GEOLOGICAL SURVEY OF CANADA
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A DETAILED STUDY OF THE PHYSICAL AND THERMAL PROPERTIES OF NORMAN WELLS-ZAMA PIPELINE CORE SPECIMENS

FINAL REPORT

for

GEOLOGICAL SURVEY OF CANADA
ENERGY, MINES AND RESOURCES

D.E. Patterson and D.W. Riseborough
Geotechnical Science Laboratories
Carleton University
Ottawa, Canada
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Canada

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FOREWORD

This report documents work undertaken as part of the federal government's Permafrost and Terrain Research and Monitoring Program along the 868 km Norman Wells to Zama oil pipeline. The 324 mm diameter, shallow burial (1 m) pipeline, traverses the discontinuous permafrost zone of northwestern Canada and began operation in April 1985. A joint monitoring program with Interprovincial Pipe Lines (NW) Ltd. was established following the signing of an environmental agreement between the pipeline company and the Department of Indian and Northern Affairs (INAC) in 1983. INAC coordinates the government's monitoring program in which Energy, Mines and Resources' Geological Survey of Canada, the National Research Council's Institute for Research in Construction, and Agriculture Canada's Land Resource Research Institute participate.

A major component of this research and monitoring program involves the detailed quantification of changes in the ground thermal regime and geomorphic conditions at thirteen instrumented sites along the route. This project was developed in cooperation with the Permafrost Research Section of the Geological Survey in order to examine and quantify the effects of pipeline construction, operation and maintenance in thaw sensitive terrain. Many components of this research are contracted out.

The work undertaken in this contract report describes but one aspect of these site investigations. Interpretations contained herein are often limited to the specific data base under analysis and may thus not present an integrated or comprehensive analysis of all site observations. The opinions and views expressed by the authors are their own and do not necessarily reflect those of the Geological Survey of Canada or Indian and Northern Affairs.

Funding for the research and analyses reported herein was largely provided by INAC's Northern Affairs Program, with contributions from the Northern Oil and Gas Action Program (NOGAP).

Margo Burgess
Scientific Authority
Permafrost Research Section
Geological Survey of Canada

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Analysis of the Physical Properties of Core Specimens from the Norman Wells to Zama Oil Pipeline

I Introduction

This report summarizes the results of physical properties testing on core specimens from the Norman Wells to Zama oil pipeline route. Soil cores from three sites were examined in detail to provide information needed in interpreting geophysical and thermal data. These sites were:

1. 85-7B Table Mountain, 271.5 km from Norman Wells and 7.3 m west of the pipeline;
2. 85-12B Jean Marie Creek, 607.9 km from Norman Wells and 8.9 m east of the pipeline.
3. 85-8A Manner's Creek, 556.9 km from Norman Wells and 5.3 m west of pipeline.

Samples obtained during the 1984 field program were also examined.

The core specimens are housed in the Geological Survey of Canada's cold room at Carleton University. Previously, these were described and photographed for inventory purposes (Patterson et al. 1987). The description included information on soil type, inclusions within the soil, ice type and orientation. Frozen density and thermal conductivity were also determined at cold room temperatures (-10 C).

The following information was obtained for the core specimens examined:

1. total density
2. dry density
3. total ice/water content
4. grain-size characteristics
5. pore water salinity
6. temperature-dependent phase composition

Thaw consolidation tests were carried out on certain specimens to assist in interpreting field measurements of soil settlement.

Temperature-dependent thermal conductivity values were obtained for major soil groups to provide information for ground thermal modelling (soil groups were determined on the basis of grain-size and phase composition data).

A summary of the specimens examined in this study is presented in section 3 for each borehole. Sub-samples representative of the general physical characteristics of the profile were chosen as well as ones which exhibited unique characteristics.

The numbering system used to identify specimens gives the borehole, the core and sub-specimen number. The depths indicated on the summary tables denote the position of the sub-sample within the soil profile. For example, 85-7B C3a indicates that the specimen is from the 1985 field season at site 7B and the sub-specimen "a" of the third core. The cores are generally 40 to 80 cm in length and are subdivided into 1 to 3 subsections of 15 to 40 cm to facilitate transport.

II Physical Properties Tests

2.1 Introduction

Test methods are described in the following sections. References to standard procedures are given where appropriate. Tests which do not have an established procedure are described in more detail.

2.2 Total Water Content, Frozen and Dry Density Tests

Prior to thawing, specimen length, circumference and total mass was determined. This information was used to check the frozen density estimates obtained during the preliminary analysis (Patterson et. al. 1987). Total mass was determined again since material was scraped from the surface of each specimen in the previous study to facilitate core description. Core volume was determined by calculation from the measured circumference and length. Cores which had ragged edges were trimmed to provide a uniform length. At least 15 cm of core was used for subsequent analysis.

The samples were allowed to thaw in sealed bags for 48 hours and the mass was checked again. If consolidation tests were performed on a specimen, then the sample length was determined after consolidation (see section 2.9).

The samples were then broken up and material from several places within the core was removed for water content determination. In general, at least 25% of the total sample mass was used in this test. Mass was determined in the wet state and again in the dry state after 24 hours of oven drying at 105 C. This procedure of sub-sampling for water content determination was adopted by the author's since some of the specimens were clay rich and it was felt that oven drying may affect the results of grain-size and phase composition tests. The remainder of the specimen was allowed to air dry and sub-samples were used for particle density, phase composition and grain-size testing.

The mass of solids and water in the sample was determined from the masses present in the sub-sample using the following relationships:

$$Msc = (Mtc * Mss) / Mtt$$

where Msc is the mass of solids in the specimen; Mtc, is the total mass of the core; Mss, is mass of solids in the sub-sample, and Mtt is the total mass of the sub-sample. The mass of water/ice was determined from the difference between Mtc and Msc. However, if any free water drained during the course of thaw, the total mass of the core specimen was reduced by this amount in order to obtain a proper estimate of Msc. The mass of excess water was then added to the mass of water calculated using the above procedure.

The degree of saturation, ice content and unfrozen water content were determined from phase composition, density and water content data. An example for specimen 7B C2a is given below. V denotes volume; M, mass and the letters t, s, w, i and v stand for total, solids, water, ice and voids respectively. The total frozen density, dry bulk density and particle density are given as Pt, Pb and Pd respectively. The gravimetric water content (water and ice) determined upon thawing is w and the gravimetric unfrozen water content is wu and represents the value at -5.0 C (cold room temperature):

from tests

Vt	1380 cm^3
Pd	2.704 g cm^{-3}
Mt	2228.65 g
Ms	1630.63 g
Mw	598.01 g
w	36.67 g g^{-1}, %
wu	9.0 g g^{-1}, %

calculated values

Pt	1.615 g cm^{-3}
Pb	1.182 g cm^{-3}
Vs	Ms/Pd = 603.04 cm^3
Vv	Vt - Vs = 776.95 cm^3

The total mass of water, Mw, can be partitioned into unfrozen water, Mwu, and ice, Mi, and their volumes determined using 1.0 g cm^{-3} as the density of water and 0.917 g cm^{-3} for ice.

Mwu wu * Ms = 146.76 g

Vw 146.76 cm3

Mi Mw - Mwu = 451.25 g

Vi Mi / 0.917 g cm^{-3} = 492.10 cm^3

Vi + Vw = 638.86

% saturation = 82.23 %

The particle density of representative specimens was obtained using the the "pycnometer method" as outlined by Blake and Hartge (1986). The pycnometers used have a nominal volume of 50 cm^3. Generally, 20 to 25 g of soil was tested with all masses being determined to +/- 0.00001 g.

2.3 Particle Size Characteristics

The procedure used to determine the particle size characteristics of the specimens is outlined in Gee and Bauder (1986). Particle size analysis was performed on the size fraction < 2 mm. Small sieves were used to obtain size distribution within the sand range (2 mm to 0.05 mm) while the pipette method was used on the silt and clay fractions (<0.05 mm). Material greater than 2 mm was also examined for size and mineral composition.

For some specimens, mechanical dry-sieving was used since the sand fraction, from visual analysis, constituted more than 85% of the total mass. Size distribution within the silt and clay size fractions was determined by sedimentation analysis.

2.4 Soluble Salts and Electrical Conductivity

Electrical conductivity and soluble salt concentration was determined using the procedures outlined in Rhoades (1982). About 100 grams of dry soil was mixed with 100 g of distilled water. The samples were then left to stand for 24 hours to ensure a state of equilibrium had been reached. Pore water was extracted using pressurized nitrogen. The electrical conductivity was determined using standard bridge techniques with

KCl as the standard.

Due to differences in equivalent weights, conductivities and the type and amount of the ions present in the pore water, the relationships between electrical conductivity, σ, and salt concentration are only approximate. Rhoades (1982) suggests that the following relationships are useful, however:

total cation (or anion) concentration

$$\text{meq/litre} \approx 100\ \sigma,\ \sigma \text{ in S m}^{-1}$$

salt concentration

$$\text{g/litre} \approx 6.4 * \sigma,\ \sigma \text{ in S m}^{-1}$$

2.5 Mineralogy

Several samples from borehole 7B were analysed using X-ray diffraction to determine mineralogical composition. The analysis was carried out at the Department of Earth Sciences, Carleton University. The main interest in the analysis was to see if there was substantial quartz in the clay fraction.

Sub-samples of the < 20, 5, 2 and 1 μ size fractions were obtained during the particle size analysis. X-ray diffraction peaks can be used to provide a qualitative estimate of quartz content. A quantitative analysis would require the addition of known amounts of quartz at different concentrations by mass, and a subsequent calculation of quartz content from peak heights.

2.6 Phase Composition

The unfrozen water content-temperature relationships for a variety of specimens was determined using Time-domain Reflectometry (TDR). Sub-samples were mixed with distilled water, allowed to stand for at least two days and then packed into 18 cm long coaxial lines. An effort was made to reproduce the field density as closely as possible.

Careful measurements were made of the masses (+/-0.00001 g) prior to filling the coaxial line and after the completion of testing. The specimens were frozen and thawed several times prior to performing the tests. Temperature control was provided by immersing the coaxial line in an ethylene glycol bath (+/-0.01 °C).

Measurements of the apparent dielectric constant, Ka, were obtained on thaw cycles. Estimates of the volumetric unfrozen water content, θu, were made using the following relationship:

$$\theta u = -1.458x10^{-1} + 3.868x10^{-2}\ Ka - 8.502x10^{-4}\ ka^{2} + 9.920x10^{-6}\ Ka^{3}$$

This relationship was determined by Smith (to be published) and is based upon comparison of TDR and NMR data for a wide variety of soils and sub-freezing temperature conditions. The relationship yields slightly different values of θu for a given Ka than would be obtained using the relationship found by Topp et al. (1980). The reason for the apparent discrepancy lies in the fact that the relationship determined by Topp et al. (1980) was for unfrozen soils of varying degrees of saturation. In a frozen soil at a comparable water content, one has ice present which has a dielectric constant of about 3.2 compared to a value of 1 for air. The author's feel that equation (1) provides a more representative estimate of θu at cold temperatures and/or low values of θu for initially saturated samples.

2.7 Thaw Consolidation

Thaw consolidation tests were performed on many of the core samples in order to aid in interpreting field observations of settlement. The samples chosen represented the major soil groups or were ones which had a low total density (hence, possibly a high ice content).

The cores were cut to length (15 to 20 cm) in the frozen state and placed in lucite containers having a diameter slightly larger than the sample diameter. If the sample did not move freely with the container, excess material was scraped off the surface until it did.

The samples were then removed from the cold room and covered to prevent evaporation or sublimination. Uncontrolled thawing was carried out using a nominal load of 3 kg (surface area of specimen was approximately 100 cm^2). The strain upon thaw was determined from differences in the sample length before and after thaw. Any water which drained during thaw was collected.

2.8 Thermal Conductivity Tests

The temperature-dependent thermal properties of major soil groups was determined using a cylinder probe. The samples were selected on the basis of grain size and phase composition data. Tests were performed on saturated remoulded samples with every effort being made to replicate the _in situ_ water content and density.

The samples were subjected to two freeze/thaw cycles, and allowed to stand for a week before the tests began. Standing allows the moisture in the sample to equilibrate with its surroundings, and the freeze/thaw cycles give the sample some structure. Tests were done on thaw cycles with at least twelve hours between test temperatures.

The presence of water in frozen materials influences thermal property test procedures in four ways and the following factors must be considered when examining test results:

1. Latent heat release associated with the temperature change induced by the test.

2. Sensible and latent heat transfer due to moisture migration, induced by the temperature gradients established within the specimen during the test.

3. Reversible variations in thermal conductivity during the test (spatial and time dependent) due to the temperature dependent phase composition.

4. Irreversible specimen inhomogeneity induced by moisture migration.

These problems become severe in soils near the freezing point using the common methods of determining thermal properties which require prolonged and/or substantial heating of the test specimen.

With the equipment and procedure used, testing time is limited to 180 seconds and the temperature rise of the probe is generally less than 0.1 °C. Because of this, phase change is minimized and water redistribution should be negligible.

The experimental results (change in temperature versus time) are fit to the analytical model using a non-linear regression program to solve for the thermal properties. The model requires heat capacity information which is determined from the physical properties of the sample and phase composition information (obtained via TDR from parallel line probes embedded in the test specimen). Since heat capacity can be determined, an estimate of the thermal conductivity can be made.

After all tests are analysed, each of the three thermal properties are plotted against temperature to see which test temperatures require further examination. As a rule, the properties should plot as smooth functions of temperature and this is generally the case for the thermal diffusivity versus temperature curve. If the temperature-thermal diffusivity curve appears reasonable but the other curves do not, the apparent heat capacity is adjusted and the analysis repeated.

III Summary of Findings

3.1 Core Descriptions

The core descriptions provided in this section are largely based on those presented in Patterson et. al. (1987). Additional observations made during thawing and subsequent testing are also included.

3.1.1 Borehole 7B

The samples examined from Borehole 7B, are summarized in Table 1. As indicated, the samples in this borehole are largely silty clays with gravel inclusions containing stratified or distinctly oriented ice formations (VS, ground ice classification). The ice lenses tended to be very thin and were not continuous across the sample diameter. After the samples had thawed, they tended to breakup into a marked blocky structure generally following the position of the small hair-like ice lenses. The inclusions ranged in size from several millimeters to several centimeters and were a mix of rock types and were generally well-rounded. The greatest concentration was found in the 7.7 to 11.1 m layer. The mineralogical analysis indicated a fair amount of quartz and chlorite with a wide mix of clay minerals.

The thawed material was very plastic with a significant clay content $< 1\mu$. There was considerable shrinkage when the material was allowed to air dry. The thawed material was also found to

Table 1 Core Description and Ice Classification as Determined in the Cold Room for Borehole 7B

Specimen	Depth (m)	Visual Soil Classification (in cold room)	Inclusions	Ice Type	Ice Shape
7B C1	0.8 - 1.2	silty clay	gravel	VS	lenses
7B C2	1.2 - 1.7	silty clay	gravel	VS	lens
7B C3a	1.7 - 2.1	silty clay	gravel	VS	lens
7B C4a	2.4 - 2.8	silty clay		VS	lenses
7B C5a	3.2 - 3.6	silty clay	gravel	VS	lens
7B C6a	4.5 - 4.7	silty clay	gravel	VS	lens
7B C7a	4.7 - 5.0	silty clay	gravel	VS	lens
7B C8b	5.8 - 6.1	silty clay	gravel	VS	lens
7B C9a	6.3 - 6.5	silty clay	gravel	VR	grains
7B C10b	7.3 - 7.5	silty clay	gravel	VS	grains
7B C11a	7.8 - 8.0	silty clay	gravel	VS	lens
7B C12a	8.5 - 8.8	silty clay	gravel	VS	lenses
7B C13c	9.9 - 10.1	clay	gravel	VR	grains
7B C14a	10.1 - 10.3	silty clay	gravel	VR	grains
7B C15a	10.8 - 11.1	silty clay	gravel	VS	lens/vein
7B C16a	11.6 - 11.9	silty clay	gravel	NB	
7B C17a	12.3 - 12.6	silty clay		VS	lens
7B C18b	13.3 - 13.6	silty clay	gravel	VS	lens
7B C19a	13.9 - 14.2	silty clay	gravel	VS	lens/vein
7B C20a	14.5 - 14.8	silty clay	gravel	VR	lens/vein

consolidate quite readily under load as shown in Figure 1.

The thaw strain is summarized in section 3.2.2. Samples in the top 1.7 m showed about a 10% thaw strain which, if combined with the consolidation after thaw, could lead to substantial settlement.

3.1.2 Borehole 12B

Table 2 summarizes the descriptions for Borehole 12B. The top 2.9 m was peat overlaying a somewhat sandy silt. The top 60 cm of peat was relatively dry (for a peat) while the rest was ice rich. Significant thaw strain was observed in the peat.

The interface between the peat and mineral soil was also ice rich and consolidated readily. In general, the mineral soil layer was ice rich and consolidated readily upon thaw.

3.1.3 Borehole 8A

Table 3 summarizes the descriptions for borehole 8A. The material is sandy down to about 5 m and a silty clay beneath. The sands were light in colour in the upper 2 m grading to blackish layered sands in the 2 to 5 m layer. Shell fragments were found in sample C5b (2.6-3.1 m).

