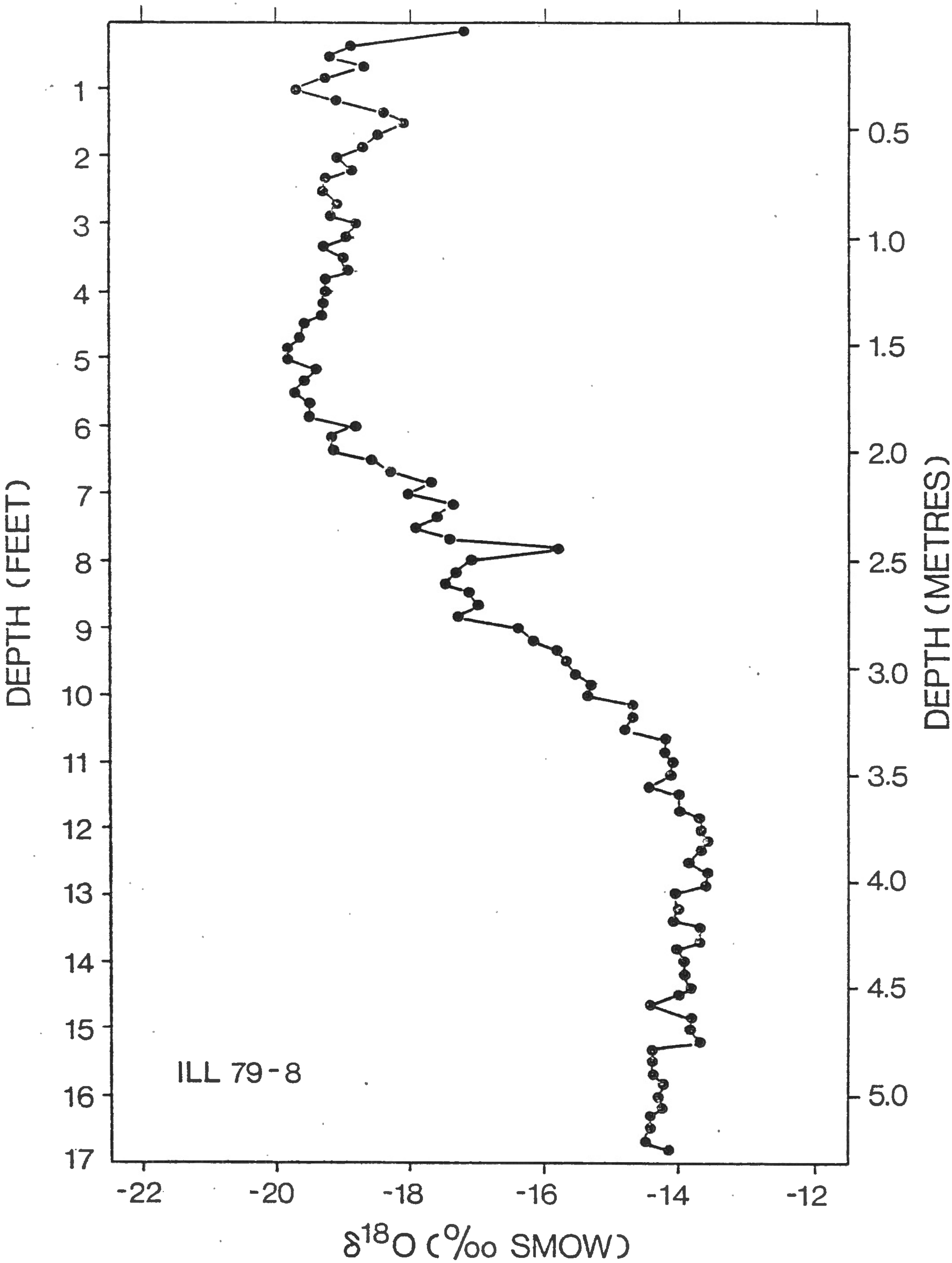

Figure 11. ^{18}O with depth for core 79-8

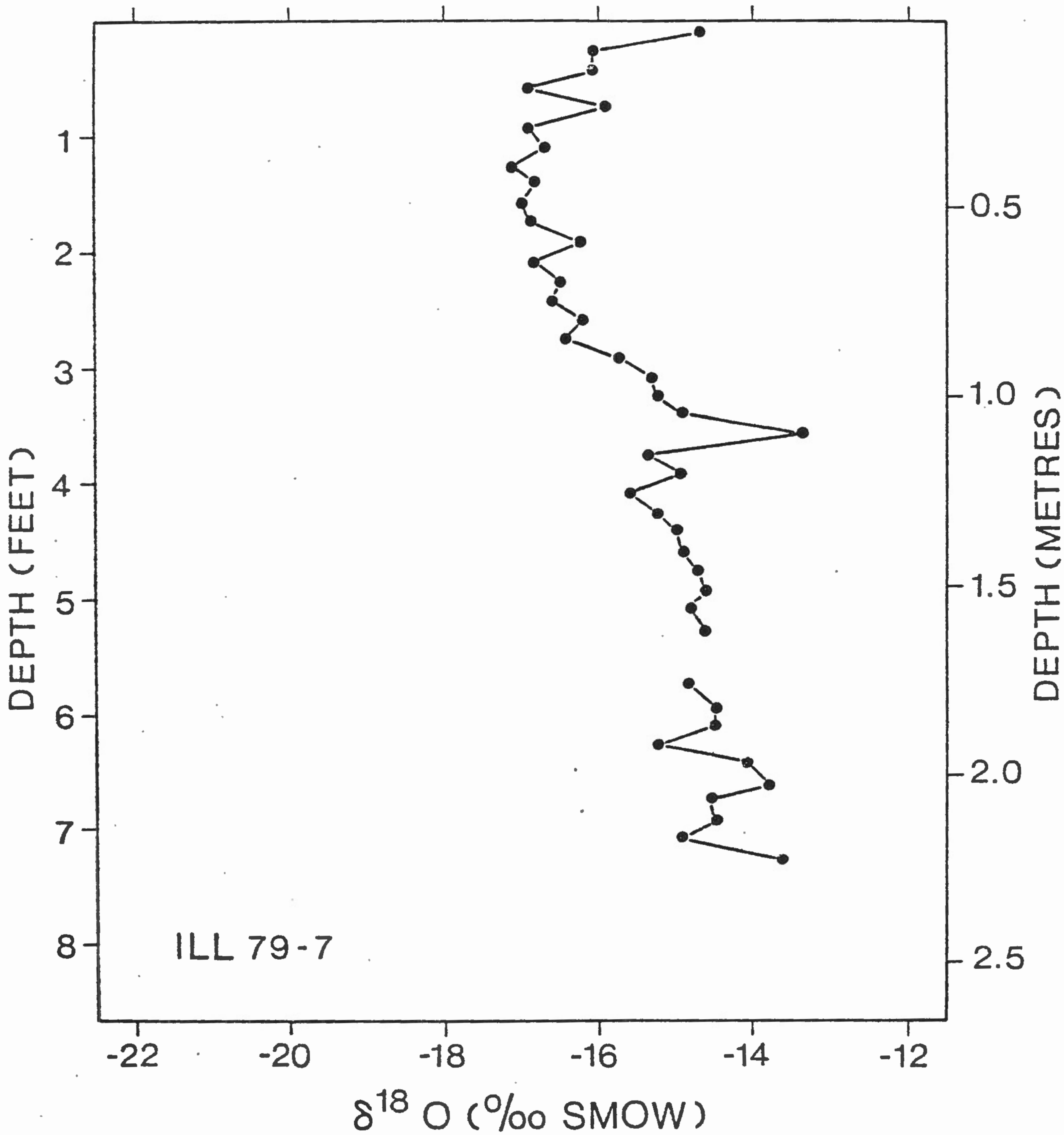

Figure 12. ^{18}O with depth for core 79-7

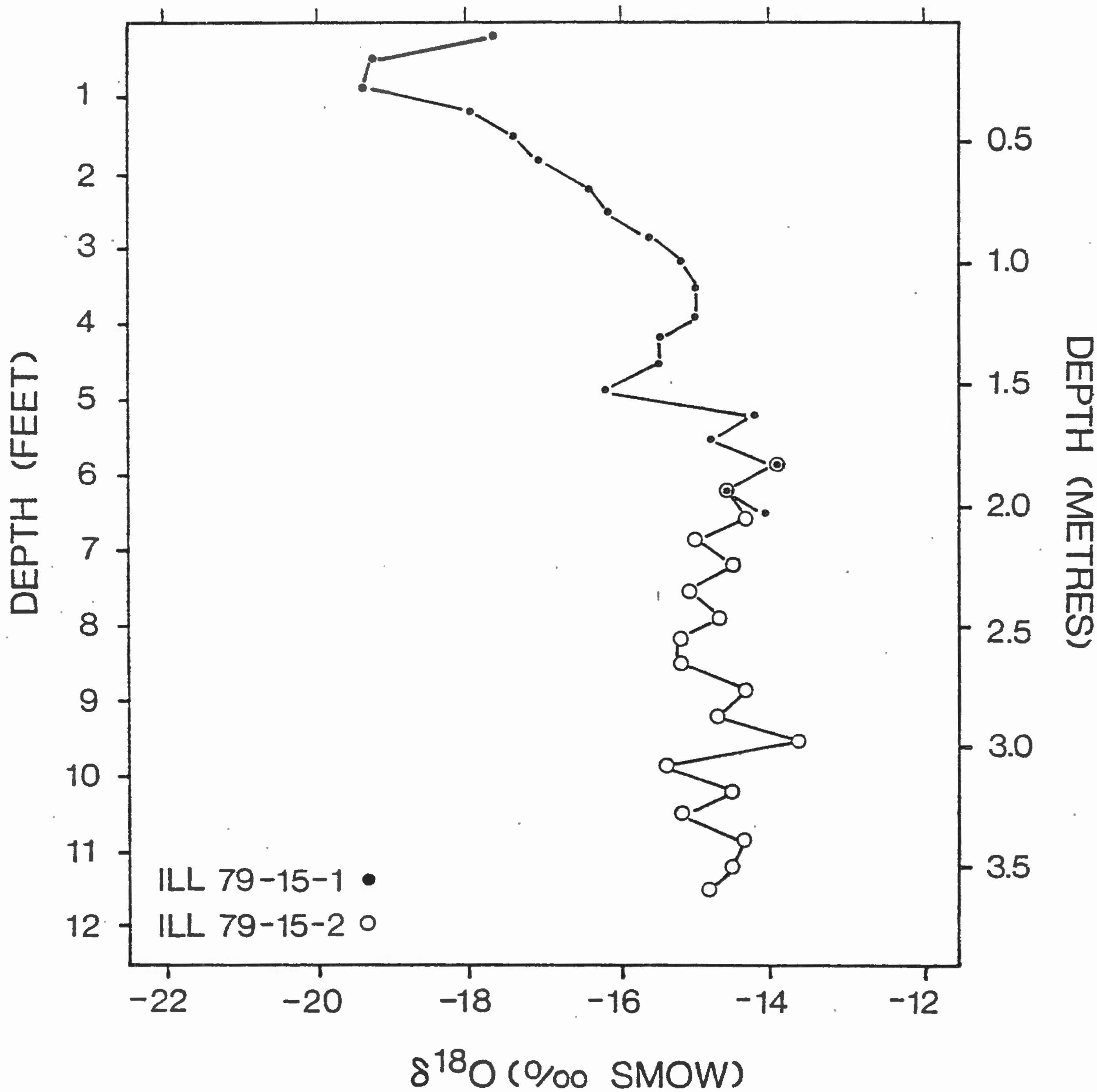

Figure 13. ^{18}O with depth for core 79-15

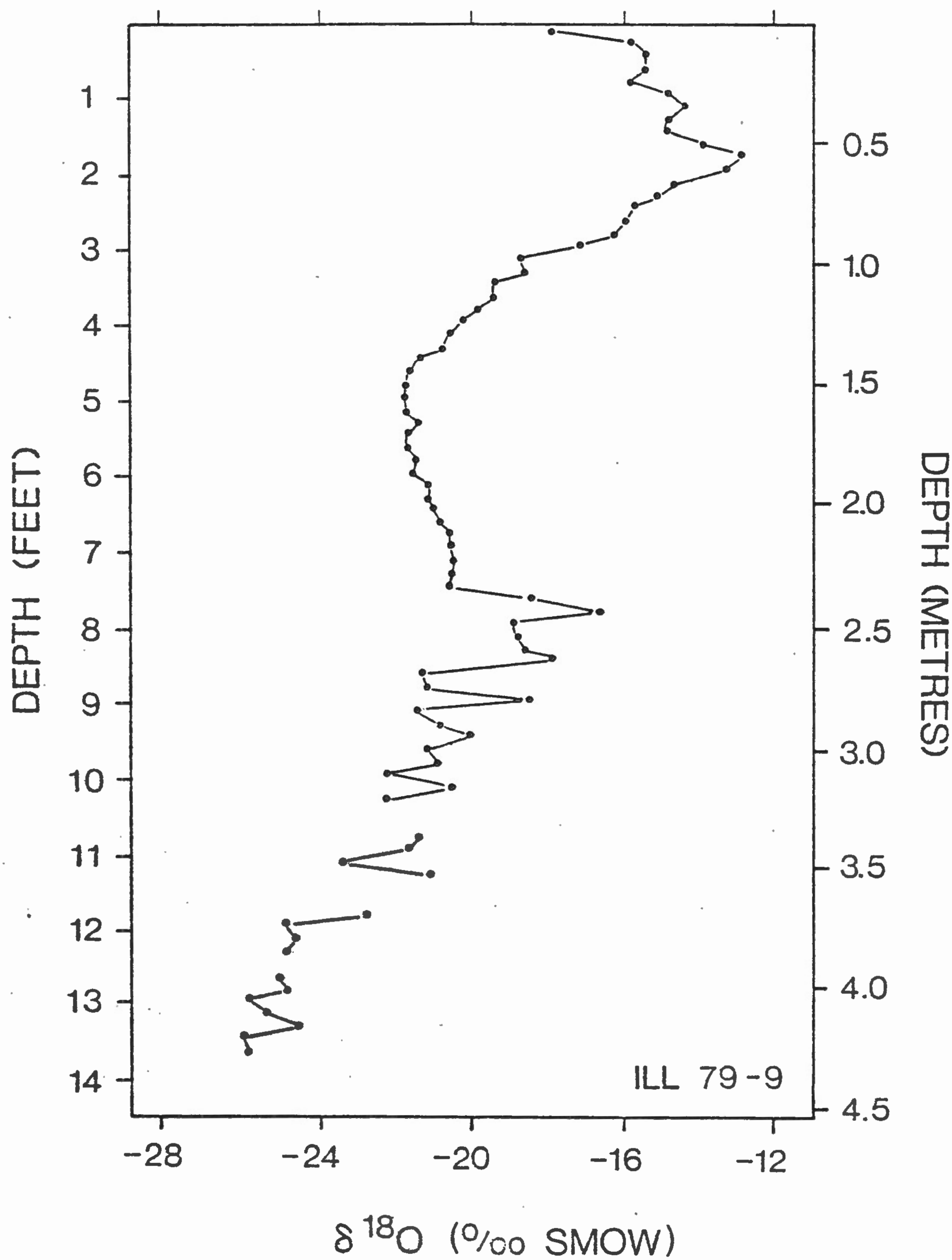

Figure 14. ^{18}O with depth for core 79-9

similar to the upper sections of the cores such as 79-2 and 79-3. Starting at a depth of 2.5 metres, the profile shifts steadily from -18 to $-26^{0}/oo$ at the bottom of the core. The importance of this profile is that there is no indication of the warmer ($-14^{0}/oo$) waters within this sill. To preserve the permafrost and the negative ^{18}O contents in this sill, the lake must have been sufficiently shallow to permit freezing into the bottom sediments during winter. Based on ice thicknesses formed with the present climatic conditions, this would place an upper limit of 1 to 1.5 metres on the water depth. If recent sedimentation is neglected, this would mean that the level of the previous (Hypsithermal?) lake could not have been more than 1 to 1.5 metres above the level of Illisarvik prior to drainage and possibly was much below this maximum. This lake would of course represent one of possibly many phases existing in the Illisarvik basin before the latest lake. The water mass encountered at depth in core 79-2 would then quite likely represent a different phase of this ever evolving water body.

3.1.3.2 Tritium

By examining the tritium concentrations of these waters, it is possible to describe moisture migration during the past 30 years. The tritium present in the water is the result of thermonuclear testing in the atomosphere during the 1950's and early 1960's. The tritium profiles would reflect on the validity of the conclusion based on stable isotopes because if tritium were found at depth, some of the observations made above for cores outside of the actual lake bed could not be sustained.

Undoubtedly, a series of different lakes have occupied the Illisarvik basin during the post-glacial period. The radiocarbon data indicate that the basin contained some water throughout this period, while the oxygen-18 contents suggest that the lakes were constantly changing and evolving.

