GEOTECHNICAL STUDIES OF PERMAFROST, FORT GOOD HOPE-NORMAN WELLS REGION

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GEOTECHNICAL STUDIES OF PERMAFROST IN THE FORT GOOD HOPE-NORMAN WELLS REGION, N.W.T.

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The data for this report were obtained in part as a result of investigations carried out under the Environmental-Social Program, Northern Pipelines, of the Task Force on Northern Oil Development, Government of Canada. While the studies and investigations were initiated to provide information necessary for the assessment of pipeline proposals, the knowledge gained is equally useful in planning and assessing highways and other development projects.

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1. SUMMARY

Three terrain types, glacial tills, alluvial, and glaciolacustrine deposits, which have been classified principally on the basis of their genesis, morphology, and constituent materials, have been investigated and each map-unit has been found to be variable with respect to soil types. Considerable ice (>20%) was found in each of these units, particularly in the alluvial and glaciolacustrine deposits; high ice contents in the tills were restricted to the upper 5 metres (16 feet). Burial of a hot pipeline, therefore, is considered inadvisable in the alluvial and glaciolacustrine deposits and in most areas with till deposits; burial of a chilled gas pipeline may be acceptable depending on the topography, time of construction, moisture supply, and the time interval between construction and the beginning of transmission of chilled gas.

Due to recent climatic trends, ground temperatures in the upper tens of metres generally were warmer than expected from records of temperatures at depth, but permafrost was found at every drilling location except in disturbed or recently infilled areas. Limited data indicate that thermal conductivity values of permafrost samples vary anomalously with moisture content and are generally quite low. As anticipated, considerable proportions of the moisture in fine-grained frozen soils exist in the liquid phase even at fairly low temperatures, reducing the amount of heat required to cause thawing.

Even when the above factors are taken into consideration, the finite element program, developed by the Computer Science Centre (Department of Energy, Mines and Resources) and based on the assumption that heat transfer may occur by conduction only, underestimated the considerable depths of thaw that could be generated by the change in the mean annual ground surface temperature due to construction of a road. The hypothesis was developed, therefore, that heat transfer by convection into the permafrost was possible, considerably increasing the rate of thaw. The implications of greater settlement and risk of instability are pointed out. Considerable additional research in specific areas is recommended, in particular, the rate of thaw beneath roads constructed on permafrost and the effect of thawing and consolidation on shear strength.

2. INTRODUCTION

2.1 GENERAL NATURE AND SCOPE OF STUDY

"Permafrost, or perennially frozen ground, is defined exclusively on the basis of temperature and refers to the thermal condition of earth materials such as soil and rock when their temperature remains below 32°F continuously for a number of years. Permafrost

> includes ground which freezes in one winter, remains frozen through the following summer and into the next winter. This is the minimum limit for the duration of permafrost." (Permafrost Map of Canada, 1967).

Any changes to the existing thermal regime brought about by engineering activities or by climatic changes cause changes to the ice-water proportions of frozen soils, and in certain cases affect the physical behaviour of the soils and the stability and integrity of engineering structures or slopes.

The basis of the project is the study of permafrost in its natural state so as to explain its present behaviour, and by observing its response when subjected to field disturbances and laboratory tests, to develop a rational quantitative method of predicting permafrost behaviour when affected by engineering construction or other changes in conditions.

2.2 SPECIAL OBJECTIVES

These include:

(a) the characterization, in engineering and cryogenic terms, of the principal soils that comprise the main terrain units which have been classified principally on the basis of their genesis and morphology;

(b) the relation of standard index properties of soils to their thermal parameters of conductivity and diffusivity with the intention of developing a method of deducing thermal behaviour of soils from standard engineering tests;

(c) the development of mathematical models relating engineering performance of the terrain to properties of the soil material.

2.3 GENERAL RELATIONSHIP TO PIPELINE DEVELOPMENT

2.3.1 Problems Associated with Pipeline Development

Changes to existing thermal regimes will be the prime cause of engineering geology problems connected with pipeline construction and integrity. These changes will be the result of investigation and construction activities and of pipeline operating temperatures (Lachenbruch, 1970; Isaacs and Code, 1972).

2.3.1.1 Investigation and Construction activities

The initial changes caused by investigation and construction can be divided into three classes: (a) changes in the vegetation cover, (b) changes in local relief, and (c) changes in drainage.

The first of these, changes in the vegetation cover, is associated with removal of timber and removal of or damage to the moss or tundra mat, including damage caused by vehicular movements. Vegetation removal or damage permits an increase in incident solar radiation, a change in albedo or reflectivity of the surface, and alterations in: (a) the thermal conductivity and diffusivity of the tundra mat by compressing or damaging it, (b) the rate of evapotranspiration, (c) the accumulation of snow, (d) drainage patterns, and possibly in (d) evaporation due to shifts in wind directions.

The overall effect of vegetation cover removal or damage is to produce an increase in mean annual ground surface temperature resulting in a deeper active layer and in some cases, massive or complete degradation of the permafrost. This may be accompanied by settlement, ponding, and erosion, with the degree of damage being a function of temperature increase, existing thermal regime, soil type, moisture content including ground ice content, shape of the thawed zone, topography, and rate of vegetation regeneration.

Changes in local relief such as those caused by grading, excavating, embankment, and road or airfield construction may be accompanied by changes in exposure affecting incident radiation, snow accumulation, drainage, and possibly air currents affecting evaporation.

The effects of alterations to local relief are functions of the type, orientation, and extent of the activity, changes in the mean annual ground surface temperature, soil type, moisture content, existing thermal regime, and geographic location. As road building entails the removal of trees and the removal or covering over of the moss or tundra mat with granular fill, the main effect is similar to that outlined above for vegetation cover damage.

Changes in surface drainage may result from changes in vegetation and local relief and from the effects of changes in the mean annual ground surface temperature and of pipeline temperatures. Draining existing ponds or intercepting existing drainage systems changes the hydrologic regime in the area, may cause erosional problems, and affects the thermal regime. Ponding of water results in an increase in absorption of solar radiation, increases the temperatures in the underlying soil, and may cause thawing of the frozen banks and of the underlying permafrost.

2.3.1.2 Pipeline temperatures

The first comprehensive treatment of the possible thermal effects of a heated pipeline in permafrost was published by Lachenbruch (1970) and is the basis for most of the following comments:

(a) If heat transfer by convection occurs, the amount of thaw incurred will be several times that calculated using the conductive theory only.

(b) If the sediments possess excess ice and, when thawed, low hydraulic conductivity (permeability), a semi-liquid slurry may form which could exist for years. Because of the slow dissipation of pore pressure, shear strengths could be low and depending on the slope of the hill and the dimensions of the thawed volume, could permit flow downhill, thus endangering the pipeline.

The pipeline may settle considerably if the shear strength of the thawed soil is sufficiently low. Downward movement of the pipeline will, of course, increase the rate of thaw.

(c) Differential settlement of the pipeline may occur under several conditions: (1) where the pipeline passes from a "stiff" material into a thawed slurry, (2) where lateral differences in porosity, moisture content, and thawed shear strength exist, and (3) where the pipeline passes across ice wedges or masses which thaw at different rates than the surrounding sediments.

Depending on the amount of differential settlement and the length of pipeline over which it occurs, severe stresses may occur in the pipeline.

(d) Where the pipeline crosses saturated or oversaturated sediments, a depression will form over the pipeline. If the depression is discontinuous, a series of ponds may develop which could, by increased absorption of solar radiation, enlarge their banks by thawing the ice-rich permafrost. Draining these ponds may remove the buoyant forces on the pipeline and possibly lead to severe stresses. If the depression is continuous a stream channel could develop, altering the drainage and hydrologic regime of the surrounding area. Erosional problems also may occur.

(e) Loosely packed, saturated sands and silts, either occurring naturally or developing due to thawing, may liquefy when subjected to natural or man-made vibrations.

(f) Heat from the pipeline may affect the surface and plant-root temperatures over a limited width, may reduce drastically the accumulation of snow, and may cause local ground fog to form. Depending on the inflow of water and the permeability of the overlying sediment, the depression that may form over the pipeline may be wet or very dry.

Operation of a chilled gas pipeline below $0^{\circ}C$ could cause problems of a different type:

(a) The pipeline may act as a focus for the growth of ice lenses, depending on the soil type in which it is embedded and the availability of moisture. This may result in a jacking action on the pipeline as well as the creation of a barrier to groundwater flow. The barrier could modify the hydrologic regime in the area and perhaps cause a serious ground-icing problem in the winter and ponding and thawing in the summer.

(b) A chilled pipeline may cause freezing and damming of effluent groundwater which is necessary for the spawning of certain species of fish.

(c) The low temperatures of such a pipeline may result in restricted stream flow developing at underwater crossings of shallow rivers.

(d) Restriction of the active layer to less than 30 cm (12 inches) will affect plant life adversely (Bliss and Wein, 1972)

2.3.2 Research into the Problems

The engineering behaviour of frozen ground cannot be divorced from its thermal behaviour. It is essential, therefore, to understand the thermal processes involved in determining the present state of the frozen ground and that which may occur when any of the operating conditions are changed significantly. Present research, therefore, has been concentrated predominantly on the thermal aspects of the engineering behaviour of frozen ground.

A quantitative approach is being taken in assessing the significance of these problems and in attempting their solution. To meet the special objectives listed above, the following information is being collected: (a) type and extent of vegetation, (b) soil type and properties, viz. grading, Atterberg limits, bulk density, specific gravity, (c) volumetric specific heat (volumetric thermal capacity) of frozen and unfrozen permafrost samples at various temperatures, (d) total moisture content and percentages of frozen and unfrozen water content at various temperatures, (e) thermal conductivity and diffusivity at various temperatures, and (f) thermal profiles, mean annual ground surface temperatures, and amplitudes of the annual temperature waves.

The significance and contribution of the above data to the behaviour of permafrost are explained in the various corresponding sections of the paper. Technical terms and ice-content rating adopted are defined in the Glossary.

3. CURRENT STATE OF KNOWLEDGE

In late 1970 when the project was initiated, systematic mapping of surficial geology and landforms in the Mackenzie Valley was in progress (Hughes, 1970). No data were available linking thermal properties to soil type, water content, and temperature for the terrain units. Little information was available on mean annual ground surface temperatures and thermal profiles; only a limited amount of data had been collected on the engineering index properties.

As data on the thermal conductivity of permafrost soils, either frozen or thawed, are not available, much less linked to the terrain units in the Mackenzie Valley, users generally are obliged to estimate values from results obtained from other soils (Kersten, 1949; Higashi, 1952; Penner, 1962, 1970; de Vries, 1963).

The current approach is to use thermal properties from Kersten's publication (Kersten, 1949), dealing with a very limited number of soils which were compacted mechanically at various moisture contents and frozen in the laboratory. A few measurements of thermal properties of permafrost have been made in the last two years (Watson *et al.*, 1973), but there has been no systematic approach linking thermal and engineering properties to the existing terrain units.

Some engineers (Speer *et al.*, 1973) have attempted to link settlement resulting from thawing to frozen bulk densities, but the data show a high degree of scatter (Fig. 1).

4. STUDY AREA

The Fort Good Hope-Norman Wells area was chosen for this research because a wide variety of terrain types exists in this region. The work was concentrated in two physiographic divisions of the Fort Good Hope area, namely the Anderson and Peel Plains (Fig. 2), and in the corresponding physiographic division of the Norman Wells area, the Mackenzie Plain.

The Anderson and Peel Plains are characterized principally by flat, featureless plains of glaciolacustrine sediments or thin morainal till. A considerable percentage of the former is covered by many closely-grouped small lakes and traversed by river channels and erosional gullies. Large complex glaciofluvial deposits exist near the mouths of the Mountain and Hare Indian Rivers. A large esker of coarse sand and gravel is situated northeast of Fort Good Hope between eolian deposits of fine sand and silt. Bedrock consists of nearly flat-lying or gently folded Devonian limestones and shales and Cretaceous sandstones and shales.

The Mackenzie Plain comprises deposits of morainal till, glaciolacustrine sands, silts and clays, glaciofluvial sands and gravels, and eskers. Fluvial reworking of some of these deposits has produced fans, terraces, and plains; eolian activity has resulted in dunes of fine and medium sand. Underlying bedrock consists predominantly of Devonian shales and sandstones on the east side of the Mackenzie River and Cretaceous shales on the west side.

The study area is approximately 200 km (125 miles) by 100 km (60 miles) and is depicted as being in the zone of discontinuous permafrost (Permafrost Map of Canada, 1967). The amount, form, and distribution of ground ice were expected to vary considerably with soil type, location, relief, vegetation, and ground temperature. Ground temperature and permafrost thickness were considered to be functions of air temperature, soil type, vegetation cover, proximity to rivers or lakes, and exposure to climatic influences.

5. METHODS AND SOURCES OF DATA

As the information available was not of the quantity nor the quality necessary and was not linked to the terrain units, it was necessary to devise field programs which would enable the collection of these data. To link the data to the terrain unit, drilling was necessary. The need to measure thermal parameters of the permafrost soils and to obtain ground temperatures and thermal profiles in a permafrost environment meant that special drilling techniques had to be devised. Frozen core had to be obtained with the minimum possible physical and thermal disturbance and the drill holes had to have minimum thermal disturbance so as to allow the temperatures in the boreholes to approach equilibrium as quickly as possible.

5.1. FIELD TECHNIQUES

5.1.1 Methods of drilling successfully in permafrost for the recovery of frozen core, in both summer and winter, have been developed and reported elsewhere (Isaacs and Code, 1972; Isaacs, 1973). Frozen permafrost core can be brought to the laboratories at Ottawa with negligible changes in core temperature (Isaacs, 1973).

5.1.2 Determinations of index and thermal properties of frozen permafrost core were made in a field laboratory in Fort Good Hope and have been described elsewhere (Isaacs and Code, 1972; Judge, 1972; Lawrence, 1972).

5.1.3 Multi-thermistor cables were installed in boreholes to obtain mean annual ground temperatures, thermal profiles, and in situ thermal properties (Isaacs and Code, 1972).

5.2 EXPERIMENTAL TECHNIQUES

5.2.1 Laboratory determinations of thermal conductivity and diffusivity were carried out by the Earth Physics Branch, Department of Energy, Mines and Resources.

A limited number of thermal conductivity values for different soils at various moisture contents and at approximately the same temperature has been obtained using "divided-bar" and "needle-probe" equipment in the field laboratory at Fort Good Hope.

The "divided-bar" method has been described by Judge (1972) and consists essentially of measuring the thermal gradient across a soil sample and obtaining the thermal conductivity of the sample by comparing the gradient across the sample to the gradient across the fused silica discs of known conductivity at the ends of the sample. Each sample must be allowed to reach equilibrium before measurements are made and the entire system must be mounted in an environmental chamber with accurate temperature control.

The "needle-probe" equipment is essentially a miniature version of that described by Lachenbruch (1957). A small diameter hole was drilled about three inches deep into the soil sample using a high speed (30,000 rpm) Dremel Moto Tool and the probe inserted. The probe consisted of a metal tube sealed at one end with an axial heater element and a thermistor placed about mid-way along the long axis of the tube. When the probe thermistor indicated equilibrium between the sample and the probe, current was passed continuously through the filament. The temperature increase, measured by the thermistor, was recorded as well as the corresponding time intervals from the start of heat generation. Thermal conductivity and diffusivity can be obtained from the data (Lachenbruch, 1957).

There are advantages and disadvantages to both methods. Soil samples, particularly clays, may take substantial times to achieve equilibrium gradients with the "divided-bar" equipment and in practice, it has been difficult to limit the temperature difference between the ends of the samples. On the other hand, the temperature rise in the transient "needle-probe" method involves a latent heat component particularly between -2.5° and $0^{\circ}C$. To limit the temperature rise so as to restrict the latent heat factor, this equipment was modified to allow the current to be measured more accurately and hence to be maintained at a smaller value.

Currently, the thermal conductivities of permafrost samples brought back to Ottawa are being determined for a variety of soil types and moisture contents, using mainly the "divided-bar" equipment installed in a cold room. The variation of conductivity with temperature is also being investigated.

5.2.2 In situ Thermal Diffusivities

Multi-thermistor cables, installed in some twenty diesel-fuel filled boreholes are being read at frequent intervals using a Wheatstone bridge that was specially designed by the Earth Physics Branch to limit the heat dissipated in the thermistor to ten microwatts. The associated low current avoids problems of self-heating and changes in calibration caused by higher current flows.

The variations of temperatures with time at various depths in each borehole are calculated from the readings. The temperature waves at ground surface are, at depth, attenuated in amplitude and modified with respect to phase due to the thermal properties of the soil. A knowledge of the temperature fluctuations throughout the borehole, therefore, may be used to calculate "apparent in situ diffusivities".

5.2.3 Laboratory Determinations of Volumetric Specific Heat and Unfrozen Water Contents

Volumetric specific heats, which may be used in conjunction with thermal conductivity values to calculate thermal diffusivities, and unfrozen water contents of permafrost samples currently are being determined using a calorimetric method. The temperature range being investigated is from -8^{0} to $+1^{0}$C. Permafrost samples are immersed in a silicone fluid at -8^{0}C in a bucket of an adiabatic calorimeter and measured quantity of heat, in known increments, is put into the silicone. From the rises in temperature of the silicone and core, over the above range, specific heats and unfrozen water contents are calculated.

Heat transfer from the bucket to its surroundings is practically eliminated by automatic controls on the calorimeter which keep the temperature of the surrounding jacket very close to that of the bucket. To allow these controls to function, warm and cold supplies of a circulating fluid must be maintained to the jacket throughout the entire experiment, about 200 hours. A system had to be devised that would do this automatically in the demanding conditions of the cold room where the experiment must be conducted. The experimental equipment and procedure are described fully elsewhere (Isaacs and Desai, in preparation).

5.2.4 Index Properties

A considerable number of determinations of engineering index properties, viz. Atterberg limits, grain size distributions, moisture contents, specific gravities, dry densities, etc. were done on core and chip samples; also, a number of mineralogical determinations were done on selected samples by x-ray diffraction.

5.2.5 Ground Temperatures

The data currently being used to obtain values of "in situ diffusivities" also are being employed to develop the thermal profiles of the terrain units and to obtain mean annual ground surface temperature values in a variety of undisturbed and disturbed areas.

5.3 DATA ANALYSIS

5.3.1. Laboratory Values of Thermal Conductivity and Diffusivity

To date, thirty values of thermal conductivity of samples with known water contents and grain size distributions have been received from the Earth Physics Branch. These correspond to the same approximate temperature (-5.5°C). Table I shows the values of conductivity, related moisture contents and grain sizes as well as estimates of the corresponding Atterberg limits and activities. Additional data, as yet incomplete, are shown in Table II. No laboratory values of thermal diffusivity are available.

Mineralogical identifications indicate that the composition of the clay minerals is constant with respect to type and percentage. Groupings of thermal conductivity values with their corresponding water contents have been made on the basis of grain sizes, Atterberg limits, and activities (Appendix II).

5.3.2 In situ thermal diffusivities

A computer program, code-named DIFF, for the calculation of thermal diffusivity from temperature data collected over a considerable length of time was constructed by I. Crain of the Computer Science Centre, Department of Energy, Mines and Resources. It is based on an iterative method of fitting a chosen diffusivity to the equations (Carslaw and Jaeger, 1959; Crain, 1967), and by the method of least squares, comparing the calculated temperature curves for fit, in both amplitude and phase, to the actual smoothed temperature curves. The program then indicates whether a greater or smaller diffusivity should be tried. The Powell (1964) method of steepest descent for non-linear least squares is used for more efficient utilization of computer time.

The data from the Fort Good Hope boreholes, which were collected over a period of about 18 months, were used to calculate preliminary values of "in situ diffusivities" corresponding to known depths and thicknesses of soil over particular temperature ranges. In the case of certain soils and temperature ranges, these values, of necessity, will incorporate a latent heat term. In most cases extension of these values to other temperature ranges is dependent on the derivation of calculated values of thermal diffusivity from laboratory tests of thermal conductivity and volumetric specific heat proving correspondence with the in situ values over their temperature ranges.

5.3.3 Laboratory Values of Volumetric Specific Heats and Unfrozen Water Contents

Development of the equipment and operational technique has taken about a year, beginning in December 1971, and tests on five samples currently are complete. The volumetric specific heats of samples above $0^{\circ}C$ were calculated based on the following assumptions:

(a) no ice exists at temperatures greater that $0^{\circ}C$

(b) the latent heat of fusion of water is 79.68 calories per gram throughout the test range of temperature

(c) the heat capacity values of all the sample components and their temperature coefficients are known

(d) during thawing, the only process that involves a heat effect is the absorption of the latent heat of melting.

A computer program has been written which, from the raw experimental data, calculates and plots the following if required:

(a) variation of apparent volumetric specific heat with temperature

(b) variation of true volumetric specific heat with temperature

(c) variation of apparent specific heat (thermal capacity) with temperature

(d) variation with temperature of unfrozen water as a percentage of dry weight

(e) variation with temperature of unfrozen water as a percentage of total water content

(f) variation of cumulative volumetric heat with temperature

(g) variation of cumulative volumetric latent heat with temperature

Some of the curves derived from the data may be used as input into the finite element program that was developed to investigate theoretically the thermal degradation of permafrost caused by engineering activities (Section 6.6). Other data, in particular the variation of unfrozen water content with negative Centigrade temperatures, are discussed later.

5.3.4 Index Properties

Engineering classification of the soils was made on the basis of grain size distributions and Atterberg limits. Soils in each borehole are shown in the borehole logs which were constructed according to the unified Soil Classification System; Atterberg limits, moisture contents, and other data are shown graphically beside the soil and ice logs (Appendix I). The latter have been compiled according to the NRC/CRREL Technical Memorandum #79 (Pihlainen and Johnston, 1963).

The data for boreholes drilled near Fort Good Hope in 1971 (Fig. 3) and for those near Norman Wells in 1972 (Fig. 4) are shown in Appendix 1.

5.3.5 Ground Temperatures

The thermistor cables in the boreholes drilled with chilled fluids in 1971 have been read on a regular basis since December 1971; those in the Norman Wells region, which were put down in the spring of 1972, have been monitored since July of that year. As of July 1973, therefore, between 12 and 19 months of temperature data are available for analysis.

Plotting of the monthly data for the 1971 boreholes, particularly for borehole DH-1-71, indicated that the permafrost in the upper 20 metres (55 feet) may be considerably warmer than the temperatures at depth implied (Fig. 5). The mean annual temperature at each thermistor level was calculated and annual temperature profiles for each borehole were constructed (Figs. 6, 8, 9, 10). In cases where there were no thermistors at ground surface, extension of these profiles to the surface yielded approximate values of recent annual ground surface temperatures.

6. DISCUSSION OF RESULTS

6.1 DISTRIBUTION OF SOIL TYPES AND GROUND ICE IN TERRAIN UNITS

6.1.1 Glacial Till

The following boreholes were drilled in glacial till units:

SS-2-71, WD-4-71, WD-5-71, WD-11-71, DH-2-71, R-1, MV, SD, and 7B (see Figs. 3, 4, and Appendix I for explanation of terminology).

The following are tentative conclusions based on the data from these holes:

(a) The tills in the Fort Good Hope area appear to be considerably coarser than the tills close to Sans Sault Rapids, that is, on the south side of the glaciolacustrine deposit.

(b) For the Fort Good Hope tills, the more clayey zones which occur near the surface exhibit the Vr type of ice while the ice in the coarser zones containing GM, SP, and GP soils was classified as being of the Nbn type. Excess ice (not visible) was present to about the 4-metre (13-foot) depth in the more clayey soils. Peat cover for the borehole on the east side of the Mackenzie River was very thin but was moderately thick at the drill site on the west side.

(c) Peat cover in the boreholes near Sans Sault Rapids varied from 30 to 180 cm (1 to 6 feet). In each case there was a 60 to 170 cm (2 to 5.5 foot) thick layer with considerable visible ice beneath. Below this organic zone, the soils were generally clays or clayey and ice type varied from Ice and Soil through the entire range to Nf. High ice concentrations (>20%), however, appear limited to the upper 5 metres (16 feet).

(d) Two boreholes, MV and 7B, were located in glacial till on the east side of the Mackenzie River in the Norman Wells area. There were two others, similarly located on the west side, but one of these was in the thawed zone beneath the Canol Road. As all these holes were drilled primarily by chip drilling, permafrost ice types could not be identified correctly and ice-type logs could not be constructed.

Generally the tills on both sides of the Mackenzie River in this region appear to consist predominantly of clays and silts with some gravel. At borehole 7B, however, beneath 3 metres (10 feet) of a highly plastic clay, there was considerably more sand and gravel in the silt till than at other locations. As shown in the boreholes, the depth to the shale bedrock underlying the till on the east side varied from 6 to 7 metres (20 to 25 feet).

From field observations, the organic silts and clays near the surface and the soils immediately beneath contained considerable ice. During drilling substantial ice was observed to a depth of about 3 metres (10 feet).

(e) In the tills of the Norman Wells, Sans Sault Rapids, and Fort Good Hope areas, the moisture contents below the 5-metre (15-foot) depth were commonly low, in the order of 15-20% in clayey soils and less in more granular soils.

In summary, the soil types within the tills are variable in the study area but appear to be more clayey in the Sans Sault Rapids and Norman Wells regions than near Fort Good Hope. Considerable ice may be encountered in the upper 5 metres (15 feet), particularly if there are upper layers of organic silts and clays, and even more so if there is considerable peat cover. Beneath the 5-metre (15-foot) depth, the moisture contents are low, generally less than 20%, and ice normally occurs as thin partings, individual ice inclusions, or is not visible.

Additional information from drilling done in 1973 (P.J. Kurfurst, pers. comm., 1974) indicates that areas of till may exist between Tsintu River and Fort Good Hope and between Snafu Creek and Chick Lake (Fig. 3) where the upper 3 to 3.5 metres (10 to 12 feet) consist of a silt or silty sand and possess very low ground-ice contents (<10%).

6.1.2 Alluvial Deposits

The following boreholes were drilled in alluvial deposits commonly overlying glaciolacustrine deposits:

SS-4-71, SS-5-71, SS-6-71, SS-7-71, SS-8-71, SS-9-71, DH-3-71, 7D (see Figs. 3, 4, and Appendix I).

On the basis of information from these boreholes, the following tentative conclusions were drawn:

(a) Peat cover varied from nil, as in the case of a recent infilling of a lake (SS-9-71), to 180 cm (6 feet).

(b) Generally soils of the CL or OH type overlay coarser-grained soils; these clays, immediately below the peat cover, commonly possessed considerable ice (>20%) as do coarser silty soils.

(c) The void spaces in the alluvial terrace gravels (DH-3-71) appeared to be completely filled with ice.

(d) In SM type soils, ice commonly was of the Nbn or Vr type while in CL or OH soil types, it was Nbe, Vr, Vs, or Ice and Soil.

(e) Excess ice (not visible) was logged as occurring to the 5-metre (15-foot) level but may occur to greater depths; the log for DH-3-71 shows moisture contents greater than the liquid limit at the 11-metre (35-foot) depth.

In conclusion, therefore, in alluvial deposits there are usually layers of clay (CL or OH), generally with considerable ice (>20%), overlying coarser-grained deposits (SM, SP-SM, SP, GW, GP, ML). If the underlying soils are silty, they will have much excess ice, but moisture contents (non-visible ice) greater than the liquid limit may be possible at depths to 11 metres (35 feet) in the clays beneath the coarser-grained deposits.

6.1.3 Glaciofluvial Deposits

Only one borehole, SS-3-71 (Appendix 1 and Fig. 3), drilled to a depth of 2.5 m (8 feet), was in a deposit classified as glaciofluvial. As the vegetation was badly damaged by fire and as drilling occurred quite late in the year, no permafrost was detected in the hole.

Due to disturbance, any permafrost would have been quite warm; since the soil beneath the shallow, clayey silt cover was a gravel-sand-silt mixture, moisture contents probably would have been quite low. If permafrost were present, the ice-type probably would have been Nf and difficult to detect under these conditions.

6.1.4 Glaciolacustrine Deposits

6.1.4.1 The following boreholes were put down in glaciolacustrine deposits in the Sans Sault Rapids-Fort Good hope areas:

SS-1-71, WD-1-71, WD-2-71, WD-3-71, WD-6-71, WD-7-71, WD-8-71, WD-9-71, WD-10-71, DH-1-71, DH-4-71 (see Fig. 3 and Appendix 1).

A survey of the drill logs indicates that these deposits are variable in texture and consist of silty sands, clayey sands, silts, clays of low to medium plasticity, clays of high plasticity, or any combination of the above. Borehole WD-8-71 was located in silts and clays of low to medium plasticity, while borehole DH-4-71, situated only 50 metres (160 feet) away, below the 2-metre (6-foot) depth was in a sequence of clays of high plasticity and of low to medium plasticity. The occurrence of ice also varied from almost no ice being visible until the 8 metre (25 foot) depth in WD-8-71 to considerable ice (>20%) being present throughout in DH-4-71.

The amount of ice in DH-4-71 and in other boreholes such as WD-6-71 and WD-9-71 is difficult to explain if they are considered to be representative of the terrain in which they are drilled. As WD-8-71 was so close to DH-4-71 and yet so different in soil type and ice content, it seems reasonable to assume that the moisture at DH-4-71 and similar boreholes was extracted from the surrounding soils; this is a localized occurrence and probably due to different rates of freezing. The mechanism of this hypothesis is not understood fully as yet.

A study of the borehole logs indicates that excess ice (non-visible) may occur even to the 27-metre (90-foot) depth, and moisture contents greater than the liquid limits may exist as deep as the 20-metre (65-foot) level.

Thicknesses of peat at boreholes varied from zero to about three metres (10 feet) and in certain cases were intermixed with silt. Moisture contents in the peat were very high as was expected, and ice types ranged from Nbn to Vs.

Most of the clays in this area are of low to medium plasticity, the exception being at DH-4-71 where considerable clay of the CH type is present. The assumption cannot be made, however, that the quantity of ice at DH-4-71 results from the presence of highly plastic clay for several boreholes with CL type clay possessed even more ice.

As the activity of a soil (i.e., the ratio of the plasticity index to the clay fraction expressed as the per cent dry weight of the less than 2μ fraction) bears a general correlation to the clay-mineral composition (Gillot, 1968), it has been used as one of the criteria for soil comparison in the discussion of thermal properties. X-ray diffraction results indicate that the proportion of the clay mineral types for these soils is fairly constant at about 53% illite and 47% chlorite. The scatter in the activities therefore is probably indicative of the varying quantities of non-clay minerals present in the clay-size range.

In summary, the glaciolacustrine deposits of the Sans Sault Rapids-Fort Good Hope areas are variable as to soil type, ground cover thickness, and amount of ice present. While it is thought that local variations in ice contents may be functions of differential rates of freezing as well as of soil types and initial moisture contents, presently available information is insufficient to substantiate this hypothesis.

Excess ice (non-visible) and moisture contents greater than the liquid limits may occur at considerably greater depths in other terrain type soils.

6.1.4.2 In the Norman Wells area, the following holes were drilled in glaciolacustrine deposits:

CCU, SA , GL2U, GL1, TL (See Fig. 4 and Appendix I)

Borehole CCU was drilled in a disturbed area. At both CCU and TL chip drilling was the main method of advancing the boreholes. From the limited data, the following tentative conclusions have been drawn:

(a) Peat cover may be quite variable if no distinction is made between swampy areas such as SA and areas at other boreholes. Outside of swampy areas the peat cover was found to be less than 30 cm (12 inches).

(b) The glaciolacustrine deposits at CCU, which consist of fine sand and silty sand, can be delineated from aerial photographs.

(c) Boreholes TL, GL1, and GL2U are located in terrain units classified as glaciolacustrine deposits of silt and clay. Drilling results generally agreed with the classification but at GL1 detected a layer of sand, approximately 3 metres (10 feet) thick, immediately below the peat cover. The majority of the clay found in these boreholes is of high plasticity in contrast to clays in similar deposits in the Sans Sault Rapids-Fort Good Hope area. In TL and GL2U, there was an organic silt or clay layer about 1.5 metres (5 feet) thick just below the peat cover.

(d) The deposits at SA consisted of clays and clayey silts beneath substantial peat cover. Immediately below the peat, the soil was an organic clay of high plasticity similar to that at TL.

(e) Ice type varied with the boreholes but two of the boreholes in frozen ground, GL1 and TL, indicated that ice was mainly of the Vr type. At GL2U, however, considerable quantities of Nbn, Nbe, Vs, and Ice and Soil types were logged. In this borehole also, very high water contents were found in clay samples exhibiting no visible ice as deep as 13 metres (43 feet). In the other boreholes, high moisture contents of soil samples with no visible ice were not recorded below the upper four metres (13 feet).

From the very limited data, it appears that these deposits generally consist of clays of high plasticity with an organic silt or clay layer immediately below thin peat cover. In place of this organic silt or clay, however, a veneer of fine sand and silty sand may exist.

Ice types varied from Nf to Ice and Soil but the boreholes were too few in number to draw any conclusions regarding the main ice type. Very high water contents, as deep as 13 metres (42 feet) in one borehole, were found in samples exhibiting no visible ice. High water contents, other than in visible ice, appeared in the upper four metres (13 feet) in the other boreholes.

6.1.5 Summary and Conclusions

6.1.5.1 Glacial Tills

The tills may consist of gravels, sands, silts, clays, or mixtures of these, but generally they appear to be more clayey in the Sans Sault Rapids and Norman Wells regions than in the Fort Good Hope area. High ice content (>20%) may be visible in the upper 5 metres (15 feet), but the moisture contents are commonly quite low below this depth (15 to 20% in clayey soil and less in the more granular soils). Below the 5-metre (15-foot) depth, only small amounts of ice (<10%) are visible.

6.1.5.2 Alluvial Deposits

These deposits may be clays, silts, sands, gravels, or combinations of these soils. Considerable ice (>20%) commonly occurs near the surface. Moisture contents greater than the liquid limit may be encountered at depths up to 11 metres (35 feet) in clays underlying the coarser deposits.

6.1.5.3 Glaciolacustrine Deposits

(a) In the Sans Sault Rapids-Fort Good Hope area, these may consist of silty sands, clayey sands, silts, clays of low to medium plasticity, clays of high plasticity, or any combination of the above. Ground cover thickness (peat varies from 0 to 3 metres (0 to 10 feet)) and visible ice contents vary from negligible to greater than 20%. Non-visible excess ice and moisture contents greater than the liquid limits may occur at considerably greater depths (27 metres (90 feet), 20 metres (65 feet) respectively) than have been found in other terrain types.

(b) In the Norman Wells region peat cover is generally less than 30 cm (12 inches) except in swampy areas. The soils may be sands or more commonly, silts or clays. Clays in these deposits are generally of high plasticity in contrast to the clays in the Sans Sault Rapids-Fort Good Hope area. Ice types varied from Nf to Ice and Soil, and visible ice contents ranged from low (<10%) to considerable (>20%). In one borehole very high water contents were found at depth in samples exhibiting no visible ice. In the other boreholes, however, high water contents other than in visible ice appeared limited to the upper four metres (13 feet).

6.1.5.4 Glacial tills above the 5-metre (15-foot) depth and alluvial and glaciolacustrine deposits throughout their depths will present serious problems of settlement and stability if allowed to thaw.

6.2 GROUND TEMPERATURES

Permafrost or perennially frozen ground is defined solely on the basis of temperature, and it is not always possible to determine by drilling whether the ground is frozen. The presence and extent of permafrost sometimes may be defined only by temperature measurements. The engineering behaviour of permafrost is not only a function of its temperature being at $0^{o}C$ or less but also of how much lower than $0^{o}C$ its temperature is. This is particularly true of clays where the percentage of unfrozen water to total water content changes most rapidly between $-2.5^{o}C$ and $0^{o}C$. It is important, therefore, to know not only that permafrost is present but also what are the temperatures and how they vary with time. As will be shown later, permafrost is in a non-equilibrium state even when undisturbed by man and in order to predict the effects of engineering activities, it is essential that present conditions and the ongoing processes are understood.

The factors affecting permafrost are described below and temperature records from a number of boreholes in the Fort Good Hope-Norman Wells region are discussed in detail. Variations in thermal profiles and temperature ranges may be seen as well as responses to climatic changes which are present in practically every borehole to a greater or lesser degree, depending on the soil type, amount and distribution of moisture and vegetation cover.

6.2.1 Thermal Considerations

If the mean annual ground surface temperature were held constant for a sufficient length of time so that equilibrium conditions could be established, the depth of permafrost would be a function of the mean annual ground surface temperature, the heat flow from the earth, and the average thermal conductivity of the earth materials.

For the usual state of a varying mean annual ground surface temperature, non-equilibrium conditions prevail and permafrost temperatures, particularly in the upper 30 metres (100 feet) constantly are adjusting to those variations. The response of the permafrost is a function not only of the mean annual ground surface temperature, initial temperature, and heat flow from the earth but also of the thermal diffusivity and latent heat to be removed or added. In the temperature range of $-2.5^{o}C$ to $0^{o}C$ the most important factor is the latent heat involved in the temperature change.

6.2.2 Climate

Climate is the principal factor affecting the formation and existence of permafrost. Past climate, primarily the climate of several thousands of years ago, was responsible for the formation of permafrost. Present climate affects the existing permafrost but its effect is modified greatly by vegetation. The removal of this vegetation, particularly in the Fort Good Hope-Norman Wells area, can cause severe regression of permafrost.

The three main factors of climate which affect the mean annual ground surface temperature are mean annual air temperature, snow cover, and incident solar radiation. It is the mean annual ground surface temperature which controls the aggradation or degradation of permafrost.

6.2.3 Terrain Factors

Vegetation, drainage, and snow cover are the most important terrain influences on permafrost; relief, soil and rock type are lesser factors affecting permafrost.

The presence of vegetation assists in the protection of permafrost by: (a) providing an insulating cover of moss, (b) restricting the amount of solar radiation incident at ground level by tree growth, (c) preventing the removal of snow cover by wind, and (d) cooling the ground surface in the growing season by evapotranspiration.

Poor drainage results in the formation of permanent and seasonal ponds and lakes. Depending on location and depth, these ponds and lakes, by increased absorption of solar radiation, may lead to the development of unfrozen zones beneath them even though they may be frozen to the bottom in the winter.

Snow cover affects heat transfer to the underlying ground because of albedo and insulating qualities. Melting of the snow in the spring, however, absorbs considerable amounts of heat. Substantial early snowfalls shield the underlying ground from subsequent colder air temperatures and may result in higher mean annual ground surface temperatures. Vegetation helps to prevent removal of snow by wind, thus exposed areas tend to be more affected by winter temperatures.

The three principal aspects of relief affecting permafrost temperatures are snow accumulation, slope orientation, and drainage. The effects of snow accumulation have been dealt with above. Incoming solar radiation on a south-facing slope is greater than on a north-facing slope, which tends to cause higher mean annual ground surface temperatures. A well-drained slope responds more quickly to changes in temperature as latent heat requirements are much less.

As mentioned in Section 6.2.1, under steady-state conditions for a constant heat flow from the earth and a constant mean annual ground surface temperature, the thickness of permafrost is governed by the thermal conductivity of the soil and rock materials. Near the surface where temperature fluctuates during the year and mean annual ground surface temperature is not constant, unsteady-state heat flow conditions prevail and the response of the earth material is controlled by its diffusivity, albedo, and latent heat demand. For the same vegetative cover, exposure, etc., the temperatures in the underlying soils and the depth of the active layer are functions of the above parameters. As an example, a high water content soil such as a clay generally will have a less deep active layer due to the damping effect of the latent heat required to produce changes in state.

6.2.4 Occurrence of Permafrost

The Fort Good Hope-Norman Wells area lies well south of the southern limit of continuous permafrost, as defined by the Permafrost Map of Canada (1967). However, in the boreholes drilled in this area in 1971, 1972, and 1973 and discussed below in this report and elsewhere (Isaacs and Code, 1972; Isaacs, 1972, 1973; Heginbottom and Kurfurst, 1973; Kurfurst and VanDine, 1973; Kurfurst *et al.*, 1973), in no case was permafrost absent except in disturbed areas and in a recently infilled lake. It appears highly probable, therefore, that in this region permafrost will be encountered everywhere except in disturbed areas or under lakes and rivers.

6.2.5 Thermal Profiles

6.2.5.1 Fort Good Hope

In the summer of 1971, four boreholes were drilled with chilled drilling fluids to depths ranging from 13 to 32 metres (40 feet to 105 feet). Multi-thermistor cables were installed in them and temperatures have been recorded at monthly intervals since December 1971. As the temperatures did not appear to attain equilibrium for several months, only the readings from the beginning of 1972 have been used.

Site DH-1-71

This borehole was situated on the east bank of the Mackenzie River behind an exposure of considerable reticulated ice in a glaciolacustrine deposit of sand, silt, and silty clay. The circulating fluid used in the drilling of this borehole was Therminol 55, an impure alkyl-benzene, reputedly possessing excellent heat-transfer properties at low temperatures. During drilling, it became obvious that Therminol was far from ideal as drilling with it proved difficult at temperatures close to 0°C (Isaacs and Code, 1972) and its use was discontinued. The borehole, however, was left filled with this fluid and it has since become apparent that the temperature wave from the ground surface is damped out by the fluid; thus, recorded temperatures do not vary much from the average temperatures.

The monthly temperatures for this drill hole (Fig. 5) indicate that the depth of permafrost is about 48 metres (160 feet). The projection of the thermal profile from depth toward the surface shows that the mean annual ground surface temperature corresponding to this gradient should be approximately -2.3°C.

As the monthly temperatures above the 21-metre (70-foot) depth plotted to the right of the projected gradient, the monthly variation in temperature of each thermistor was plotted and the mean annual temperature for that thermistor obtained. The divergence from the thermal profile AB, projected from the readings of the lower thermistors (Fig. 6), confirmed that the upper zone of the permafrost was warmer than expected. The portion of the curve CD is explained as the result of the warming trend occurring in the climate in this part of the northern hemisphere prior to 1943 (M.K. Thomas, pers. comm., 1973). The section DE similarly can be explained as a result of the cooling trend in the climate since 1943, and EF as a result of a local change in mean annual ground surface temperature due to a fire in 1969 and drilling operations in 1971. The drilling fluid used was Therminol which killed and blackened the vegetation in a 6-metre (20-foot) diameter circle about the borehole. There is a possibility that a fire in 1967 and possibly an unmapped earlier one have contributed to lessening the effect of the cooling trend shown by DE. The southwestern exposure of the site very likely also helped to negate the cooling trend.

Site DH-4-71

Located in a large area of many small lakes, this borehole intersected approximately 1.5 metres (5 feet) of silt and sand overlying clays of low to high plasticity. Considerable quantities of ice (>20%) were recorded over most of the depth.

Figures 7 and 8 were constructed similarly as for the borehole at DH-1-71. The same basic explanations apply for CD, DE, and EF of Figure 8 as those for Figure 6. The cooling trend is not very marked in this borehole, probably due to the lack of trees in the area about the drill hole. Presumably the effect on the mean annual ground surface temperature did not become significant until the fire in 1969 and the drilling operations in 1971, which are advanced as explanations for EF.

The wide variance in permafrost depth for almost identical values of B (projected mean annual ground surface temperature) partly is due to topographic differences and proximity of a large lake but mainly to the different thermal characteristics of the soils. This is borne out by the apparent greater response to the warming trend at DH-1-71, which also has the greater depth of permafrost.

Site DH-2-71

Six metres (20 feet) of a predominantly clayey till with low moisture contents overlie a shale bedrock as shown in the log of this borehole (Appendix 1). Figure 9 applies to this borehole and corresponds to Figure 6 of DH-1-71. Warming and cooling trends are pronounced, but the magnitude of warming is much less than shown in the previous two boreholes, probably because the upper metre (3 feet) of the overburden possesses a high moisture content (>100% by weight), mainly in the form of ice lenses. Presently an active layer is forming which is nearly one metre (3 feet) deep and which contains considerable water due to the melting of ice and the poor drainage of this flat-lying terrain. A great amount of heat is absorbed in the melting of the ice and as the thermal conductivity of water is one quarter that of ice, the amount of heat transmitted to the soil below is restricted. Because the till below the upper ice-rich zone has very low water contents (<20%), the thermal conductivities and diffusivities are relatively low and responses to temperature changes are poor.

The rapid response to a diminution in the mean annual ground surface temperature is rather surprising until it is remembered that the $0^{\circ}C$

isotherm could not have penetrated very far in the summer (less than one metre) because of latent heat requirements and that once frozen, ice is a much better conductor of heat than water is. Moreover, because of the openness of the site, snow cover is rarely thick and winter temperatures are not modified to the same extent as at other sites.

The warming due to the fire and drilling operations is not evident at the shallowest thermistor level (less than one metre (3 feet)), probably for the same reasons as mentioned above, that is, due to the amount of ice near the surface and thinness of the snow cover.

As the cable was damaged irrepairably below ground surface level in January 1973, presumably by the pressure exerted in the formation of ice in the drill hole, no further data can be collected from this site.

<u>Site DH-3-71</u>

Figure 10 indicates the mean annual temperatures existing in this borehole. As the thermistors could not be placed in the hole deeper than 12 metres (40 feet), the depth of permafrost cannot be ascertained with accuracy.

The borehole log (Appendix 1) shows that the upper 6 metres (20 feet) consists primarily of about one metre (3 feet) clay overlying approximately 5 metres (17 feet) of sands and gravels. All void space in the sands and gravels appeared to be filled with ice.

Where there is considerable ice in the form of lenses, visible ice in voids, etc. rather than bound in a clayey soil in a form which cannot be seen with the naked eye, there will be rapid responses to temperature changes due to (a) the relatively high thermal diffusivity of ice and (b) the small amount of heat involved in phase change, below approximately $0^{o}C$, unlike a clay where a high percentage of the moisture changes phase between $-2.5^{o}C$ and $0^{o}C$.

The mean annual temperature at a depth of 1.5 metres (5 feet) has been estimated as the resistance of this thermistor could not be read on the majority of occasions. A rapid response to a decreasing temperature may be explained similarly, as due to the high thermal diffusivity of ice.

All major changes in mean annual ground surface temperature are reflected in the thermal profile (Figure 10) including the increase EF, attributed at the other holes to recent fires and the 1971 drilling operation. There is no evidence, however, of a recent fire at this site but a clearing did exist prior to the 1971 drilling operations. There are indications that this clearing was made for exploration drilling in the winter of 1970-71 or possibly in the preceding winter. The creation of this clearing and its enlargement for the 1971 drilling operations are the probable reasons for the increase in mean annual ground surface temperature; this increase in temperature is due to an increase in incident solar radiation and to a lack of snow cover diminution because of orientation.

6.2.5.2 Norman Wells

Sites GL2U and TL

The borehole at GL2U is on the west side of the Mackenzie River (Fig. 4) and consists primarily of a glaciolacustrine deposit of ice-rich organic silt of medium plasticity, 1.2 metres (4 feet) thick, overlying clays of medium to high plasticity (Appendix 1). Considerable ice was encountered below the 5-metre (15-foot) depth. The borehole at TL on the east side of the Mackenzie River (Fig. 4) is located about 5 metres (15 feet) from a seismic line and approximately 30 metres (100 feet) from a shallow lake. It was drilled in a glaciolacustrine deposit consisting of about 2 metres (7 feet) of an organic clay of high plasticity overlying inorganic clays of medium to high plasticity (Appendix 1). Ice lenses, 2 to 5 cm (1 to 2 inches) in thickness, occurred at about 30-cm (one-foot) intervals with a 10-cm (4-inch) ice-rich layer just below the peat cover.

The thermal profiles constructed for 1972-73 (Figs. 11 and 12) are very similar in that both boreholes appear to have an identical estimated thickness of permafrost. The mean annual ground surface temperatures obtained from the projections of the lower straight portions of the profiles are both close to $-2.8^{\circ}C$. The two curves also show the warming of the upper permafrost regions, presumably due to the warming trend ending in the 1940's.

Dissimilarities, however, may be noticed; GL2U has not been affected by the warming to the same extent or depth, and TL shows no response to the cooling of the climate since 1943.

Reasons for the dissimilarities in the thermal profiles may be as follows:

(a) At GL2U, the very high ice content in the organic silt, in which the active layer would be found would require a considerable quantity of heat to melt the ice and would restrict heat transmission to the soil below. The response to an increase in temperature, therefore, would be expected to be less than at TL.

(b) The lack of respose at TL to the cooling trend in the climate since 1943 is difficult to explain unless there had been some disturbance to this site many years ago during the original clearing for the seismic line, which then went unnoticed during clearing for the drilling operations. If this were the case, the soils would have been warmed to a greater extent and to a greater depth than at GL2U. As no evidence of earlier clearing had been detected, however, this hypothesis presently is given little weight and the lack of response remains a puzzle.

Site GL1

This borehole, situated within about 5 km (3 miles) of TL on the east side of the Mackenzie River (Fig. 4), is also in a glaciolacustrine deposit. The soils consist of about 3 metres (10 feet) of silty sand grading to gravelly sand overlying clays of high to medium plasticity (Appendix 1). Ice was not visible in the sands, which varied from poorly bonded to well bonded; in the clays ice generally occurred as random lenses less than 3 cm (1 inch) thick.

The thermal profile constructed for this drill hole (Fig. 13) shows that permafrost is warmer than at GL2U and TL and appears to be only about 35 metres (115 feet) thick. The deviation of the profile from its projection at depth generally is not as great as for TL, which probably can be explained by the presence of much denser tree growth at the GL1 site than at the TL site. The cooling trend since 1943 is barely evident, unlike the dramatic reaction to the clearing and drilling operations shown by EF. Temperature records (Figs. 7 and 14) show how much more responsive soils with low water contents, such as at GL1, are to changes in ground surface temperature in contrast to soils with high water contents, particularly clays, such as at DH-4-71.

Site SA

This borehole (Fig. 4) is located in about 2 metres (7 feet) of ice-rich peat, overlying one metre (3 feet) of organic clay and ice, above 1.2 metres (4 feet) of ice-rich inorganic clay (Appendix 1). Below the next 2 metres (6 feet) of clayey silt with ice was 4 metres (14 feet) of siltstone with clay seams and ice partings and then weathered shale grading into soft shale with no visible ice.

Monitoring of temperatures from July 1972 to the present time has indicated that the depth of thaw extends as deep as 1.4 metres (4.5 feet), despite the very high ice content in the peat cover. There are, however, two reasons for such a deep active layer. Firstly, trees on this site are so small and scattered that they have practically no effect on the amount of incoming solar radiation; secondly, in the summer there is a considerable amount of water covering large areas of the site, particularly near the borehole (P.J. Kurfurst, pers. comm., recorded 39 cm (14 inches) of water on July 12, 1972). The water surface possesses an albedo and insulating qualities different from the peat; the amount of heat absorbed by the water is much more than that absorbed by the peat. Due to the presence of free water, a considerable depth of thaw in the order of several metres would have been generated except for the very high ice content which requires great quantities of heat to melt the ice.

The kink in the curve (Fig. 15) at the 3-metre (10-foot) depth, DE, may be due to the cooling trend since 1943 but if so, the clearing and drilling operations in 1972 changed the mean annual ground surface temperature to such an extent that the climatic change appears to have been all but obscured.

Below-ground mean temperatures are considerably warmer than in the other boreholes although the estimated thickness of permafrost lies between that of GL1 and GL2U. Presumably the relatively warm temperatures are the result of the high moisture contents of the peat and clays which, because of the great quantity of latent heat to be removed, have prevented the temperatures from becoming as cold as those existing in other soils.

The gradient in the siltstone and shale is similar to that existing in the shale at site 7B on the east side of the Mackenzie River (see below).

Site 7B

The underlying bedrock of soft shale at this location (Fig. 4) is covered by approximately 6.6 metres (22 feet) of till, which grades from a clay of high plasticity (3 metres (10 feet) thick) to a silty sand with gravel to a clayey, silty sand with gravel (Appendix 1). An ice-type profile is not available as this borehole was made primarily by chip drilling.

The thermal profile (Fig. 16) is similar to the other profiles discussed already in that the warming and cooling trends are present. Between the 6 and 10.5-metre (20- and 35-foot) depths, however, there is a kink in the thermal profile towards the warm side. Attempts to explain this divergence do not appear warranted at present as a borehole about 9 metres (30 feet) away revealed that the thickness of till there was only 3.3 metres (11 feet). The thickness of permafrost indicated in Figure 16 is considered to be less reliable than estimates made for other drill holes because of the variation in overburden thickness.

Sites MV and 7D

Appendix 1 shows the stratigraphic and physical data for borehole MV. This borehole, which is located on the east side of the Mackenzie River (Fig. 4), indicates that a predominantly clayey till, 7.5 metres (25 feet) thick, overlies the shale bedrock. Because sampling was primarily by chip drilling, no ice log could be constructed but the till possessed a high ice content (>20%) between the 0.6 and 1.2-metre (2- and 4-foot) depths. Thin partings of ice were observed in the few cores which were taken down to a depth of about 30 metres (100 feet).

Similarly in borehole 7D (Fig. 4 and Appendix 1), about 60 metres (200 feet) from a large lake, there were 4 metres (15 feet) of a gravelly, sand-silt alluvial terrace below 1.2 metres (4 feet) of a silty clay deposit with substantial ice at the 0.6-metre (2-foot) depth. The underlying bedrock was also shale, weathered in the upper 2.4 metres (8 feet). As only chip drilling was done at this site, no logs have been constructed.

The temperature data required for the calculation of the thermal profiles and in situ diffusivities are incomplete as yet; the thickness of permafrost at MV is about 37 metres (121 feet) and at 7D is 26 metres (86 feet). Explanations for differences must await construction of the thermal profiles.

Summary

The thickness of permafrost is not constant in the Fort Good Hope-Norman Wells region. Where soil type, vegetation cover, relief, and moisture content are similar, thicknesses of permafrost are similar (sites GL2U and TL). Where dissimilarities exist, particularly in near-surface conditions, the thicknesses of permafrost vary significantly (sites TL and GL1, for example).

Permafrost temperatures are generally warmer near the surface (upper 10 or 20 metres (35 to 70 feet)) than at depth due to the climatic warming trend up to the 1940's; the response to this warming, however, is a function of vegetation cover, soil type, and moisture content. If the vegetation cover remains unchanged, the most important factor in the response is the amount of moisture present in the near-surface organic and mineral deposits.

Rate of temperature change in permafrost in response to an exterior influence is a function of initial temperature, frozen and unfrozen water content, thermal conductivity and diffusivity, and hydraulic conductivity. The rate of temperature change, in particular the rate of thawing, affects the rate of consolidation and development of shear strength and hence, settlement and stability.

The temperature data, which have been used to provide ground temperature information also is being utilized to check the predictive capabilities of the computer program which was designed to investigate the aggradation or degradation of permafrost (Section 6.6).

6.3 THERMAL CONDUCTIVITIES

Prediction of the thermal behaviour of permafrost and unfrozen earth materials and hence their engineering behaviour requires a knowledge of the thermal properties of conductivity and diffusivity. Very little data are available linking thermal properties with soil types, water contents and temperatures for the terrain units in the Mackenzie Valley Transportation Corridor. The data available now are still quite limited, but an attempt has been made below to correlate these values of thermal conductivities with soil types and to explain the relationships obtained.

Estimates were made of Atterberg limits, applicable to the thermal conductivity samples, based on the grain size distribution of these samples and of other samples nearby with similar distributions and known limits. From size distribution and Atterberg limits, activities also were estimated.

From the limited data available, five groups have been constructed with three to five samples in each group (Appendix II). Other possible groupings were tabulated but data points were too few for plotting. Plotting of the thermal conductivity values against natural water content (<u>see</u> Appendix II) revealed that the relationship was not linear except possibly over narrow ranges of moisture content values. Generally, thermal conductivity appears to vary abruptly and non-linearly with moisture content. One graph of the variation of thermal conductivity with water content for the test temperature and a certain soil type appears to yield a "saw-tooth" type of curve (<u>see</u> Appendix II, Group B), similar in certain respects to a dry density-moisture content curve. As the data are insufficient, however, all curves must be considered only as indicative of the type of behaviour.

The reason for this non-linearity of the curves is not known but it is suspected that for low moisture contents, most of the water freezes and the relationship of conductivity with moisture content is nearly linear. As the water content increases, however, a greater percentage of the moisture remains unfrozen and the overall thermal conductivity decreases. At higher values of moisture content the proportion of mineral soil to ice to unfrozen water is such that the thermal conductivity increases with increasing moisture content and then decreases. When the moisture content becomes very high, the thermal conductivity appears to increase linearly but remains below that of ice, indicating that a substantial amount of the moisture is in the form of unfrozen water.

An additional factor affecting the thermal conductivity value may be differences in the salinity of the pore water. Whether substantial differences exist or whether their effects would be significant is not known at present.

As mentioned before, Kersten (1949) worked with a small number of soil types. These soils were compacted in the laboratory at a variety of moisture contents, frozen, and then tested. In general, the thermal conductivity tests were conducted on samples with relatively low moisture contents at various degrees of saturation, and the relationship of conductivity with moisture content at constant dry density appears to be essentially linear in this range of moisture contents. Samples of permafrost core from the Mackenzie Valley were found to be close to or at 100% saturation and therefore Kersten's diagram of the variation of thermal conductivity of silt and clay soils at about 25°F with dry density and moisture content is more relevant to these samples than his other published data. His graph (see Appendix II) indicates that the thermal conductivity of these soils, if they are 100% saturated, should be nearly constant at about 2.0 ± 0.5 W/m°K in the moisture content range of say, 19 to 34%. In his conclusions, however, Kersten states that "for saturated frozen soils the data indicate no well-defined relationship between density and conductivity". The recent values obtained from samples of Mackenzie Valley soils show that the relationship of thermal conductivity to moisture content is more complex than Kersten's graph implies. Moreover, considerable quantities of permafrost exist with water contents that are substantially higher than the values encountered by Kersten; thus, his data cannot be extrapolated to yield the appropriate thermal conductivity values.

The conclusion of the most immediate significance to the engineer is that thermal conductivities of permafrost samples at temperatures about -5.5°C are generally less than expected from Kersten's data; values ranged from 0.78 to 2.45 W/m°K but with further testing, the overall range is expected to expand, that is, lower and higher values will be encountered. Much permafrost exists at temperatures warmer than -5.5°C, and in the zone of -2.5°C to 0°C, the percentage of unfrozen water is much higher and thermal conductivity lower than that obtained at the lower temperatures.

It should be noted that in some groups data have been used from boreholes up to 70 km (40 miles) apart. Boreholes DH-1-71 and DH-4-71 are in glaciolacustrine deposits while borehole DH-3-71 is in a similar deposit that subsequently has been modified by glaciofluvial action. Provided the mineralogical composition does not vary, the relationship of thermal conductivity with moisture content does not appear to depend on how the sample was formed. Knowledge of the origin, however, may assist in understanding the range of thermal values existing in the permafrost. For example, borehole DH-2-71 is situated in till over shale. As expected, at temperatures around -5.5°C the moisture contents in the till below the upper metre (3 feet) or so, which is predominantly ice, are very low with correspondingly low thermal conductivity values. Because the moisture contents are so low, it is expected that the thermal conductivity will remain essentially constant for most temperatures below about 0°C.

6.4 THERMAL DIFFUSIVITIES

For heat transfer calculations dealing with transient conditions, thermal diffusivity is a more important parameter than thermal conductivity. For rates of thaw, the amount of latent heat involved is also very significant. Diffusivity is a function of conductivity, however, and a variable apparent diffusivity, which differs from true diffusivity in that the effect of latent heat is included, may be used in calculating rates of thaw.

Although laboratory values of thermal diffusivity for soils in the Mackenzie Valley are not available, it proved possible, as outlined in Section 5.3.2, to calculate values of "in situ or apparent diffusivity" corresponding to the temperature ranges to which the soil had been subjected. It should be clearly understood that these "diffusivities" include a latent heat term and in most instances their use should be restricted to the temperature ranges from which they were calculated. Also they should be treated as preliminary and subject to change.

Values of "in situ diffusivities" have been calculated for three of the Fort Good Hope boreholes (sites DH-2-71, DH-3-71, and DH-4-71) and for a number of the Norman Wells boreholes and are shown graphically in Appendix II. The importance of the fluid left in the borehole surrounding the thermistor cable is demonstrated by the fact that data from the borehole at DH-1-71 could not be used in these calculations as the Therminol in the borehole damped out the amplitude of the temperature wave.

6.5 VOLUMETRIC SPECIFIC HEATS AND UNFROZEN WATER CONTENTS

Thermal diffusivities may be calculated from values of thermal conductivities if the corresponding volumetric specific heats are known. Unfrozen water contents are of interest because they help to explain the variations in apparent and true volumetric specific heats as well as the anomalous behaviour of permafrost during thawing. To obtain volumetric specific heats and unfrozen water contents the laboratory calorimetric equipment and technique were developed.

The results of tests on five samples are included in Appendix II. The samples from boreholes GL2U and GL1 have been classified as clays of high plasticity (CH) with liquid limits greater than 50%, while the sample from DH-1-71 is a fine sand-silt mixture with some clay (ML).

It should be noted that at temperatures less than about $-2.5^{\circ}C$, changes in specific heats and unfrozen water contents are negligible for these samples. The major changes to apparent specific heats and unfrozen water contents occur between $-2.5^{\circ}C$ and $0^{\circ}C$.

Most of the permafrost in the Fort Good Hope-Norman Wells region exists at temperatures between $-2.5^{\circ}C$ and $0^{\circ}C$ and as the graphs (Appendix II) indicate that soils with very high percentages of fine-grained materials possess considerable moisture in the liquid phase (greater than half of the total moisture content in most cases), the effect of high unfrozen water contents must be considered in the thermal and engineering behavious of these soils.

The implications of high unfrozen water contents are serious:

(a) The rate of thaw will be underestimated greatly if all the moisture present is considered to be in the form of ice at temperatures below $0^{o}C$.

(b) Movement of water in permafrost must be considered as possible and so must its effect on heat transfer (see Section 7.6).

(c) In some soils, consolidation may begin at temperatures significantly below $0^{o}C$, thus preventing the build-up of high excess pore pressures.

6.6 MATHEMATICAL SIMULATION OF AGGRADATION AND DEGRADATION OF PERMAFROST

The aggradation and degradation of permafrost due to climatic changes and engineering activities are being simulated mathematically with a computer program (TRAMPS - Temperature Analysis of Multi-phase Systems) developed by P. Hibbert of the Computer Science Centre, Department of Energy, Mines and Resources. An important assumption inherent in the program is that heat transfer can occur by conduction only. This program has been used in a study of the effects of road construction (the Canol Road) on permafrost and some of the results of the computations are discussed in Section 7.

The analysis of the heat flow problem is being carried out using the finite element method. There are several examples in the literature on the use of this approach with respect to linear cases; because of the large computational times involved, however, it has not been applied extensively to highly non-linear problems encountered in phase-change phenomena.

Some of the assumptions inherent in the method are as follows:

(a) Every cross-section is the same as every other cross-section. This implies that there is no heat flow parallel to the continuous heat source.

(b) The cross-section being investigated is composed of a large number of triangular elements which are interconnected at the nodes or joints.

(c) Each element may be composed of a different material but the material is uniform throughout the area of the element.

(d) The temperature variation across an element is constrained to being linear.

(e) Specified nodes may be designated as heat sources or sinks by specifying their temperatures, which may be time dependent.

(f) The latent heat effect does not occur instantaneously at a particular temperature but is considered to be part of the specific heat and is spread over a small but finite temperature range.

(g) The variation of thermal conductivity with temperature also is taken into account.

When the network of elements is being constructed, care must be taken to ensure that small elements occur in regions of steep changes in the thermal gradient so that the temperature profile may be modelled adequately. The network also must be large enough in extent so that thermal changes will be negligible at the boundaries at the latest times investigated.

The solution of this non-linear problem requires that a large number of linear solutions for small time-steps be carried out and accumulated. Thus in the limit, the model approaches reality as the time increment approaches zero. It is important that the time interval be small enough so that each element, as it passes through a phase change, exists in the temperature range of the change for a number of time steps so that the latent heat may be incorporated fully.

7. THE CANOL ROAD

7.1 HISTORY

In the spring of 1942, with the consent of the Canadian Government, the United States War Department decided to develop the Norman Wells oil-field to produce at least 3,000 barrels of oil per day and to construct a pipeline from Norman Wells to Whitehorse on the Alaskan Highway. A refinery would be built at Whitehorse to supply gasoline not only to users of the highway and planes but primarily to Fairbanks, Alaska.

As construction was to begin initially from the Norman Wells end, an estimated 50,000 tons of freight had to be transported from Edmonton by rail, road, water, winter roads, and air. For construction of the actual pipeline, a road had to be built not only to carry the construction traffic but also to permit year-round maintenance.

The first Canol Camp was located across the river from Norman Wells on the west side of the Mackenzie and acted as a reception area for the freight arriving along the river. The civilian camp was fairly small at freeze-up in 1942 with a population of only a hundred men, but the Corps of Engineers had their own quarters nearby. As work progressed, the camp was relocated away from the river on high ground and as the work force increased to more than a thousand persons, another larger camp was built on even higher ground several miles inland.

In the winter of 1942 to 1943, a line was cut by tractor trains operating out of Camp Canol, but actual road construction did not get under way until May 1943. Generally, wherever it was thought that permafrost existed on the right-of-way, which had been cleared of trees, the vegetation cover was left as undisturbed as possible, and fill was placed on top of this cover. Photographs (Finnie, 1945) indicate that in other areas the organic cover was removed, the subgrade shaped, and fill placed on it.

The entire Canol Road was passable to traffic on December 31, 1943 and the pipeline was completed on February 16, 1944. In April 1944 the first crude oil flowed into the refinery at Whitehorse but operations were abandoned later that year, and at the end of World War II, much of the equipment and most of the pipe was salvaged. The road has been mainly unused since except by seismic parties in the winter.

7.2 EXPECTED EFFECTS OF ROAD CONSTRUCTION

Tree removal preceded road construction during which about one metre (3 feet) of fill was dumped over the organic cover where permafrost obviously was present. Because of this, the mean annual surface temperature of the Canol Road therefore is greater than the mean annual surface temperature of the ground prior to road construction. This is due in part to: (a) the increase in incident solar radiation caused by removal of the trees, and (b) damage to the organic cover, which reduces its insulating capacity by compressing it and eliminates the evapotranspiration effect.

Additional factors mentioned before (Section 2.3) include snow accumulation, drainage, wind shifts affecting evaporation, and so forth. The effect of snow accumulation may be particularly marked for sections of the Canol Road which in winter are covered with snow unlike a well-travelled road, and hence are insulated from winter temperatures. Poor drainage along the sides of the road also may cause ponds to form and as incident solar radiation will be absorbed to a greater degree by the water in the pond than by the surrounding vegetation, increased thaw will occur beneath the water.

7.3 INVESTIGATION IN 1972

The 1972 drilling program had a two-fold purpose: (a) to develop a winter drilling technique for the recovery of permafrost core, and (b) to obtain data and frozen permafrost samples from the various terrain units in the Norman Wells area.

During the program, borehole R-1 (Fig. 4 and Appendix 1) was put down in the middle of the Canol Road by air drilling with a Mayhew 1000 truck-mounted drill. Below the seasonally frozen crust, no permafrost was encountered within the borehole, which was limited to a depth of 9 metres (30 feet) as the water-table was found to be at 8 metres (27 feet). As subsequent drilling at several undisturbed locations near the road revealed permafrost to a depth of at least 9 metres (30 feet) near a large lake and to at least 15 metres at locations away from the lake, in March of the same year seismic refraction profiling was done by J.A. Hunter (Geological Survey of Canada). Interpretation of the profiles shot along the centre line of the road showed only seasonal frost in the upper few metres. No first arrival high velocities, indicative of permafrost at depth, were present. A possible refraction from a depth of about 30 metres (100 feet) was observed.

Naturally, the possibility that road construction could result in such great depths of thaw caused considerable concern, and therefore an attempt was made to simulate mathematically the thermal regression that had occurred since construction of the road.