The field log indicated that the material was poorly-bonded to about 3 m and well-bonded with no excess ice to 5 m. The thaw consolidation tests indicated thaw strains of 14.3 % for Cla (0.2-0.8 m) decreasing to about 2.3 % for C5b (2.6-3.1 m) so some excess ice was present. The silty clay material between 6.9 to

Figure 1 Consolidation Tests for Samples 7B C1 and 7B C2

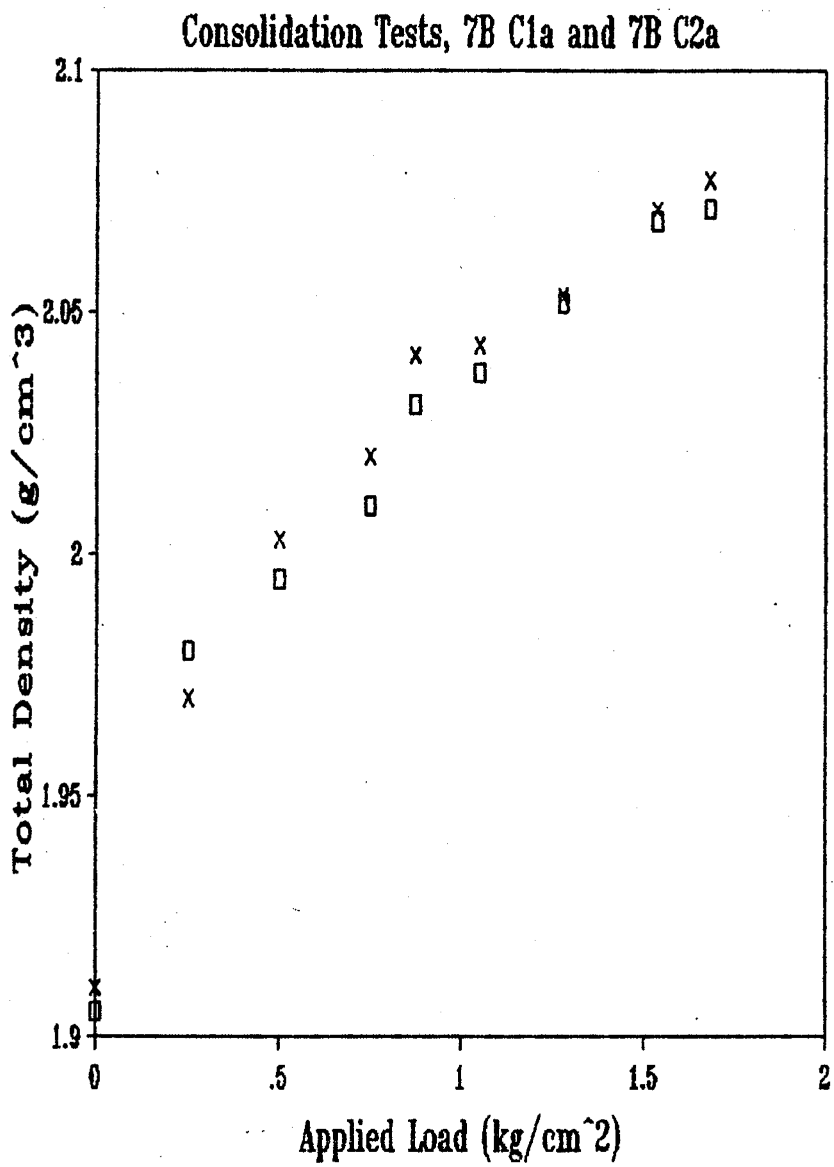


Table 2 Core Description and Ice Classification as Determined in the Cold Room for Borehole 12B

Specimen	Depth (m)	Visual Soil Classification (in cold room)	Inclusions	Ice Type	Ice Shape
12B C1a	0.0 - 0.6	peat		NB	
12B C2a	0.6 - 1.2	peat		NB	
12B C3a	1.2 - 1.7	peat		VS	lens
12B C4a	1.7 - 2.3	peat		NB	
12B C5a	2.3 - 2.8	peat		VC	random
12B C5c		peat/silty clay		VS	lens/grain
12B C6a	2.8 - 3.2	clay/silt		VS	lens/vein
12B C7A	3.2 - 3.8	silt		VS	lens
12B C8a	3.8 - 4.8	silt		VS	lens/grain
12B C9a	4.8 - 5.5	silt	gravel	VS	lens/grain
12B C9c		clayey silt	gravel	VS	lens/grain
12B C10a	5.5 - 6.3	sandy silt	gravel	VS	lens/grain
12B C11a	6.3 - 7.4	silty fine sand	gravel	VS	lens/grain
12B C11c		silty fine sand	gravel	VS	lens

Table 3 Core Description and Ice Classification as Determined in the Cold Room for Borehole 8A

Specimen	Depth (m)	Visual Soil Classification (in cold room)	Inclusions	Ice Type	Ice Shape
Specimen	Depth (m)				
8A C1a	0.2 - 0.8	sand	organic	NB	
8A C2b	0.8 - 1.5	sand		NB	
8A C3a	1.5 - 2.1	sand		NB	
8A C4a	2.1 - 2.6	sand		NB	
8A C5b	2.6 - 3.1	sand		NB	
8A C6a	3.1 - 3.9	sand		NB	
8A C7a	3.9 - 4.7	fine sand		NB	
8A C8a	4.7 - 5.6	sand/silty clay		VS	lens
8A C9a	5.6 - 6.1	silty clay		VS	lens/vein
8A C10a	6.1 - 6.9	clay		VS	lens/vein
8A C11a	6.9 - 7.6	silty clay		VS	lens/grain
8A C12a	7.6 - 8.5	silty clay		VS	lens/grain

8.5 m also exhibited thaw strain.

3.2 Physical Properties, Borehole 7B

3.2.1 Density and Water Content

Density and water content data for borehole 7B are summarized in Tables 4 and 5 and Figures 3.1 and 3.2. Table 4 gives the frozen density, dry density and gravimetric water content for the samples examined. Table 5 shows the percentage composition of mineral matter, ice+water and air determined from physical properties and phase composition information.

In general, the top 2.1 m or so had more water/ice than lower depths and was less dense, probably reflecting the existing and/or historic active layer. The top 1.7 m was not completely saturated with ice/water and could reflect conditions at the time of sampling. An ice rich layer occurs at 8.5-10.3 m depth. The material beneath was relatively uniform in terms of density and water content.

3.2.2 Thaw Strain

As mentioned earlier, thaw consolidation was examined for selected samples prior to other testing. A nominal load was used and thawing was uncontrolled. The results serve to illustrate the variations which exist within a borehole and to provide a guide to possible amounts of settlement in the field.

The thaw strains noted for Site 7B are summarized in Table 6.

Table 4 Results of the Physical Properties Tests for Borehole 7B

Specimen	Depth (m)	Density ($Mg\ m^{-3}$) frozen	dry	Total Water Content ($kg\ kg^{-1}$, %)
7B C1	0.8 - 1.2	1681	1295	29.70
7B C2	1.2 - 1.7	1615	1182	36.67
7B C3a	1.7 - 2.1	1874	1494	25.47
7B C4a	2.4 - 2.8	1884	1555	21.22
7B C5a	3.2 - 3.6	2012	1645	22.38
7B C6a	4.5 - 4.7	1976	1611	22.70
7B C7a	4.7 - 5.0	2035	1707	19.22
7B C8b	5.8 - 6.1	1990	1539	22.65
7B C9a	6.3 - 6.5	2009	1728	17.70
7B C10b	7.3 - 7.5	1981	1539	22.31
7B C11a	7.8 - 8.0	1995	1640	21.62
7B C12a	8.5 - 8.8	1915	1489	28.61
7B C13c	9.9 - 10.1	1757	1319	33.21
7B C14a	10.1 - 10.3	1705	1188	30.13
7B C15a	10.8 - 11.1	2003	1623	23.42
7B C16a	11.6 - 11.9	2076	1749	18.71
7B C17a	12.3 - 12.6	2095	1768	14.47
7B C18b	13.3 - 13.6	1897	1576	20.37
7B C19a	13.9 - 14.2	1947	1632	19.26
7B C20a	14.5 - 14.8	2019	1681	20.10

Table 5 Volumes of Solids, Water, Ice and Air for Borehole 7B

Specimen	Depth (m)	Percentage Composition		
		Solids	Air	Ice + Water
7B C1	0.8 - 1.2	48.00	11.06	41.00
7B C2	1.2 - 1.7	43.70	10.01	46.29
7B C3a	1.7 - 2.1	54.82	4.90	49.11
7B C4a	2.4 - 2.8	63.17	-	38.48
7B C5a	3.2 - 3.6	60.35	0.85	38.80
7B C6a	4.5 - 4.7	59.13	2.30	38.57
7B C7a	4.7 - 5.0	62.65	3.36	34.39
7B C8b	5.8 - 6.1	59.54	1.71	38.75
7B C9a	6.3 - 6.5	65.47	1.55	32.98
7B C10b	7.3 - 7.5	59.43	2.49	38.08
7B C11a	7.8 - 8.0	60.19	2.48	38.27
7B C12a	8.5 - 8.8	54.63	0.12	45.25
7B C13c	9.9 - 10.1	48.39	4.92	46.69
7B C14a	10.1 - 10.3	43.59	0.97	55.44
7B C15a	10.8 - 11.1	59.55	0.33	40.12
7B C16a	11.6 - 11.9	64.17	1.57	34.26
7B C17a	12.3 - 12.6	64.88	0.95	34.17
7B C18b	13.3 - 13.6	57.82	7.89	34.29
7B C19a	13.9 - 14.2	59.91	6.54	33.55
7B C20a	14.5 - 14.8	61.68	2.23	36.09

Figure 3.1

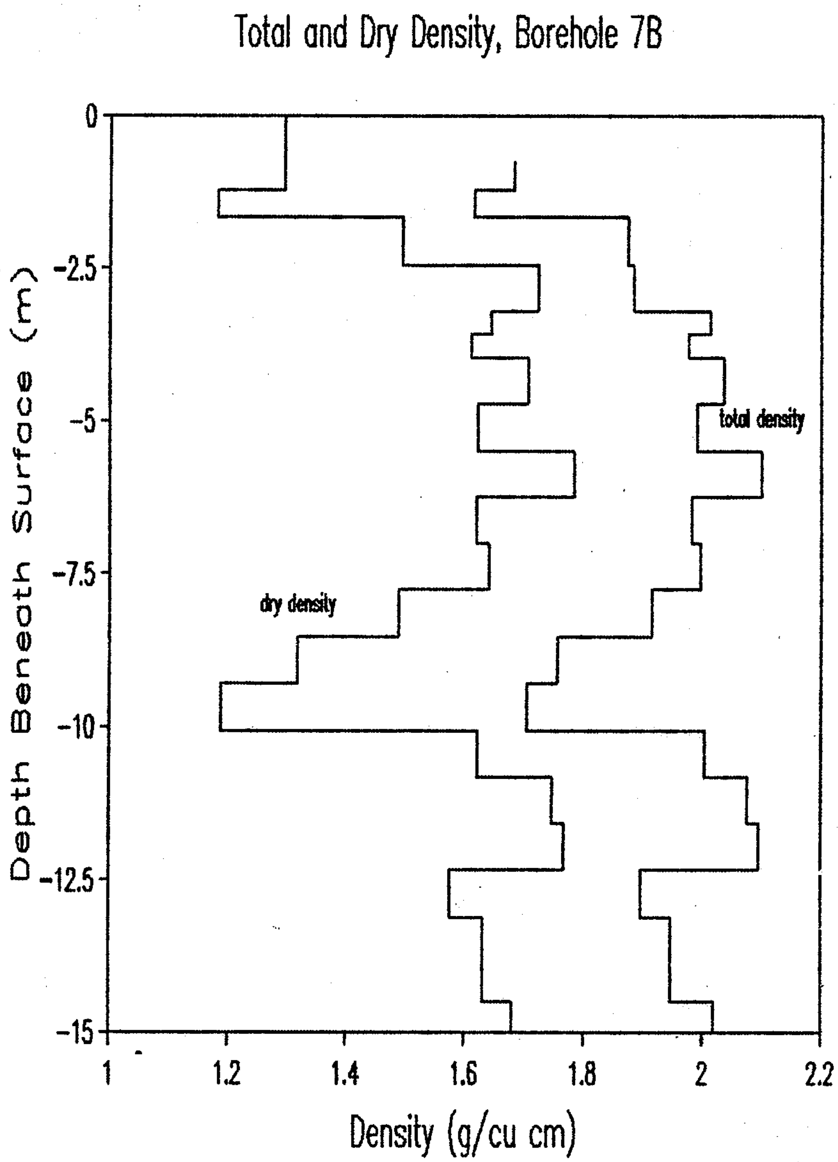
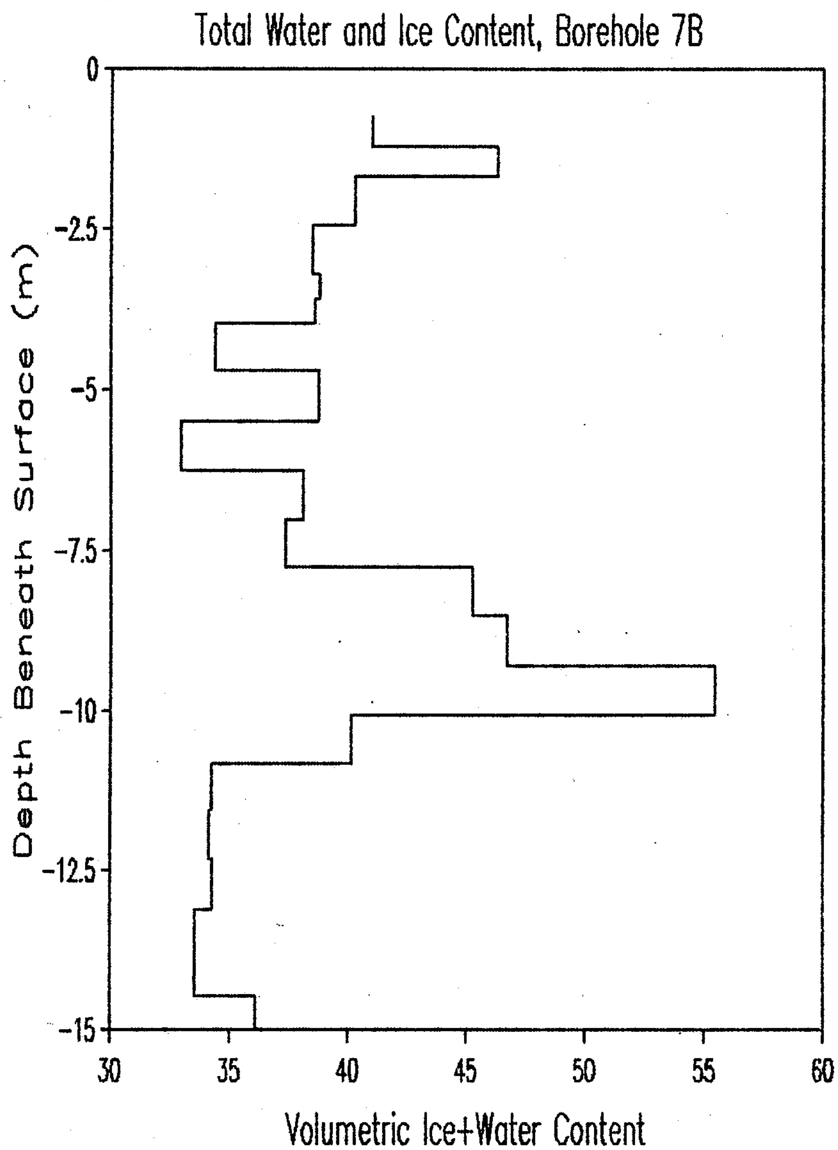

Total and Dry Density, Borehole 7B
0
-2.5
-5
-7.5
-10
-12.5
-15
1
1.2
1.4
1.6
1.8
2
2.2
Density (g/cu cm)
Depth Beneath Surface (m)
total density
dry density

Figure 3.2



Total Water and Ice Content, Borehole 7B
0
-2.5
-5
-7.5
-10
-12.5
-15
Depth Beneath Surface (m)
30
35
40
45
50
55
60
Volumetric Ice+Water Content

Table 6 Thaw Strain for Borehole 7B

Sample	Depth (m)	Thaw Strain (%)
7B C1	0.8 - 1.2	9.4
7B C2	1.2 - 1.7	10.7
7B C3a	1.7 - 2.1	2.7
7B C4a	2.4 - 2.8	1.3
7B C5a	3.2 - 3.6	0.7
7B C6a - 11a	4.5 - 8.0	<1.0
7B C12a	8.5 - 8.8	4.7
7B C13c	9.9 - 10.1	7.9
7B C14a	10.1 - 10.3	18.5
7B C15a - 20a	10.8 - 14.8	<1.0

The near surface zone (C1 and C2) exhibited moderate thaw strain. Sample 7B C1 had no free water drainage while 7B C2 yielded about 0.83 cm excess water even though the sample was not completely saturated (see Table 5). The only other sample to yield excess water was 7B C14a, the amount being about 3.2 cm.