Beyond the shoreline of Illisarvik, tritium is confined to the active layer. As shown in core 79-3 (Figure 15) and 79-8 last year (Michel and Fritz, 1980), the active layer reaches a peak concentration of just

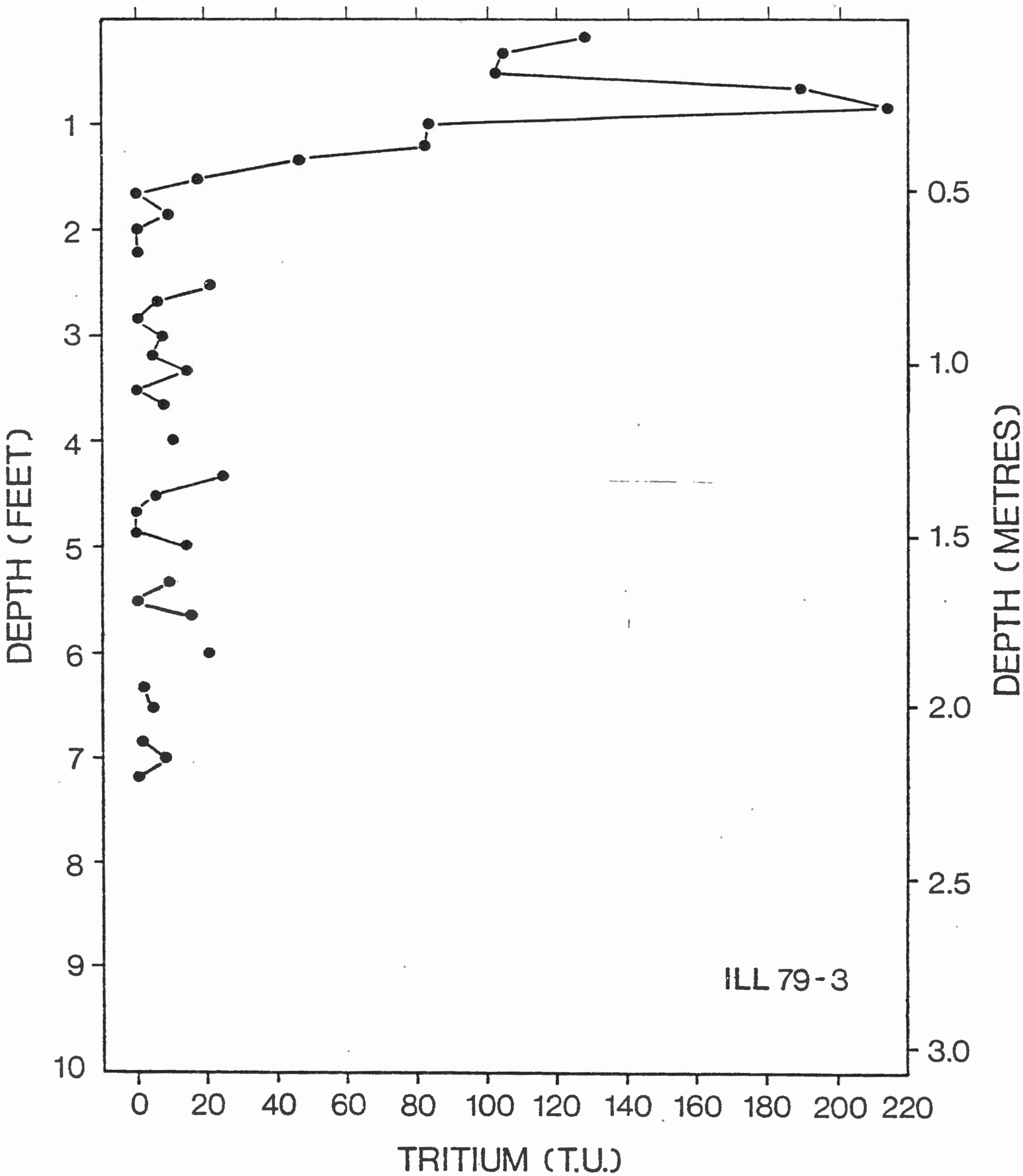

Figure 15. ^{3}H with depth for core 79-3

under 220 T.U. and then decreases rapidly to background levels. The active layer waters extracted from core 80-4 also show this to be the case. The Pingo Lake core (79-15) yielded the highest tritium levels to date of 269 T.U. The tritium-active layer relationship indicates that the active layer is as thick today as it was 30 years ago and that no tritium-labelled water has migrated downwards into the permafrost more than a few centimetres. No tritium has been detected below the permafrost table in any of the samples analysed.

In sharp contrast, the tritiated lake waters were shown in core 79-4 (Figure 16) last year to have migrated downwards through the sedimentary pile almost 2 metres. The tritium profile for these unfrozen sediments is much broader in comparison to the compressed active layer profile. The shape of the curve with its gradual depletion of tritium would appear to indicate that diffusion is the major process involved in the downward migration of the moisture. Core 80-6 collected in 1980 from a location adjacent to 79-4, yielded a tritium profile identical to the one for 79-4. This suggests that the freezing front advancing downwards through the sediments after drainage of the lake has had very little effect on the rate of tritium migration. A similar type of diffusion profile appears to be present for core 79-6, although the analytical work on these samples is not yet complete.

3.1.4 Pingo

Last year, the pingo growing in the centre of the Pingo Lake basin was examined through the recovery of a single core, 79-14. In order to further study this feature, a series of three holes were drilled in 1980 to form an east-west section through the pingo. Each hole was spaced approximately six metres apart.

In borehole 80-1, minor amounts of excess ice were recovered, but no massive ice was encountered. On the western flank of the pingo, borehole 80-3 intersected a 40 cm section containing 50 to 70% ice.

Borehole 80-2 intersected massive ice with less than 20% soil from 24 cm to 985 cm where the hole ended in massive ice, with only one exception.

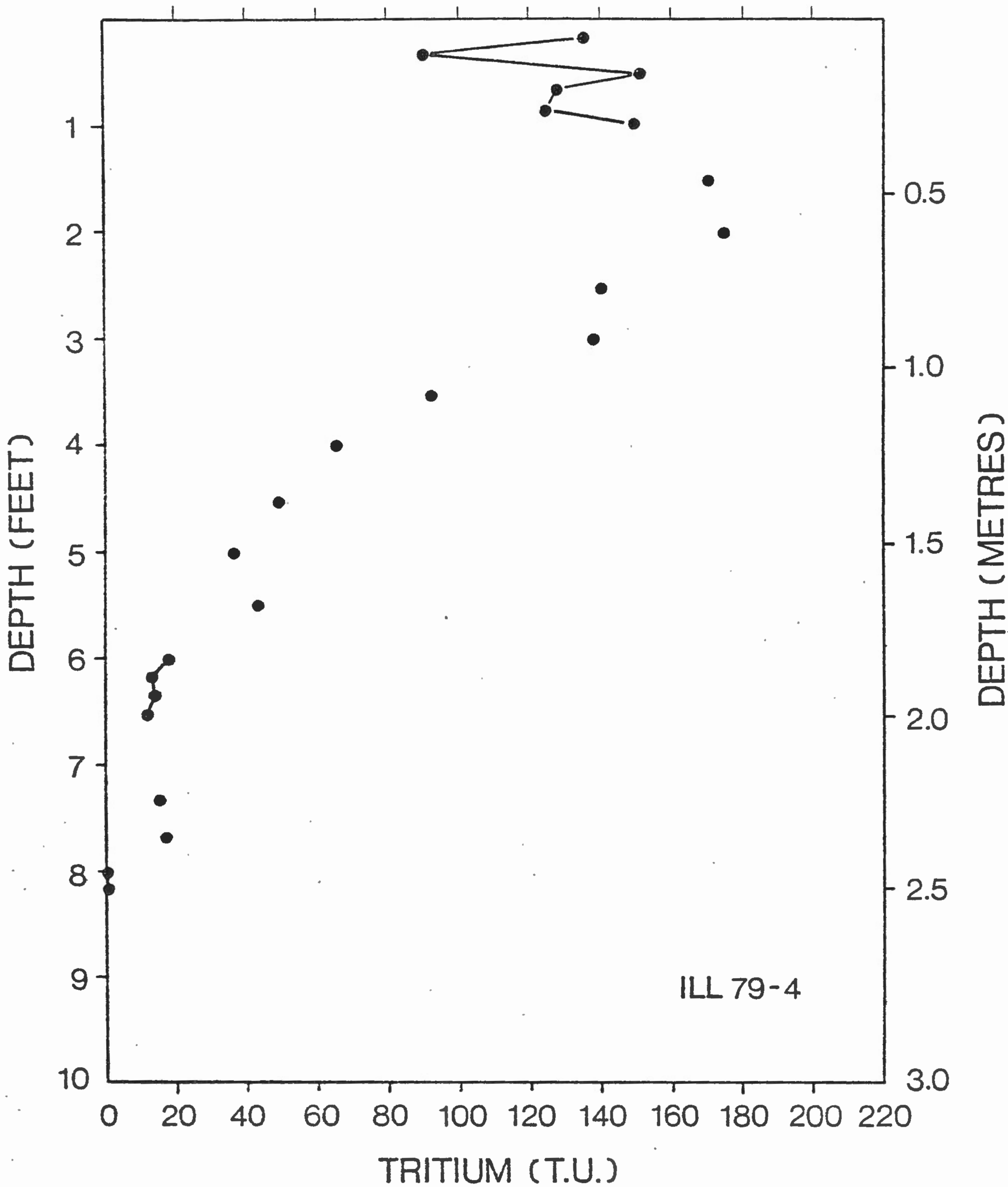

Figure 16. ^3H with depth for core 79-4

A zone from 4.75 metres to 6.25 metres contains 20% or more soil. Soil concentrations of over 50% occur at depths of approximately 5 and 6 metres. It should be noted that the pingo rises about 5 metres above the surrounding lake bed, whereas, the ice core continues several metres below this level.

