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LABORATORY STUDIES TO INVESTIGATE ISOTOPE EFFECTS OCCURRING DURING THE FORMATION OF PERMAFROST

43 pp., including 17 figures

F. Michel & P. Fritz
University of Waterloo Research Institute

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Earth Physics Branch
1 Observatory Crescent
Ottawa Canada
K1A 0Y3

Direction de la physique du globe
1, place de l'Observatoire
Ottawa Canada
K1A 0Y3

RESUME

The study describes some preliminary laboratory experiments to investigate and quantify oxygen and hydrogen isotope effects occurring during the freezing of water in saturated and unsaturated soils, and some continued work on the deuterium contents of frost mound samples from Fort Norman in the Mackenzie Valley.

Uniform columns of soil were prepared, subjected to freezing temperatures at one end, and subsequently analysed for the distribution of oxygen isotopes. The first experiment verified that isotope fractionation is induced at high temperature gradients but indicated that isotopic balance is maintained within the column. A second experiment designed to test the temperature monitoring system revealed the freezing rates in different types of soils, illustrating the complex thermal relationships present.

The analyses of deuterium contents of the frost mound samples confirmed with one exception that the isotope contents are indicative of continued fractionation within a residual pool not being replenished by outside water.

Suggestions and recommendations for an enlarged program of laboratory measurements are included in the report.

RESUME

L'étude décrit des essais préliminaires en laboratoire pour rechercher et quantifier les effets des isotopes d'oxygène et d'hydrogène que l'on constate au cours de la congélation de l'eau dans des sols saturés et non saturés, ainsi que des travaux qui se poursuivent sur la teneur en deutérium des échantillons de tertres gelés prélevés à Fort Norman, dans la vallée du Mackenzie.

On a donc préparé des colonnes de sol uniformes, les soumettant au gel à une extrémité pour ensuite analyser la répartition des isotopes d'oxygène. Lors du premier essai, on a vérifié que la différenciation isotopique se produisait à des gradients de température élevés; cependant, les résultats ont démontré que l'équilibre isotopique était maintenu à l'intérieur de la colonne. Le second essai, destiné à vérifier le système de surveillance de la température, a permis de révéler les degrés de congélation dans différents types de sols, illustrant ainsi les relations thermiques complexes mises en cause.

Les analyses de la teneur en deutérium des échantillons de tertres gelés ont permis de confirmer, à une exception près, que la teneur en isotope était révélatrice d'une différenciation continue à l'intérieur d'une nappe d'eau résiduelle non alimentée de l'extérieur.

Figurent à ce rapport des suggestions et des recommandations relatives à un programme plus poussé de mesures en laboratoire.

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LABORATORY STUDIES TO INVESTIGATE ISOTOPE EFFECTS OCCURRING DURING THE FORMATION OF PERMAFROST

Contract Serial # OSU77-00172

Final Report

Prepared for

DEPT. OF ENERGY MINES AND RESOURCES

F. Michel
P. Fritz

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

Introduction

1.1 Previous Studies

During the summer of 1976, field cores were collected from various locations along the Mackenzie Valley and Polar Gas Pipeline routes as part of WRI project #606-12 (DSS file #06SU. 23235-6 - 0681). In that study, significant and systematic variations in oxygen-18 and tritium contents were documented. This observation indicates either that any downward infiltration of modern water through existing permafrost does not alter the isotopic composition of the frozen water, i.e. it does not interact with it or, that no downward movement of water through the permafrost takes place.

On the basis of the isotope data three zones of groundwater activity can be distinguished within the frozen horizons a) a very young, active zone with high tritium contents, b) a zone of mixing and c) a deeper zone with tritium-free permafrost and low oxygen-18 contents. Within these zones some additional variations in isotope contents were observed resulting in spikes. It is suspected that these additional variations are due to isotope effects occurring during the freezing of the water. The large differences in oxygen-18 contents (~10 $^{o}/_{oo}$) between the upper and lower zones are believed to reflect age differences. A paper on the results of the study was accepted for presentation at the 3rd International

Permafrost Conference to be held in Edmonton during July 1978.

Mackay (1971) and Mackay et al (1972) have reported massive icy beds representing relict Pleistocene permafrost in the western Canadian Arctic. Mackay (personal communication) has also found variations in the oxygen-18 contents of frozen water with depth through the study of deep core samples. Although these variations are becoming better documented as a widespread phenomenon; the basic processes creating these variations are still not understood.

1.2 Terms of Reference

This study was an outgrowth of the results of the previous study (DSS file #06SU. 23235-6-0681) and was designed to focus on the basic processes affecting the environmental isotopes during the formation of permafrost. The objectives of the present study (WRI project #606-12-02, DSS file #02SU. 23235-7-0768) were

a) to develop experimental procedures in the laboratory to investigate isotope effects which may occur during the freezing of water in unsaturated and saturated soils and

b) if such procedures could be developed within the time available, to quantify these isotope effects in order to permit a more detailed discussion of the formation and stability of permafrost.

1.3 Scope of Present Study

This report describes the work completed to date in developing the equipment and experimental procedures. Data obtained during experimental testing of the equipment are discussed in relation to fundamental guidelines for future experiments. Data obtained from the continuation of the previous contract are also discussed in relation to the earlier findings. Finally, this report suggests a course along which further work should be directed.

Work Completed

2.1 Equipment Development

Initially, a set of three columns were constructed using 15.25 cm diameter PVC pipe. The pipe was pre-sectioned into 5 cm lengths to facilitate in the cutting of the frozen cores upon completion of an experiment. The lowermost section of each column was bonded to 3 mm thick PVC sheeting to form a stable base. Numerous attempts to produce water tight seals around joints between the sections resulted in the selection of silicon sealant as the ideal material.

Modifications to the original column design involved the installation of ports as drains in the lowermost section of each column and the edge of each ring was grooved to permit the installation of thermocouple wire every 5 cm.

Thermocouples are presently constructed using teflon coated copper constantine, type T wire which has been spot welded at the tip. Water created potentials were considered as insignificant and therefore the thermocouples were not enclosed within any kind of protective shield. Figure 1 illustrates the fully assembled apparatus for a column at present.

Problems were encountered during the process of sealing the wires in the column. The silicon sealant did not adhere well to the teflon coating on the thermocouples. Several applications were needed to prevent leakage of water past the thermocouples and even then care was required so as not to move the wires more than necessary. It was felt that the teflon coating was required due to its flexibility at the low temperatures encountered during use of dry ice.

The thermocouple meter used during the experimental testing was a Doric Trendicator 400A Type T model capable of reading to 0.1°C.

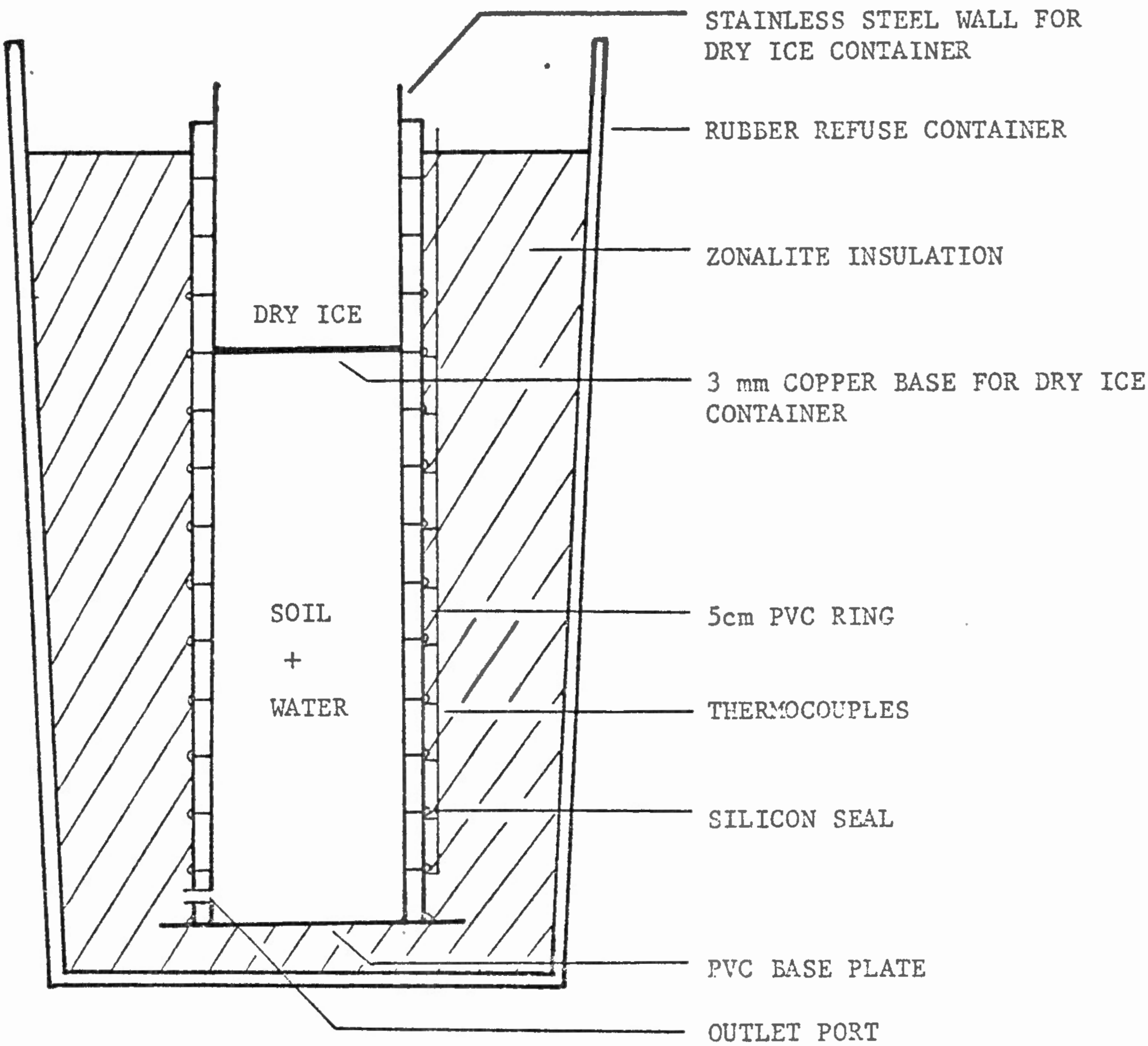

Figure 1: Illustration of assembled apparatus for laboratory experiments of isotope variations in frozen soils.

During the course of this work, dry ice was employed as the cold source due to the high cost of thermoelectric cooling units. However, the temperature gradient developed through the soil by using dry ice was excessive and further use of dry ice is not highly recommended if isotope variations are to be observed in future experiments.

Three separate grain size ranges were chosen for the soil types in order to observe variations created due to the differences and properties of the soils. The grain size curves for the three types are shown on figure 2. The coarse silt to very fine sand and the fine to medium sand were obtained from glacial deposits at Hawkesville, Ontario while the fine sand was obtained from surficial deposits at Chalk River, Ontario. As shown by figure 2, all three soil types are well sorted. For the purposes of the experimental tests, these soils were used as is without further sieving for exact uniformity. Before use in an experiment, the soil was air dried to a moisture content of less than 0.1%.

The water used during experimental testing was from a deionized water supply within the isotope laboratory. This water maintains a relatively constant oxygen-18 content.

2.2 Experimental Testing

Lengthy delays encountered during the purchasing, construction and assembly of the equipment resulted in only two experimental tests being conducted. The first experiment; conducted on the basic column design without thermocouple modifications; employed the use of all three columns and soil types. The soil was mixed with excess water to achieve saturation and then emplaced in the column with only minor packing. The excess water from the surface of the column was removed and the dry ice cylinder inserted.