3.2.3 Grain-size Characteristics

The grain-size analysis for the < 2mm size fraction for borehole 7B is summarized in Table 7 and Figure 3.3. The material is generally clay rich and very plastic. There are three major groupings of material which can be differentiated on the amount of sand and clay. These groupings were used to select

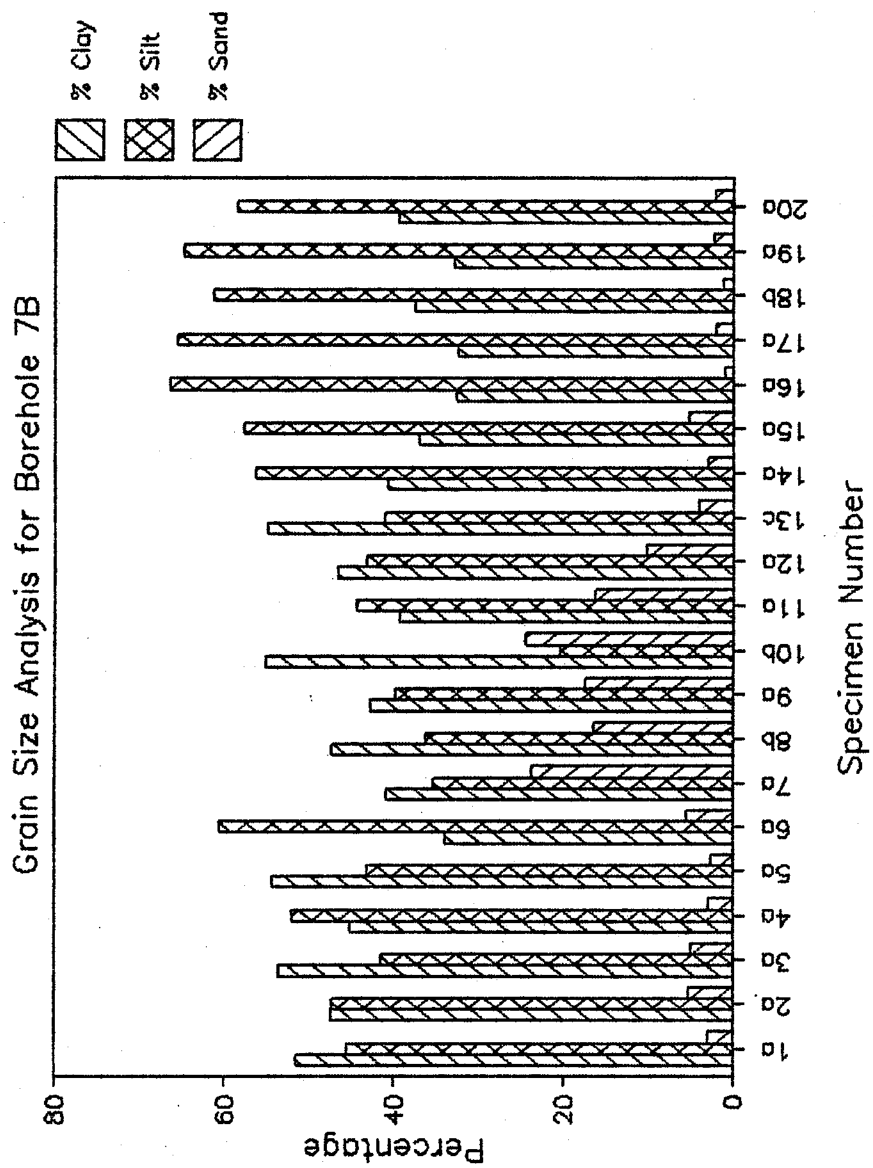
Table 7 Grainsize for Borehole 7B

	% Finer Than									
	size in mm									
No.	2	1	.5	.25	.1	.05	.02	.005	.002	.001
1a	100.0	99.6	99.2	98.9	98.3	97.0	91.4	65.3	51.5	41.9
2a	100.0	99.6	99.0	98.4	97.8	94.7	92.8	64.6	47.4	37.8
3a	100.0	99.6	99.3	98.9	98.4	95.0	95.8	69.4	53.5	43.0
4a	100.0	99.3	98.6	98.3	97.7	97.1	97.0	63.1	45.1	35.4
5a	100.0	99.6	99.2	98.9	98.5	97.4	96.8	65.7	54.3	39.2
6a	100.0	99.3	98.7	98.2	97.4	94.5	89.5	47.6	33.9	26.9
7a	100.0	96.4	93.2	90.7	85.9	76.2	74.4	55.6	40.9	32.9
8b	100.0	93.2	90.3	87.2	84.3	83.5	81.5	60.9	47.3	39.5
9a	100.0	94.8	92.2	89.7	85.7	82.5	76.9	56.9	42.7	33.9
10b	100.0	87.2	84.9	83.1	79.4	75.6	73.8	70.3	55.1	44.3
11a	100.0	93.5	91.4	89.6	86.4	83.7	75.9	53.1	39.3	31.6
12a	100.0	97.9	96.0	94.5	92.6	89.8	81.9	60.4	46.6	39.2
13c	100.0	99.3	98.7	98.1	96.9	96.0	92.1	72.9	54.9	45.0
14a	100.0	99.5	99.1	98.7	98.0	97.0	92.0	58.4	40.7	32.1
15a	100.0	99.1	98.2	97.5	96.0	94.8	86.1	52.7	37.0	28.9
16a	100.0	99.8	99.5	99.4	99.2	99.0	87.6	48.2	32.5	25.7
17a	100.0	99.4	99.0	98.8	98.3	98.0	88.6	48.9	32.4	25.2
18b	100.0	99.9	99.7	99.6	99.3	98.8	89.9	53.6	37.5	30.5
19a	100.0	99.7	99.3	99.1	98.3	97.7	84.5	47.8	32.9	26.3
20a	100.0	99.5	99.0	98.7	98.2	97.9	92.8	59.0	39.4	31.7

Table 7 continued

Sample	Depth	% Sand	% Silt	% Clay
1a	0.76-1.22	3.0	45.5	51.5
2a	1.22-1.68	5.3	47.3	47.4
3a	1.68-2.09	5.0	41.5	53.5
4a	2.44-2.82	2.9	52.0	45.1
5a	3.20-3.58	2.6	43.1	54.3
6a	4.50-4.72	5.5	60.6	33.9
7a	4.72-5.01	23.8	35.3	40.9
8b	5.77-6.07	16.5	36.2	47.3
9a	6.25-6.53	17.5	39.8	42.7
10b	7.31-7.53	24.4	20.5	55.1
11a	7.77-8.03	16.3	44.4	39.3
12a	8.53-8.81	10.2	43.2	46.6
13c	9.87-10.06	4.0	41.0	54.9
14a	10.06-10.32	3.0	56.3	40.7
15a	10.82-11.11	5.3	57.7	37.0
16a	11.58-11.83	1.0	66.5	32.5
17a	12.34-12.58	2.0	65.6	32.4
18b	13.3-13.6	1.2	61.3	37.5
19a	13.87-14.17	2.3	64.9	32.9
20a	14.48-14.75	2.1	58.5	39.4

Figure 3.3


Grain Size Analysis for Borehole 7B
% Clay
% Silt
% Sand
Percentage
0
20
40
60
80
1a
2a
3a
4a
5a
6a
7a
8b
9a
10b
11a
12a
13c
14a
15a
16a
17a
18b
19a
20a
Specimen Number

materials for thermal conductivity tests. The groupings are as follows:

Depth	Sample	% sand	% silt	% clay
0.0 - 3.6	7B C1a-C5a	3.8	45.9	50.3
4.7 - 8.0	7B C7a-C11a	19.7	35.2	45.1
10.8 - 14.8	7B C15a-C20a	2.3	62.4	35.3

Between each group, there is a grading of material to the next group. The observed differences most likely reflects changes in the depositional environment.

3.2.4 Conductivity and Salinity

The conductivity and salinity data obtained for site 7B are summarized in Figures 3.4 and 3.5. These data were obtained from 1:1 extracts of the pore water and serve to illustrate differences between samples. The figures show a higher concentration of pore water salts in the 3.0 to 7.5 m layer which almost corresponds with a boundary change in grain-size. The material in this zone is sandier than the layers above and below and perhaps the salinity/conductivity data reflect differences in mineral composition or solubility of the coarser fraction.

Figure 3.4

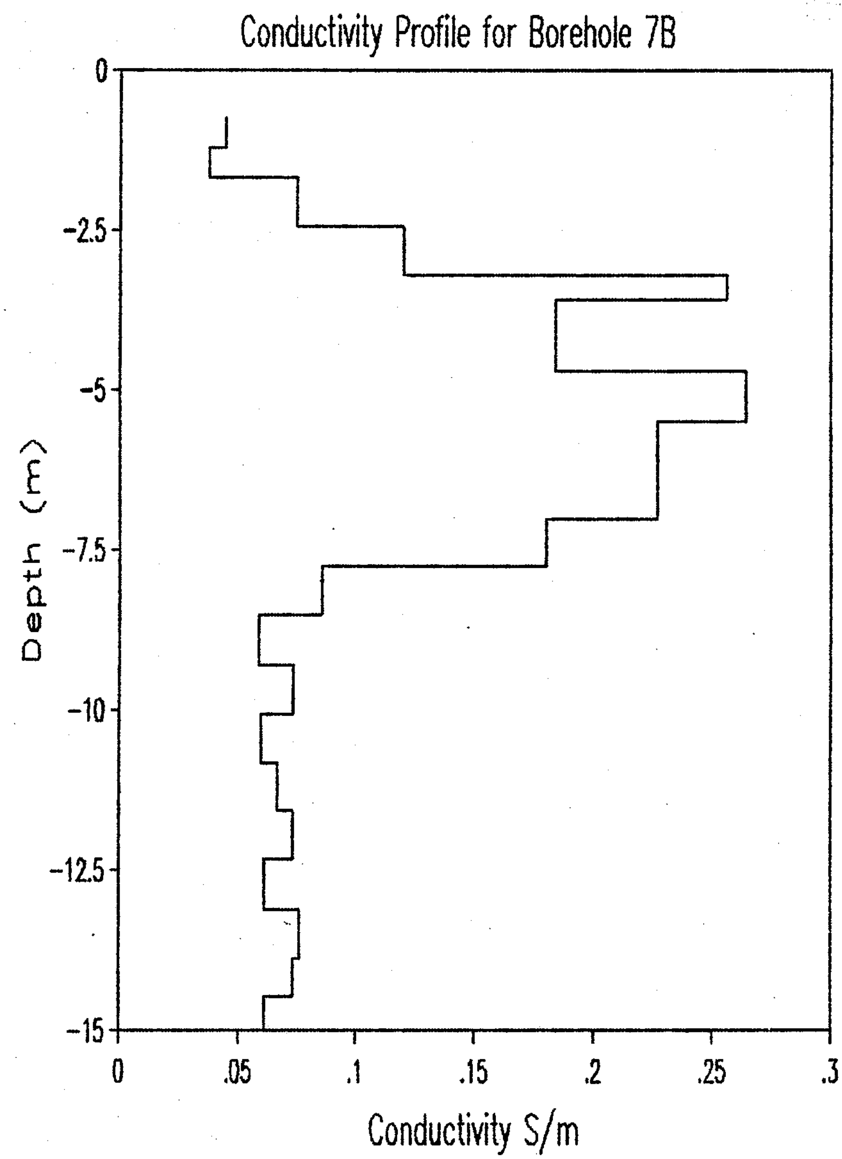
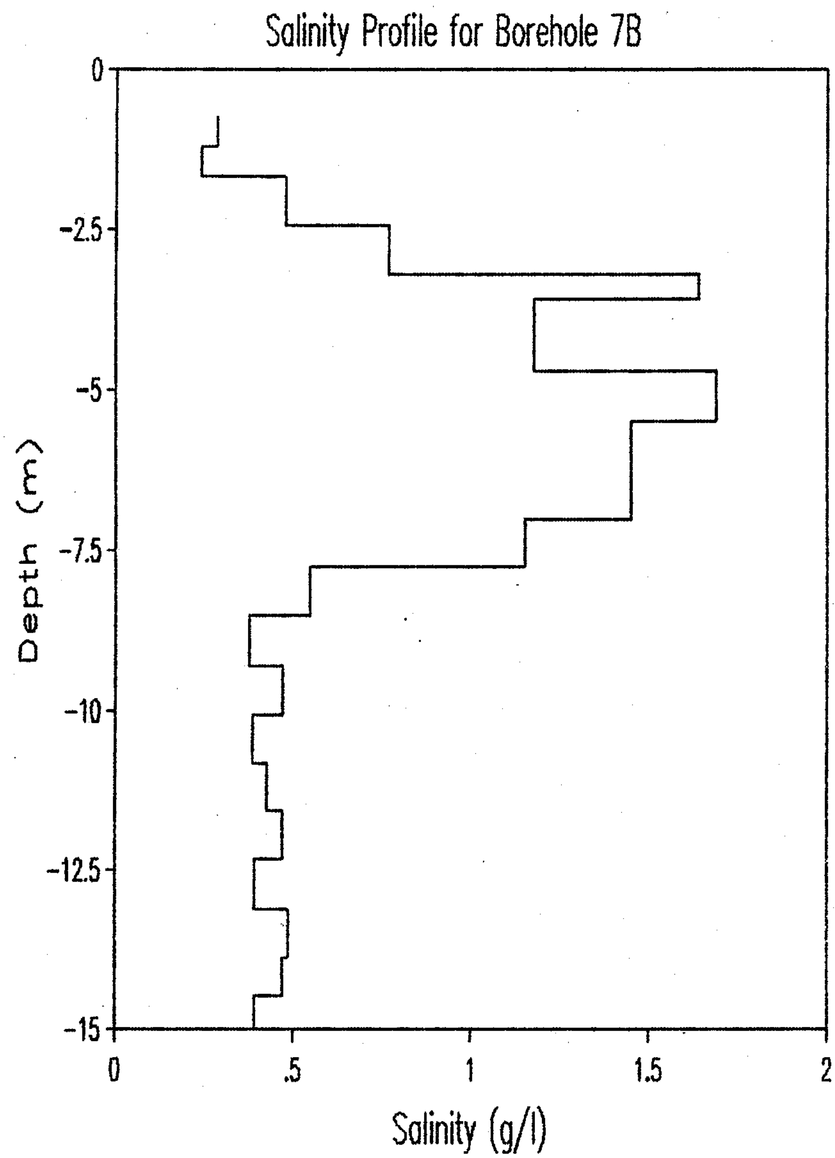

Conductivity Profile for Borehole 7B
0
-2.5
-5
-7.5
-10
-12.5
-15
Depth (m)
0
.05
.1
.15
.2
.25
.3
Conductivity S/m

Figure 3.5


Salinity Profile for Borehole 7B
0
-2.5
-5
-7.5
-10
-12.5
-15
Depth (m)
0
.5
1
1.5
2
Salinity (g/l)

3.3 Physical Properties, Borehole 12B

3.3.1 Density and Water Content

Density and water content data for borehole 12B are summarized in Tables 8 and 9 and Figures 3.6 and 3.7. Since the top 2.9 m or so is peat, the densities are quite low and the water/ice content quite high. The transition between the peat and mineral soil also has a high water content and ice was quite visible forming large lenses throughout.

3.3.2 Thaw Strain

The samples from this borehole exhibited substantial thaw strain. Table 10 summarizes the findings. The consolidation tests for samples in the peat layer were done without the nominal load and could be considered minimum values. It was quite easy to consolidate them further by applying a small amount of hand pressure.

The high ice/water content of the remaining samples is also reflected in their consolidation. It is expected that settlement would be quite substantial if this material were allowed to thaw, however, the amount of consolidation would depend on the drainage characteristics at the site.