7.4. GEOTHERMAL MODEL STUDIES

The regression of permafrost beneath this site was simulated with the finite element program described in Section 6.6. At the time of modelling, information available regarding thermal profiles and thermal properties of soils in the Norman Wells region was very scanty; there were indications that permafrost temperatures were warmer than expected due to recent climatic trends (Isaacs, 1972) and that for the same types of soils with the same general topography, drainage, vegetation, and so forth, the depths of permafrost at Norman Wells were very similar to those in the Fort Good Hope-Sans Sault Rapids region.

An existing 1972 thermal profile for DH-1-71 was modified and used in the computer simulation (Fig. 17). The segment BA of this profile has been substituted for segment BEA, as segment BE is thought to be due to climatic cooling since construction of the road and segment EA due to a recent fire and drilling disturbance.

As the subgrade at site R-1 consists of a very silty clay with a low water content (about 17½%), thermal parameters assumed were those used by Lachenbruch (1970) for "silt" (Table III). As the grain size and moisture content of the road fill did not differ much from those of the subgrade, thermal properties that differed only slightly were chosen.

The road configuration assumed is shown in Figure 18. Beyond the toe of the road side-slope the mean annual ground surface temperature was kept constant although during construction there would have been some change due to right-of-way clearing, and since construction, to climatic change. The temperature along the surface of the road side-slope was varied linearly from the assumed new mean annual ground surface temperature on the road surface to the original mean annual ground surface temperature existing at the toe of the slope.

The depth of thaw for these calculations has been defined as corresponding to the 0°C isotherm. The computed depths of thaw beneath the road thirty years after construction are shown in Figure 19 as a function of assumed increases in mean annual ground surface temperature. Two different frozen moisture contents have been assumed. The possible range of spring and fall shapes of the thaw bulb are shown in Figure 20 indicating that configuration is dependent on the ground temperature existing at the sides of the road and on the initial thermal profile. Removal of or disturbance to the vegetation beyond the shoulders will result in increased thaw in those regions and the shape of the upper portions of the thaw bulb will be altered.

7.5. DISCUSSION OF 1973 INVESTIGATIONS

An extensive drilling progam was carried out along the Canol Road in March 1973 (Kurfurst and VanDine, 1973) using a truck-mounted B-61 drill with a continuous flight auger. Drill holes were 15 cm (6 inches) in diameter and ranged down to 36 metres (120 feet) in depth.

Twenty-four holes, ranging in depth from 5 to 36 metres (16 to 120 feet), were drilled at five different sites along the Canol Road (Fig. 4) and six thermistor cables between 13 and 30 metres (40 and 100 feet) in length were installed and are being read at regular intervals to provide a continuous record of ground temperatures at various depths.

Seismic and electical resistivity measurments were made at some of the sites in conjunction with the drilling and are described in detail elsewhere (Kurfurst et al., 1973); three of the sites, R-1, GL2U, and HL, also are dealt with in greater detail in the same reference.

Site R-1

Two more holes were drilled at this site. One hole, 25 metres (83 feet) deep drilled on the shoulder of the road, did not encounter frozen material other than seasonal frost. The other hole, 25 metres (83 feet) to the east of the first and within the original right-of-way clearing, was similar throughout its 22-metre (72-foot) depth. The water-table was found to be at about 5.5 metres (18 feet). Because of access problems, no other holes were drilled at this site.

Based on the limited data available in this area, a reasonable estimate of the increase in mean annual ground surface temperature would be 8° to 10°C. Figure 19 gives the calculated thaw depths corresponding to this increase as about 15 metres (50 feet). Even if the increase in the mean annual ground surface temperature is 16° to 20°C, the thaw depths should be between 17 and 22 metres (56 and 72 feet).

Since no permafrost was encountered to a drilling depth of 25 metres

(83 feet) at this site, it appears that heat conduction may not be the only heat transfer process taking place during thawing of some types of frozen soil and that heat transfer by convection of water from the thaw zone into the permafrost may be occurring. A tentative explanation of how this process may operate is advanced in Section 7.6.

Site CA

This site is on the airport built at Camp Canol, on a high ridge several miles from the Mackenzie River. Three holes were put down, two on the airfield and one on the cleared right-of-way to the northeast of the runway.

Below the seasonally frozen crust, which varied between 1.5 and 2 metres (5 and 6.5 feet) in thickness, no permafrost was encountered in the boreholes which ranged in depth from 16 to 34 metres (52 to 110 feet). The soils were a sandy silt till, 5 to 10 metres (16 to 33 feet) in thickness, overlying a silty clay. The water-table appeared to be between 11 and 14 metres (36 and 46 feet). Thermistors placed to a depth of 30 metres (100 feet) indicated that the soil was relatively warm (temperatures greater that $1^{o}C$); the runway appeared to be in excellent shape and had been used recently as an airfield.

Site CCU

Site CCU is located on the Norman Wells side of the ridge on which the third Camp Canol was built. This borehole was drilled to a depth of 9 metres (29 feet) in the spring of 1972. The soil, a fine sand to sandy silt, was logged as unfrozen as water in the drill hole prevented advancement.

Shallow thermistors were installed in hand-augered holes to a maximum depth of nearly 6 metres (18 feet) in the summer of 1972 and have been monitored since then. Some ice crystals were encountered during the augering but appeared to occur only in a half-metre (1.6 foot) thick band about 3 metres (10 feet) down.

In the 1973 drilling program, five holes were drilled across the road at this location to depths varying from 17 to 29 metres (55 to 96 feet). The boreholes were logged as unfrozen beneath the seasonally frozen crust, and water was encountered at depths varying between 3 and 4 metres (10 and 13 feet). The soil consisted of about 15 metres (50 feet) of fine sand to sandy silt overlying 14 metres (46 feet) of clay; bed-rock was weathered sandstone.

Thermistors were installed to a depth of about 24 metres (79 feet) and currently are indicating temperatures slightly below $0^{o}C$ at depths beyond 3 metres (10 feet). Permafrost, although very warm, appears to be present at depth at this site in contrast to the CA and R-1 sites which are located in similar soil. This is probably because this location is very exposed; records of snow depths over the past winter show that the snow frequently is removed by wind or is not allowed to accumulate as in more protected areas nearby.

Site GL2U

Site GL2U (Fig. 4 and Appendix I) is located in a glaciolacustrine silt-clay deposit overlying shale. In 1972 a 15-metre (50-foot) borehole was put down and a thermistor cable was installed in the permafrost in a location covered with black spruce and situated about 15 metres (50 feet) to the north of the road. In 1973, five holes (Fig. 21) were drilled at this site to depths varying from 5 to 25 metres (16 to 82 feet) as shallow seismic profiling in July 1972 indicated that there should be a thawed zone about 10 metres (33 feet) deep beneath the road. Three holes were drilled on the road which were logged as unfrozen to a depth of 3 metres (10 feet) beneath the seasonally frozen crust. Below this depth the silty clay was frozen, with the ice content estimated as varying from 10 to 35% by volume. The other two holes which were in undisturbed areas were frozen throughout.

A thermistor cable was installed to a depth of about 22 metres (72 feet) in the borehole drilled near the centre of the road. Although readings may not have stabilized by that date, temperature profiles for April 13, 1973 for this centre-road location and for the 1972 location north of the road are shown in Figure 22. The warming under the road caused by the increase in mean annual ground surface temperature is obvious as temperatures below the seasonal frost level reach $-1^{\circ}C$ only at a depth of about 12 metres (40 feet) while the corresponding temperatures in the undisturbed zone off the road are lower than $-2^{\circ}C$.

The absence of a great depth of thaw at this site was at first surprising, particularly as snow records over the 1972-73 winter indicated that the site was reasonably protected from the wind. Further analysis of data from the 1972 borehole, however, revealed that in the undisturbed permafrost the upper 1.2 metres (3 feet) of peat and organic silt possessed moisture contents greater than 100% by weight (Appendix 1). A great quantity of heat would be required to melt the ice in these layers and the rate of thaw beneath the road would be greatly retarded.

The thawed zone, interpreted from the seismic profiling as well as from DC and VLF resistivity profiles done in 1973, is explained as follows: a great deal of the water in the soil beneath the road is unfrozen at these relatively warm temperatures; this is shown in Figure 23 where the variation with temperature of unfrozen water content, as a percentage of total moisture content, has been plotted for a representative sample taken from the borehole in the undisturbed zone. As the proportion of unfrozen water to ice increases, the seismic velocities decrease giving rise to anomalies.

Site HL

Site HL is located about one kilometre (.5 miles) west of Heart Lake (Fig. 4) in fine silt-clay deposits with moderate ice content. The underlying bedrock is dense clay-shale with a considerably weathered upper zone.

Nine holes, ranging in depth from 10 to 33 metres (33 to 110 feet), were drilled across the road and in nearby disturbed and undisturbed areas (Fig. 24). The boreholes through the road (HL-73-2, HL-73-3, HL-73-4, HL-73-7), indicated that beneath the seasonally frozen crust, the clay-silt and silty clay were thawed throughout the depths of the boreholes (13 to 33 metres (43 to 110 feet)). Groundwater was present in all four holes at depths from 4 to 5 metres (13 to 16 feet).

Two holes (HL-73-6 and HL-73-8) were drilled on the right-of-way which had been cleared during construction but since had been overgrown. Unfrozen soil was found in only one hole, HL-73-8, which was close to the road. In an area of trails, which obviously had been much used during construction, the soil was logged as unfrozen beneath the frozen crust to a depth of 10 metres (33 feet) and as frozen below this (HL-73-1). The other two holes (HL-73-5 and HL-73-9) were located in vegetation-covered areas on both sides of the road. The hole situated in the unburnt zone (HL-73-9) was entirely in frozen material while the hole in a recently burnt area (1969) was in frozen ground except for a few metres immediately below the seasonal frost.

Thermistor cables were placed in boreholes HL-73-1 and HL-73-3. The readings indicated that the soil beneath the road is thawed completely while the soil in the area that was badly disturbed during construction and was logged as thawed is at a temperature of just less than $0^{o}C$ at depths greater than 3 metres (10 feet). Seismic and resistivity profiles indicated the thawed zone beneath the road and although both seismic and VLF resistivity located the warm zone beneath the trails (interpreted as thawed), DC resistivity did not.

The asymmetry in the shape of the thaw zone under the road is probably due to the presence, in most years, of a pond of water about 0.5 metres (1.5 feet) deep on the north side of the road. The incident solar radiation is absorbed to a greater degree by the water in the pond than by the surrounding vegetation and this results in increased thaw beneath the water.

7.6 POSSIBLE HEAT CONVECTION PROCESSES

There may be at least two processes controlling convective heat flow in the permafrost. One process has been described by Harlan (1973), which he states as analogous to the mechanism of water transport in unsaturated soils. In his view,

> "... a Darcian approach is applied from a hydrologic point of view to the mathematical description of the hydrodynamics of fluid transport in partially frozen soils. This approach is in sharp contrast, at least in the conceptual aspects, to the capillary model which has been widely used in studies of frost heaving phenomena."

Harlan considers a thermal gradient in a partially frozen soil as analogous to a hydraulic gradient in an unsaturated soil since the unfrozen water content appears to be mainly a function of temperature (Hoekstra, 1967). Therefore, based on the energy state as expressed by Gibbs free energy,

> "... in a partially frozen soil, migration of water occurs as a result of a hydraulic gradient set-up by a decrease in porewater pressure at the frozen-unfrozen soil boundary. Provided the continuity of the unfrozen water is maintained, the rate of liquid transfer should depend on the magnitude of the thermal gradient, the temperature of the system and the surface area". (Harlan, 1973).

In other words, water is attracted to the frozen-unfrozen soil boundary of the hydraulic gradient associated with the thermal gradient, but since most soils contain some unfrozen water at temperatures below $0^{o}C$, migration of water also can occur within the frozen zone itself under the thermal gradient existing within it.

In the other process, as the temperature of the permafrost increases, some of the ice changes state to water, and with this change of state there is an associated negative pore pressure, that is, there is a tendency to pull water into the pore spaces where ice has been changed to water.

Another consideration, which may or may not be significant, depending on the thermal gradient and quantity of heat transfer, is the contribution due to gravity.

In the case of a thaw zone beneath the road or a hot pipeline, therefore, free water in that zone will be drawn into the permafrost immediately below where the temperature is at about $0^{o}C$. This mobile water is itself at or very near to $0^{o}C$ and cannot contribute much heat to the permafrost without undergoing a change of state. By moving into the frozen soil beneath the thaw interface, however, it tends to satisfy the pressure demands at that point (depending on the hydraulic conductivity) and allows water to migrate from there to yet colder permafrost. It is this water, migrating from warm permafrost to colder permafrost, that is considered to be the main contributor to convective warming.

Heat transfer by conduction is the most inefficient of heat transfer mechanisms. Heat transfer by convection enables thawing to occur at rates several orders of magnitude greater than for cases where heat transfer is by conduction only.

7.7 CONCLUSIONS

Construction of the Canol Road and airport has resulted in an increase in the mean annual ground surface temperature such that the underlying permafrost has been warmed to a considerable extent. In several areas this warming has resulted in thaw to great depths.

Significant visible settlement at the moment appears to be restricted to areas with soils, such as peat, which have large water or ice contents in the upper few feet and which are very compressible. In certain other soils it is felt that the road may be supported by the arching of soil across the top of the thaw bulb. Whether such arching would collapse under heavy traffic is unknown.

The model study, based on heat flow by conduction only, predicted considerable depths of thaw beneath the road; the drilling at site R-1, however, has shown that the model underestimates the depth of thaw. Thaw processes in permafrost therefore appear to involve heat transfer not only by conduction but also by convection of water near the thaw boundary into the permafrost.

Field results from sites R-1, CA, and HL show a range of shapes of the upper portion of the thaw bulb due to disturbance to the vegetation beyond the shoulders of the road, to ponding of water by the roadside, and probably to different initial thermal regimes and mean annual ground surface temperatures.

8. CONCLUSIONS

1. Drilling in permafrost for the recovery of frozen core, both in summer and winter, now can be very successful due to the development of the necessary techniques (Isaacs and Code, 1972; Isaacs, 1973). Frozen permafrost core can be brought to the laboratories at Ottawa with negligible changes in temperature to the core (Isaacs, 1973).

2. Glacial tills, alluvial, and glaciolacustrine deposits were found to be variable with respect to soil types and consisted of sands, silts, clays, or combinations of these. In some instances, glacial tills and alluvial deposits also possessed substantial gravel. In the tills, high ice contents (>20%) occurred only in the upper 5 metres (16 feet) and moisture contents generally were less than 20% (by weight) below this

level. Little visible ice occurred below this depth. Alluvial and glaciolacustrine deposits, however, can contain considerable ice (>20%) particularly near the surface, and can have moisture contents greater than the liquid limits at considerable depths. Serious problems of settlement and stability occur if thaw is permitted in the upper 5 metres (16 feet) of glacial tills and at any depth in alluvial and glaciolacustrine deposits.

3. In the boreholes drilled in the Fort Good Hope-Norman Wells area in 1971, 1972, and 1973 and discussed in this report and elsewhere (Isaacs and Code, 1972; Isaacs, 1972, 1973; Heginbottom and Kurfurst, 1973; Kurfurst and VanDine, 1973; Kurfurst et al., 1973), permafrost was found in all cases except in disturbed areas and in a recently infilled lake. In this area, therefore, permafrost must be expected to be everywhere except in disturbed areas and under rivers and lakes.

4. Mean annual temperature profiles have been plotted for a number of boreholes in the Fort Good Hope and Norman Wells areas. Only at depth does a linear temperature profile exist in this permafrost; mean temperatures in the upper several metres generally are warmer than temperatures at depth would imply, apparently due to the last climatic warming trend.

Soils with considerable ice near the surface do not show much temperature response to changes in climate or small natural changes in a mean annual surface temperature. If the surface is covered with water during the summer or if there is a considerable increase in the incident solar radiation or decrease in the evapotranspiration effect, ground temperatures will increase significantly.

5. From the limited amount of data collected linking thermal conductivity to soil types at various moisture contents but at one temperature ($-5.5^{\circ}C$ approximately), it appears that thermal conductivity, at least for some soils, varies with moisture content in an irregular fashion (Appendix II) and not as expected from previous work (Kersten, 1949).

Thermal conductivity values of permafrost samples at the above temperature are low, ranging from 0.78 to 2.45 $W/m^{\circ}K$, and as most of the permafrost in this area exists at temperatures lower than the test temperature, in situ thermal conductivities are expected to be even lower. With further testing, the range of conductivity values is expected to increase, that is, lower and higher values will be encountered.

6. Values of "in situ diffusivity", which incorporate a latent heat term and are applicable only to the temperature ranges from which they have been calculated, can be derived from the annual temperature wave as it progresses into the ground. Such values have been obtained for the soils surrounding a number of boreholes in the Fort Good Hope and Norman Wells areas.

7. Tests to determine volumetric specific heats and unfrozen water contents have been made on several samples and not only have provided

data for calculation of thermal responses but also have proven that soils with high percentages of fine-grained materials possess considerable moisture in the liquid phase (generally more than half) at temperatures between -8^{0} and 0^{0}C.

8. A number of conclusions have been drawn from the study of the Canol Road (section 7.7) and are summarized here:

(a) Construction of the road has resulted in considerable warming of the permafrost underlying it because of the increase in mean annual ground surface temperature.

(b) The warming has caused thawing to occur to great depths in places along the road (in one case to at least 33 metres (110 feet)).

(c) The model study, which is based on heat transfer by conduction only, predicted considerable depths of thaw beneath the road at a selected location (between 15 and 22 metres (50 and 72 feet), depending on assumptions made) but drilling has shown that the model underestimated the depth of thaw as no permafrost was encountered in the 25-metre (82-foot) depth of the borehole.

(d) Thaw processes in permafrost appear to involve heat transfer not only by conduction but also by convection of water near the thaw boundary into the permafrost.

9. IMPLICATIONS AND RECOMMENDATIONS

9.1 IMPLICATIONS

The study has shown that:

(a) there is considerable permafrost in the Mackenzie Valley in the Fort Good Hope-Norman Wells areas

(b) this permafrost is significantly warmer than temperatures at depth would imply

(c) considerable ice (>20%) was found in each of the three major terrain types investigated

(d) very high percentages of unfrozen water (>50% of the total moisture content) may exist in fine-grained soils

(e) predictions of the rate of thaw based on heat transfer by conduction only seriously may underestimate the actual rate.

The amount of settlement and risk of instability, therefore, is greater than was expected before this research was started.

On the positive side however is the possibility that, due to the considerable percentage of unfrozen water present in fine-grained soils, consolidation of these soils as the pore pressure dissipates will begin at temperatures less than $0^{\circ}C$ and excess pore pressures will be less than they would have been otherwise.

The main problem probably will be the generation of excess pore pressures from thawing of ice lenses. As the thawed soil above the ice lens consolidates, its permeability decreases, slowing the escape of the water; thus, although there will be a volume decrease on thawing due to phase change of the ice to water, there still could be substantial pore pressure build-up at a thaw front in an ice lens, causing instability.

Considerable thaw will be generated by construction of roads over permafrost but the resulting behaviour cannot be predicted as yet. The Canol Road, which was the subject of a study, has not carried heavy traffic except in the year or so after construction and comparisons of its performance, under heavy traffic conditions,may not be valid when made with newly constructed roads. If arching of soil across the top of the thaw bulb is occurring, sudden subsidence may develop, particularly under heavy traffic.

The shape of the thaw bulb around a hot oil pipeline will be considerably different than that below a road (cf. Figs. 20 and 25) and arching cannot provide support of the pipeline or soil.

Althouth no research has been done specifically into the problems associated with the operation of a chilled gas pipeline, no data have emerged which would indicate that the problems of ice-lens growth, freezing and restriction of water flow, or damage to vegetation of the active layer will not exist.

9.2 RECOMMENDATIONS

1. As a result of the investigations of three terrain types (glacial tills, alluvial, and glaciolacustrine deposits) in the Fort Good Hope-Norman Wells area, it is considered inadvisable to bury a hot oil pipeline in the alluvial and glaciolacustrine deposits and in most till deposits. Burial of a chilled gas pipeline may be acceptable depending on the slope of the ground, time of construction, mode of construction, moisture supply, and the time interval between construction and initiation of gas chilling, however, as sections of the pipeline may be buried for three years before start-up, the thawing and possible associated settlement and/or failure caused by construction activity must be known in more detail before a decision can be made.

2. Road construction will cause thawing to considerable depths. There is a possibility that sudden settlement may occur along certain sections of a road, such as the Mackenzie Highway, but while specific areas may

be excluded from such considerations due to the soil/ice types in the subgrade, current knowledge is insufficient to allow prediction with any certainty where such settlement will occur. The designers of such roads should be made conscious of this possibility and should be urged to incorporate in the road design and construction a research program into ways of limiting the thawing beneath the road. Maintenance crews should be told of the potential settlement and encouraged to report all settlement observations.

10. RESEARCH RECOMMENDED

1. Additional investigations into the thawed zone beneath the Canol Road, beneath roads constructed since, and beneath the Mackenzie Highway are necessary to define the rate of thaw and its variance with time, soil types, percentage ice, ground temperatures, and changes in mean annual ground surface temperatures. Samples will be required for thermal and soil classification tests; instrumentation to measure temperatures and pore pressures should be installed on sections across existing roads as well as before and after the construction of new roads.

2. Concurrent with the above research, study should begin on methods of limiting thaw beneath roads constructed on permafrost.

3. An intensive study of the variation of thermal conductivity and diffusivity with soil type, moisture content, salinity of porewater, temperature, and consolidation is required for an understanding of thermal processes.

4. The possibility of a chilled gas pipeline acting as a focus for the growth of ice lenses, which may cause a jacking action on the pipeline, squeezing of the pipeline, and a barrier to the groundwater flow, should be studied.

5. The thaw-consolidation-shear strength problem of permafrost has not been examined adequately and laboratory investigation into the problem should be initiated. Research into the hypothesis that movement of moisture into permafrost occurs during thawing should be a part of this study.

6. As clearing of vegetation prior to construction will result in an increased thickness of active layer, consideration should be given to the idea of partially or gradually clearing the slopes where pipeline crossings of rivers are planned, for example, removal of 50 per cent of the trees one year, 25 per cent the following year, and so forth. The trees left after each partial clearing should aid greatly, by evapotranspiration, in the removal of excess water generated from the increased thawing. This method may prevent active layer slides associated with removal of or damage to vegetation.

11. GLOSSARY

The latent heat of fusion of water is defined as the quantity of heat required to change a unit quantity of water at $0^{o}C$ to ice at the same temperature. It has been taken in this paper as equal to 79.68 calories per gram.

Thermal capacity of a substance at a particular temperature is the quantity of heat required to change the temperature of unit mass of the substance by one degree. It is expressed in calories per gram per degree Centigrade or British Thermal Units per pound per degree Fahrenheit.

Specific heat of a substance is defined as the ratio of the thermal capacity of the substance to that of water at a chosen standard temperature. It is dimensionless and numerically equal to the thermal capacity of the substance.

Volumetric thermal capacity at a particular temperature is defined as the amount of heat necessary to change the temperature of unit volume of the substance by one degree. It is equal to the product of the thermal capacity and the density of the material. In this paper it is also referred to as the volumetric specific heat and is expressed as calories per cubic centimetre per degree Centigrade.

Thermal conductivity is the quantity of heat which flows normally across a surface of unit area per unit of time and per unit of temperature gradient normal to the surface. It has been used with units of calories or millicalories per centimetre per second per degree Centigrade or watts per metre per degree Kelvin.

Thermal diffusivity is a measure of the facility with which a substance will undergo temperature change and is the quotient of thermal conductivity and volumetric thermal capacity. Units used in the paper are square centimetres per second.

12. LIST OF CONVERSIONS

1 calorie	=	0.00397 B.T.U.
1 cal/gm ^{o}C	=	1 B.T.U./lb ^{o}F
1 cal/cm sec ^{o}C	=	420 Watts/metre ^{o}Kelvin
	=	420 W/m^{o}K

Ice-content rating adopted

In discussing segregated ice in this paper, the amount of ice by volume is often described as being low, moderate, considerable or high. The use of those terms generally apply to the following ranges:

0	-	10%	low
10%	-	20%	moderate
		>20%	considerable, high

Grain-size classification

The Unified Soil Classification System has been used throughout with the additional modification that the 2-micron size was considered to be the boundary between silt size and clay size.

13. ACKNOWLEDGEMENTS

The assistance of J.A. Code with the 1971 drilling operations, of D.E. Lawrence in setting up the field laboratories at Fort Good Hope in 1971, of D.L. Desai in determining the volumetric specific heats and unfrozen water contents, and of G.M. Loomis and R. Fehr in taking the thermistor readings, is gratefully acknowledged. Some of the thermistor cables and all of the conductivity values were supplied by the Earth Physics Branch, E.M.R.

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14. REFERENCES

Bliss, L.C. and Wein, R.W.
1972: Ecological problems associated with Arctic oil and gas development; Proceedings Canadian Northern Pipeline Research Conference, Ottawa, NRC Tech. Memo. 104

Carslaw, H.S. and Jaeger, J.C.
1959: Conduction of heat in solids; 2nd ed., Oxford University Press.

Crain, I.
1967: Influence of post-Wisconsin climatic changes on thermal gradients in the St. Lawrence Lowland; M.Sc. thesis, McGill University, Montreal.

Finnie, R.
1945: Canol; publ. by Ryder and Ingram.

Gillot, J.E.
1968: Clay in engineering geology; publ. by Elsevier Publ. Co., Amsterdam.

Harlan, R.L.
1973: Analysis of coupled heat-fluid transport in partially frozen soil; Water Resour. Res., v. 9, no. 5.

Heginbottom, J.A. and Kurfurst, P.J.
1973: Terrain sensitivity and mapping, Mackenzie Valley Transportation Corridor; in Rept. Activ., Pt. A, April to October 1972, Geol. Surv. Can., Paper 73-1.

Higashi, A.,
1952: Thermal conductivity of frozen soil; Faculty of Science, Hokkaido University, Series II (Phys.), v. IV, no. 2.

Hoekstra, P.
1967: Moisture movement to a freezing front; IUGG, Gen. Assembly of Bern, Proc. Geochem., Precip., Evap., Soil Moisture, and Hydrometry, p. 411-417.

Hughes, O.L.
1970: Surficial geology maps 1:125,000, NTS 96C, 96D, 96E, 106G, 106H; Geol. Surv. Can., Open File no. 26.

Isaacs, R.M.
1972: Thermal and engineering geological characteristics of soils, Norman Wells-Fort Good Hope area; Intern. Interim Rept., Environmental-Social Committee, Northern Pipelines.

Isaacs, R.M.
1973: Engineering geology, Mackenzie Valley Transportation Corridor; in Rept. Activ., Pt. A, April to October 1972, Geol. Surv. Can., Paper 73-1.

Isaacs, R.M., and Code, J.A.
1972: Problems in engineering geology related to pipeline construction; Proc. Can. Northern Pipeline Res. Conf., Ottawa, NRC Tech. Memo. 104.

Judge, A.S.
1972: Discussion to Problems in engineering geology related to pipeline construction; Can. Northern Pipeline Res. Conf., Ottawa, NRC Tech. Memo. 104.

Kersten, M.S.
1949: Thermal properties of soils; Bull. no. 28, Univ. of Minnesota, Inst. of Technology.

Kurfurst, P.J. and VanDine, D.F.
1973: Terrain sensitivity and mapping, Mackenzie Valley Transportation Corridor; in Rept. Activ., Part B, November 1972 to March 1973; Geol. Surv. Can., Paper 73-1.

Kurfurst, P.J., Isaacs, R.M., Hunter, J.A., and Scott, W.J.
1973: Permafrost studies in the Norman Wells region, N.W.T.; Symposium on the geology of the Canadian Arctic, Geol. Assoc. of Can., Sask.

Lachenbruch, A.H.
1957: A probe for measurement of thermal conductivity of frozen soils in place; Trans. Amer. Geophy. Union, v. 38, no. 5.

1970: Some estimates of the thermal effects of a heated pipeline in permafrost; U.S. Geol. Surv., Circ. 632.

Lawrence, D.E.
1972: Geotechnical field laboratories; in Rept. Activ., Pt. A, April to October 1971; Geol. Surv. Can., Paper 72-1.

Penner, E.
1962: Thermal conductivity of saturated Leda clay; Geotechnique, v. XII, no. 2.

Permafrost Map of Canada
1967: Division of Building Research, NRC of Can., and Geol. Surv. Can., Map 1246A, Scale 1:7,603,200.

Pihlainen, J.A. and Johnston, E.H.
1963: Guide to a field description of permafrost for engineering purposes; NRC of Can. Tech. Memo. 79.

Powell, M.J.D.
1964: A method for minimizing a sum of squares of non-linear functions without calculating derivatives; Computer Jour., v. 7, no. 2, July, p. 155.

Speer, T.L., Watson, G.H. and Rowley, R.K.
1973: Effects of ground-ice variability and resulting thaw settlements on buried oil pipelines, Proc. 2nd. Intern. Conf. on Permafrost, Yakutsk, U.S.S.R.

de Vries, D.A.
1963: Thermal properties of soils; Physics of Plant Environment, North-Holland Publ. Co., Amsterdam.

Watson, G.H., Slusarchuk, W.A., and Rowley, R.K.
1973: Determination of some frozen and thawed properties of permafrost soils; Can. Geotech. J., v. 10, no. 4,p. 592-606.

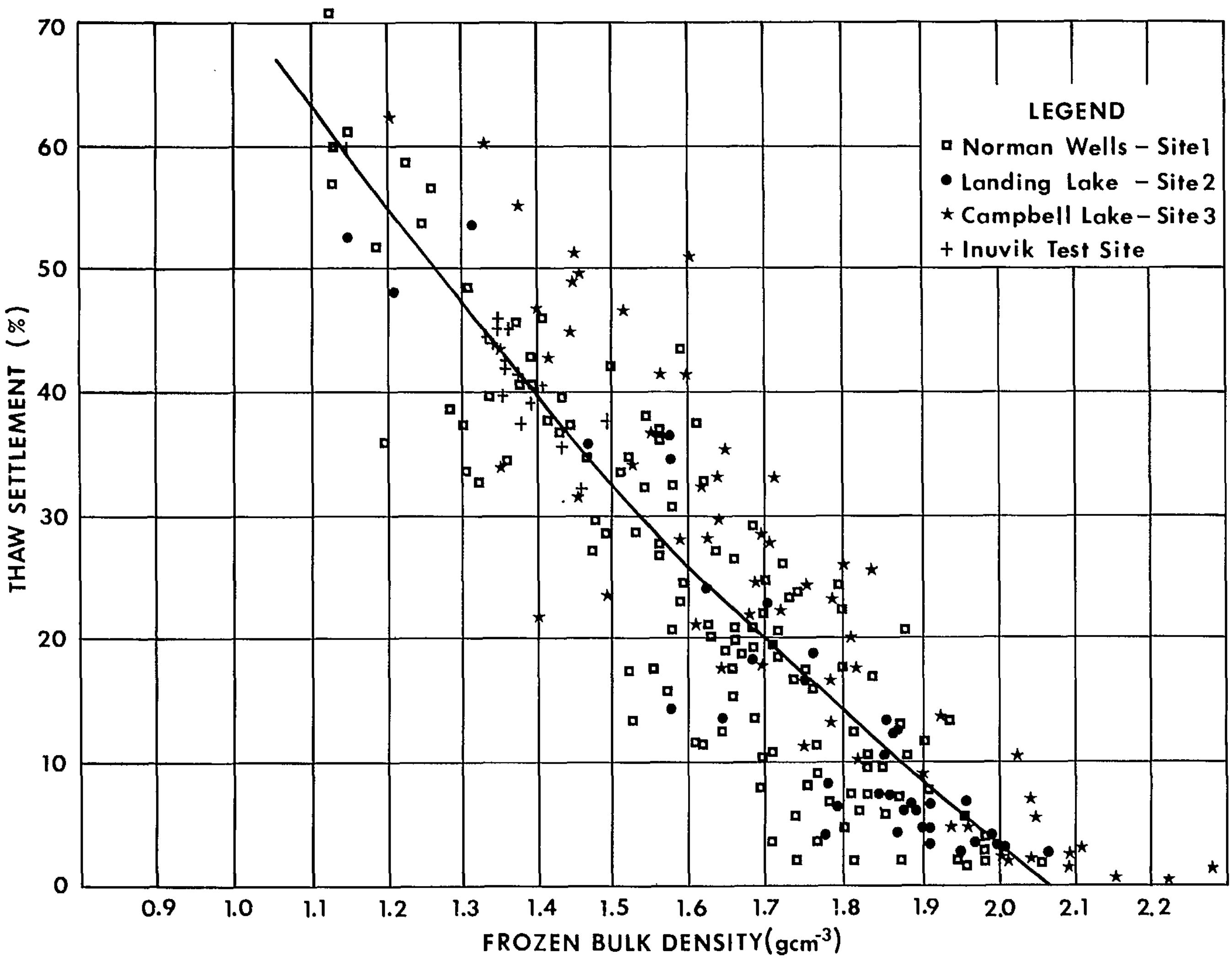


FIG. I THAW SETTLEMENT vs. FROZEN BULK DENSITY RELATIONSHIP

(after Speer, Watson & Rowley, 1973)