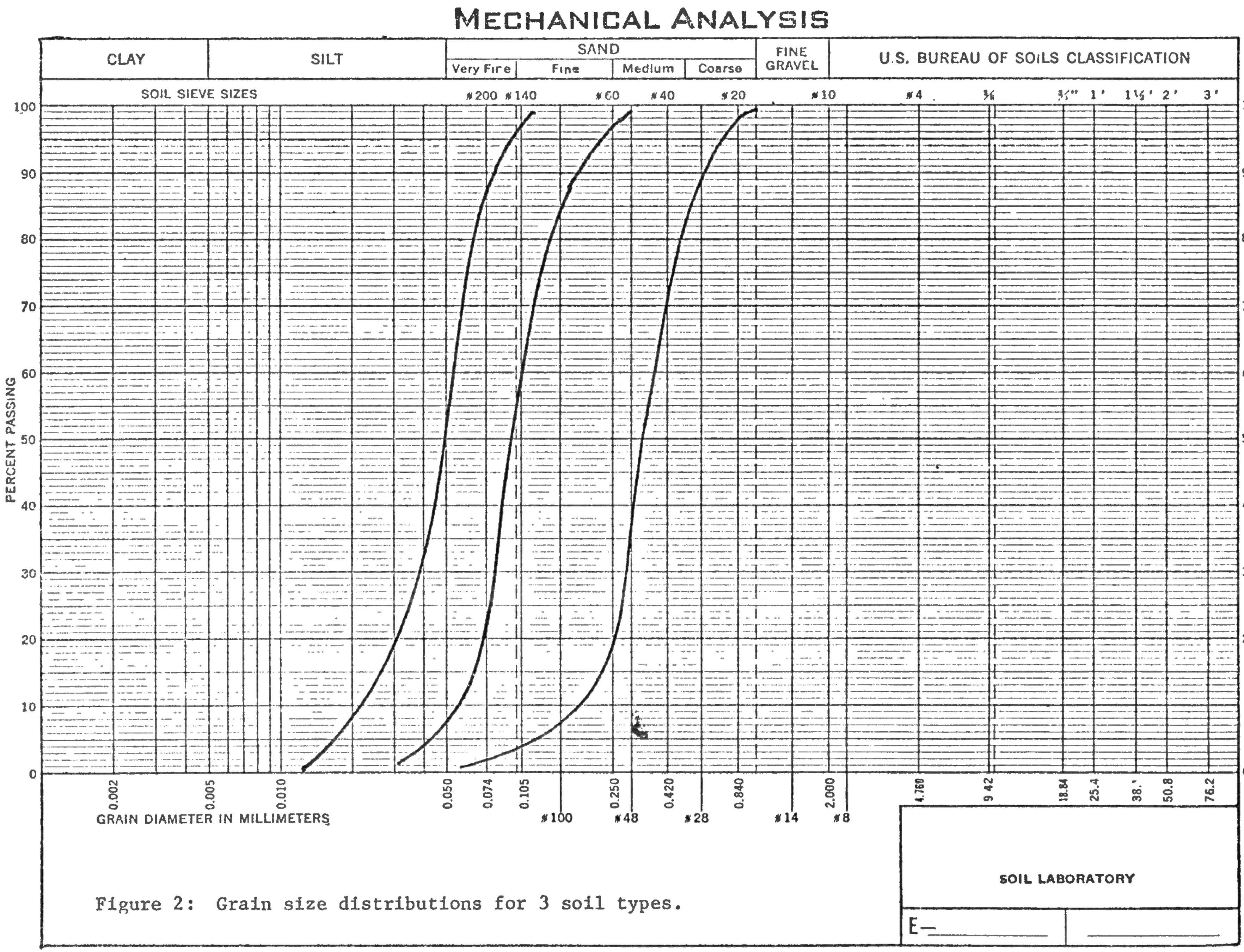

Figure 2: Grain size distributions for 3 soil types.

Initially a problem arose when the dry ice completely sublimated before additional ice became available the following day. This type of problem persisted throughout both experiments. As a result of this problem wide fluctuations in near surface temperatures occurred. These fluctuations were observed during the course of the second experiment and will be discussed in more detail in section 3.3.

Further problems arose during the first experiment when the cold room door was damaged by unknown persons. This resulted in the temperature of the cold room rising from +2°C to +15°C. An attempt to lower the temperature by reseting the temperature control to -10°C failed due to an icing problem in the refrigeration unit.

Due to the absence of the thermocouple equipment, it was impossible to determine the thermal history of the columns or when the columns were completed frozen. This initial experiment was therefore continued for a longer period of time than would normally be required.

Dismantling of the PVC rings was achieved by removing the silicon bead at the joints and separating the rings by approximately 1 mm. Attempts to cut the core using a hot wire and a hack saw failed. Finally a wide bladed chisel and hammer were employed to split the core. Once the 5 cm thick core slice was obtained, it was divided into several pieces with the central portion of the core being labelled separately from the outer edge material. This method of core splitting has to date remained as the most effective means of sampling the column. Samples were double bagged in heavy polyethelene bags and heat sealed to retain all moisture upon thawing of the samples. Water samples for analysis of the isotopes were extracted from the cores by use of a mechanical squeezer as described in the previous study.

The second experiment was designed mainly as a test of the temperature monitoring system and the ability to again prevent leaks from developing along column joints. As mentioned earlier in section 2.1, the major difficulty in sealing arose with the teflon coating of the thermocouple wires. The temperature system itself performed satisfactorily.

In order not to disturb the thermocouple wires excessively, the silt and medium sand columns were filled with dry soil. The wires were resealed using silicon which was then allowed to cure. Water was added to the columns directly but, as might be expected, problems arose in attempting to saturate the columns uniformily throughout. As will be shown in section 3.3, this method is not recommended for use in future experiments. The use of dry ice again proved to be a problem when it came to maintaining ice in the cylinders during the weekend period.

2.3 Analytical Work

Since the completion of the previous contract, the frost mounds at the Bear Rock Spring Flats, N.W.T. have been examined further by analyzing each sample for deuterium. Some of the original oxygen-18 contents reported in the previous contract report have been referenced in conjunction with other studies on the springs by van Everdingen (1978). As a result of this additional work, it is hoped that some of the cores analysed during the initial contract for oxygen-18 will be analysed for deuterium in the near future.

After the two experiments of this contract were completed, the frozen cores were sampled and analysed for their oxygen-18 contents. Oxygen-18 contents, during the first experiment, were determined separately for both the central portion of the cores and edges of the cores while only single analyses were performed on the core sections of the second experiment. Additional samples were oven dried and the moisture contents as weight percent calculated for each section.

Discussion of Results

3.1 Continuation of Previous Studies

During the early part of this contract period, while materials were being ordered for the experimental work, all of the available Bear Rock Spring Flats samples were analysed for their deuterium contents. These values are listed in Table 1 along with the oxygen-18 contents as reported previously in the earlier contract by Fritz and Michel (1977). A plot of the deuterium contents for BRD-1 and BRD-2 (figure 3) produces a curve very similar to the oxygen-18 plot shown in figure 4. The major discrepancy occurs in sample 25. The oxygen-18 content of this sample was unusually negative compared to the samples above and below. The deuterium content alternatively is unusually positive when compared to these adjacent samples. This sample was considered as unexplainable last year and the same must be stated at the present time. Unfortunately no further sample exists from which repeat analyses could be attempted.

The remainder of the samples when plotted using either isotope are indicative of continual fractionation within a residual pool which is not being continually renewed with outside water. This type of process is described schematically by van Everdingen (1978, figure 15) in relation to the growth of these annual frost mounds.

When oxygen-18 and deuterium contents are plotted against one another as in figure 5 further information can be obtained. The Meteoric Water Line for precipitation as described by Craig (1961) has a worldwide slope of 8. This slope varies slightly for specific regions, but for the Mackenzie Valley it is probably very close to the worldwide line. Theoretically, fractionation processes which may affect the

TABLE 1: Oxygen-18 and deuterium contents of springs and frost mound waters, Bear Rock Spring Flats, N.W.T.

SAMPLE NO.	SAMPLE TYPE	$\delta^{18}O$ ‰ SMOW	δD ‰ SMOW
75-21	SPRING	-23.6	-179.2
75-101	"	-22.9	-177.1
75-102	"	-22.9	-176.6
75-103	"	-22.8	-175.3
75-104	"	-23.2	-178.4
75-105	"	-22.4	-176.3
BR-1	ICE	-20.4	-146.1
BR-2	"	-20.6	-139.9
BR-3	"	-20.5	-140.9
BR-4	"	-20.7	-143.9
BR-5	"	-20.7	-156.1
BR-6	"	-20.7	-151.2
BR-7	"	-20.7	-140.2
BR-8	"	-20.7	-153.4
BR-9	"	-20.2	-144.9
BR-10	"	-20.4	-140.5
BR-11	"	-20.6	-148.6
BR-12	"	-20.8	-151.5
BR-13	"	-20.7	-151.5
BR-14	"	-20.6	-155.7
BRD-1-1	CORE	-18.3	--
BRD-1-2	"	-20.9	--
BRD-1-3	"	-20.8	--
BRD-1-4	"	-21.7	-150.5
BRD-1-5	"	-21.3	-114.2
BRD-1-6	"	-21.5	-142.6
BRD-2-1	CORE	-22.7	-172.5
BRD-2-2	"	-22.9	-174.8
BRD-2-3	"	-23.0	-174.6
BRD-2-4	"	-22.8	-175.6
BRD-2-5	"	-23.0	-175.9
BRD-2-6	"	-23.1	-172.5
BRD-2-7	"	-23.0	--
BRD-2-8	"	-23.1	-176.8
BRD-2-9	"	-23.1	--
BRD-2-10	"	-23.1	-177.7
BRD-2-11	"	-23.2	-179.4
BRD-2-12	"	-23.4	-180.8
BRD-2-13	"	-23.7	-182.6
BRD-2-14	"	-23.9	-183.0
BRD-2-15	"	-23.7	-182.4
BRD-2-16	"	-23.7	-182.2
BRD-2-17	"	-24.0	-181.8
BRD-2-18	"	-24.3	-184.8
BRD-2-19	"	-24.6	-186.5
BRD-2-19A	"	-25.0	-189.2
BRD-2-20	"	-25.6	-193.0
BRD-2-21	"	-25.7	-192.3

TABLE 1 (continued)

SAMPLE NO.	SAMPLE TYPE	$\delta^{18}O$ $^{o}/_{oo}$ SMOW	δD $^{o}/_{oo}$ SMOW
BRD-2-22	CORE	-26.2	-194.0
BRD-2-23	"	-26.1	-196.2
BRD-2-24	"	-25.4	--
BRD-2-24A	"	-25.3	-192.3
BRD-2-25	"	-26.8/-26.5	-180.7
BRD-2-26	"	-25.3	-190.4
BRD-2-27	"	-24.7	-184.8
BRD-2-28	"	-24.6	-184.3
BRD-2-29	"	-24.9	-185.5
BRD-2-30	"	-24.9	-188.0
BRD-2-31	"	-24.6	-184.6
BRD-2-32	"	-24.6	-186.6
BRD-2-33	"	-24.6	-186.7