The oxygen-18 profile for core 80-2 is shown in Figure 17. The shift within the active layer to more negative values is similar to the profile of core 79-14 (Figure 18). However, the similarity between the cores ends upon entering the massive ice of the pingo. Within the top 7 metres of core 80-2, the oxygen-18 contents are generally constant between -24 and -26^{0}/oo. The only major shifts that occur coincide with the soil concentrations at depths of 5 and 6 metres which were noted above. The reason for this relationship is not fully understood, but may be related to changes in the rate of freezing and thus the isotope fractionation because of the presence of excess soil. This hypothesis is supported by changes in the bubbles contained within the ice. Vertically oriented bubble trains throughout the upper 4.5 metres change relatively quickly to numerous tiny bubbles within the soil rich zone. Below 6.25 metres the bubbles are again vertically oriented in planes with individual bubble diameters of 1 mm.

The bubbles gradually increase in size to 3 mm by a depth of 8 metres, indicating that the rate of freezing was decreasing. Below 8 metres, these large bubbles are no longer strongly oriented as they were above. The large positive shift in oxygen-18 contents, in conjunction with the large non-oriented bubbles, suggests that a different water mass has been encountered.

The relationship between this lower ice body and the upper isotopically more negative ice is unknown. Any interpretation of the formation of the pingo must not only deal with the data obtained from this core, but also must take into account the data from core 79-14. If as suggested last year the upper 2 metres of ice in core 79-14 represents water injected into the upper levels that froze under closed system conditions, then it is possible that the lower ice (δ^{18}o = -16^{0}/oo) could be older than the ice above it. Determination of the deuterium contents for these samples should be able to answer some of the questions still unanswered.

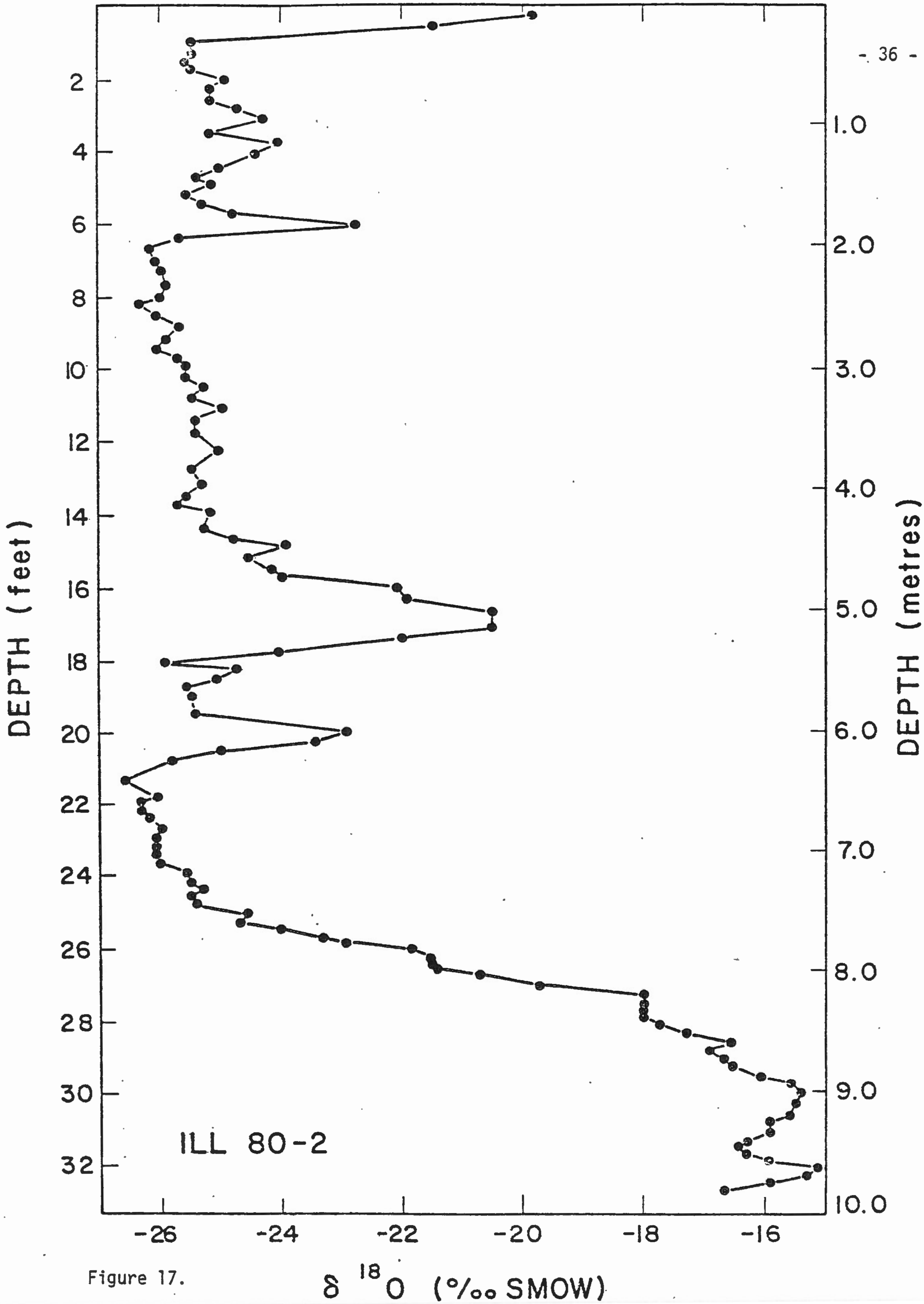
DEPTH (feet)
DEPTH (metres)
ILL 80-2
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
-26
-24
-22
-20
-18
-16
δ 18O (‰ SMOW)

Figure 17.