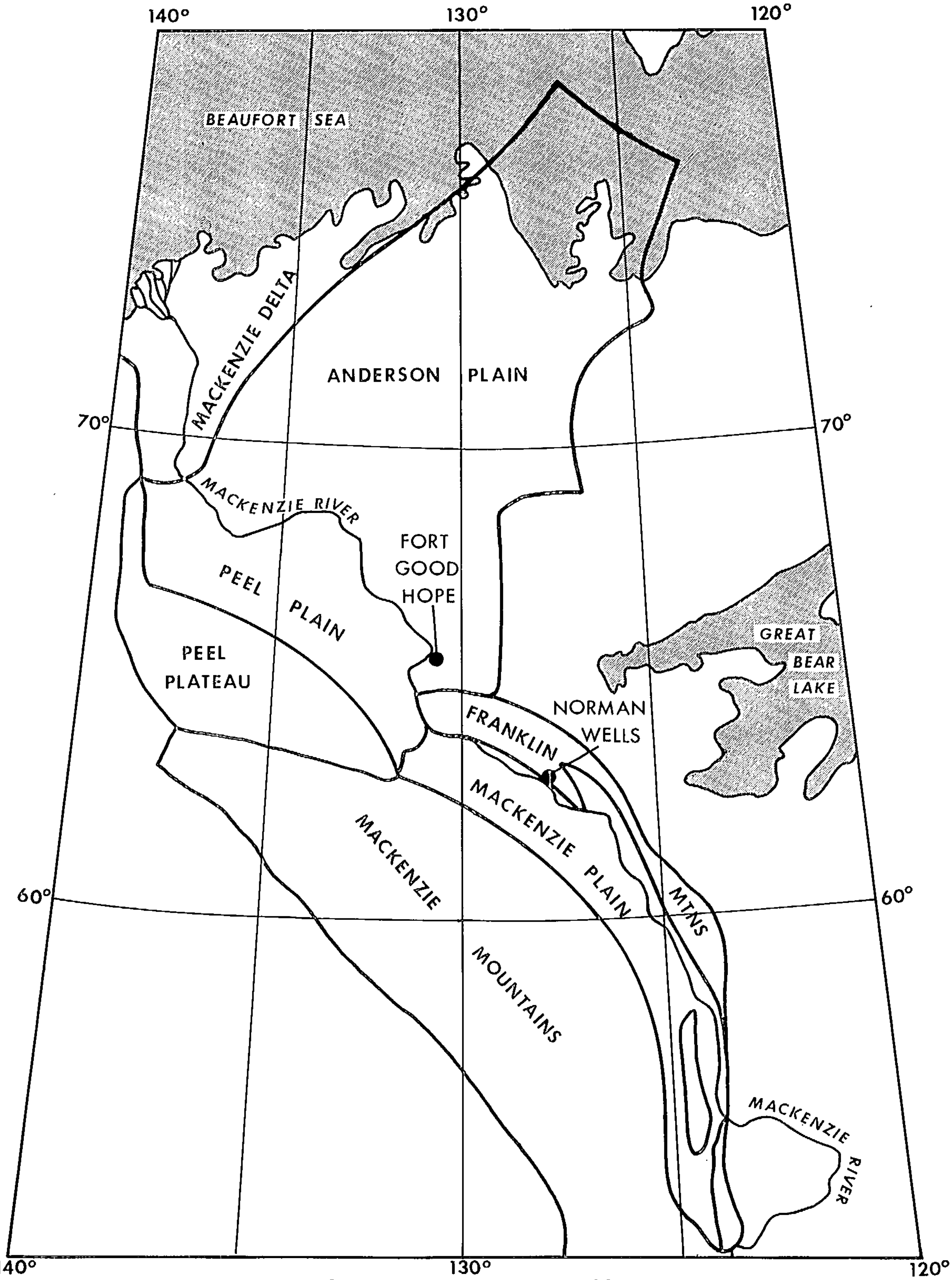


FIG.2

GENERAL LOCATION

PHYSIOGRAPHIC DIVISIONS

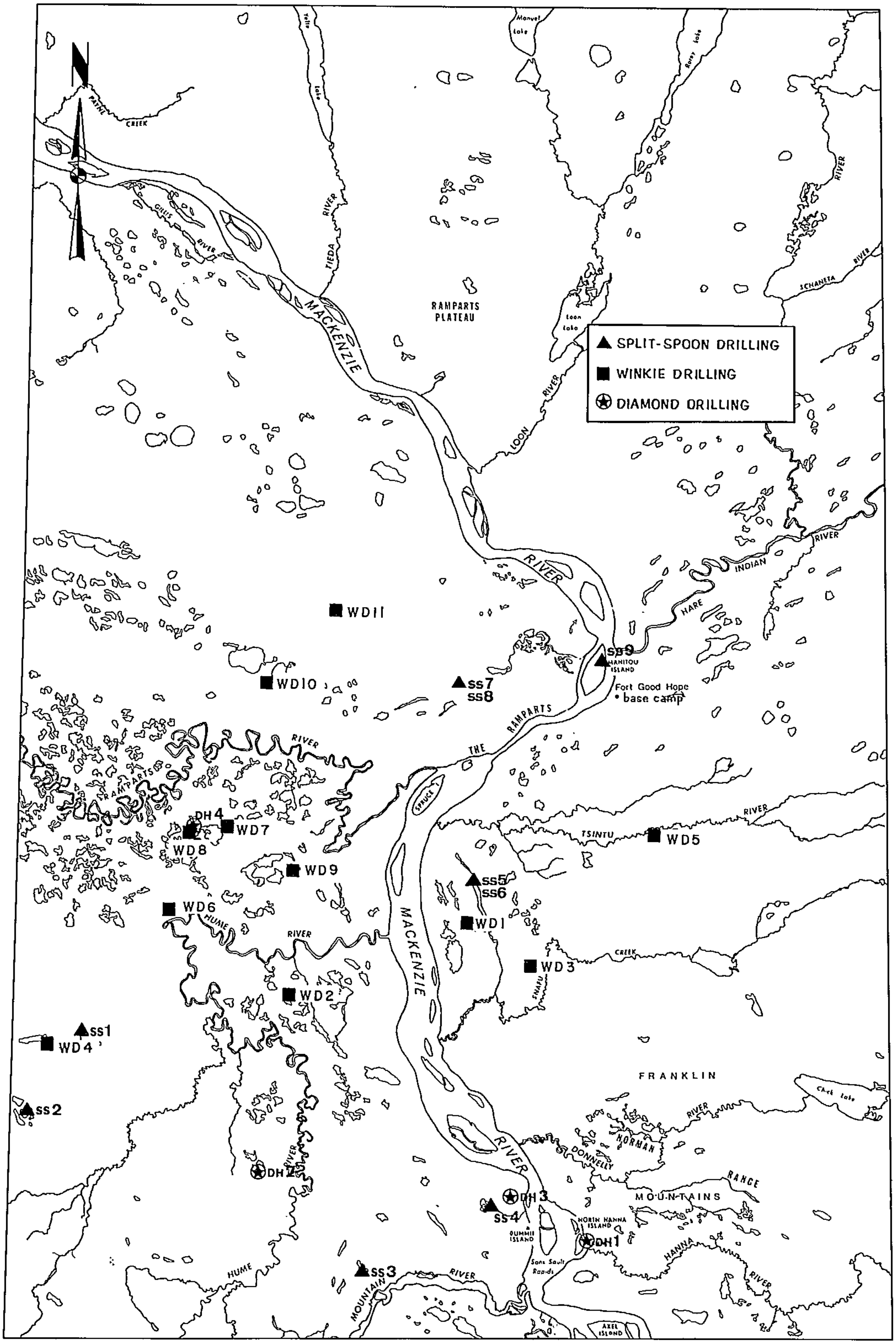


FIGURE 3: LOCATIONS OF 1971 DRILL HOLES

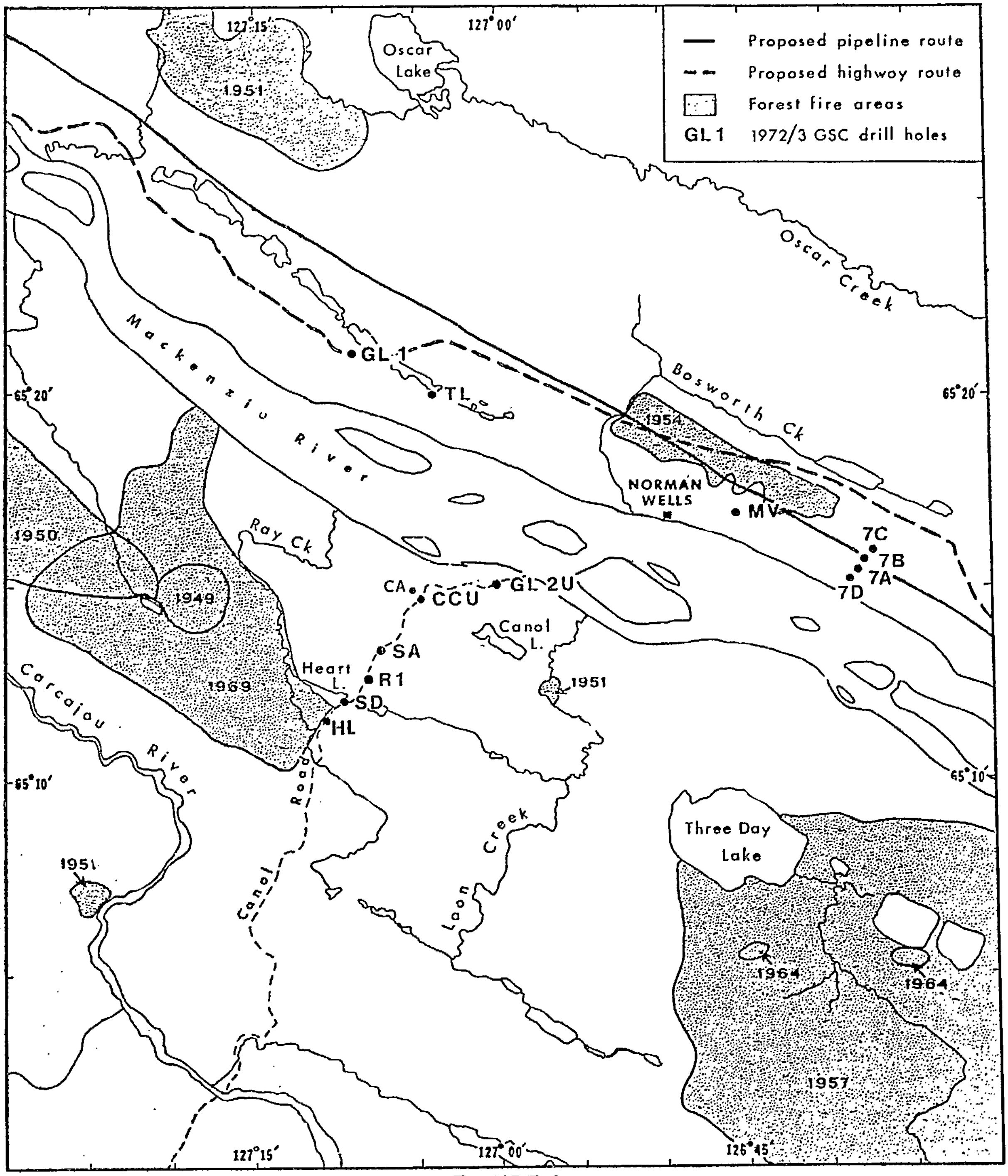


FIGURE 4

LOCATIONS OF 1972/3 GSC DRILL HOLES

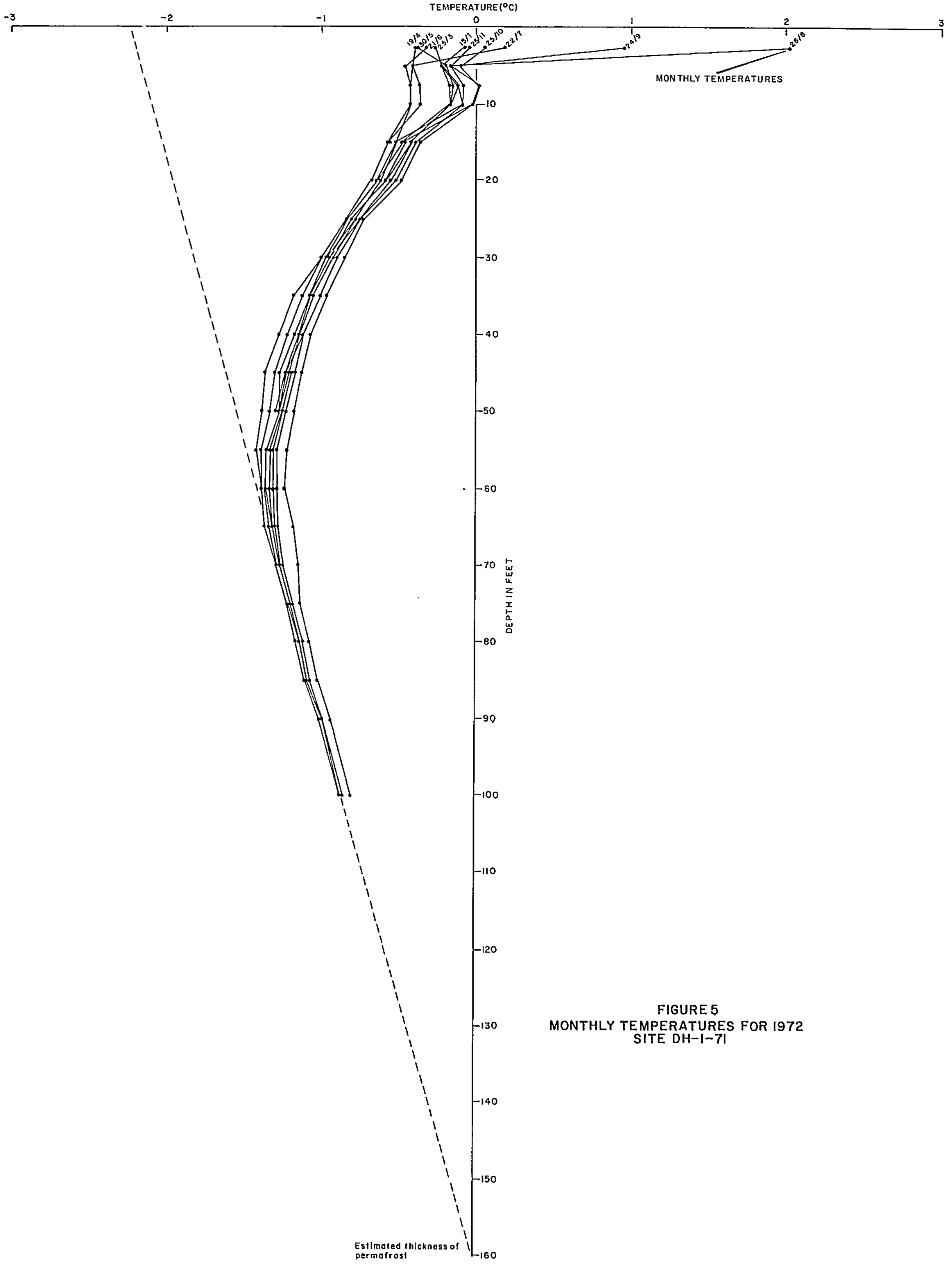


FIGURE 5
MONTHLY TEMPERATURES FOR 1972
SITE DH-1-71

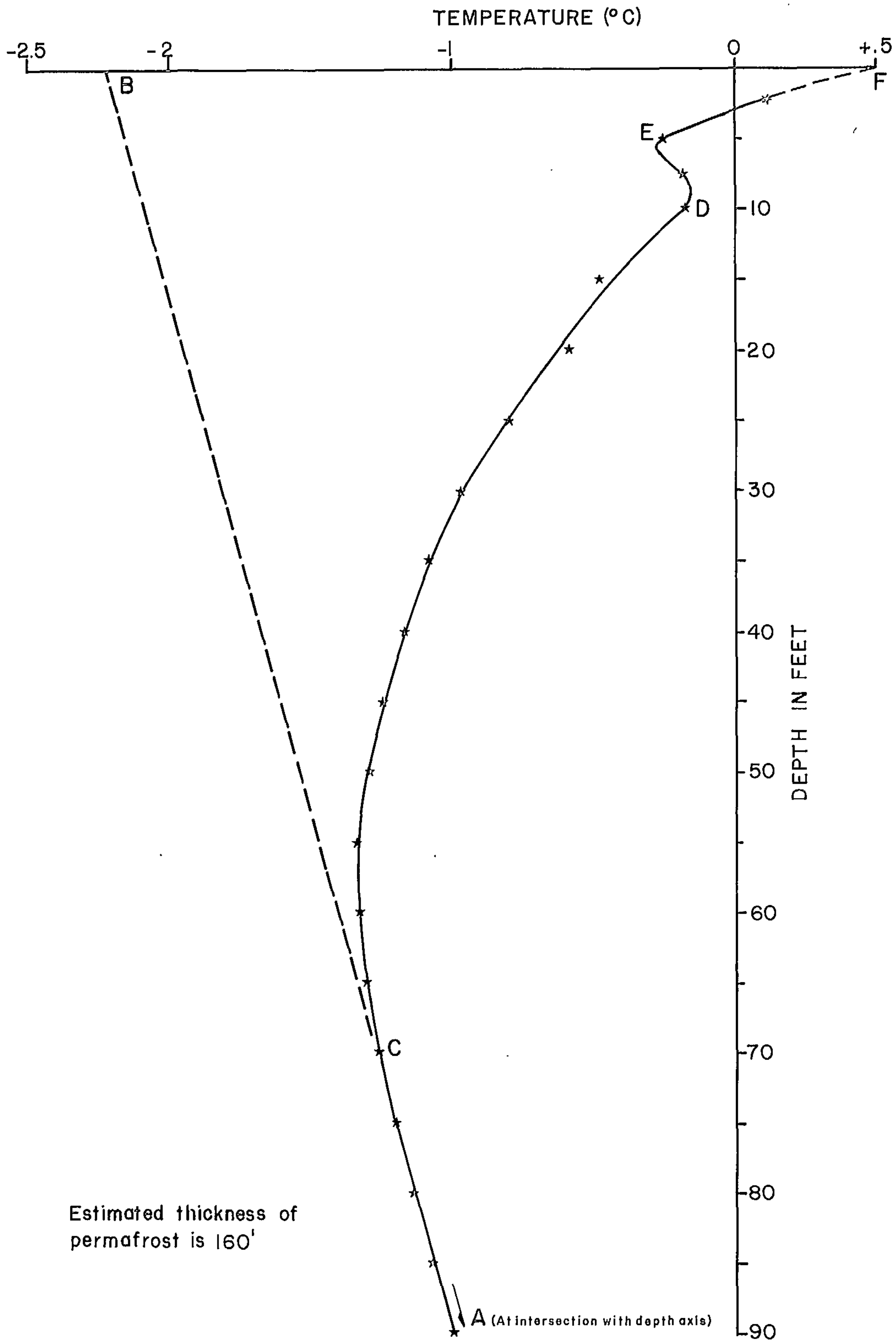


FIGURE 6: THERMAL PROFILE (1972), SITE DH-1-71

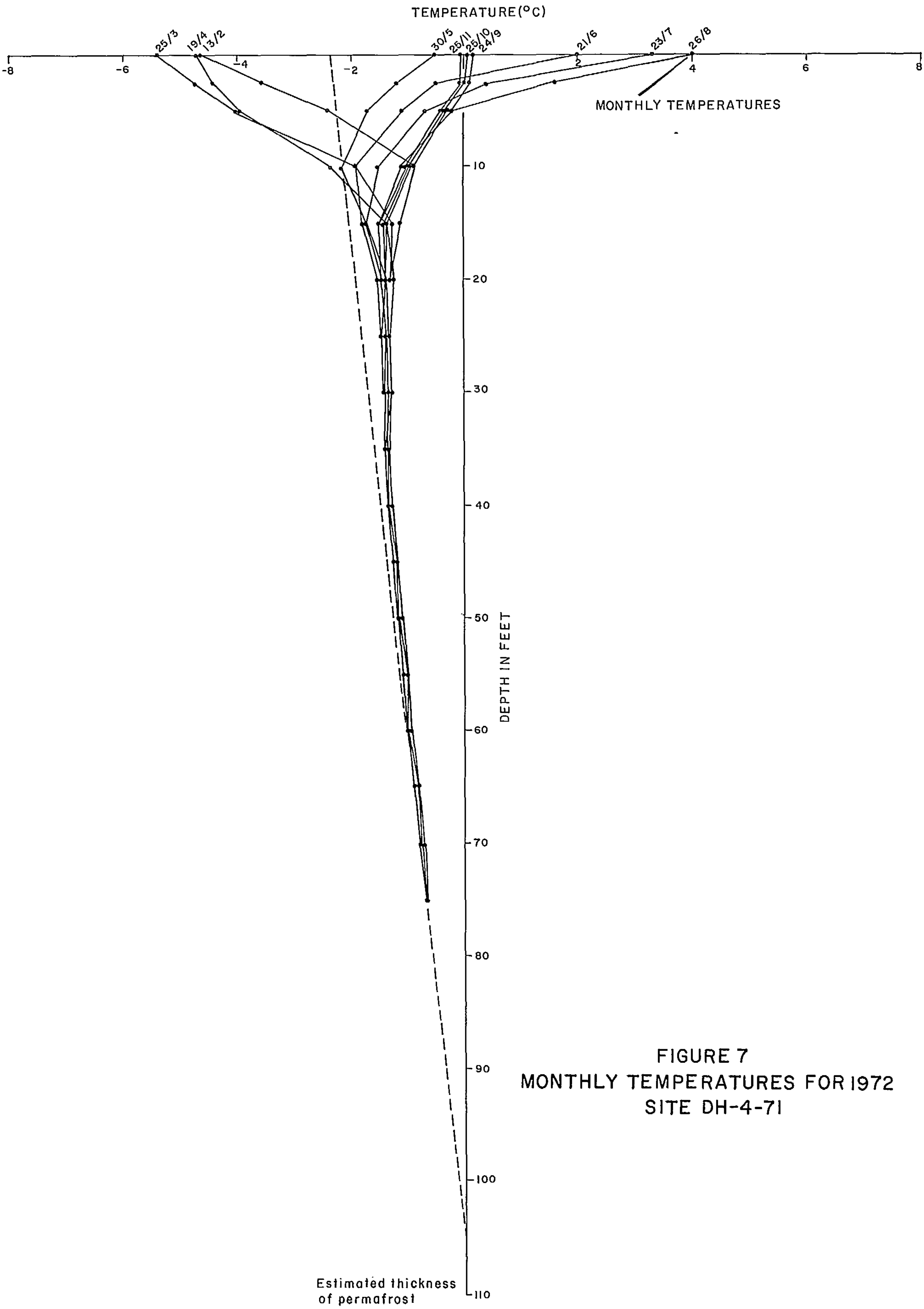


FIGURE 7
MONTHLY TEMPERATURES FOR 1972
SITE DH-4-71

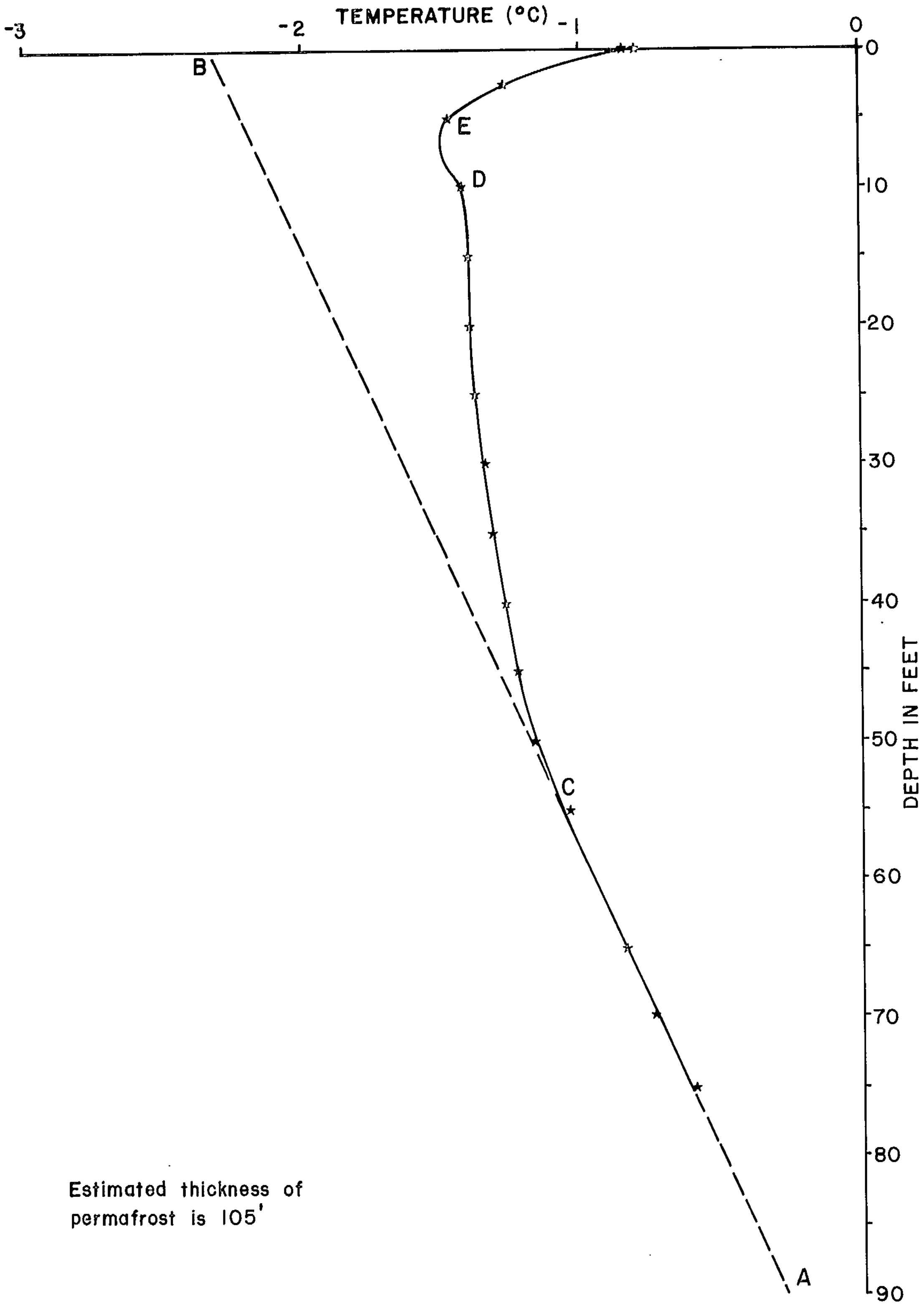


FIGURE 8: THERMAL PROFILE (1972), SITE DH-4-71

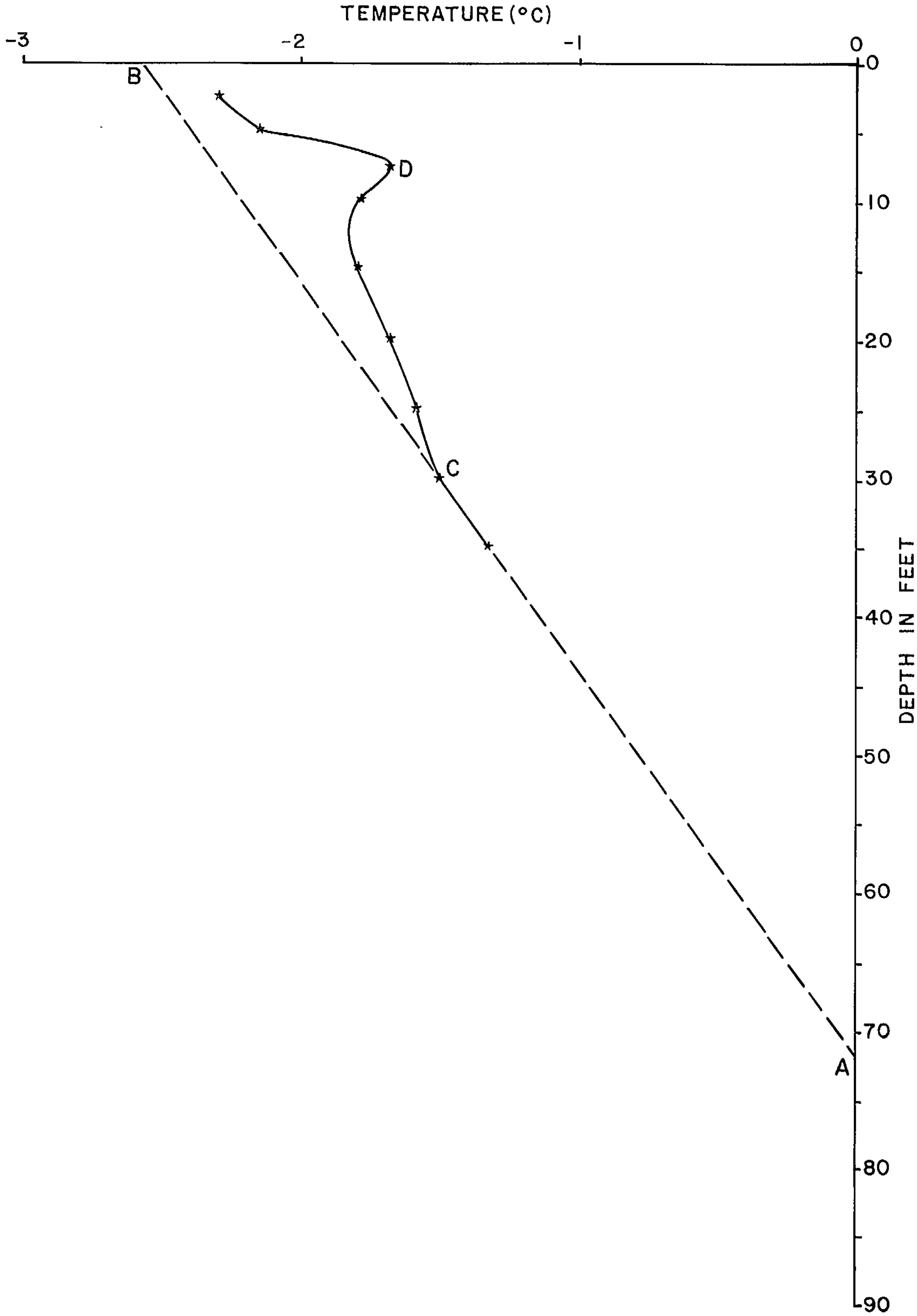


FIGURE 9: THERMAL PROFILE (1972), SITE DH-2-71

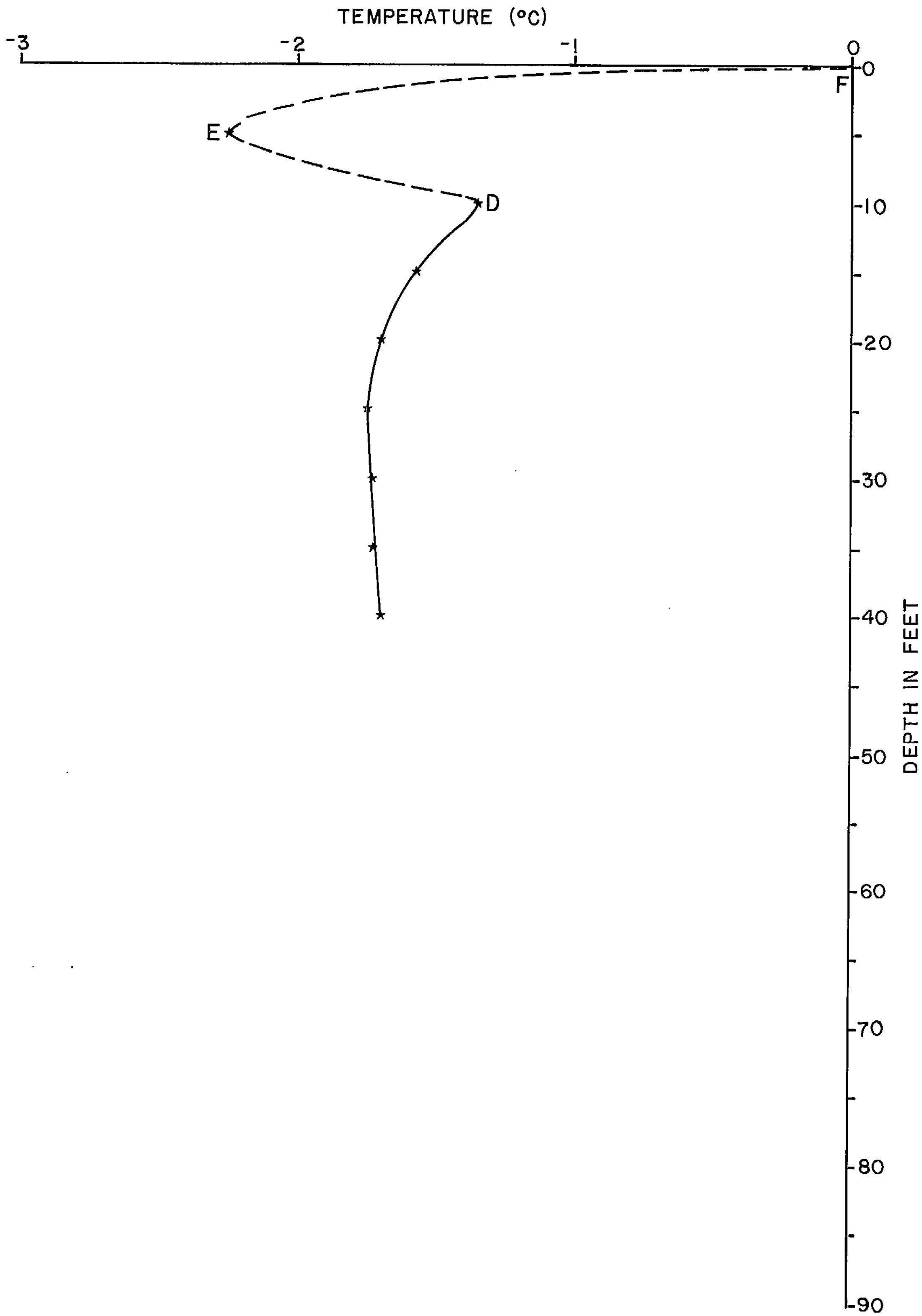


FIGURE 10: THERMAL PROFILE (1972), SITE DH-3-71

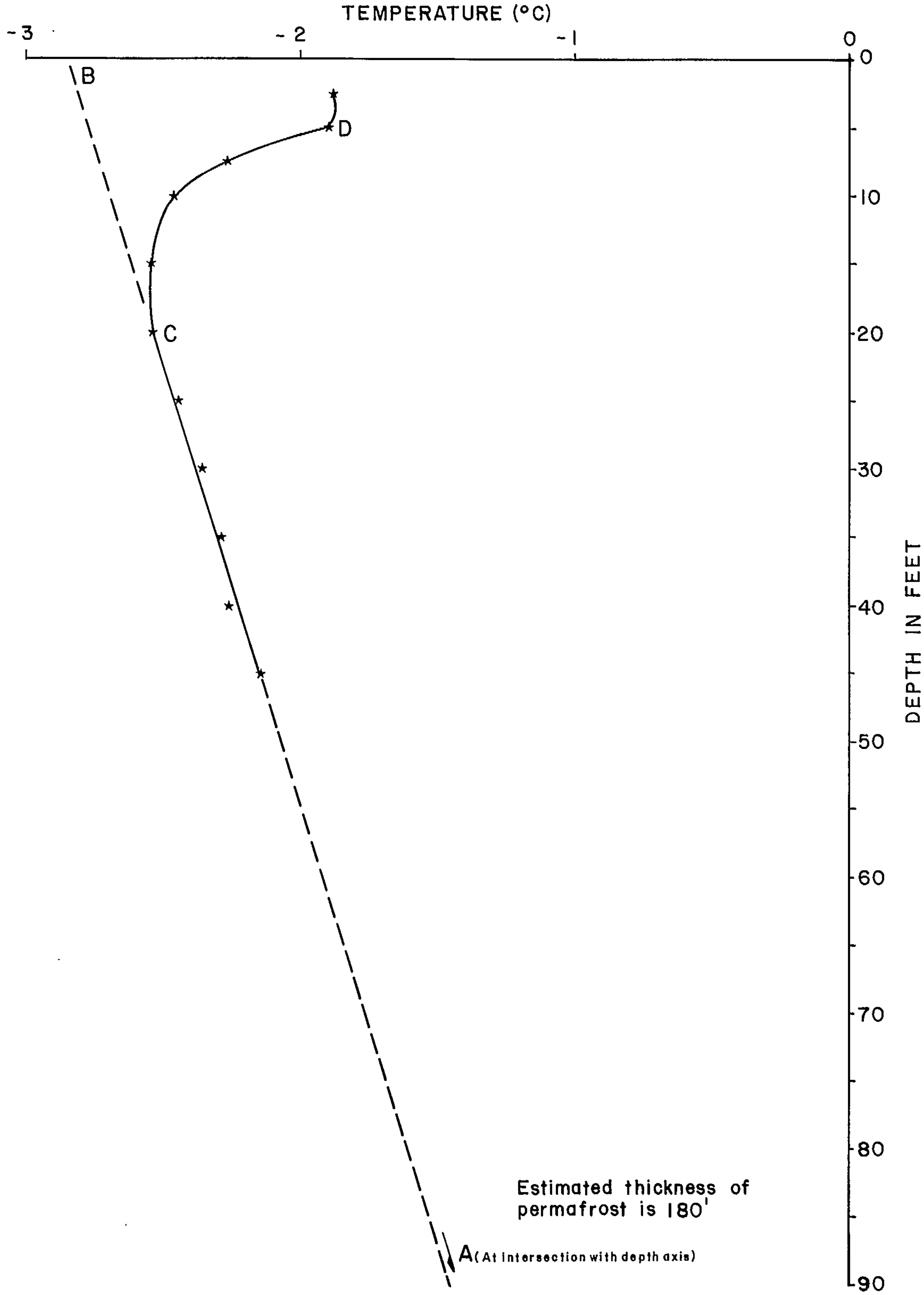


FIGURE 11: THERMAL PROFILE ('72-'73), SITE GL2U

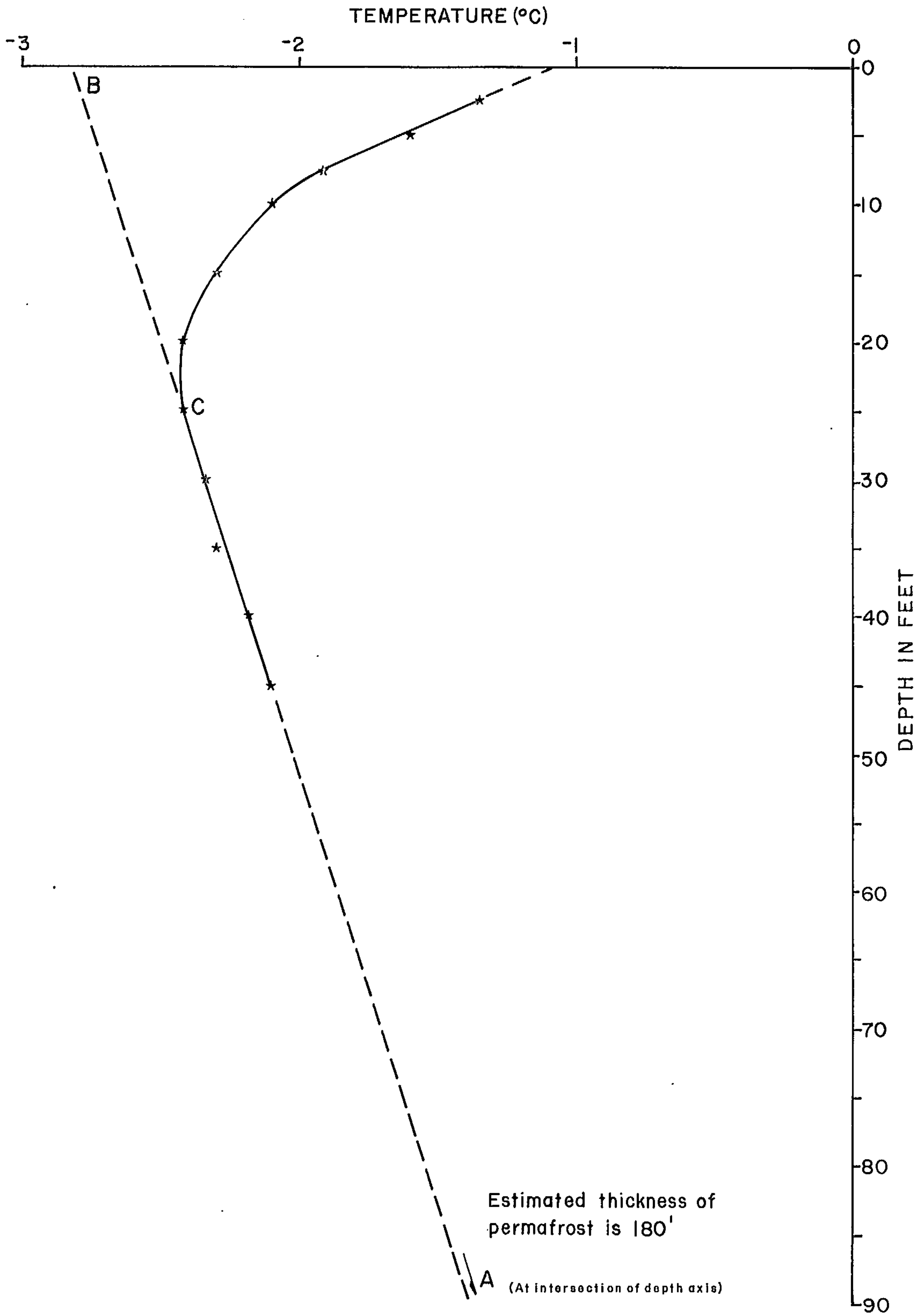


FIGURE 12: THERMAL PROFILE ('72-'73), SITE TL

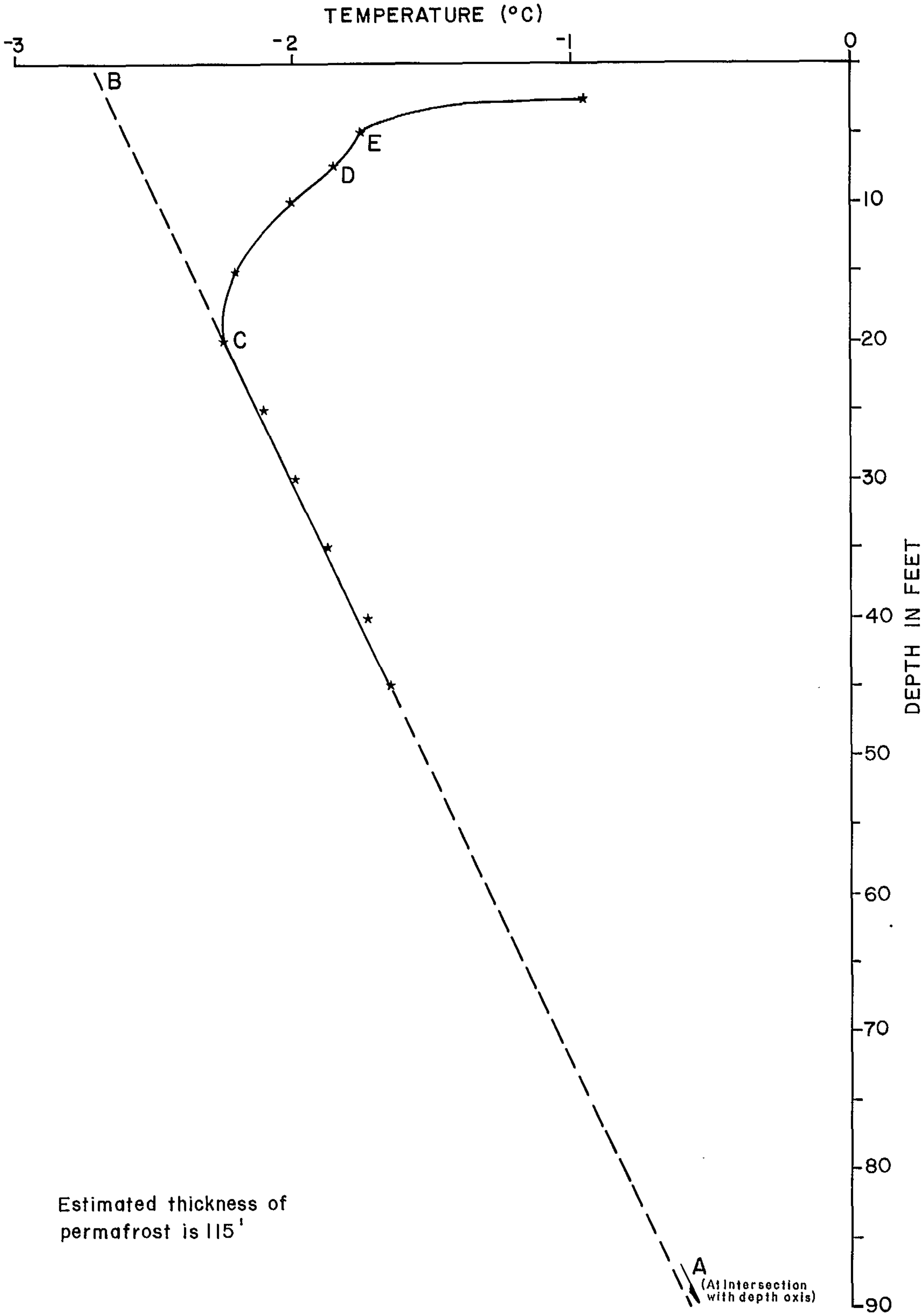


FIGURE 13: THERMAL PROFILE ('72-'73), SITE GL1

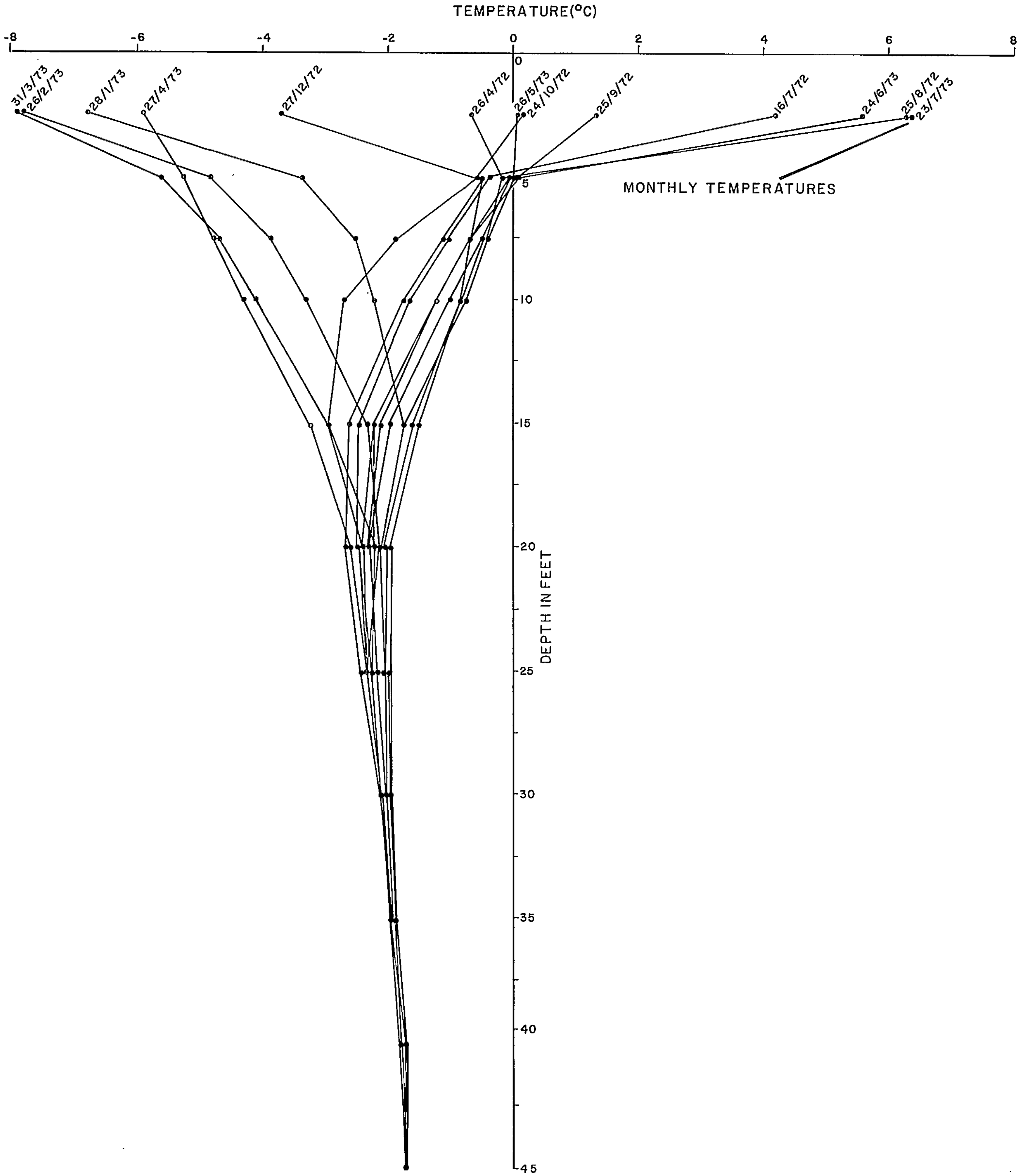


FIGURE 14: MONTHLY TEMPERATURES (1972-73), SITE GL1

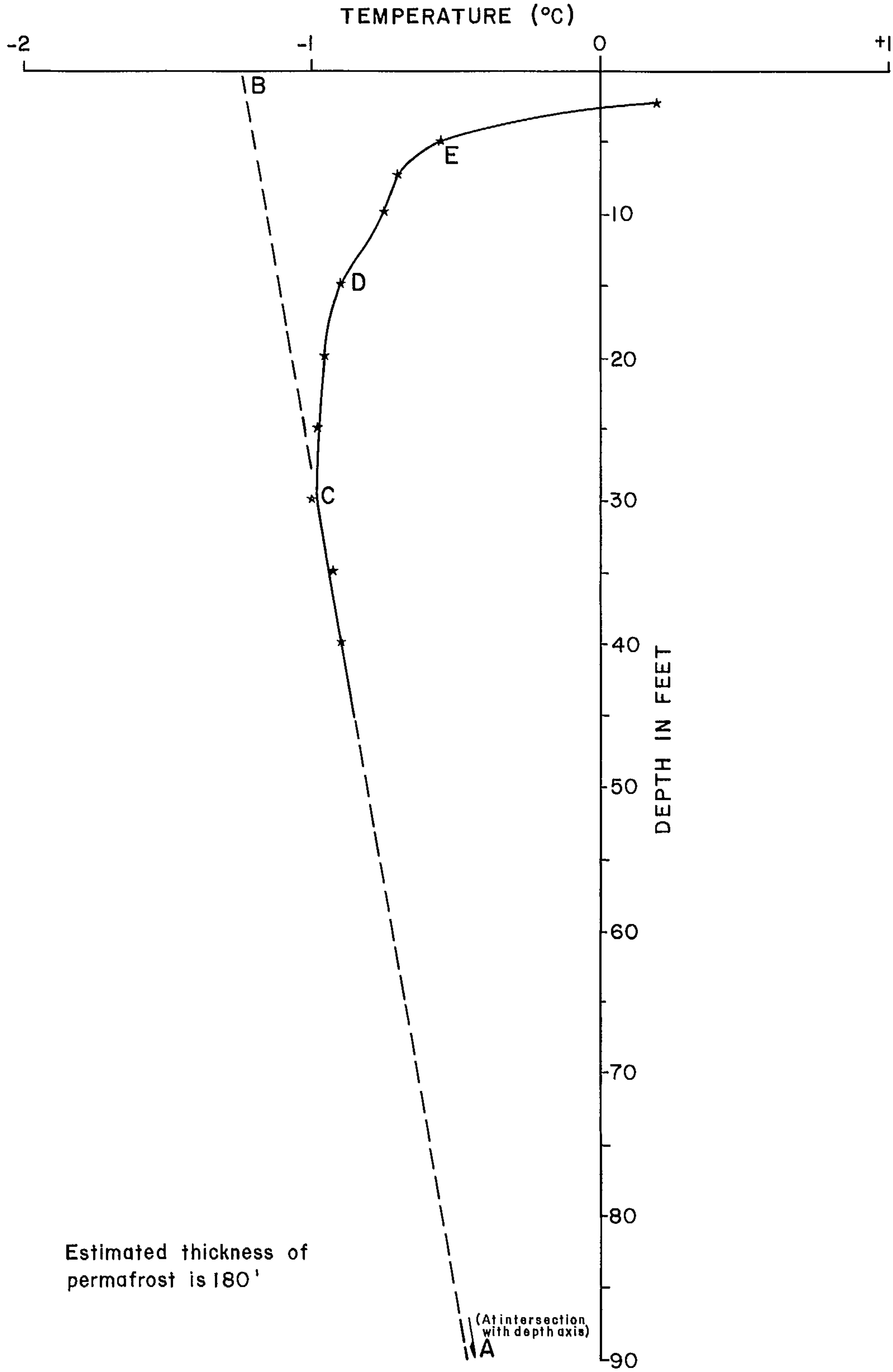


FIGURE 15: THERMAL PROFILE ('72-'73), SITE SA

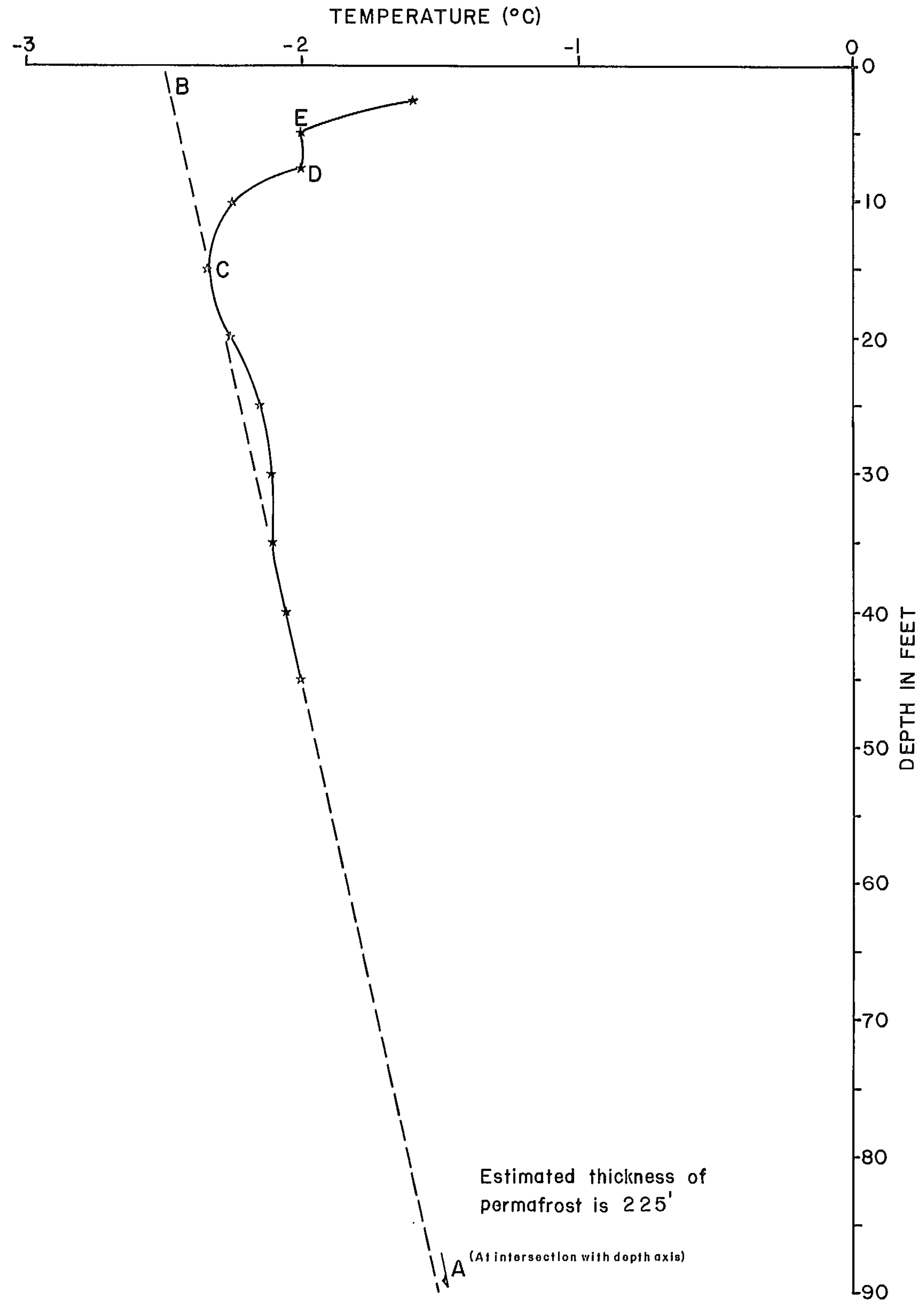


FIGURE 16: THERMAL PROFILE ('72-'73), SITE 7B

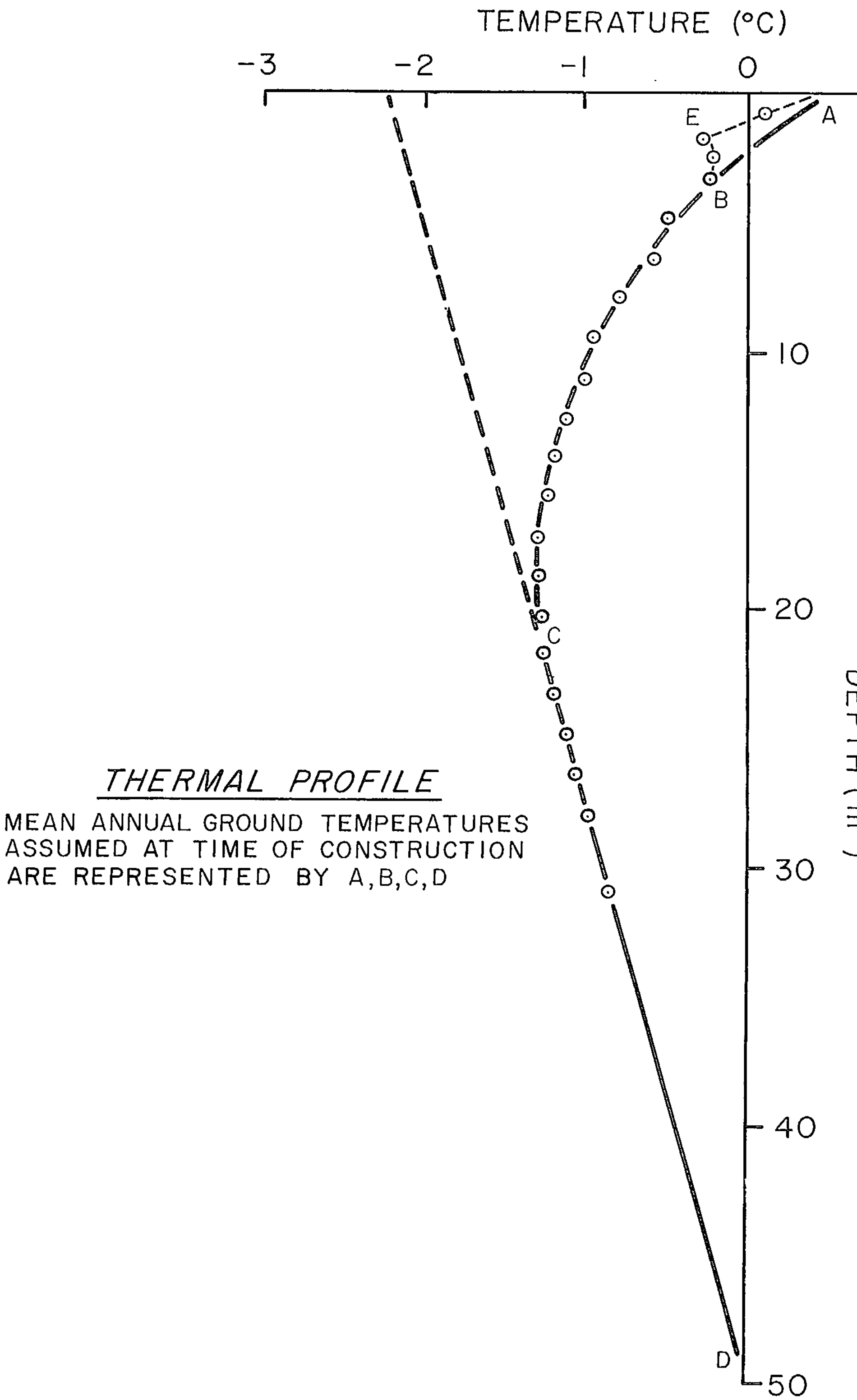


FIGURE 17: MODIFIED THERMAL PROFILE ASSUMED AT R-1

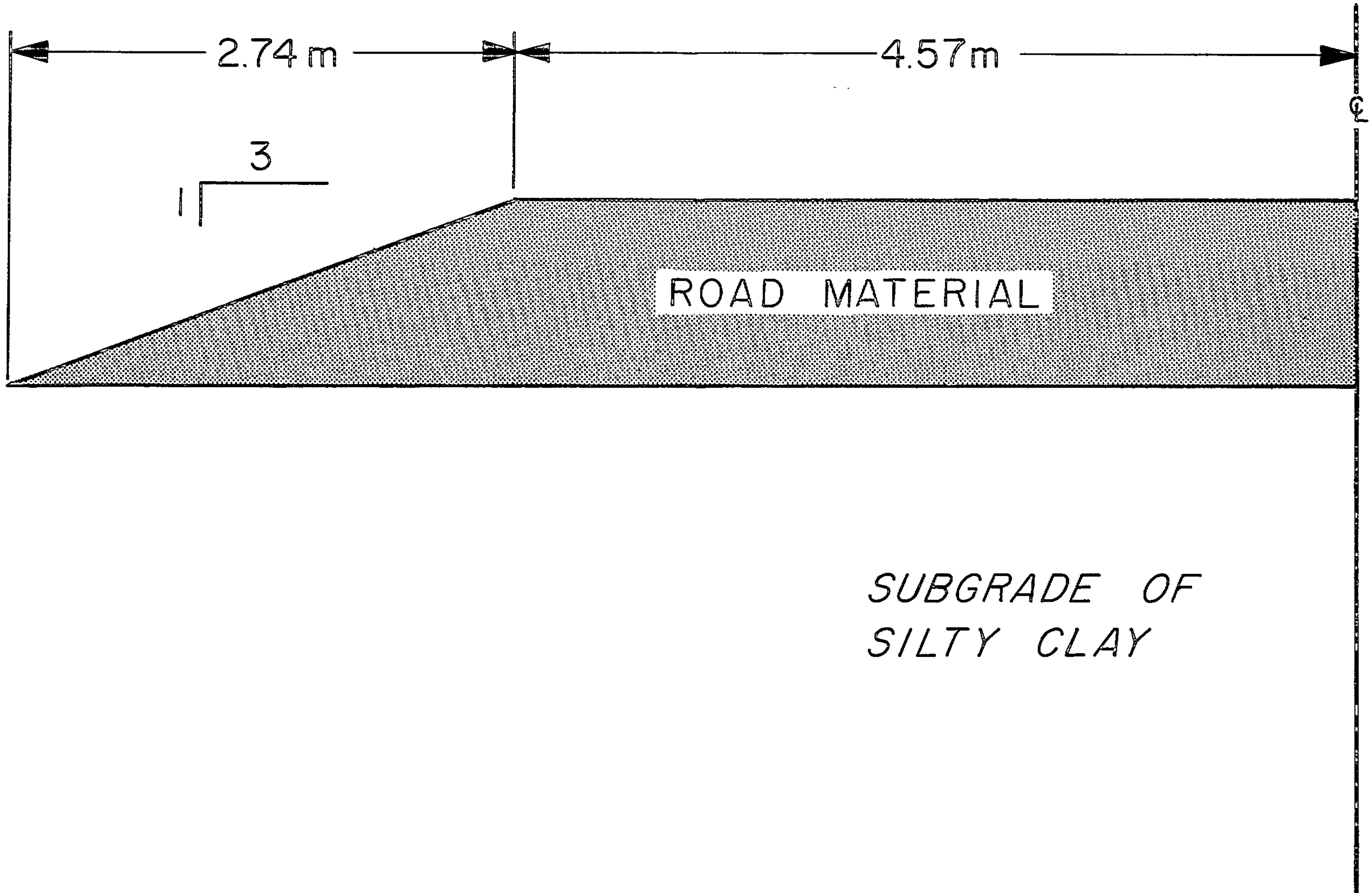


FIGURE 18: ASSUMED CONFIGURATION OF ROAD

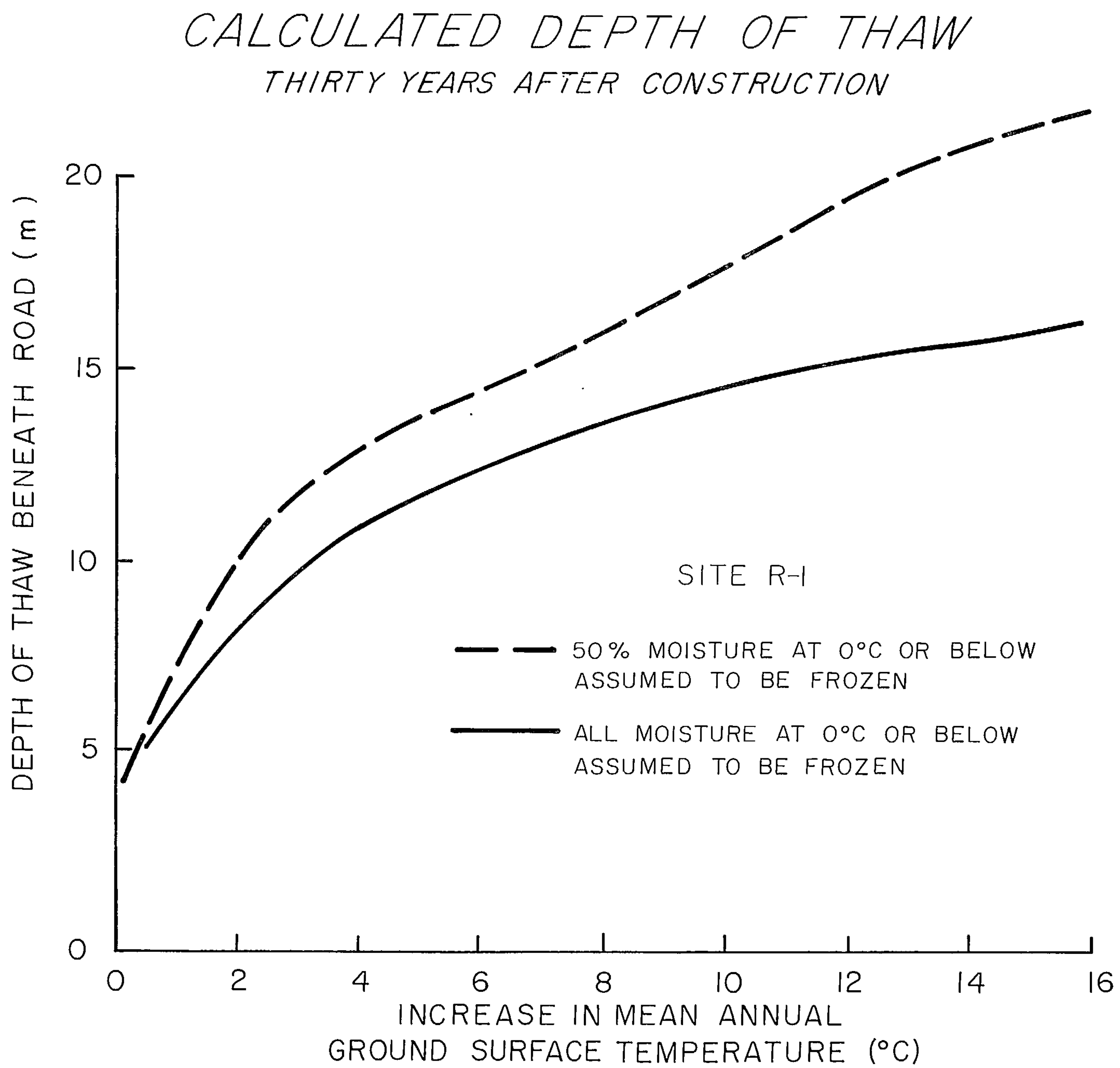
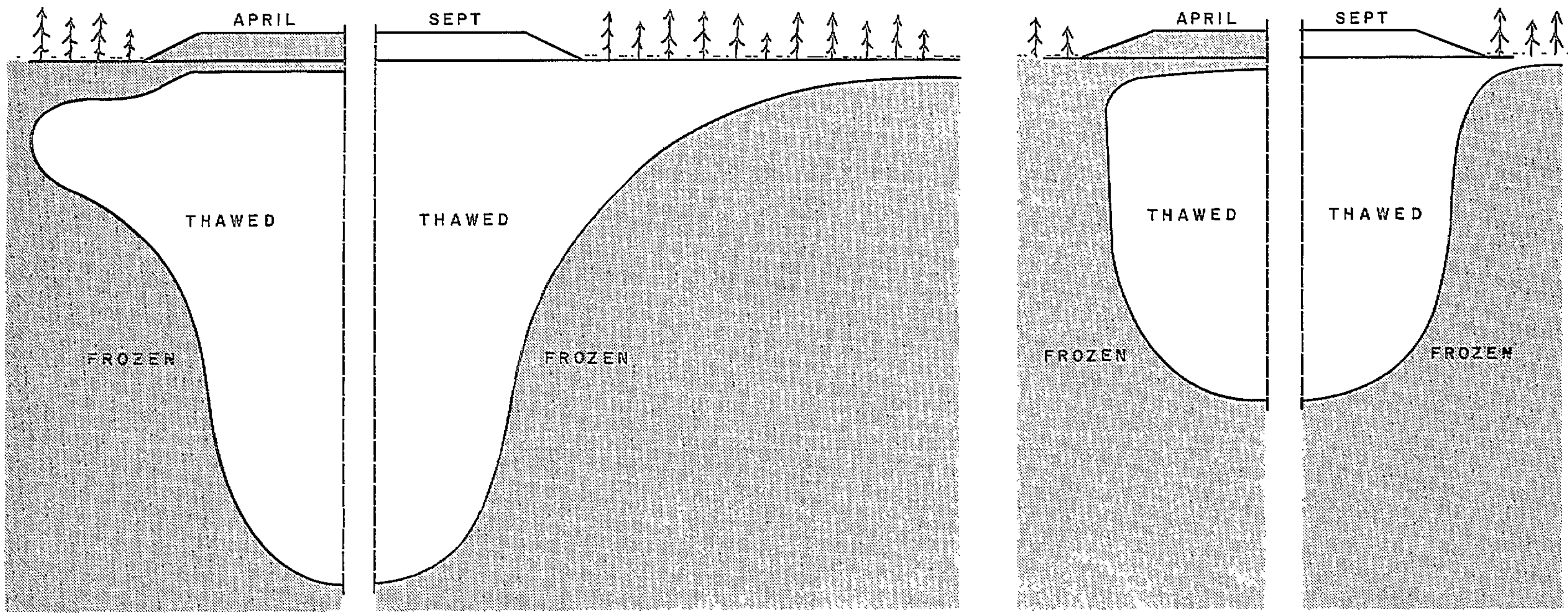


FIGURE 19: CALCULATED DEPTH OF THAW AT R-1

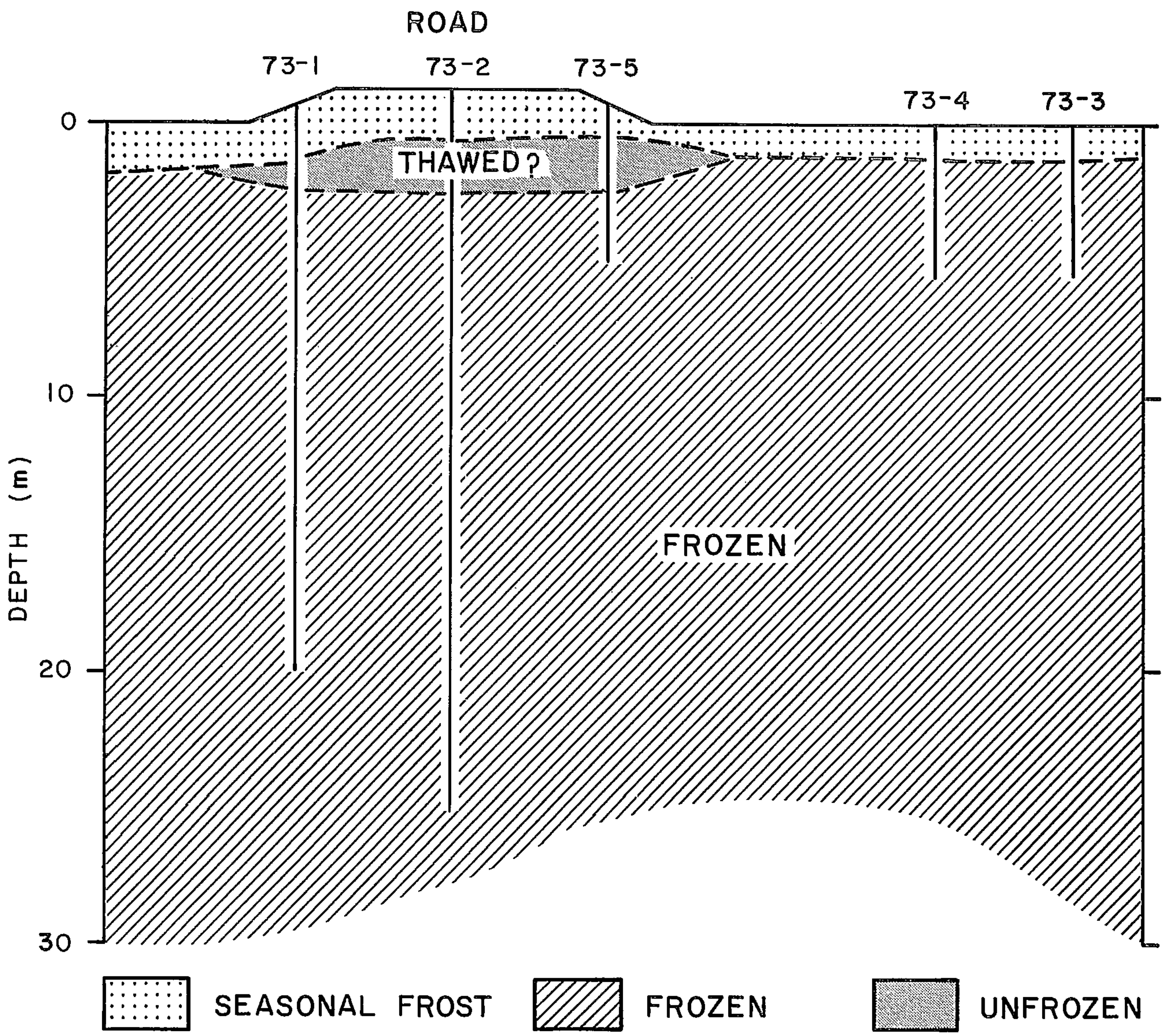
THIRTY YEARS AFTER CONSTRUCTION



(a) Initial thermal profile as in Figure 17
(1) non-linear temperature gradient
(2) mean annual ground surface temp. = +0.5°C
(3) depth to base of permafrost = 48.8 metres

(b) Initial thermal profile assumptions
(1) linear temperature gradient
(2) mean annual ground surface temp. = −2.2°C
(3) depth to base of permafrost = 48.8 metres

FIGURE 20: THAW CONFIGURATIONS FOR R-1 INTERPRETED FROM COMPUTER ANALYSES



SITE GL2U

FIGURE 21: PROFILE CONSTRUCTED FROM DRILLING RESULTS

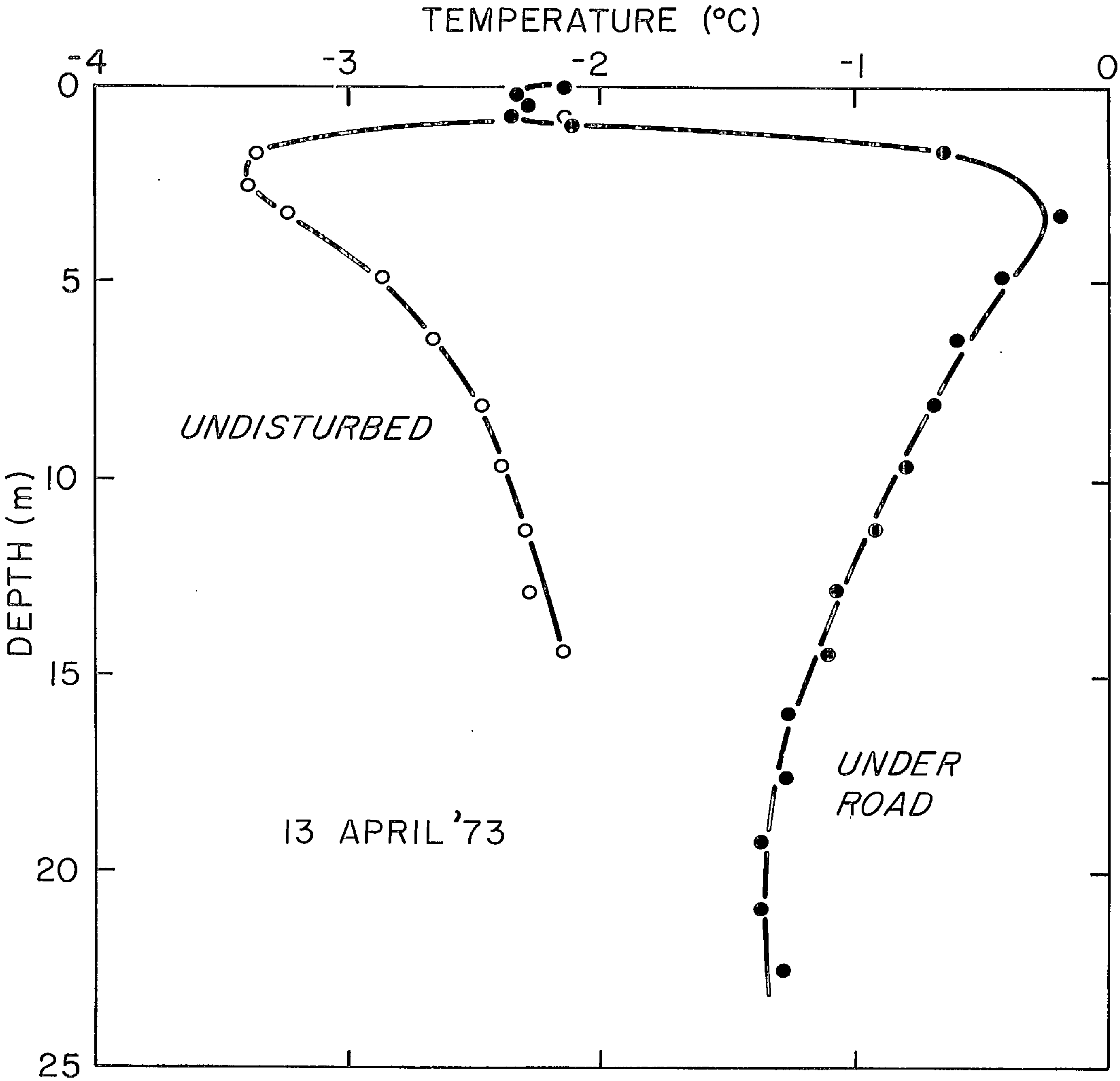


FIGURE 22: MEASURED TEMPERATURE PROFILES, SITE GL2U

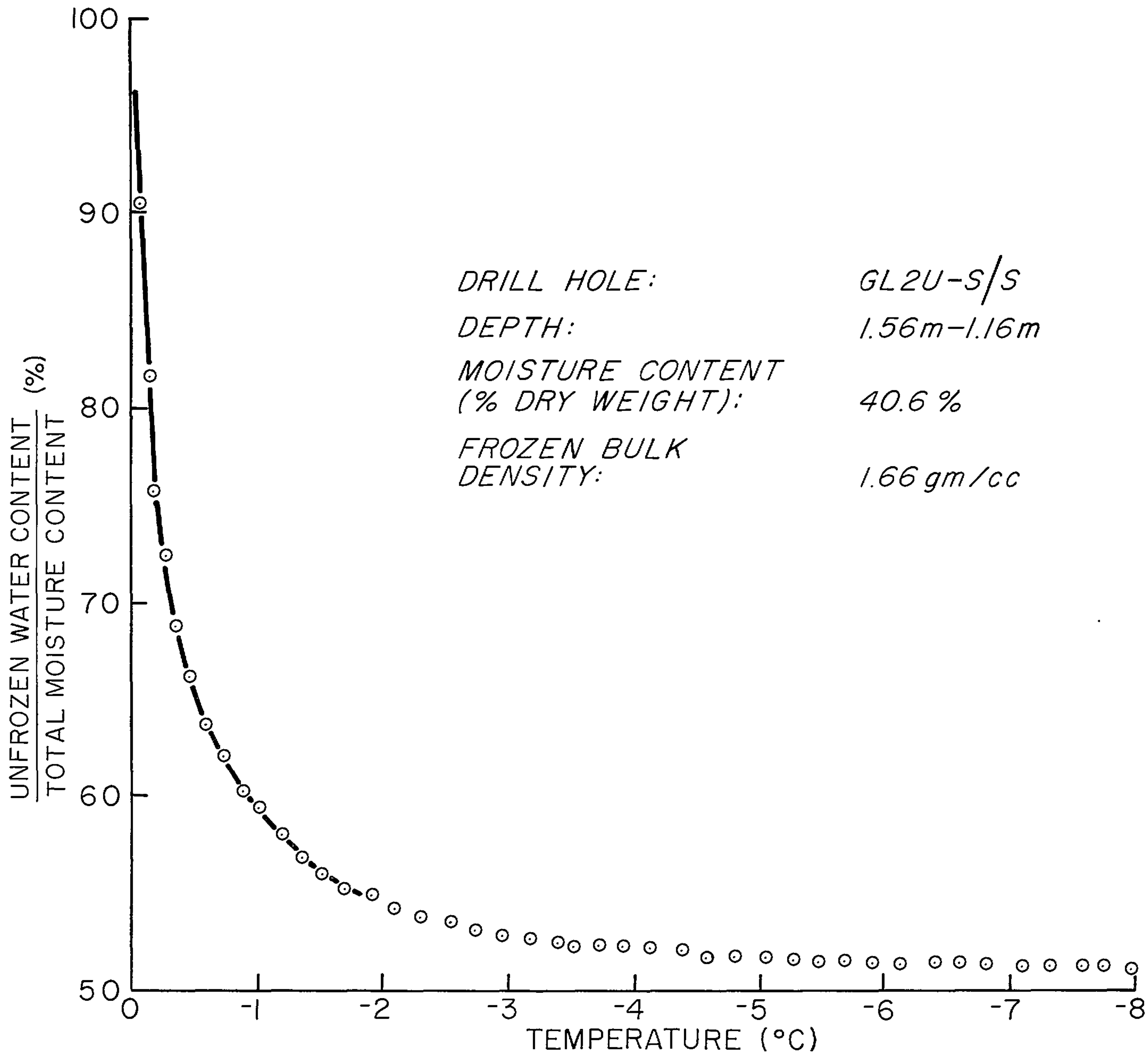
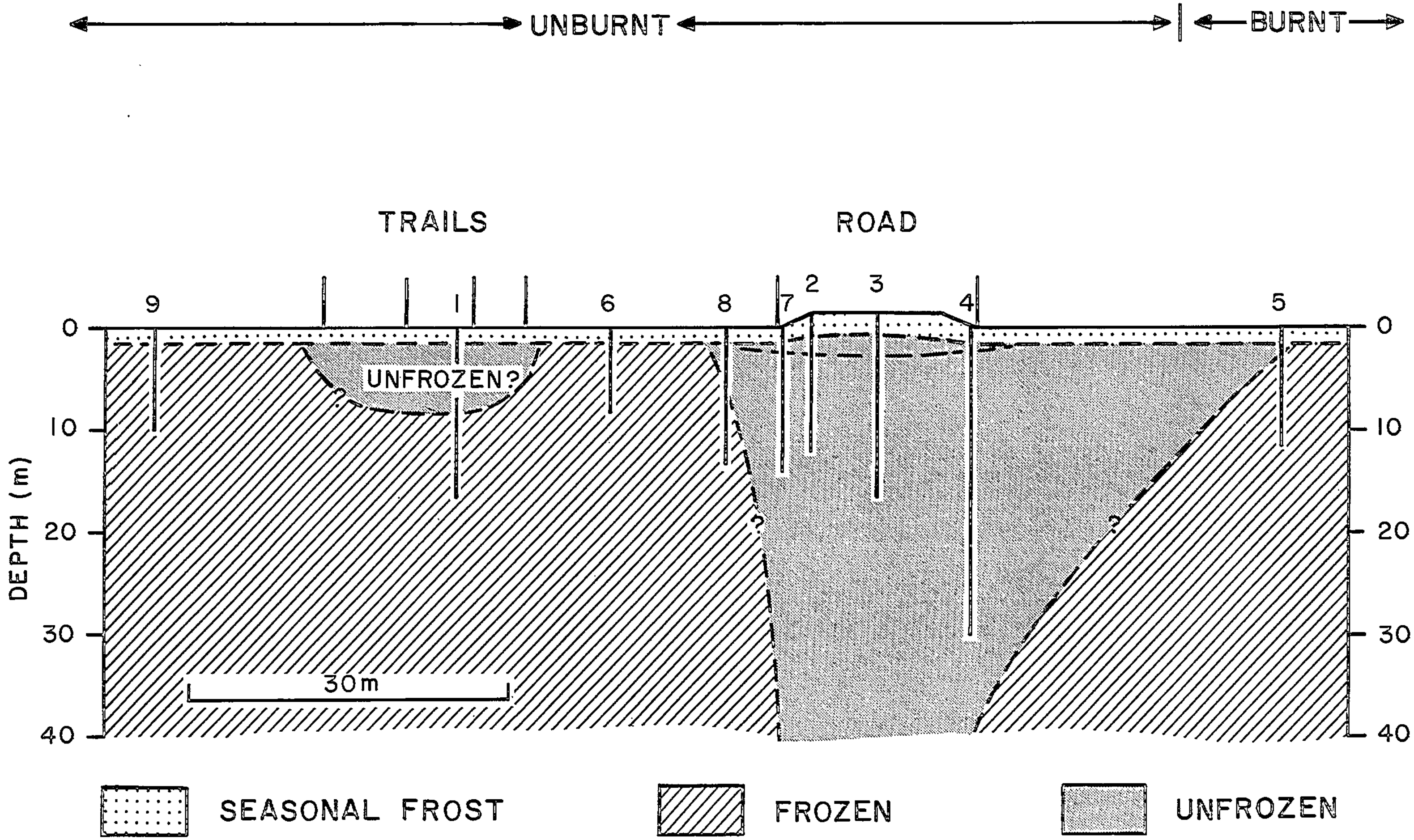


FIGURE 23: UNFROZEN WATER CONTENT AS PERCENTAGE OF TOTAL MOISTURE CONTENT vs. TEMPERATURE



NOTE: ALL DRILL HOLES HL-73 SERIES

FIGURE 24: PROFILE CONSTRUCTED FROM DRILLING RESULTS, SITE HL

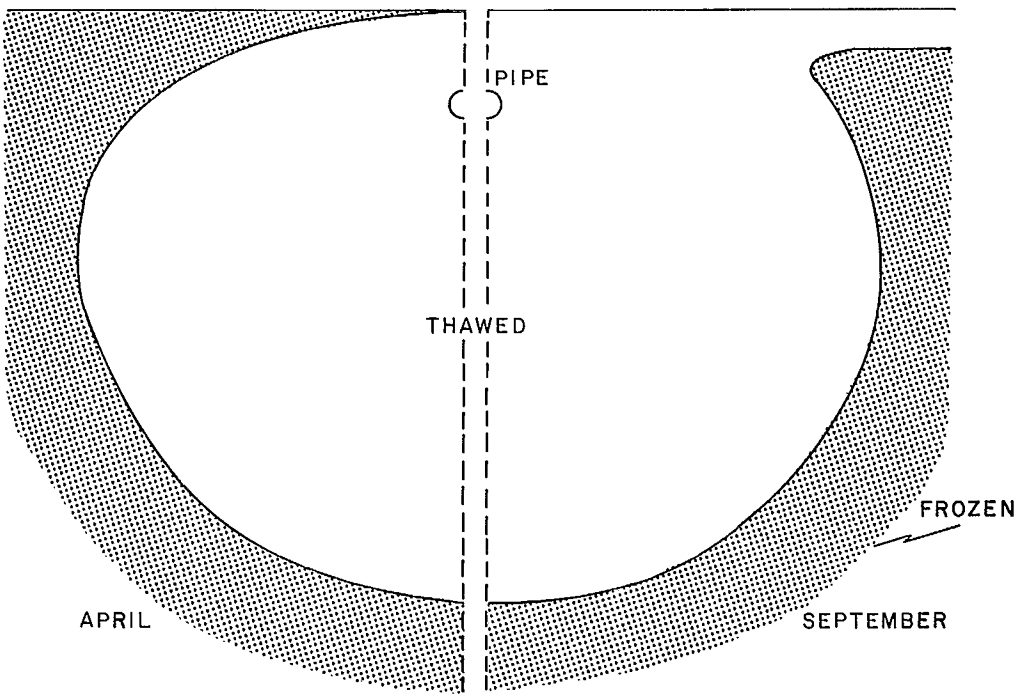


FIGURE 25: THAW CONFIGURATION AROUND WARM PIPELINE

Table I

Thermal Conductivity Values at One Approximate Temperature and Associated Water Contents, Grain Sizes, and Atterberg Limits

Borehole	Depth (ft.)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Best estimate of W_L (%)	W_P (%)	W_I (%)	Activity	Natural Water Content (%)	Thermal Conductivity (W/m°K)	Temperature (°C)
DH-1-71	19.8	-	8.0	77.0	15.0	28	21	7	0.47	25.4	1.52	-5.6
	26.9	-	11.0	79.0	10.0	24	19	5	0.50	24.0	2.36	-5.5
	33.1	-	21.5	56.9	21.6	22	19	3	0.14	23.8	1.67	-5.2
	36.6	-	4.5	86.8	8.7	23	18	5	0.57	32.0	1.99	-5.5
	42.6	-	-	58.5	41.5	37	18	19	0.46	24.7	1.98	-5.4
	55.3	-	1.0	46.5	52.5	49	18	31	0.59	21.2	1.65	-5.6
	63.0	-	0.5	46.3	53.2	50	18	32	0.60	27.1	1.57	-5.6
	68.2	-	-	44.0	56.0	52	19	33	0.59	19.5	1.24	-5.8
	73.5	-	1.0	88.9	10.1	24	19	5	0.50	24.2	2.45	-5.6
	79.2	-	38.5	53.0	8.5	20	16	4	0.47	28.4	2.41	-5.7
	84.1	-	8.5	42.3	49.2	39	15	24	0.49	22.6	1.34	-6.1
	91.0	-	34.0	58.5	7.5	20	16	4	0.53	25.7	2.00	-5.7
	95.3	-	17.5	73.8	8.7	24	19	5	0.57	25.2	2.17	-5.6
	101.3	-	1.5	47.4	51.1	50	18	32	0.63	21.8	1.35	-5.8

DH-2-71	15.7	2.5	32.0	44.2	21.3	26	15	11	0.52	7.7	0.78	-5.5
	19.7	5.0	23.0	51.7	20.3	27	17	10	0.49	9.3	1.27	-5.7
DH-3-71	20.1	-	-	70.0	30.0	25	14	11	0.37	21.2	2.40	-5.6
	30.0	-	9.0	71.5	19.5	24	14	10	0.51	21.0	1.72	-5.6
	34.8	-	-	56.3	43.7	46	23	23	0.53	22.4	1.00	-5.6
	40.1	-	-	55.3	44.7	47	23	24	0.54	22.8	1.43	-5.5
	49.8	-	-	52.7	47.3	50	24	26	0.55	19.6	1.64	-5.7
DH-4-71	10.2	-	-	35.5	64.5	65	23	42	0.65	128.6	1.08	-5.0
	17.9	-	-	36.8	63.2	64	23	41	0.65	104.2	1.04	-5.0
	25.0	-	-	58.0	42.0	40	19	21	0.50	27.3	1.61	-5.0
	34.8	-	-	46.6	53.4	51	20	31	0.58	24.7	1.15	-5.1
	40.0	-	-	33.6	66.4	68	24	44	0.66	167.0	1.17	-5.1
	45.8	-	-	22.5	77.5	82	28	54	0.70	27.5	1.52	-5.1
	54.4	-	-	56.3	43.7	48	20	28	0.64	29.9	0.97	-5.1
	73.7	-	-	39.1	60.9	58	22	36	0.59	34.1	0.98	-5.0
	79.8	-	-	47.3	52.7	52	21	31	0.59	34.1	1.04	-5.1

Table II

Thermal Conductivity Values at Several Temperatures

						Best estimate of				Natural	Thermal Conductivity (W/m°K) at			
Borehole	Depth (ft.)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	W_L (%)	W_P (%)	W_I (%)	Activity	Water Content (%)	$-2.5^{\circ}C$	$-5.0^{\circ}C$	$-7.5^{\circ}C$	$-10.0^{\circ}C$
GL1	0.88	*	*	*	*	*	*	*	*	*	1.80	1.23	1.47	1.57
	12.21	*	*	*	*	*	*	*	*	*	0.89	1.01	1.44	1.03
	12.46	*	*	*	*	*	*	*	*	*	1.19	1.25	1.28	1.27
	14.92	*	*	*	*	*	*	*	*	*	1.56	1.57	1.55	1.43
	16.58	*	*	*	*	*	*	*	*	*	1.71	1.70	1.76	1.78
	17.00	*	*	*	*	*	*	*	*	*	1.58	1.44	1.64	1.69
	17.67	*	*	*	*	*	*	*	*	*	1.24	1.24	1.36	1.25
GL2U	1.75	*	*	*	*	*	*	*	*	*	1.46	1.47	1.52	1.52
	5.25	*	*	*	*	*	*	*	*	*	1.21	1.23	1.25	1.31
	5.67	*	*	*	*	*	*	*	*	*	1.27	1.30	1.47	1.37
	5.71	*	*	*	*	*	*	*	*	*	1.34	1.47	1.45	1.50
	9.00	*	*	*	*	*	*	*	*	*	1.58	1.31	1.34	1.37
	9.04	*	*	*	*	*	*	*	*	*	1.27	1.34	1.42	1.39
	11.13	*	*	*	*	*	*	*	*	*	1.07	1.23	1.26	1.28
	11.17	*	*	*	*	*	*	*	*	*	1.40	1.48	1.50	1.45
	16.50	*	*	*	*	*	*	*	*	*	1.74	1.59	1.75	1.72
	16.54	*	*	*	*	*	*	*	*	*	1.47	1.69	1.71	1.66
	21.96	*	*	*	*	*	*	*	*	*	1.43	1.38	1.44	1.44
	22.00	*	*	*	*	*	*	*	*	*	1.46	1.50	1.69	1.61
	22.04	*	*	*	*	*	*	*	*	*	1.28	1.20	1.26	1.29
	31.38	*	*	*	*	*	*	*	*	*	1.32	1.45	1.52	1.54
	31.42	*	*	*	*	*	*	*	*	*	1.35	1.50	1.47	1.45

* – Samples have not been returned by Earth Physics Branch, and therefore grain size and moisture content tests have not been done.

Table III

Thermal Parameters Assumed in Model Study

	Road Fill		Subgrade	
	Frozen	Thawed	Frozen	Thawed
Thermal conductivity (mcal per cm sec ^{o}C	3.5	3.0	5.0	3.4
Thermal diffusivity (cm^{2} per sec)	0.010	0.006	0.012	0.006
Natural water content (per cent dry weight)	16		17.5	
Volumetric specific heat (cal per cm^{3} per ^{o}C)	0.35	0.50	0.42	0.57

Appendix I

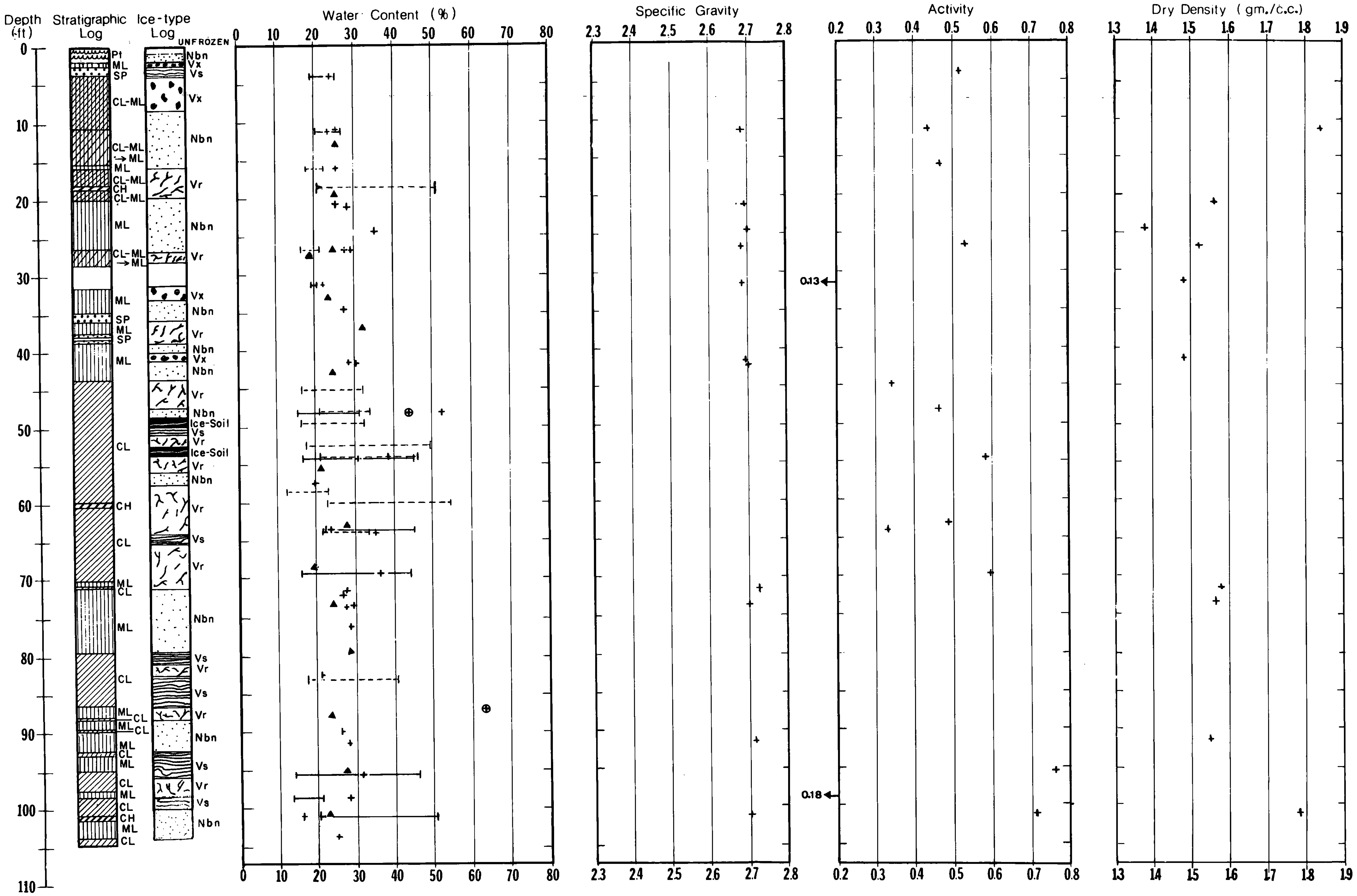
Stratigraphic and Physical Data

Drill hole: DH-1-71

Date(s) drilled: June 16 to June 29, 1971

Site description: The drill site, located on the east bank of the Mackenzie River about 50 metres (165 feet) from the edge of the bank, was about 15 metres (50 feet) above the level of the river and was surrounded by deep gullies. The ground was slightly hummocky and covered with moss and peat. A fire in recent years destroyed the moderately dense timber. Drainage was good.

Genetic Classification of Overburden: Glaciolacustrine deposit of silts, sands and clays under moderate peat cover.



SOIL :-

- SP: poorly-graded grey medium sand
- ML: dark-grey silt and fine sand
- CL: dark-grey inorganic silty clay of low to medium plasticity
- CL-ML: dark-grey clayey silt
- CL-ML → ML: dark-grey clayey silt grading to a mixture of silt and fine sand
- OL: black and brown mottled organic silt
- CH: grey inorganic clay of high plasticity
- Pt: peat
- Lost core

UNIFIED SOIL CLASSIFICATION SYSTEM

ICE :-

- Nf: ice not visible, poorly bonded
- Nbn: ice not visible, well bonded, no excess ice
- Nbe: ice not visible, well bonded, excess ice
- Vx: visible ice less than one inch thick, individual ice inclusions
- Vr: visible ice less than one inch thick, random or irregularly oriented ice formations
- Vs: visible ice less than one inch thick, stratified or distinctly oriented ice formations
- ICE AND SOIL: visible ice greater than one inch thick, ice with soil inclusions

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM #79

W_P —+— W_L Atterberg limits + natural water contents (uncontaminated samples)

W_P - - + - - W_L Atterberg limits + natural water contents (Thermінol - contaminated samples)

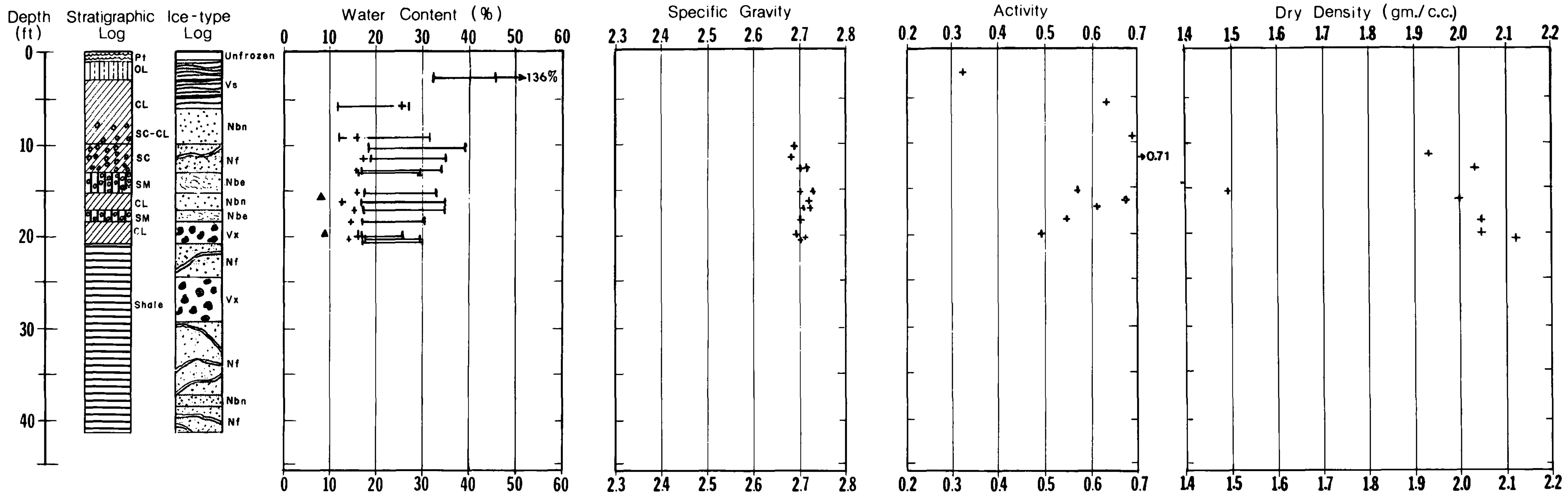
▲ Water contents from thermal conductivity samples

⊕ (excess) natural water contents

DH-1-71 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: DH-2-71

Date(s) drilled:	June 30 to July 28, 1971
Site description:	This drill site lay just off the intersection of two seismic lines. The ground was very hummocky but regionally flat and poorly drained. All tree cover had been destroyed in a recent fire.
Genetic Classification of Overburden:	Glacial till deposit of clays and sandy clays over shale.