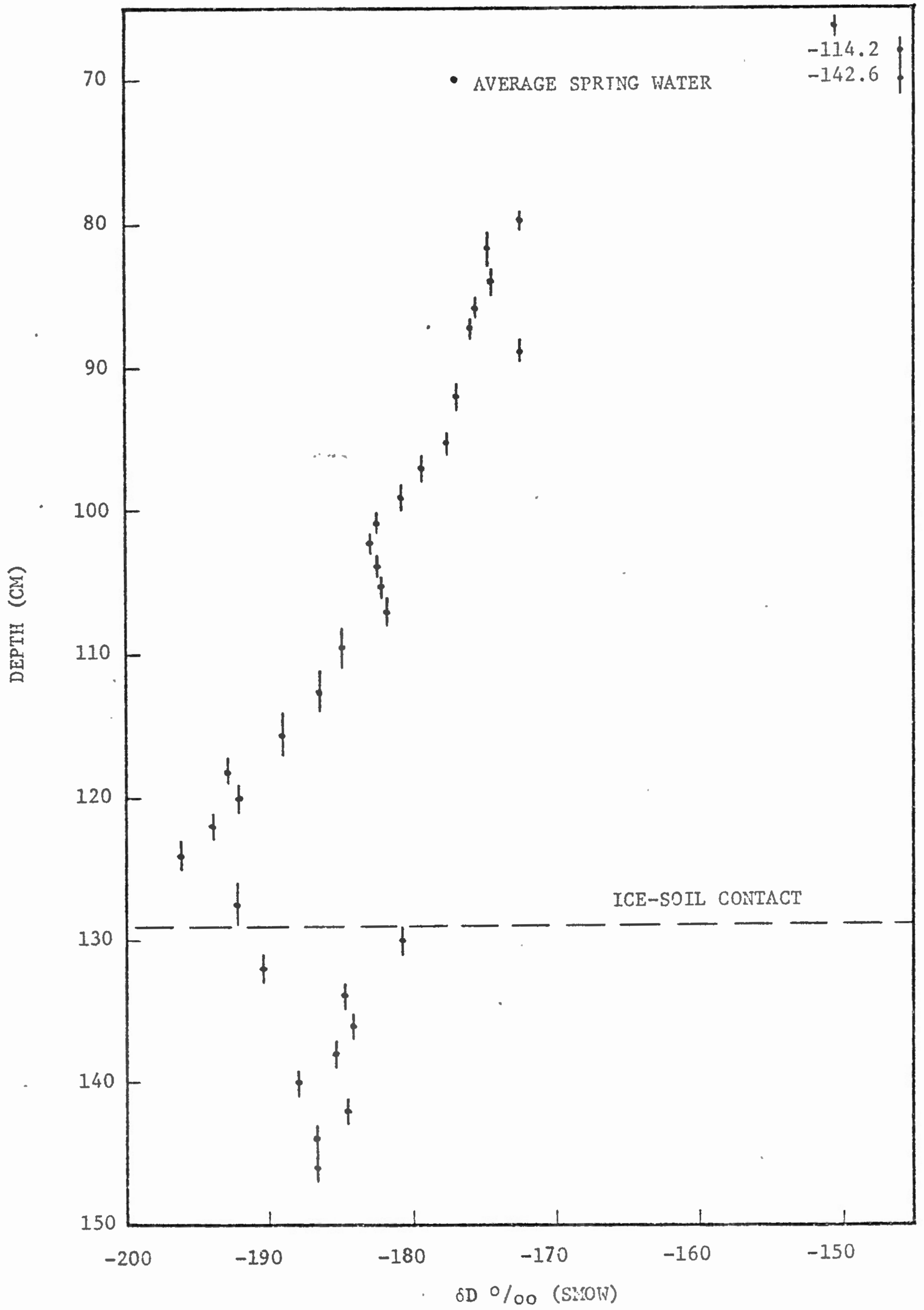

Figure 3: δD °/oo SMOW versus depth for cores BRD - 1 & 2

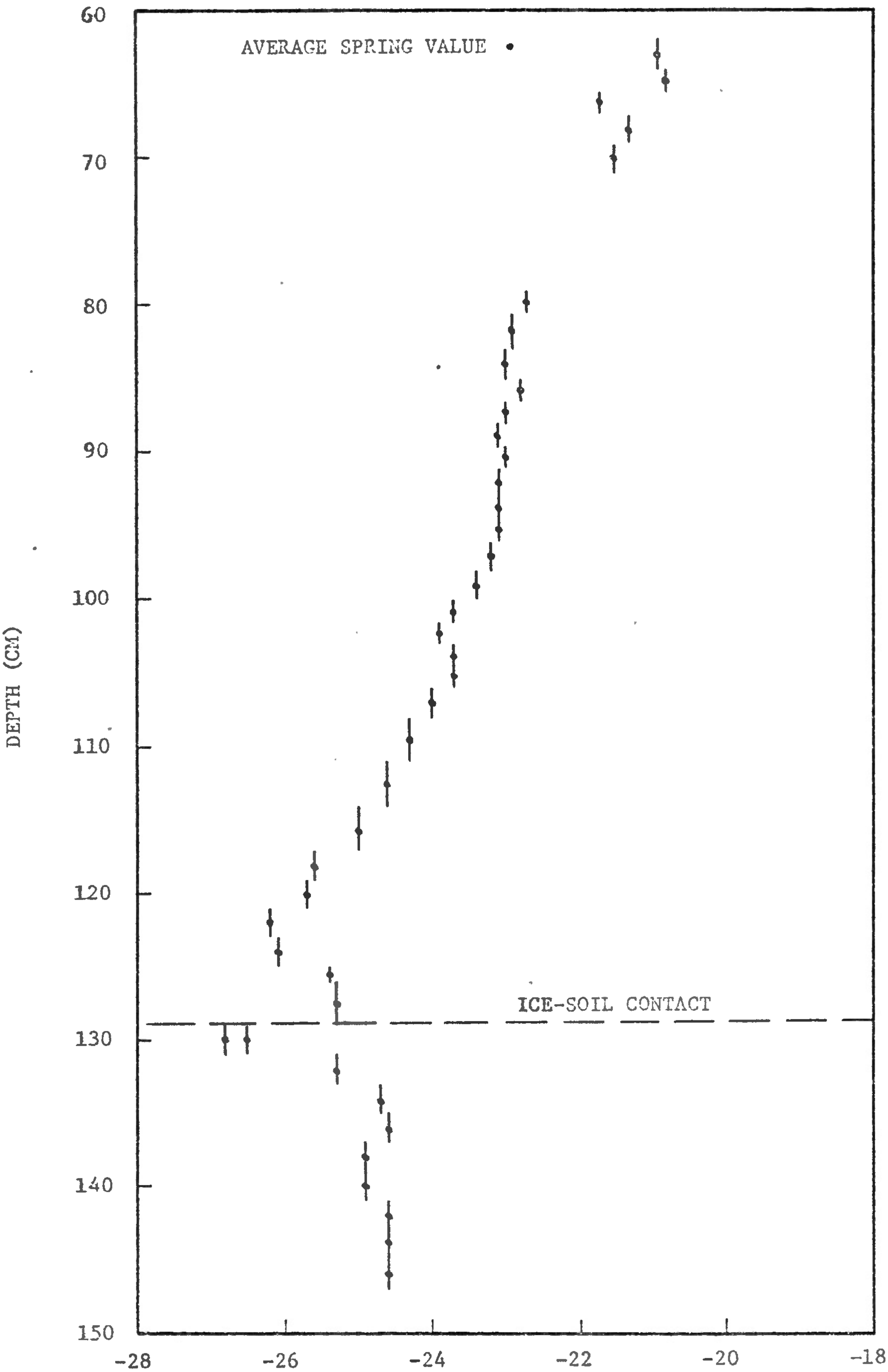

Figure 4: $\delta^{18}O$ $^o/_{oo}$ SMOW versus depth for cores BRD - 1 & 2.

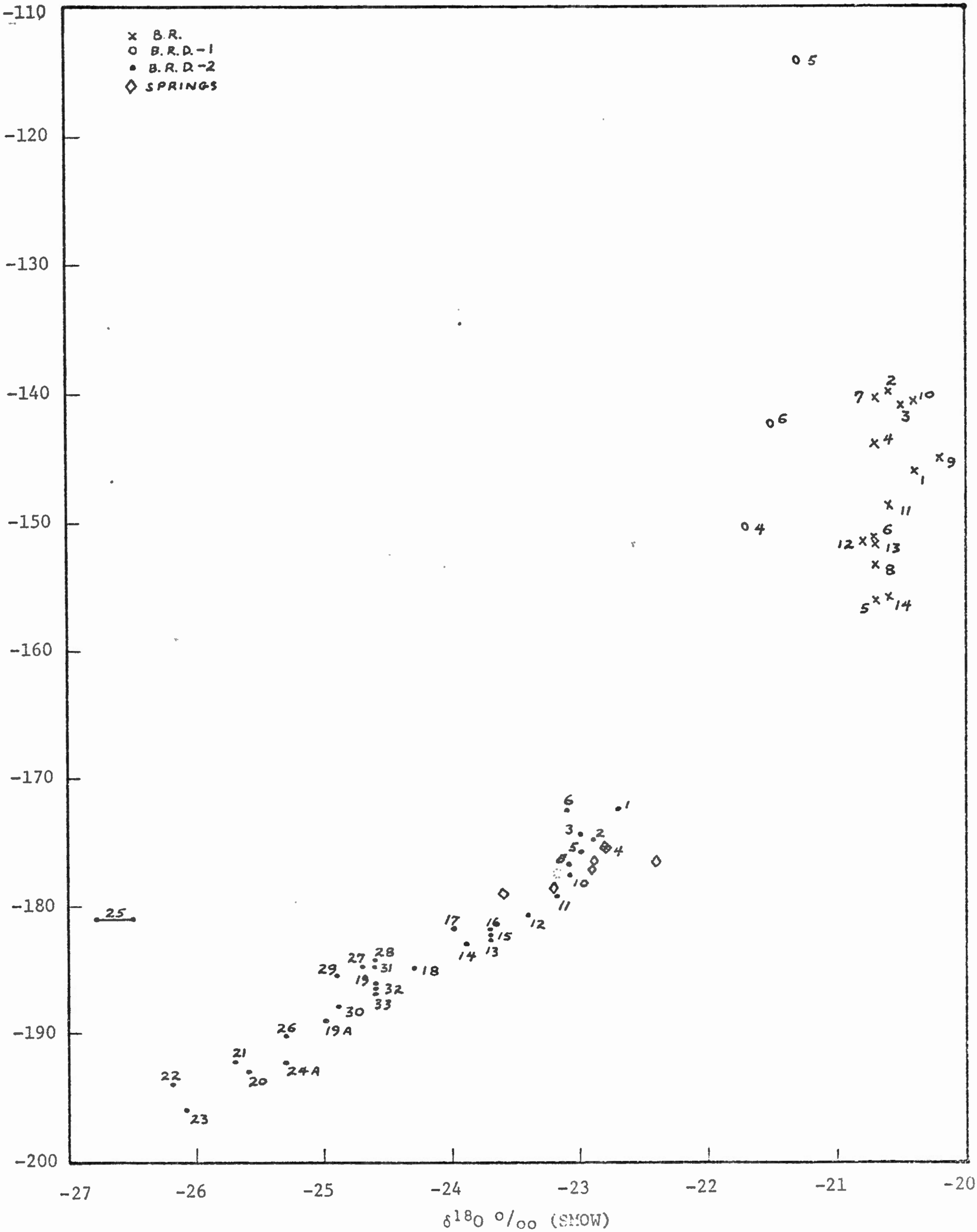

Figure 5: $\delta^{18}O$ vs. δD for Bear Rock Frost Mounds.

isotopic composition of meteoric waters should always result in a lower slope than 8.

In figure 5, the slope of the lower portion of the curve is close to 6 which is reasonable for waters which have undergone fractionation within a closed system as previously described. The lowest values (samples 22 and 23) correspond to the final aliquot of water remaining unfrozen in the residual pool. These samples in figures 3 and 4 plot as the negative bulge near the lower ice-soil contact. Freezing of the pool of water originated with samples 1 and 33 and progressively froze towards the center. Since the last water to freeze was sample 22, it is possible to say that most of the freezing was due to negative air temperatures resulting in freezing from the top downwards. Samples 25 to 33 may or may not have originally been part of the unfrozen water mass, but it is certain that their water was derived from the same source. The most reasonable source for this water would be the springs which cluster near the upper core samples in figure 5.

Problems arise in examining and attempting to explain the phenomena displayed by the BRD-1 and BR cores. These two cores represent different water masses but appear, as would be expected by their similar position in the structure of the frost mounds, to represent similar processes acting upon their isotope contents. Unfortunatley, it is impossible at present to describe these processes as it would appear that these analyses produce slopes of approximately 100; in clear contradiction to theory. Cores BRD-1 and BR were collected during the month of June whereas BRD-2 was collected during early September. Although BRD-2 represents a continuation of coring in the BRD-1 hole, there exists a two month thaw break which coincides with the abrupt change in slopes. It would appear that a complete coring of one or more of these frost mounds will be required before any concrete answers can be reported.

3.2 Present Experiments

The experiments conducted to date were designed primarily for the purpose of testing the equipment and different methods of preparing the soil and water in the columns. Each experiment emphasizes different aspects of the procedure and will therefore be discussed separately.