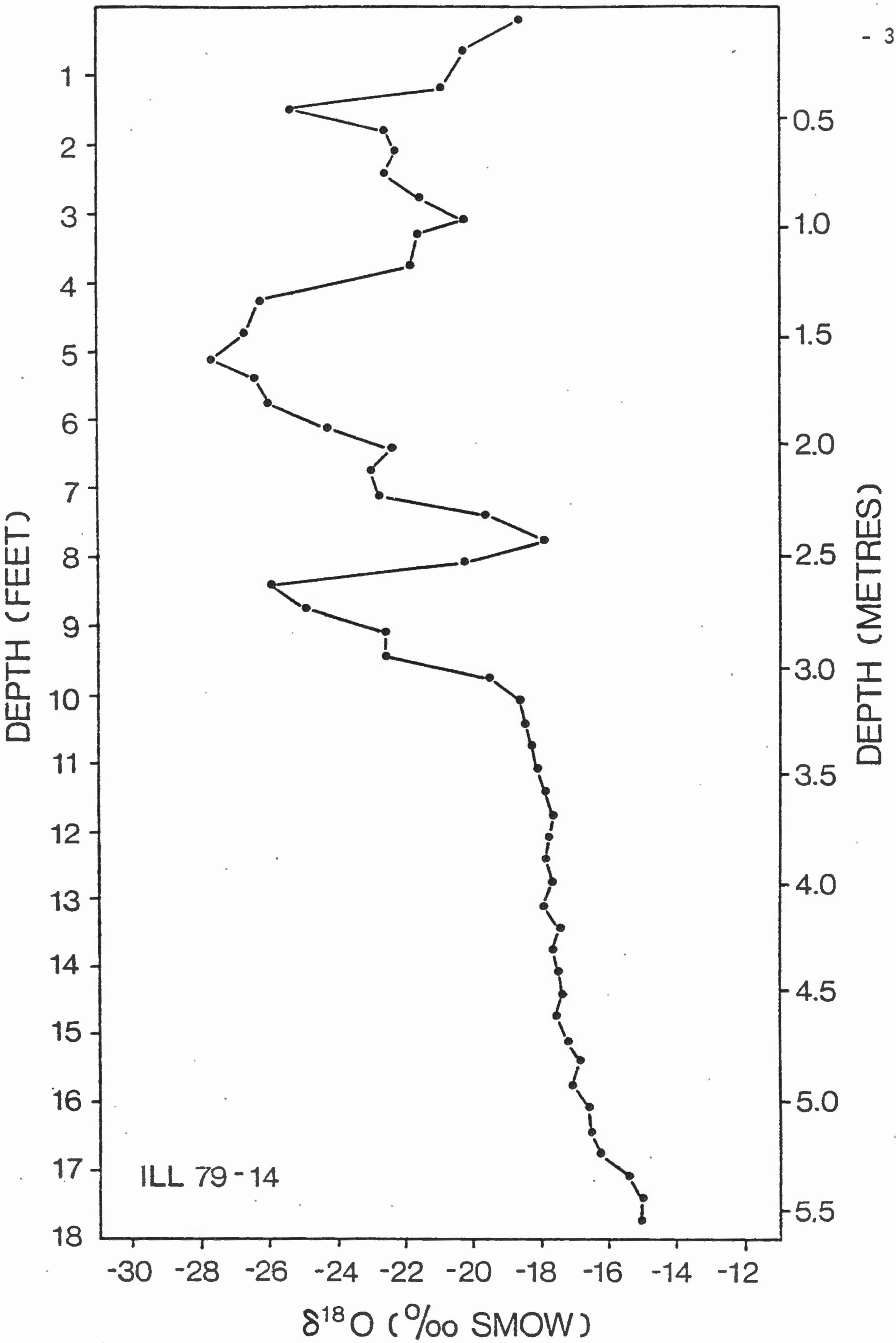

Figure 18. ^{18}O with depth for core 79-14

3.1.5 Ice Wedges

In 1979, two ice wedges which intersected the drainage channel were sampled. Ice wedge #2 was sampled by drilling horizontally from the sea cliff face perpendicular to the long axis of the wedge.

Analysis of the oxygen-18 contents of this core (Figure 19) shows a gradual change within the clay-silt soil towards the boundary of the ice wedge. The wedge itself is clearly defined by the large differences in oxygen-18 content. Although this wedge is considerably smaller than ice wedge #1, the two wedges have nearly identical oxygen-18 contents of about -22.5^{o}/oo. In comparison, the ice wedge (?) feature encountered in borehole 80-4 has an average oxygen-18 content of -24.5^{o}/oo. The differences between these two groups is possibly due to minor differences in the isotope contents of the snow cover, because the upper permafrost waters of cores 79-3 and 79-8 also differ by approximately 2^{o}/oo in their oxygen-18 contents.

3.2 Laboratory Experiments

3.2.1 Introduction

During this contract period, a total of seven experiments were performed and are labelled in sequence with the experiments conducted in previous years. The construction of a new squeezer was completed with the expectation of being able to extract water from the unsaturated sample of column 7. In anticipation, column 10 was run this year using unsaturated materials, but unfortunately no water has been recovered to date. Due to the incompleteness of the isotope analyses, columns 13 and 14 will be discussed in detail at a later time. The experimental setup was the same as that employed during the previous year.

3.2.2 Experiment 8

For this experiment, a 45 cm column was packed with a saturated Hawkesville silt. None of the excess water was removed, thereby leaving a thin film of water at the top of the column, 1 cm below the lip. Two bags

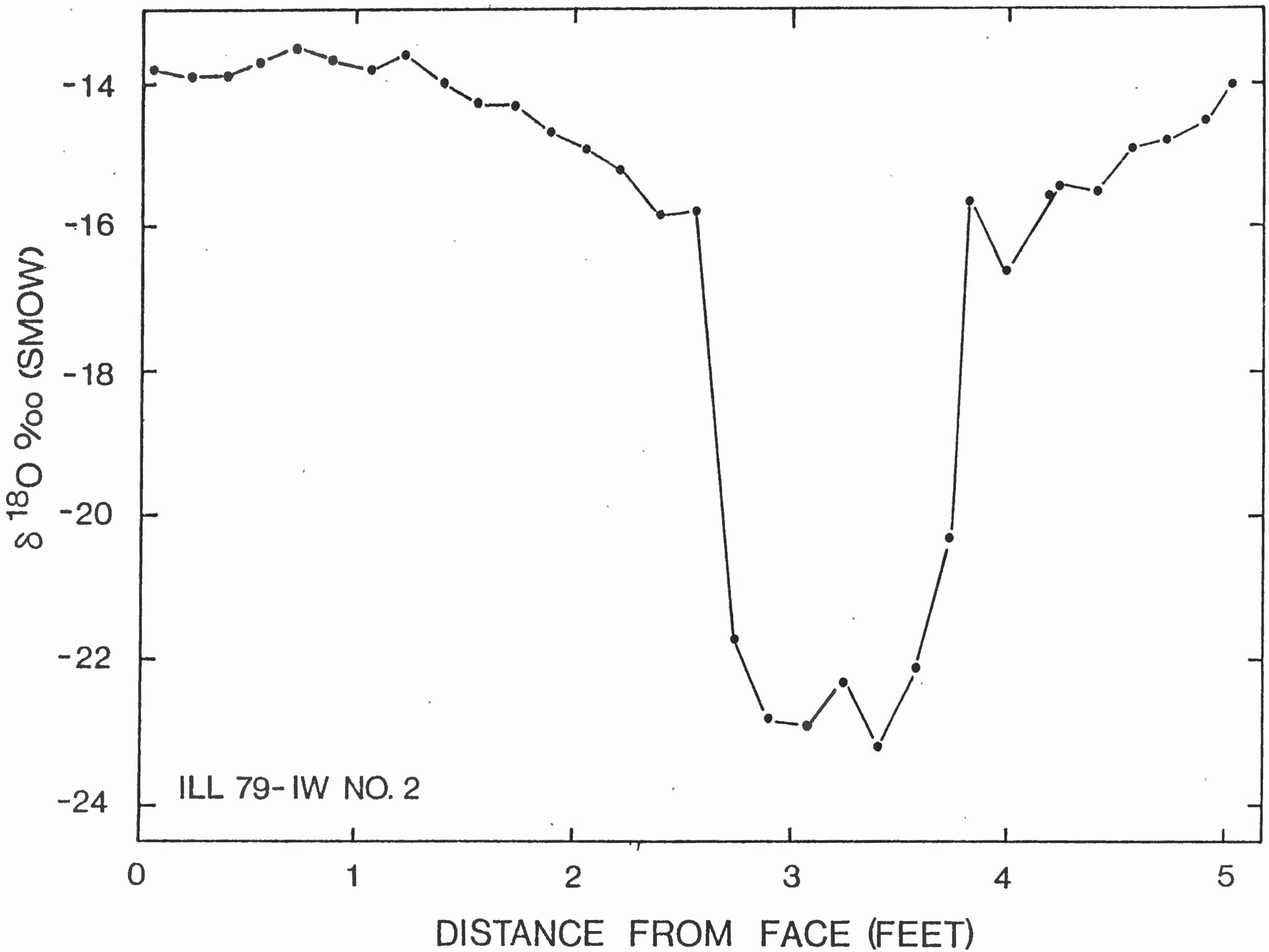

Figure 19. ^{18}O with depth for core IW#2

of the saturated silt were collected after the column had been filled. Bag 'A' was placed in the freezer for the duration of the experiment while bag 'B' was kept in the room at room temperature (20-23^{o}C).

The temperature throughout the experiment was increasing downward. A stabilized freezing front was established by 91 hours between a depth of 10 to 15 cm and it was maintained or very slowly lowered to the 15 cm mark by the end of the experiment at 768 hours.

When the column was sectioned, the frozen-unfrozen boundary was located at a depth of 13.5 cm. Immediately below the contact the silt was extremely soupy and approximately 10 ml. of free water was collected. A sample of frost on the underside of the top heater was collected as was a sample of frost on the freezer walls. Within the frozen silt a number of small sub-horizontal (VR) ice lenses up to 2 mm thick were observed. The presence of these lenses indicated that cold air was able to enter near the top edge of the column in addition to the cold passing through the top heater. The freezing front itself was planar and horizontal.

Both oxygen-18 and deuterium isotopes have been examined for this column and these data are listed in Table 5. When these data are plotted, as in Figure 20, the two isotopes mirror each other exactly. The frost on the heater block of course has a more positive isotope content because of evaporation and condensation fractionation processes. A steady shift to more positive isotope contents can be seen within the frozen sediments, peaking on the frozen side of the interface. This is followed by a dramatic shift to very negative contents in the unfrozen silts immediately below the boundary. Below this the isotope contents return to near normal initial values. The sharp change at the frozen-unfrozen boundary clearly demonstrates that the heavy isotopes are concentrated in the lower energy ice phase as predicted by theory. Because of the slowness at which the isotopes can diffuse through the soil, the water below the boundary becomes depleted. The size of this negative peak must, therefore, depend upon the rate at which the isotopes can diffuse within the unfrozen sediments. Slow diffusion will result in the generation of a large shift between the positive and negative peaks up to the equilibrium fractionation. A rapid transfer would decrease the size of the negative peak so that it may become very difficult to detect.