3.3.3 Grain-Size Characteristics

The mineral samples of this borehole were quite silt-rich, ranging from about 50-75%. The data are summarized in Table 11 and Figure 3.8. Differences in the proportions of sand and silt

Table 8 Results of the Physical Properties Tests for Borehole 12B

Specimen	Depth (m)	Density ($Mg\ m^{-3}$) frozen	dry	Total Water Content ($kg\ kg^{-1}$, %)
12B C1a	0.0 - 0.6	-	-	278.26
12B C1c	0.0 - 0.6	731	113	549.23
12B C2a	0.6 - 1.2	910	101	797.24
12B C3b	1.2 - 1.7	866	90	862.67
12B C4a	1.7 - 2.1	775	62	1155.90
12B C4c	2.1 - 2.3	869	43	1932.69
12B C5a	2.3 - 2.9	834	56	1386.39
12B C6a	2.9 - 3.2	1265	648	64.77
12B C7A	3.2 - 3.8	1498	1035	44.76
12B C8a	3.8 - 4.7	1662	1156	43.72
12B C9a	4.7 - 5.1	1597	1042	53.30
12B C9b	5.1 - 5.3	1745	1247	39.99
12B C9c	5.3 - 5.6	1738	1234	42.39
12B C10b	5.6 - 6.3	1621	1274	27.29

Table 9 Volumes of Solids, Water, Ice and Air for Borehole 12B

Specimen	Depth (m)	Percentage Composition		
		Solids	Air	Ice + Water
12B C1a	0.0 - 0.6	-	-	-
12B C1c	0.0 - 0.6	14.07	18.52	67.41
12B C2a	0.6 - 1.2	12.67	0.00	87.33
12B C3b	1.2 - 1.7	11.24	4.14	84.62
12B C4a	1.7 - 2.1	7.71	14.53	77.76
12B C4c	2.1 - 2.3	5.34	4.60	90.06
12B C5a	2.3 - 2.9	7.01	8.17	84.82
12B C6a	2.9 - 3.2	23.99	9.19	66.82
12B C7A	3.2 - 3.8	38.34	11.59	50.07
12B C8a	3.8 - 4.7	42.83	2.49	54.68
12B C9a	4.7 - 5.1	38.58	1.33	60.09
12B C9b	5.1 - 5.3	46.18	0.00	53.82
12B C9c	5.3 - 5.6	46.03	0.00	54.79
12B C10b	5.6 - 6.3	47.52	4.33	46.62

Figure 3.6

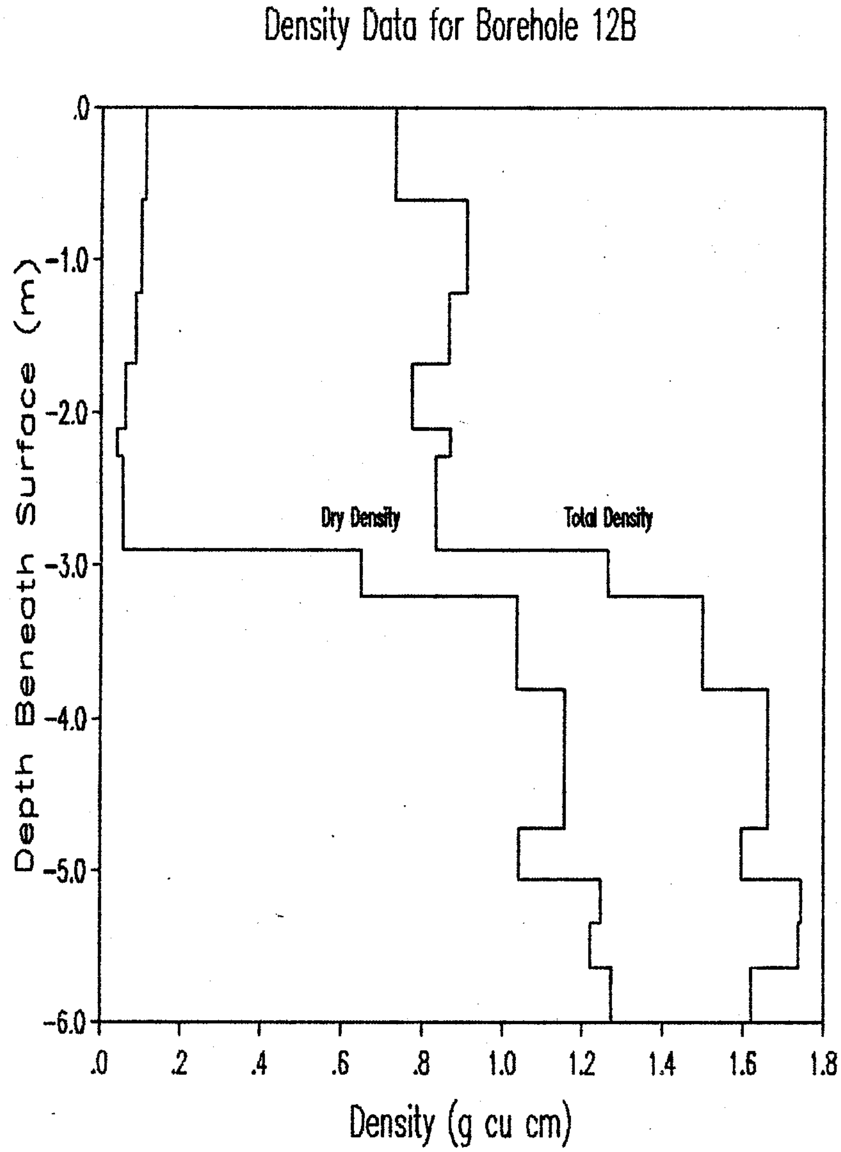
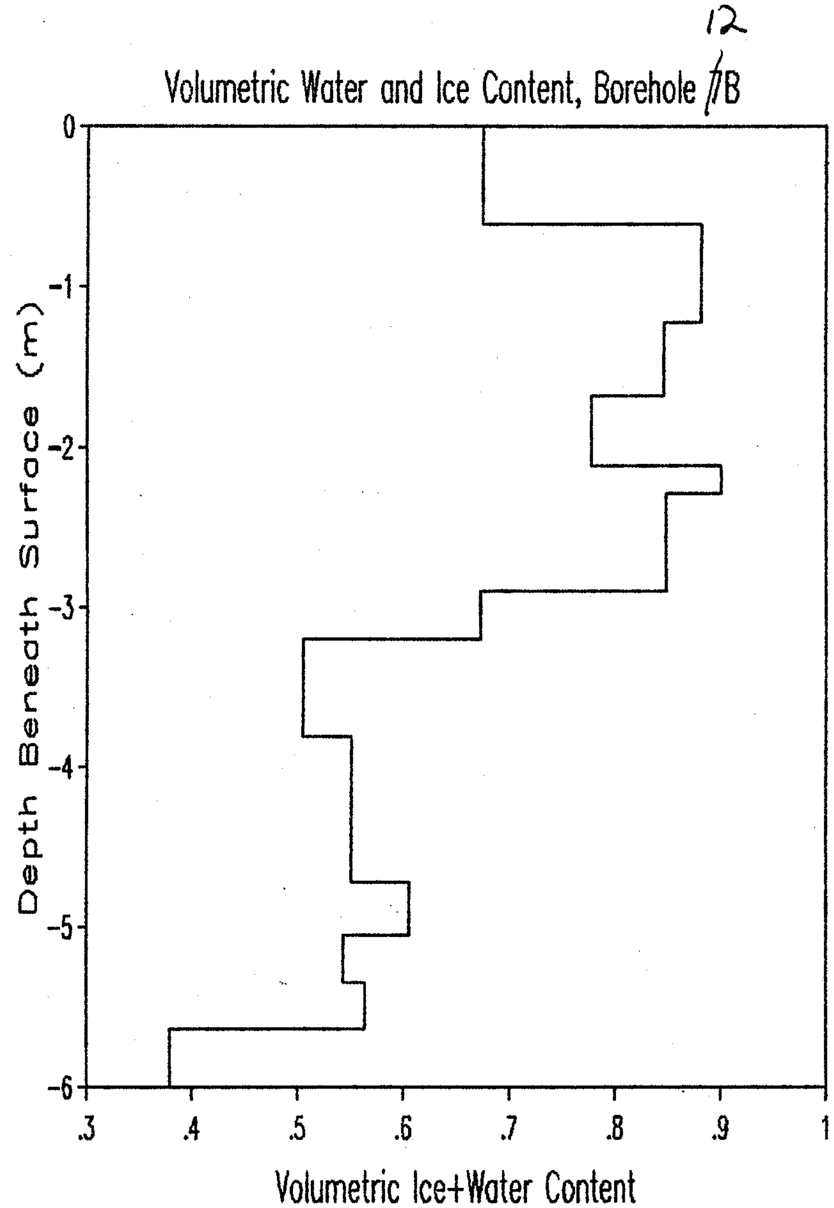

Density Data for Borehole 12B
Dry Density
Total Density
Depth Beneath Surface (m)
.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
.0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
Density (g cu cm)

Figure 3.7



Volumetric Water and Ice Content, Borehole 12B
0
-1
-2
-3
-4
-5
-6
Depth Beneath Surface (m)
.3
.4
.5
.6
.7
.8
.9
1
Volumetric Ice+Water Content

Table 10 Thaw Strain for Borehole 12B

Specimen	Depth (m)	Thaw Strain (%)
12B C1a	0.0 - 0.6	-
12B C1c	0.0 - 0.6	7.6
12B C2a	0.6 - 1.2	35.6
12B C3b	1.2 - 1.7	22.8
12B C4a	1.7 - 2.1	37.5
12B C4c	2.1 - 2.3	37.2
12B C5a	2.3 - 2.9	-
12B C6a	2.9 - 3.2	43.8
12B C7A	3.2 - 3.8	25.3
12B C8a	3.8 - 4.7	19.7
12B C9a	4.7 - 5.1	35.8
12B C9b	5.1 - 5.3	34.7
12B C9c	5.3 - 5.6	16.7
12B C10b	5.6 - 6.3	23.1

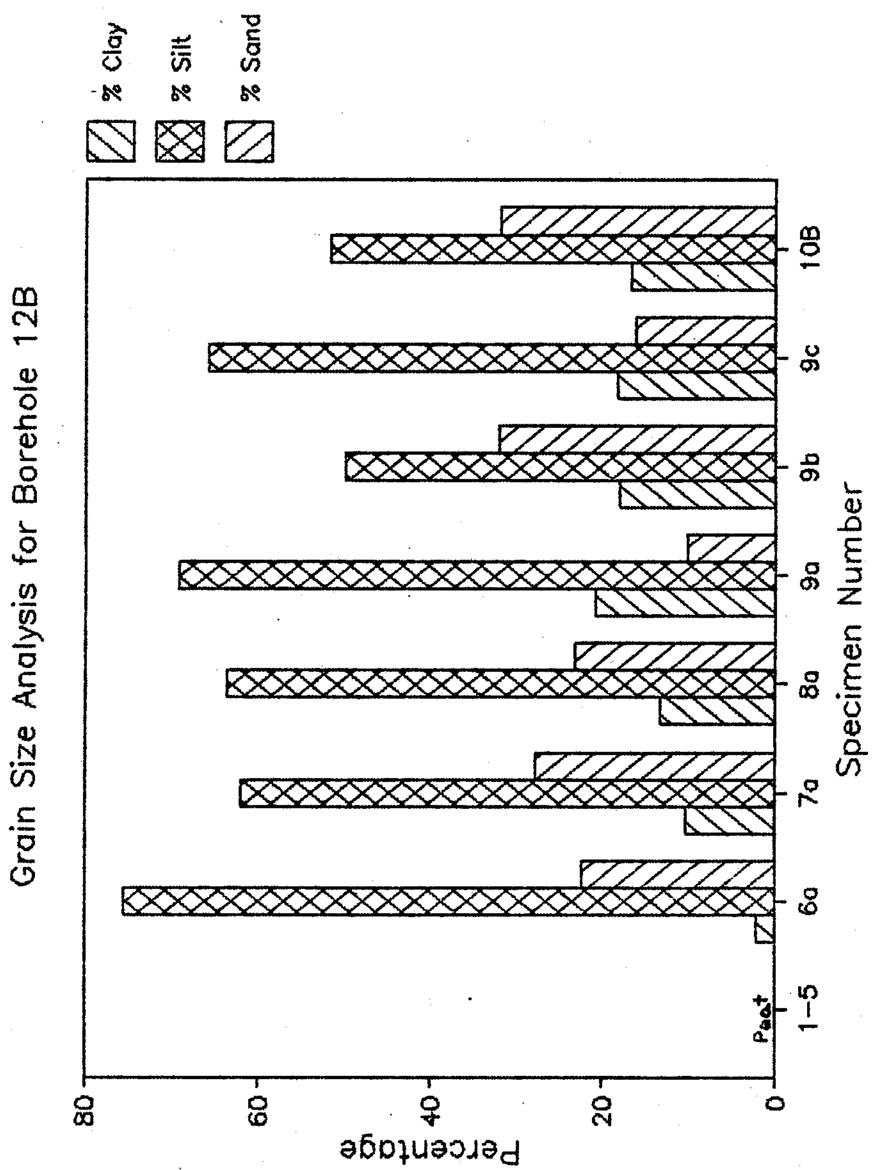
- indicates tests could not be performed

Table 11 Grainsize for Borehole 12B

No.	size in mm 2	1	.5	.25	% Finer Than .1	.05	.02	.005	.002	.001
1-5	peat									
6a	100.0	99.7	99.3	96.5	83.4	77.7	39.9	3.7	2.1	1.0
7a	100.0	98.7	98.1	92.3	81.2	72.3	35.7	15.2	10.3	7.9
8a	100.0	99.1	98.6	97.6	81.9	76.9	42.9	19.7	13.2	10.2
9a	100.0	99.2	98.6	98.1	93.3	89.9	72.8	34.7	20.8	15.1
9b	100.0	96.8	94.4	80.5	71.1	68.0	50.4	27.6	18.1	13.5
9c	100.0	99.3	98.1	96.7	90.7	83.9	67.7	31.9	18.2	13.0
10b	100.0	96.5	93.3	90.6	81.3	68.2	52.8	27.4	16.6	11.7

Sample	Depth	% Sand	% Silt	% Clay
1-5	0-2.90	0	0	0
6a	2.90-3.20	22.3	75.5	2.1
7a	3.20-3.81	27.7	62.0	10.3
8a	3.81-4.72	23.2	63.6	13.2
9a	4.72-5.06	10.1	69.1	20.8
9b	5.06-5.35	32.0	49.9	18.1
9c	5.35-5.64	16.1	65.7	18.2
10B	5.64-6.25	31.8	51.6	16.6

Figure 3.8



Grain Size Analysis for Borehole 12B
% Clay
% Silt
% Sand
Percentage
0
20
40
60
80
1–5
6a
7a
8a
9a
9b
9c
10B
Specimen Number

was evident, however, no consistent pattern was discernable.

3.3.4 Conductivity and Salinity

The conductivities for the mineral samples from this borehole were quite low falling in the range of 2.5 to 4.3 x 10^{-2} S m^{-1} (salinities, 0.13 - 0.23 g l^{-1}). This was expected since the material is silt rich.

3.4 Physical Properties, Borehole 8A

3.4.1 Density and Water Content

Density and water content data are summarized in Tables 12 and 13 and Figures 3.9 and 3.10. The top 5.6-6.0 m of the profile was fairly dense having a average water/ice content of about 40 cm^3 cm^{-3}, %. Below 6.0 m, the densities decreased and water/ice content increased. The variations correspond to changes in the grain-size characteristics as discussed in section 3.4.3.

3.4.2 Thaw Strain

The thaw strain observed the samples in this borehole are summarized in Table 14. The thaw strain in the top 3 m decreased from 14.3 % to 2.3 % and was negligible in the 3 to 6.9 m layer before increasing again.

3.4.3 Grain-size Characteristics

The grain-size characteristics for this site are summarized in Figure 3.11 and Table 15. The top 3.9 m was extremely sandy with the dominant grain-size being between 0.1-0.25 mm. A transition layer was found between 3.9 and 5.6 m and the material beneath was a silty clay with little sand. Significant ice was present at depths greater than 7.0 m. The field log indicates that the profile was unfrozen at depths greater than 9.1 m, hence, the iciness could reflect water movement upward to the silty clay layer.

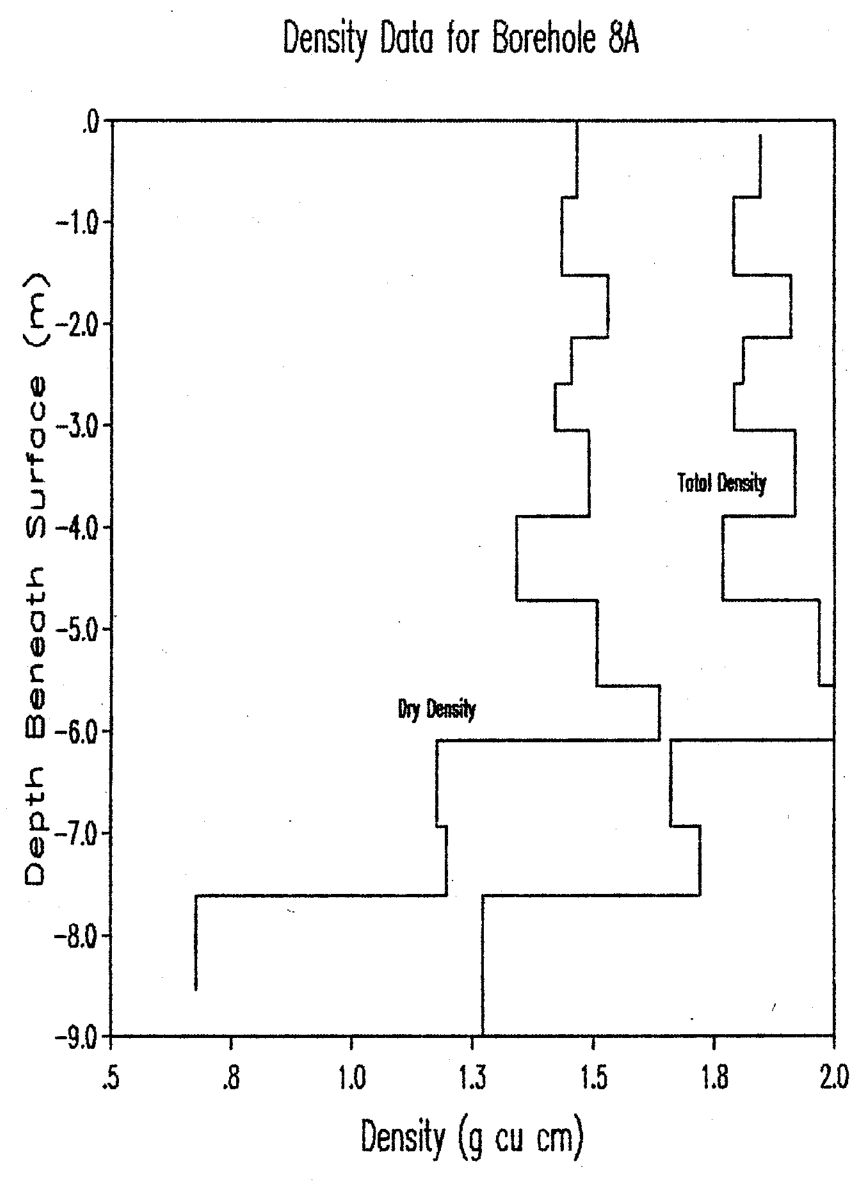
Table 12 Results of the Physical Properties Tests for Borehole 8A