Table 2 lists the moisture contents as weight percent for each of the three soil types examined during the initial experiment and these are plotted in figure 6. The first number designates the soil size as 1 - silt, 2 - fine sand, and 3 - medium sand. These samples were collected from the outer edge of the column and may not be indicative of the central core, although upon visual examination there did not appear to be any noticeable difference in the moisture contents.

The uppermost samples of ice represent excess water which was ponded on the surface after the dry ice cylinder was inserted. Major changes in the moisture contents occur in the upper samples during the transition from 100% water to the average moisture content. This transition occurs more rapidly as the soil becomes progressively coarser. The uniformity in the moisture contents of all three columns is attributable to the pre-mixing of the soil and water before packing in the column. The reason for fluctuations of up to 3% in adjacent samples is not known. It was originally expected that there would be a decrease in water near the base of the columns due to compaction of the overlying soil column but this does not appear to be present in this experiment.

In examining the oxygen-18 profile of these cores (table 3 and figure 7), appreciable variations are visible. The ice layer of columns 1 and 2 show no variation between the edge and center samples while no-

TABLE 2: Moisture contents of experiment 1 cores.

CORE NO.	SAMPLE NO.	DEPTH (CM)	WEIGHT % WATER
1	1	0-1	ICE
1	2	1-5	46.5
1	3	5-10	24.4
1	4	10-15	18.8
1	5	15-20	19.5
1	6	20-25	20.1
1	7	25-30	17.8
1	8	30-35	17.5
1	9	35-39	20.1
1	10	39-40	-
2	0	0-1	ICE
2	1	1-2.5	ICE
2	2	2.5-5	28.3
2	3	5-10	23.7
2	4	10-15	23.7
2	5	15-20	23.9
2	6	20-25	25.0
2	7	25-30	24.0
2	8	30-35	27.3
2	9	35-39	27.1
2	10	39-40	22.4
3	1	1-4	FROST
3	2	4-5	ICE
3	3	5-6	ICE
3	4	6-10	20.3
3	5	10-15	18.2
3	6	15-20	19.8
3	7	20-25	19.6
3	8	25-30	20.1
3	9	30-35	19.5
3	10	35-40	21.4
3	11	40-42.5	20.6
3	12	42.5-45	20.2

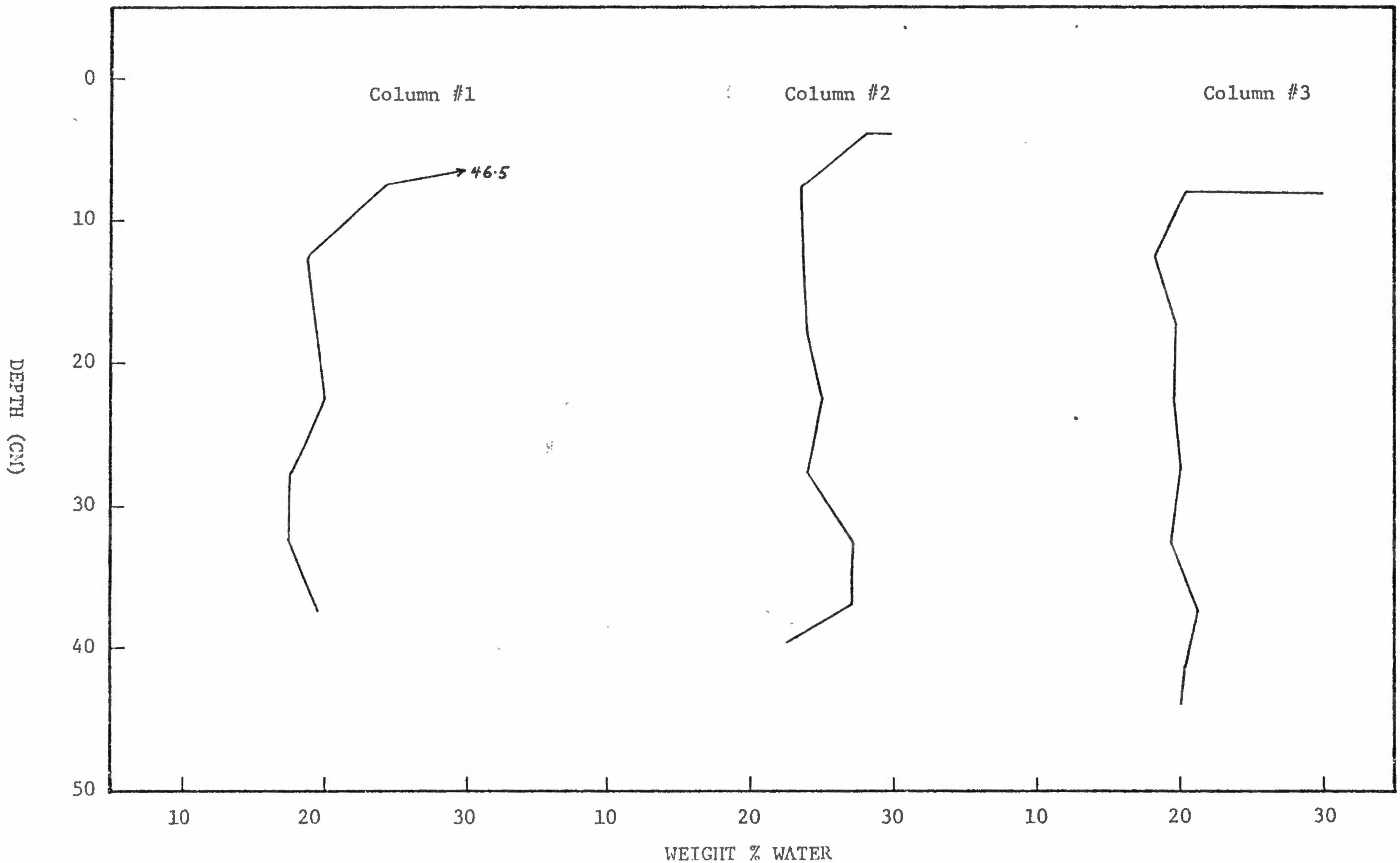

Figure 6: Moisture contents of columns in experiment #1.

TABLE 3: Oxygen-18 contents of experiment 1 cores.

CORE NO.	SAMPLE NO.	CENTER $\delta^{18}O$ °/oo SMOW	EDGE $\delta^{18}O$ °/oo SMOW
1	INITIAL	-10.6	-
1	1	-10.5	-10.5
1	2	-10.2	-10.4
1	3	-10.3	-10.1
1	4	-10.5	-10.2
1	5	-10.3	-10.3
1	6	- 9.9	-10.1
1	7	-10.1	-10.1
1	8	-10.0	-10.5
1	9	-10.2	-11.5
1	10	-10.1	-
2	INITIAL	-10.0	-
2	0	- 8.9	- 8.7
2	1	- 9.5	- 9.5
2	2	- 9.5	- 9.6
2	3	- 9.4	-10.2
2	4	-10.0	-10.2
2	5	- 9.9	-10.2
2	6	-10.7	-10.3
2	7	- 9.7	- 9.9
2	8	- 9.9	-10.0
2	9	-10.0	- 9.8
2	10	-10.1	-
3	INITIAL	-10.7	-
3	1	- 9.7	-
3	2	- 8.9	-
3	3 UPPER	-10.4	-10.3
3	3 LOWER	-11.0	
3	4	-11.8	-10.7
3	5	-10.8	-10.4
3	6	-10.7	-10.6
3	7	-10.5	-10.7
3	8	-10.8	-10.8
3	9	-10.7	-10.8
3	10	-10.5	-10.0
3	11	-10.7	-10.8
3	12	-10.8	-

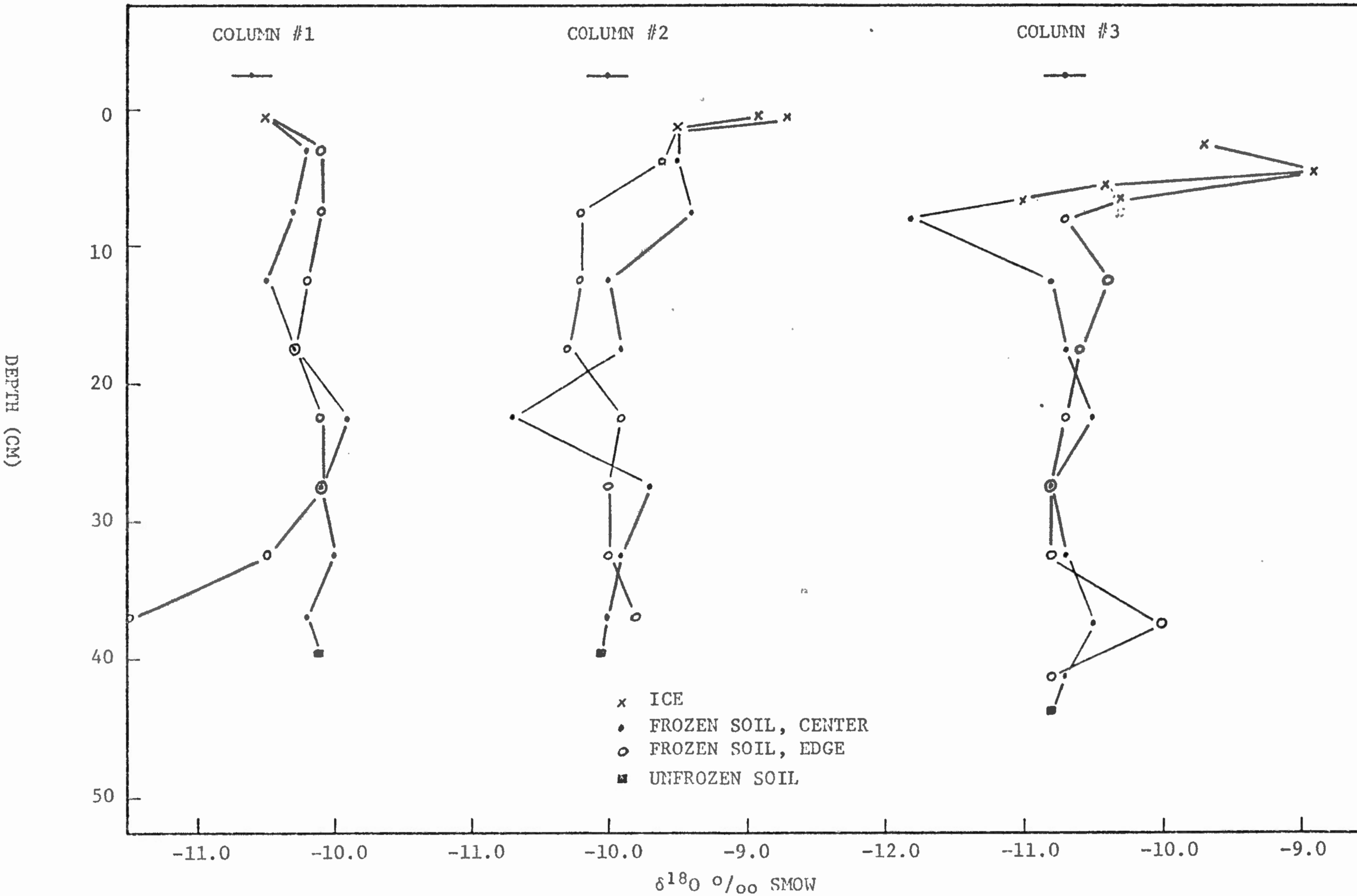

Figure 7: $\delta^{18}O$ °/oo versus depth for columns in experiment #1.

edge samples were taken for column 3. The similarity suggests relatively rapid freezing of the upper free water at a uniform rate across the surface of the basal copper plate.

The variations between edge and center samples remain small throughout column 1 until near the bottom of the profile. Above this section, both the edge and center samples are slightly positive in comparison with the initial isotope composition of the water. The negative swing near the bottom would therefore represent the residual water which has been continually depleted in oxygen-18. Because volumes of soil were not measured for each sample, it is impossible to calcualte isotope balances for any of the columns.