Table 5: ^{18}O and ^{2}H data for column 8

Sample	Depth (CM)	^{18}O ($^{o}/oo$ SMOW)	^{2}H ($^{o}/oo$ SMOW)
TAP	-	-11.0	-76
INITIAL 'A'	-	-10.6	-74
INITIAL 'B'	-	-10.7	-75
FREEZER FROST	-	-14.2	-98
8-FROST	0-1	- 9.2	-65
8-ICE	1-3	- 9.3	-67
8-1	3-5	-11.6	-80
8-2	5-10	-11.0	-75
8-3	10-13	-10.6	-72
8-4	13-13.5	-10.2	-69
8-5	H_2O from 13.5	-11.5	-68
8-6	13.5-15	-11.7	-80
8-7	15-20	-11.2	-77
8-8	20-25	-11.1	-74
8-9	25-30	-10.8	-76
8-10	30-35	-10.8	-74
8-11	35-40	-10.7	-73
8-12	40-45	-11.0	-75

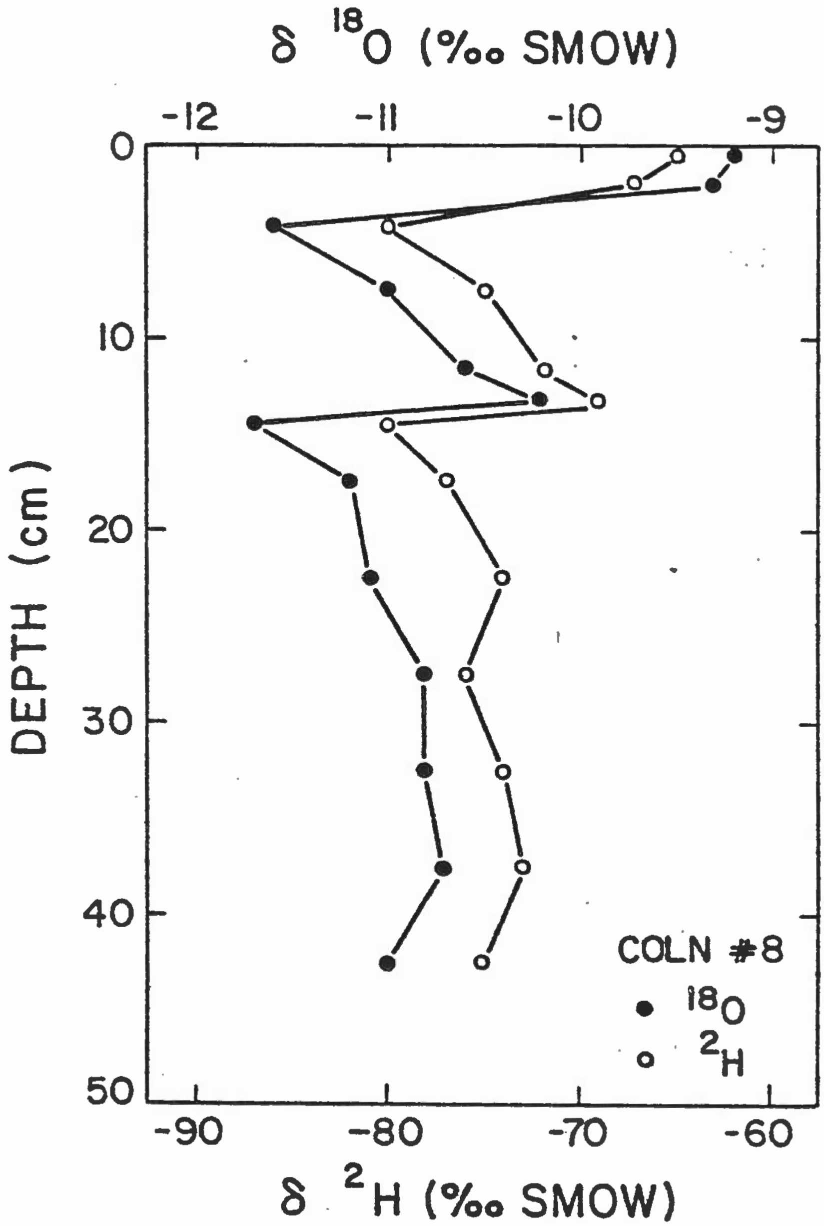

Figure 20. ^{18}O with ^{2}H profiles for column 8

It is interesting to note the difference in shift direction for the isotopes of the free water at the freezing front (square symbols in figure). This opposing shift is very similar to the previously unexplained phenomenon noted near the base of the Bear Rock Frost Blister core (Michel and Fritz, 1978a). Whether this feature is due to slightly different rates of freezing or to some other fractionation process is uncertain at present, but a more detailed examination of the data should begin to provide some of the answers.

3.2.3 Experiment 9

In this experiment, a 45 cm column was filled with saturated Hawkesville silt as in experiment 8. An attempt was made to drain the excess water by opening the tube at the base of the column, but a slurry of silt quickly blocked this opening. When this failed, a syringe was used to withdraw approximately 25 mls of excess water from the top of the column, leaving behind a thin layer of water as in the previous experiment. Again a 2 cm air space was left at the top of the column.

The temperature increased downwards throughout the entire column except for the top 5 cm. Within this interval the temperature increased from the 5 cm depth upwards to the top heater. A small leak of cold air around the edge of the heater block created this temperature reversal and resulted in the freezing front surface becoming slightly concave rather than planar. When the column was dismantled after 690 hours, a number of vertical ice lenses were discovered near the outer edge of the column. Within the majority of the column these lenses were horizontal to sub-horizontal. The upper 2 cm of silt was cold but unbonded.

The isotope data (Table 6) plotted in Figure 21 demonstrates the importance of the temperature gradient on the isotope profiles. Positive isotope peaks occur at the frozen-unfrozen boundary (16-17 cm) and in the upper part of the column where the temperature was at a minimum. The isotope profile at the stabilized freezing front can be related to the shift generated in experiment 8. The upper peak, however, must be related solely to the temperature profile. Fractionation of the isotopes along a temperature gradient would result in the heaviest, least mobile isotopes being concentrated where the temperature is at a minumum. Such a process would be

Table 6: ^{18}O and ^{2}H data for column 9

Sample	Depth (CM)	^{18}O ($^{o}/oo$ SMOW)	^{2}H ($^{o}/oo$ SMOW)
TAP	-	-11.2	-75
INITIAL	-	-10.9	-72
EXCESS	-	-10.8	-74
9-1	2-4	-11.5	-79
9-1A	4-5	- 9.2	-67
9-2 UPPER	5-7.5	- 9.6	-69
9-2 LOWER	7.5-10	-10.7	-73
9-3	10-15	-11.0	-76
9-4 FROZEN	15-17	- 9.7	-71
9-4 UNFROZEN	17-20	-11.0	-77
9-5	20-25	-11.0	-75
9-6	25-30	-11.0	-77
9-7	30-35	-11.0	-75
9-8	35-40	-11.0	-76
9-9	40-45	-11.1	-74