Specimen	Depth (m)	Density ($Mg\ m^{-3}$) frozen	Density ($Mg\ m^{-3}$) dry	Total Water Content ($kg\ kg^{-1}$, %)
8A C1a	0.2 - 0.8	1726	1337	29.13
8A C2b	0.8 - 1.5	1846	1465	26.01
8A C3a	1.5 - 2.1	1792	1433	25.01
8A C4a	2.1 - 2.6	1910	1529	24.88
8A C5b	2.6 - 3.1	1812	1454	24.62
8A C6a	3.1 - 3.9	1793	1421	26.17
8A C7a	3.9 - 4.7	1919	1490	28.76
8A C8a	4.7 - 5.6	1767	1341	31.76
8A C9a	5.6 - 6.1	1969	1507	30.67
8A C10a	6.1 - 6.9	2021	1635	23.62
8A C11a	6.9 - 7.6	1660	1176	41.11
8A C12a	7.6 - 8.5	1721	1198	43.64

Table 13 Volumes of Solids, Water, Ice and Air for Borehole 8A

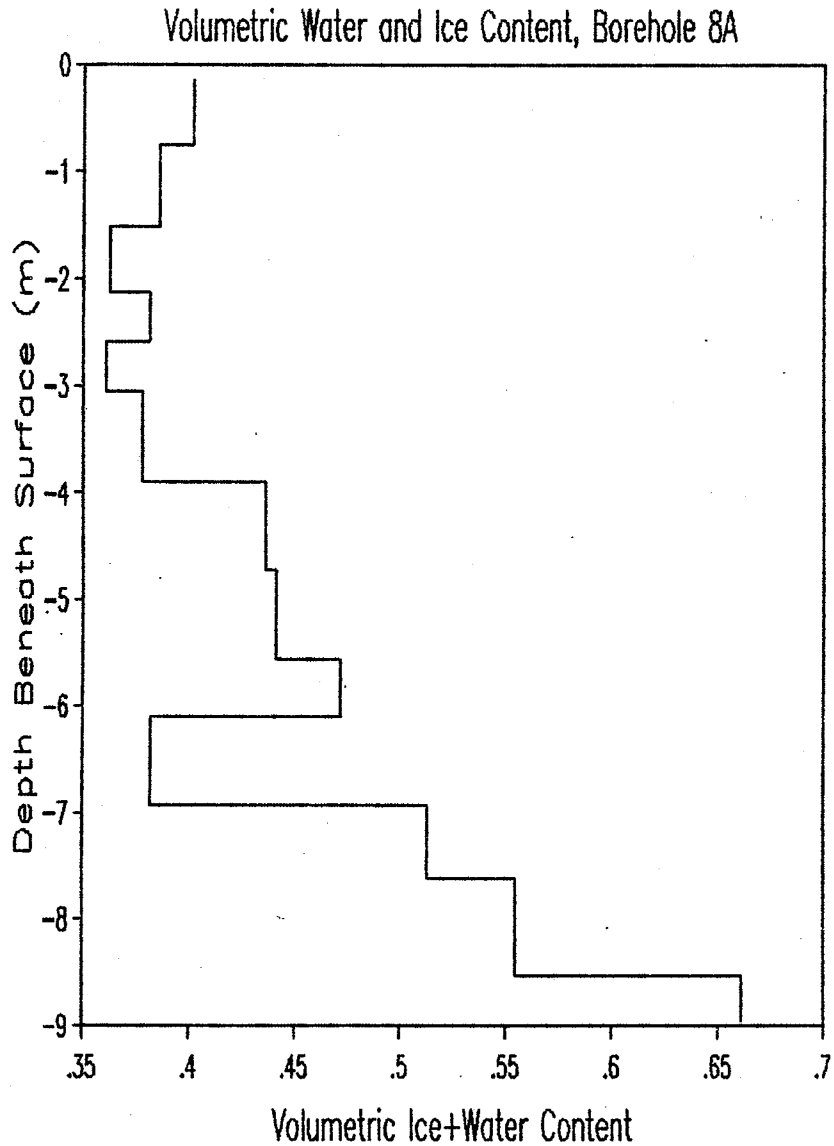
Specimen	Depth (m)	Percentage Composition		
		Solids	Air	Ice + Water
8A C1a	0.2 - 0.8	49.89	9.93	40.18
8A C2b	0.8 - 1.5	54.65	6.79	38.56
8A C3a	1.5 - 2.1	53.48	10.25	36.27
8A C4a	2.1 - 2.6	57.07	4.77	38.16
8A C5b	2.6 - 3.1	54.24	9.65	36.11
8A C6a	3.1 - 3.9	53.02	9.17	37.81
8A C7a	3.9 - 4.7	55.60	0.79	43.61
8A C8a	4.7 - 5.6	50.03	5.84	44.13
8A C9a	5.6 - 6.1	52.83	0.00	47.17
8A C10a	6.1 - 6.9	61.01	0.79	38.20
8A C11a	6.9 - 7.6	43.90	4.78	51.32
8A C12a	7.6 - 8.5	44.70	0.00	55.47

Figure 3.9



Density Data for Borehole 8A
Total Density
Dry Density
.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
-9.0
Depth Beneath Surface (m)
.5
.8
1.0
1.3
1.5
1.8
2.0
Density (g cu cm)

Figure 3.10



Volumetric Water and Ice Content, Borehole 8A
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
Depth Beneath Surface (m)
.35
.4
.45
.5
.55
.6
.65
.7
Volumetric Ice+Water Content

Table 14 Thaw Strain for Borehole 8A

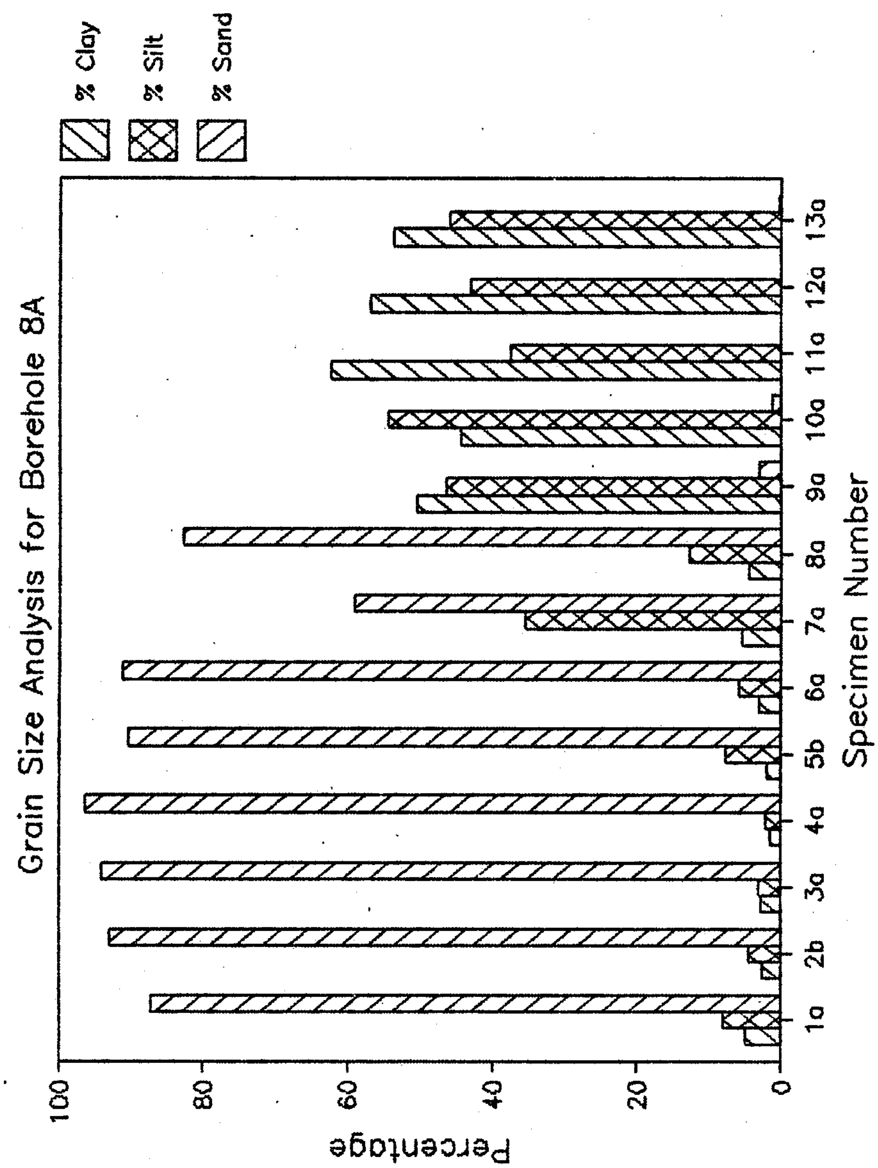
Specimen	Depth (m)	Thaw Strain (%)
8A C1a	0.2 - 0.8	14.3
8A C2b	0.8 - 1.5	10.2
8A C3a	1.5 - 2.1	6.0
8A C4a	2.1 - 2.6	5.7
8A C5b	2.6 - 3.1	2.3
8A C6a	3.1 - 3.9	0.0
8A C7a	3.9 - 4.7	1.7
8A C8a	4.7 - 5.6	0.0
8A C9a	5.6 - 6.1	0.0
8A C10a	6.1 - 6.9	0.0
8A C11a	6.9 - 7.6	7.0
8A C12a	7.6 - 8.5	10.0

Table 15 Grainsize for Borehole 8A

No.	Size in mm 2.0	1	.5	.25	.1	.05	.02	.005	.002	.001
	% Finer Than									
1a	100.0	100.0	100.0	87.1	27.1	12.9	9.0	6.4	4.9	4.2
2b	100.0	100.0	99.3	85.4	12.9	6.9	5.3	3.8	2.5	2.1
3a	100.0	100.0	99.5	87.7	15.7	5.9	4.9	3.7	2.8	2.3
4a	100.0	100.0	100	82.5	9.9	3.6	3.1	2.4	1.5	1.3
5b	100.0	100.0	100	92.1	15.6	9.6	3.3	2.9	1.9	1.8
6a	100.0	100.0	99.0	87.3	19.2	8.8	6.4	4.3	3.0	2.5
7a	100.0	99.9	99.8	99.5	57.2	41.0	14.2	8.9	5.4	4.0
8a	100.0	100.0	99.6	98.4	32.3	17.2	11.9	7.1	4.5	2.9
9a	100.0	100.0	99.9	99.9	99.1	97.1	94.5	72.7	50.6	36.0
10a	100.0	100.0	100.0	100.0	99.7	98.8	95.6	52.6	44.4	32.3
11a	100.0	100.0	100.0	100.0	100.0	99.9	98.6	83.0	62.4	45.8
12a	100.0	100.0	100.0	100.0	100.0	99.9	97.4	80.2	56.9	41.5
13a	100.0	99.9	99.9	99.9	99.8	99.7	99.7	77.3	53.8	38.7

Sample	Depth	% Sand	% Silt	% Clay
1a	0.15-0.76	87.2	7.9	4.9
2b	0.76-1.52	93.0	4.5	2.5
3a	1.52-2.13	94.1	3.1	2.8
4a	2.13-2.59	96.4	2.0	1.5
5b	2.59-3.05	90.4	7.7	1.9
6a	3.05-3.89	91.2	5.8	2.9
7a	3.89-4.72	59.0	35.5	5.4
8a	4.72-5.56	82.8	12.7	4.5
9a	5.56-6.10	2.9	46.5	50.6
10a	6.10-6.93	1.2	54.4	44.4
11a	6.93-7.62	0.1	37.5	62.4
12a	7.62-8.53	0.1	43.1	56.9
13a	8.53-9.37	0.3	45.9	53.8

Figure 3.11


Grain Size Analysis for Borehole 8A
% Clay
% Silt
% Sand
Percentage
0
20
40
60
80
100
Specimen Number
1a
2b
3a
4a
5b
6a
7a
8a
9a
10a
11a
12a
13a

3.4.4 Conductivity and Salinity

The conductivity and salinity data for this site are summarized in Figures 3.12 and 3.13. In general, the values for both are quite low. The results for the top 3 m are a factor of 2 or 3 less than those for the remainder of the profile and no obvious explanation can be offered as to why.

Figure 3.12

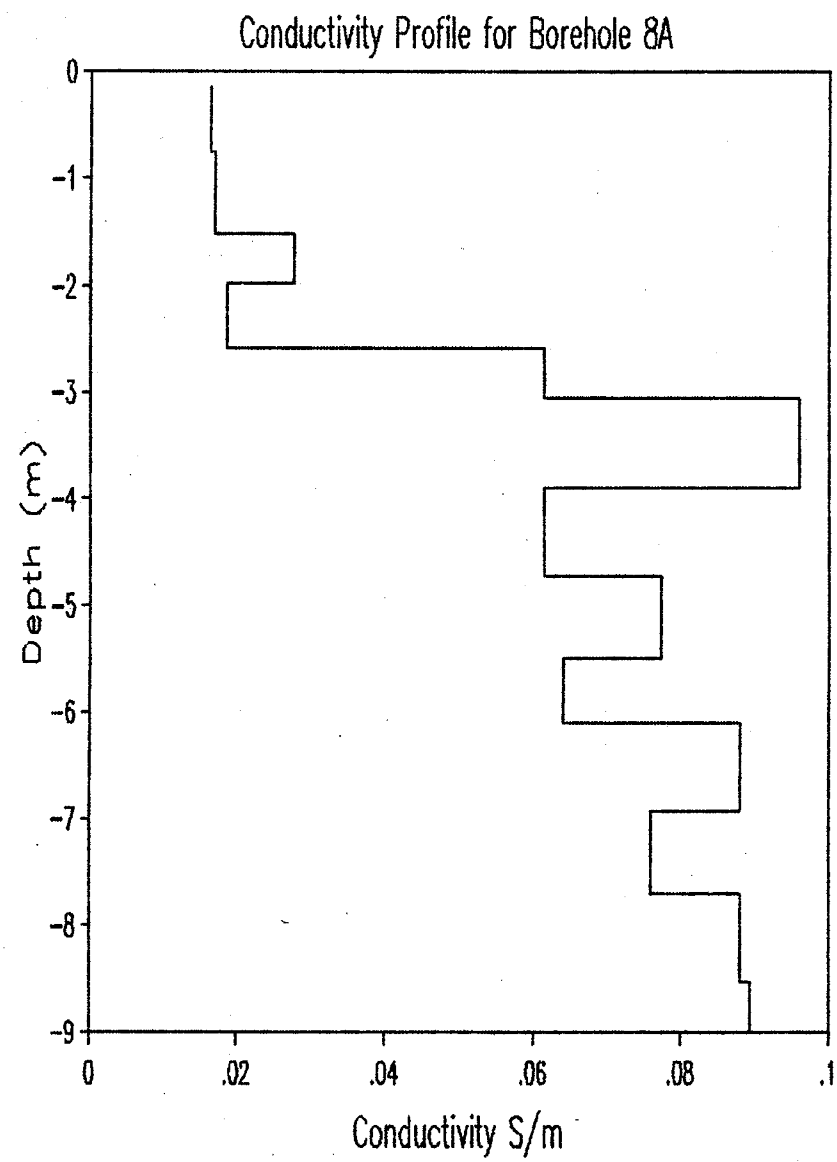
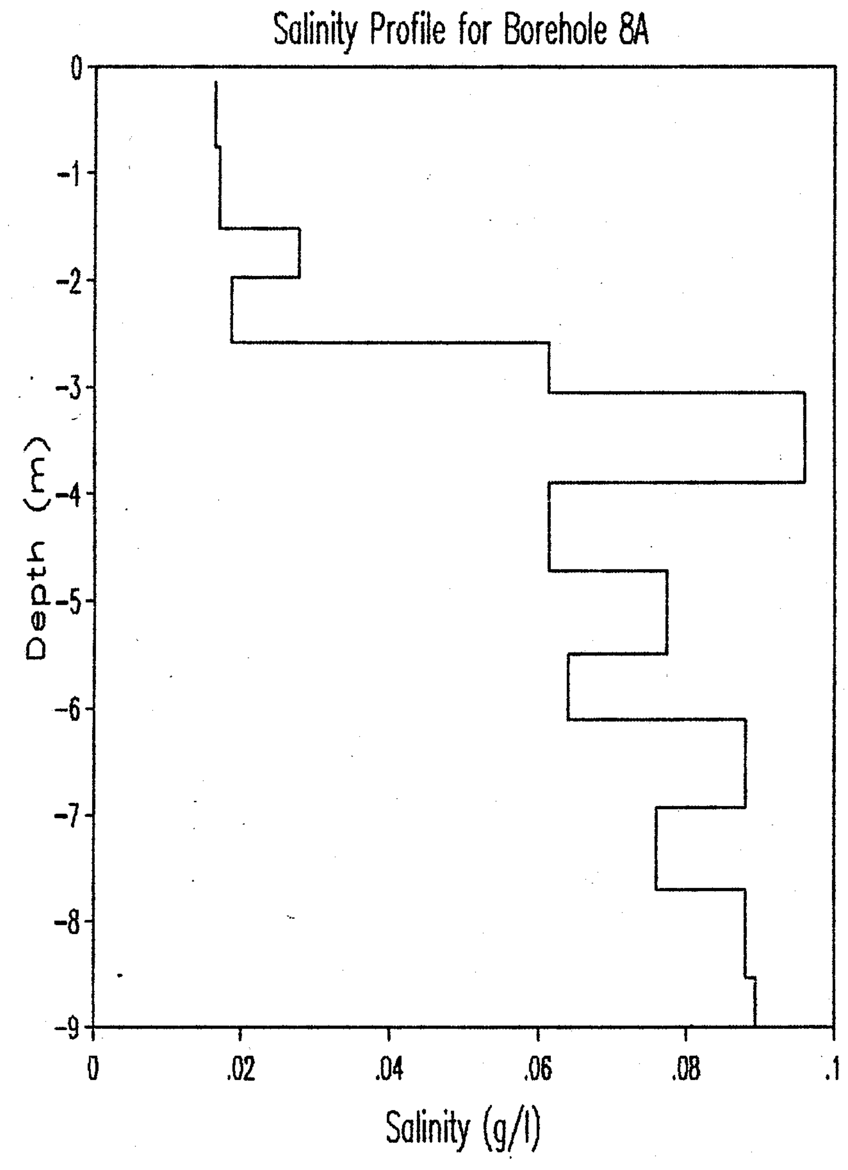

Conductivity Profile for Borehole 8A
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
Depth (m)
0
.02
.04
.06
.08
.1
Conductivity S/m

Figure 3.13



Salinity Profile for Borehole 8A
Depth (m)
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
0
.02
.04
.06
.08
.1
Salinity (g/l)

3.5 Selected Information for Borehole 3B

Selected physical properties for borehole 3B were determined for three samples. The materials are distinctly different in terms of their grain-size and physical composition. The density, water content and thaw strain information are summarized in Table 16 and the grain-size characteristics are summarized in Table 17.