In column 2, the surface ice is enriched in oxygen-18 in comparison to the initial isotope content of the water. The remainder of the column contains water of similar isotopic composition to the initial water. The single negative spike near the midpoint of the column may be due to an accumulation of oxygen-18 depleted water which was quickly frozen upon refilling of the dry ice cylinder. Because the edge sample indicates a reverse trend, this fractionation may be confined to the one particular level, although any explanation at present is strictly speculation.

The upper profile of column 3 indicates that a large fractionation of the oxygen-18 isotopes is occurring between the ice and the underlying sediment pore water. The size of the isotope variation (2.9 $^{o}/oo$) is indicative of ice-water fractionation systems as described by Suzuoki and Kimura (1973). Below this upper portion there appears to be no fractionation of the isotopes throughout the remainder of the column.

In general, the oxygen-18 profiles generated during this initial experiment indicates that it is possible to produce isotope fractionations within all three grain size ranges examined. It is also reasonable to assume that an isotopic balance is maintained within the column.

For the second experiment only columns 1 and 3 were used. In order to prevent excess disturbance of the thermocouple wires, the soils were placed in the columns dry. Water of a known isotopic composition was then added.

Unfortunately, as shown by the figures in table 4 and the plot in figure 8, the water did not penetrate the lower 30 cm of the silt column. Attempts were made to ensure complete saturation but these apparently failed. The decrease in moisture content from saturation near the top to near air dry values occurred over a range of 10 cm, similar to the range noted for column 1 in the initial experiment.

The coarser sand material in column 3 was more amendable to saturation by this method than was the silt. The moisture contents of the sand in this experiment are very similar to those for the first experiment. Excess water appears to have drained into the lower part of the column thereby raising the moisture content of the lowermost section by 6.5%.

As a result of these variations in moisture contents for the silt, only the upper four samples yielded sufficient water for analysis of the oxygen isotope composition. The uppermost section (number 11) represents uplift of the dry ice cylinder by 1 cm above the original top of the soil.

The oxygen-18 contents for both columns are listed in table 5 and plotted in figure 9. Due to the shortness of the section available for isotope analysis in column 1, it is impossible to discuss whether

TABLE 4: Moisture contents of experiment 2 cores.

CORE NO.	SAMPLE NO.	DEPTH (CM)	WEIGHT % WATER
1	11	- 1-0	20.4
1	10	0-5	18.5
1	9	5-10	19.1
1	8	10-15	16.5
1	7	15-20	6.7
1	6	20-25	0.1
1	5	25-30	0.2
1	4	30-35	0.1
1	3	35-40	0.1
1	2	40-45	0.1
1	1	45-50	0.1
3	10	0-5	22.8
3	9	5-10	20.5
3	8	10-15	18.6
3	7	15-20	18.5
3	6	20-25	21.8
3	5	25-30	19.0
3	4	30-35	19.4
3	3	35-40	19.5
3	2	40-45	19.2
3	1	45-50	25.8

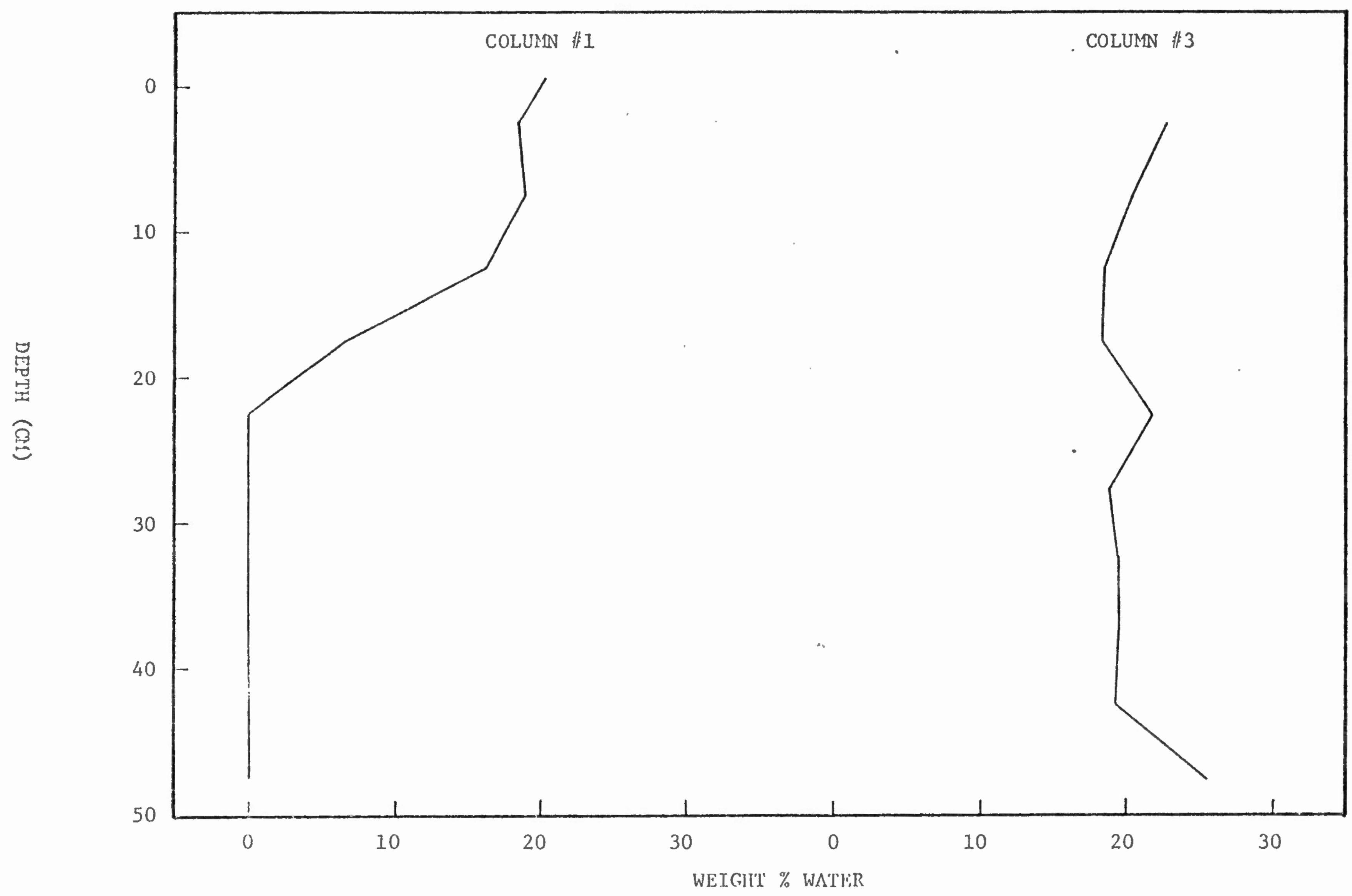

Figure 8: Moisture contents of columns in experiment #2.

TABLE 5: Oxygen-18 contents of experiment 2 cores

CORE NO.	SAMPLE NO.	$\delta^{18}O$/oo SMOW
1	INITIAL	-10.8
1	11	-10.8
1	10	-10.9
1	9	-10.7
1	8	-10.5
3	INITIAL	-10.9
3	10	-10.8
3	9	-10.9
3	8	-10.8
3	7	-10.5
3	6	-10.8
3	5	-10.1
3	4	-10.8
3	3	-10.3
3	2	-10.2
3	1	-10.2

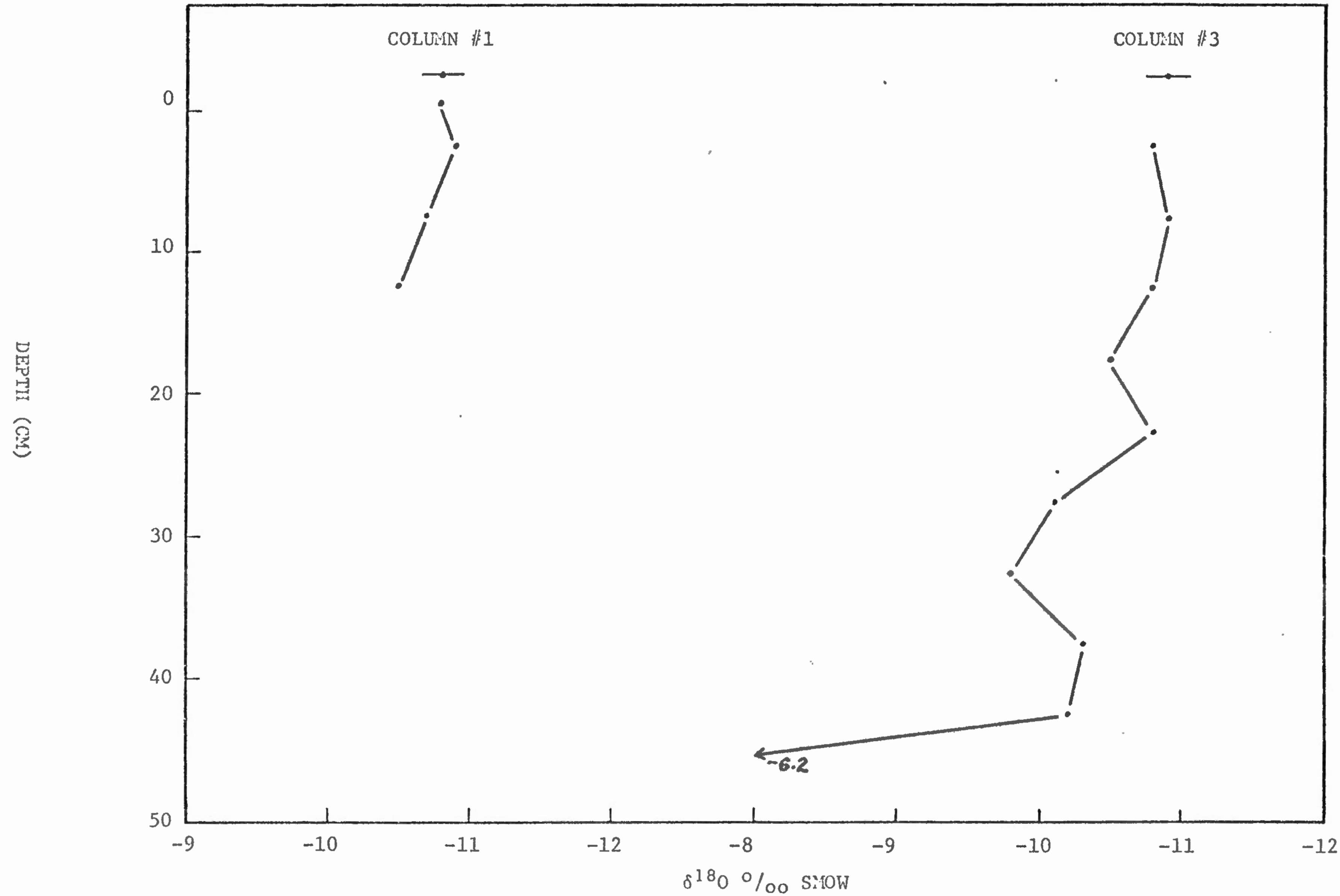

Figure 9: $\delta^{18}O$ SMOW versus depth for columns in experiment #2.

any trends are developing.

The isotope profile for column 3 indicates no major deviation from the initial water's composition until section 5 at a depth of 25 cm. The four sections, 5 through 2, produce a positive fractionation of up to 1 $^{o}/oo$. The lowermost sample is extremely positive and may in part be due to poor sample preparation caused by a high silt content resulting in the water sample being very muddy. Since separate edge versus center samples were not analysed as in the first experiment, it is difficult to say whether an isotopic balance was maintained.

The major data collection for the second experiment was in the area of temperature monitoring and profiling. The temperature profiles with depth over the length of the experiment are divided into three sections as figures 10 to 12 for column 1 and figures 13 to 15 for column 3.