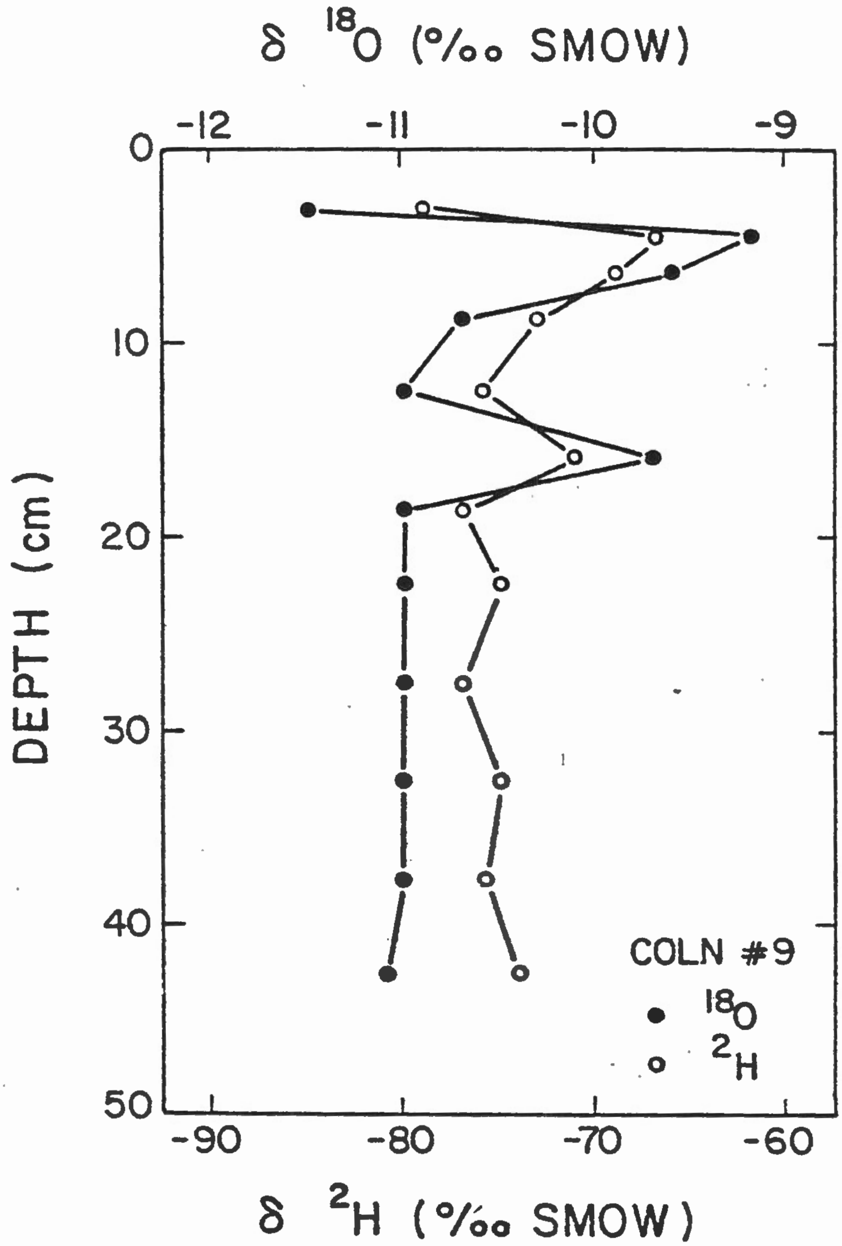

Figure 21. ^{18}O and ^{2}H profiles for column 9

similar to the one described for the evaporation and condensation of frost in the upper air space of experiment 8.

3.2.4 Experiment 11

The setup for this experiment consisted of a 45 cm column containing 25 cm of saturated medium-coarse Hawkesville sand overlain by 18 cm of saturated Hawkesville silt. A 2 cm air space was once again left at the top of the column.

The temperature of the top heater was kept at or near the temperature recorded at a depth of 5 cm so that no reversal in the gradient occurred. Within the column, the temperatures steadily increased with depth throughout the 845 hours of the experiment. According to the temperature data, the freezing front was maintained at a depth of 16 to 17 cm for most of the experiment, but upon dissection of the column, the frozen-unfrozen boundary was located at a depth of 15 cm. It is not known whether this minor discrepancy is due to a calibration drift in the meter used or whether a slight freezing point depression existed within the silt. Horizontal ice lenses up to 2 mm thick were noted within the frozen silt.

The isotope data have been tabulated in Table 7 and plotted in Figure 22. No detailed sampling was attempted at the frozen-unfrozen contact and as a result the isotope profile are not as sharp as in experiment 8. Nevertheless, it is clear that the heavy isotopes were again concentrated in the ice phase at the stabilized freezing front. A small negative shift is visible in the unfrozen silt layer beneath, but there was no disturbance of the initial isotope contents for the waters within the underlying sand.

3.2.5 Experiment 12

The column for this experiment was constructed identical to column 11. In this experiment, however, the freezing front was permitted to migrate downwards into the underlying sand unit. A short (100 hour) stabilization of the freezing front occurred at the interface of the two layers, but the major freezing front stabilization occurred several centimetres into the sand.

Table 7: ^{18}O and ^{2}H data for column 11

Sample	Depth (CM)	^{18}O ($^{o}/oo$ SMOW)	^{2}H ($^{o}/oo$ SMOW)
TAP	-	-10.9	-77
11-1	2-5	-11.0	-75
11-2	5-10	-10.7	-73
11-3	10-15	-10.1	-69
11-4	15-21	-11.1	-77
11-4A	Silt-sand interface	-10.7	-74
11-5	21-25	-10.7	-76
11-6	25-30	-10.8	-74
11-7	30-35	-10.8	-75
11-8	35-40	-10.7	-75
11-9	40-45	-10.4	-75

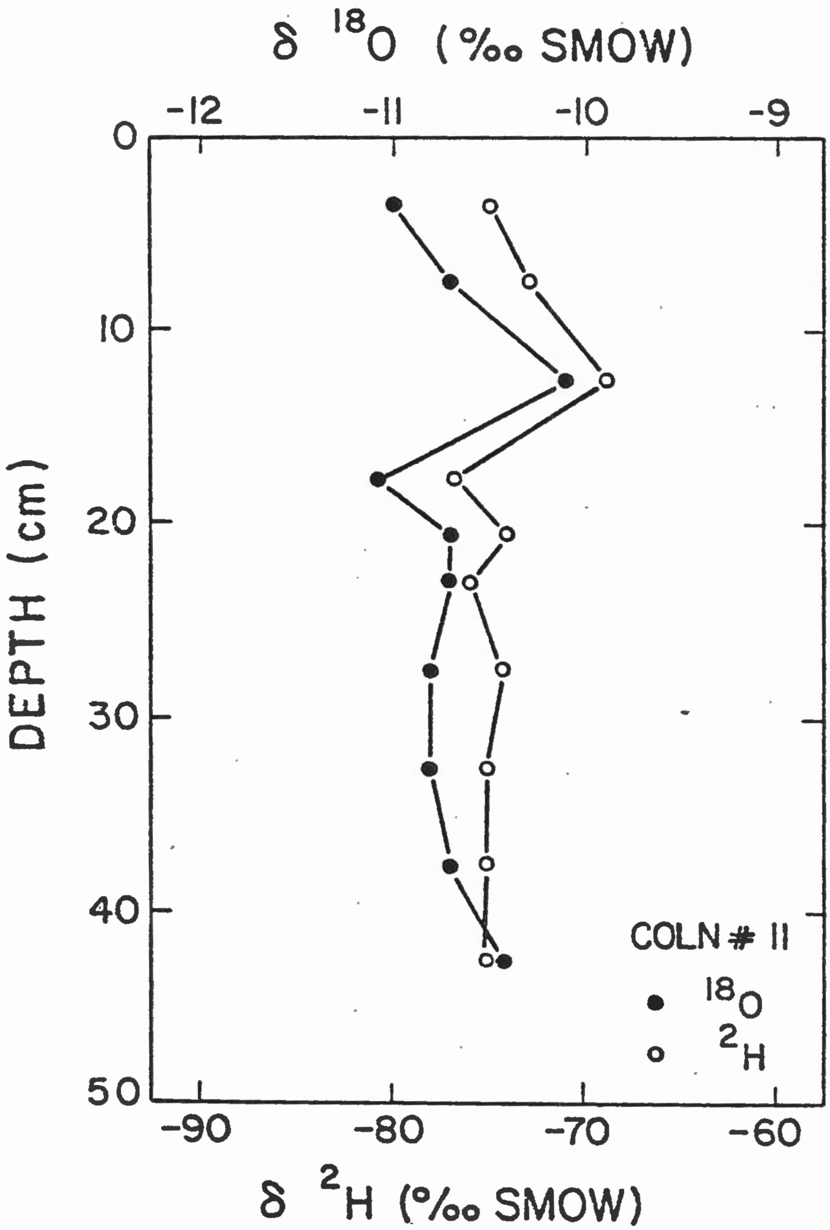

Figure 22. ^{18}O and ^{2}H profiles for column 11

A number of tiny horizontal ice lenses were noted within the silt, but none were present within the frozen sand. At the contact of the two layers a thin rippled ice surface was observed, however. The frozen-unfrozen boundary occurred at a depth of 27 cm and some 50 ml of free excess water was extracted at this contact.

The isotope data listed in Table 8 are plotted in Figure 23. A small positive shift is visible in the lower part of the silt unit with a corresponding negative peak immediately below. The major shift occurs at the frozen-unfrozen contact in the sand where the freezing front had been stabilized. The oxygen-18 shift is considerably larger than the deuterium peak. The isotope contents of the excess water immediately below the freezing front (square symbols in figure) yield a pattern identical to that of column 8. The deuterium contents are the same in the ice and the water while the oxygen-18 contents are markedly different. This would suggest that the oxygen-18 exchange is confined to a very narrow layer whereas the deuterium exchange and fractionation takes place over a much wider zone. This may indicate that the diffusion rate of the deuterium is somewhat higher than that of oxygen-18. Such a discussion, however, must be left for a later time.