DH-2-71 STRATIGRAPHIC AND PHYSICAL DATA

SOIL:-

Pt: peat

SM: dark-brown to grey silty sand with some gravel

SC: brown gravelly sand-clay

SC-CL: brown gravelly sand-clay of low to medium plasticity

CL: grey gravelly silty clay of low to medium plasticity

OL: mottled yellow-brown organic silt-clay of medium plasticity

UNIFIED SOIL CLASSIFICATION SYSTEM

W_P —+— W_L Atterberg limits + natural water contents

▲ Water contents from thermal conductivity samples

ROCK:-

Shale, dark grey to black

ICE:-

Nf: ice not visible, poorly bonded

Nbn: ice not visible, well bonded, no excess ice

Nbe: ice not visible, well bonded, excess ice

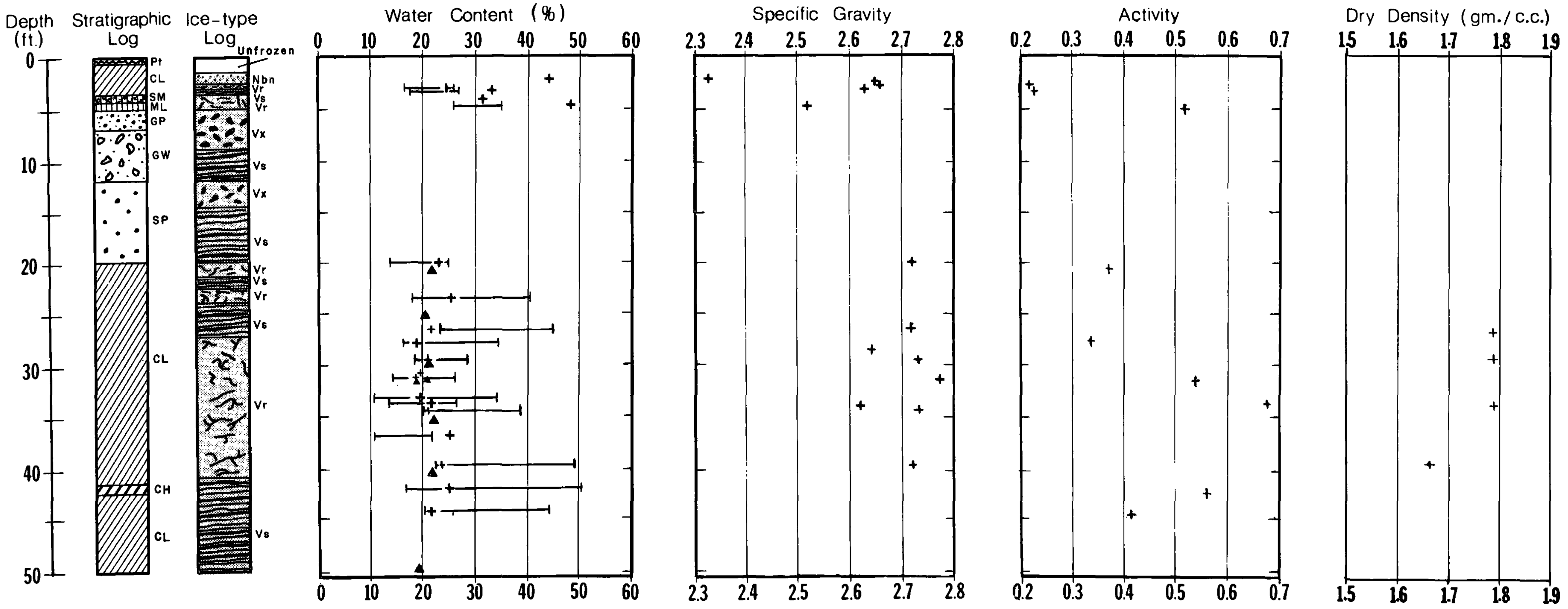
Vx: visible ice less than one inch thick, individual ice inclusions

Vs: visible ice less than one inch thick, stratified or distinctly oriented ice formations

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM #79

Drill hole: DH-3-71

Date(s) drilled:	July 20 to 31, 1971 and August 2 to 4, 1971
Site Description:	The drill was located in a clearing in a dense forest on the slope of a terrace about 2 km (1 mile) from the west bank of the Mackenzie River. The clearing existed prior to these drilling operations and probably dated from the previous winter or the one before. The drill site was fairly level but shallow gullies criss-crossed the slope. Drainage was good.
Genetic Classification of Overburden:	Alluvial deposit of clay, sands and gravels over clay beneath a thin peat cover.



DH-3-71 STRATIGRAPHIC AND PHYSICAL DATA

SOIL:-

Pt: peat

GW: dark-brown well-graded gravel-sand mixture with very little fines

GP: dark-brown poorly-graded gravel-sand mixture with very little fines

SP: dark-grey poorly-graded gravelly sand with negligible fines

....*SOIL (cont'd)*:-

SM: dark-brown silty fine sand with some gravel

ML: dark-brown clayey silty sand with some gravel and organic material

CL: dark-grey (except near the surface where the colour is yellow brown) silty clay of low to medium plasticity

CH: dark-grey silty clay of high plasticity

ICE:-

Nbn: ice not visible, well bonded, no excess ice

Vx: visible ice less than one inch thick, individual ice inclusions

Vr: visible ice less than one inch thick, random or irregularly oriented ice formations

Vs: visible ice less than one inch thick, stratified or distinctly oriented ice formations

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM #79

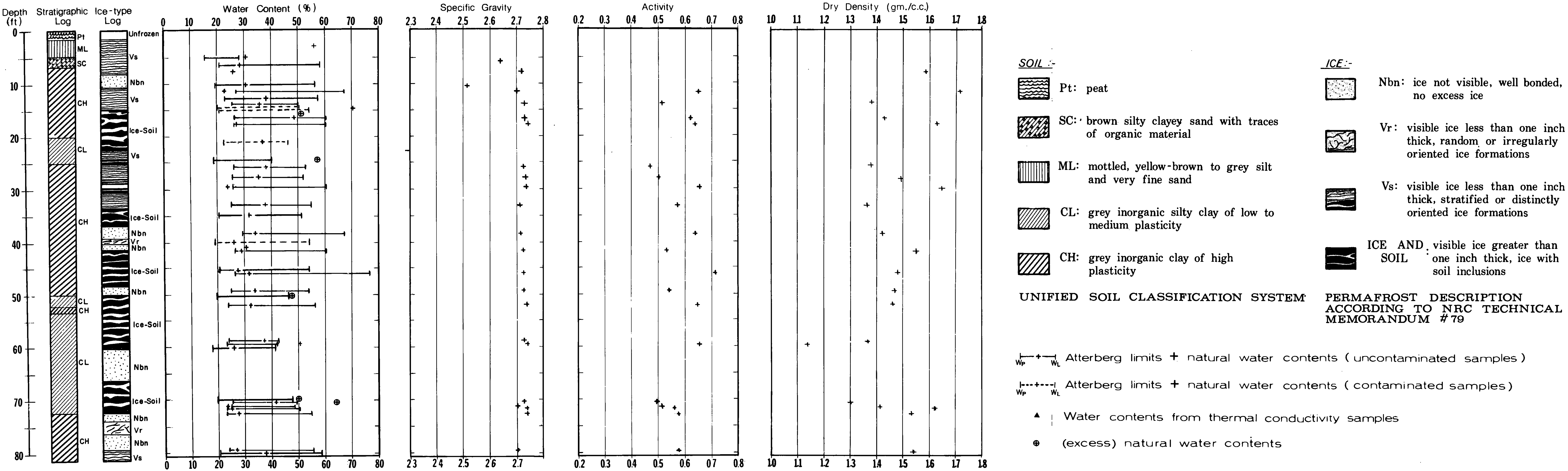
UNIFIED SOIL CLASSIFICATION SYSTEM

W_P —+— W_L Atterberg limits + natural water contents

▲ Water contents from thermal conductivity samples

Drill hole: DH-4-71

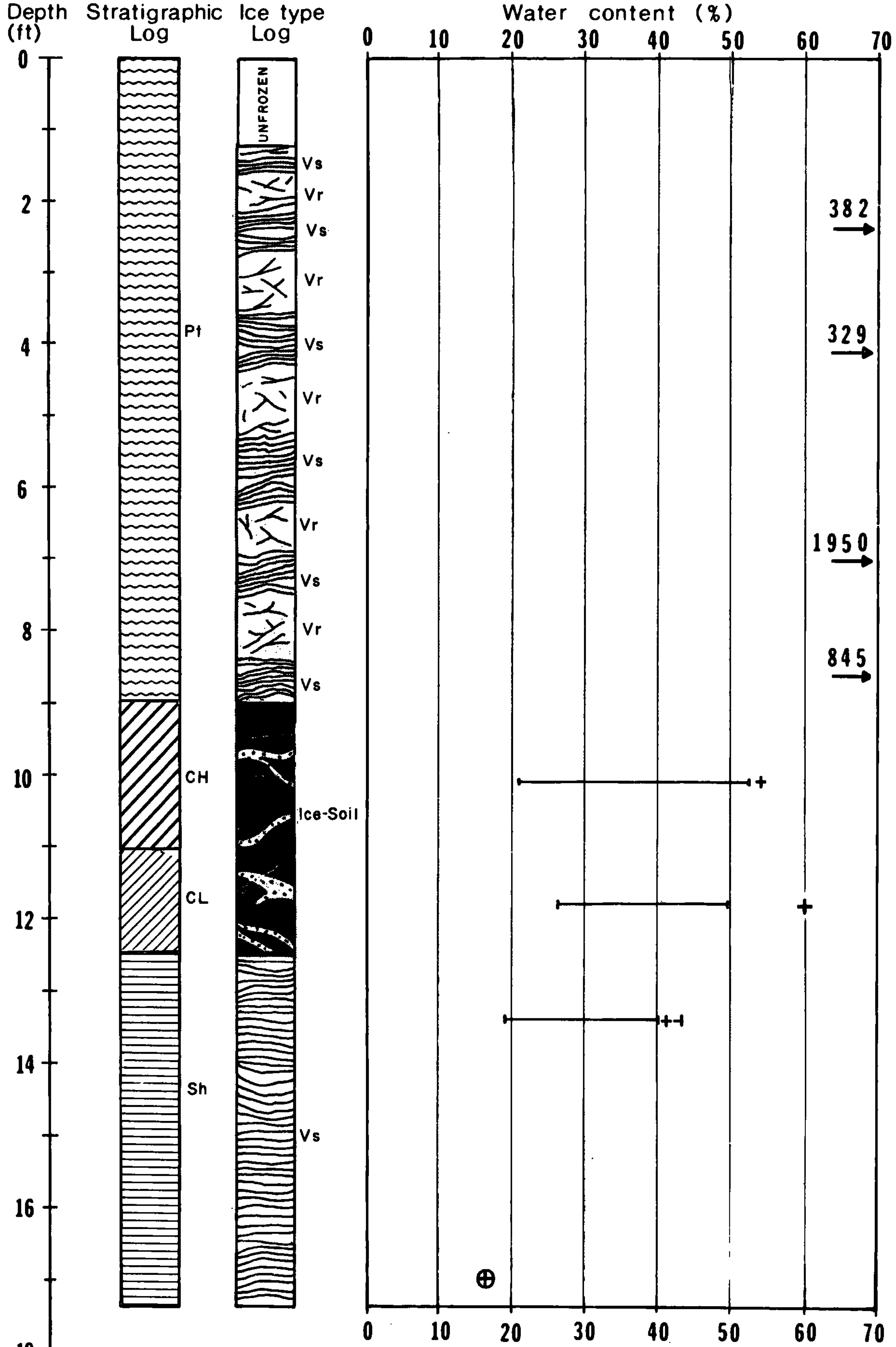
Date(s) drilled:	August 6 to 21, 1971
Site description:	This slightly hummocky area was relatively flat with remnants of thin forest that had been destroyed by a recent fire. The drill was set up over an old dried-up bog and was about 100 metres (330 feet) from a lake with a swampy margin.
Genetic Classification of Overburden:	Glaciolacustrine deposit of predominantly clay overlain by silt and sand. Moderate peat cover.



DH-4-71 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: SS-1-71

Date(s) drilled:	August 8 and 9, 1971
Site description:	The equipment was located about 70 metres (230 feet) from the edge of a large lake in an area that had been burnt many years before and revegetated with tall grasses in the area of the old lakebed. Beyond the lakebed, the area was very flat and covered with a coniferous forest about 6 to 10 metres (20 t0 33 feet) high. The drill site was situated about 2 metres (6 feet) above the adjacent lakebed and had fair drainage.
Genetic Classification of Overburden:	Glaciolacustrine plain of clay with substantial peat cover.



SOIL

Pt: dark brown peat with wood chips

CL: dark grey silty clay of medium plasticity

CH: dark grey silty clay of high plasticity

ROCK

Sh: dark grey shale heavily weathered becoming less weathered with depth

ICE

Vr: visible ice less than one inch thick, random or irregularly oriented ice formations

Vs: visible ice less than one inch thick, stratified or distinctly oriented ice formations

ICE AND SOIL: visible ice greater than one inch thick, ice with soil inclusions

UNIFIED SOIL CLASSIFICATION SYSTEM

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM # 79

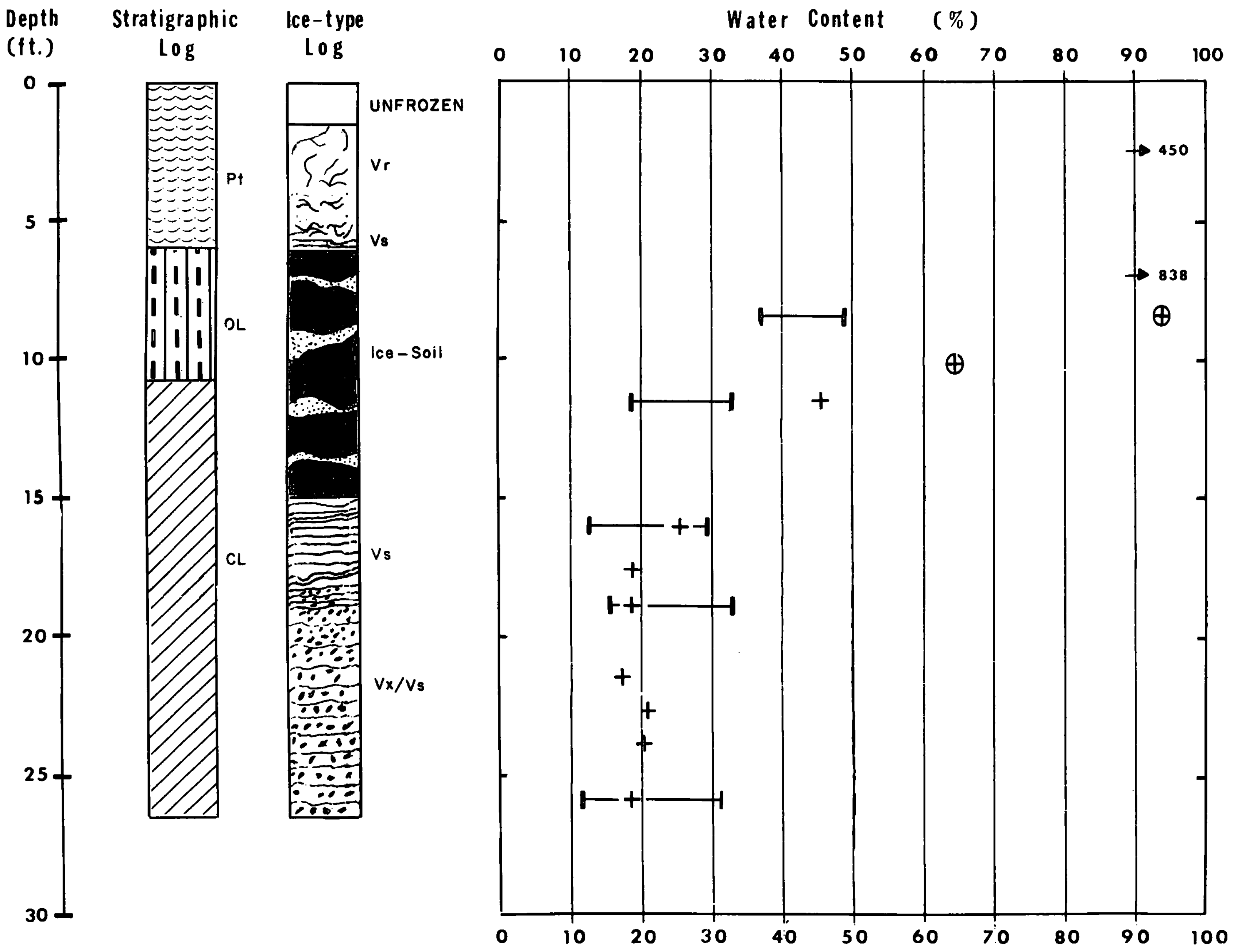
W_P —+— W_L Atterberg limits + natural water contents

⊕ (excess) natural water contents

SS-1-71 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: SS-2-71

Date(s) drilled:	August 11 and 12, 1971
Site Description:	The area was very flat with hummocks up to 80 cm (30 inches) in height and 1.5 metres (5 feet) in diameter. The ground cover consisted of moss, sedge, and cowbushes up to 30 cm (12 inches) in height as well as scattered coniferous trees. The site was poorly drained and surrounded by numerous bogs.
Genetic Classification of Overburden	Moraine plain, that is, glacial till, predominantly clay with substantial peat cover.



Soil :

Pt: reddish-brown peat

OL: organic silty clay with some fine gravel & sand

CL: gravelly silty clay from 10.8 ft. getting less gravelly and more sandy with depth to 18.0 ft. From 18 ft. sandy silty clay becoming more gravelly with depth. Gravel consists predominantly of sandstone and shale fragments.

UNIFIED SOIL CLASSIFICATION SYSTEM

W_p ⊢ + ⊣ W_L ATTERBERG LIMITS + NATURAL WATER CONTENTS

⊕ (EXCESS) NATURAL WATER CONTENTS

Ice :

Vx: visible ice less than one inch thick, individual ice inclusions

Vr: visible ice less than one inch thick, random or irregularly oriented ice formations

Vs: visible ice less than one inch thick, stratified or distinctly oriented ice formations

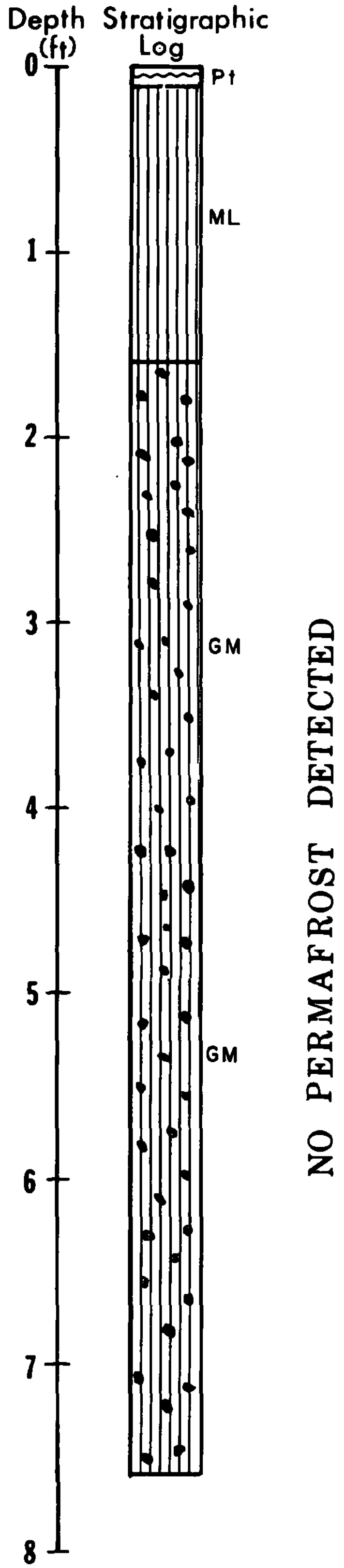
Ice & Soil: visible ice greater than one inch thick, ice with soil inclusions

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM NO. 79

SS-2-71 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole : SS-3-71

Date(s) drilled:	August 13, 1971
Site Description:	The drill rig was located about 15 metres (50 feet) from a seismic line in a burnt forest of mainly coniferous trees up to 15 metres (50 feet) high. The actual drill site was on a 5-metre (16-foot) high ridge, which was one in a series of approximately the same size. The area had been burnt recently and moss or peat cover was absent. The ground immediately around the machine was quite flat but drainage was fairly good.
Genetic Classification of Overburden:	Glaciofluvial deposit of gravel, sand and silt.



SOIL

Pt : peat

GM: gravel - sand - silt mixture, gravel being sandstone + siltstone

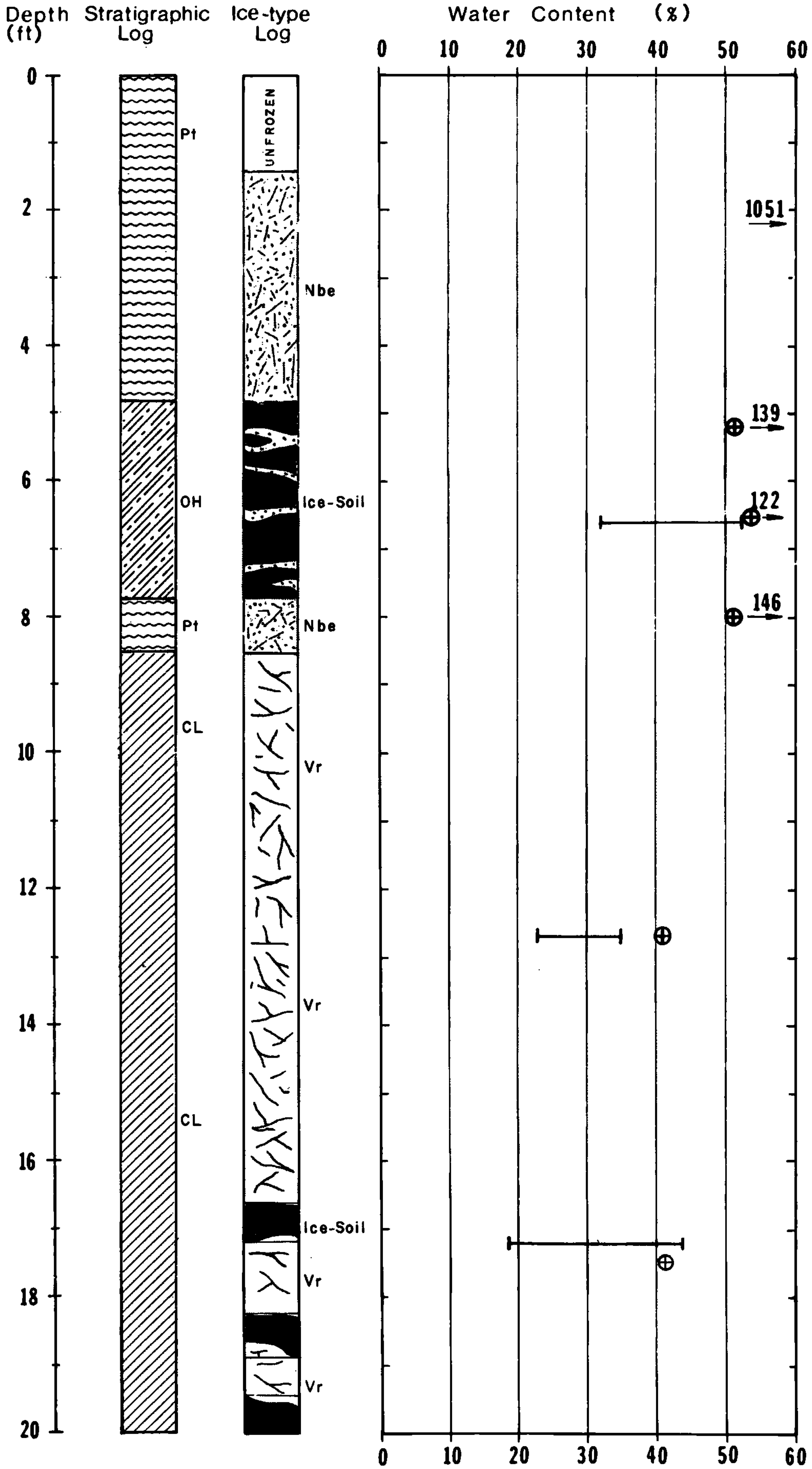
ML: light brown clayey silt

UNIFIED SOIL CLASSIFICATION SYSTEM

SS-3-71 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: SS-4-71

Date(s) drilled:	August 14 to 16, 1971
Site Description:	The drill rig was located on one corner of the intersection of two seismic lines. It was surrounded by a forest of coniferous and deciduous trees with a ground cover of thick moss and some lichen. Although the area was flat with little or no relief and the seismic lines were swampy, the drainage at the drill site was quite good.
Genetic Classification of Overburden:	Alluvial deposit of clay over glaciolacustrine deposit of clay with substantial peat cover.



SOIL

Pt: light brown peat

CL: grey silty clay of low to medium plasticity; with fine gravel between 8·5' and 9·5'

OH: grey organic clay of high plasticity

ICE

Nbe: ice not visible, well bonded excess ice

Vr: visible ice less than one inch thick, random or irregularly oriented ice formations

ICE AND SOIL: visible ice greater than one inch thick, ice with soil inclusions

UNIFIED SOIL CLASSIFICATION SYSTEM

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM #79

w_p —+— w_L Atterberg limits + natural water contents

⊕ (excess) natural water contents

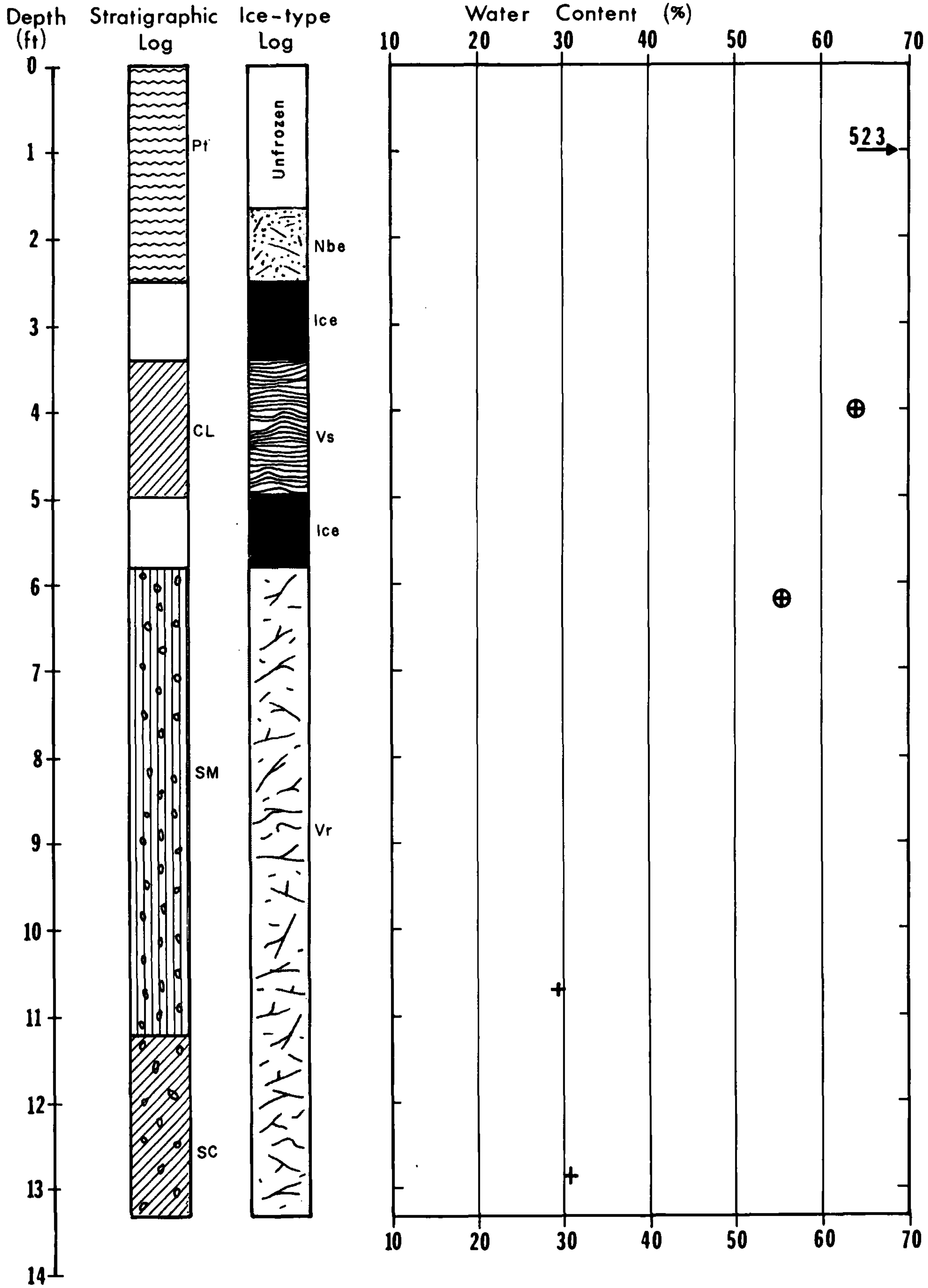
SS-4-71 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: SS-5-71

Date(s) drilled: August 17, 1971

Site Description: The equipment was located over the water-filled edge of a raised-centre polygon about 100 metres (330 feet) from a lake. The area was very flat, poorly drained with many bogs, and had suffered a recent fire. It was covered with low scrub and brush up to one metre (3 feet) high with a coniferous forest of medium density nearby.

Genetic Classification of Overburden: Alluvial deposit of clay over a glaciolacustrine deposit of silty sand to silty clayey sand with moderate peat cover.



SOIL

Pt: dark brown and woody peat

SM: light grey silty sand

SC: light grey silty clayey sand

CL: grey inorganic silty clay of low to medium plasticity

ICE

Nbe: ice not visible, well bonded, excess ice

Vr: visible ice less than one inch thick, random or irregularly oriented ice formations

Vs: visible ice less than one inch thick, stratified or distinctly oriented ice formations

ice

UNIFIED SOIL CLASSIFICATION SYSTEM

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM # 79

w_p ⊢—+—⊣ w_l Atterberg limits + natural water contents

⊕ (excess) natural water contents

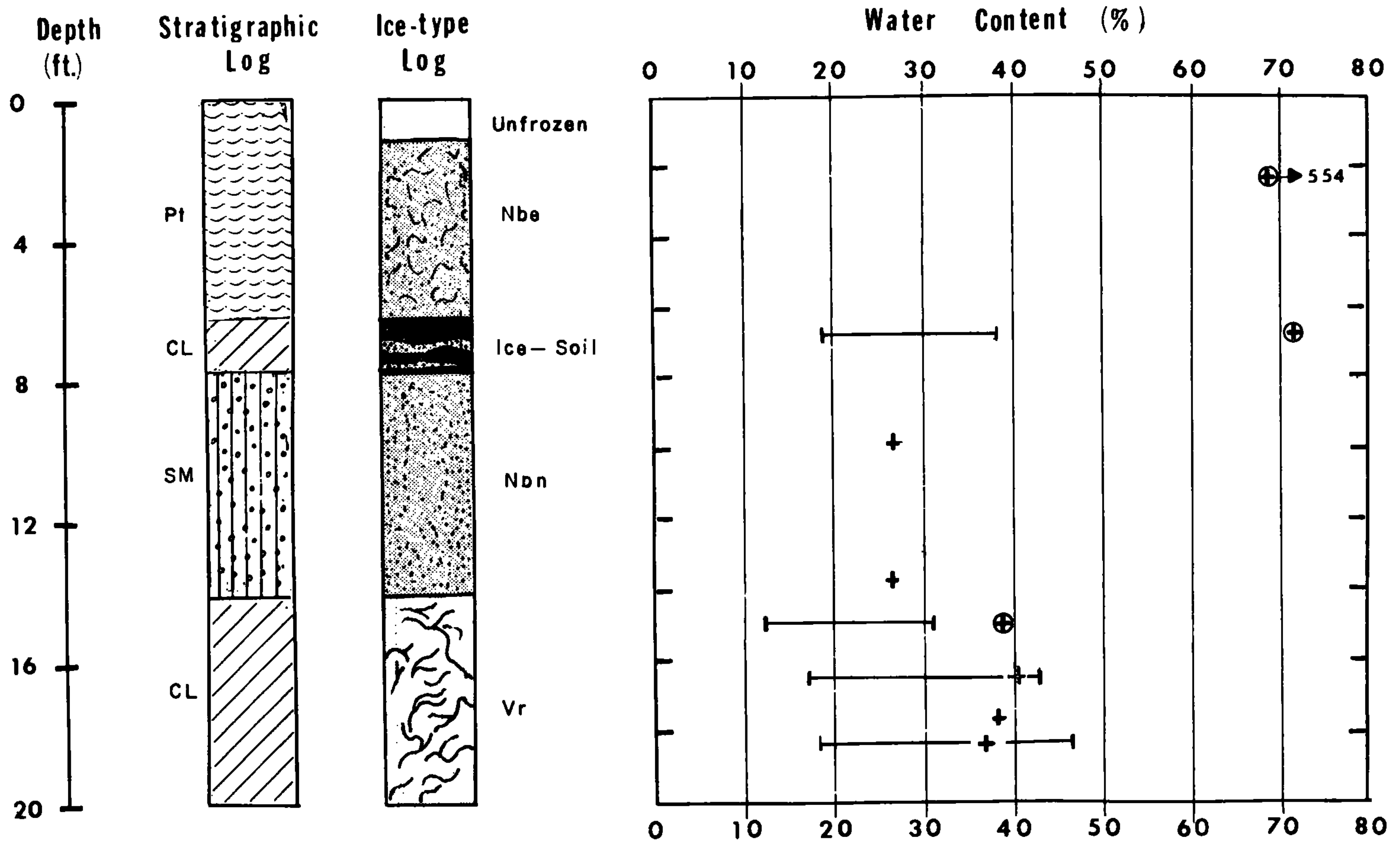
SS-5-71 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: SS-6-71

Date(s) drilled: August 18, 1971

Site Description: The general area was the same as that described for SS-5-71 but this hole was drilled in the raised centre of the polygon, about 5 metres (16 feet) away from SS-5-71.

Genetic Classification of Overburden: Alluvial deposit of clay over a glaciolacustrine deposit of silty sand and clay with substantial peat cover.



Soil:-

Pt: dark brown peat

CL: gravelly silty inorganic clay of low to medium plasticity

SM: grey silty sand becoming less silty with depth. At 13.2 ft. the sand becomes coarser and contains pebbles

UNIFIED SOIL CLASSIFICATION SYSTEM

W_p ⊕ W_L

⊕ EXCESS NATURAL WATER CONTENTS
ATTERBERG LIMITS + NATURAL WATER CONTENTS

Ice:-

Nbn: ice not visible, well bonded, no excess ice

Nbe: ice not visible, well bonded, excess ice

Vr: visible ice less than 1 inch thick, random or irregularly oriented ice formation

ICE AND SOIL: visible ice greater than 1 inch thick, ice with soil inclusions

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM NO. 79

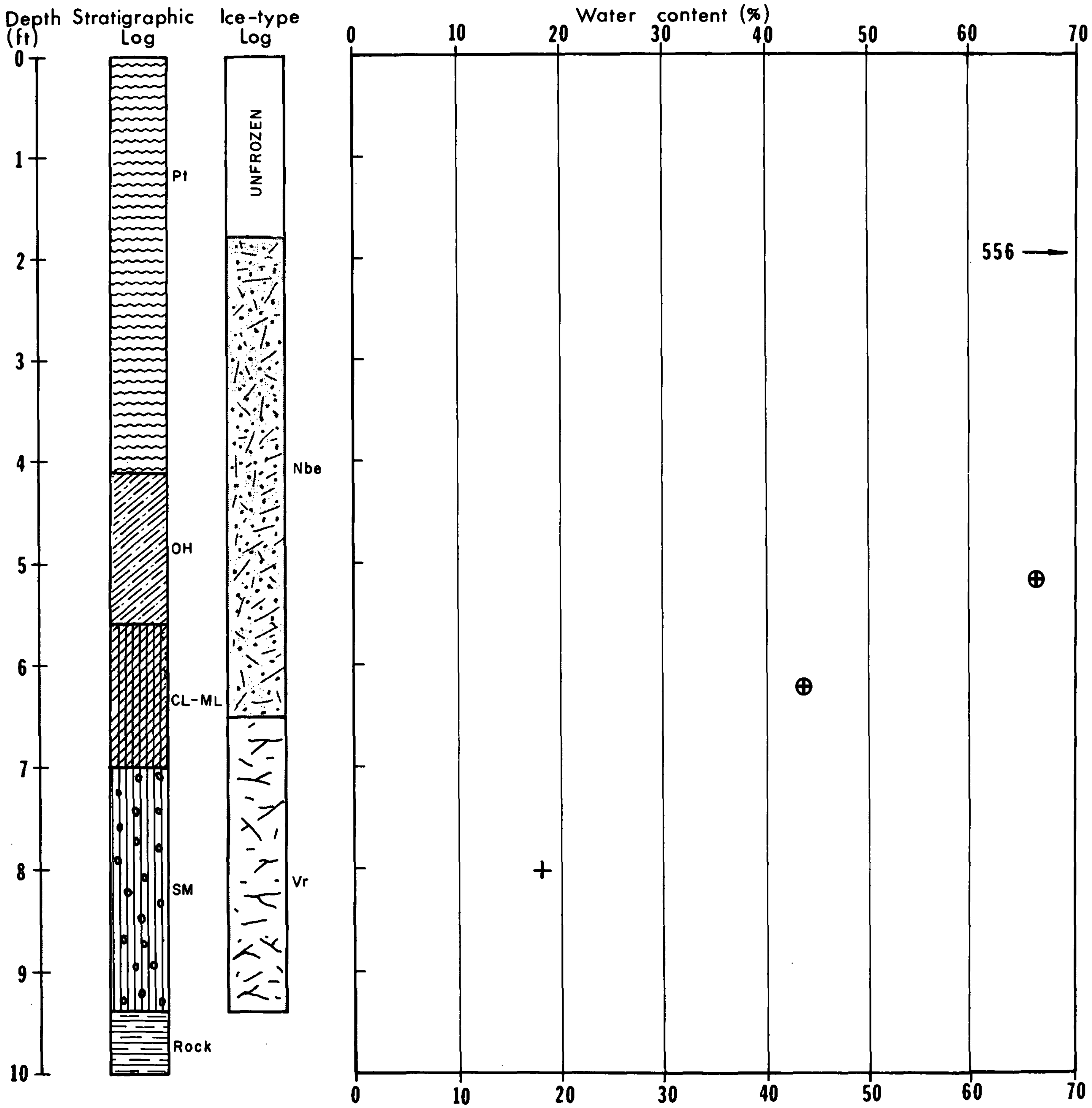
SS-6-71 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: SS-7-71

Date(s) drilled: August 19, 1971

Site Description: The drill was located over the swampy centre of a raised-edge polygon amidst a large number of similar polygons in a very flat area. On one side of this area there was a coniferous forest about 15 metres (50 feet) high and to the other side about 4 km (2.5 miles) away there was a 50-metre (165-foot) high ridge. The polygon itself was covered with grasses about 70 cm (28 inches) high.

Genetic Classification of Overburden: Alluvial deposit of clay and sandy-clay over a glaciofluvial deposit of silty fine sand over sandstone; substantial peat cover.



SOIL

Pt: dark brown peat with a decreasing wood content and increasing density with depth

OH: light brown organic clay of high plasticity with a large peat content between 4' and 5'

CL–ML: light brown sandy silt-clay

SM: dark brown silty fine sand with sandstone fragments

ROCK

weathered sandstone

ICE

Nbe: ice not visible, well bonded, excess ice

Vr: visible ice less than one inch thick, random or irregularly oriented ice formations

UNIFIED SOIL CLASSIFICATION SYSTEM

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM # 79

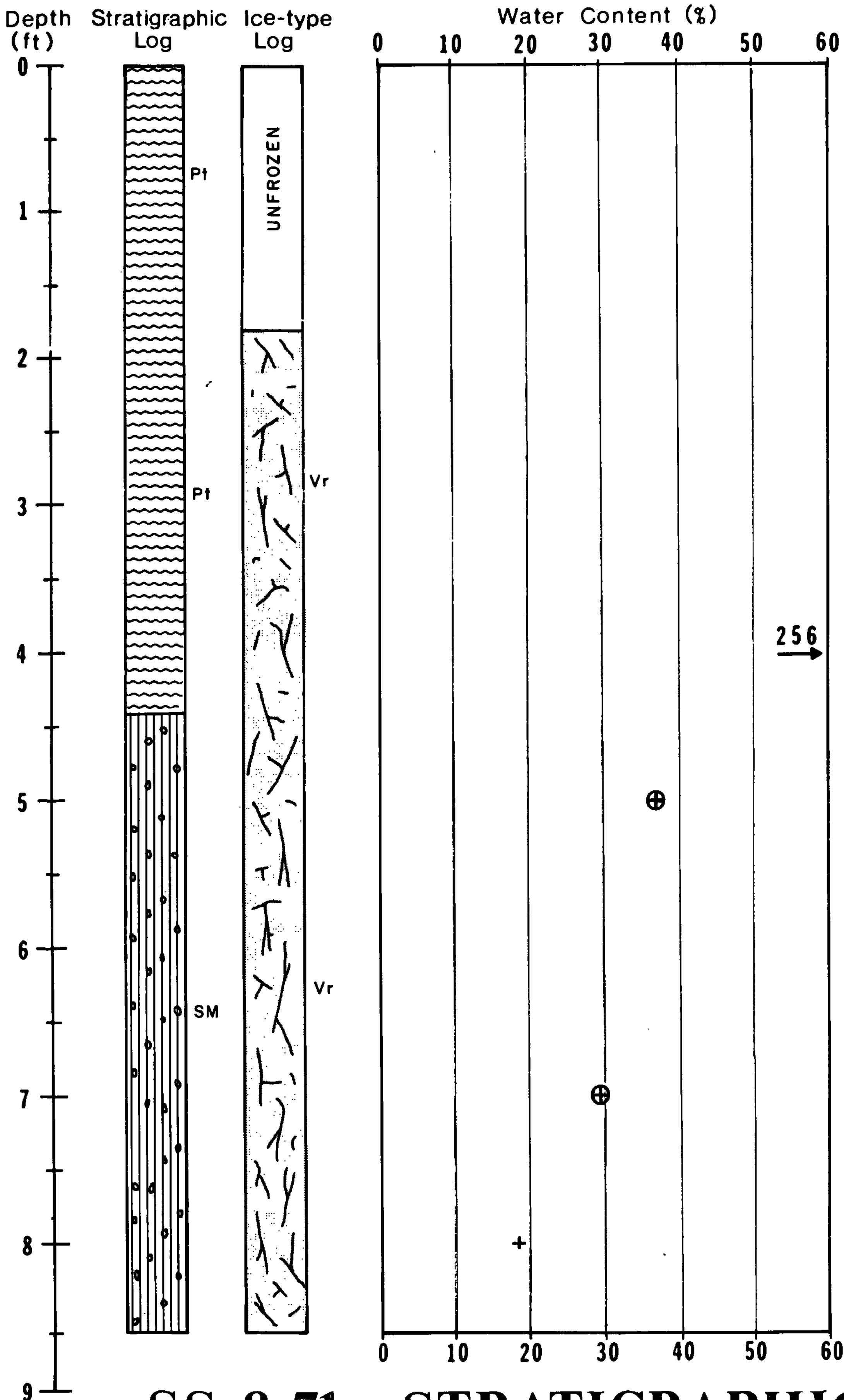
W_P ⊢—+—⊣ W_L Atterberg limits + natural water contents

⊕ (excess) natural water contents

SS-7-71 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: SS-8-71

Date(s) drilled:	August 20, 1971
Site description:	This drill hole was situated on the dry raised edge of the polygon in whose centre drill hole SS-7-71 was located. The edge was covered with scrub and brush as well as some moss.
Genetic Classification of Overburden:	Glaciofluvial deposit of silty sand with substantial peat cover.



SOIL

Pt: peat with some sand + chips of wood and sandstone

SM: light brown silty sand with the occasional clay pocket and gravel after 7' depth

ICE

Vr: visible ice less than one inch thick, random or irregularly oriented ice formations

UNIFIED SOIL CLASSIFICATION SYSTEM

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM #79

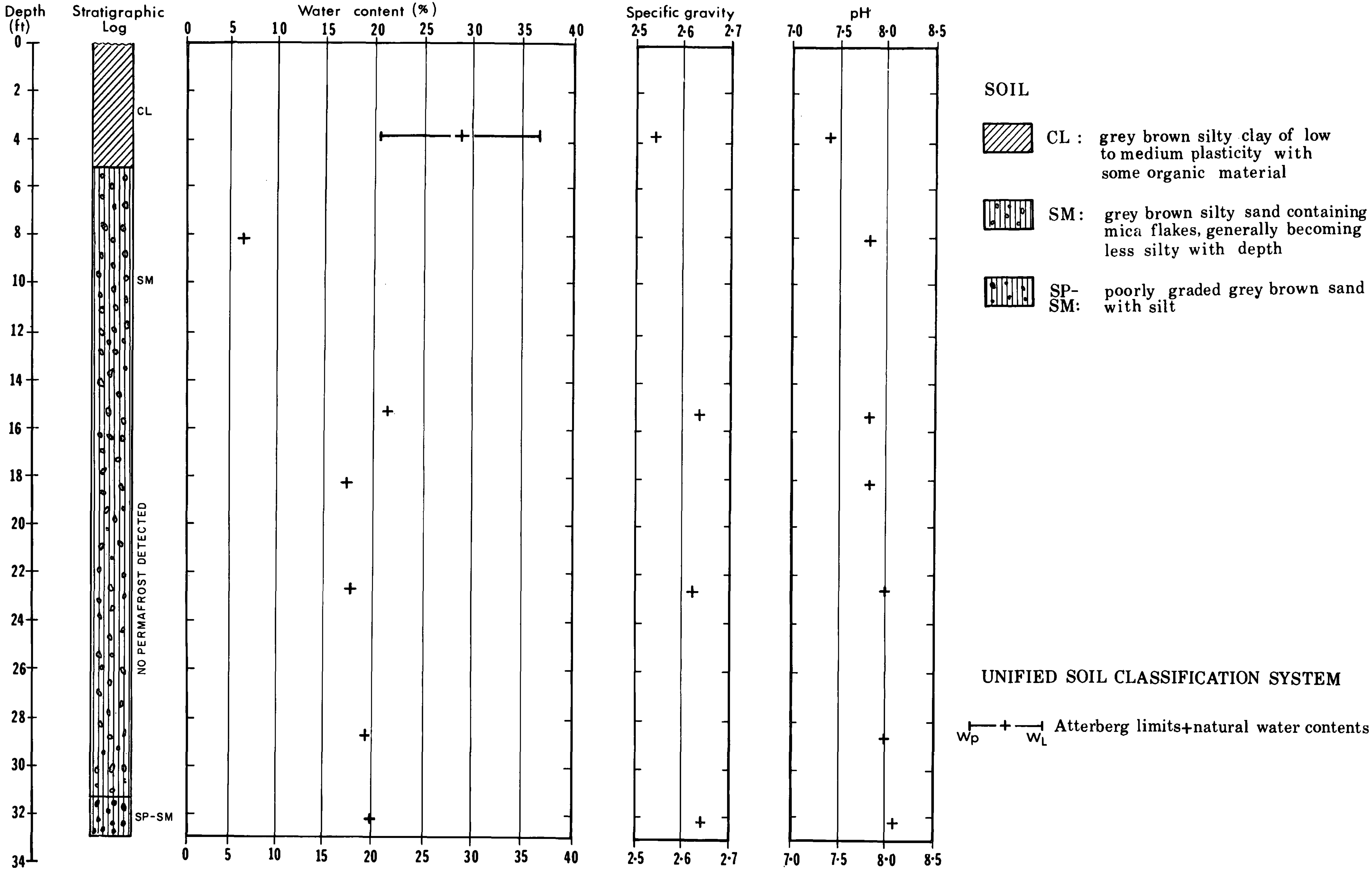
w_p + w_L Atterberg limits + natural water contents

⊕ (excess) natural water contents

SS-8-71 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: SS-9-71

Date(s) drilled:	August 23 and 24, 1971
Site Description:	The drill was set up on a 2-metre (7-foot) high ridge in the centre of and along the length of an old lake bed on Manitou Island. The lake bed was 200 metres (660 feet) wide by about 1,300 metres (4,300 feet) long and was covered by grasses about 70 cm (28 inches) high. The drill site was well drained.
Genetic Classification of Overburden:	Alluvial deposit of silty clay over silty sand and sand with silt.



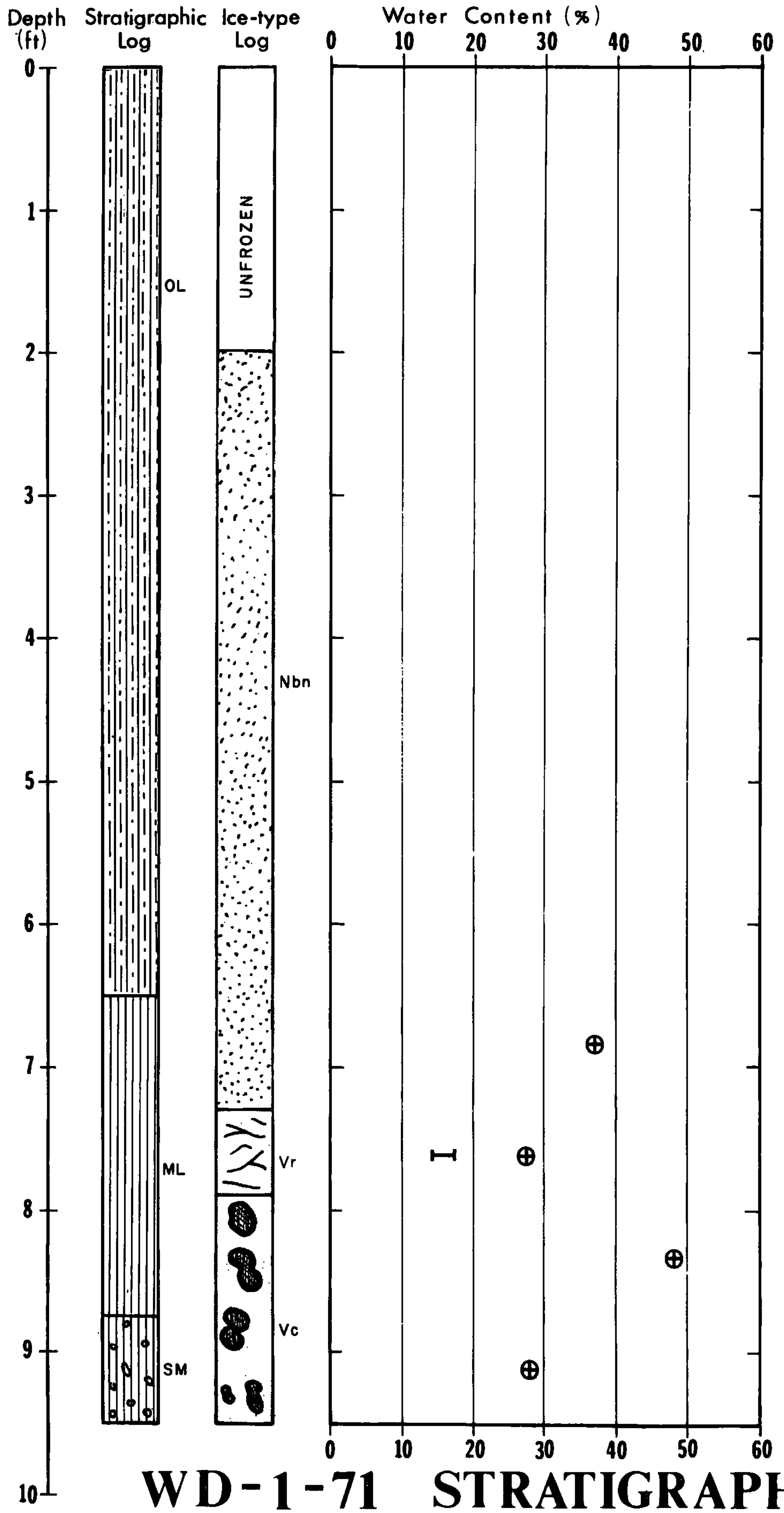
SS-9-71 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: WD-1-71

Date(s) drilled: June 16 to 19, 1971

Site Description: The site had very low relief with hummocks up to 70 cm (28 inches) high, and 1.5 metres (5 feet) in diameter, which were covered with moss, lichen, and shrubs. The cleared area (65 x 130 metres (215 by 425 feet)) was surrounded by 5 to 6-metre (16- to 20-foot) tall trees, but the drill site within this area was located near a swamp. Drainage was poor.

Genetic Classification of Overburden: Glaciolacustrine deposit of silts and fine sands with substantial peat cover.



SOIL

OL: mixture of silt and peat

ML: silty fine sand with some organic material between 6·5' and 7·25', becoming siltier with depth

SM: medium to fine silty sand with some fine gravel

ICE

Nbn: ice not visible, well bonded, no excess ice

Vc: ice less than one inch thick, ice coatings on particles

Vr: visible ice less than one inch thick, random or irregularly oriented ice formations

UNIFIED SOIL CLASSIFICATION SYSTEM

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM # 79

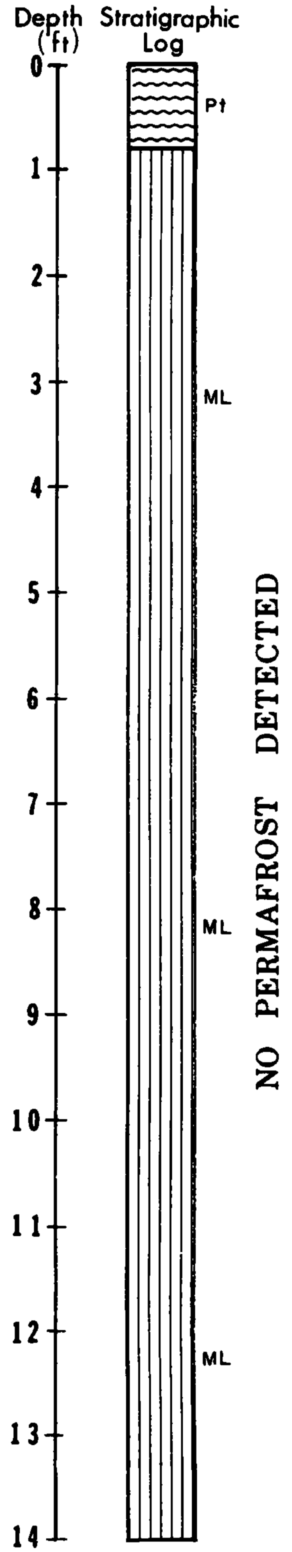
W_P ⊢—+—⊣ W_L Atterberg limits+natural water contents

⊕ (excess) natural water contents

WD-1-71 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: WD-2-71

Date(s) drilled:	June 20 and 26, 1971
Site Description:	The drill was located on the western toe of a north-south ridge, which was about 8 to 10 metres (26 to 33 feet) high. The coniferous forest on the site had been burnt several years previously and had not regenerated to any appreciable extent. Drainage was fair with no large swamps or bogs although there was a lake nearby.
Genetic Classification of Overburden:	Glaciolacustrine deposit of silty fine sand with thin peat cover.



SOIL

Pt : black peat

ML: silty fine sand becoming coarser with depth

UNIFIED SOIL CLASSIFICATION SYSTEM

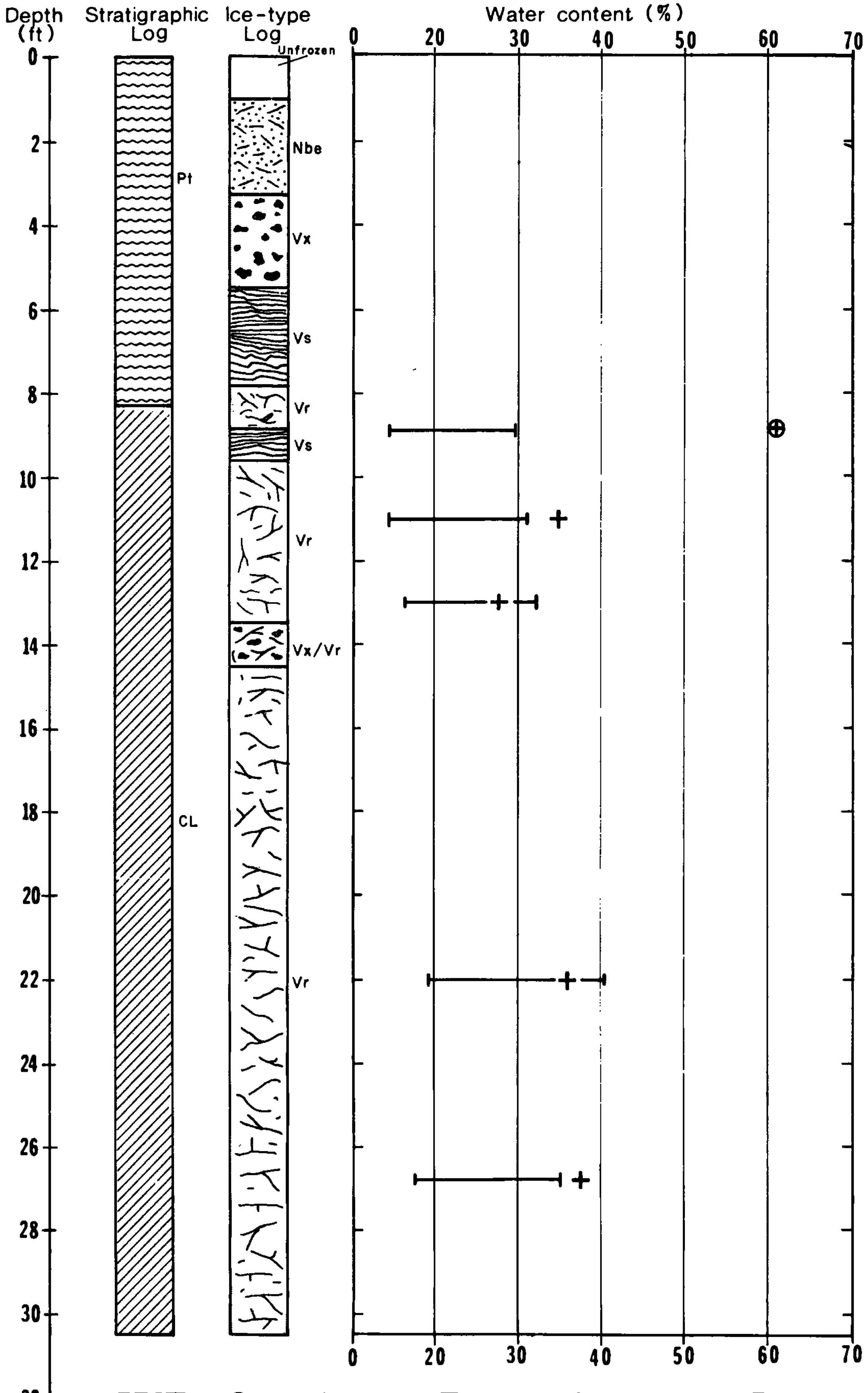
WD-2-71 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: WD-3-71

Date(s) drilled: June 26 to 29, 1971

Site Description: The area was very flat with a low ridge (3 metres (10 feet)) about 70 metres (230 feet) north of the drill. There were small shrubs up to one metre (3 feet) high on hummocks; coniferous growth, which had been damaged in a fire many years previously, had not regenerated. On the site was a large peat bog and a lake and marsh on either side of the drill; drainage was poor.

Genetic Classification of Overburden: Glaciolacustrine deposit of silty clay with a substantial peat cover.



WD-3-71 STRATIGRAPHIC AND PHYSICAL DATA

SOIL

Pt: dark brown peat

CL: grey to brown-grey silty clay of low to medium plasticity

ICE

Nbe: ice not visible, well bonded, excess ice

Vx: visible ice less than one inch thick, individual ice inclusions

Vr: visible ice less than one inch thick, random or irregularly oriented ice formations

Vs: visible ice less than one inch thick, stratified or distinctly oriented ice formations

UNIFIED SOIL CLASSIFICATION SYSTEM

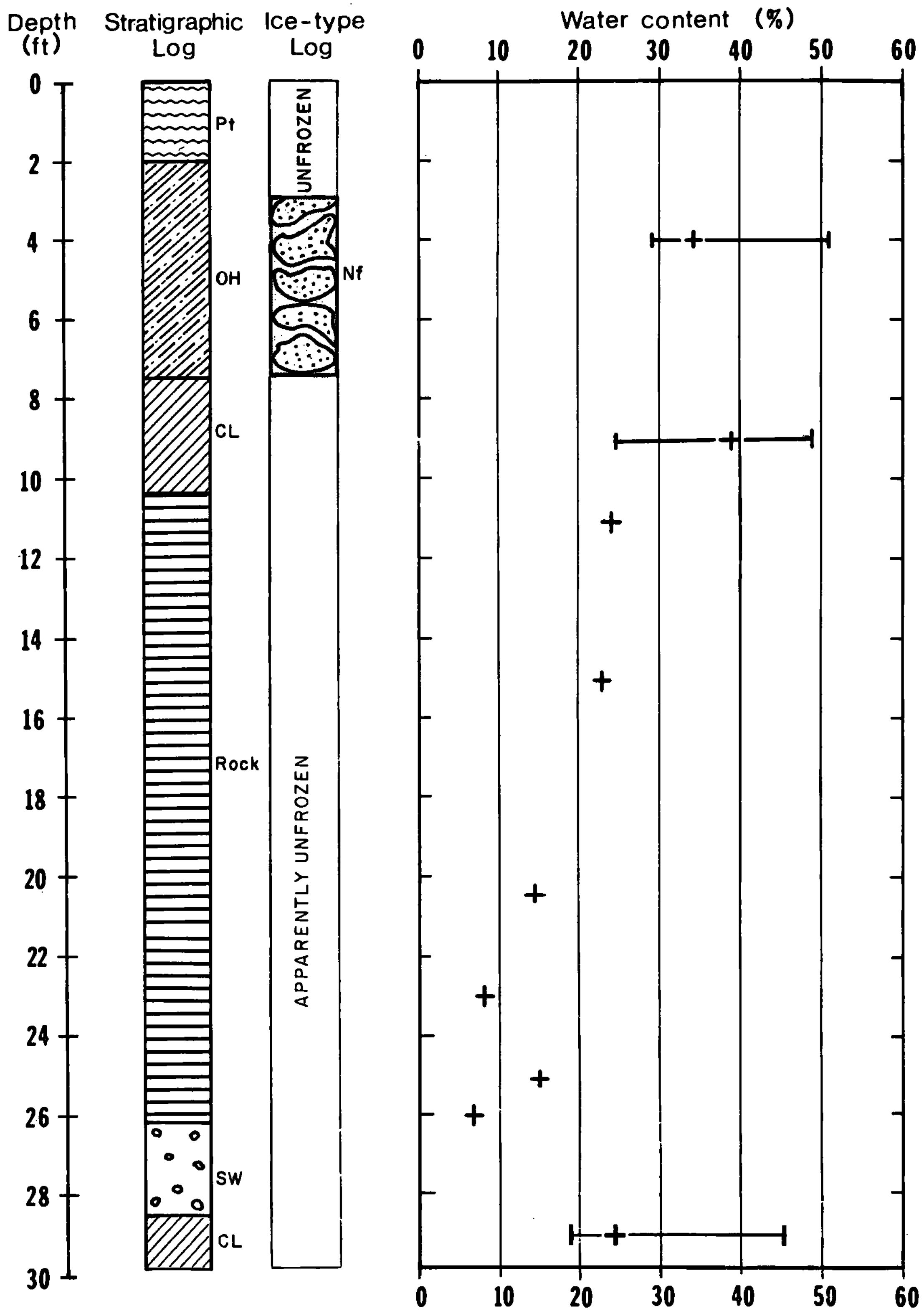
W_P —+— W_L Atterberg limits + natural water contents

⊕ (excess) natural water contents

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM #79

Drill hole: WD-4-71

Date(s) drilled:	July 2 and 3, 1971
Site description:	There is an elongated east-west ridge immediately to the south of a similarly elongated lake. The drill site was located 200 metres (655 feet) higher in elevation and the lake. Approximately 25 metres (82 feet) to the west of the drill hole was a swamp with about 15 cm (6 inches) of water. Small scrawny trees and patches of burnt grasses covered the area. Drainage at the site was fair.
Genetic Classification of Overburden:	Glacial till deposit of clay, shale erratic, and sand with moderate peat cover.