Sample 3B C1 is a silty sand; sample 3B C2 is dominated by coarse sand of a wide mineral mix while 3B C3 is a clayey silt with most of the material in the fine silt class. The markedly differing grain-size characteristics for these materials would represent differing depositional environments (consult the original borehole log).

Table 16 Physical Properties of Borehole 3B

Specimen	Depth (m)	Density ($Mg\ m^{-3}$) frozen	Density ($Mg\ m^{-3}$) dry	Total Water Content ($kg\ kg^{-1}$, %)	Thaw Strain (%)
3B C1	1.15 - 1.50	1533	1075	42.57	28.6
3B C2	4.15 - 4.50	1939	1537	26.18	5.1
3B C3	7.70 - 8.20	1826	1455	24.50	1.2

Table 17 Grainsize for Borehole 3B

	% Finer Than									
No. / Size in mm	2.0	1	.5	.25	.1	.05	.02	.005	.002	.001
C1	100.0	99.8	99.2	75.5	60.8	60.3	42.8	21.8	14.8	13.8
C2	100.0	59.6	33.6	31.0	4.3	2.1				
C3	100.0	99.4	99.2	98.7	98.3	97.8	95.5	49.5	32.2	23.0

3.6 Phase Composition Information for Borehole Samples

The results of phase composition tests are summarized in Appendix I. Graphs showing the variation in dielectric constant, volumetric unfrozen water content and gravimetric unfrozen water content are provided along with tabular data.

3.7 Dielectric Properties of Woodchips

The dielectric properties of woodchips was determined since woodchips are used to insulate some of the slopes along the pipeline route and TDR probes are used to monitor the hydrologic state at the monitoring stations. The woodchips were provided by the Scientific Authority and were generally in the 0.5 to 3 cm size range (long axis). The chips appeared fresh with no greying characteristic of aged wood.

The variation in dielectric constant with water content in the unfrozen state was determined first so that phase composition information could be obtained during thermal conductivity tests. The results are shown in Figure 3.14 and are summarized in Appendix II.

3.8 Results from Thermal Conductivity Tests

The results from the thermal conductivity tests are summarized in Appendix III for the materials tested.

The mineral samples tested represented the three grain-size groups identified for site 7B as shown in Figure 3.15. The grain-size characteristics are identified as: 1a-5a, 7a-11a and

Figure 3.14

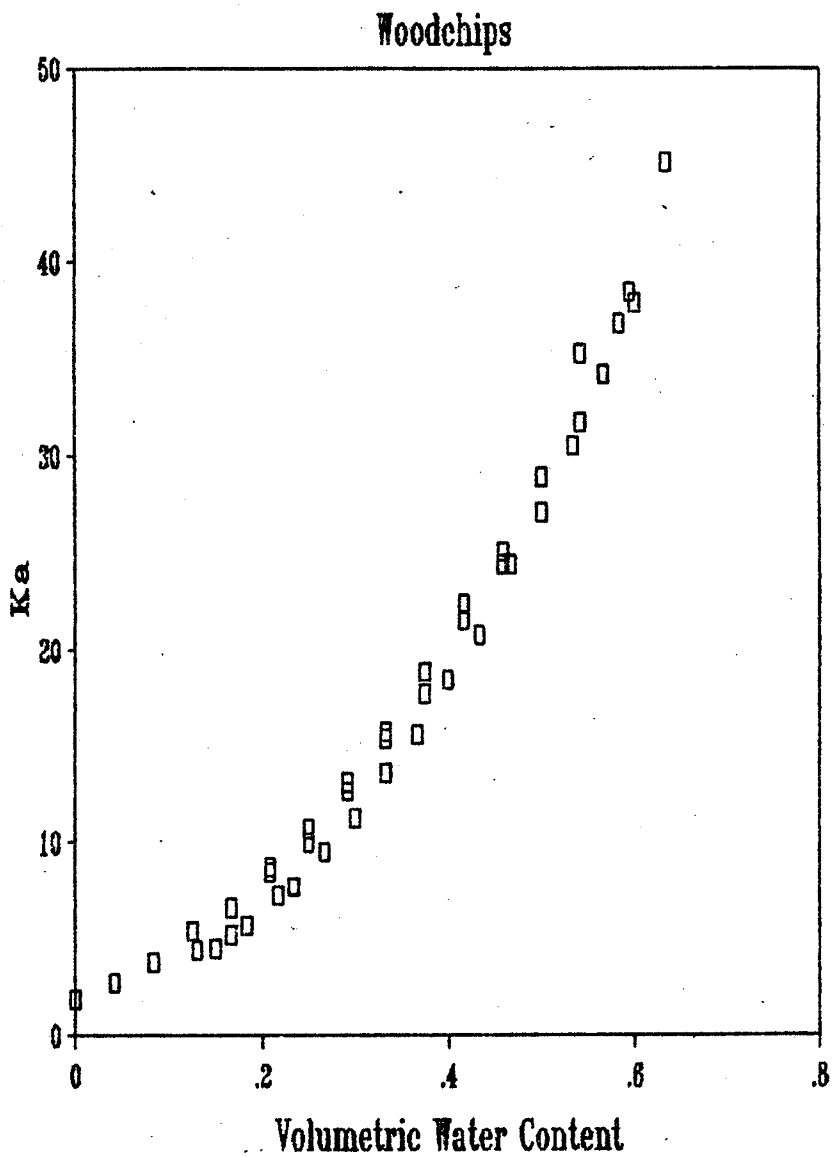
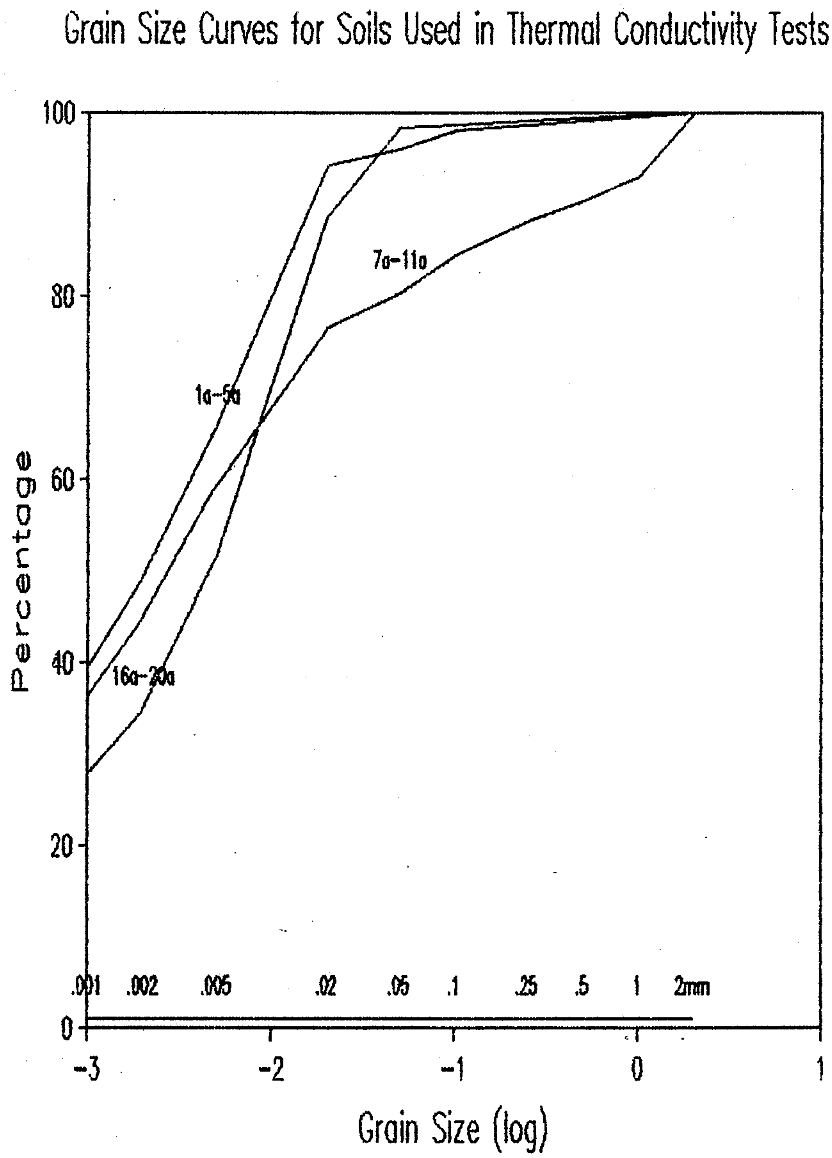


Figure 3.15



Grain Size Curves for Soils Used in Thermal Conductivity Tests
100
80
60
40
20
0
Percentage
7a-11a
1a-5a
16a-20a
.001
.002
.005
.02
.05
.1
.25
.5
1
2mm
-3
-2
-1
0
1
Grain Size (log)

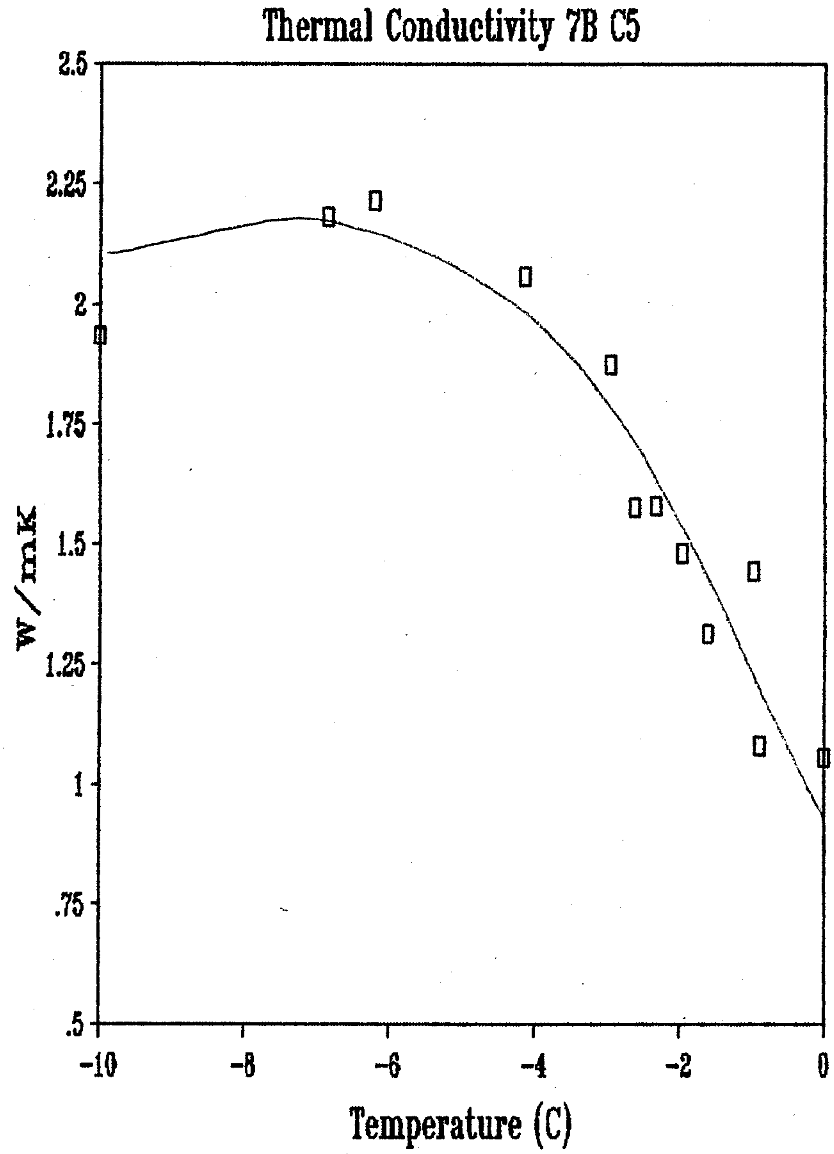
16a-20a. A saturated peat and a saturated woodchip sample were also tested.

The test rusults are summarized in Figures 3.16 to 3.19. The scatter in the curves generally reflects uncertainties in estimates of the apparent heat capacity. Obvious deviations are experimental in nature.

The test results at the coldest temperatures for 7B C5, 7B c8 and 7B C19 are generally a bit lower than those determined by Patterson et al. (1987). This may be attributed to differences in the methods of determining thermal conductivity but more likely reflects the fact that one set of tests was done on undisturbed samples while the other was carried out on remoulded samples.

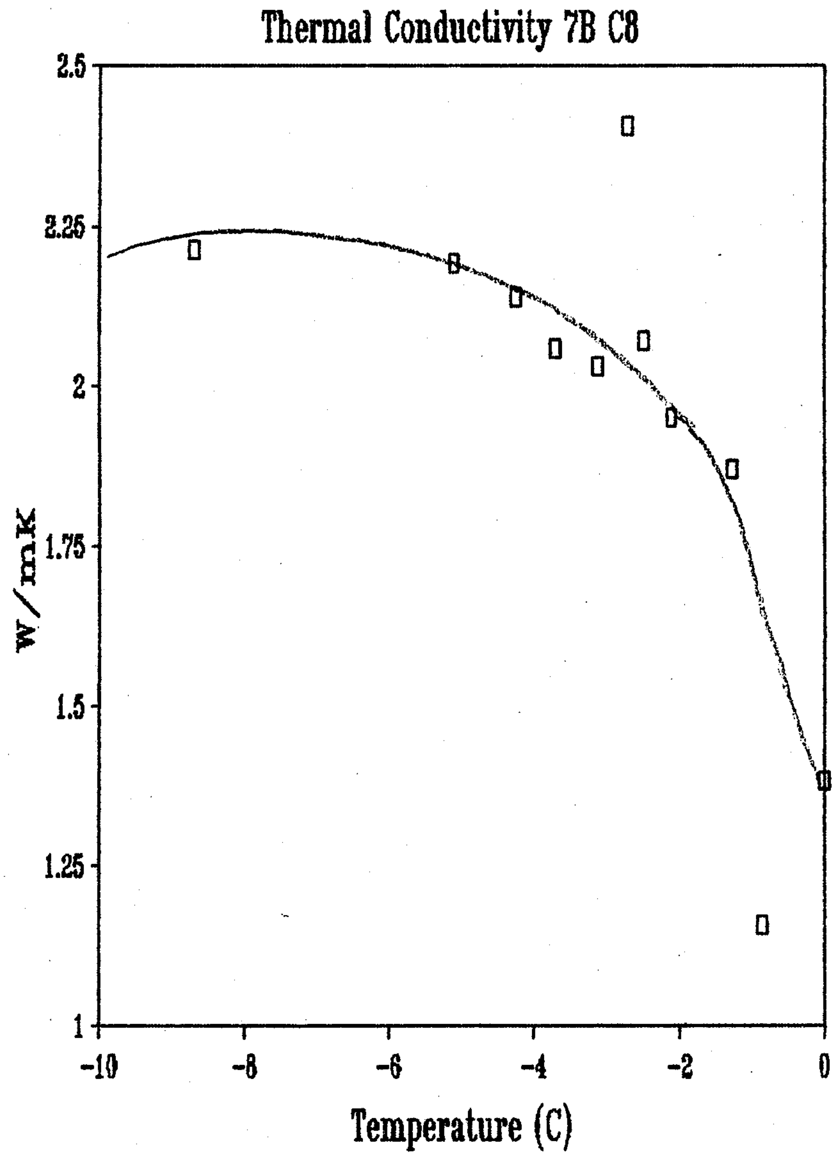
The thermal conductivity of the peat sample (Figure 3.19) indicates that some unfrozen water exists at sub-0°C temperatures. Since the dielectric constant-unfrozen water content relationship for peat has not been examined in much detail, the thermal conductivity values near 0°C could be different. The overall thermal conductivity values suggest that the sample was not completely saturated although every effort was made to ensure that it was.