Table 8: ^{18}O and ^{2}H data for column 12

Sample	Depth (CM)	^{18}O ($^{o}/oo$ SMOW)	^{2}H ($^{o}/oo$ SMOW)
TAP	-	-10.9	-77
12-1	3-5	-10.7	-78
12-2	5-10	-10.8	-77
12-3	10-15	-10.7	-74
12-4	15-19	-10.9	-73
12-5	19-20	-11.5	-78
12-6	20-25	-11.0	-78
12-7	25-27	- 9.9	-75
12-8	H_2O from 27	~~-11.1~~	-75
12-9	27-30	-10.7	-80
12-10	30-35		-80
12-11	35-40	-10.7	-83
12-12	40-45	-10.9	-79

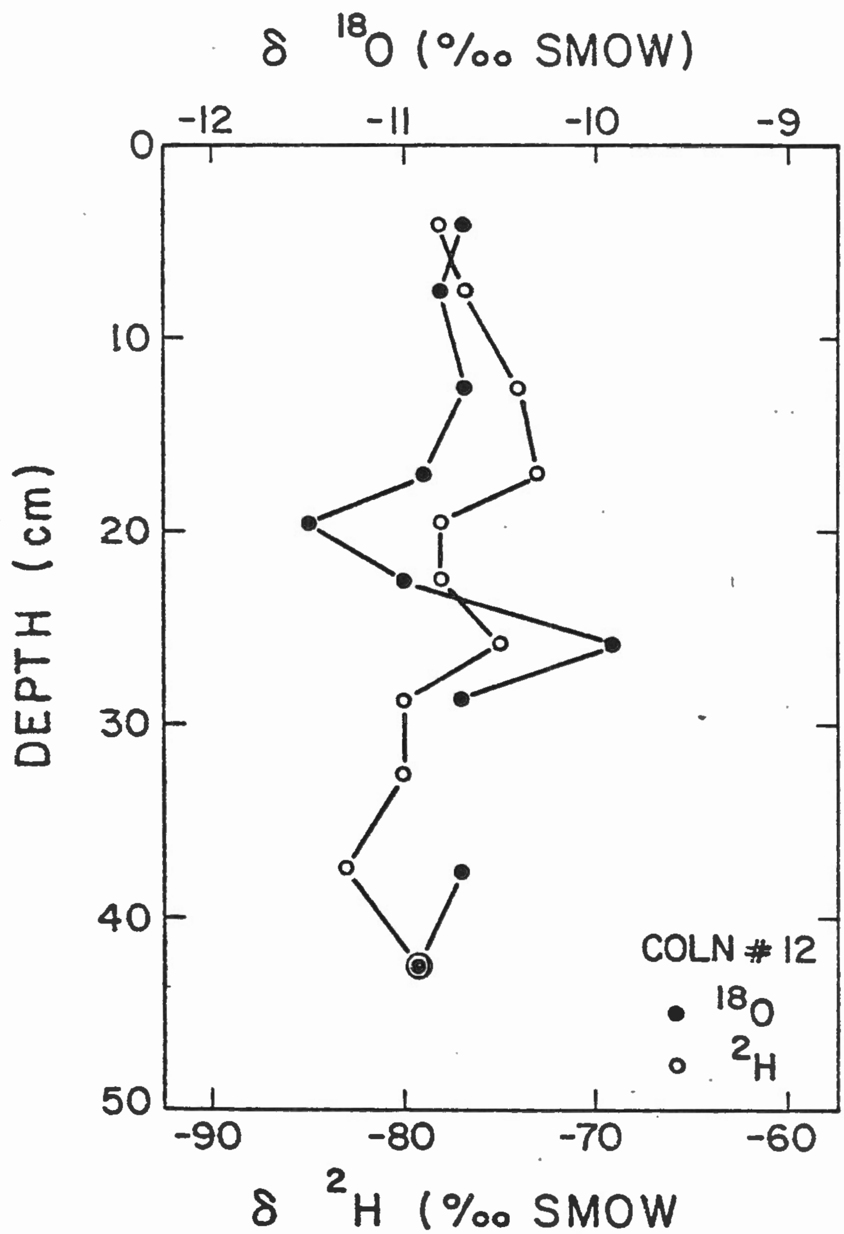

Figure 23. ^{18}O and ^{2}H profiles for column 12

4. SUMMARY AND CONCLUSIONS

4.1 Illisarvik

During May of 1980, a number of additional cores were collected from the Illisarvik site to supplement the original set of cores obtained in 1979. By supplementing the stratigraphic work on the sediments with radiocarbon dating of the organics and an isotope study of the pore waters within the lake talik and the permafrost, it is possible to begin to unravel the history of this basin. From the work completed to date, the following statements can be made for the Illisarvik area.

1. Radiocarbon dating of the basal organic silts from near the centre of the basin indicate that the original lake formed between 6500 and 8500 years ago.
2. The central ridge of the peninsula contains relict permafrost waters with oxygen-18 contents of $-31^{0}/oo$.
3. A larger body of water, encompassing the Illisarvik and Pingo Lake basins, existed during a period of warmer climatic conditions. (Hypsithermal?). The waters from this lake had oxygen-18 contents of approximately $-14^{0}/oo$.
4. On the basis of isotope data obtained from a sill separating the two basins, the level of this larger lake was a maximum of 1.0 to 1.5 metres above Illisarvik Lake. Most likely it was well below this maximum.
5. Groundwater movement has occurred only within the top 2 to 3 metres of the permafrost in the last few thousand years. This would indicate that the rate of groundwater movement through the permafrost, for at least the Illisarvik area, is very slow.
6. Outside of the lake basin, tritium is confined to the top 0.5 metres which corresponds to the average thickness of the active layer, whereas, tritium has migrated downwards through the unfrozen lake sediments to a depth of about 2 metres.
7. Preliminary interpretation of the isotope data for the pingo in the centre of Pingo Lake suggests that the upper section of the ice core consists of ice formed from water which had been injected above the original core.

8. Continuous sampling of the pingo demonstrated that the ice core extends at least several metres below the elevation of the surrounding lake bed.
9. Both of the ice wedges sampled along the drainage channel contain ice with similar oxygen-18 contents, even though they are very different in size. The oxygen-18 contents are relatively uniform throughout the wedge ice but are several per mil more negative than the adjacent soil.

When combined, these results describe a peninsula with a central ridge that has been stable for several thousands of years flanked by a lower plain which has been constantly evolving. A series of lakes, with oscillating water levels, has continuously occupied at least portions of the Illisarvik and Pingo Lake basins for the past 6500 to 8500 years. Coastal erosion resulted in drainage of the Pingo Lake basin and a lowering of water in the Illisarvik Lake basin. A shoal dividing the two basins became the controlling sill for the Illisarvik Lake level which persisted until the time of drainage in 1978.

4.2 Laboratory Experiments

Of the seven column experiments conducted during the present contract period, four have been described in this report. The remaining three are still awaiting completion of the isotope analytical work. Ice lenses were generated within the silt size material used but not within the sand.

In all of the experiments examined, a shift in the isotope contents was generated as a result of a stabilized freezing front. These shifts, although easily detected, were only about half of the magnitude predicted by theory for ice and water in equilibrium. This may be the result of slower exchange due to the presence of the soil or the result of a large sampling interval.

Experiment 9 demonstrated that the isotopes are affected by temperature reversals with the lowest temperature level concentrating the heavier oxygen-18 molecules. Isotope contents of the unfrozen waters did not appear to be affected beyond a few centimetres of the frozen-unfrozen boundary.

In two of the experiments it was possible to sample excess water located immediately below the frozen-unfrozen boundary. The isotope analyses for both waters yielded deuterium contents the same as the overlying ice while the oxygen-18 contents were much more negative than the ice above. This phenomenon is similar to the previously unexplainable feature discovered in the Bear Rock Frost Blister. It is still somewhat unclear as to why this variation occurs, but it should be resolved with further study.

On the basis of the work at Illisarvik and other field sites in addition to the findings in the laboratory experimental studies, it is possible to make several more general statements regarding the usefulness of isotopes and the significance of isotope variations in permafrost waters.

1. Isotope studies of waters within the permafrost provide insight into the history and stability of the permafrost.
2. Isotope studies permit the delineation of groundwater movement through the recognition of different water masses.
3. Stable permafrost conditions have persisted in some areas since the end of the Wisconsin with no appreciable groundwater movement since that time.
4. Shifts in the isotope profile, that are maintained for some depth, are the result of climatic change.
5. Small scale shifts, that do not continue with depth, are the result of fractionation processes during freezing. To generate these 2 to $3^{0}/oo$ shifts (for oxygen-18), the freezing front must either be advancing very slowly or be stabilized for a period of time.

4.3 Suggestions for Continued Work

The usefulness of isotopes in detecting water movement has been successfully demonstrated during the present contract. The continuation of the Illisarvik program would further enhance our knowledge of moisture migration during permafrost aggradation. Further work is also needed to better describe the processes involved in the generation of pingos, ice wedges and other permafrost phenomena.

Finally, it is necessary to expand this research to other areas in order to fully prove that the findings are valid throughout the Arctic. Areas of immediate concern, such as the Alaska and Dempster Highway pipeline routes, should be given priority. Core samples are available from these routes at the present time. 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.

In future investigations, the sampling interval would be determined by the information required. Long term variations or the migration of water through the ground can be detected using a sampling interval of a metre or more, while the determination of a stabilized freezing front or short term moisture migration studies would require detailed sampling on the order of 5 to 10 centimetres throughout the section of interest.

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