SOIL

Pt: dark brown peat

SW: dark brown medium to coarse sand

CL: above 10·4' grey black silty clay of medium plasticity with shale fragments; below 28·6' light grey to white inorganic clay of medium plasticity with seams of calcareous siltstone

OH: grey brown organic silty clay of high plasticity

ROCK

weathered shale with seams and pockets of low to medium plasticity clay and layers of calcareous siltstone

ICE

Nf: ice not visible, poorly bonded

NOTE: apparently unfrozen below 7·5' but permafrost difficult to detect in these soils with this drilling method

UNIFIED SOIL CLASSIFICATION SYSTEM

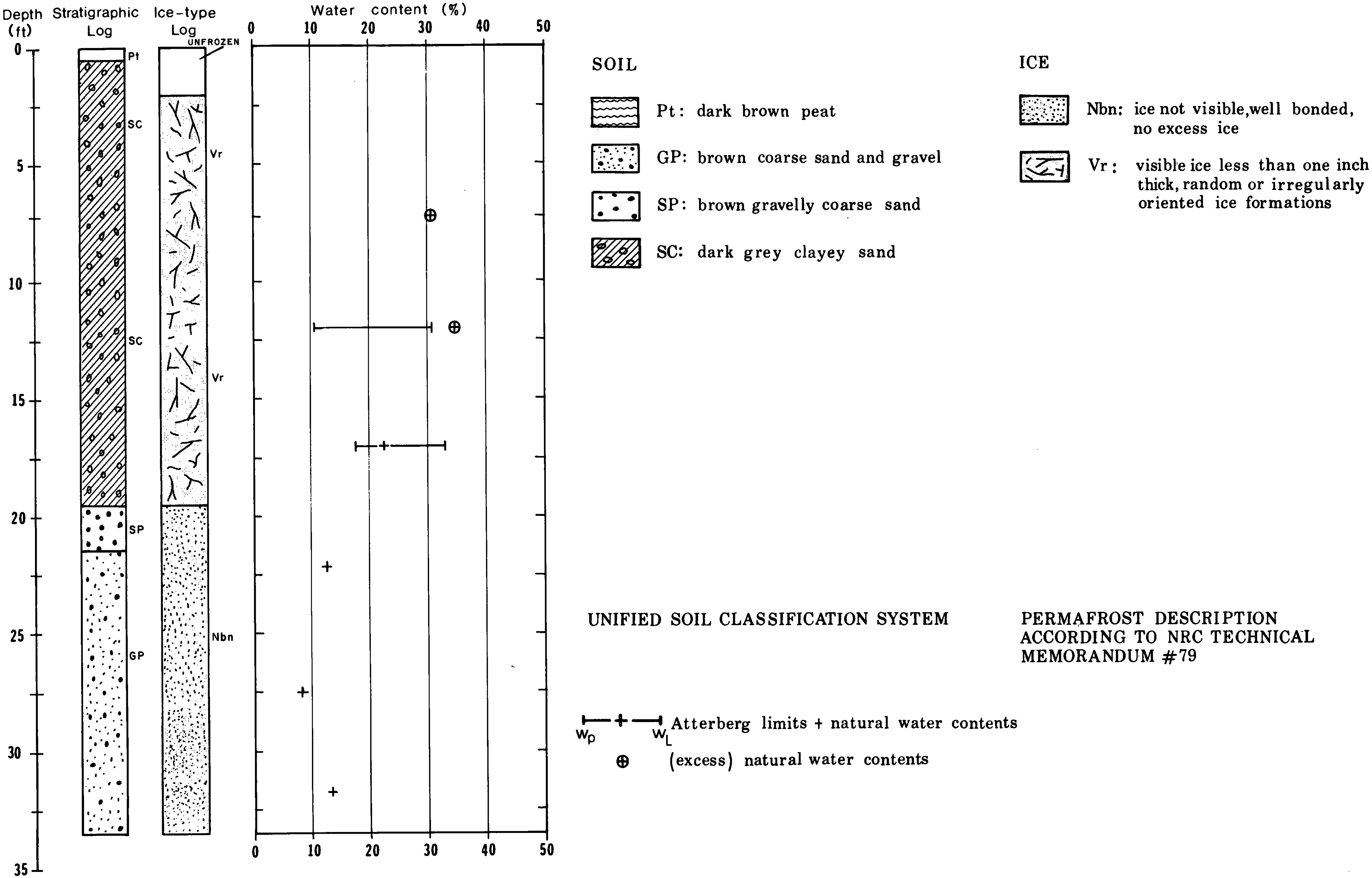
PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM #79

W_P ⊢—+—⊣ W_L Atterberg limits + natural water contents

WD-4-71 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: WD-5-71

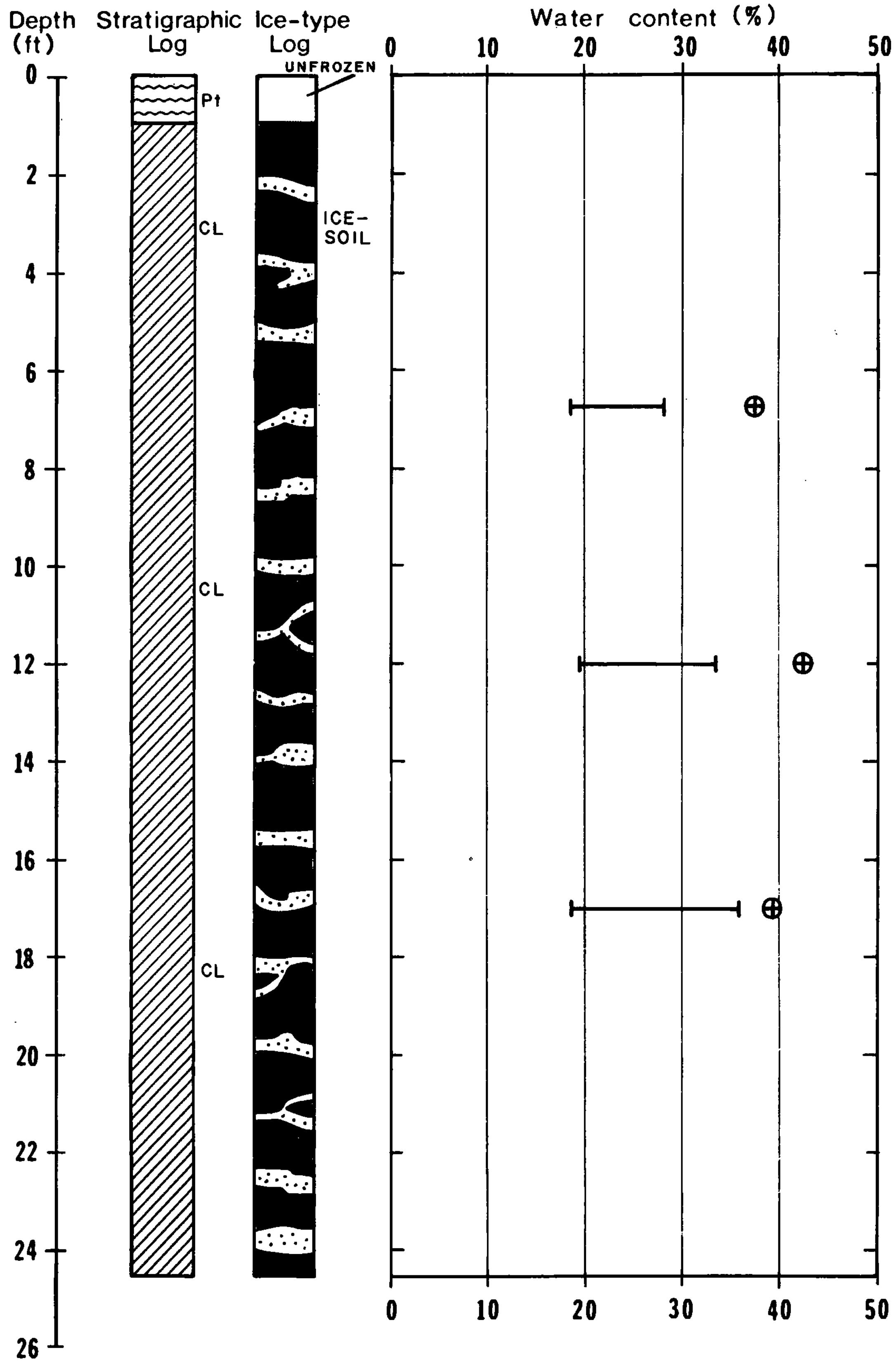
Date(s) drilled:	July 10 and 12, 1971
Site description:	The site was very flat and was covered by hummocks, some of which were very large, a medium-dense forest, low scrub, moss, and lichen. Drainage was fair with a few scattered bogs and an old lakebed in the area.
Genetic Classification of Overburden:	Glacial till deposit of clayey sand over sand and gravels with thin peat cover.



WD-5-71 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: WD-6-71

Date(s) drilled:	July 15 and 16, 1971
Site Description:	The actual drill site was fairly flat although near the drill there were variations in elevation of up to 5 metres (16.5 feet). The drill was located in a clearing in a dense forest amidst a mixture of woody and non-woody brush, up to 2.5 metres (8 feet) high, with small areas of moss cover. Drainage was fairly good.
Genetic Classification of Overburden:	Glaciolacustrine deposit of clay with thin peat cover.



SOIL

Pt: dark brown peat + moss

CL: dark grey silty clay of low to medium plasticity

ICE

ICE AND SOIL: visible ice greater than one inch thick, ice with soil inclusions

UNIFIED SOIL CLASSIFICATION SYSTEM

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM # 79

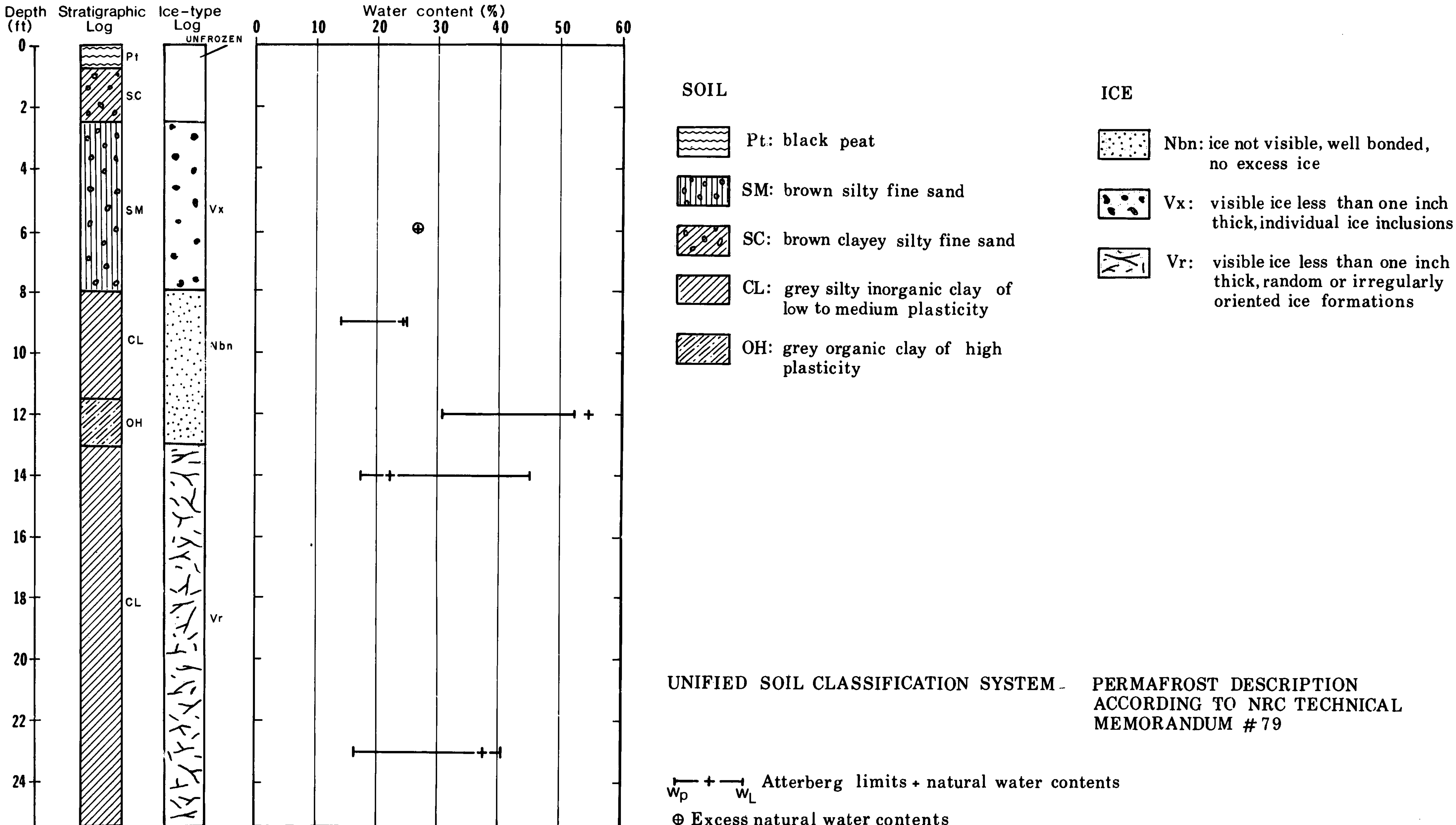
w_P —+— w_L Atterberg limits + natural water contents

⊕ (excess) natural water contents

WD-6-71 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: WD-7-71

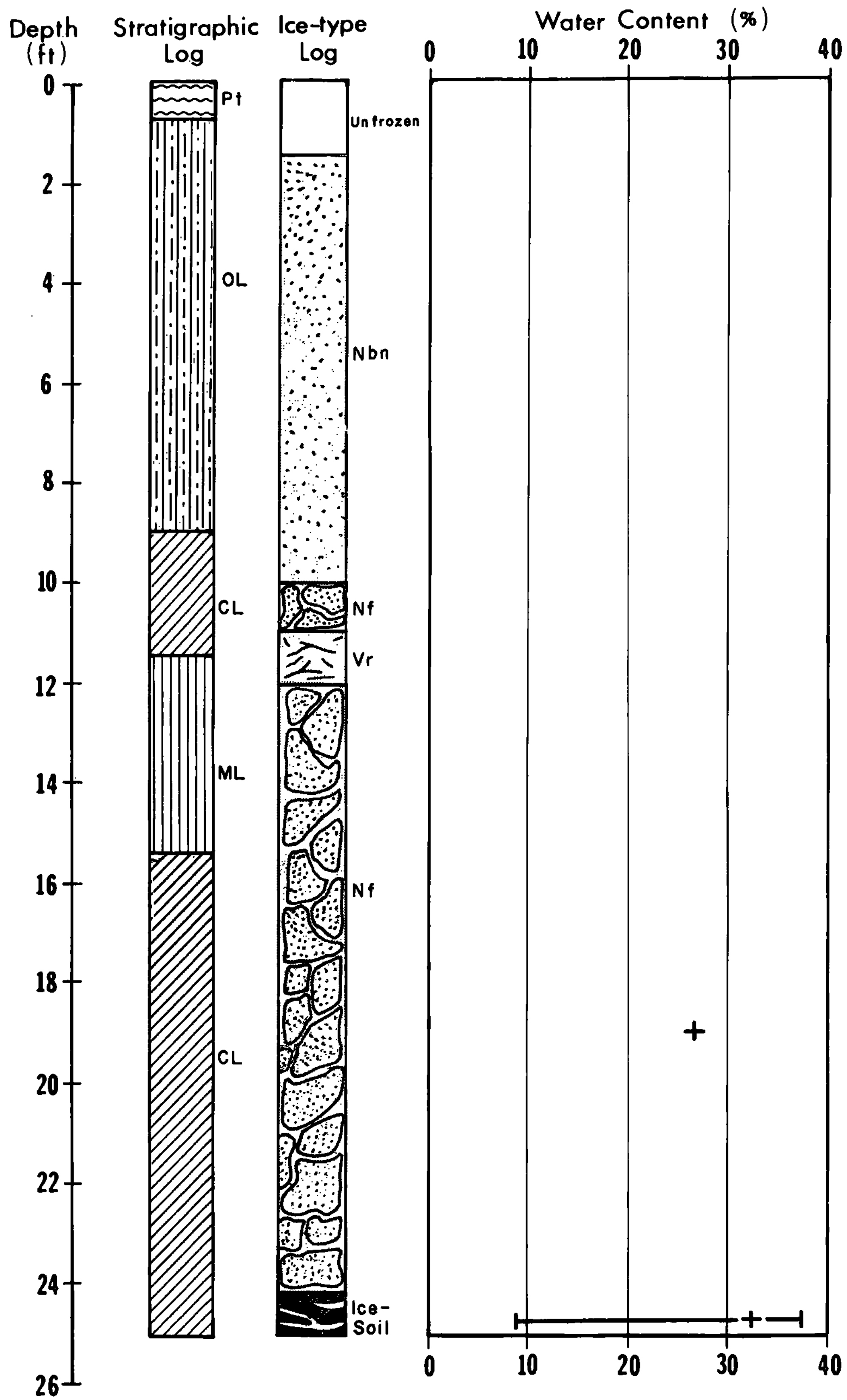
Date(s) drilled:	July 14 and 21, 1971
Site description:	The drill site was in a green, unburnt area covered by coniferous trees, 2 to 10 metres (6 to 33 feet) in height. The ground was fairly flat and covered by mosses and grasses.
Genetic Classification of Overburden:	Glaciolacustrine deposit of sands over clays with a thin peat cover.



WD-7-71 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: WD-8-71

Date(s) drilled:	July 24 and 25, 1971
Site Description:	The drill site was on a hummocky knoll covered with grasses, and was about 3 metres (10 feet) higher than an adjacent swamp that bordered on a lake. The trees in the area were 10 to 15 metres (33 to 50 feet) in height but had suffered considerable fire damage in recent years. Drainage was good.
Genetic Classification of Overburden:	Galaciolacustrine deposit of silts and clays with thin peat cover.



SOIL

Pt: peat

ML: grey to pale brown fine sandy silt

CL: between 9·0' and 11·5' grey silty clay with some organic matter. From 15·4' grey sandy silty clay

OL: dark brown organic silt

UNIFIED SOIL CLASSIFICATION SYSTEM

ICE

Nf: ice not visible, poorly bonded

Nbn: ice not visible, well bonded, no excess ice

Vr: visible ice less than one inch thick, random or irregularly oriented ice formations

ICE AND SOIL: visible ice greater than one inch thick, ice with soil inclusions

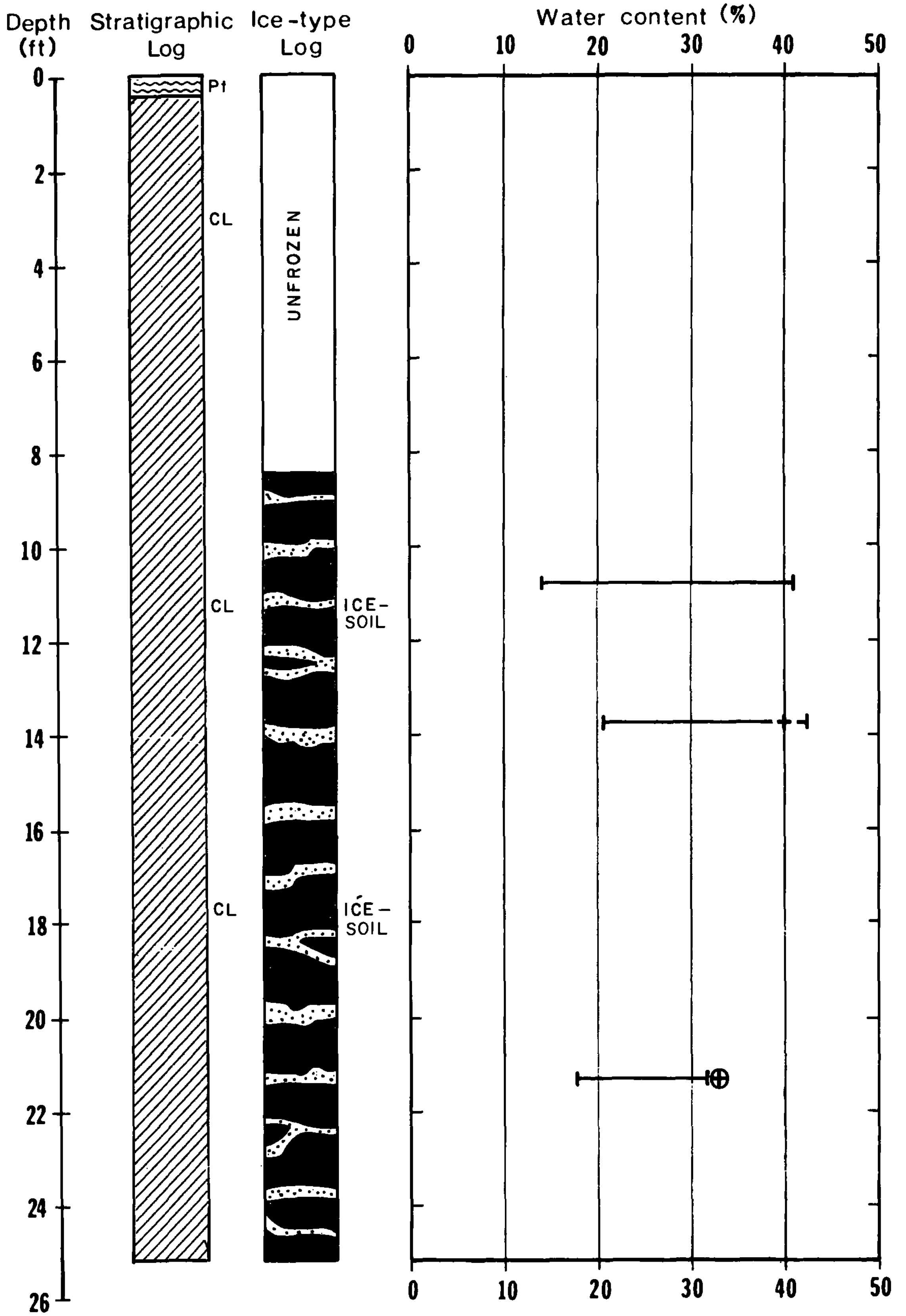
PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM # 79

W_P ⊢—+—⊣ W_L Atterberg limits + natural water contents

WD-8-71 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: WD-9-71

Date(s) drilled:	July 26 and 27, 1971
Site Description:	The drill was located at the intersection of two seismic lines on very flat ground with poor drainage and local water-filled depression along the lines. Adjacent to the seismic lines, the ground was slightly hummocky and grass covered. Trees 3 to 6 metres (10 to 20 feet) in height had been burnt by fire in recent years.
Genetic Classification of Overburden:	Glaciolacustrine deposit of sandy silty clay, over silty clay, under thin peat cover.



SOIL

Pt : dark brown burnt peat

CL : light brown sandy silty clay to depth of 7'. Some organic matter. Below 7' grey silty inorganic clay of medium plasticity

ICE

ICE AND SOIL : visible ice greater than one inch thick, ice with soil inclusions

UNIFIED SOIL CLASSIFICATION SYSTEM

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM # 79

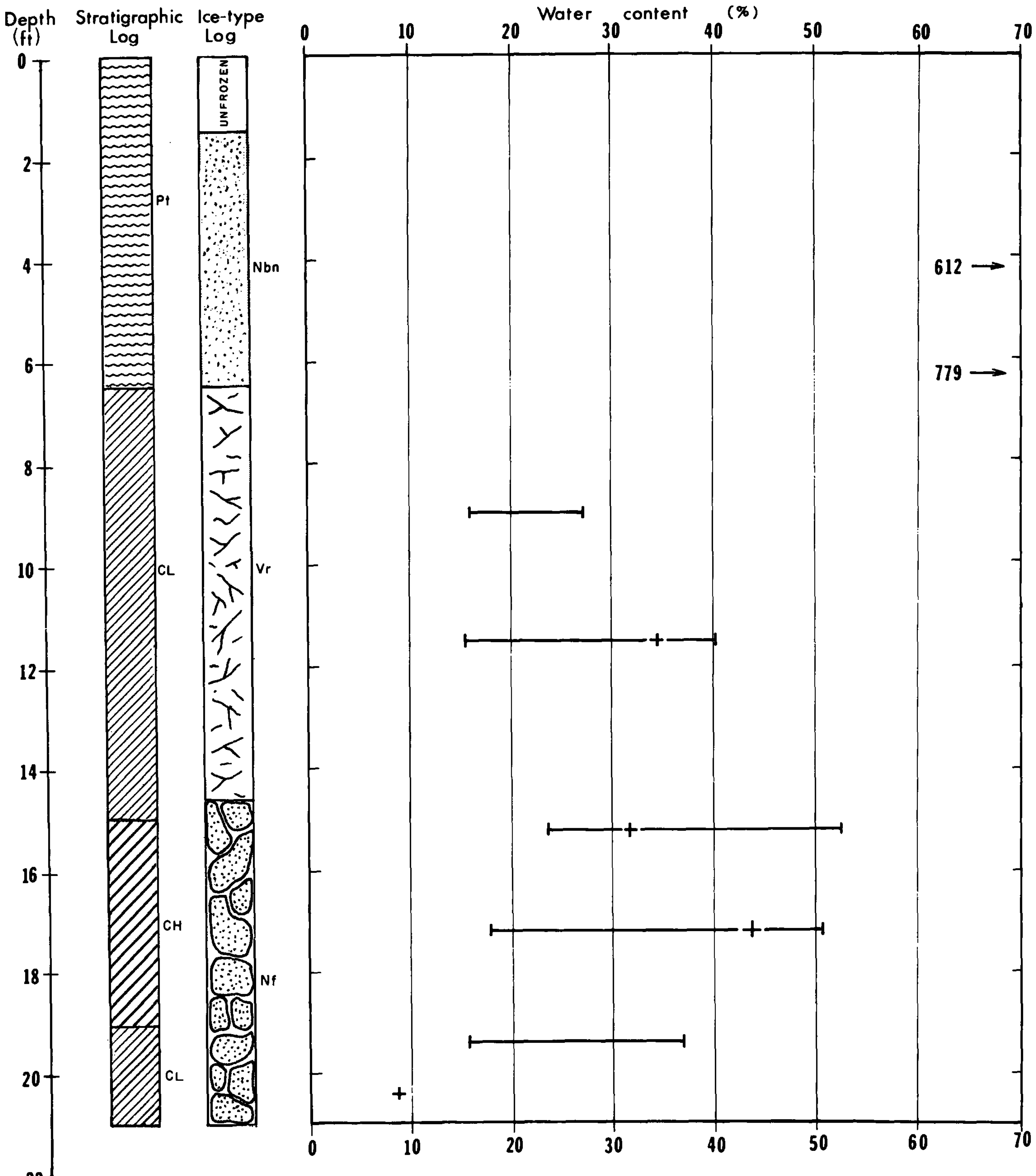
w_p ⊢—+—⊣ w_L Atterberg limits + natural water contents

⊕ (excess) natural water contents

WD-9-71 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: WD-10-71

Date(s) drilled:	July 28 and August 2, 1971
Site Description:	The area was very flat and covered with a sparse coniferous growth which had been burnt several years previously. The ground was hummocky and was covered with lichen and very low scrub. Although there was a lake 40 metres (130 feet) from the drill site, the drainage was quite good.
Genetic Classification of Overburden:	Glaciolacustrine deposit of clays under a substantial peat cover.



SOIL

Pt: dark brown peat

CL: grey silty inorganic clay of low to medium plasticity

CH: grey inorganic clay of high plasticity

ICE

Nf: ice not visible, poorly bonded

Nbn: ice not visible, well bonded, no excess ice

Vr: visible ice less than one inch thick, random or irregularly oriented ice formations

UNIFIED SOIL CLASSIFICATION SYSTEM

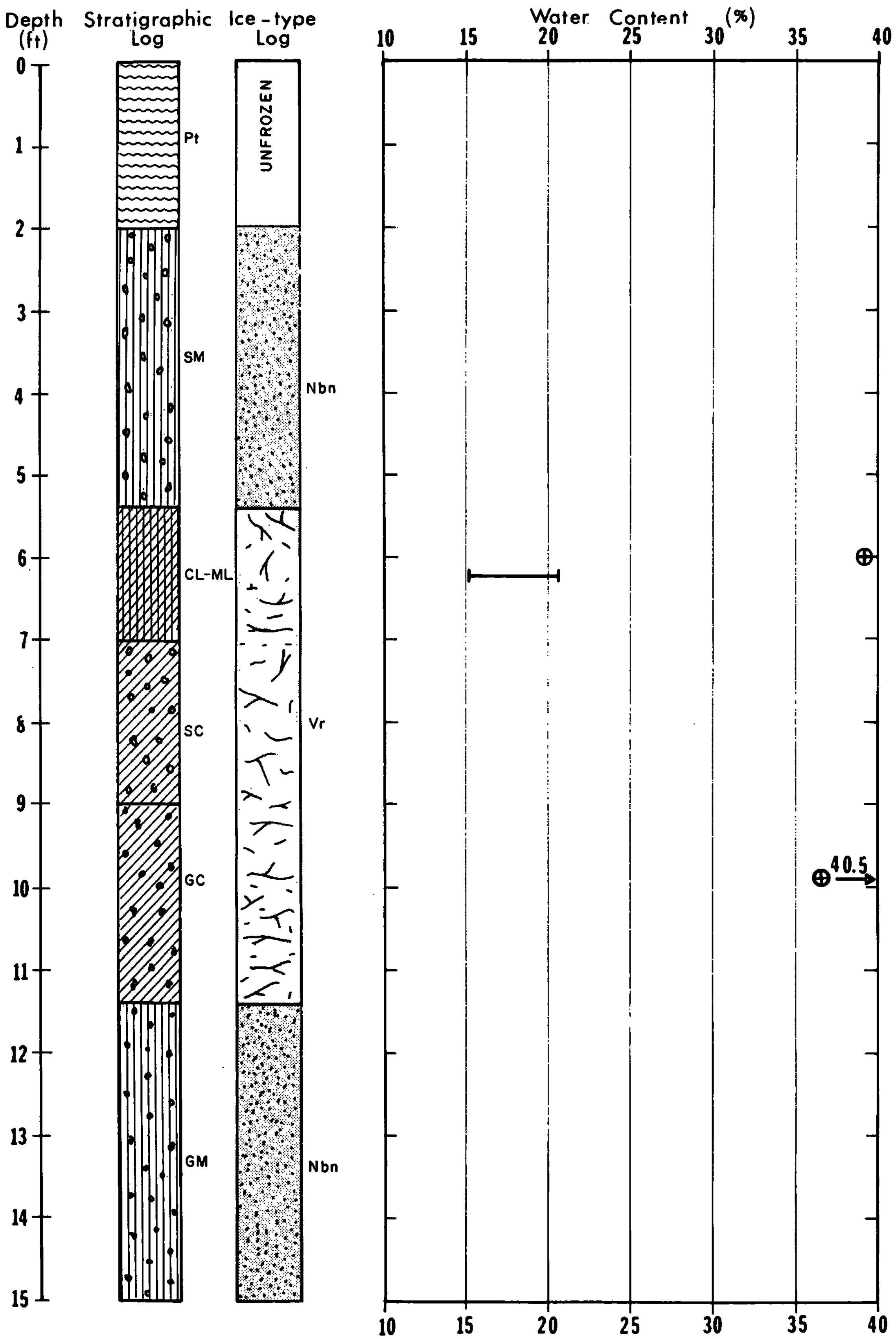
PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM # 79

W_p —+— W_L Atterberg limits + natural water contents

WD-10-71 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: WD-11-71

Date(s) drilled:	August 3 and 6, 1971
Site Description:	The site was very flat and consisted of small burnt areas and swampy zones. The drill was located on the edge of a swampy area covered with long grasses and some low scrub. Drainage was poor.
Genetic Classification of Overburden:	Glacial till deposit of sands and sandy clays under moderate peat cover.



WD-11-71 STRATIGRAPHIC AND PHYSICAL DATA

SOIL

- Pt: dark brown peat
- GM: gravel-sand-silt mixture with some clay
- GC: gravel-sand-clay mixture
- SM: golden brown silty sand with some organic material
- SC: clayey sand with some gravel
- CL-ML: sandy silty clay with some gravel

ICE

- Nbn: ice not visible, well bonded, no excess ice
- Vr: visible ice less than one inch thick, random or irregularly oriented ice formations

UNIFIED SOIL CLASSIFICATION SYSTEM

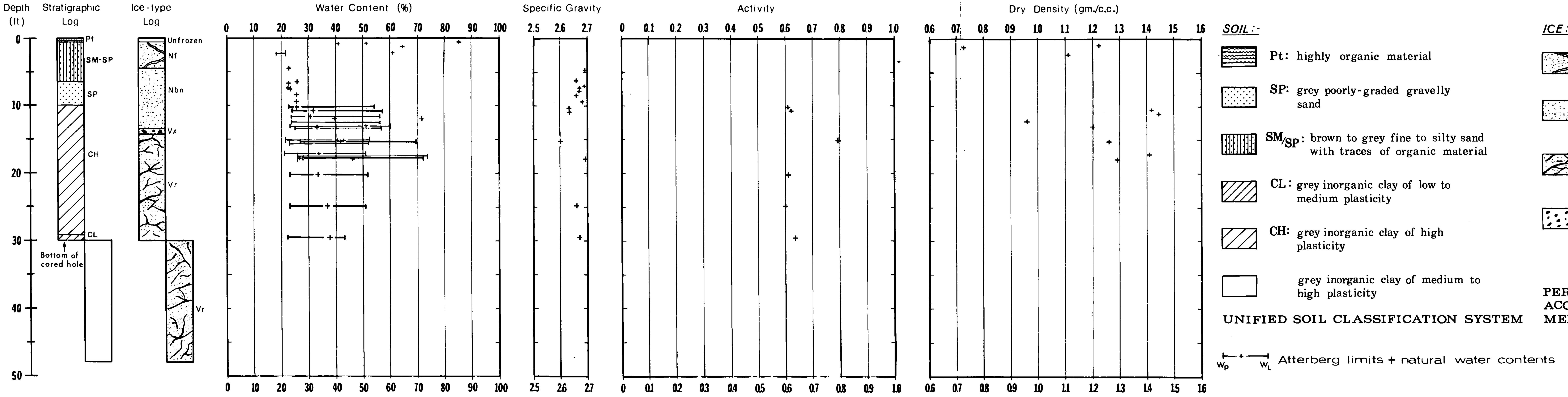
PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM # 79

W_P —+— W_L Atterberg limits + natural water contents

⊕ (excess) natural water contents

Drill hole: GL1

Date(s) drilled:	March 27, 28 and April 13, 1972
Site description:	This drill site was located in a dense forest of black spruce about 15 metres (50 feet) to the west of the CNT line. The ground sloped slightly toward the line and was well drained.
Genetic Classification of Overburden:	Glaciolacustrine deposit of sand over clay with a thin peat cover.



SOIL:-

Pt: highly organic material

SP: grey poorly-graded gravelly sand

SM/SP: brown to grey fine to silty sand with traces of organic material

CL: grey inorganic clay of low to medium plasticity

CH: grey inorganic clay of high plasticity

grey inorganic clay of medium to high plasticity

UNIFIED SOIL CLASSIFICATION SYSTEM

ICE:-

Nf: ice not visible, poorly bonded

Nbn: ice not visible, well bonded, no excess ice

Vr: visible ice less than one inch thick, random or irregularly oriented ice formations

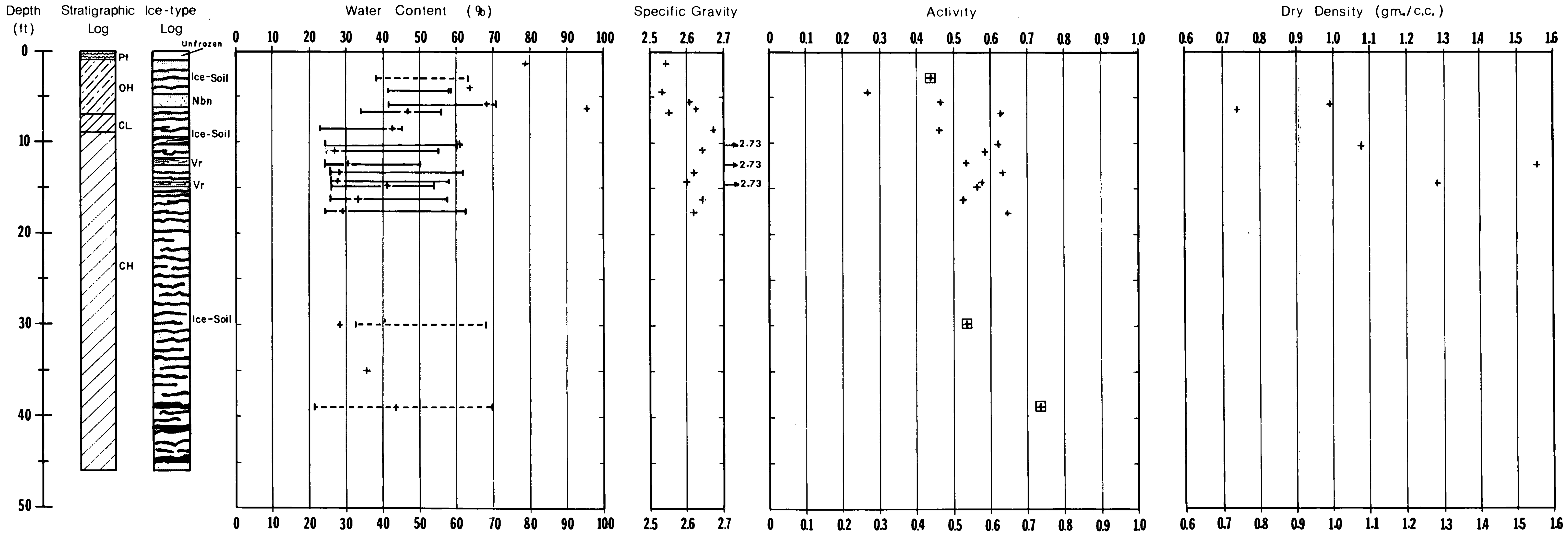
Vx: visible ice less than one inch thick, individual ice inclusions

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM # 79

GL1 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: TL

Date(s) drilled:	March 26, 1972
Site description:	This site, on the east side of the Mackenzie River, was located about 5 metres (16.5 feet) from a seismic line and about 30 metres (100 feet) from a shallow lake. The area was vegetated with a fairly dense forest of dwarf black spruce. Drainage was fairly good.
Genetic Classification of Overburden:	Glaciolacustrine deposit of clays below a thin peat cover.



SOIL :-

Pt: highly organic material

OH: blue-grey organic clay of medium to high plasticity

CH: blue-grey inorganic clay of high plasticity

CL: blue-grey inorganic clay of low to medium plasticity

UNIFIED SOIL CLASSIFICATION SYSTEM

ICE :-

Nbn: ice not visible, well bonded, no excess ice

Vr: visible ice less than one inch thick, random or irregularly oriented ice formations

ICE AND SOIL : visible ice greater than one inch thick, ice with soil inclusions

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM # 79

Wp — + — WL Atterberg limits + natural water contents

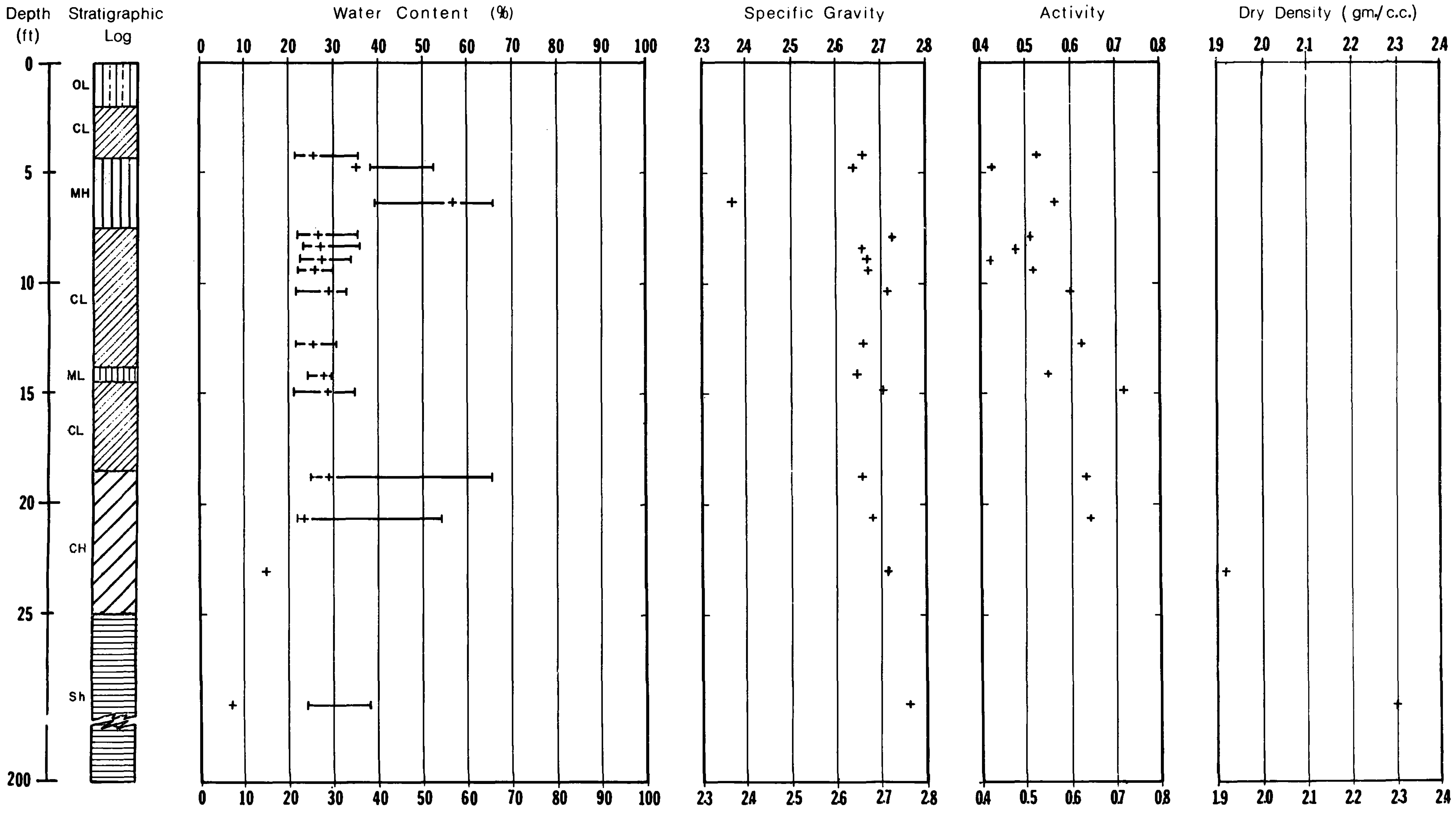
Wp - - + - - WL Atterberg limits + natural water contents (chip samples)

⊞ Activities (chip samples)

TL STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: MV

Date(s) drilled:	March 25, 1972
Site description:	The drill hole was located about 7 metres (23 feet) from a line that had been cleared recently by others. The vegetation was mainly black spruce, 5 to 6 metres (16.5 to 20 feet) tall and fairly closely spaced, and moss cover thickness varied greatly within short distances. Drainage was fair.
Genetic Classification of Overburden:	Glacial till deposit of sandy silt and clays with variable peat cover.



SOIL :-

OL: organic silty till of low plasticity

CL: brown inorganic silty clayey till with pebbles, low to medium plasticity

MH: brown inorganic clayey till of high plasticity

ML: brown inorganic silty sandy till with slight plasticity

CH: grey inorganic clay of high plasticity, sand and gravel present

UNIFIED SOIL CLASSIFICATION SYSTEM

ROCK :-

Sh: blue-grey shale

W_P + W_L Atterberg limits + natural water contents (predominantly chip samples)

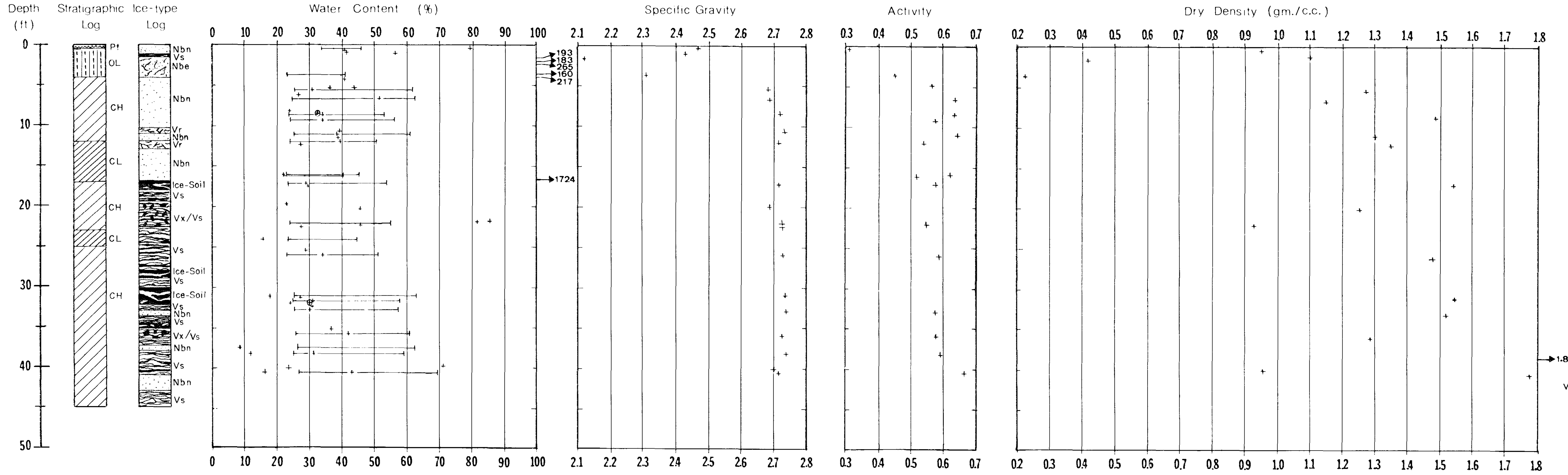
MV STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: GL2U

Date(s) drilled: April 8 and 9, 1972

Site description: This drill site was an undisturbed area of fairly dense black spruce. The drill hole was located about 15 metres (50 feet) to the north of the Canol Road between the road and an old cut line.

Genetic Classification of Overburden: Glaciolacustrine deposit of silt over clay under a thin cover of peat.



SOIL :-

Pt: brown peat, highly organic material

OL: brown organic silts and organic silt clays of low plasticity

CH: blue-grey inorganic clay of high plasticity

CL: blue-grey inorganic clay of low to medium plasticity

UNIFIED SOIL CLASSIFICATION SYSTEM

Wp + WL Atterberg limits + natural water contents

⊕ (excess) natural water contents

ICE :-

Nbn: ice not visible, well bonded, no excess ice

Nbe: ice not visible, well bonded, excess ice

Vr: visible ice less than one inch thick, random or irregularly oriented ice formations

Vx: visible ice less than one inch thick, individual ice inclusions

Vs: visible ice less than one inch thick, stratified or distinctly oriented ice formations

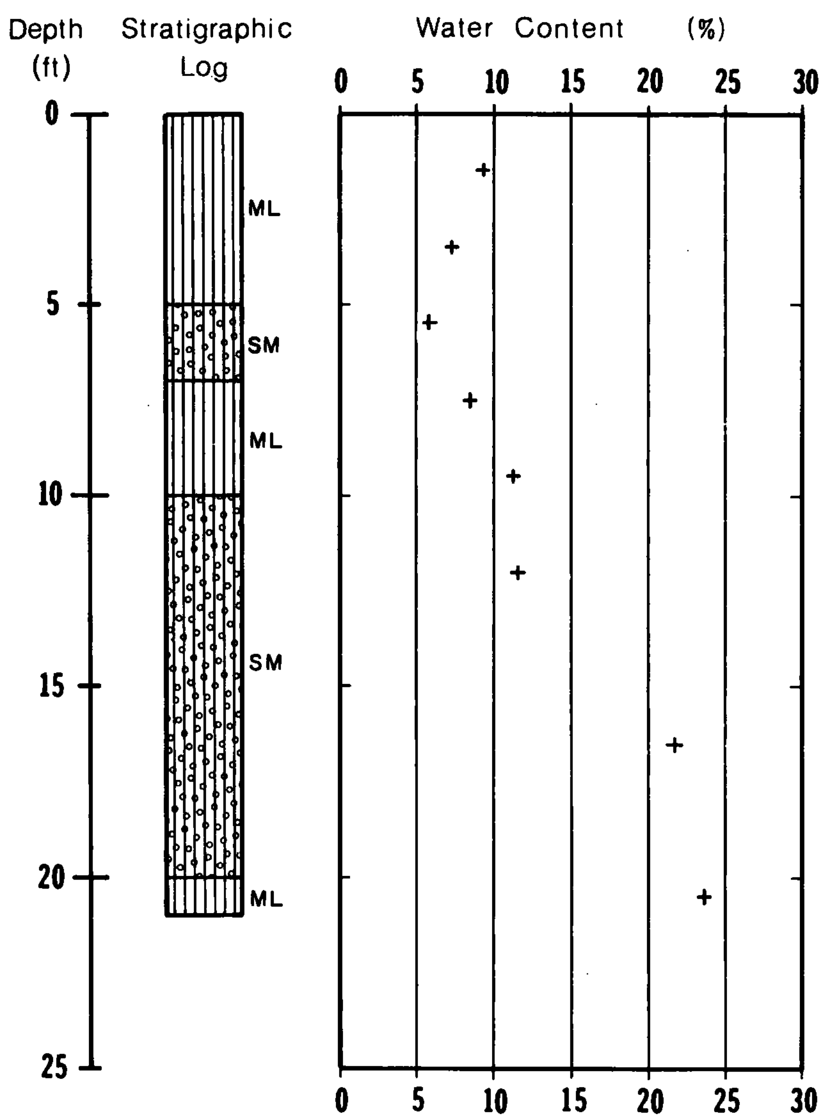
ICE AND SOIL: visible ice greater than one inch thick, ice with soil inclusions

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM #79

GL2U STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: CCU

Date(s) drilled:	April 2, 1972
Site description:	This site consisted of a clear area on a slope just to the east of the main Canol Camp. There was no ground cover and only a scattering of willow shrubs.
Genetic Classification of Overburden:	Glaciolacustrine deposit of sand.



SOIL :-

ML: light brown inorganic fine sand

SM: grey-brown silty sand

UNIFIED SOIL CLASSIFICATION SYSTEM

W_p + W_L Atterberg limits + natural water contents (chip samples)

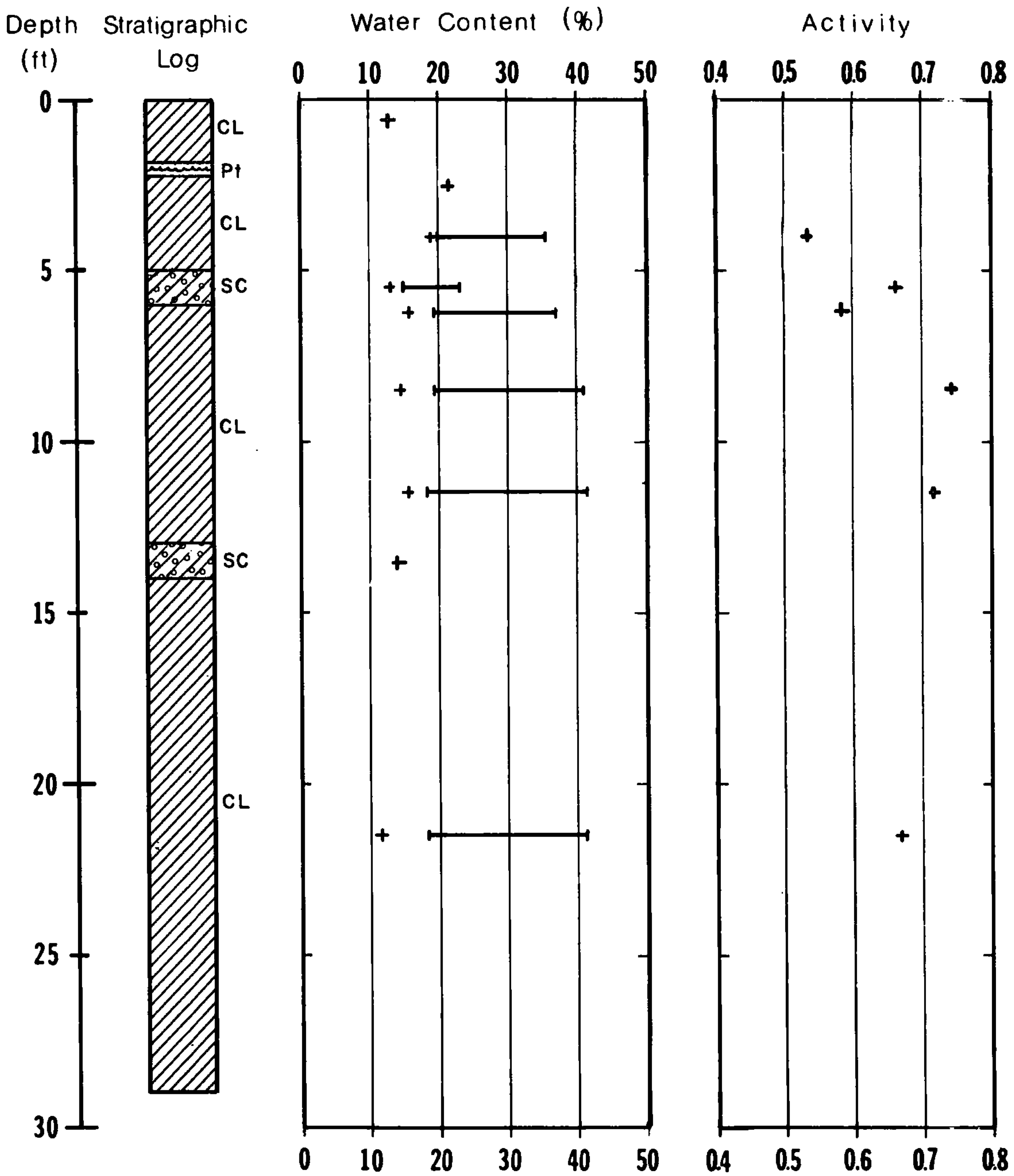
CCU STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: R-1

Date(s) of drilling: April 4, 1972

Site description: This drill hole was located in the centre of the Canol Road, approximately 2 km (1 mile) from its junction with Heart Lake. The previously cleared areas on either side of the road were overgrown with tall willows but the road surface itself was clear of vegetation.

Genetic Classification of overburden: Silty clay fill over compressed peat and glacial till, the latter consisting of silty clay with some silt and gravel.



SOIL :-

Pt: highly organic material

CL: brown to dark grey sandy silty clay of low to medium plasticity

SC: brown clayey silty sand, with some gravel

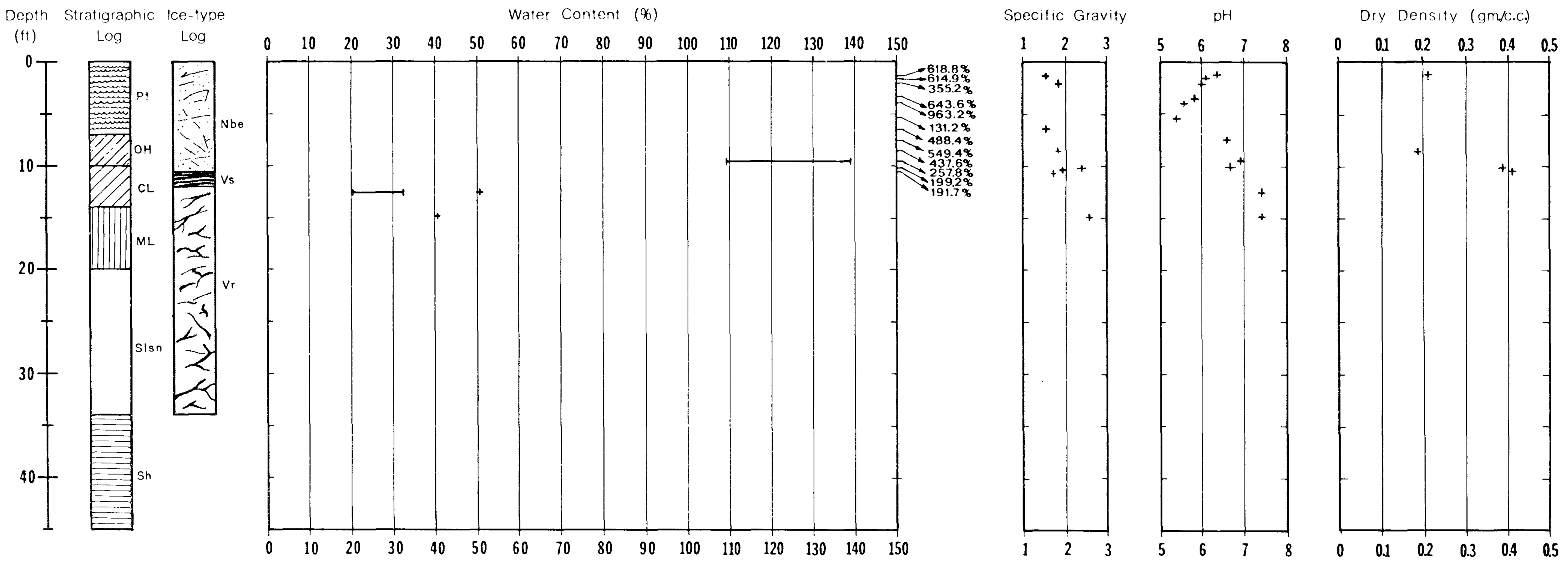
UNIFIED SOIL CLASSIFICATION SYSTEM

W_P W_L Atterberg limits + natural water contents (chip samples)

R1 STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: SA

Date(s) drilled:	April 4 and 11, 1972
Site description:	The area was a hummocky fenland with scattered trees. The site was located about 30 metres (100 feet) from the Canol Road; this area, including the road, was about 2 to 3 metres (6.5 to 10 feet) lower in elevation than the adjacent ground that was not fenland. The area was poorly drained and in summer there was considerable standing water.
Genetic Classification of Overburden:	Glaciolacustrine deposit of silts and clays over siltstone and shale; substantial peat cover.



SOIL :-

Pt: highly organic material

OH: dark organic clay of medium to high plasticity

CL: inorganic clay of low to medium plasticity

ML: clayey silts with slight plasticity

UNIFIED SOIL CLASSIFICATION SYSTEM

ROCK :-

Slsn: siltstone with occasional clay and ice layers

Sh: shale with calcareous seams

ICE :-

Nbe: ice not visible, well bonded, excess ice

Vr: visible ice less than one inch thick, random or irregularly oriented ice formations

Vs: visible ice less than one inch thick, stratified or distinctly oriented ice formations

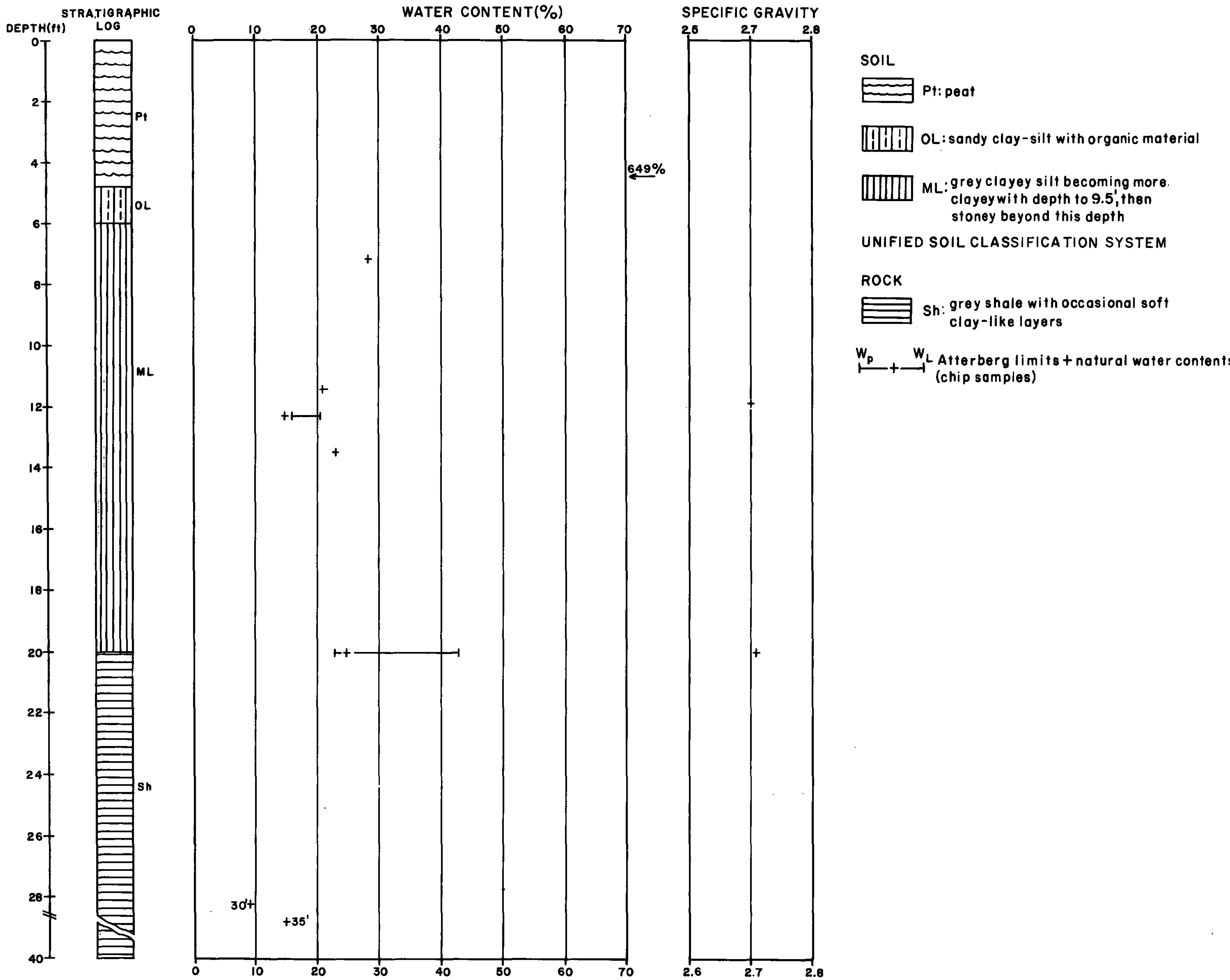
PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM # 79

W_p —+— W_L Atterberg limits + natural water contents (chip samples)

SA STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: SD

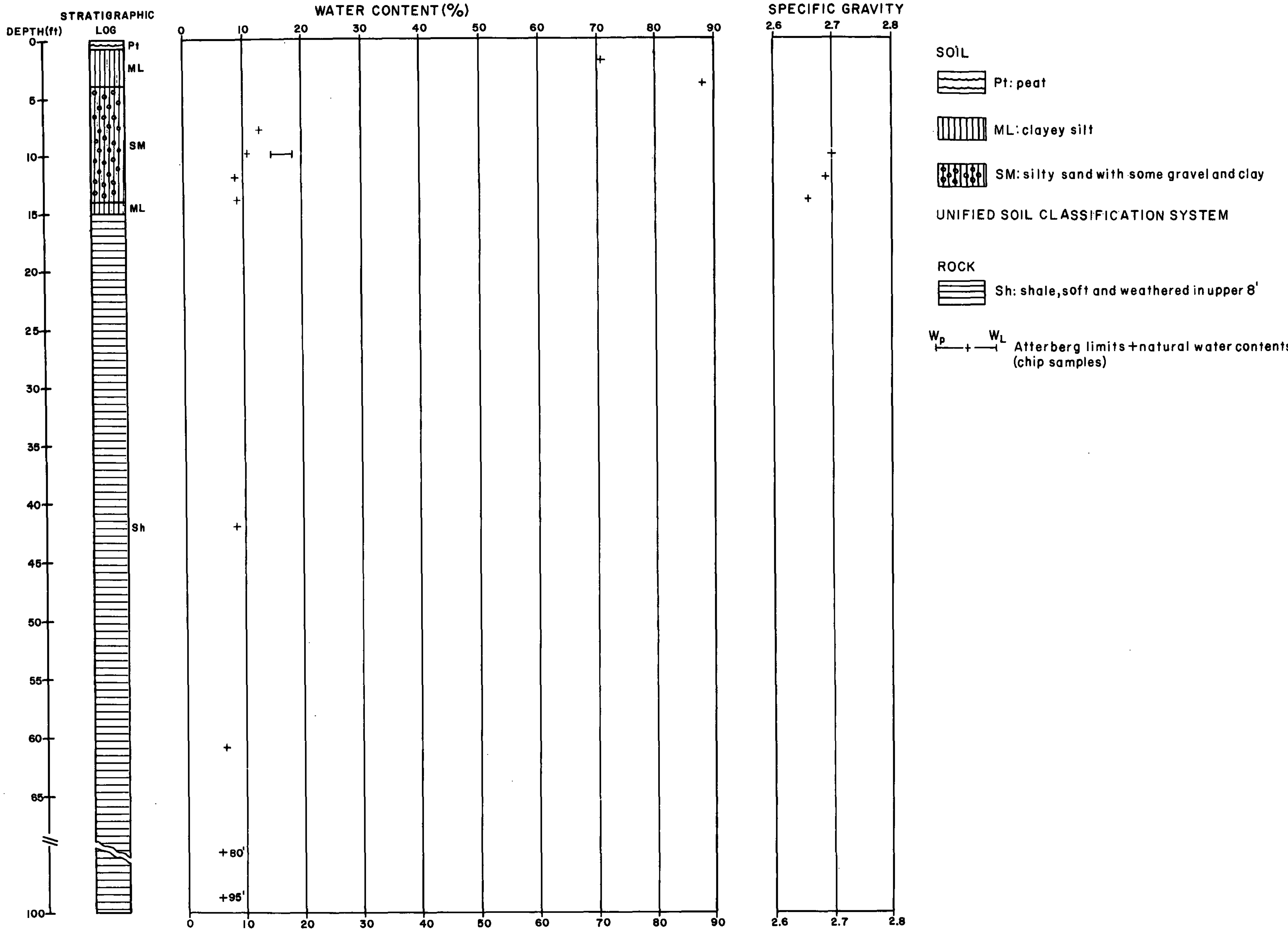
Date(s) drilled:	April 3, 1972
Site description:	A clearing was made 6 metres (20 feet) off the existing Canol Road by removing the low scrub. This drill site was located about 50 metres (165 feet) from Heart Lake on fairly level ground with good drainage.
Genetic Classification of Overburden:	Glacial till over shale beneath a substantial cover of peat.



SD—STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: 7D

Date(s) drilled:	April 14, 1972
Site description:	The drill site was located just off the intersection of two cut lines and about 70 metres (230 feet) from a large lake. Vegetation was dense, predominantly black spruce, and drainage was good.
Genetic Classification of Overburden:	Alluvial deposit of gravel and sand over shale beneath a thin peat cover.



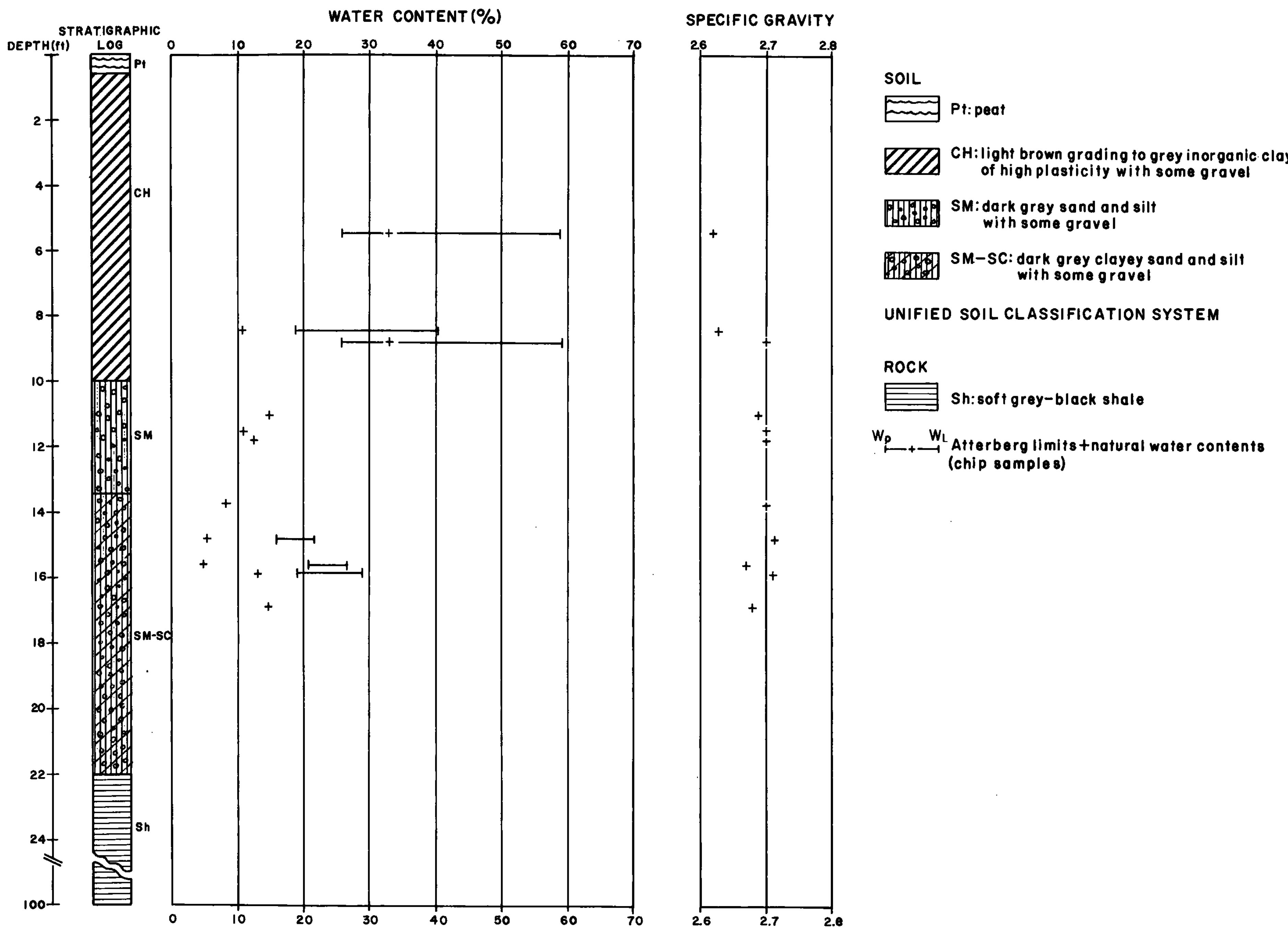
7D-STRATIGRAPHIC AND PHYSICAL DATA

Drill hole: 7B

Date(s) drilled: March 20 and 24, 1972

Site description: This drill hole was located on a slope to the east of the CNT line and about 5 metres (16.5 feet) to the north of an old seismic line. The area was covered with a medium-dense growth of dwarf black spruce. Drainage was good.