The dramatic decrease in the moisture content of column 1 over the 10 to 20 cm depth range is clearly visible in figures 10 to 12 as a definite change in slope of the temperature profile. As would be expected, freezing occurs faster in saturated silt soils than in dry silt material. The periods when dry ice was not available are clearly visible due to the rapid warming of the upper soil profile. A small section of soil near thermocouple number 1 indicates slightly cooler temperatures than the overlying sediment for at least the first 7.5 hours. The reason for this trend is not known. Cooling of the column base by the dry ice took less than 7.5 hours, but lowering of the basal temperatures took considerably longer than expected resulting in the high temperature gradients within the column. Even at the termination of the experiment, the basal temperature for column 1 was less than 2^{o}C below freezing. The temperature gradient between the top and

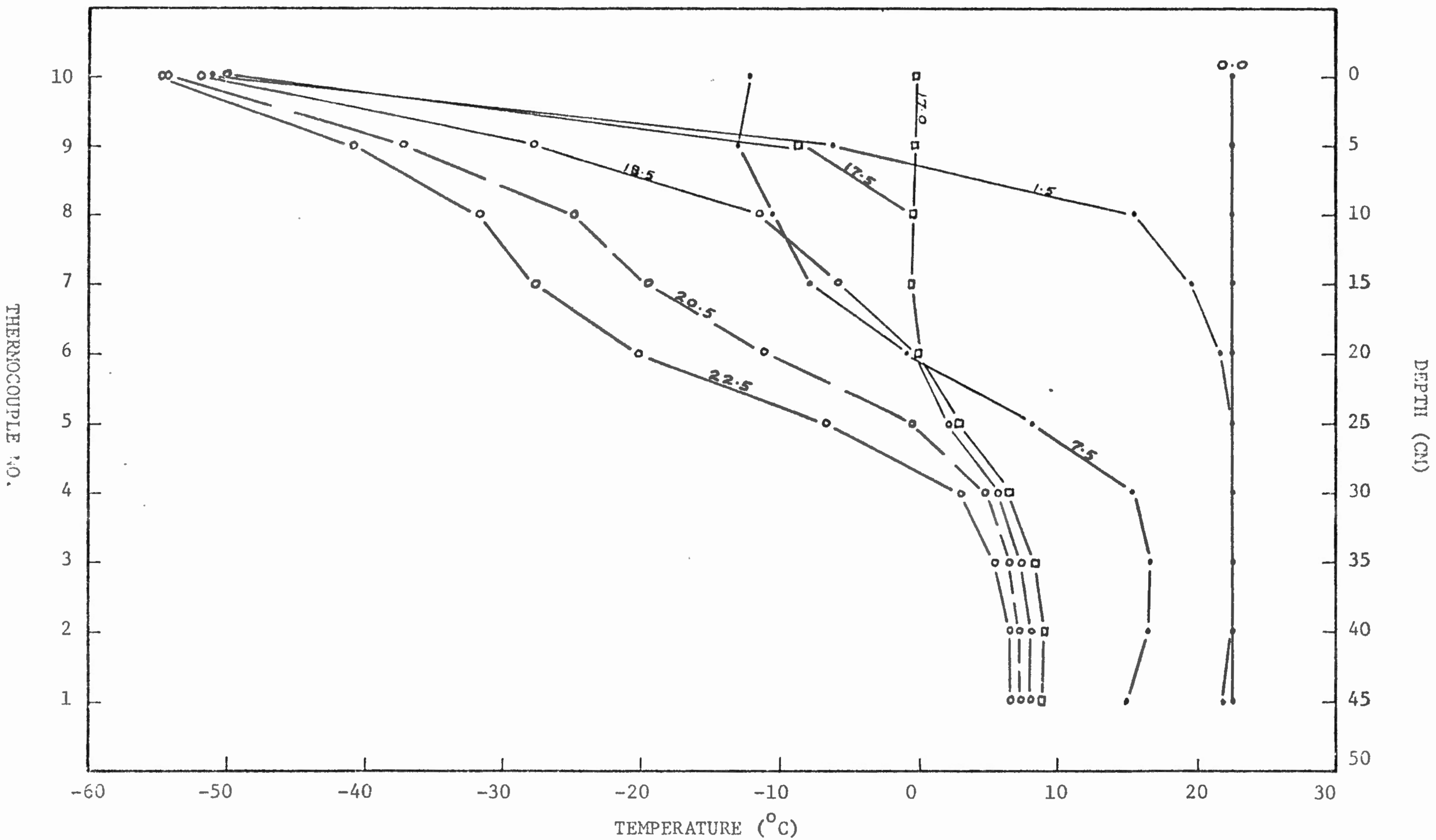

Figure 10: Temperature profiles for column #1, experiment #2; 0 to 22.5 hours.

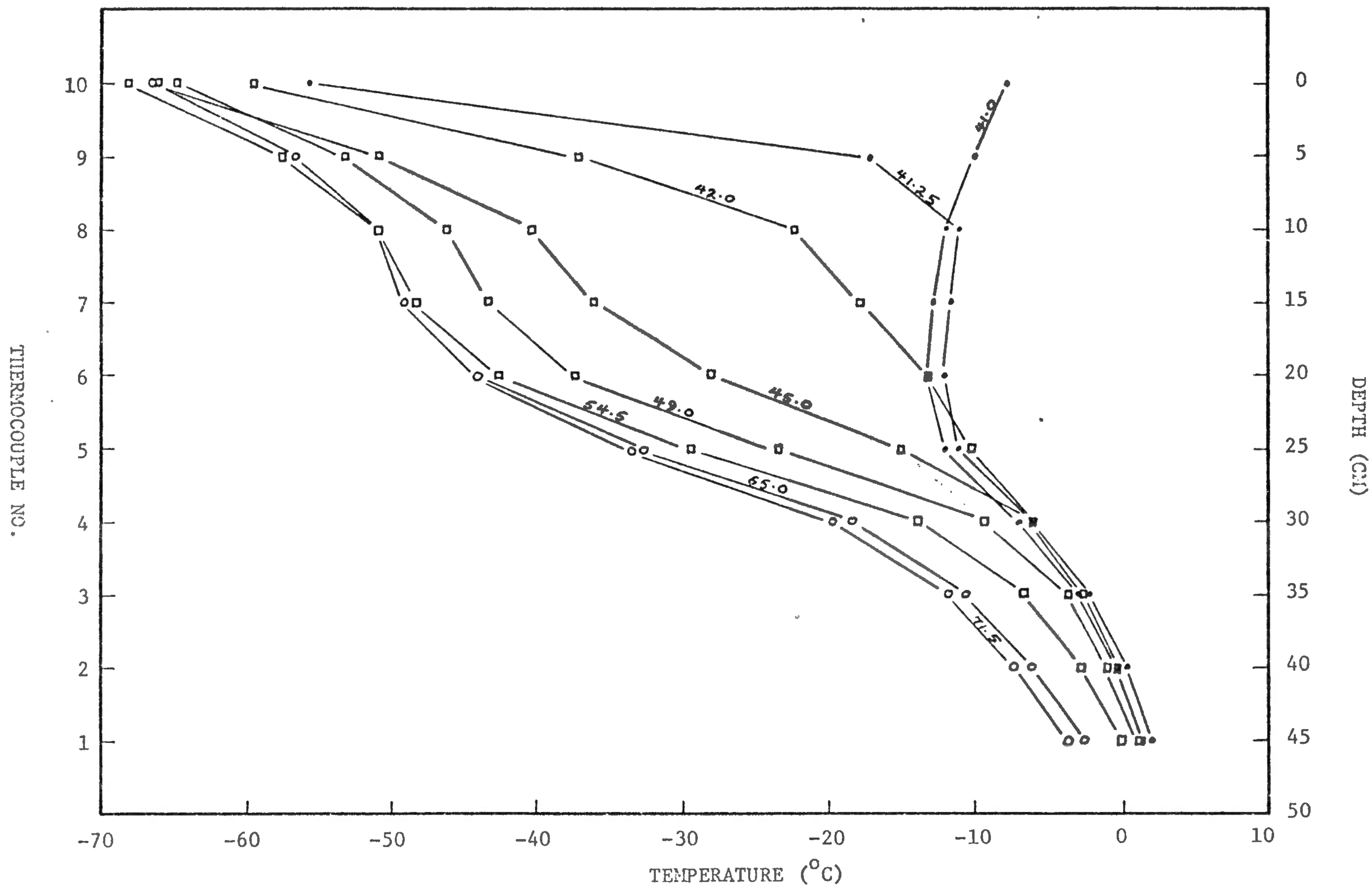

Figure 11: Temperature profiles for column #1, experiment #2; 41 to 71.5 hours.

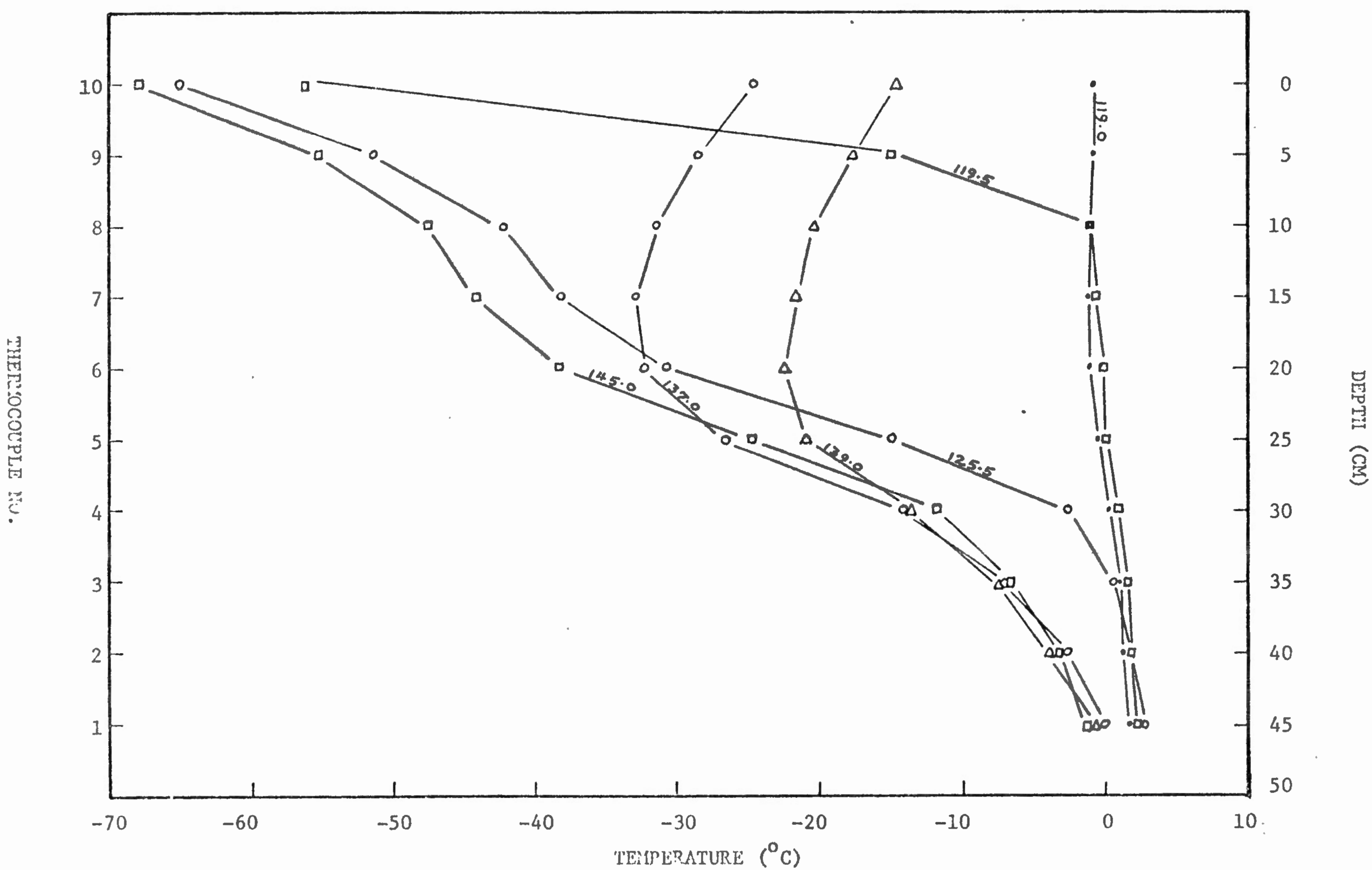

Figure 12: Temperature profiles for column #1, experiment #2; 119 to 145 hours.