Figure 3.16



Thermal Conductivity 7B C5
2.5
2.25
2
1.75
1.5
1.25
1
.75
.5
W/mK
-10
-8
-6
-4
-2
0
Temperature (C)

Figure 3.17



Thermal Conductivity 7B C8
2.5
2.25
2
1.75
1.5
1.25
1
W/mK
-10
-8
-6
-4
-2
0
Temperature (C)

Figure 3.18

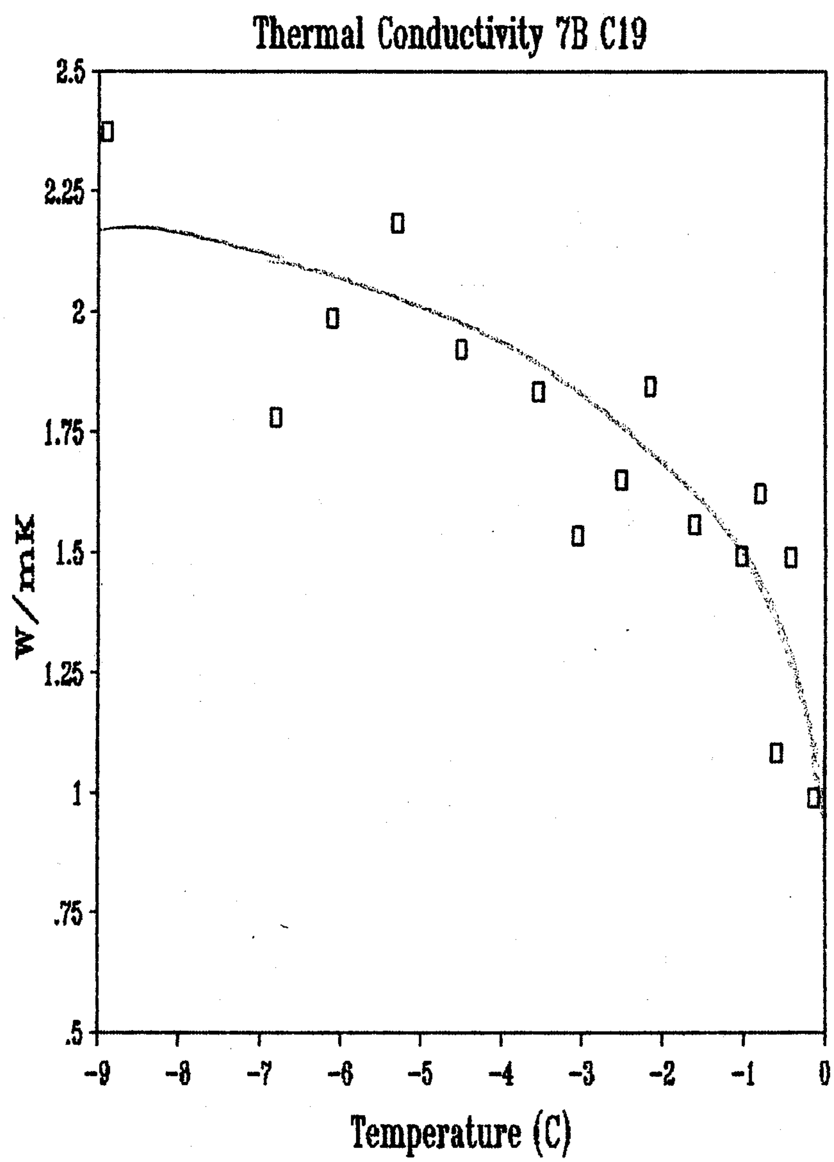
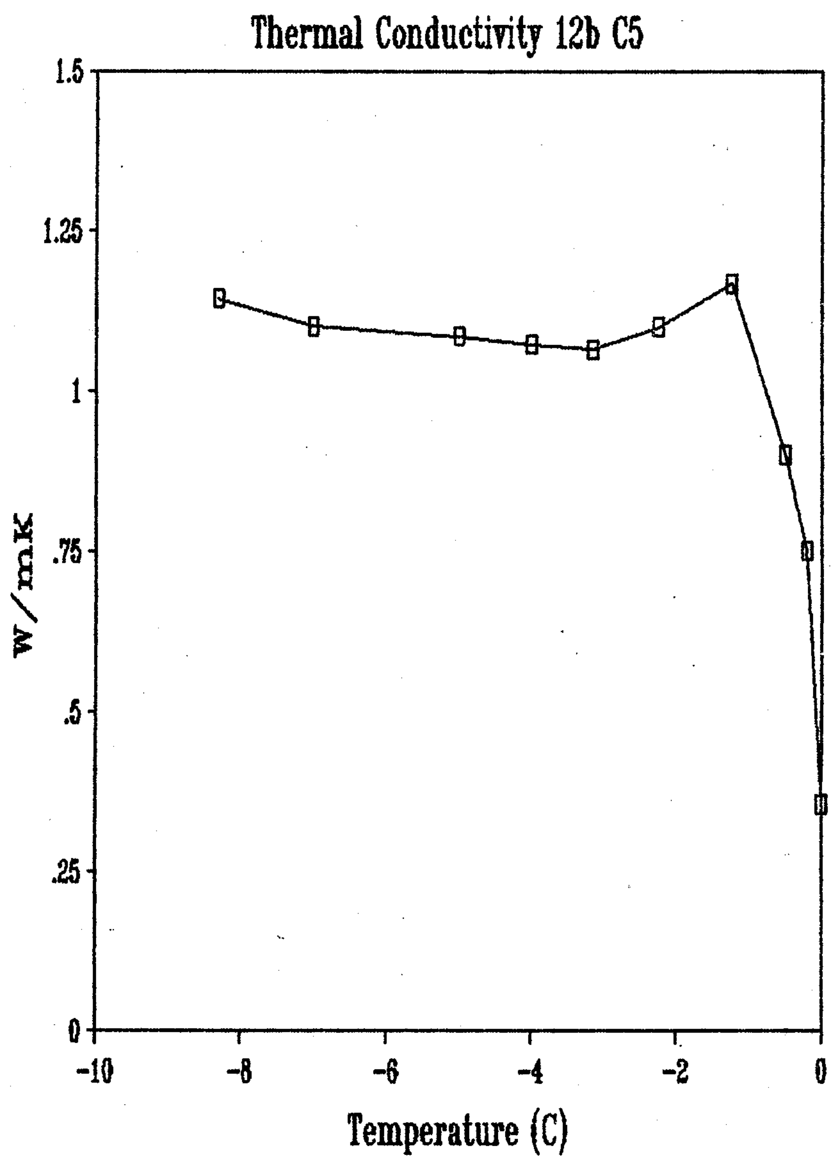

Thermal Conductivity 7B C19
W/mK
2.5
2.25
2
1.75
1.5
1.25
1
.75
.5
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
Temperature (C)

Figure 3.19


Thermal Conductivity 12b C5
1.5
1.25
1
.75
.5
.25
0
W/mK
-10
-8
-6
-4
-2
0
Temperature (C)

IV Summary

The summaries presented in the previous sections conclude the major portion of work undertaken. Presently, more studies are being carried out on a comparison of the methods of determining thermal conductivity. Also, a more detailed analysis of the peat and woodchip materials is being undertaken since they are surface materials at several of the pipeline sites and will therefore, greatly influence the ground thermal regime. Other findings will provided as separate Annexes to this report.

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Appendix I

Unfrozen Water Content Data for Selected Cores

These data were obtained using Time-domain Reflectometry (TDR). The following headings are used:

Temp. - temperature in °C

Ka - apparent dielectric constant

pb - dry bulk density in g cm^{-3}

pt - total density in g cm^{-3}

w - gravimetric unfrozen water content in g g^{-1}

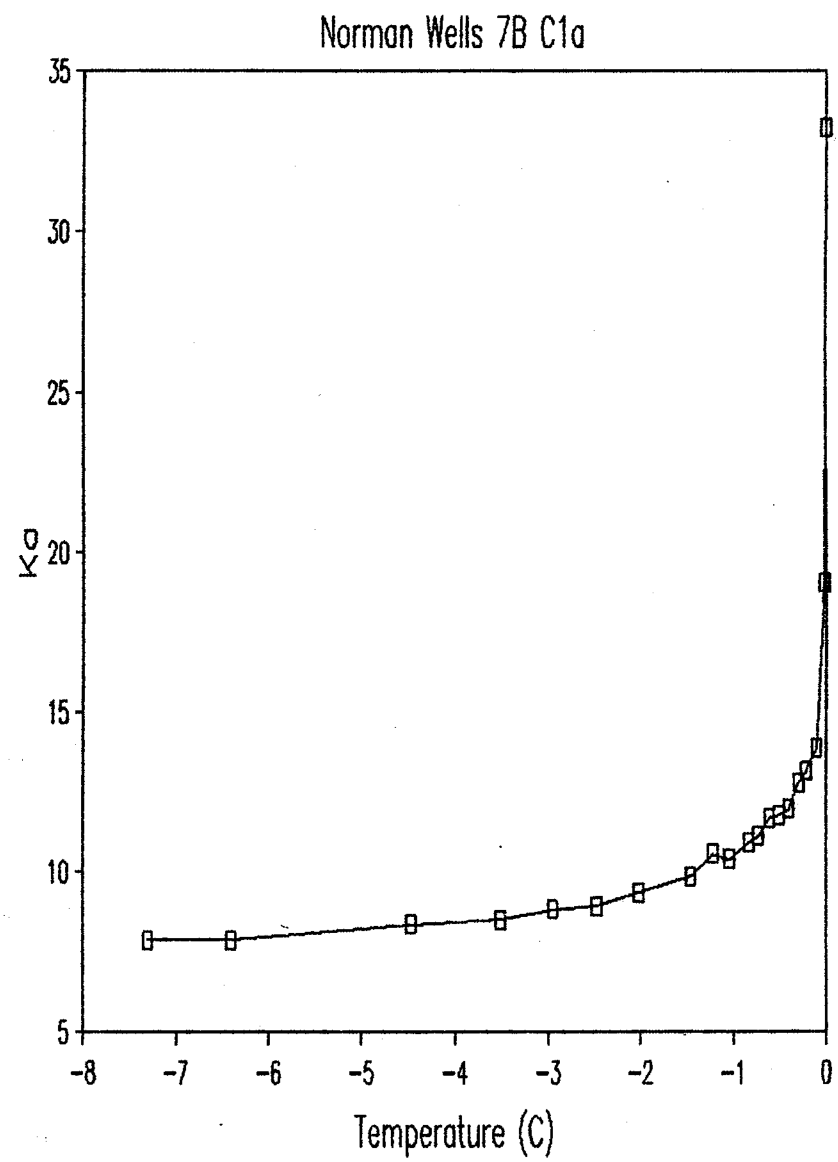
θ - volumetric unfrozen water content in cm^3 cm^{-3}

The values for density and water content given at the start of the list are for the unfrozen state determined at the conclusion of the tests.

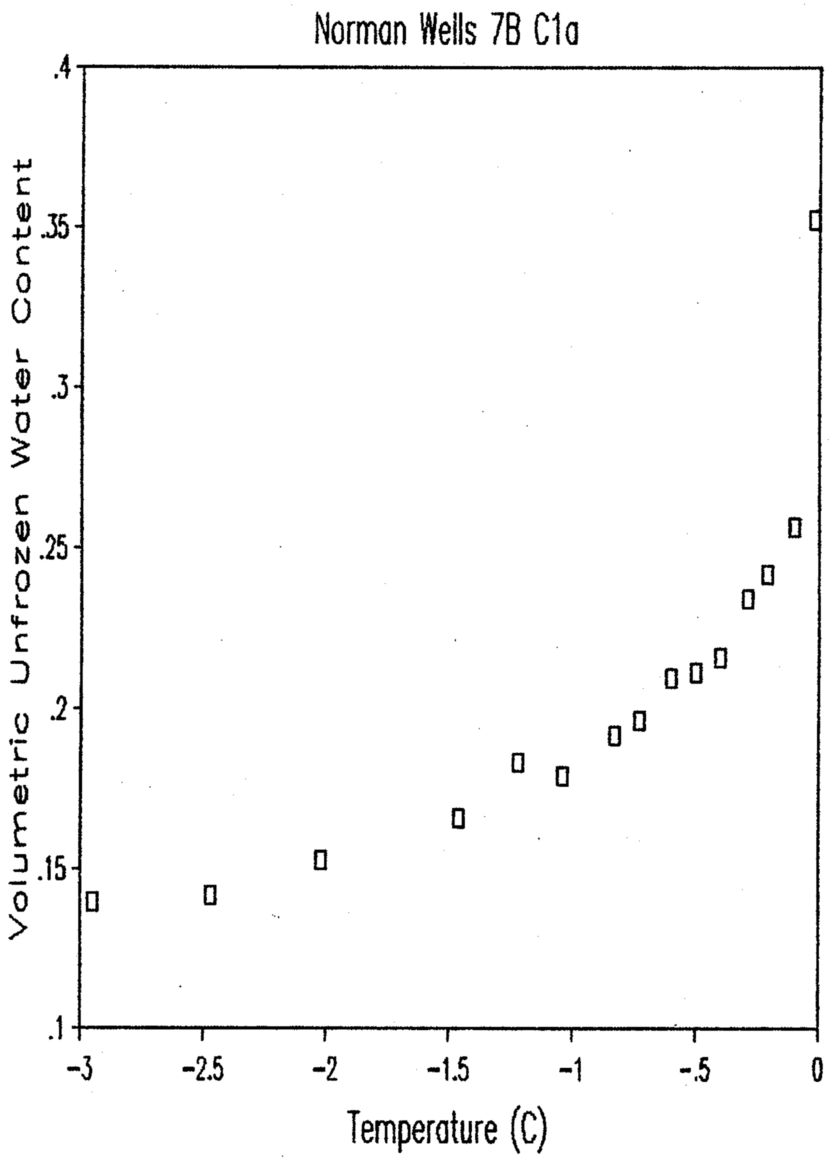
Norman Wells 7B Cla

pb = 1.3173
w = 0.3812
θ = 0.5021

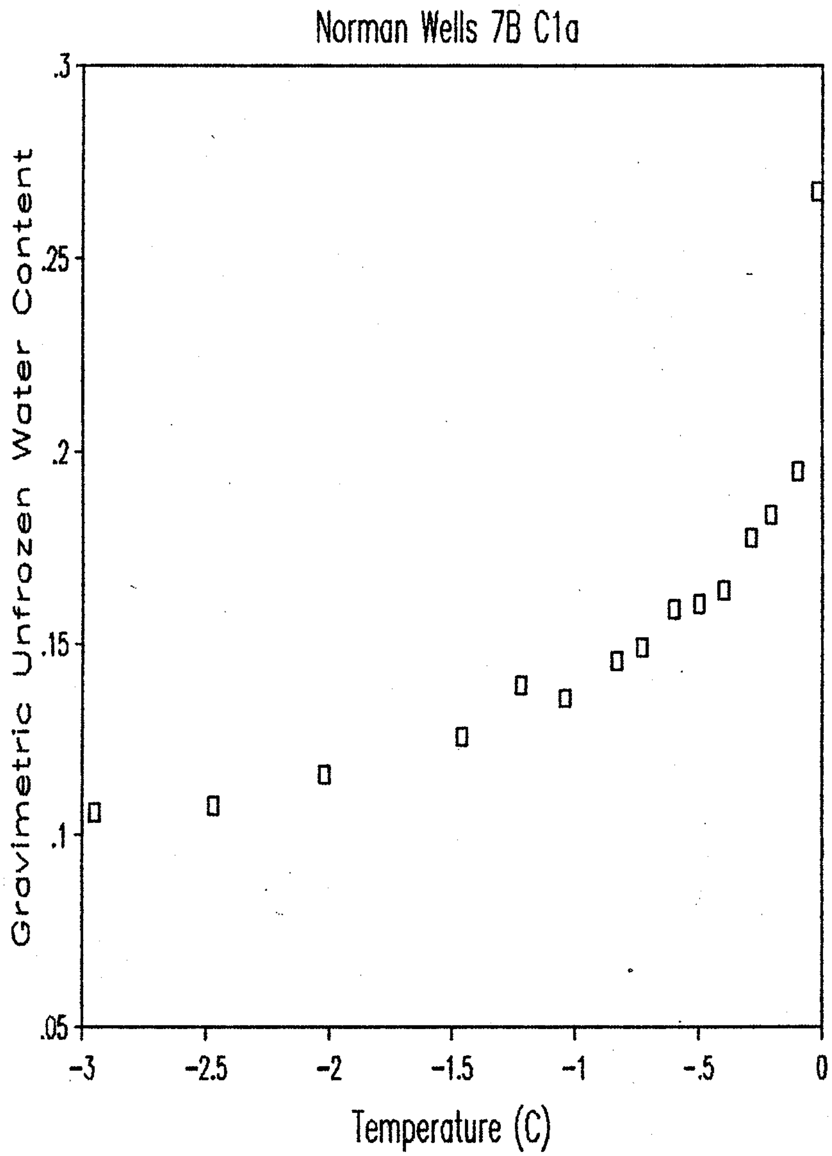
Temp.	Ka	θ	w
23.00	29.72	.5140	.3902
-7.30	7.87	.1135	.0862
-6.40	7.87	.1135	.0862
-4.47	8.35	.1267	.0961
-3.51	8.51	.1310	.0994
-2.95	8.83	.1395	.1059
-2.47	8.92	.1418	.1077
-2.02	9.34	.1528	.1160
-1.46	9.85	.1657	.1258
-1.22	10.56	.1832	.1390
-1.04	10.38	.1788	.1357
-.83	10.92	.1918	.1456
-.73	11.11	.1963	.1490
-.60	11.67	.2093	.1589
-.50	11.76	.2113	.1604
-.40	11.96	.2159	.1639
-.29	12.78	.2340	.1776
-.21	13.14	.2417	.1835
-.10	13.85	.2566	.1948
-.02	19.02	.3520	.2672
.00	33.22	.5690	.4319



Norman Wells 7B C1a
35
30
25
20
15
10
5
Ka
-8
-7
-6
-5
-4
-3
-2
-1
0
Temperature (C)