Genetic Classification of Overburden: Glacial till deposit of clay over sand over shale under a thin peat cover.



7B–STRATIGRAPHIC AND PHYSICAL DATA

Appendix II

Thermal conductivity vs. moisture content

In situ thermal diffusivities

Calorimetric test results

OTHER POSSIBLE GROUPINGS

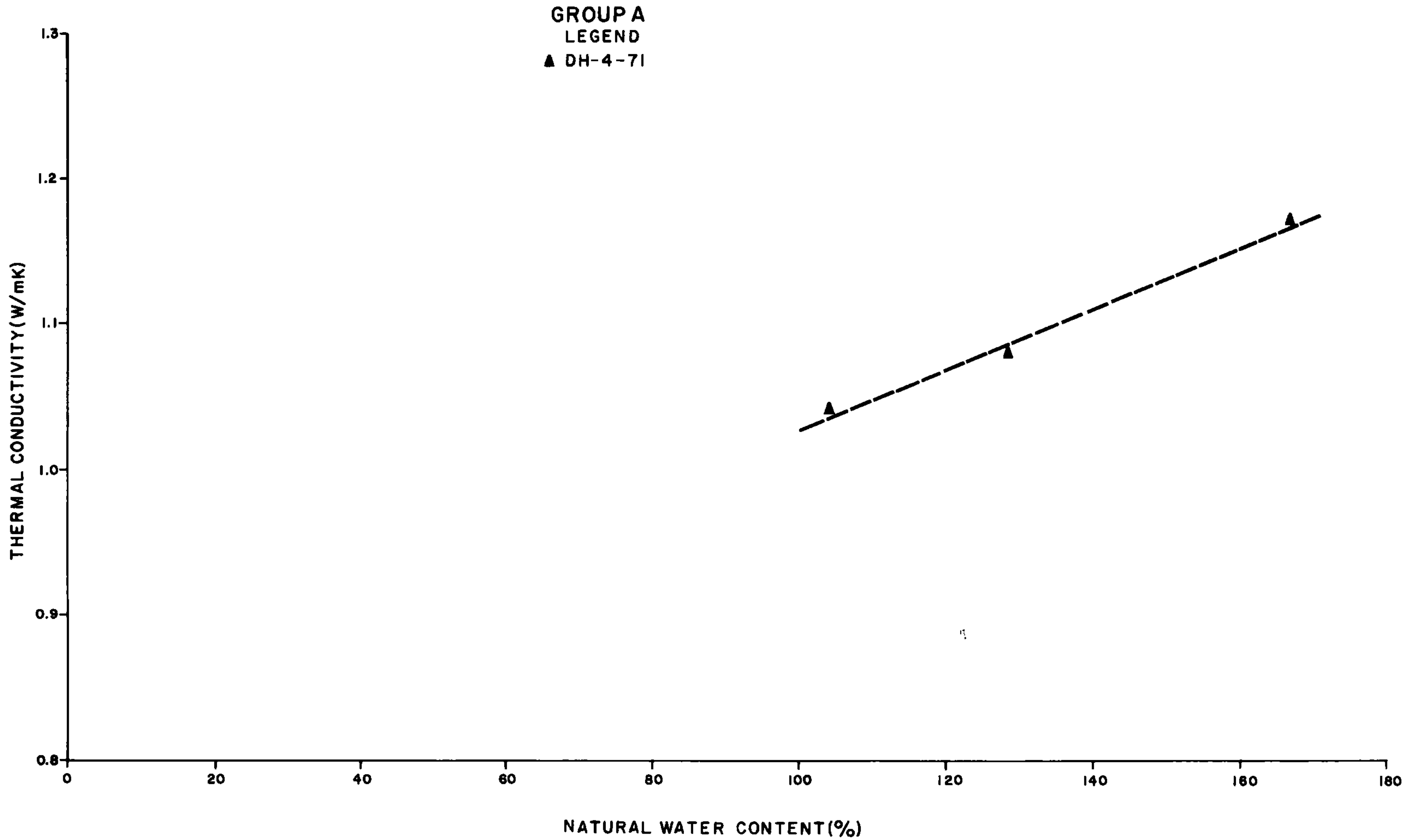
Borehole	Depth (feet)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Best estimate of W_L (%)	W_P (%)	W_I (%)	Activity	Natural Water Content (%)	Thermal Conductivity (W/m^{o}K)	Temp. (^{o}C)
DH-1-71	19.8	-	8.0	77.0	15.0	28	21	7	0.47	25.4	1.52	-5.6
DH-3-71	30.0	-	9.0	71.5	19.5	24	14	10	0.51	21.0	1.72	-5.6
DH-1-71	79.2	-	38.5	53.0	8.5	20	16	4	0.47	28.4	2.41	-5.7
DH-1-71	91.0	-	34.0	58.5	7.5	20	16	4	0.53	25.7	2.00	-5.7
DH-1-71	101.3	-	1.5	47.4	51.1	50	18	32	0.63	21.8	1.35	-5.8
DH-4-71	54.4	-	-	56.3	43.7	48	20	28	0.64	29.9	0.97	-5.1
DH-2-71	15.7	2.5	32.0	44.2	21.3	26	15	11	0.52	7.7	0.78	-5.5
DH-2-71	15.7	5.0	23.0	51.7	20.3	27	17	10	0.49	9.3	1.27	-5.7

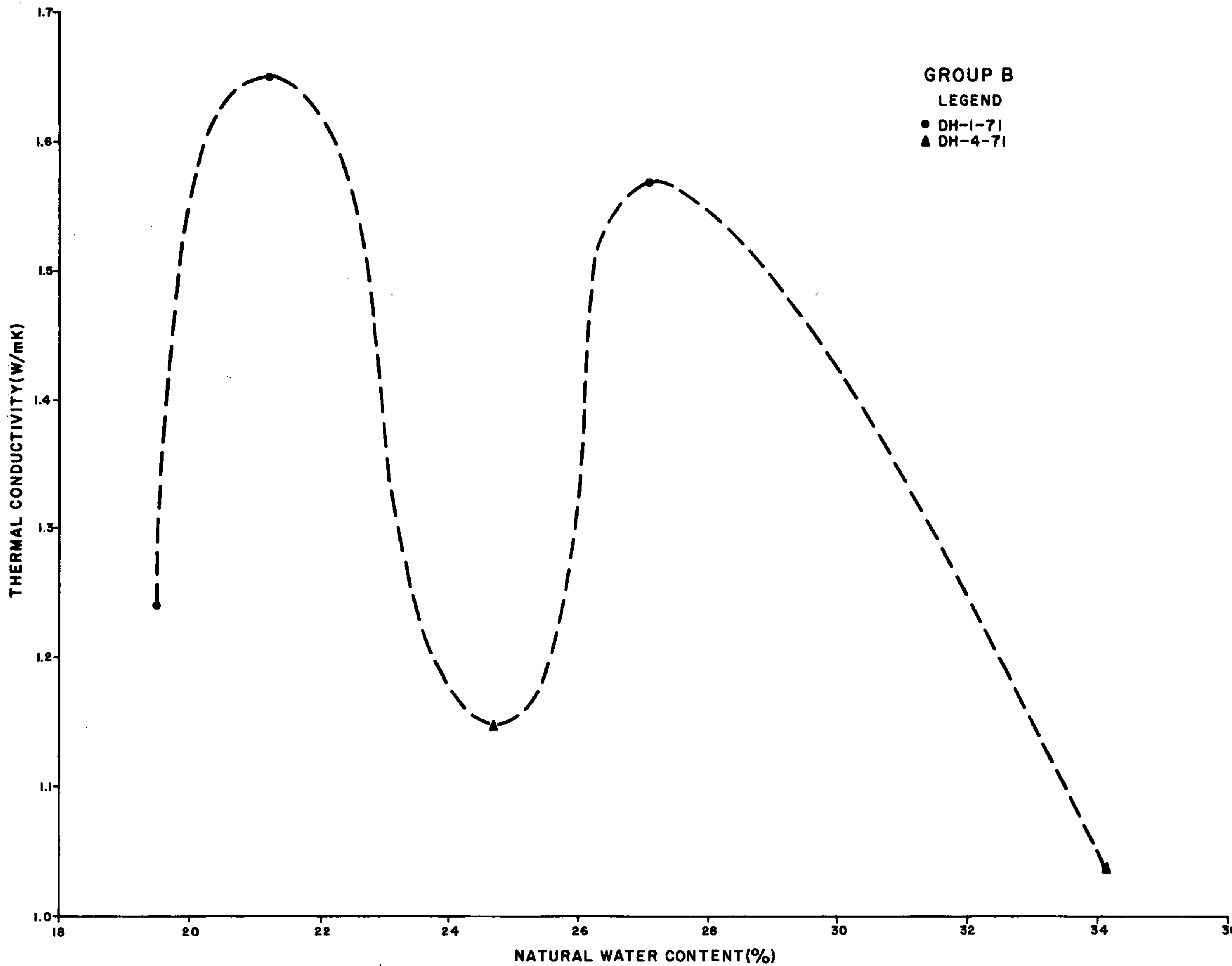
Borehole	Depth (feet)	Sand (%)	Silt (%)	Clay (%)	Best estimate of W_L (%)	W_P (%)	W_I (%)	Activity	Natural Water Content (%)	Thermal Conductivity (W/m°K)	Mean Temp. (°C)
					GROUP A						
DH-4-71	10.2	-	35.5	64.5	65	23	42	0.65	128.6	1.08	-5.0
	17.9	-	36.8	63.2	64	23	41	0.65	104.2	1.04	-5.0
	40.0	-	33.6	66.4	68	24	44	0.66	167.0	1.17	-5.0
					GROUP B						
DH-1-71	55.3	1.0	46.5	52.5	49	18	31	0.59	21.2	1.65	-5.6
	63.0	0.5	46.3	53.2	50	18	32	0.60	27.1	1.57	-5.6
	68.2	-	44.0	56.0	52	19	33	0.59	19.5	1.24	-5.8
DH-4-71	34.8	-	46.6	53.4	51	20	31	0.58	24.7	1.15	-5.1
	79.8	-	47.3	52.7	52	21	31	0.59	34.1	1.04	-5.1
					GROUP C						
DH-3-71	34.8	-	56.3	43.7	46	23	23	0.53	22.4	1.00	-5.6
	40.1	-	55.3	44.7	47	23	24	0.54	22.8	1.43	-5.5
	49.8	-	52.7	47.3	50	24	26	0.55	19.6	1.64	-5.7
					GROUP D						
DH-1-71	42.6	-	58.5	41.5	37	18	19	0.46	24.7	1.98	-5.4
	84.1	8.5	42.3	49.2	39	15	24	0.49	22.6	1.34	-6.1
DH-4-71	25.0	-	58.0	42.0	40	19	21	0.50	27.3	1.61	-5.0

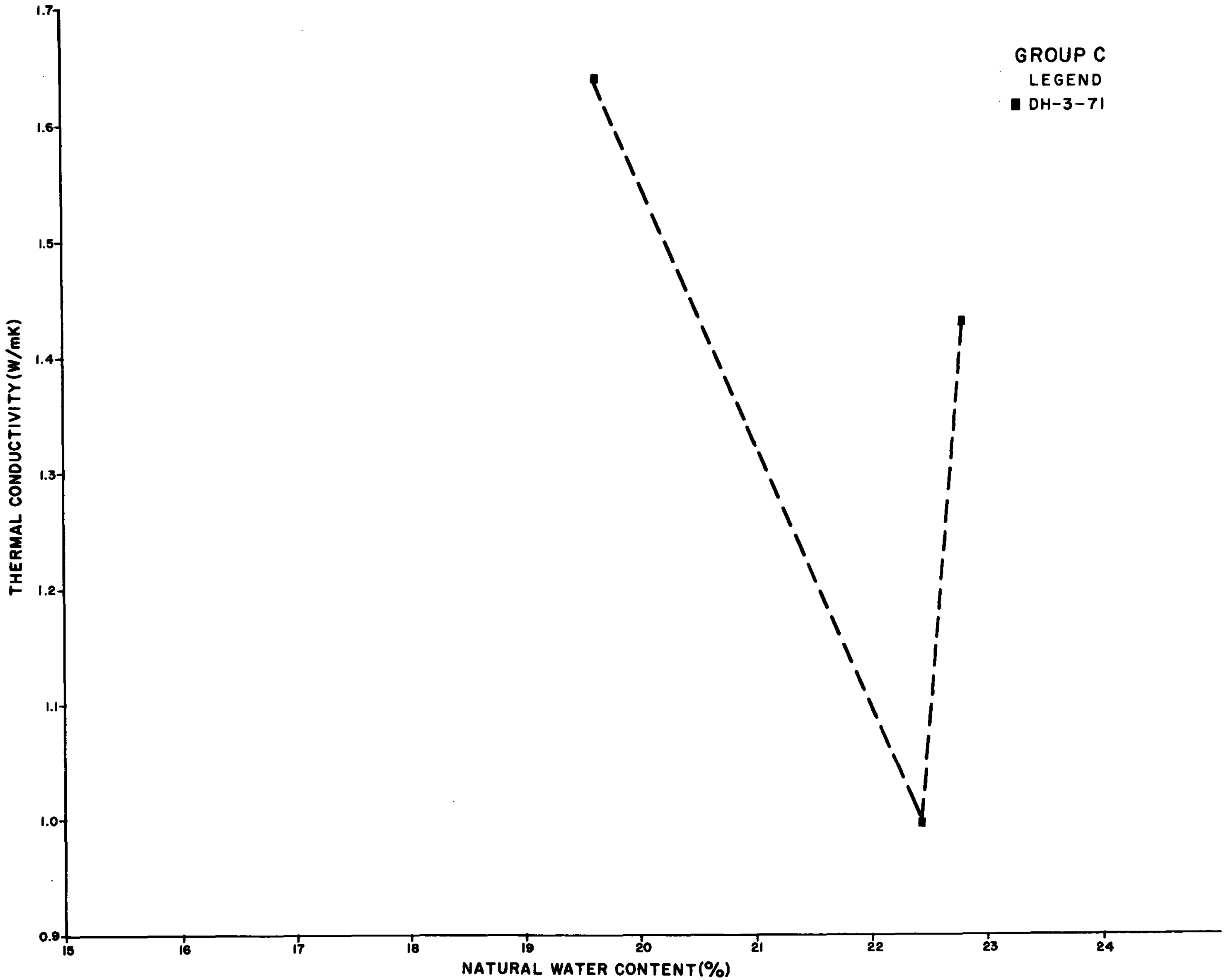
GROUP E *

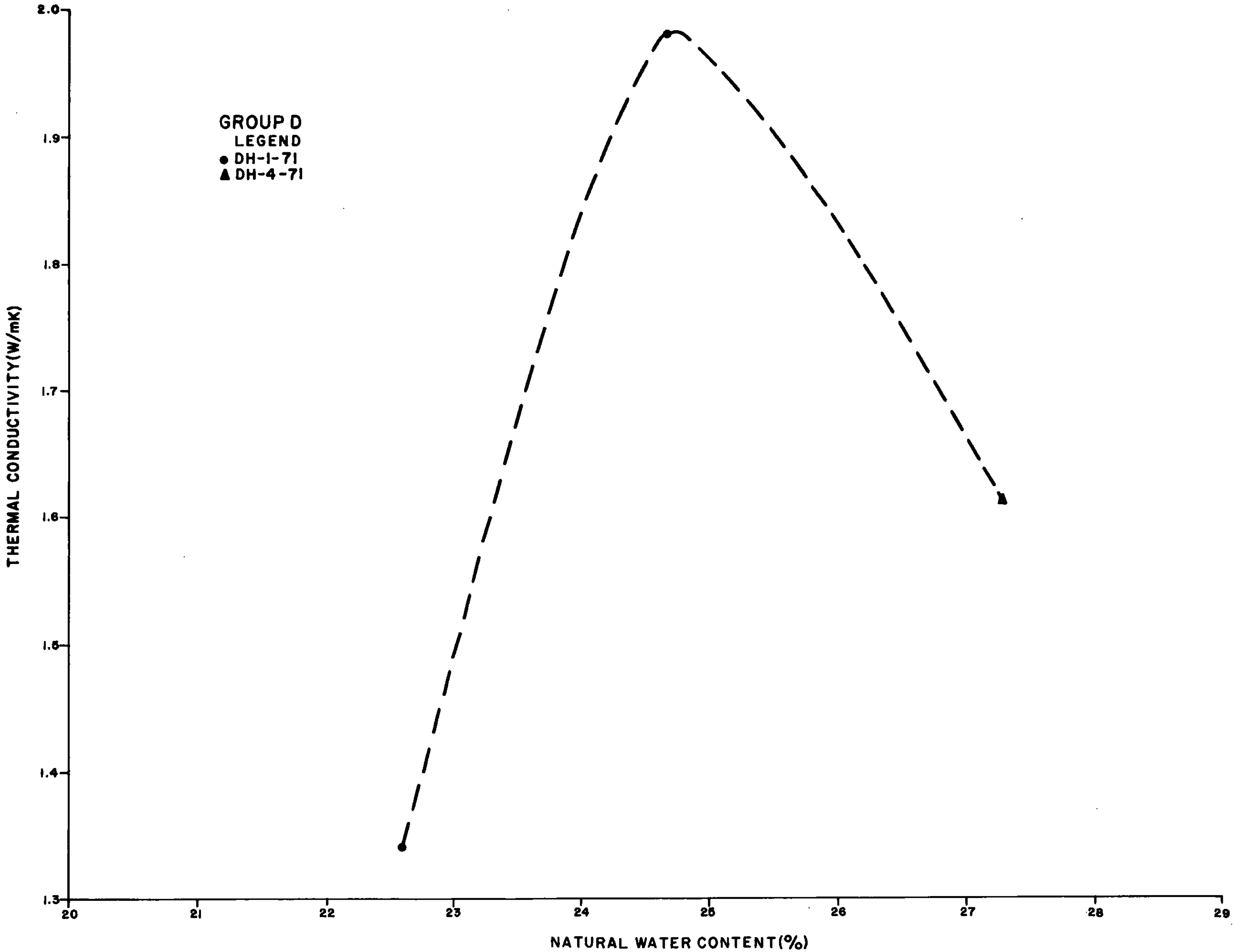
DH-1-71	26.9	11.0	79.0	10.0	24	19	5	0.50	24.0	2.36	-5.5
	36.6	4.5	86.8	8.7	23	18	5	0.57	32.0	1.99	-5.5
	73.5	1.0	88.9	10.1	24	19	5	0.50	24.2	2.45	-5.6
	95.3	17.5	73.8	8.7	24	19	5	0.57	25.2	2.17	-5.6

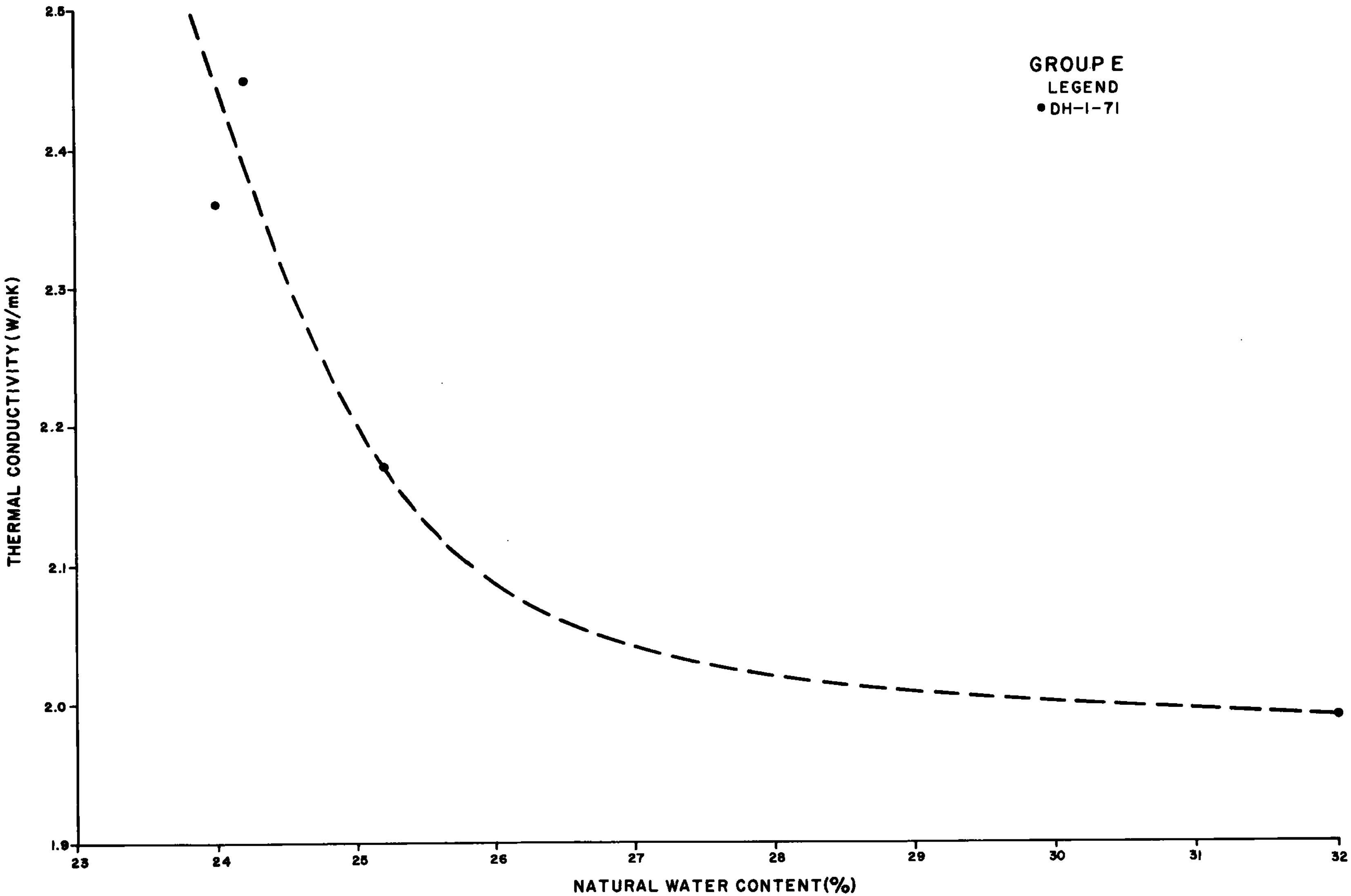
* As W_I and percentage clay are very sensitive to slight differences, activity is not a reliable guide.

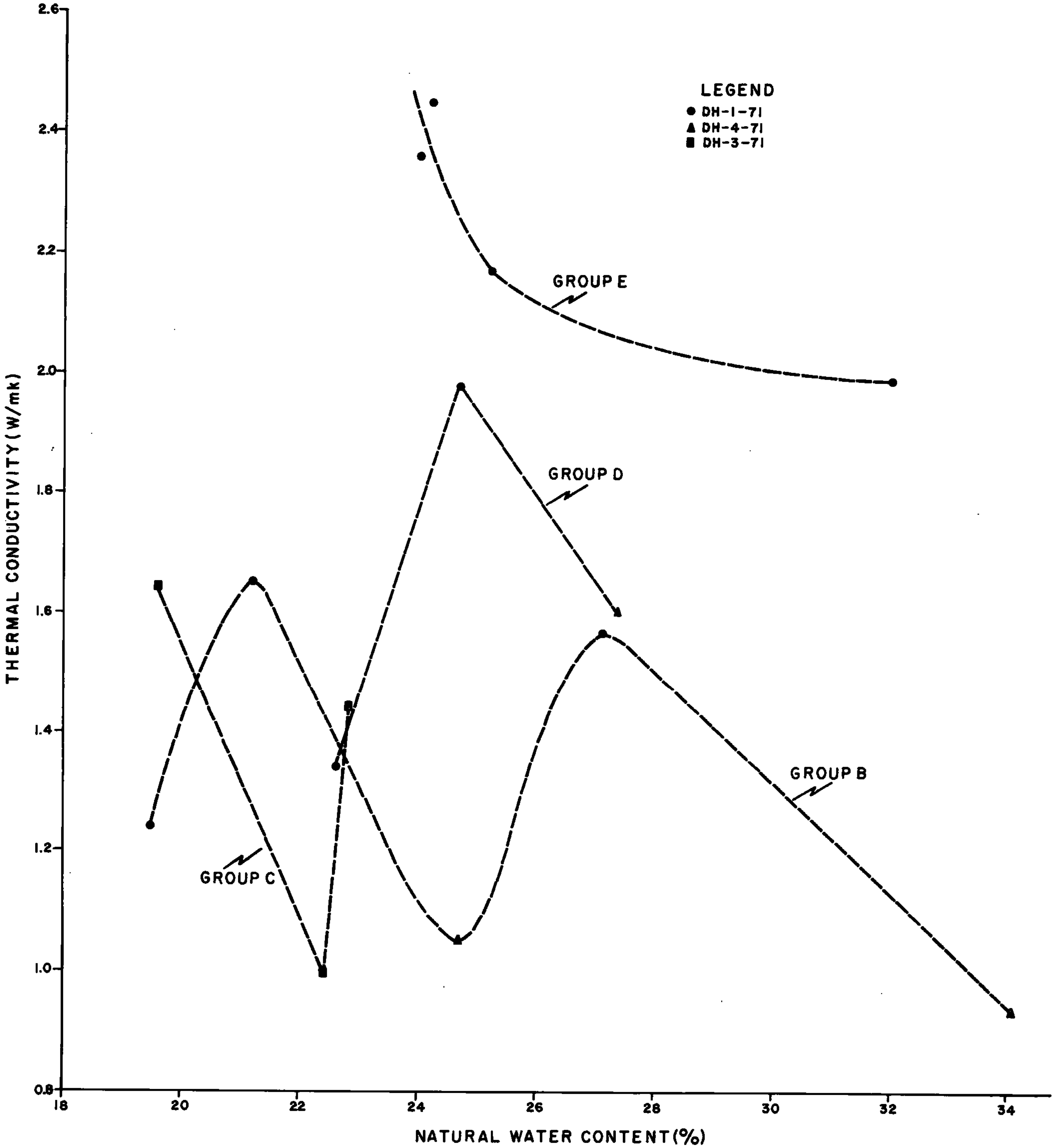

GROUP A
LEGEND
▲ DH-4-71
THERMAL CONDUCTIVITY (W/mK)
1.3
1.2
1.1
1.0
0.9
0.8
0
20
40
60
80
100
120
140
160
180
NATURAL WATER CONTENT (%)

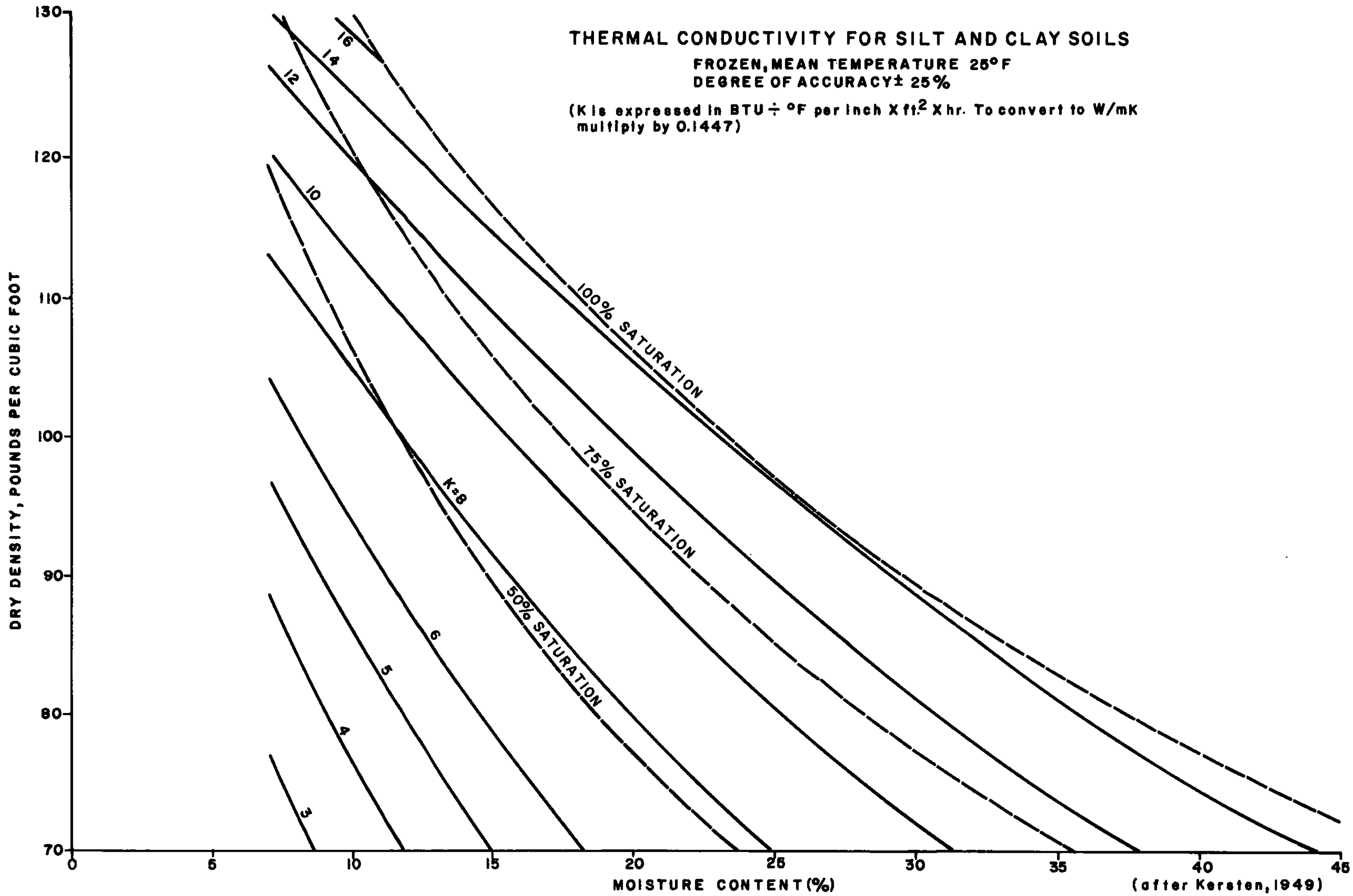

GROUP B
LEGEND
● DH-1-71
▲ DH-4-71
THERMAL CONDUCTIVITY(W/mK)
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
18
20
22
24
26
28
30
32
34
36
NATURAL WATER CONTENT(%)

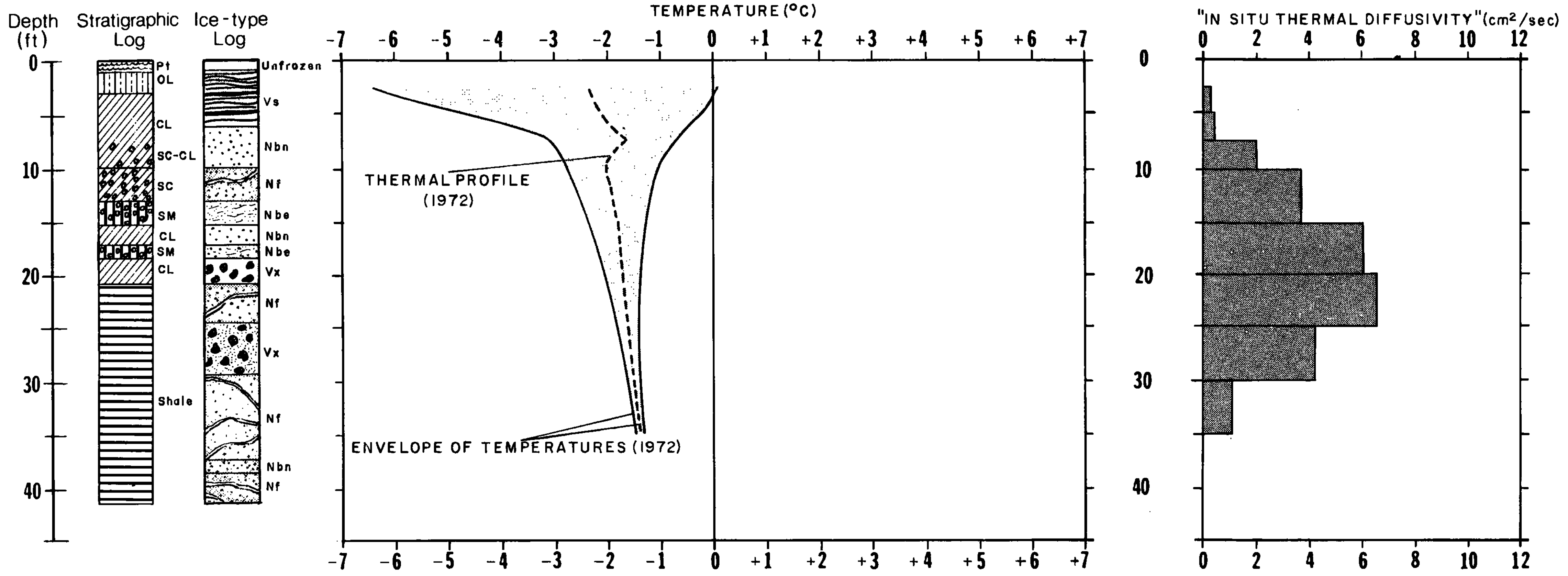

GROUP C
LEGEND
DH-3-71
THERMAL CONDUCTIVITY (W/mK)
NATURAL WATER CONTENT(%)
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
15
16
17
18
19
20
21
22
23
24


GROUP D
LEGEND
● DH-1-71
▲ DH-4-71
THERMAL CONDUCTIVITY (W/mK)
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
20
21
22
23
24
25
26
27
28
29
NATURAL WATER CONTENT (%)


GROUP E
LEGEND
DH-1-71
THERMAL CONDUCTIVITY (W/mK)
2.5
2.4
2.3
2.2
2.1
2.0
1.9
23
24
25
26
27
28
29
30
31
32
NATURAL WATER CONTENT(%)


LEGEND
DH-1-71
DH-4-71
DH-3-71
GROUP E
GROUP D
GROUP B
GROUP C
THERMAL CONDUCTIVITY (W/mk)
NATURAL WATER CONTENT (%)
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
18
20
22
24
26
28
30
32
34


THERMAL CONDUCTIVITY FOR SILT AND CLAY SOILS
FROZEN, MEAN TEMPERATURE 25°F
DEGREE OF ACCURACY ± 25%
(K is expressed in BTU ÷ °F per inch X ft.² X hr. To convert to W/mK multiply by 0.1447)
DRY DENSITY, POUNDS PER CUBIC FOOT
MOISTURE CONTENT (%)
(after Kersten, 1949)
100% SATURATION
75% SATURATION
50% SATURATION
K=8
16
14
12
10
6
5
4
3
130
120
110
100
90
80
70
0
5
10
15
20
25
30
35
40
45



DH-2-71 · GEOLOGICAL AND THERMAL DATA

SOIL:-

Pt: peat

SM: dark-brown to grey silty sand with some gravel

SC: brown gravelly sand-clay

SC-CL: brown gravelly sand-clay of low to medium plasticity

CL: grey gravelly silty clay of low to medium plasticity

OL: mottled yellow-brown organic silt-clay of medium plasticity

UNIFIED SOIL CLASSIFICATION SYSTEM

ROCK:-

Shale, dark grey to black

ICE:-

Nf: ice not visible, poorly bonded

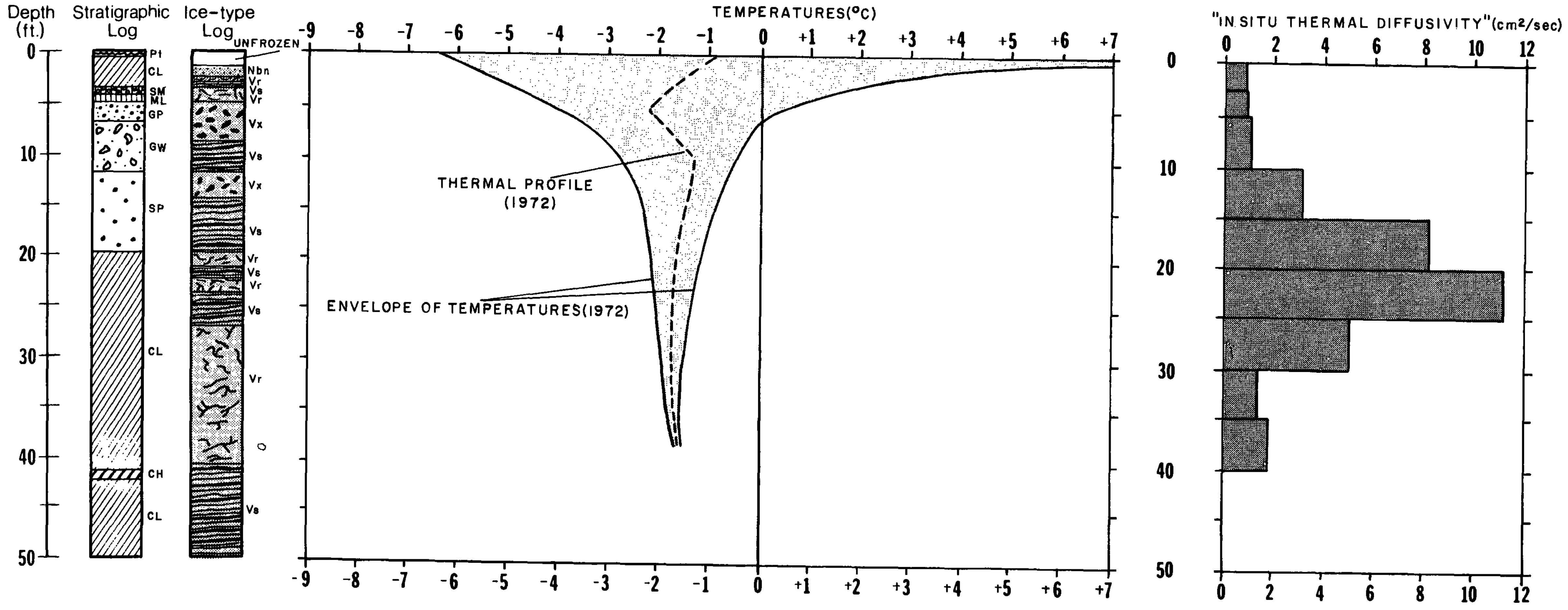
Nbn: ice not visible, well bonded, no excess ice

Nbe: ice not visible, well bonded, excess ice

Vx: visible ice less than one inch thick, individual ice inclusions

Vs: visible ice less than one inch thick, stratified or distinctly oriented ice formations

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM #79



DH-3-71 GEOLOGICAL AND THERMAL DATA

SOIL:-

- Pt: peat
- GW: dark-brown well-graded gravel-sand mixture with very little fines
- GP: dark-brown poorly-graded gravel-sand mixture with very little fines
- SP: dark-grey poorly-graded gravelly sand with negligible fines

....*SOIL (cont'd):-*

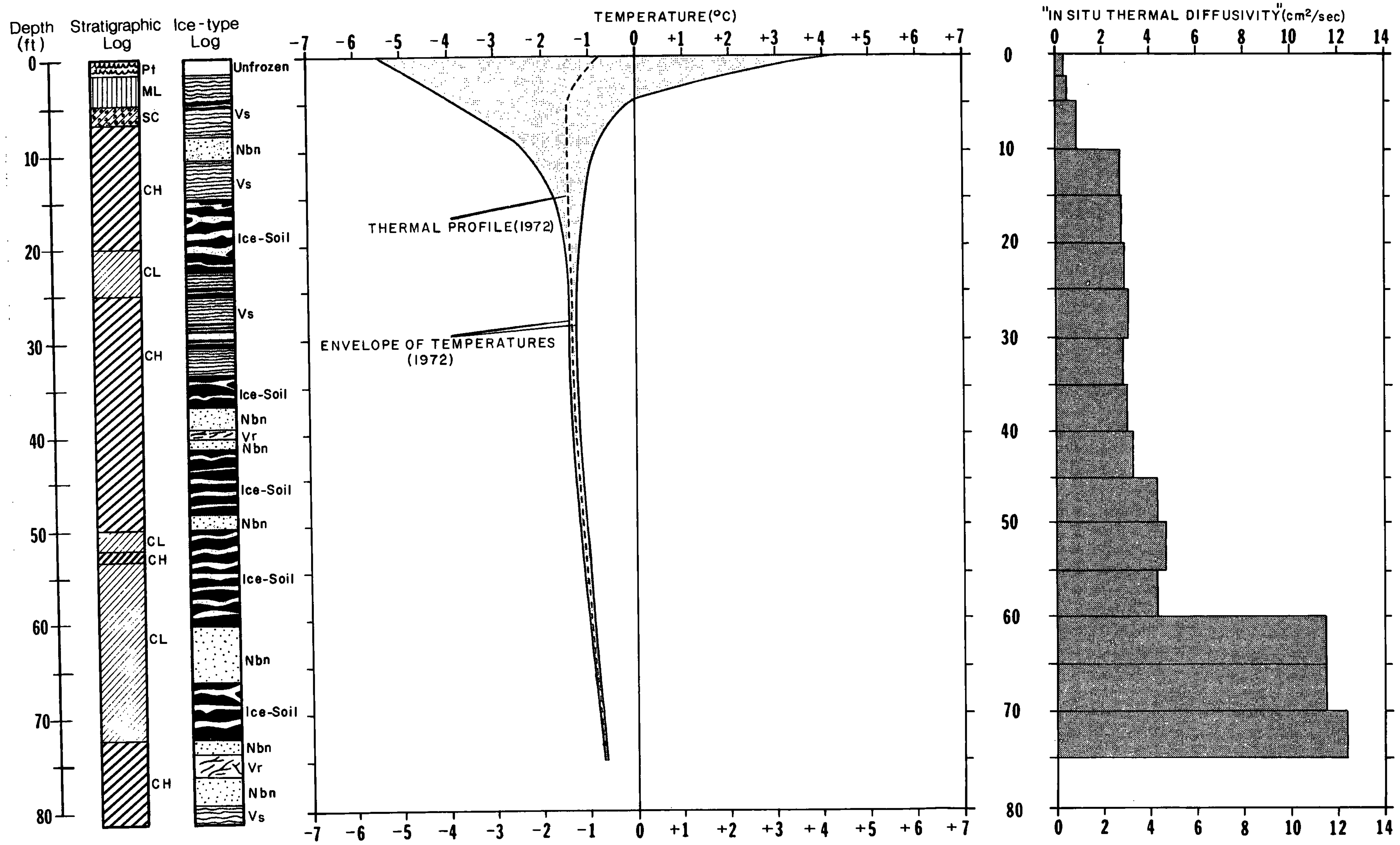
- SM: dark-brown silty fine sand with some gravel
- ML: dark-brown clayey silty sand with some gravel and organic material
- CL: dark-grey (except near the surface where the colour is yellow brown) silty clay of low to medium plasticity
- CH: dark-grey silty clay of high plasticity

UNIFIED SOIL CLASSIFICATION SYSTEM

ICE:-

- Nbn: ice not visible, well bonded, no excess ice
- Nbe: ice not visible, well bonded, excess ice
- Vx: visible ice less than one inch thick, individual ice inclusions
- Vr: visible ice less than one inch thick, random or irregularly oriented ice formations
- Vs: visible ice less than one inch thick, stratified or distinctly oriented ice formations

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM #79



DH-4-71 GEOLOGICAL AND THERMAL DATA

SOIL :-

Pt: peat

SC: brown silty clayey sand with traces of organic material

ML: mottled, yellow-brown to grey silt and very fine sand

CL: grey inorganic silty clay of low to medium plasticity

CH: grey inorganic clay of high plasticity

UNIFIED SOIL CLASSIFICATION SYSTEM

ICE :-

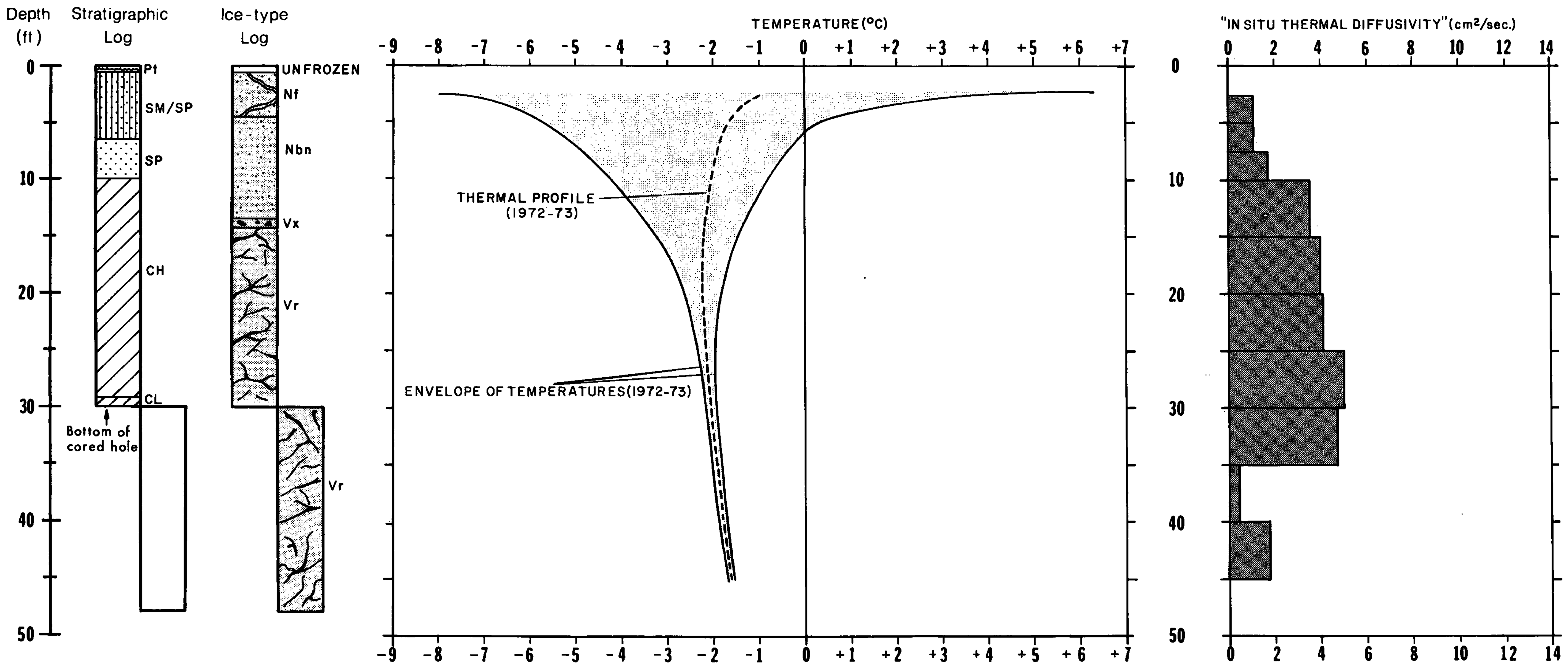
Nbn: ice not visible, well bonded, no excess ice

Vr: visible ice less than one inch thick, random or irregularly oriented ice formations

Vs: visible ice less than one inch thick, stratified or distinctly oriented ice formations

ICE AND SOIL: visible ice greater than one inch thick, ice with soil inclusions

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM #79



GL1 GEOLOGICAL AND THERMAL DATA

SOIL:-

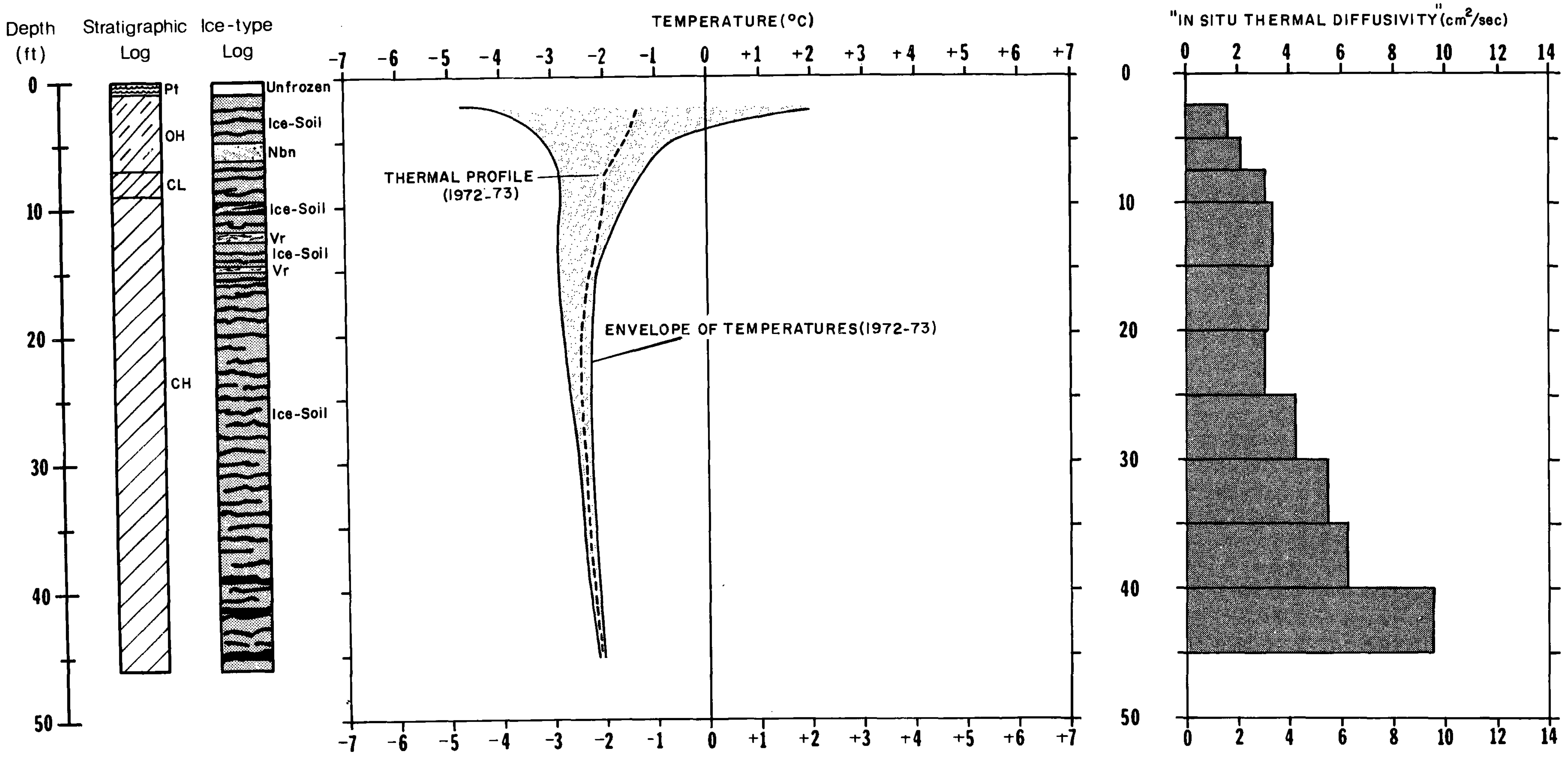
- Pt: highly organic material
- SP: grey poorly-graded gravelly sand
- SM/SP: brown to grey fine to silty sand with traces of organic material
- CL: grey inorganic clay of low to medium plasticity
- CH: grey inorganic clay of high plasticity
- grey inorganic clay of medium to high plasticity

UNIFIED SOIL CLASSIFICATION SYSTEM

ICE:-

- Nf: ice not visible, poorly bonded
- Nbn: ice not visible, well bonded, no excess ice
- Vr: visible ice less than one inch thick, random or irregularly oriented ice formations
- Vx: visible ice less than one inch thick, individual ice inclusions

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM #79



TL GEOLOGICAL AND THERMAL DATA

SOIL :-

Pt: highly organic material

OH: blue-grey organic clay of medium to high plasticity

CH: blue-grey inorganic clay of high plasticity

CL: blue-grey inorganic clay of low to medium plasticity

UNIFIED SOIL CLASSIFICATION SYSTEM

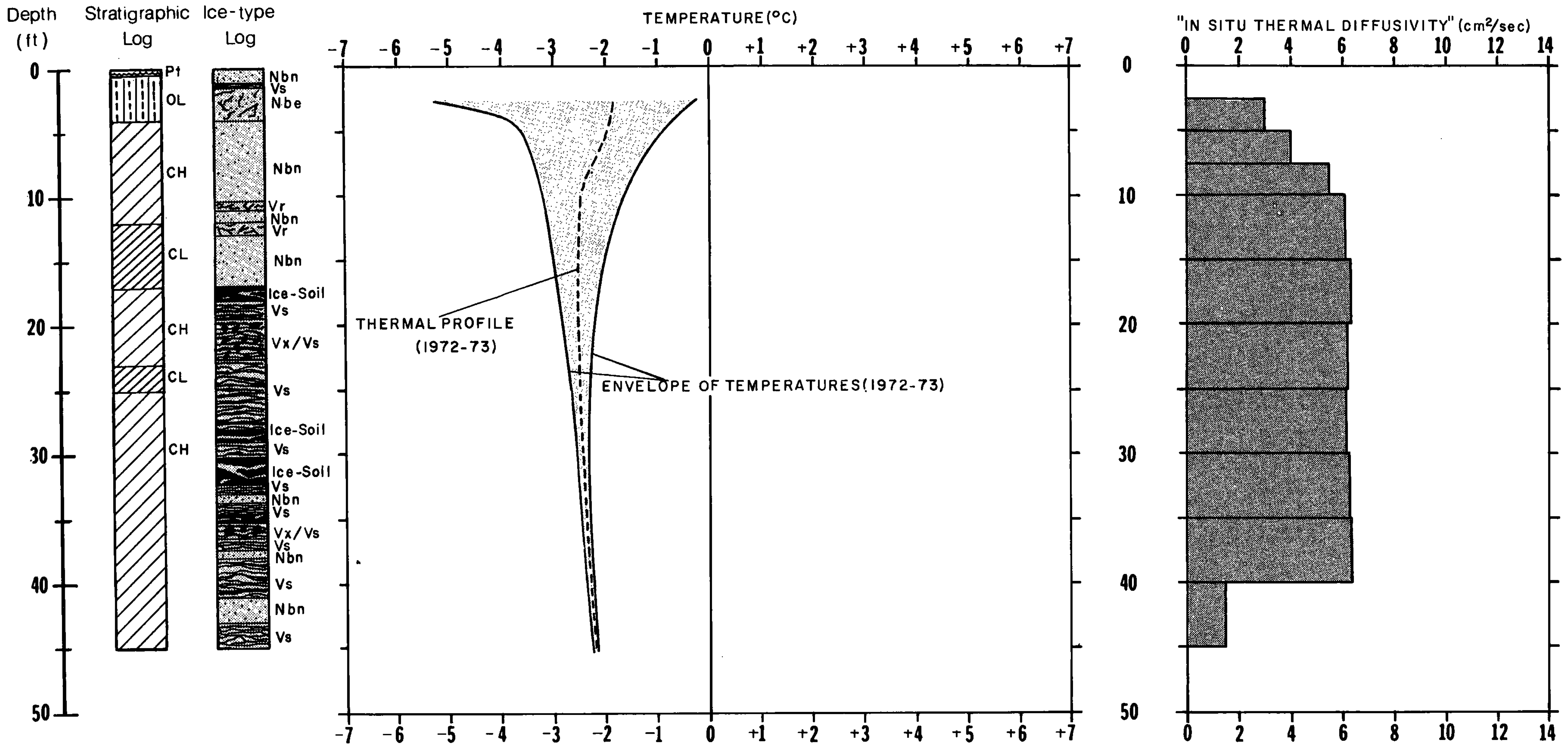
ICE :-

Nbn: ice not visible, well bonded, no excess ice

Vr: visible ice less than one inch thick, random or irregularly oriented ice formations

ICE AND SOIL: visible ice greater than one inch thick, ice with soil inclusions

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM # 79



GL2U GEOLOGICAL AND THERMAL DATA

SOIL:-

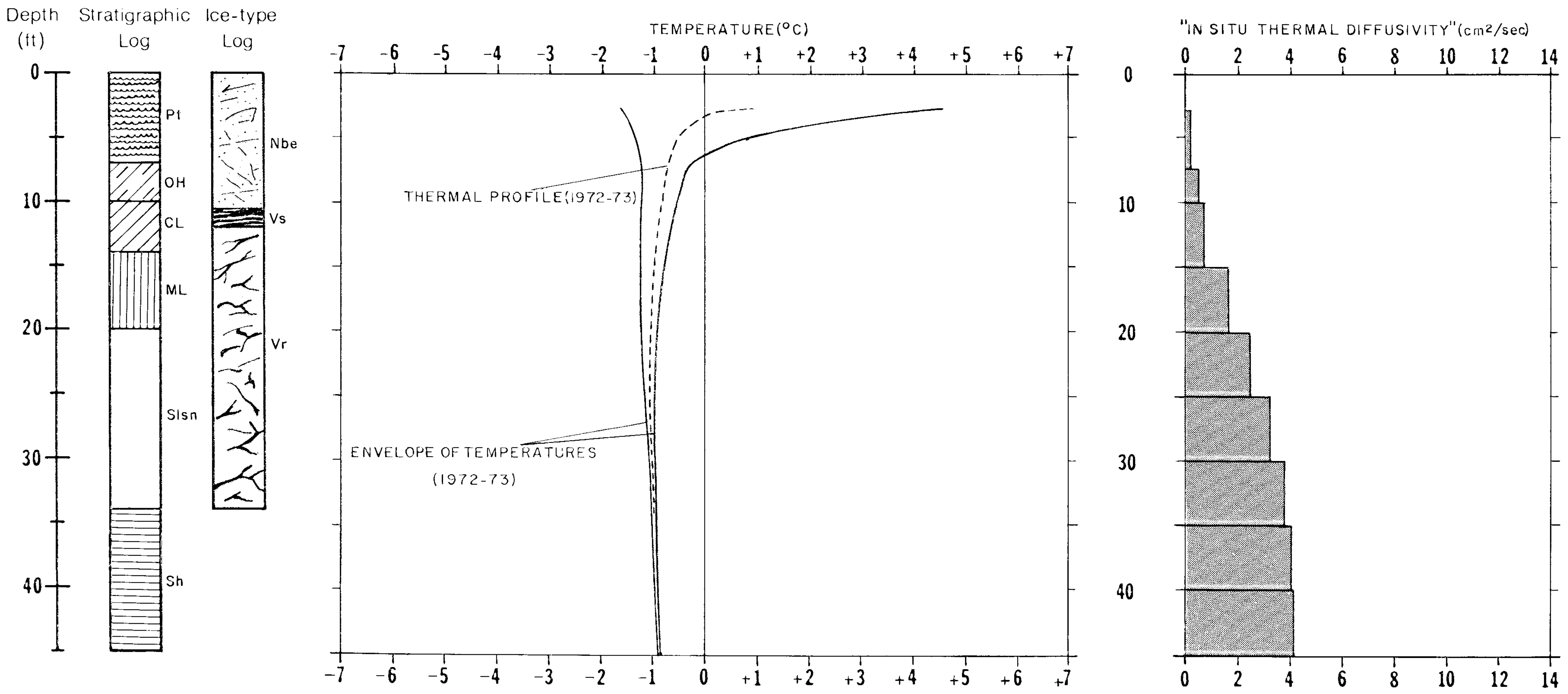
- Pt: brown peat, highly organic material
- OL: brown organic silts and organic silt clays of low plasticity
- CH: blue-grey inorganic clay of high plasticity
- CL: blue-grey inorganic clay of low to medium plasticity

UNIFIED SOIL CLASSIFICATION SYSTEM

ICE:-

- Nbn: ice not visible, well bonded, no excess ice
- Nbe: ice not visible, well bonded, excess ice
- Vr: visible ice less than one inch thick, random or irregularly oriented ice formations
- Vx: visible ice less than one inch thick, individual ice inclusions
- Vs: visible ice less than one inch thick, stratified or distinctly oriented ice formations
- ICE AND SOIL: visible ice greater than one inch thick, ice with soil inclusions

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM #79



SA GEOLOGICAL AND THERMAL DATA

SOIL :-

Pt: highly organic material

OH: dark organic clay of medium to high plasticity

CL: inorganic clay of low to medium plasticity

ML: clayey silts with slight plasticity

UNIFIED SOIL CLASSIFICATION SYSTEM

ROCK :-

Slsn: siltstone with occasional clay and ice layers

Sh: shale with calcareous seams

ICE :-

Nbe: ice not visible, well bonded, excess ice

Vr: visible ice less than one inch thick, random or irregularly oriented ice formations

Vs: visible ice less than one inch thick, stratified or distinctly oriented ice formations

PERMAFROST DESCRIPTION ACCORDING TO NRC TECHNICAL MEMORANDUM # 79

Calorimetric Test Results

Variation with temperature of apparent specific heat

Variation with temperature of apparent volumetric specific heat

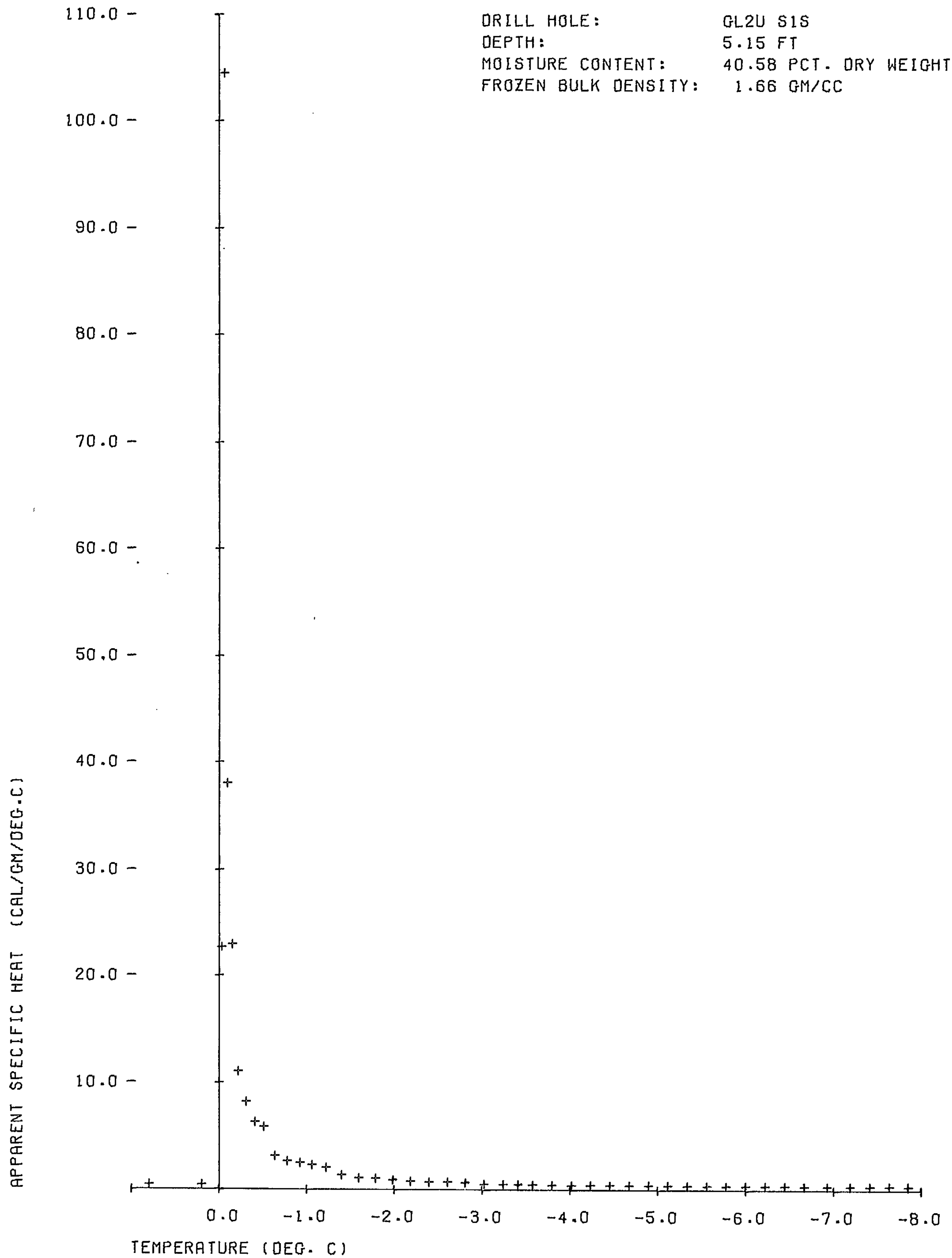
Variation with temperature of true volumetric specific heat