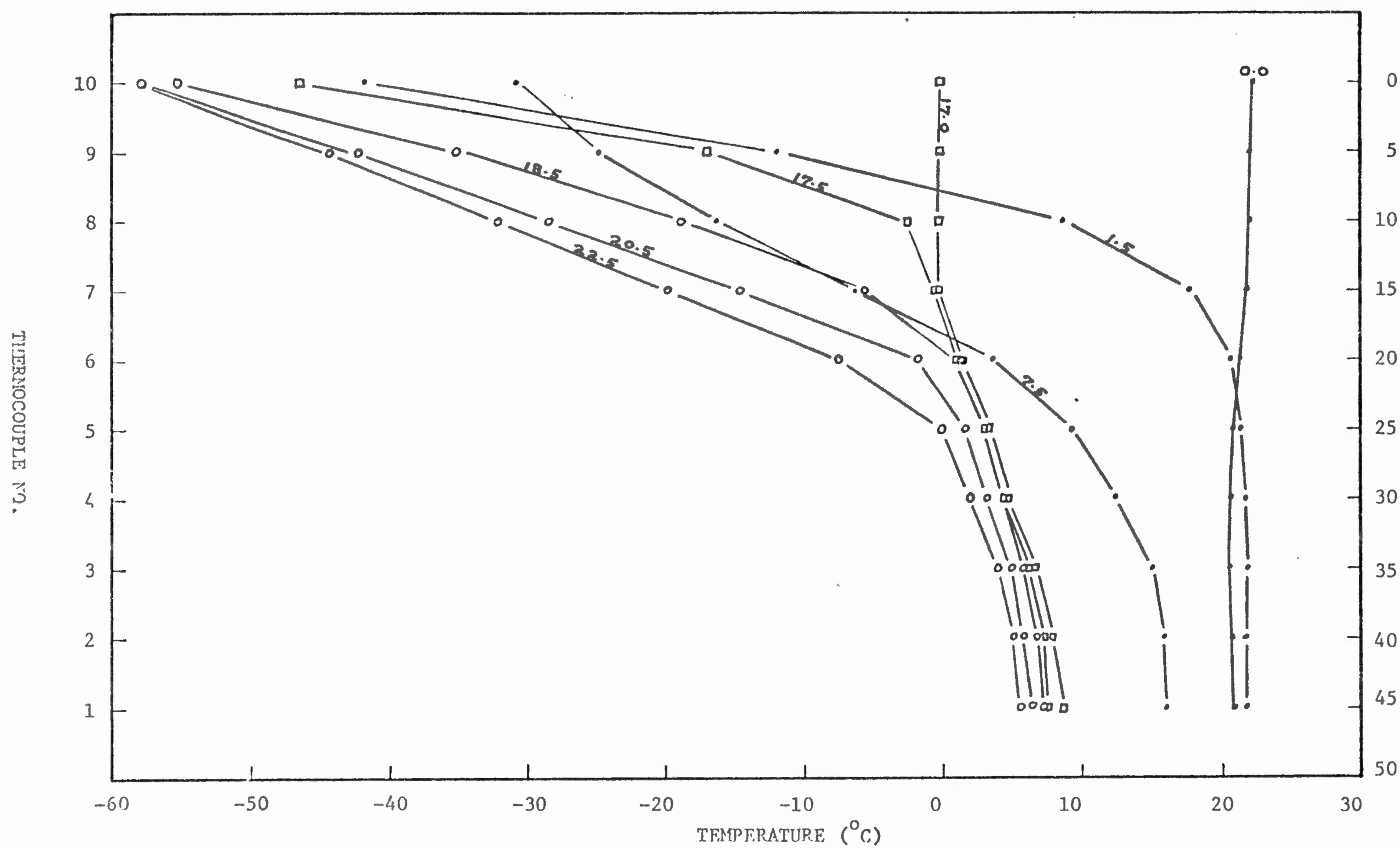

Figure 13: Temperature profiles for column #3, experiment #2; 0 to 22.5 hours.

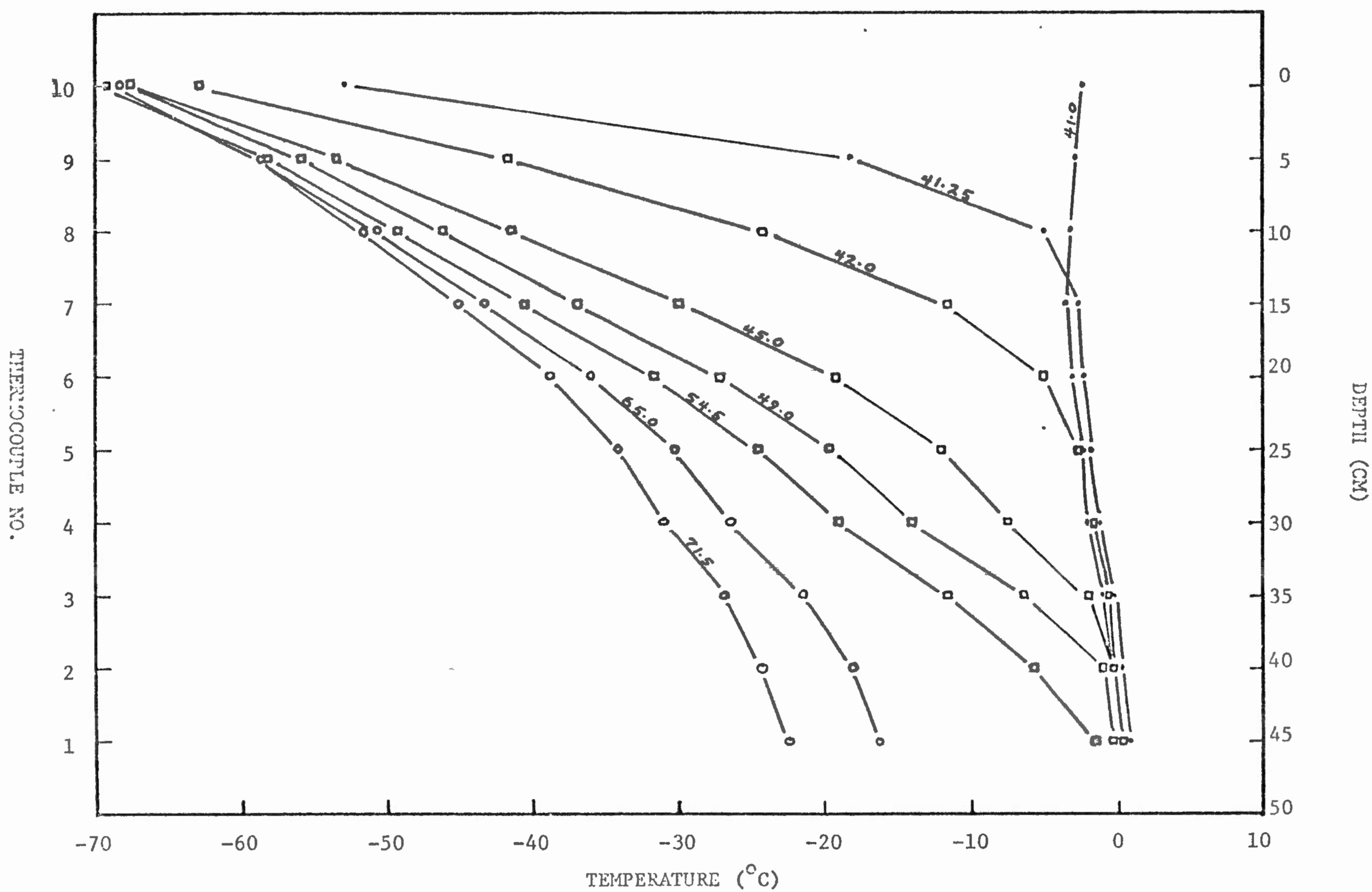

Figure 14: Temperature profiles for column #3, experiment #2; 41 to 71.5 hours.

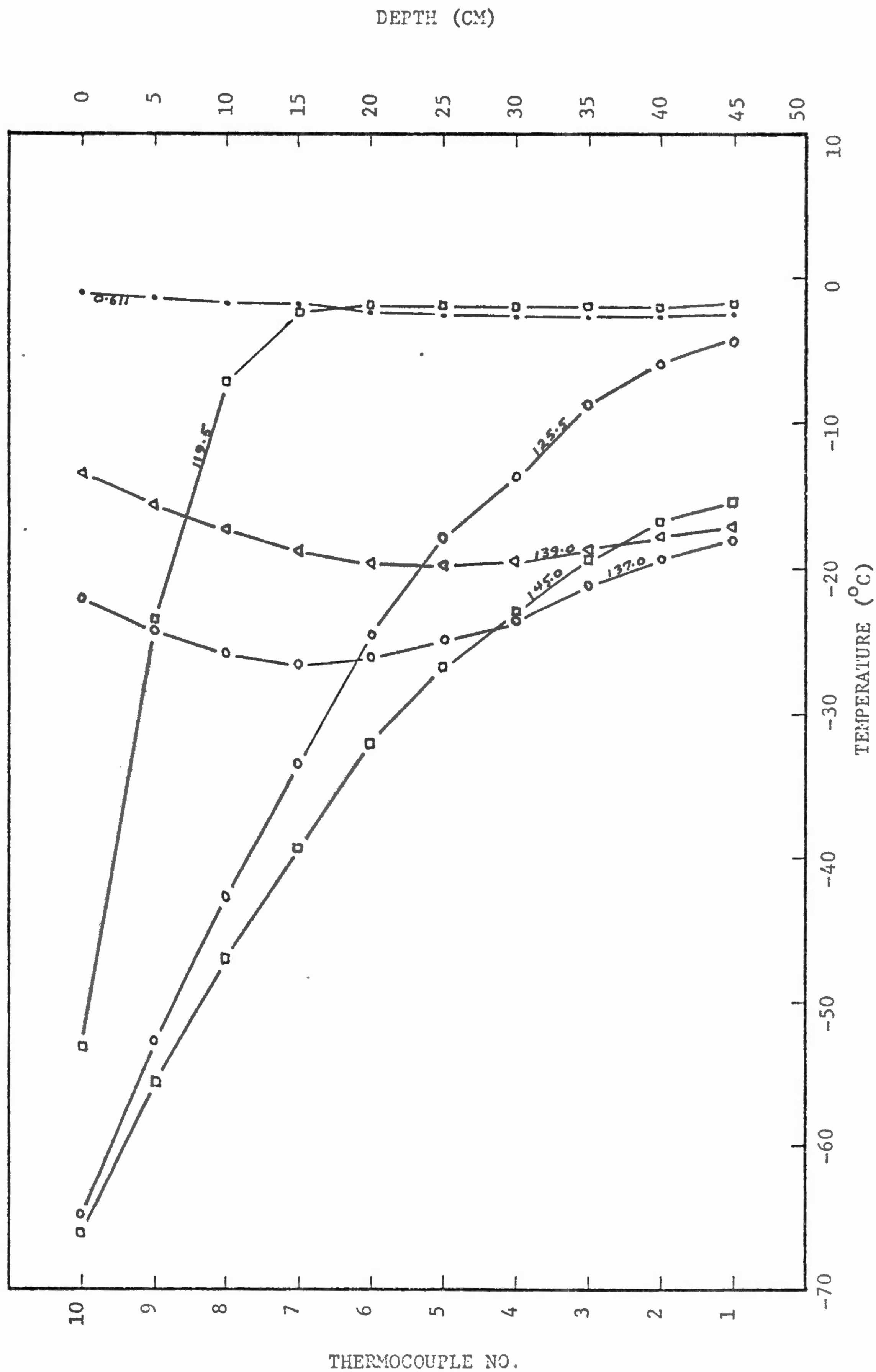

Figure 15: Temperature profiles for column #3, experiment #2; 119 to 145 hours.

bottom of the column after 145 hous of nearly continuous cooling was still in the order of 66°C.