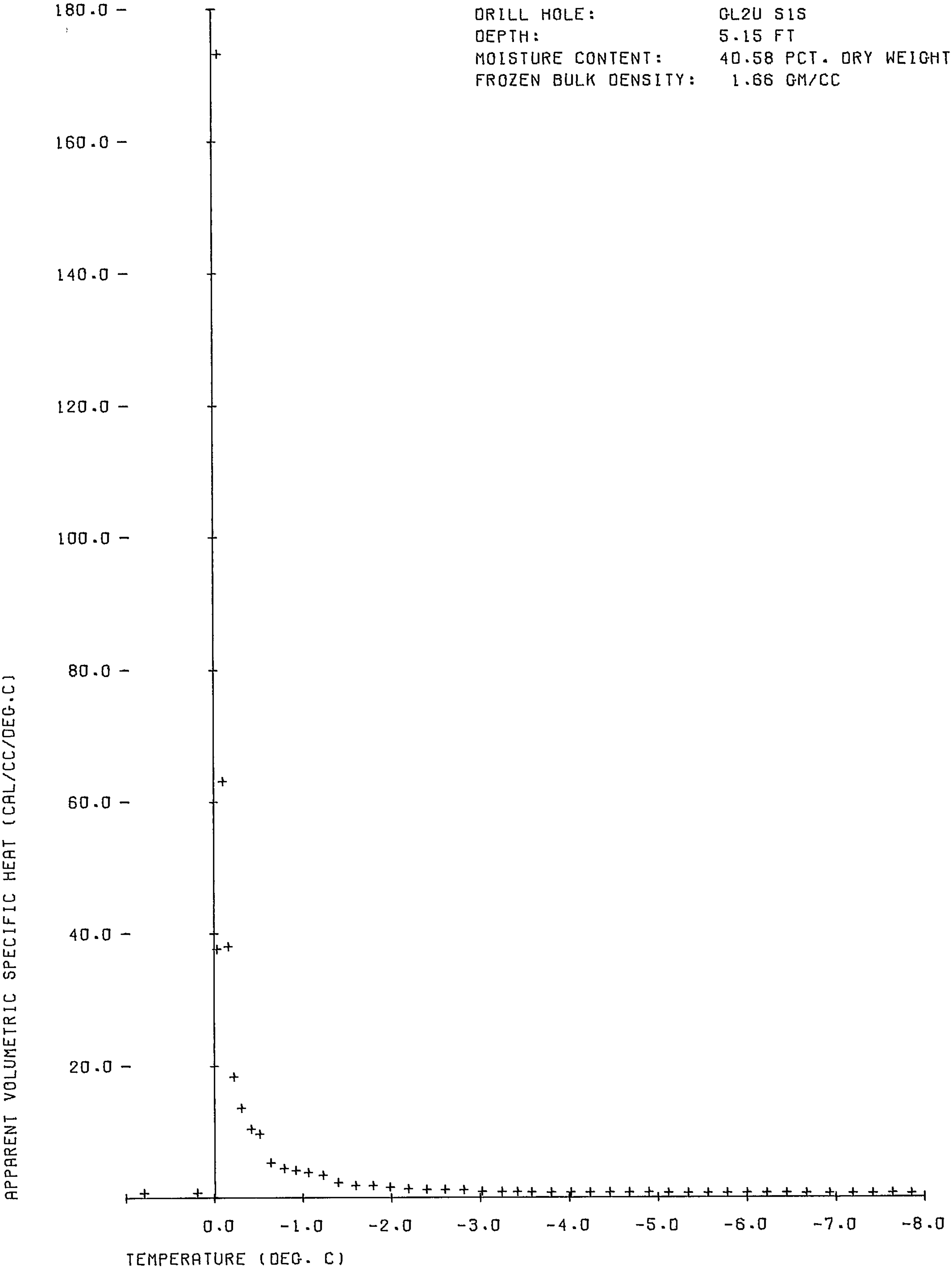
Variation with temperature of unfrozen water content as percentage of total moisture content

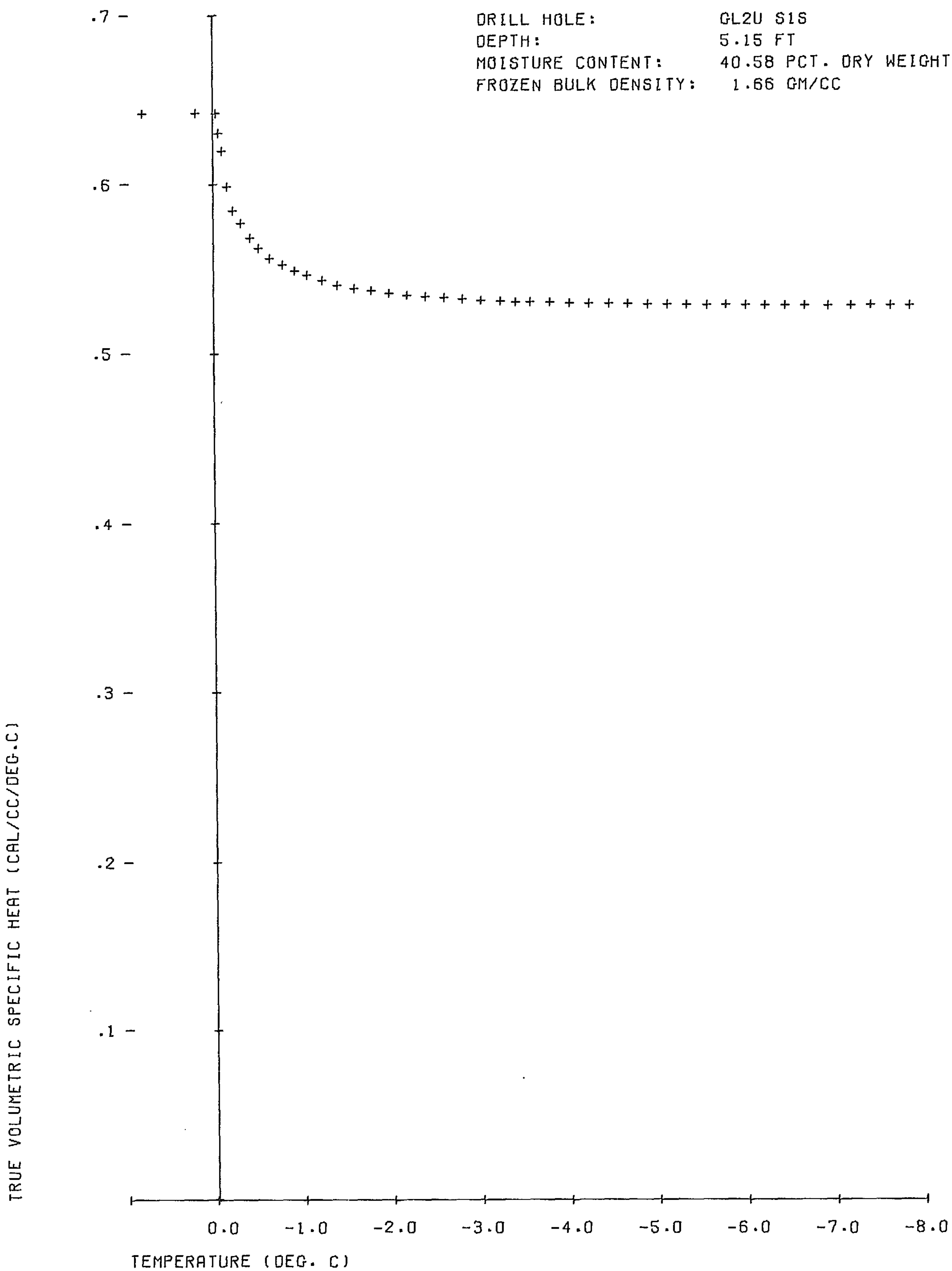
Variation with temperature of unfrozen water content as percentage of dry weight

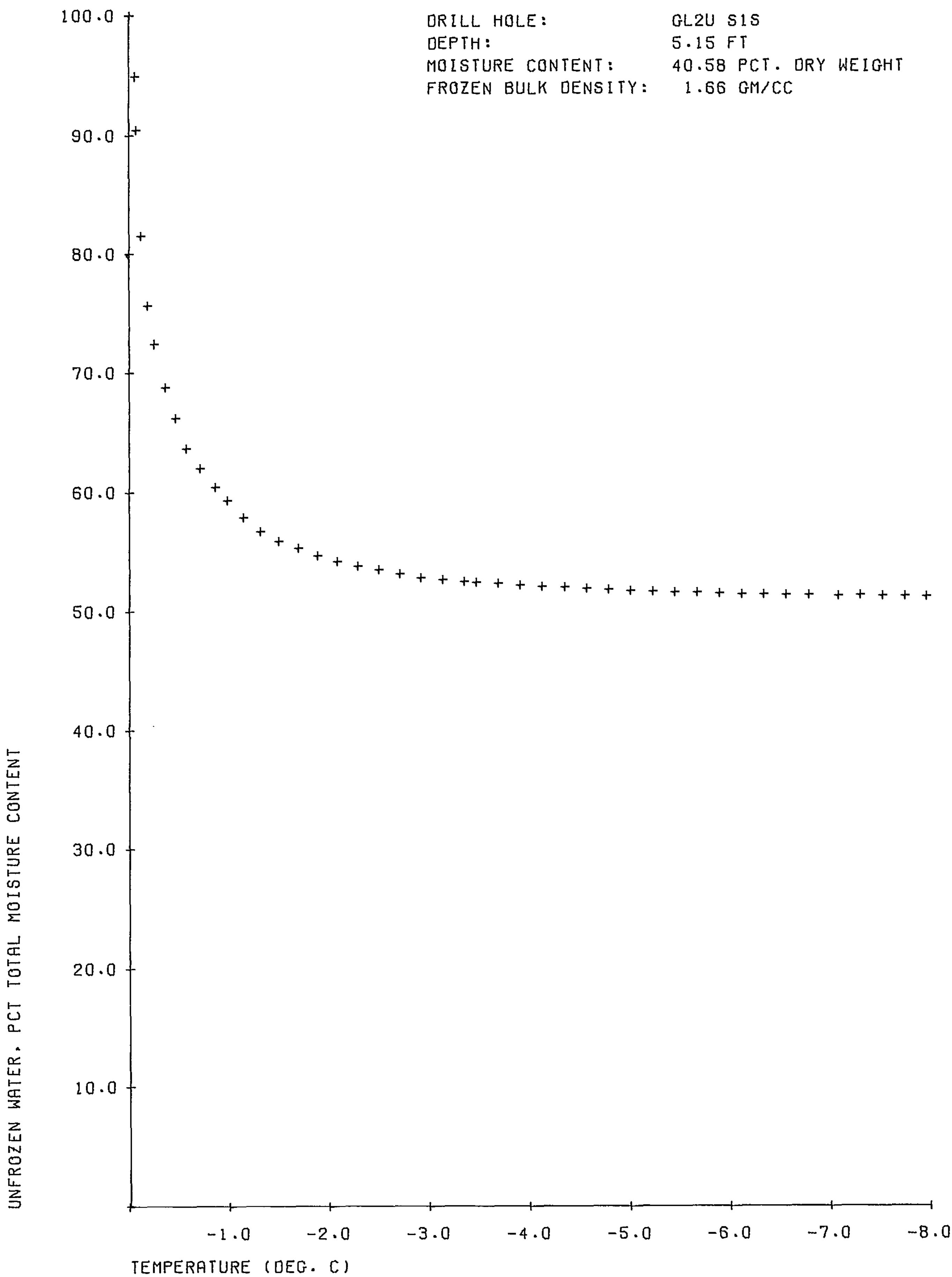
Variation with temperature of cumulative volumetric heat

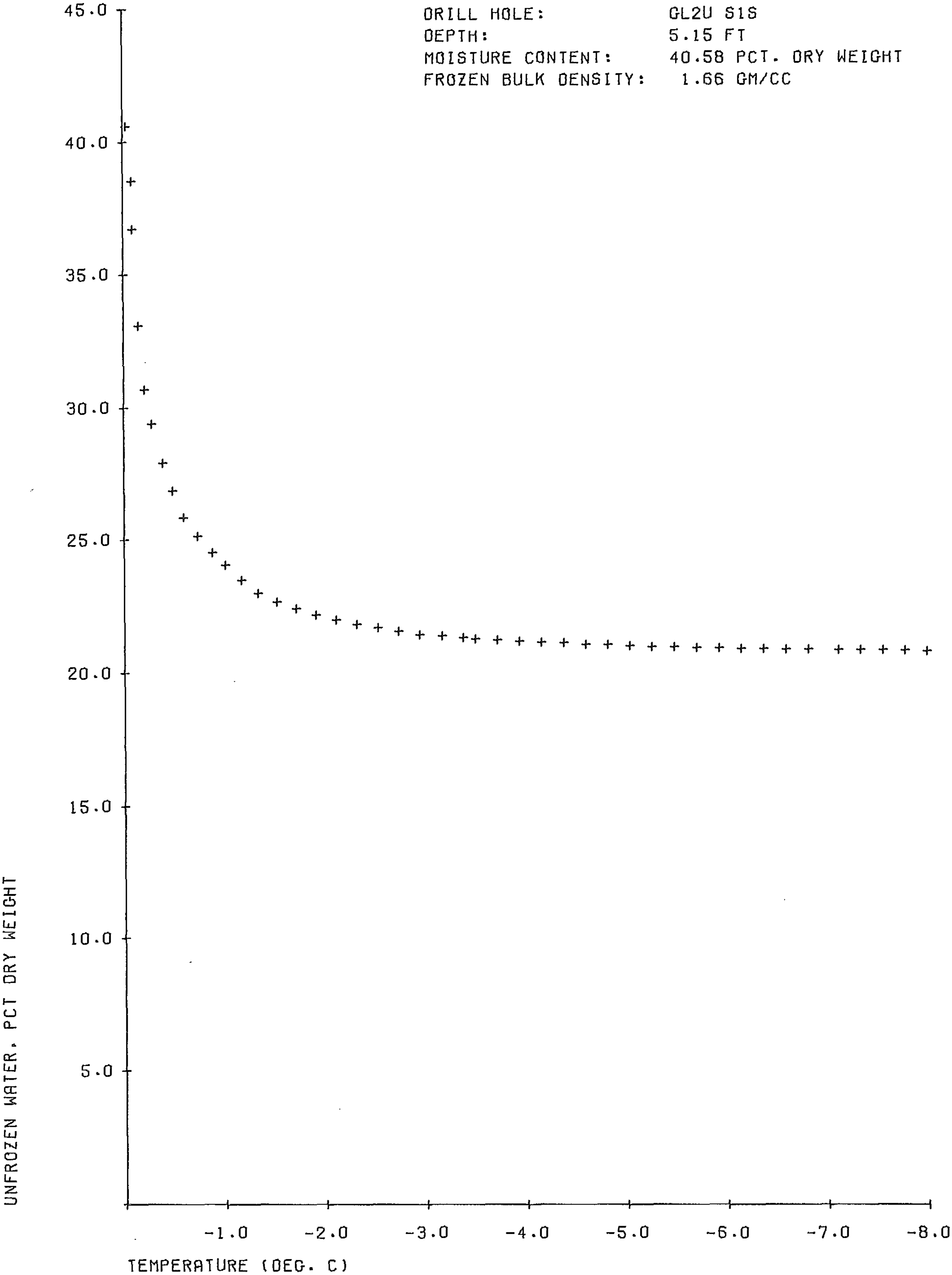
Variation with temperature of cumulative volumetric latent heat

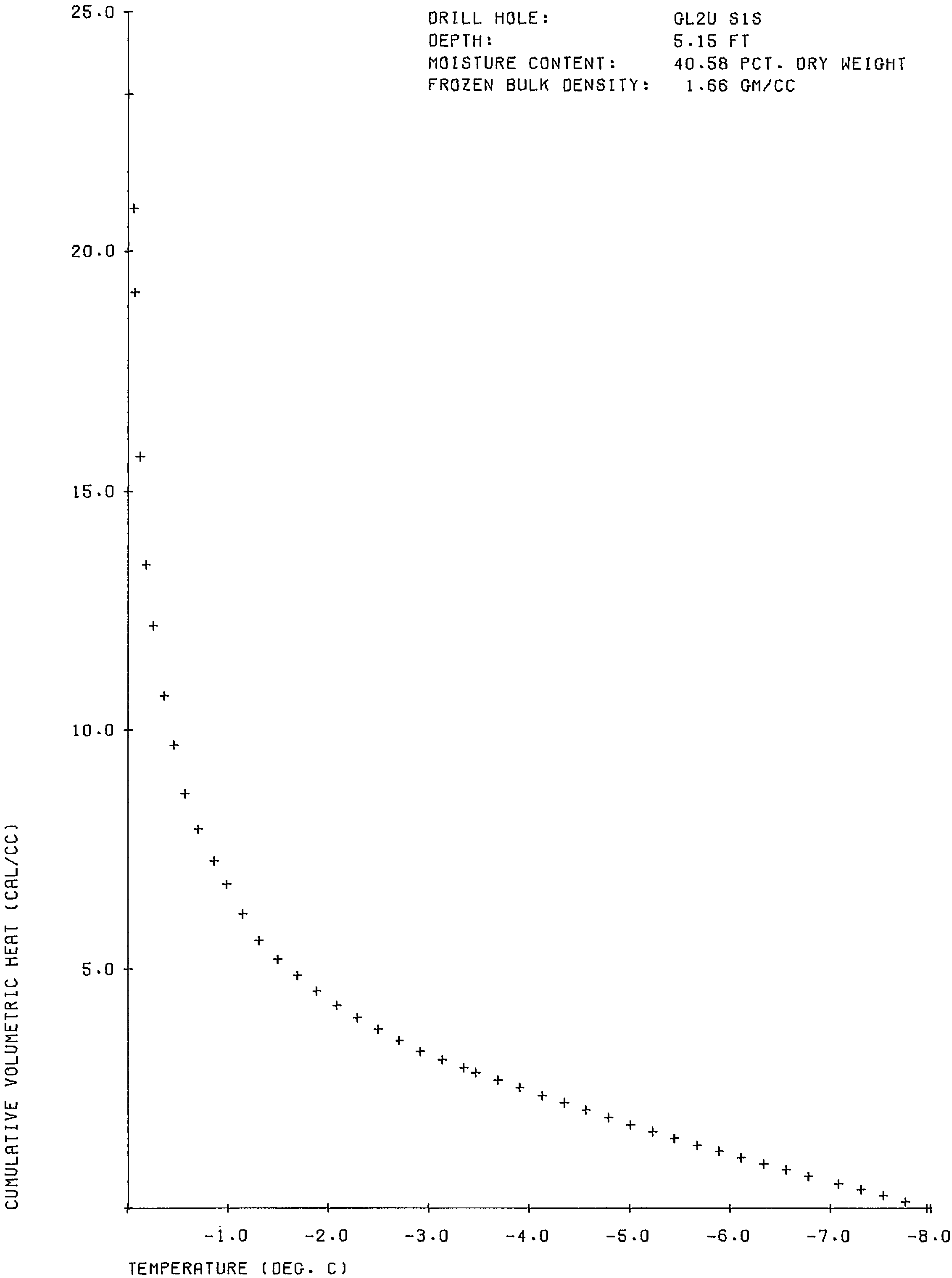

DRILL HOLE: GL2U S1S
DEPTH: 5.15 FT
MOISTURE CONTENT: 40.58 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.66 GM/CC
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
APPARENT SPECIFIC HEAT (CAL/GM/DEG.C)
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

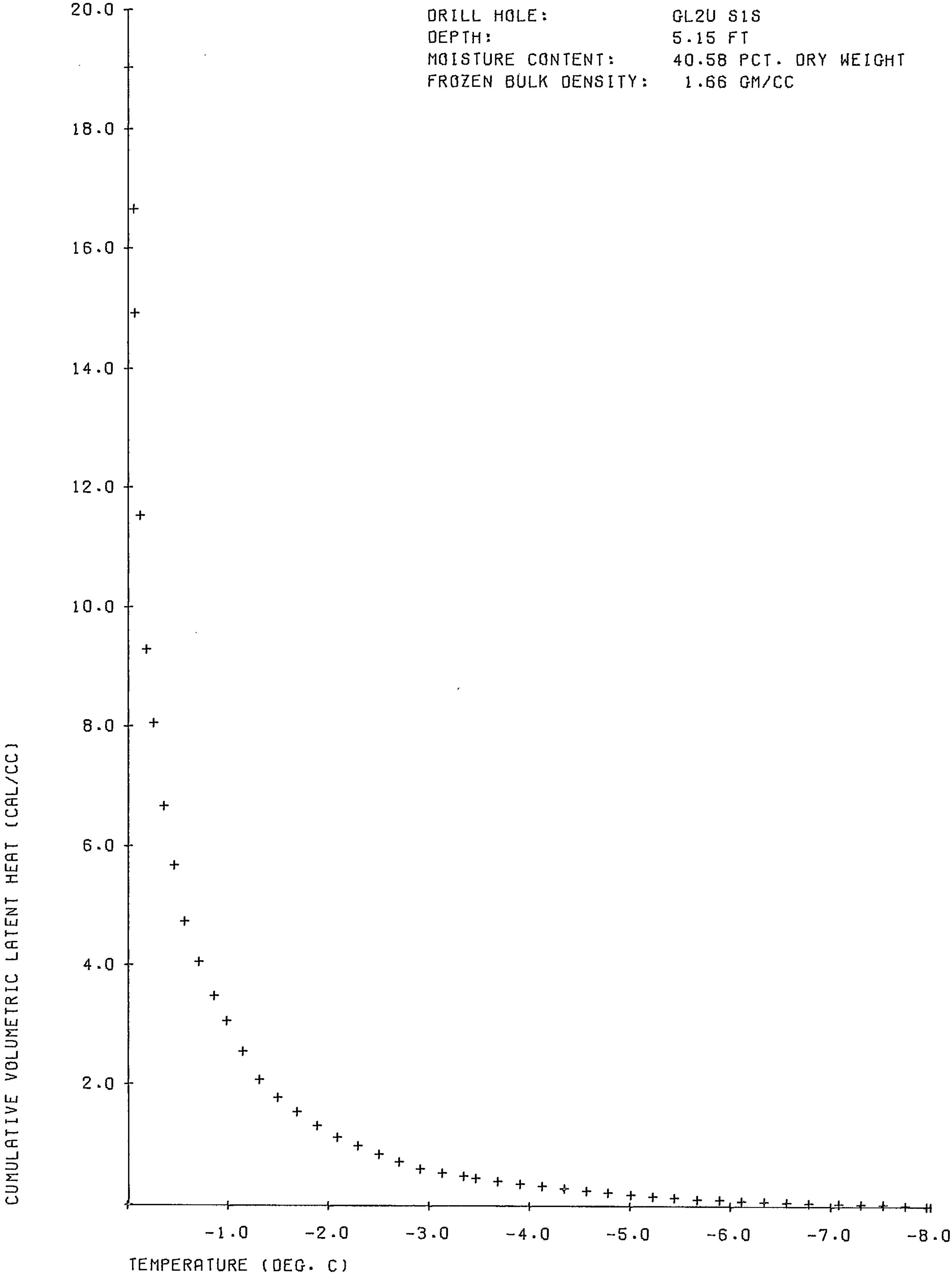

DRILL HOLE: GL2U S1S
DEPTH: 5.15 FT
MOISTURE CONTENT: 40.58 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.66 GM/CC
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
APPARENT VOLUMETRIC SPECIFIC HEAT (CAL/CC/DEG.C)
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

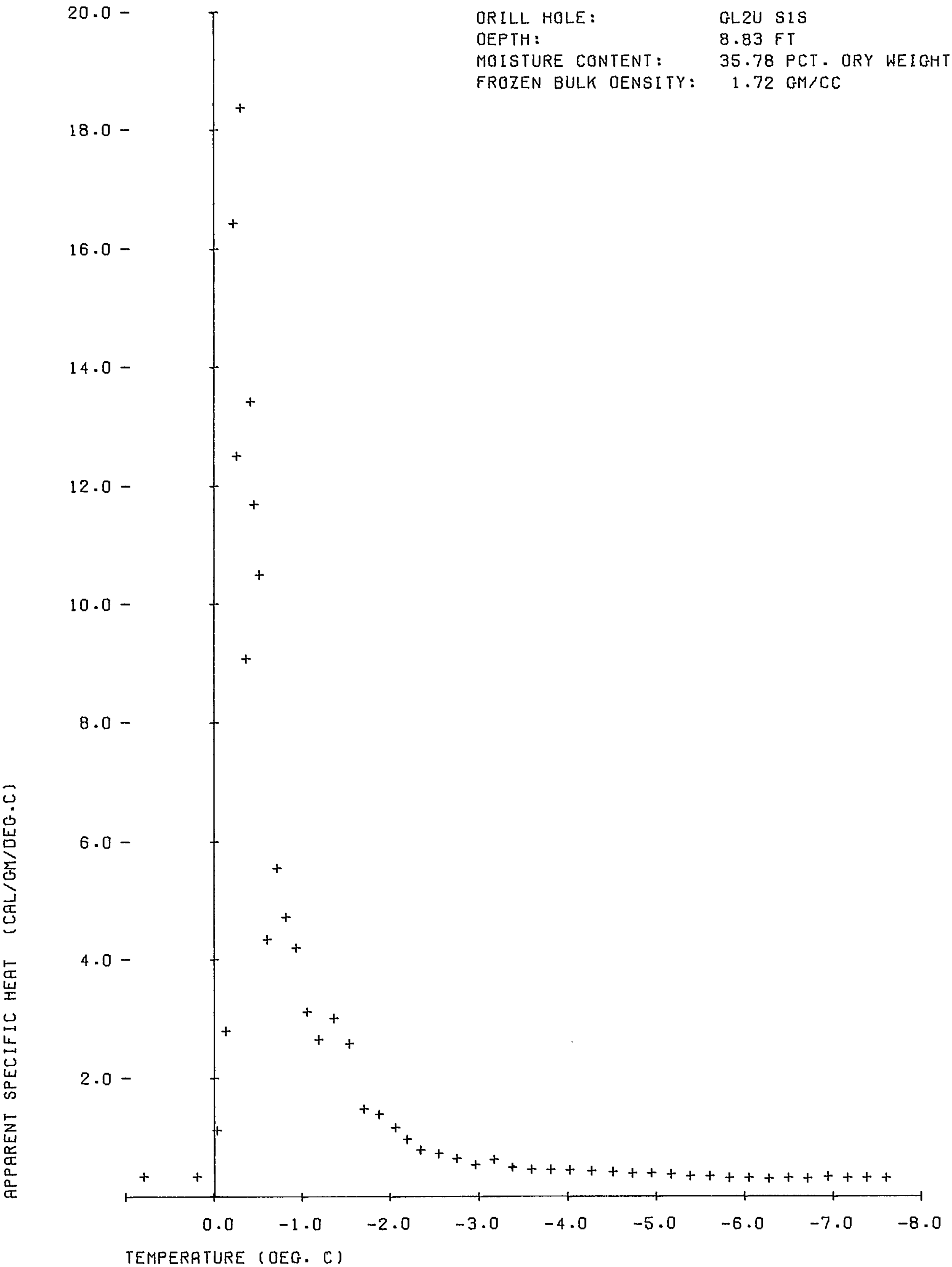

DRILL HOLE: GL2U S1S
DEPTH: 5.15 FT
MOISTURE CONTENT: 40.58 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.66 GM/CC
.7
.6
.5
.4
.3
.2
.1
TRUE VOLUMETRIC SPECIFIC HEAT (CAL/CC/DEG.C)
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

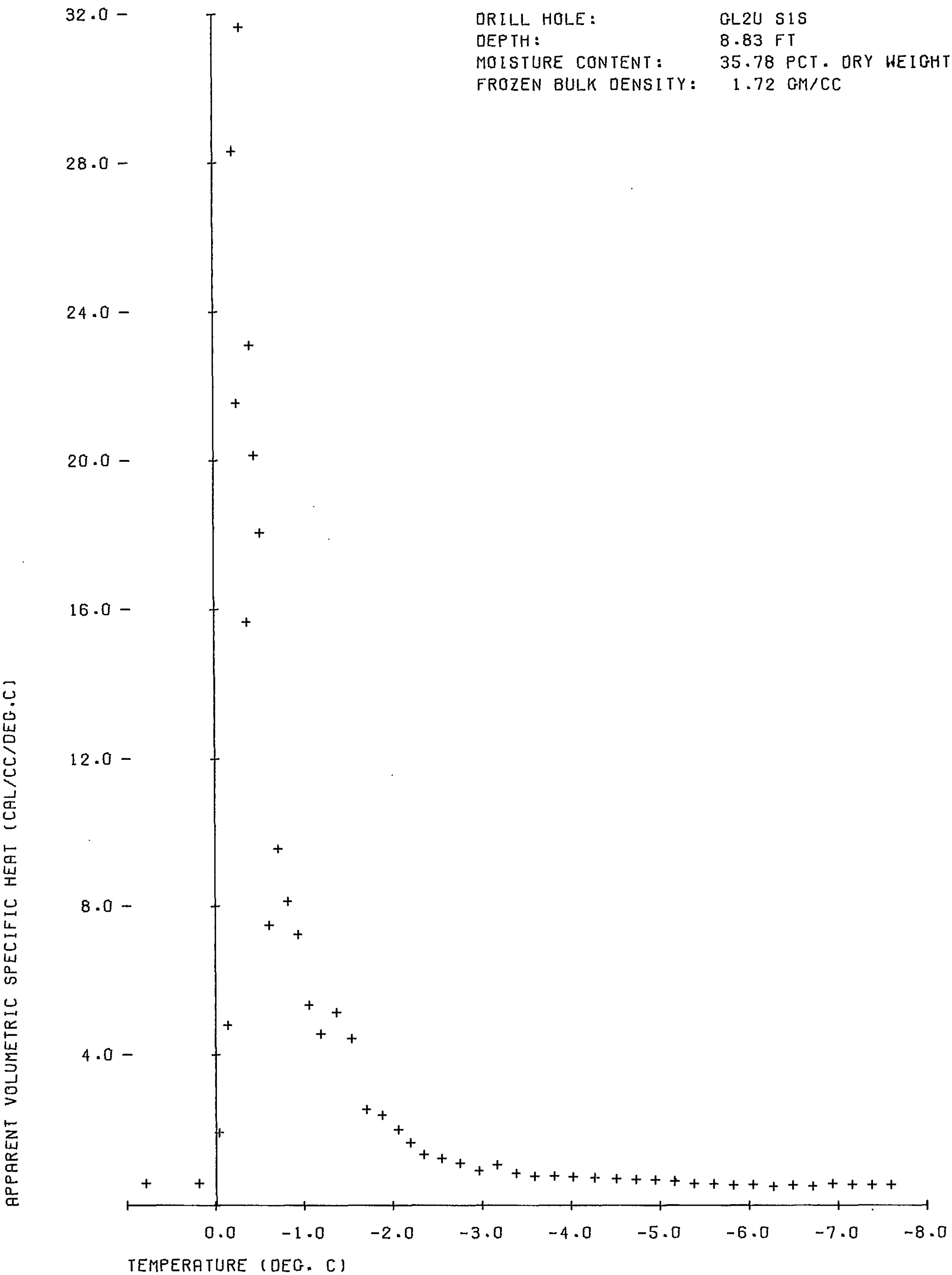

DRILL HOLE: GL2U S1S
DEPTH: 5.15 FT
MOISTURE CONTENT: 40.58 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.66 GM/CC
UNFROZEN WATER, PCT TOTAL MOISTURE CONTENT
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

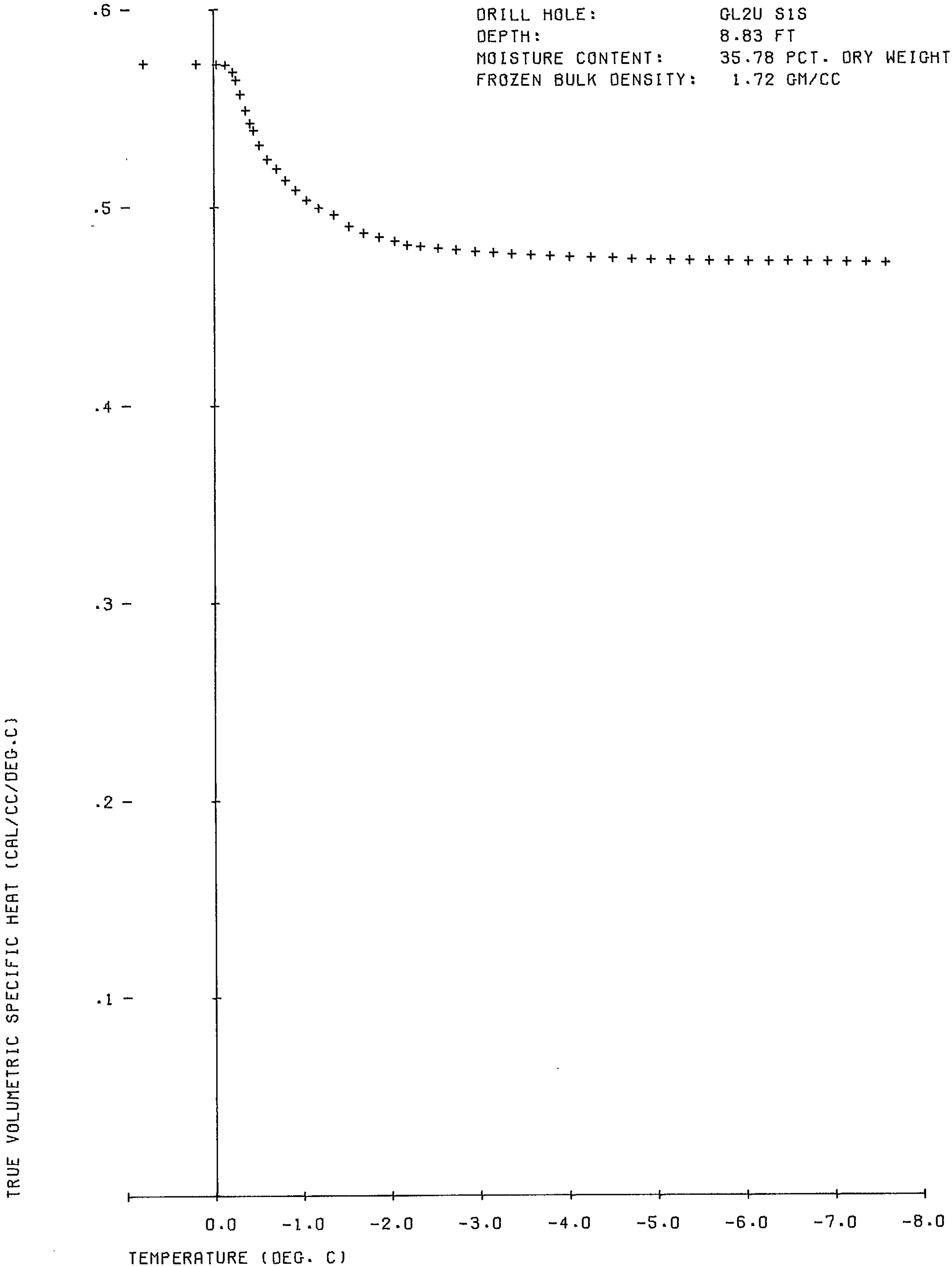

DRILL HOLE: GL2U S1S
DEPTH: 5.15 FT
MOISTURE CONTENT: 40.58 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.66 GM/CC
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
UNFROZEN WATER, PCT DRY WEIGHT
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

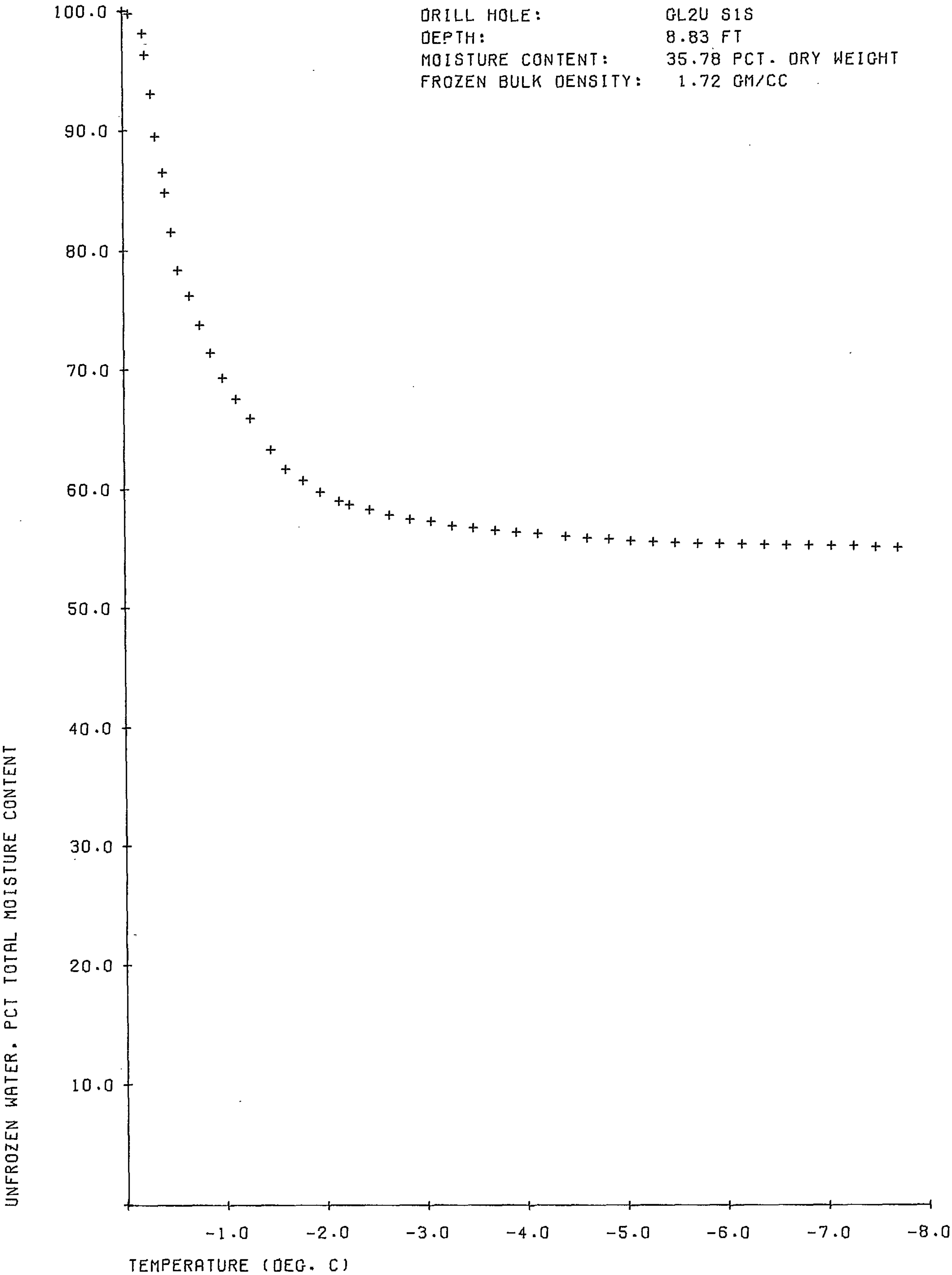

DRILL HOLE: GL2U S1S
DEPTH: 5.15 FT
MOISTURE CONTENT: 40.58 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.66 GM/CC
25.0
20.0
15.0
10.0
5.0
CUMULATIVE VOLUMETRIC HEAT (CAL/CC)
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

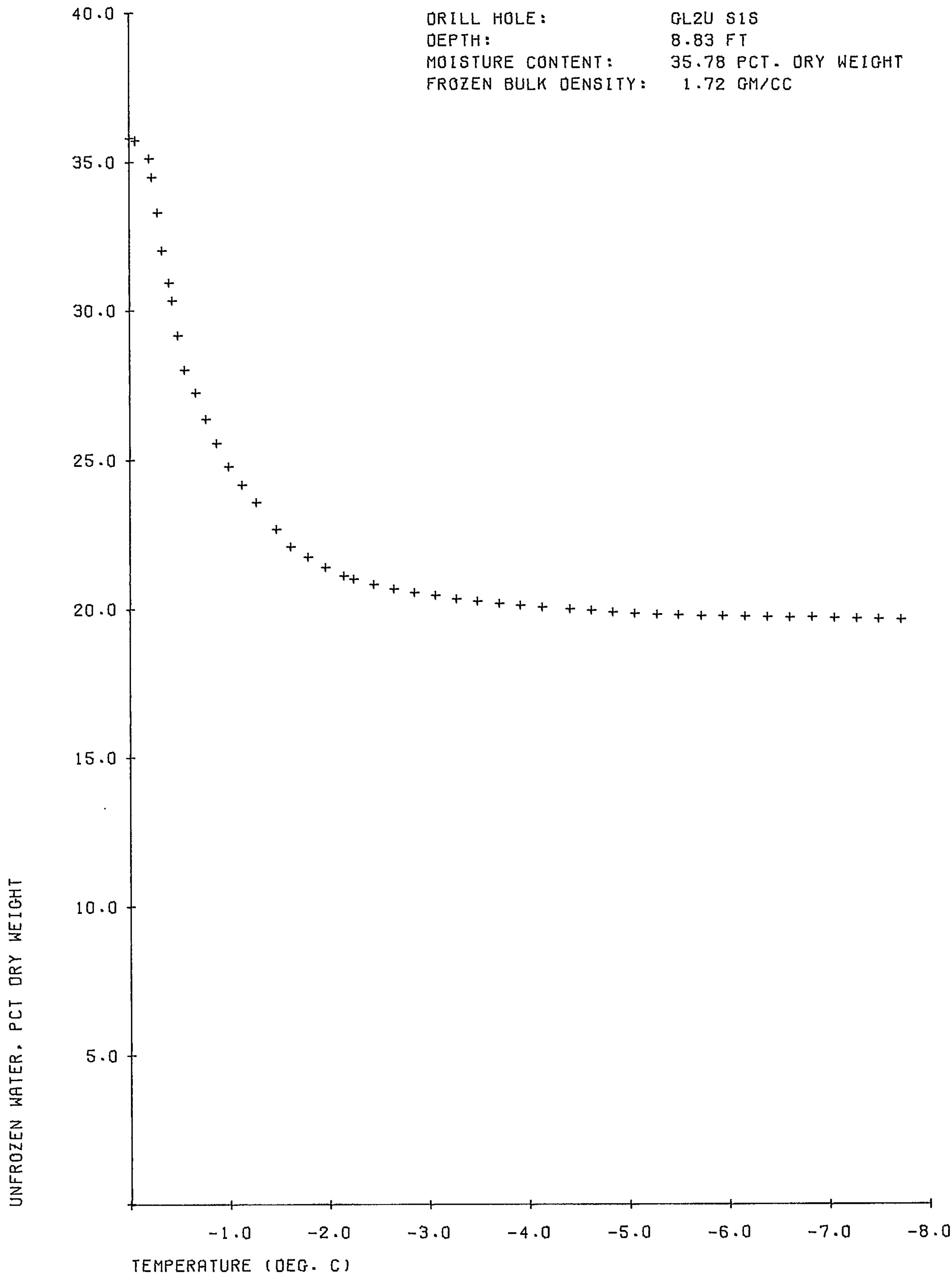

DRILL HOLE: GL2U S1S
DEPTH: 5.15 FT
MOISTURE CONTENT: 40.58 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.66 GM/CC
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
CUMULATIVE VOLUMETRIC LATENT HEAT (CAL/CC)
TEMPERATURE (DEG. C)

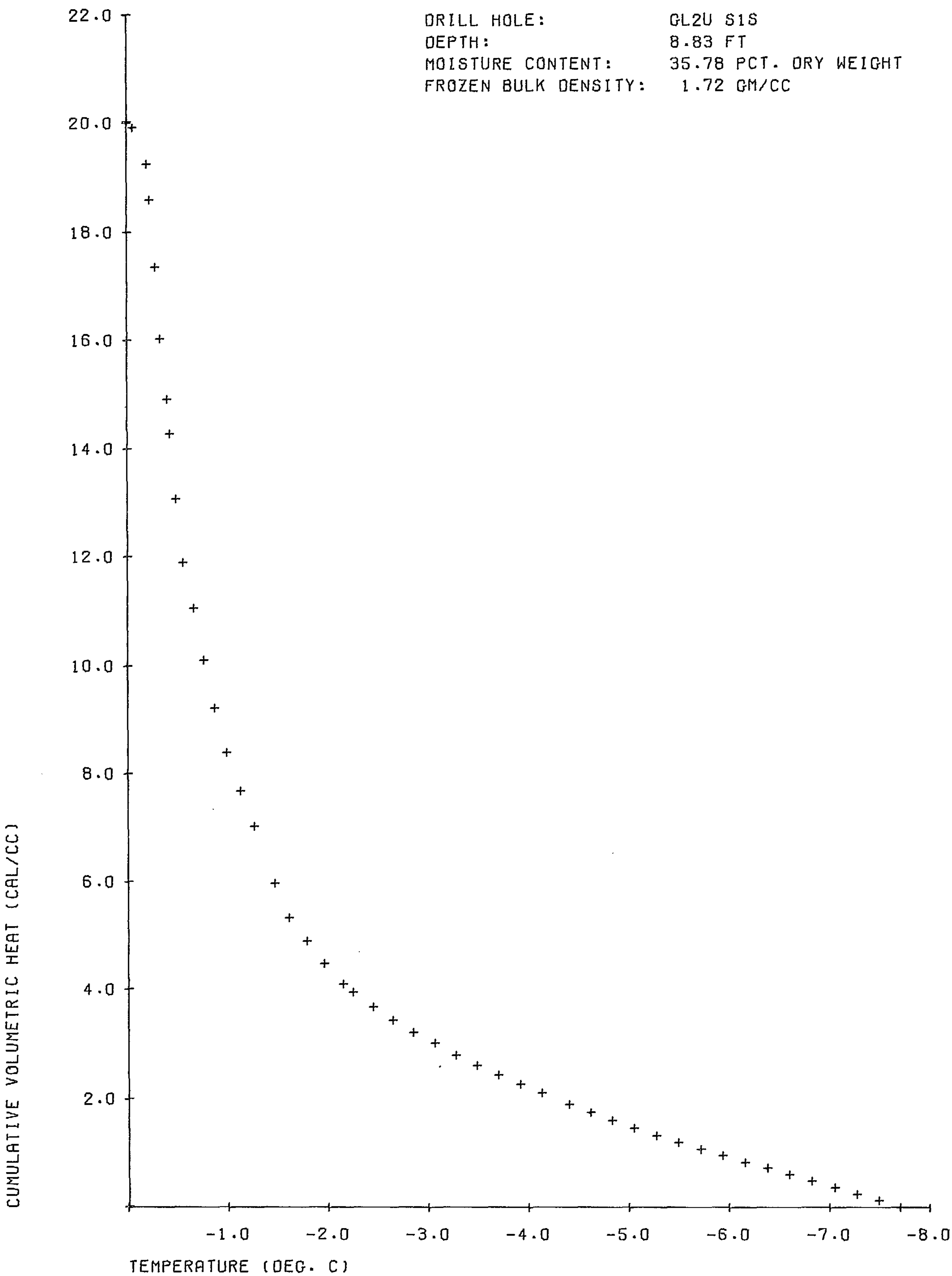

DRILL HOLE: GL2U S1S
DEPTH: 8.83 FT
MOISTURE CONTENT: 35.78 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.72 GM/CC
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
APPARENT SPECIFIC HEAT (CAL/GM/DEG.C)
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

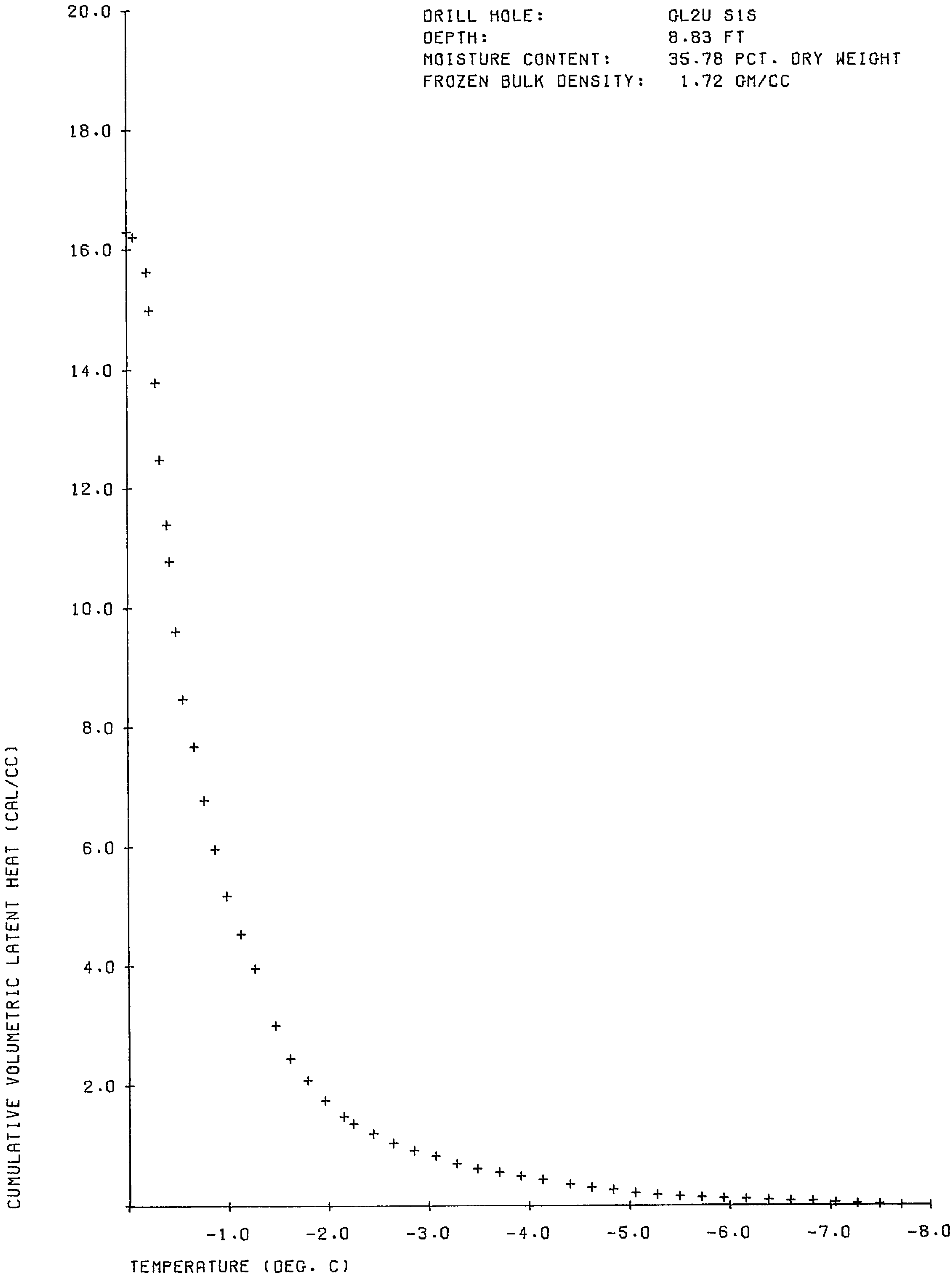

DRILL HOLE: GL2U S1S
DEPTH: 8.83 FT
MOISTURE CONTENT: 35.78 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.72 GM/CC
32.0
28.0
24.0
20.0
16.0
12.0
8.0
4.0
APPARENT VOLUMETRIC SPECIFIC HEAT (CAL/CC/DEG.C)
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

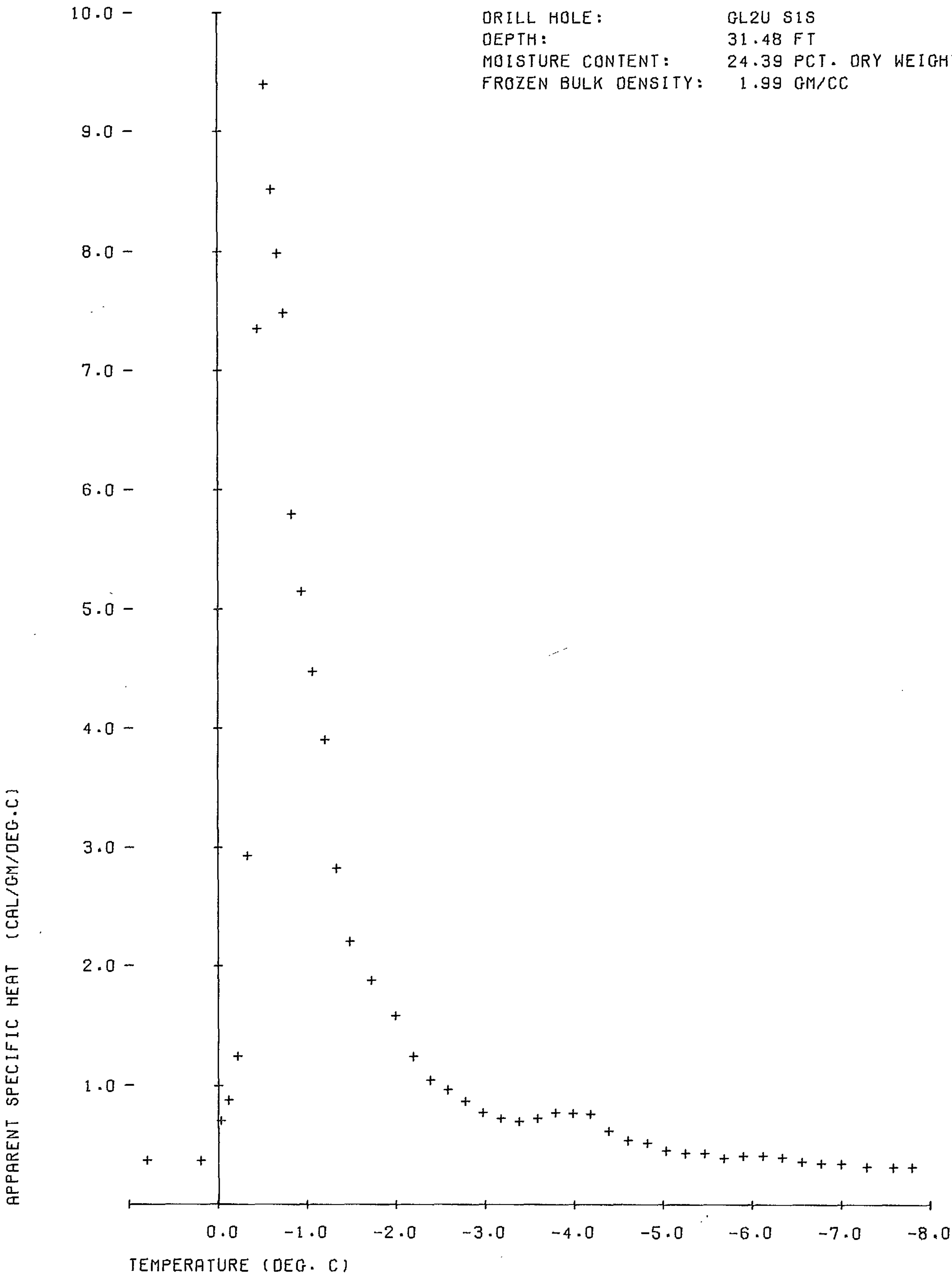

DRILL HOLE: GL2U S1S
DEPTH: 8.83 FT
MOISTURE CONTENT: 35.78 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.72 GM/CC
.6
.5
.4
.3
.2
.1
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TRUE VOLUMETRIC SPECIFIC HEAT (CAL/CC/DEG.C)
TEMPERATURE (DEG. C)

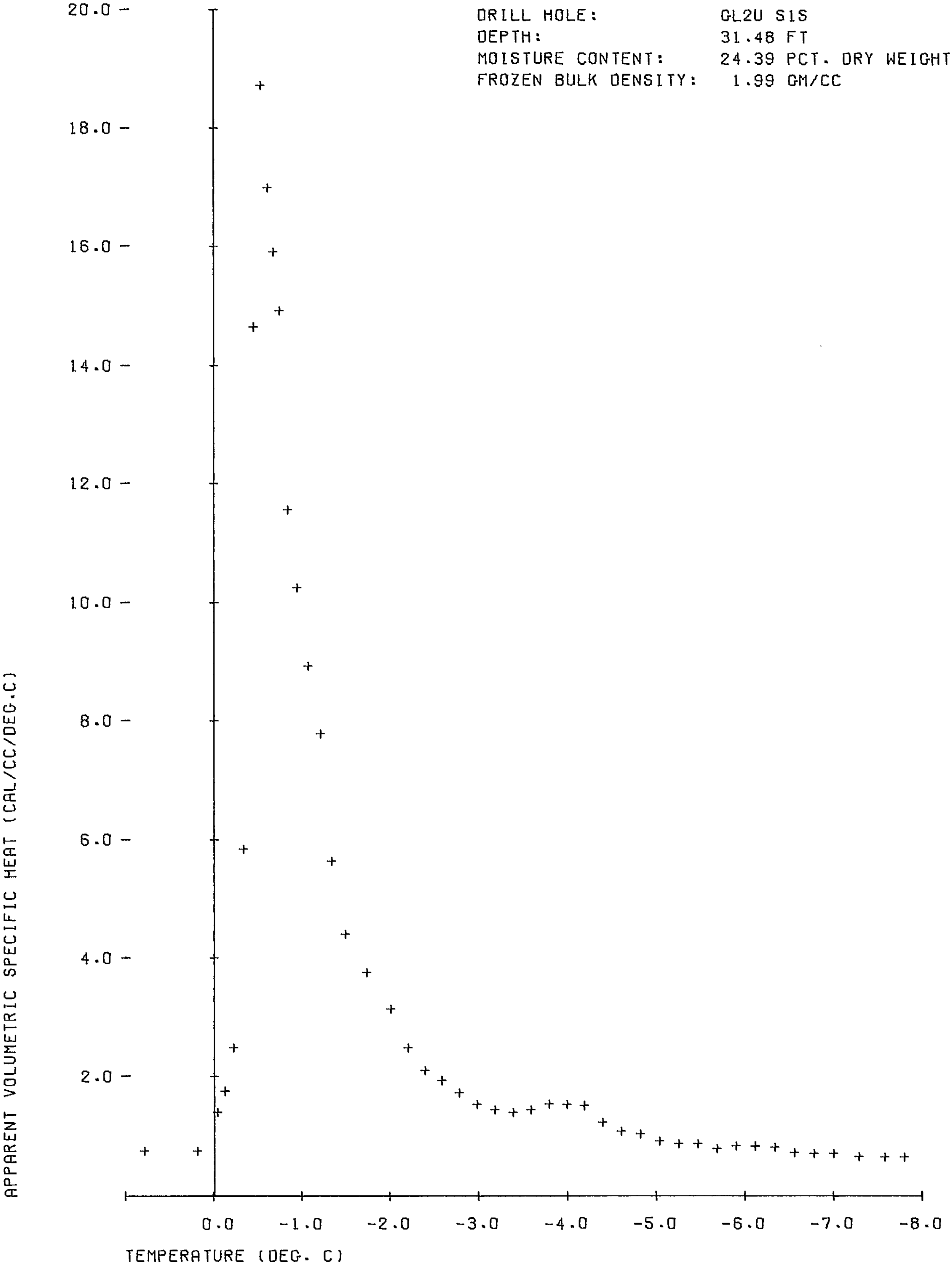

DRILL HOLE: GL2U S1S
DEPTH: 8.83 FT
MOISTURE CONTENT: 35.78 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.72 GM/CC
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
UNFROZEN WATER, PCT TOTAL MOISTURE CONTENT
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

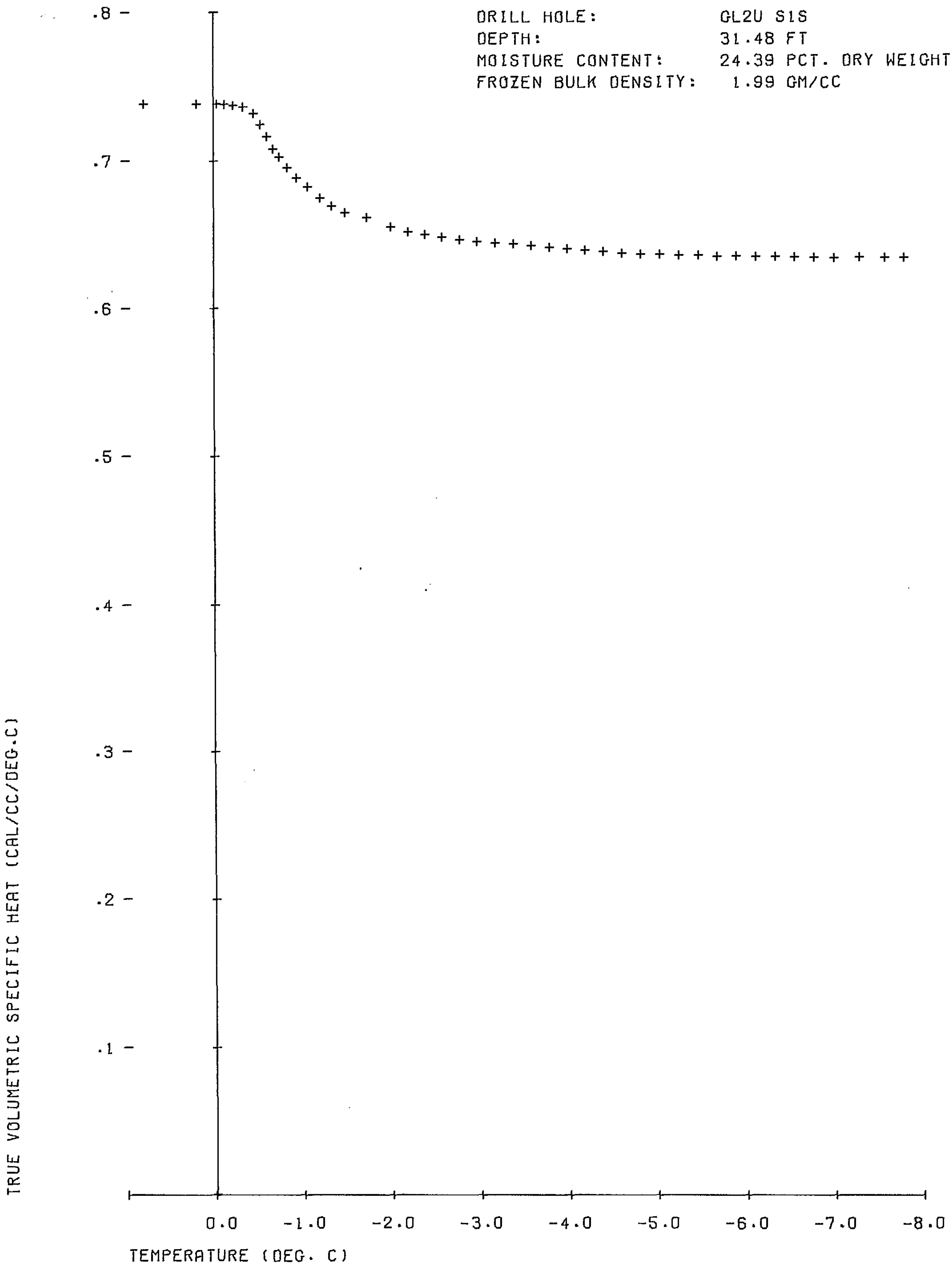

DRILL HOLE: GL2U S1S
DEPTH: 8.83 FT
MOISTURE CONTENT: 35.78 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.72 GM/CC
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
UNFROZEN WATER, PCT DRY WEIGHT
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

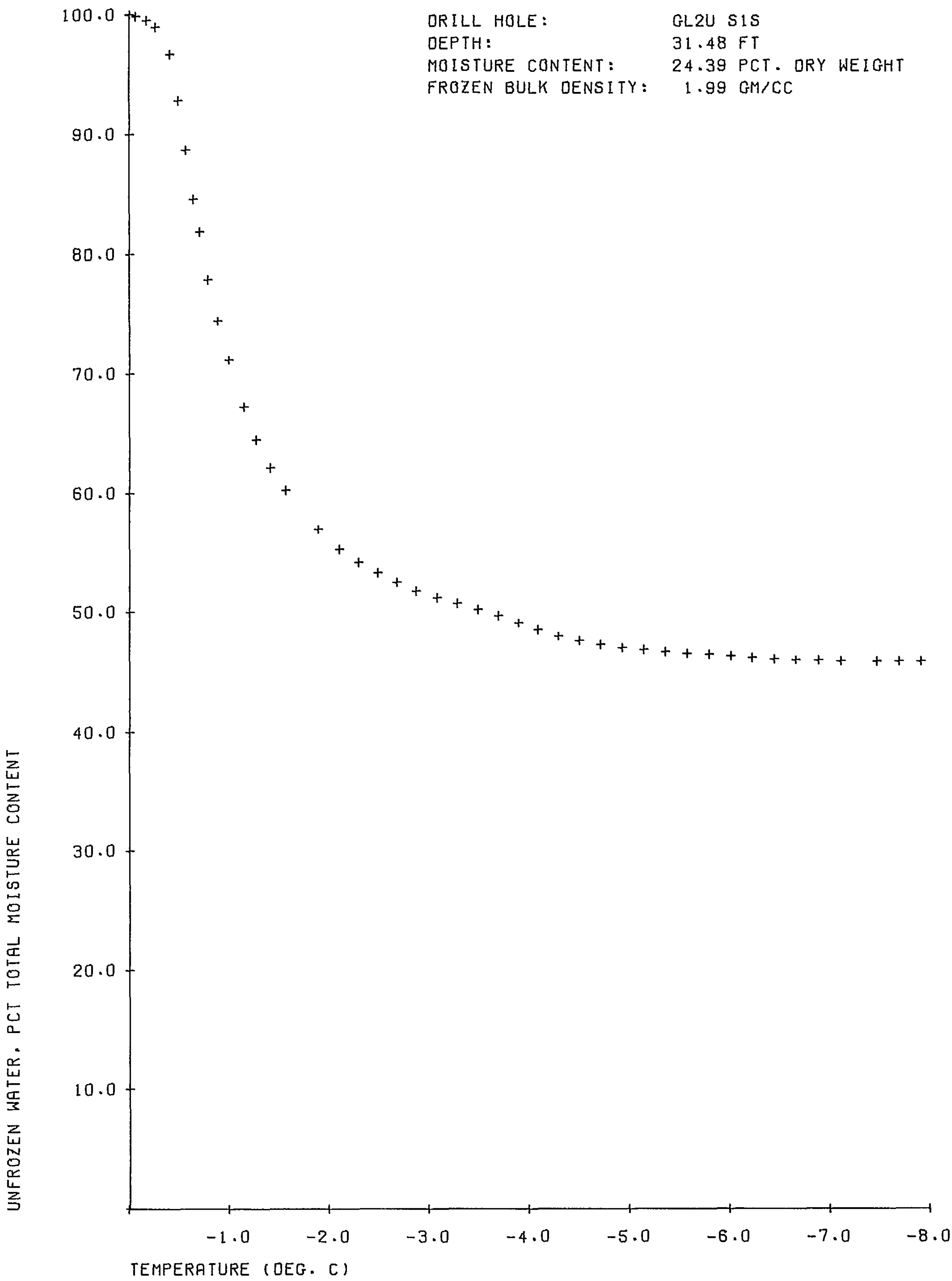

DRILL HOLE: GL2U S1S
DEPTH: 8.83 FT
MOISTURE CONTENT: 35.78 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.72 GM/CC
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
CUMULATIVE VOLUMETRIC HEAT (CAL/CC)
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

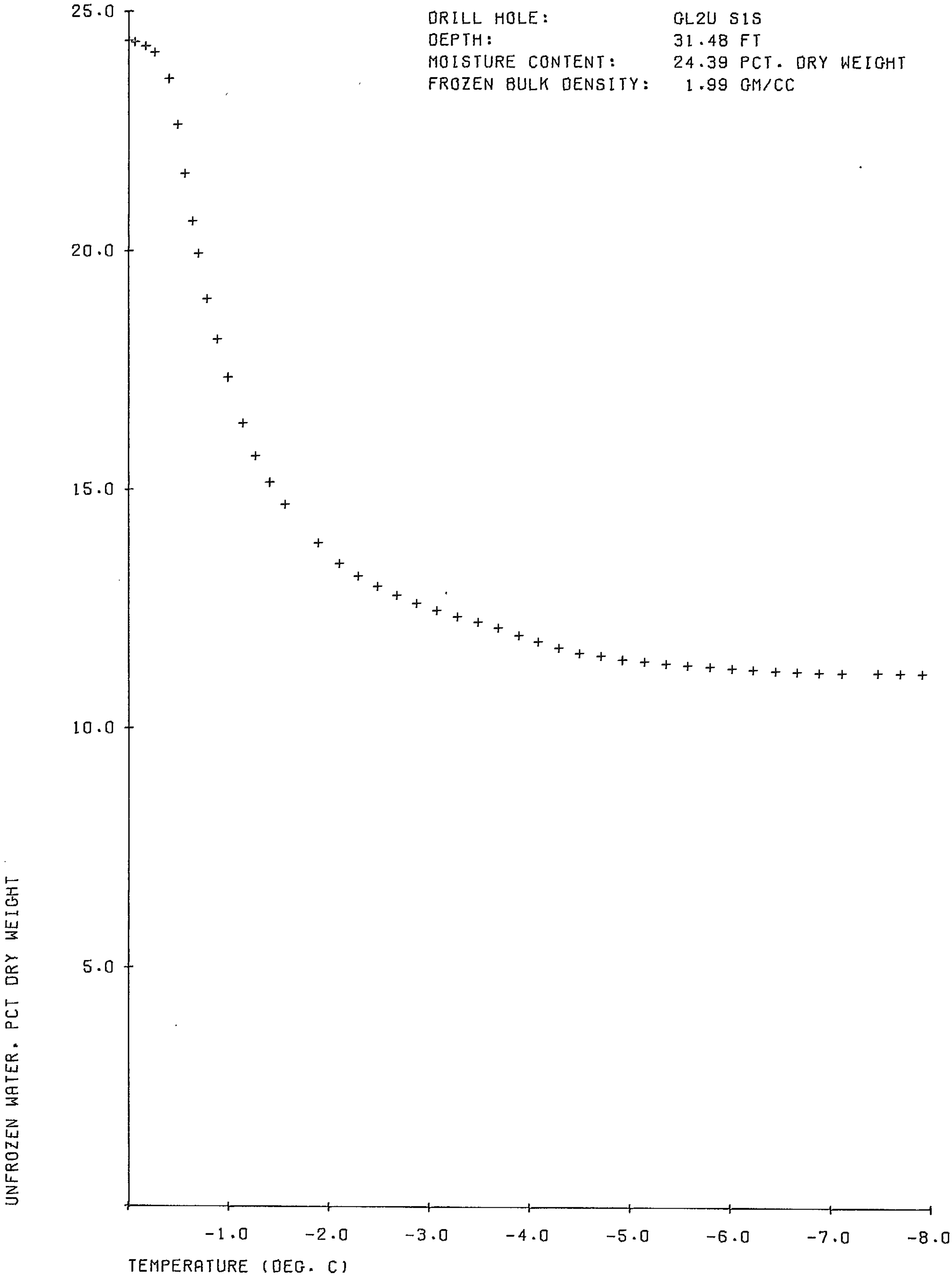

DRILL HOLE: GL2U S1S
DEPTH: 8.83 FT
MOISTURE CONTENT: 35.78 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.72 GM/CC
CUMULATIVE VOLUMETRIC LATENT HEAT (CAL/CC)
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

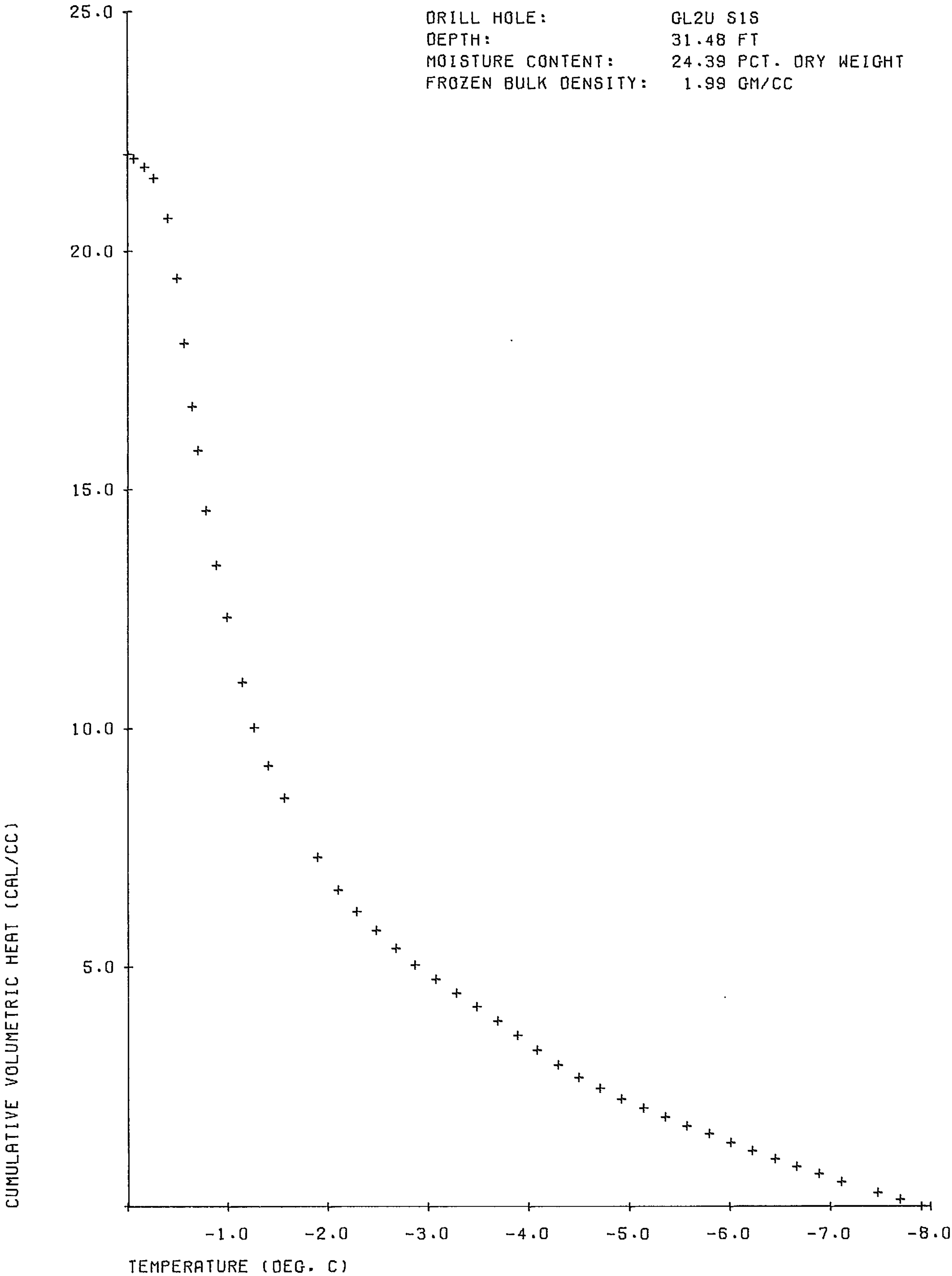

DRILL HOLE: GL2U S1S
DEPTH: 31.48 FT
MOISTURE CONTENT: 24.39 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.99 GM/CC
APPARENT SPECIFIC HEAT (CAL/GM/DEG.C)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

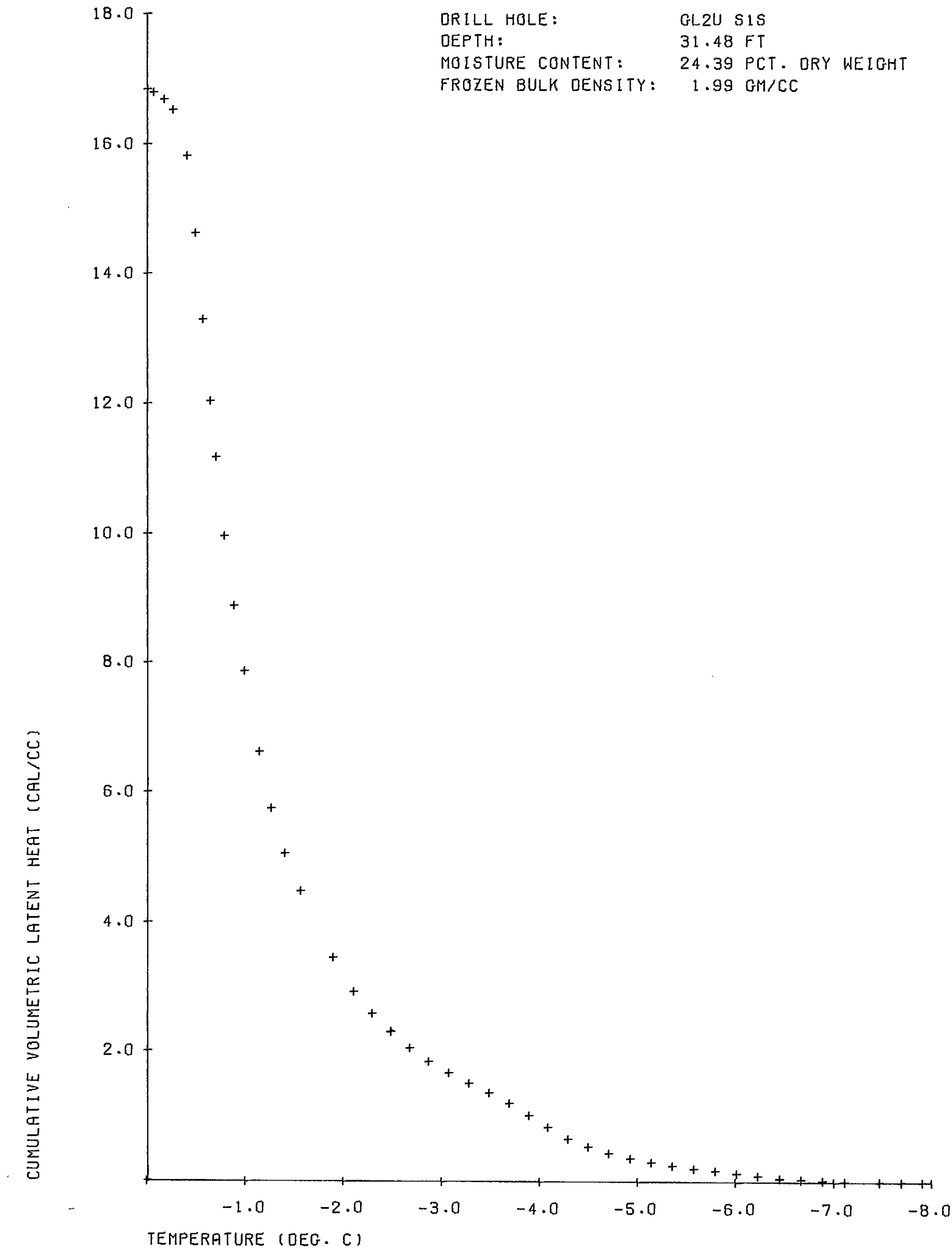

DRILL HOLE: GL2U S1S
DEPTH: 31.48 FT
MOISTURE CONTENT: 24.39 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.99 GM/CC
APPARENT VOLUMETRIC SPECIFIC HEAT (CAL/CC/DEG.C)
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

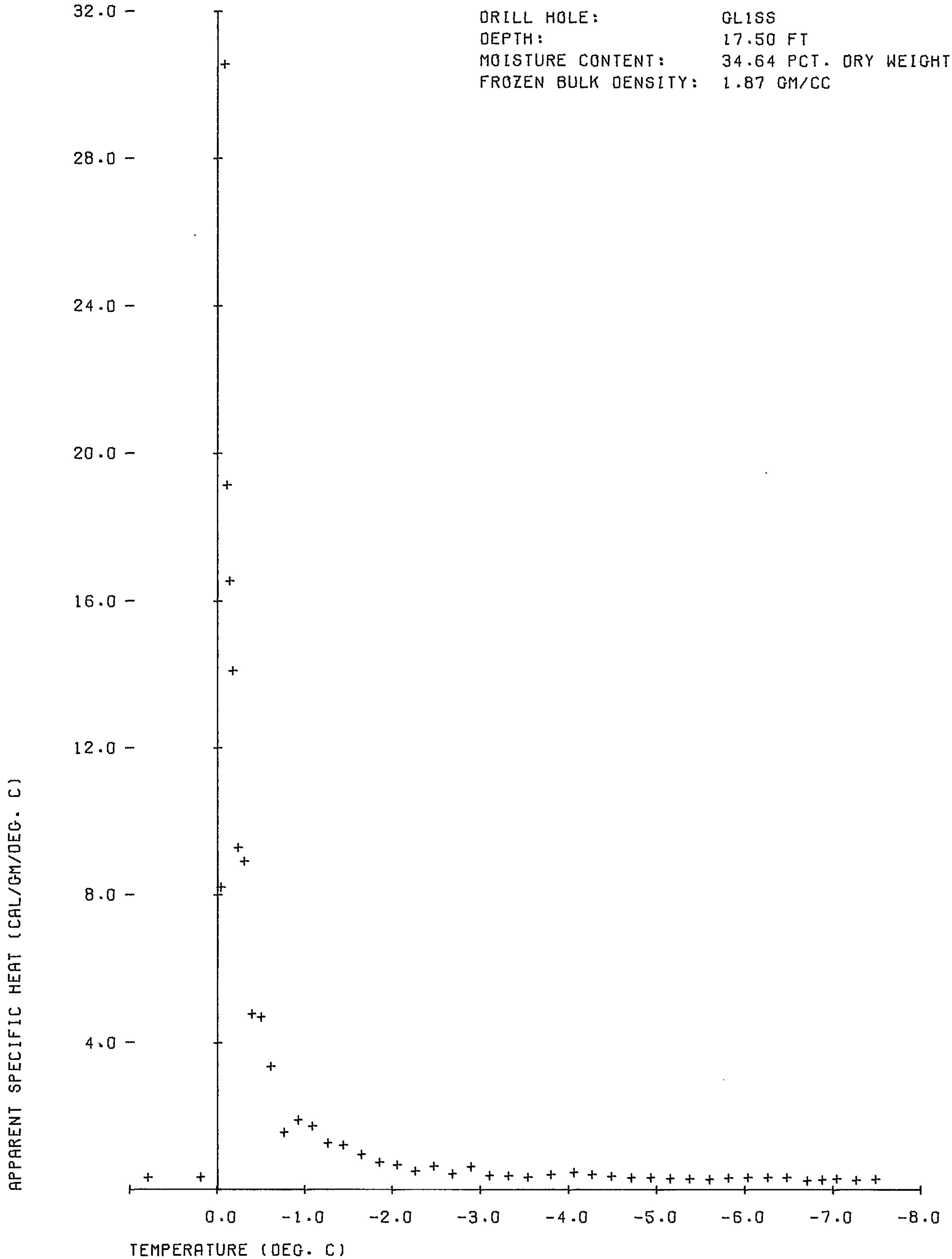

DRILL HOLE: GL2U S1S
DEPTH: 31.48 FT
MOISTURE CONTENT: 24.39 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.99 GM/CC
.8
.7
.6
.5
.4
.3
.2
.1
TRUE VOLUMETRIC SPECIFIC HEAT (CAL/CC/DEG.C)
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

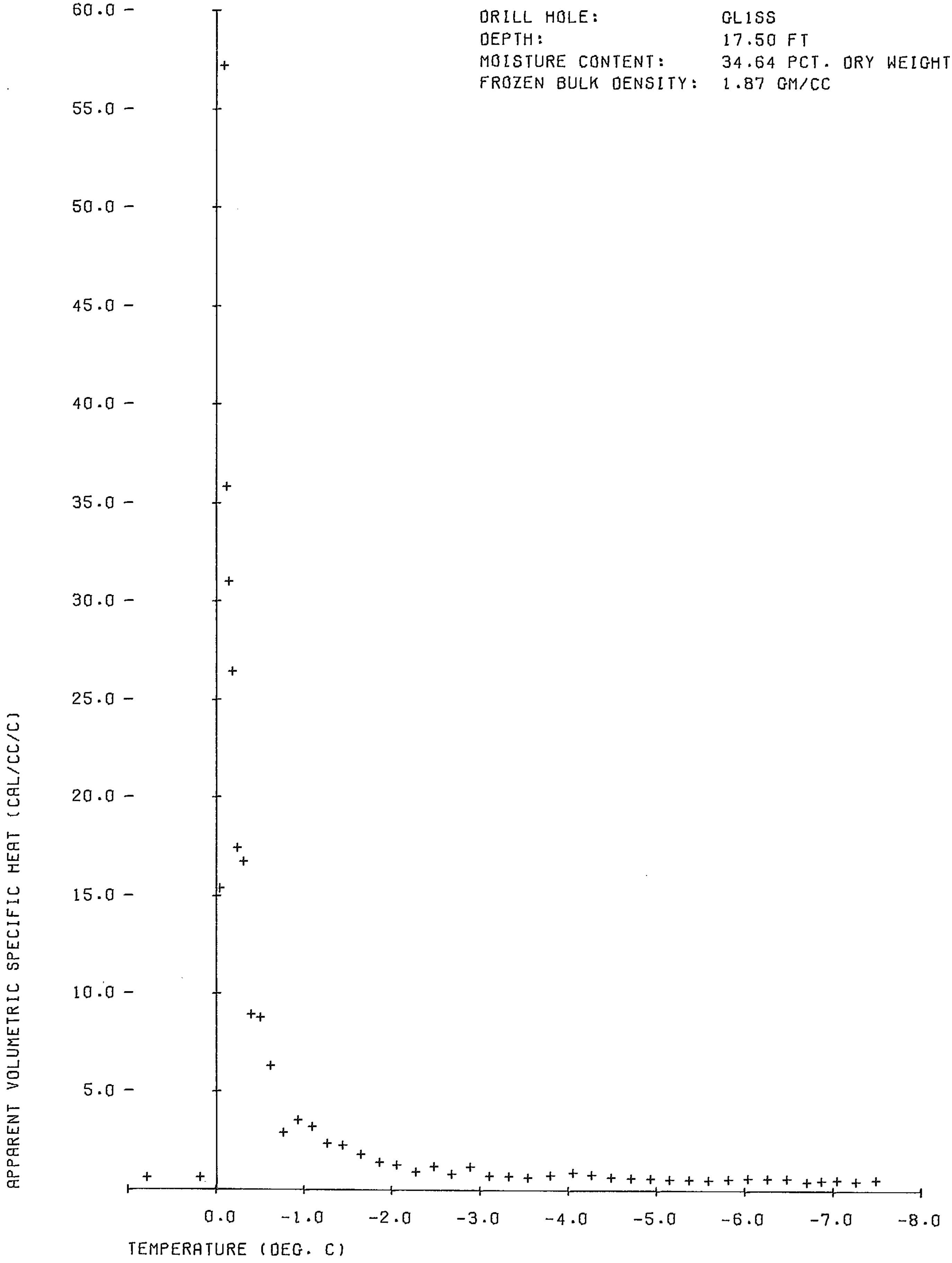

DRILL HOLE: GL2U S1S
DEPTH: 31.48 FT
MOISTURE CONTENT: 24.39 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.99 GM/CC
UNFROZEN WATER, PCT TOTAL MOISTURE CONTENT
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

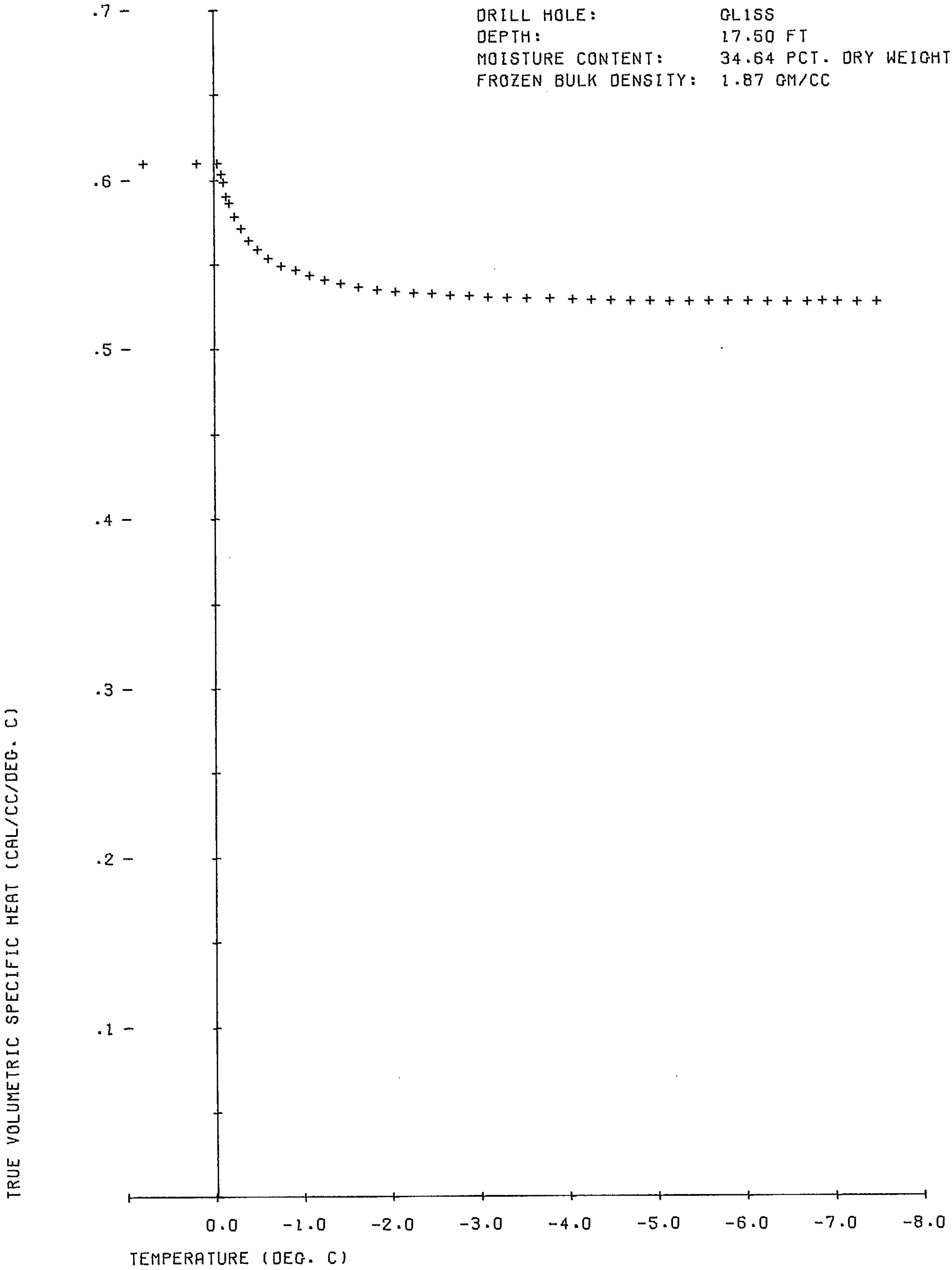

DRILL HOLE: GL2U S1S
DEPTH: 31.48 FT
MOISTURE CONTENT: 24.39 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.99 GM/CC
25.0
20.0
15.0
10.0
5.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
UNFROZEN WATER, PCT DRY WEIGHT
TEMPERATURE (DEG. C)

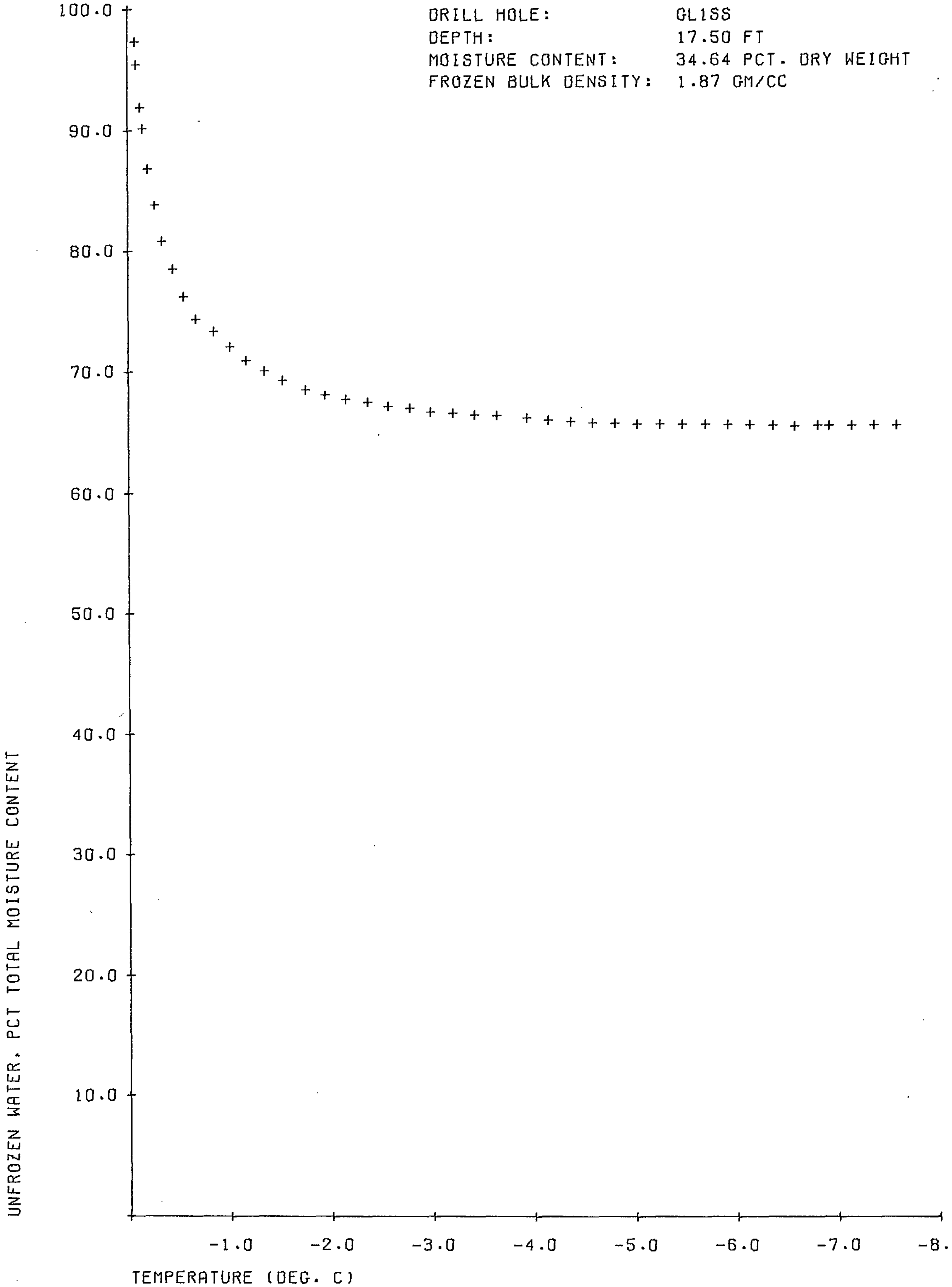

DRILL HOLE: GL2U S1S
DEPTH: 31.48 FT
MOISTURE CONTENT: 24.39 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.99 GM/CC
25.0
20.0
15.0
10.0
5.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
CUMULATIVE VOLUMETRIC HEAT (CAL/CC)
TEMPERATURE (DEG. C)

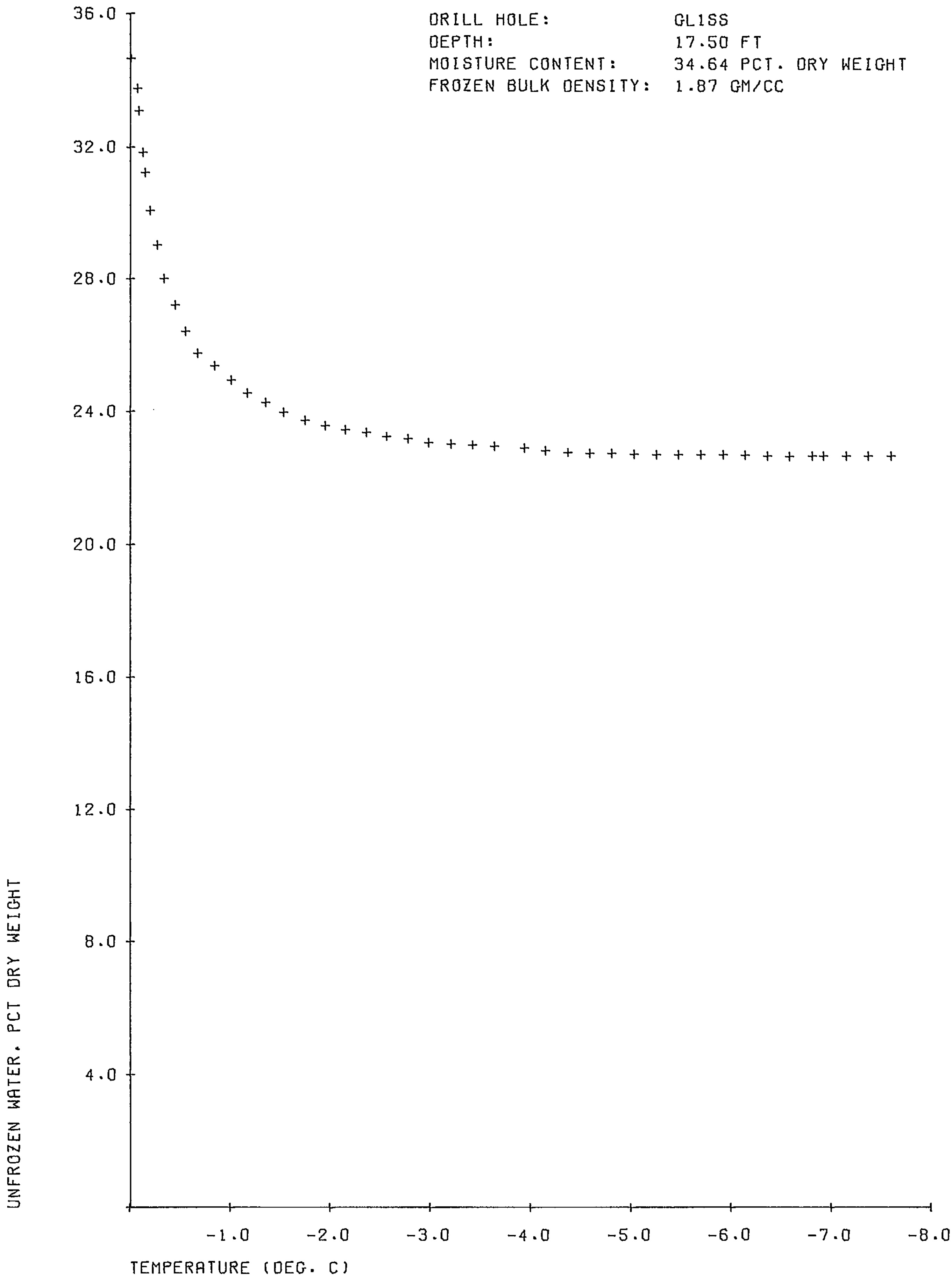

DRILL HOLE: GL2U S1S
DEPTH: 31.48 FT
MOISTURE CONTENT: 24.39 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.99 GM/CC
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
CUMULATIVE VOLUMETRIC LATENT HEAT (CAL/CC)
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

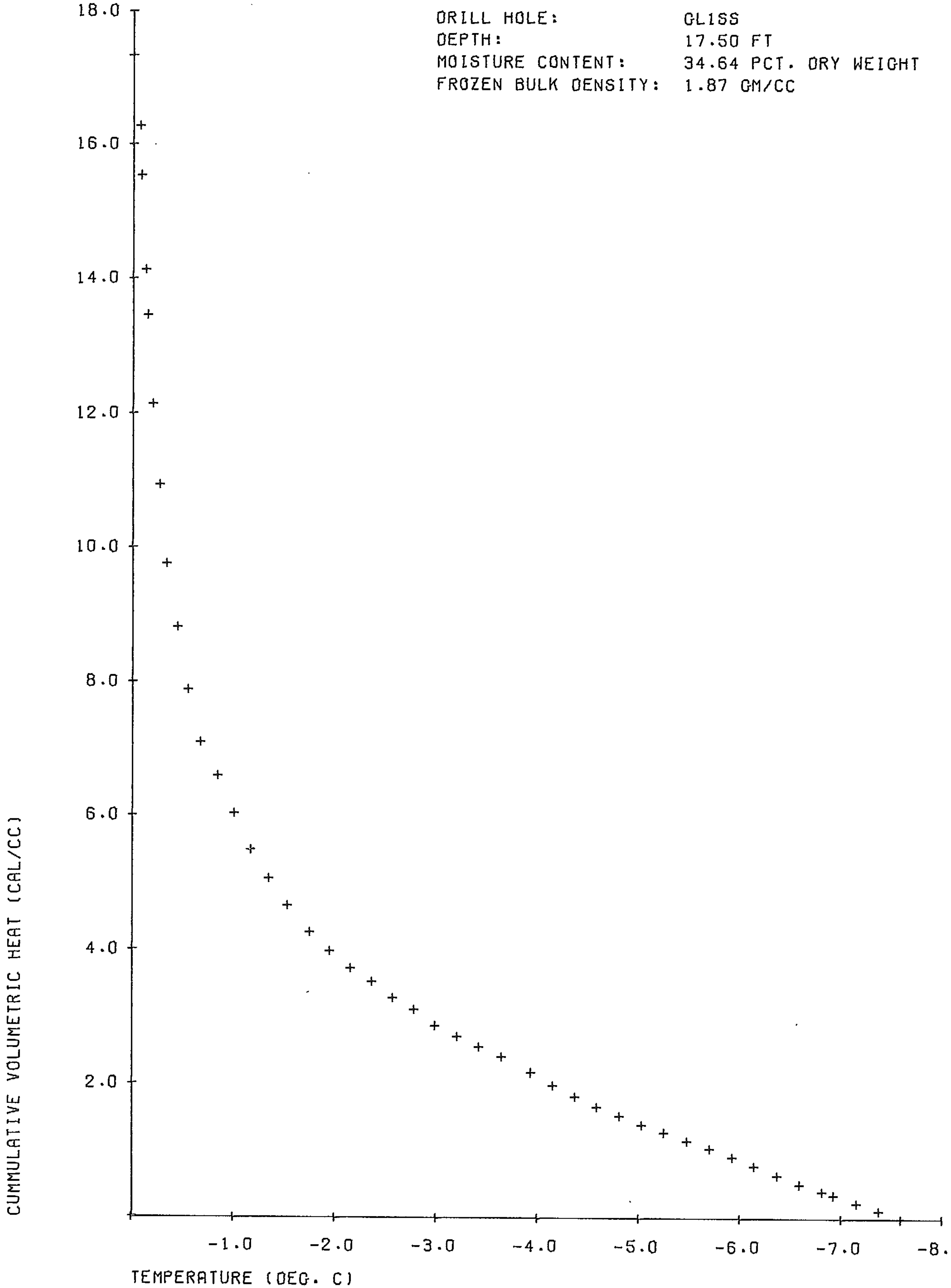

DRILL HOLE: GL1SS
DEPTH: 17.50 FT
MOISTURE CONTENT: 34.64 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.87 GM/CC
32.0
28.0
24.0
20.0
16.0
12.0
8.0
4.0
APPARENT SPECIFIC HEAT (CAL/GM/DEG. C)
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

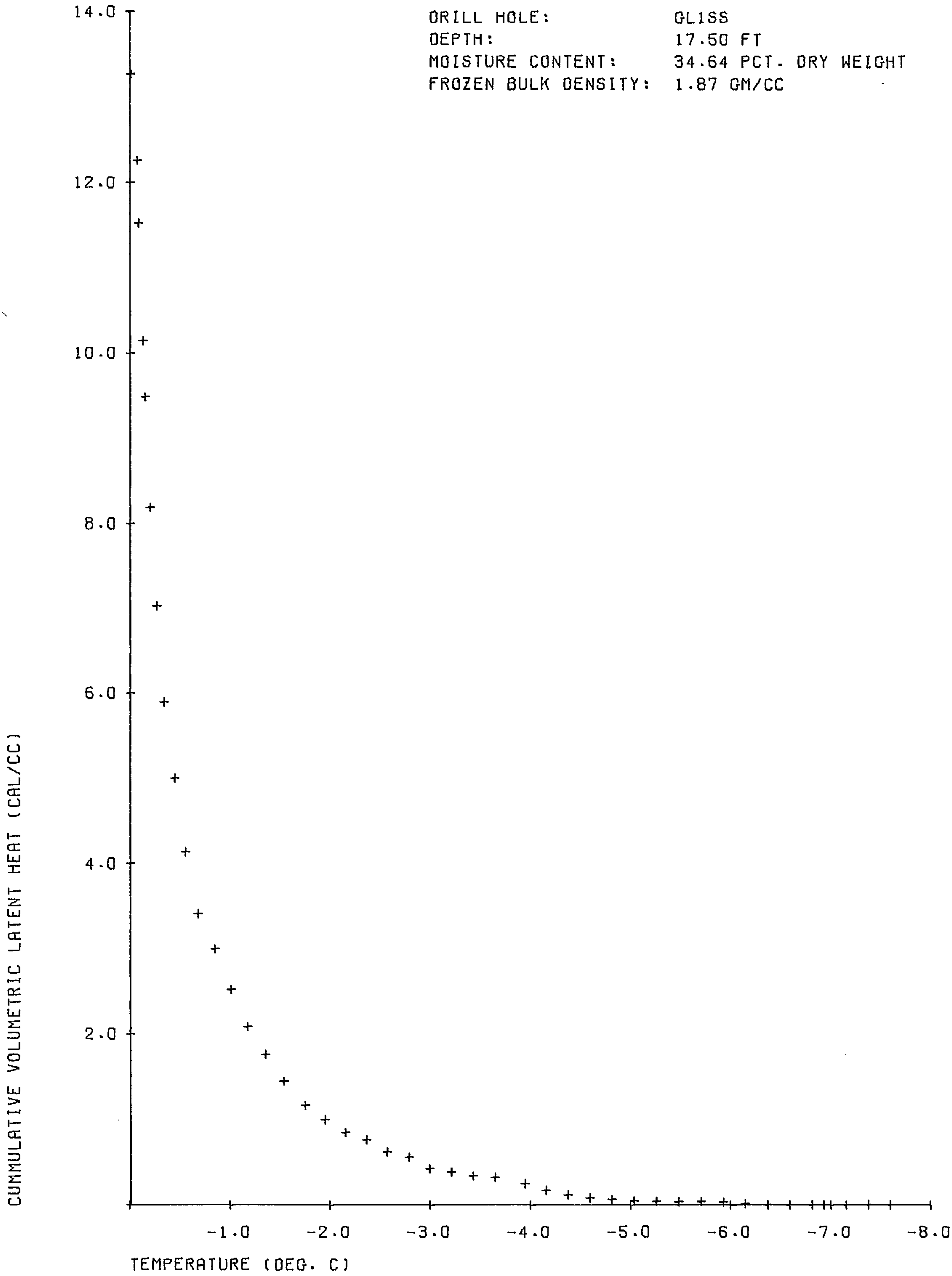

DRILL HOLE: GLISS
DEPTH: 17.50 FT
MOISTURE CONTENT: 34.64 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.87 GM/CC
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
APPARENT VOLUMETRIC SPECIFIC HEAT (CAL/CC/C)
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

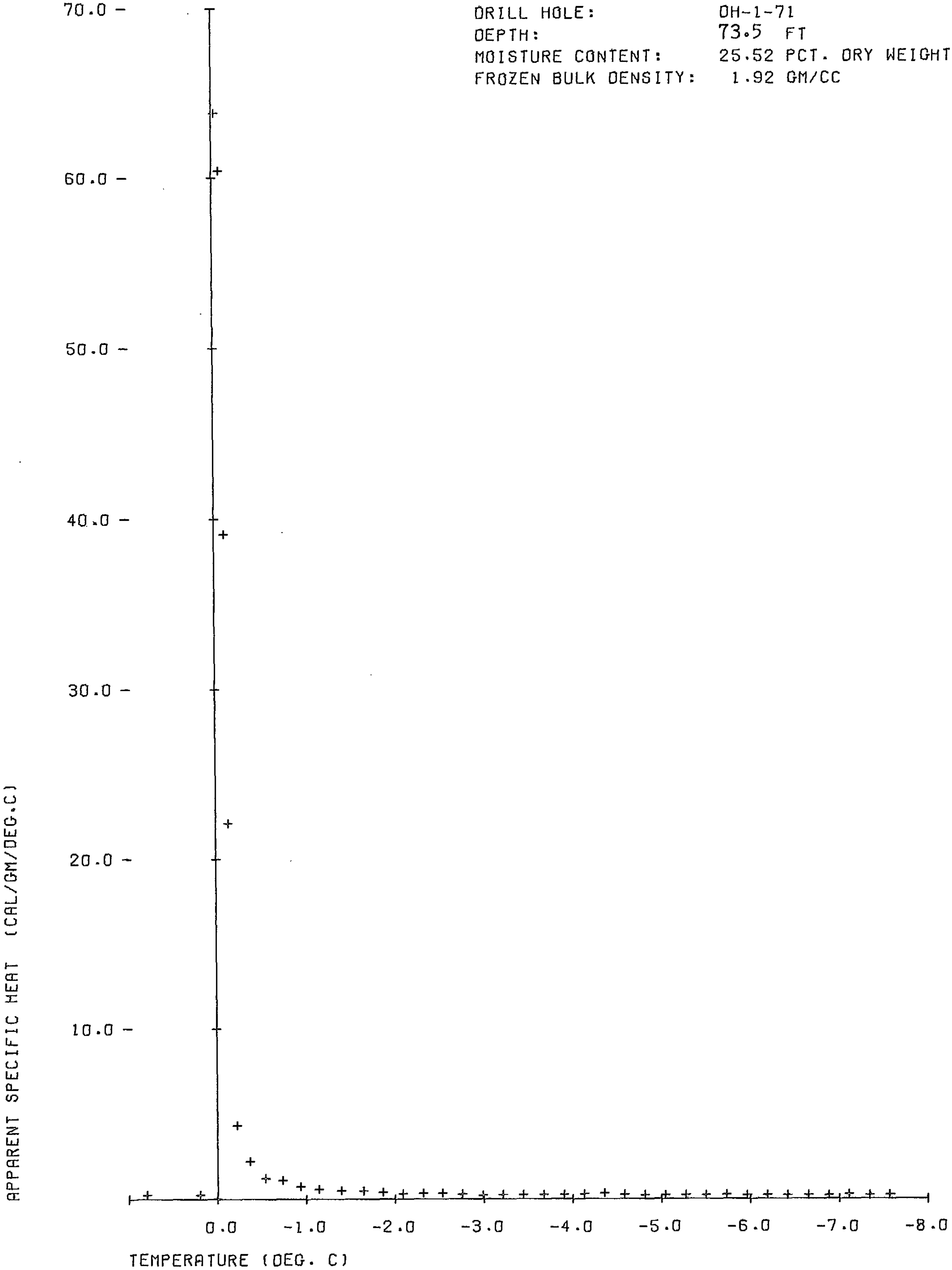

DRILL HOLE: GL1SS
DEPTH: 17.50 FT
MOISTURE CONTENT: 34.64 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.87 GM/CC
.7
.6
.5
.4
.3
.2
.1
TRUE VOLUMETRIC SPECIFIC HEAT (CAL/CC/DEG. C)
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

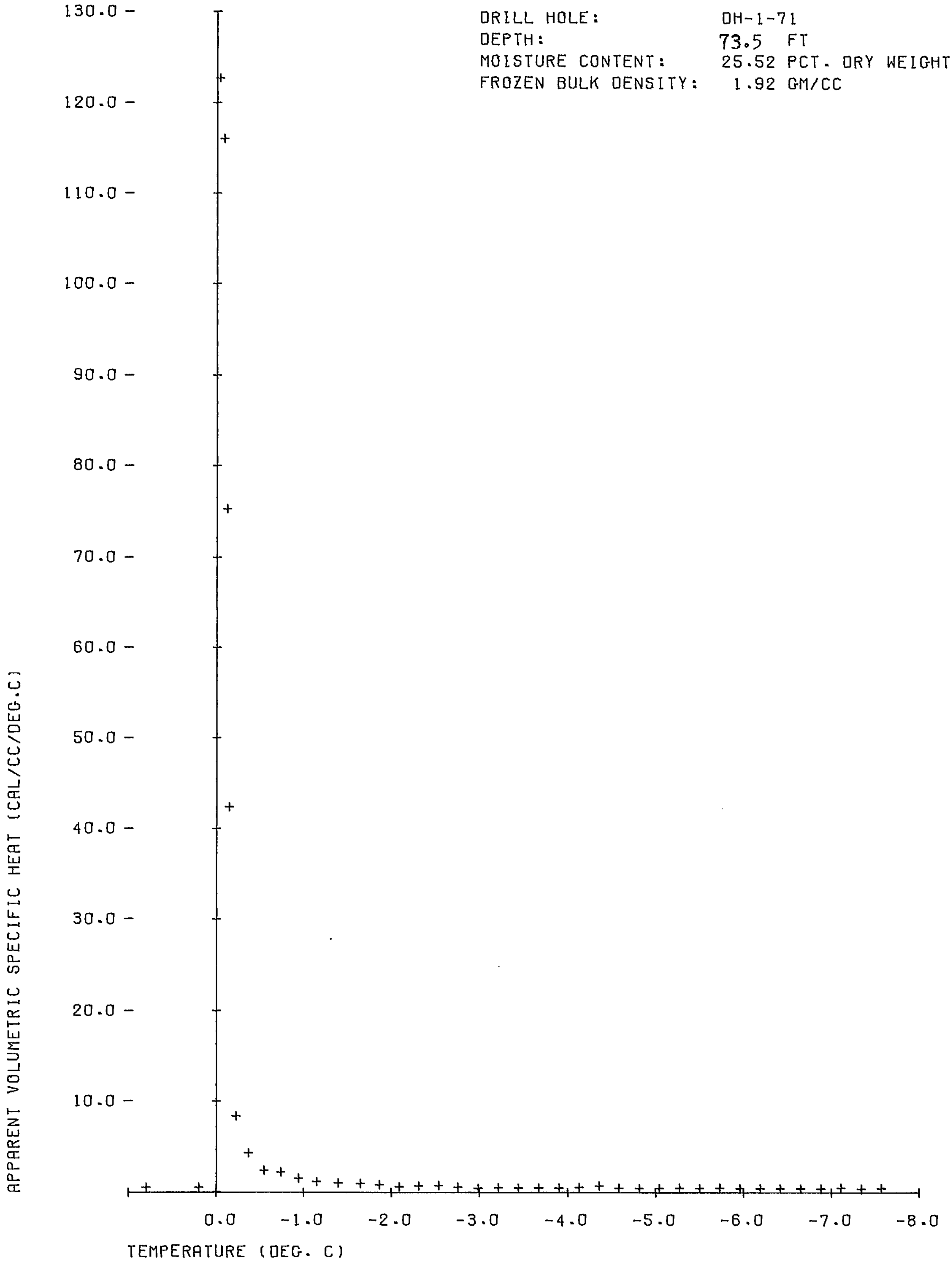

DRILL HOLE: GLISS
DEPTH: 17.50 FT
MOISTURE CONTENT: 34.64 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.87 GM/CC
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
UNFROZEN WATER, PCT TOTAL MOISTURE CONTENT
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

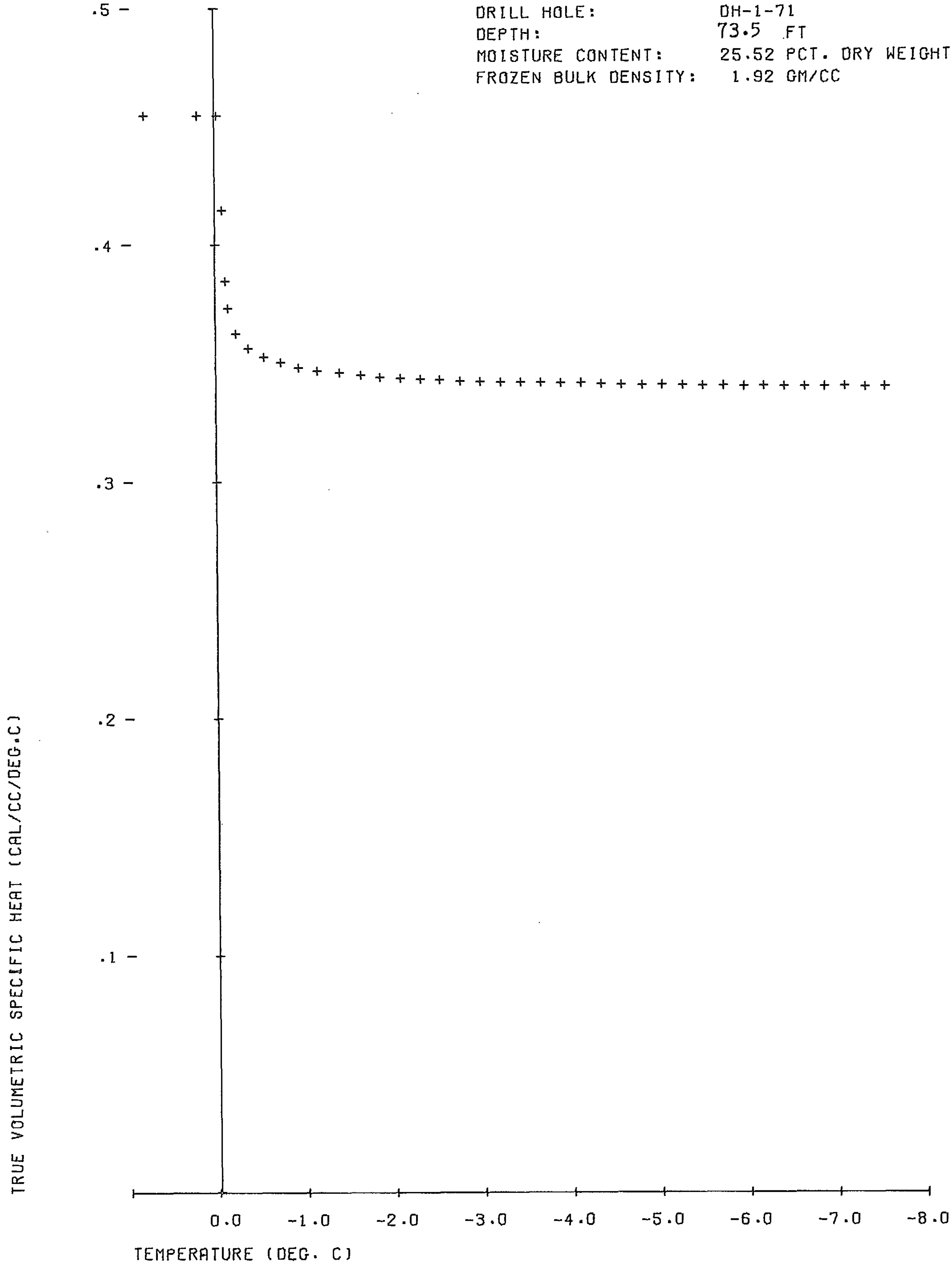

DRILL HOLE: GLISS
DEPTH: 17.50 FT
MOISTURE CONTENT: 34.64 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.87 GM/CC
36.0
32.0
28.0
24.0
20.0
16.0
12.0
8.0
4.0
UNFROZEN WATER, PCT DRY WEIGHT
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

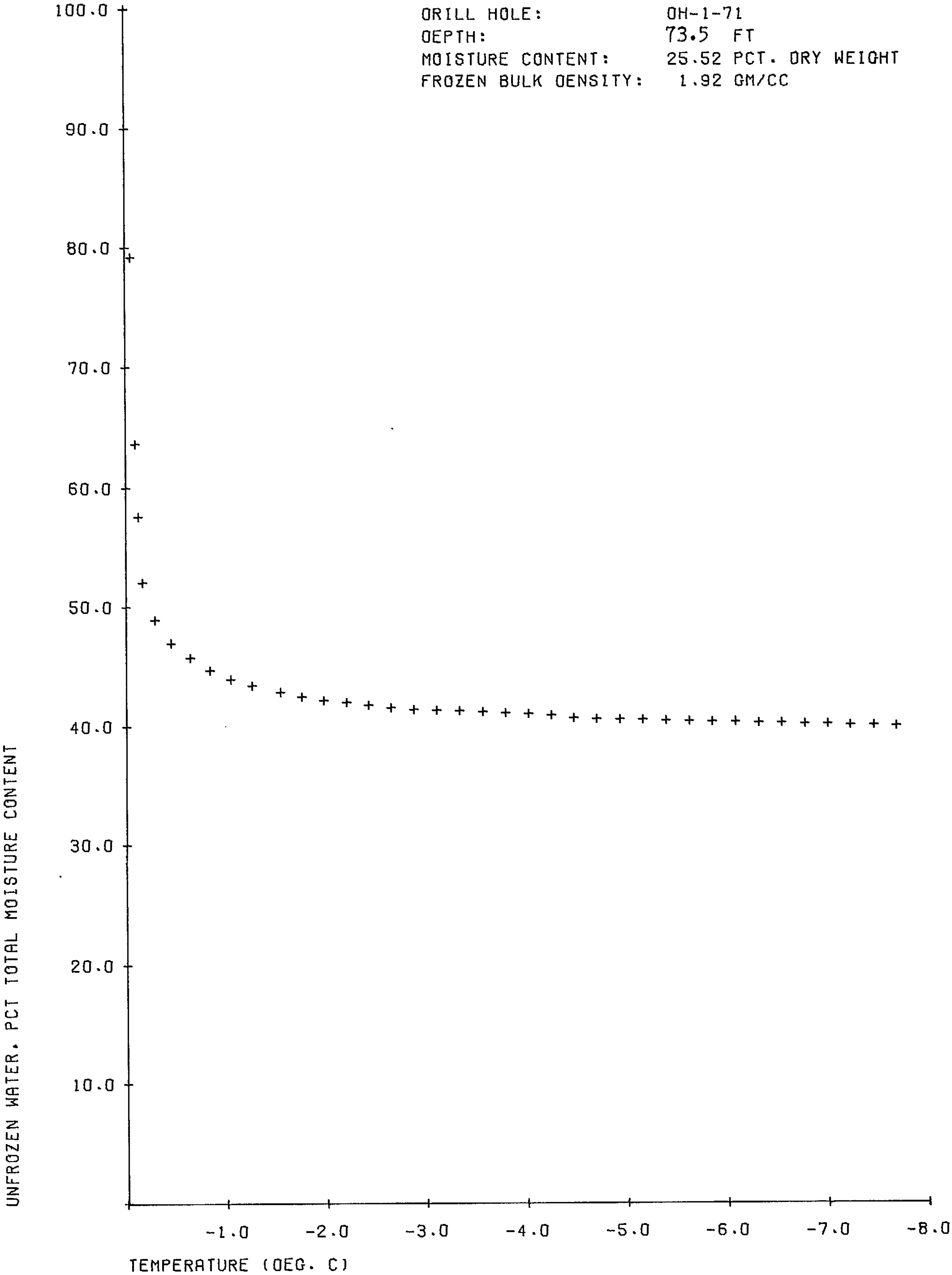

DRILL HOLE: GLISS
DEPTH: 17.50 FT
MOISTURE CONTENT: 34.64 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.87 GM/CC
CUMMULATIVE VOLUMETRIC HEAT (CAL/CC)
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

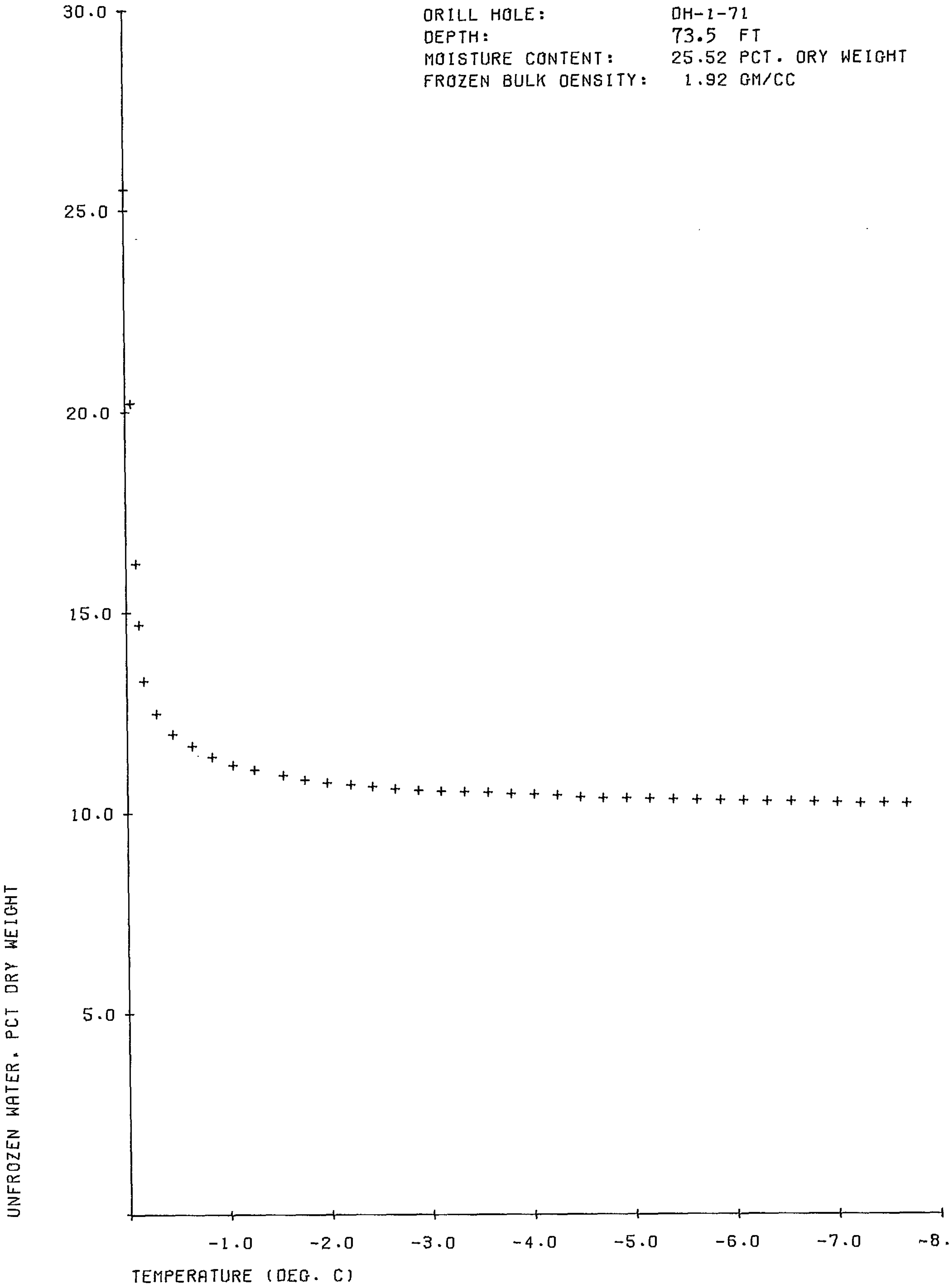

DRILL HOLE: GL1SS
DEPTH: 17.50 FT
MOISTURE CONTENT: 34.64 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.87 GM/CC
14.0
12.0
10.0
8.0
6.0
4.0
2.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
CUMMULATIVE VOLUMETRIC LATENT HEAT (CAL/CC)
TEMPERATURE (DEG. C)

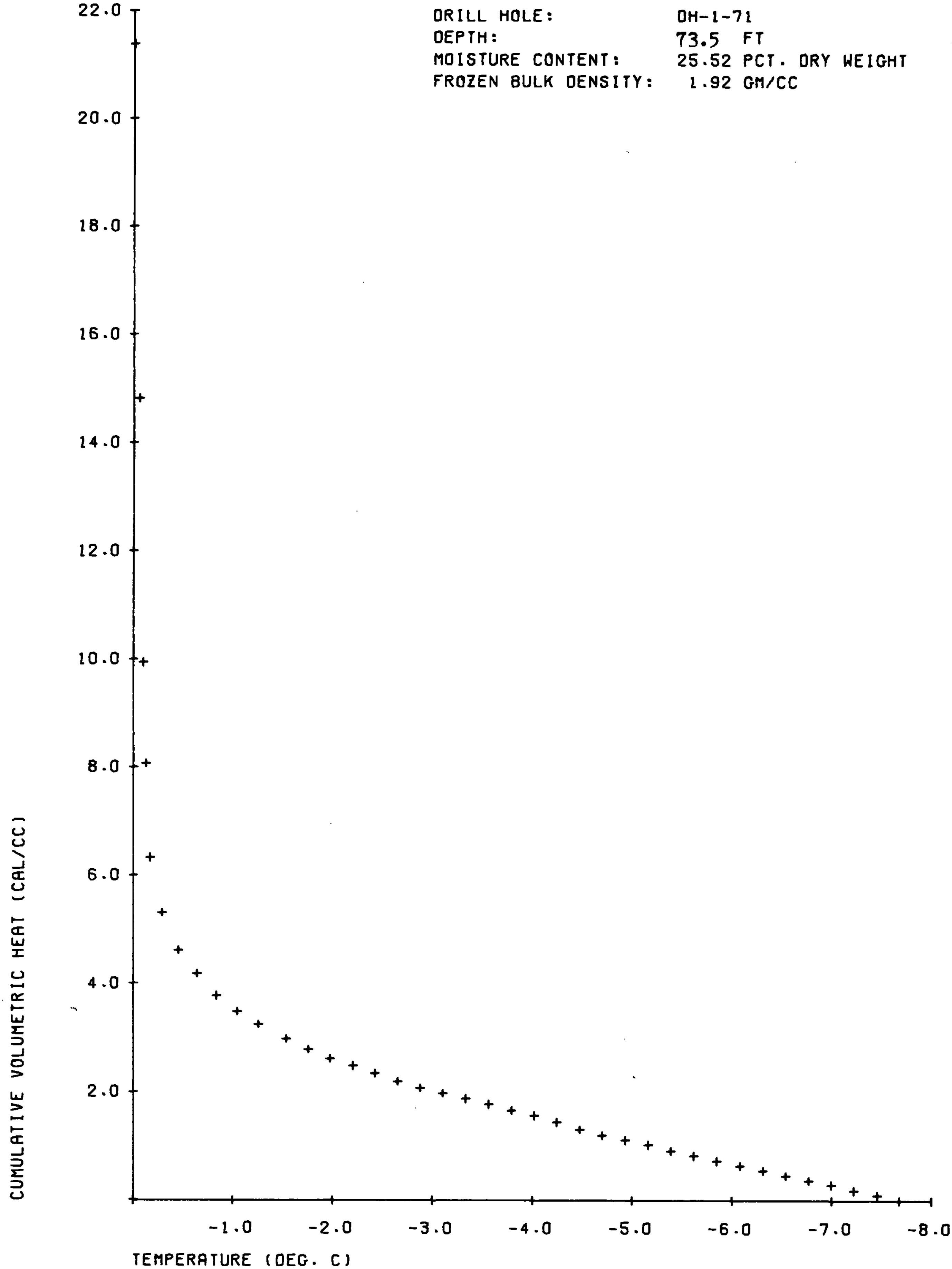

DRILL HOLE: OH-1-71
DEPTH: 73.5 FT
MOISTURE CONTENT: 25.52 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.92 GM/CC
70.0
60.0
50.0
40.0
30.0
20.0
10.0
APPARENT SPECIFIC HEAT (CAL/GM/DEG.C)
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

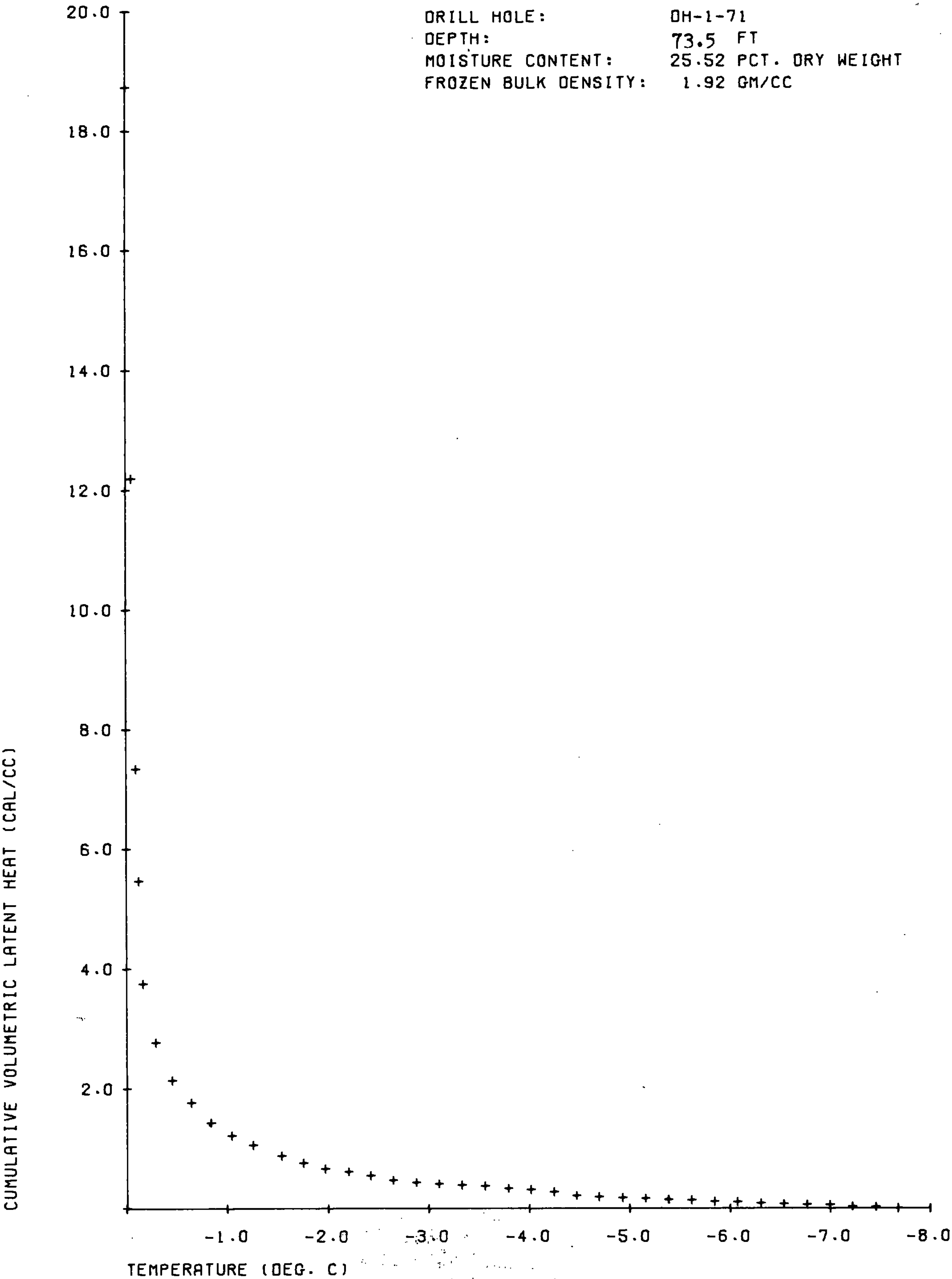

DRILL HOLE: DH-1-71
DEPTH: 73.5 FT
MOISTURE CONTENT: 25.52 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.92 GM/CC
130.0
120.0
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
APPARENT VOLUMETRIC SPECIFIC HEAT (CAL/CC/DEG.C)
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)


DRILL HOLE: DH-1-71
DEPTH: 73.5 FT
MOISTURE CONTENT: 25.52 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.92 GM/CC
.5
.4
.3
.2
.1
TRUE VOLUMETRIC SPECIFIC HEAT (CAL/CC/DEG.C)
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)


DRILL HOLE: DH-1-71
DEPTH: 73.5 FT
MOISTURE CONTENT: 25.52 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.92 GM/CC
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
UNFROZEN WATER, PCT TOTAL MOISTURE CONTENT
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)


DRILL HOLE: DH-1-71
DEPTH: 73.5 FT
MOISTURE CONTENT: 25.52 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.92 GM/CC
30.0
25.0
20.0
15.0
10.0
5.0
UNFROZEN WATER, PCT DRY WEIGHT
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)


DRILL HOLE: DH-1-71
DEPTH: 73.5 FT
MOISTURE CONTENT: 25.52 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.92 GM/CC
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
CUMULATIVE VOLUMETRIC HEAT (CAL/CC)
TEMPERATURE (DEG. C)


DRILL HOLE: DH-1-71
DEPTH: 73.5 FT
MOISTURE CONTENT: 25.52 PCT. DRY WEIGHT
FROZEN BULK DENSITY: 1.92 GM/CC
CUMULATIVE VOLUMETRIC LATENT HEAT (CAL/CC)
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
TEMPERATURE (DEG. C)

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No.74-16 4007331

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TD Geotechnical studies of
195 permafrost in the Fort Good
.P5 Hope- Norman Wells region
C3213 N.W.T. / R.M. Isaacs for the
No.74-16 4007331

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