Figures 13 to 15 display many similar features for column 3. There is, however, no change in slope as there is no major change in the moisture content of this column. Probably as a result of the uniform moisture content, the rate of freezing appears to be slightly faster in the coarser grained sand. Although both columns develop similar temperature profiles during the early part of the experiment, the base of the sand column is approximately 19°C colder than the base of the silt column after 71.5 hours. Temperature gradients in the sand column are considerably lower than for the silt column. At the termination of the experiment, this column had a basal temperature of -16°C and a gradient of only 50°C.

Closer examination of figures 10 to 15 reveals an interesting phenomenon of heat transfer ahead of the cold front. The 1.5 hour profile of figure 13 and 145 hour profile of figure 15 clearly indicate temperature rises of 1 to 3°C over the previous time profiles.

A scale expansion of four times in figure 16 of part of figure 11 and a ten times expansion in figure 17 of part of figure 14 aids in examining this phenomenon. In both figures, the increase in temperature persists in excess of one hour. By returning to the original two figures (11 and 14), it is possible to determine that the increase may persist for as long as four hours for both soil types.

This phenomenon occurs as a result of temperature increases in the upper section when the dry ice source disappears. Heat which enters the soil during this warm period becomes trapped when dry ice is added to the surface. A portion of this heat appears to migrate downwards ahead

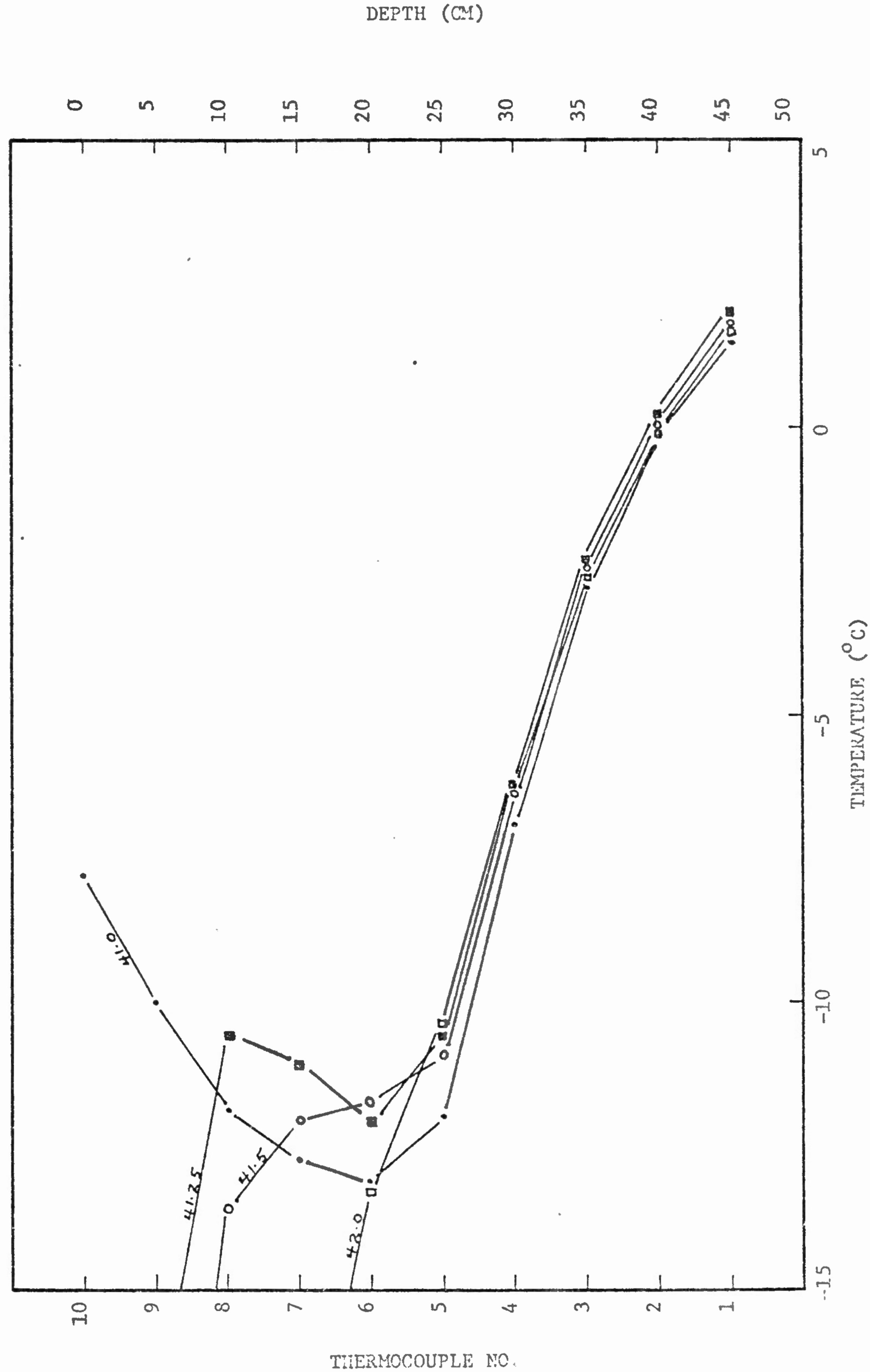

Figure 16: Expanded temperature profiles of 41 to 42 hour period; column #1, experiment #2.

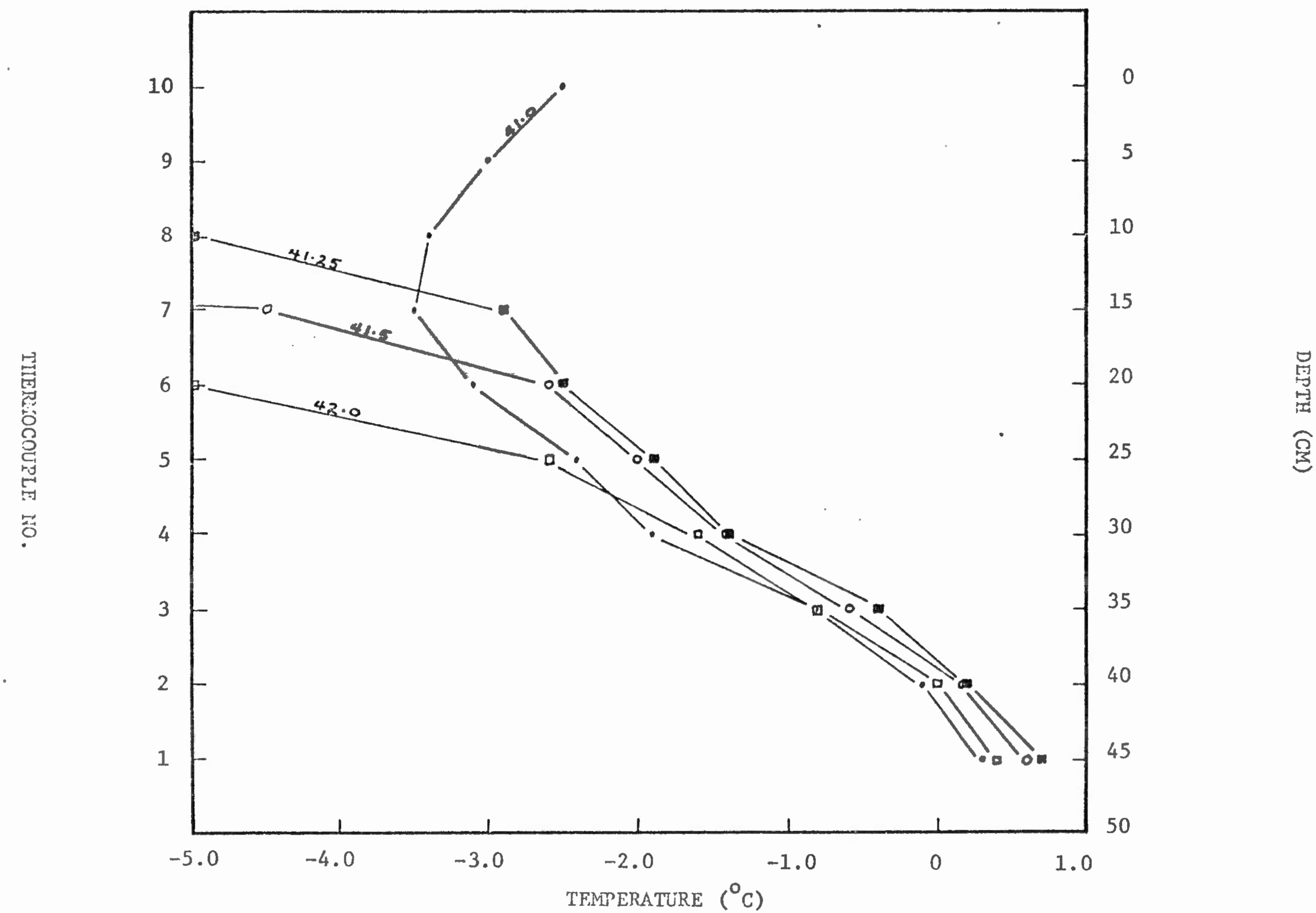

Figure 17: Expanded temperature profiles of 41 to 42 hour period; column #3, experiment #2.

of the advancing cold front. This heat diffuses uniformly throughout the lower portion of the column raising the temperature by 1 to 3°C. As the freezing front continues to advance the rate slows sufficiently to allow for gradual dissipation of the heat build up.

By employing the use of thermoelectric cooling units as opposed to dry ice, considerably smaller temperature gradients will be possible. These smaller gradients will result in slower freezing of the soil and thus allow time for larger isotope fractionations to occur. Detailed temperature monitoring of this type of controlled freezing should prove to be extremely useful in the interpretation of the isotope variations.

Conclusions

4.1 Equipment Modifications

The basic column design at present appears to be adequate for the initiation of experiments. It is suggested that additional ports be added to other rings in the columns for the purpose of injecting or withdrawing water from specific levels. There may also be some need to modify the teflon coating on the thermocouple wire to allow for superior sealing of the wire to the column. Silicon still is considered as the best sealant for this purpose. The major change required, as noted in the progress report, is to switch from the use of dry ice to thermo-electric cooling units. With these units it is possible to control the temperature of the cold source and to apply a continuous, constant temperature. This equipment would allow for better reproduction of field conditions than does the dry ice. Further modifications may become apparent during the course of specific experiments at a later date.

4.2 Experimental Findings

To date, the major objective has been to assemble equipment and prodedures for the use of experimental research into isotope variations created during the growth of permafrost. As a result of this emphasis, only two experiments have been conducted during testing of the equipment.

The first experiment, which was designed basically to test the suitability of the columns, revealed that it is possible to induce isotope fractionation in coarse-grained sediments under high thermal gradients. The results of this experiment also indicate that the isotopic balance is maintained within the column although this could not be definitely assertained.

The second experiment was designed basically to test the temperature monitoring system. Freezing rates were found to be higher in wet silts than in dry silts. A change in slope of the temperature profile clearly defines the change in moisture content throughout the entire length of the experiment. Freezing rates were also found to be higher in sands than silts with a resulting lower temperature gradient in the sand. Finally, in both the silt and sand columns, it was possible to monitor a heat pulse in the lower portion of the core. This heat entered the soil during the absence of a cold source and was forced to migrate downwards in front of the cold front once the cold source was reapplied. Application of a controlled, constant cold source and monitoring of the movement of the cold front is considered as an integral part in attempting to understand the fundamental processes involved in fractionation of the environmental isotopes during permafrost growth.

4.3 Suggestions for Continued Work

The study to date has been oriented towards the development of equipment and procedures for investigating isotope fractionation and the fundamental processes involved during permafrost growth. At this point in time, it is felt that with the modifications suggested in section 4.1 of this report that detailed experimental investigations can begin. It is therefore suggested that an experimental program be undertaken using the equipment and procedures developed to date. In order to substantiate analyses of field cores conducted to date as outlined in sections 1.1 and 3.1, it is further suggested that a separate field program be outlined and undertaken in the near future. This program could include the collection of additional cores from the frost mounds at Bear Rock Spring Flats, N.W.T. and from the proposed

Alaska Highway-Dempster Highway pipeline routes.

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