Norman Wells 7B C1a
Volumetric Unfrozen Water Content
.4
.35
.3
.25
.2
.15
.1
-3
-2.5
-2
-1.5
-1
-.5
0
Temperature (C)

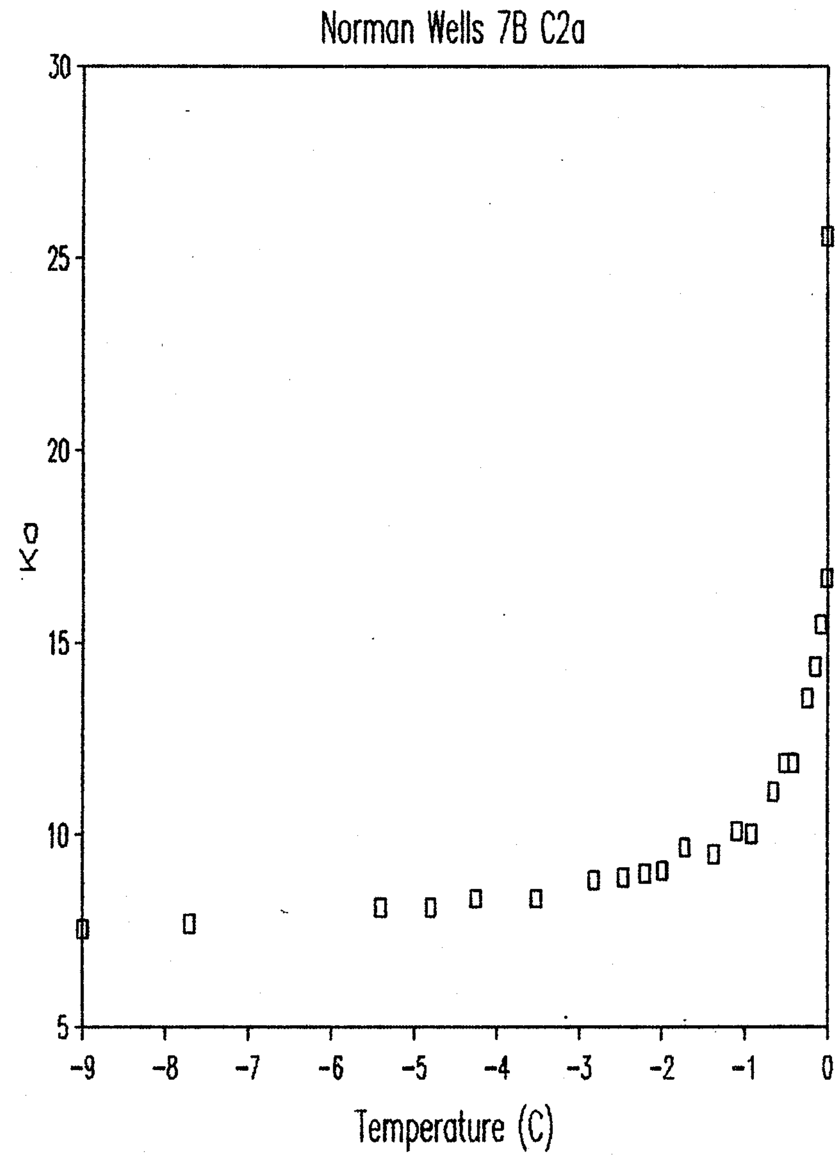


Norman Wells 7B C1a
Gravimetric Unfrozen Water Content
.3
.25
.2
.15
.1
.05
-3
-2.5
-2
-1.5
-1
-.5
0
Temperature (C)

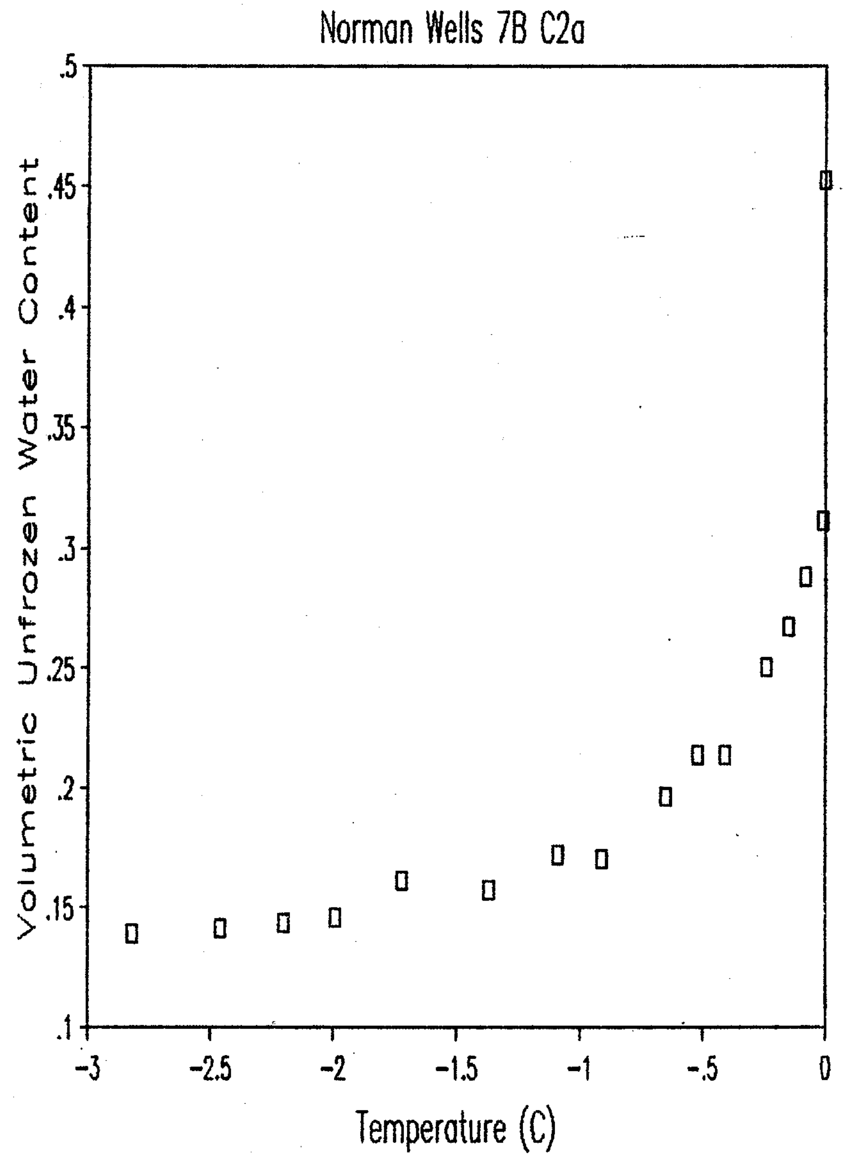
Norman Wells 7B C2a

pb = 1.392
pt = 1.870
w = 0.3436
θ = 0.4783

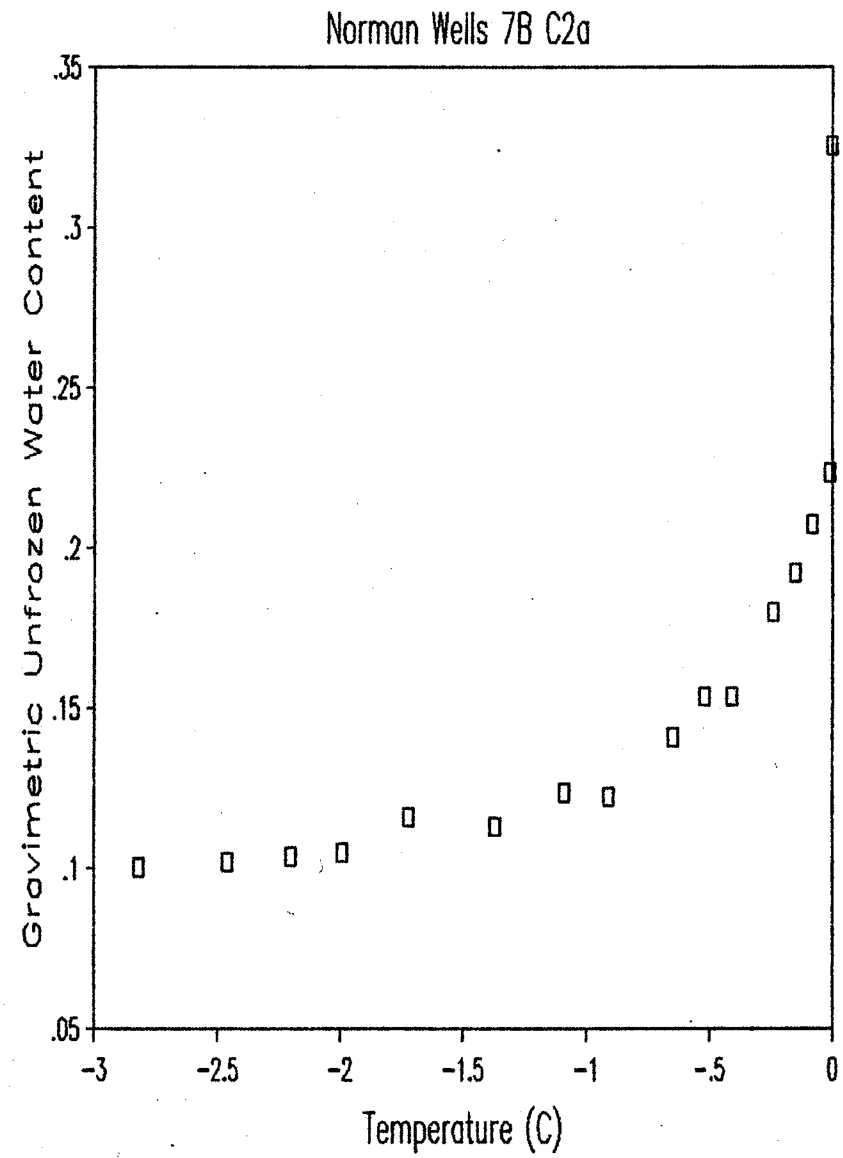
Temp.	Ka	θ	w
.00	25.57	.4528	.3253
-.01	16.67	.3111	.2235
-.08	15.45	.2884	.2072
-.15	14.38	.2674	.1921
-.24	13.55	.2504	.1799
-.41	11.87	.2138	.1536
-.52	11.86	.2136	.1534
-.65	11.11	.1963	.1410
-.91	10.03	.1702	.1223
-1.09	10.10	.1719	.1235
-1.37	9.51	.1571	.1129
-1.72	9.68	.1614	.1160
-1.99	9.08	.1460	.1049
-2.20	9.00	.1439	.1034
-2.46	8.91	.1416	.1017
-2.82	8.83	.1395	.1002
-3.52	8.35	.1267	.0910
-4.25	8.35	.1267	.0910
-4.80	8.11	.1201	.0863
-5.40	8.11	.1201	.0863
-7.70	7.71	.1091	.0783
-9.00	7.56	.1049	.0753



Norman Wells 7B C2a
30
25
20
15
10
5
Ka
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
Temperature (C)



Norman Wells 7B C2a
Volumetric Unfrozen Water Content
.5
.45
.4
.35
.3
.25
.2
.15
.1
-3
-2.5
-2
-1.5
-1
-.5
0
Temperature (C)

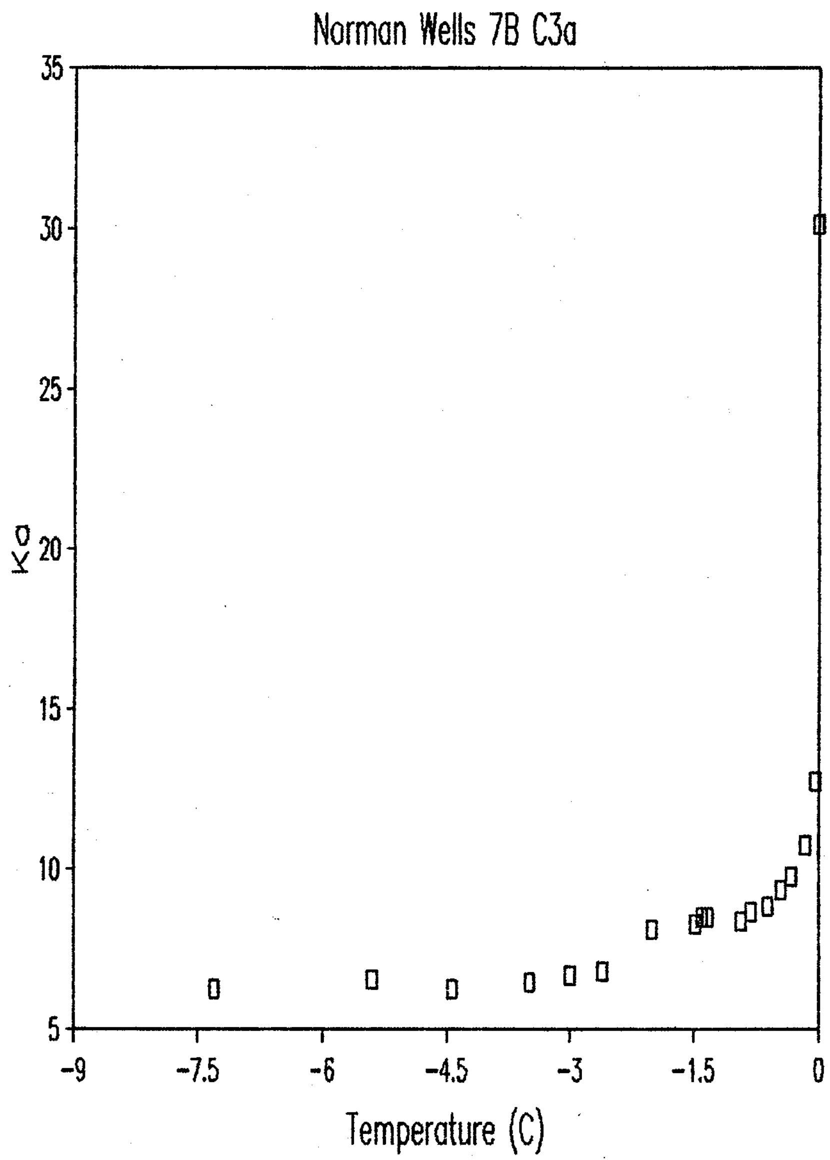


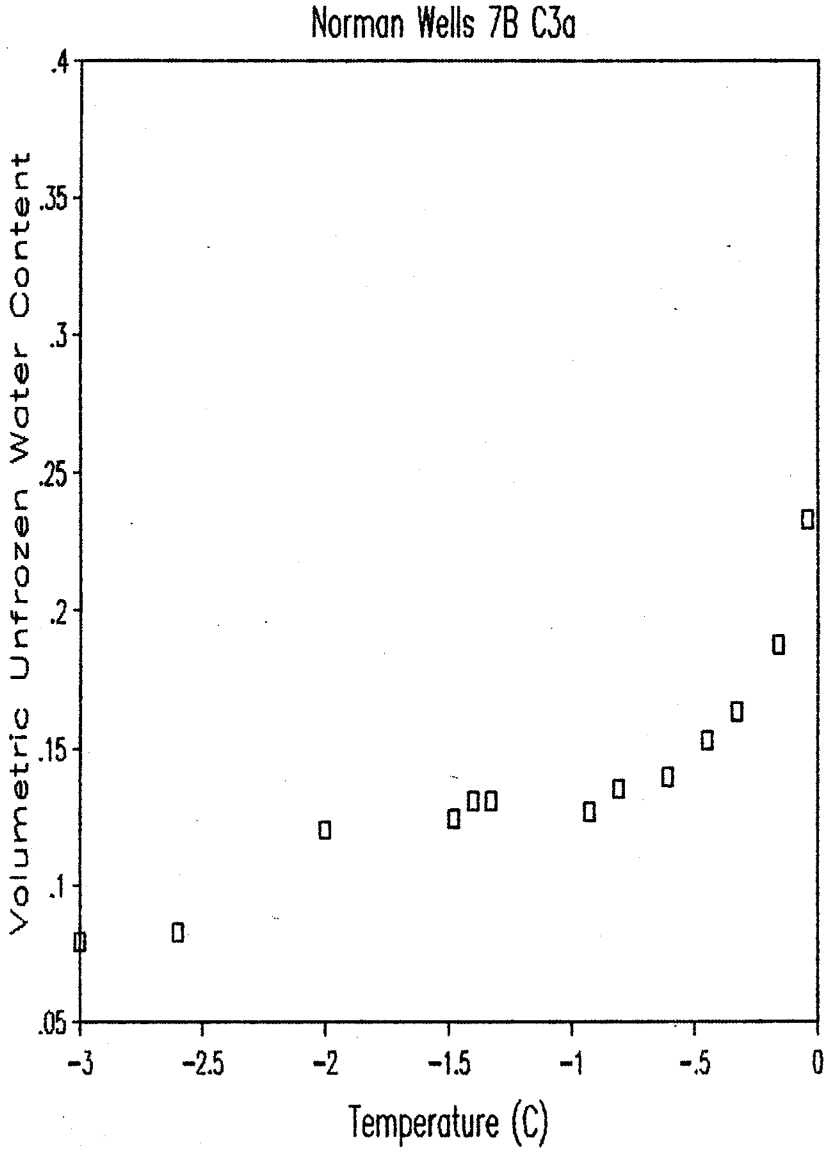
Norman Wells 7B C2a
Gravimetric Unfrozen Water Content
.35
.3
.25
.2
.15
.1
.05
-3
-2.5
-2
-1.5
-1
-.5
0
Temperature (C)

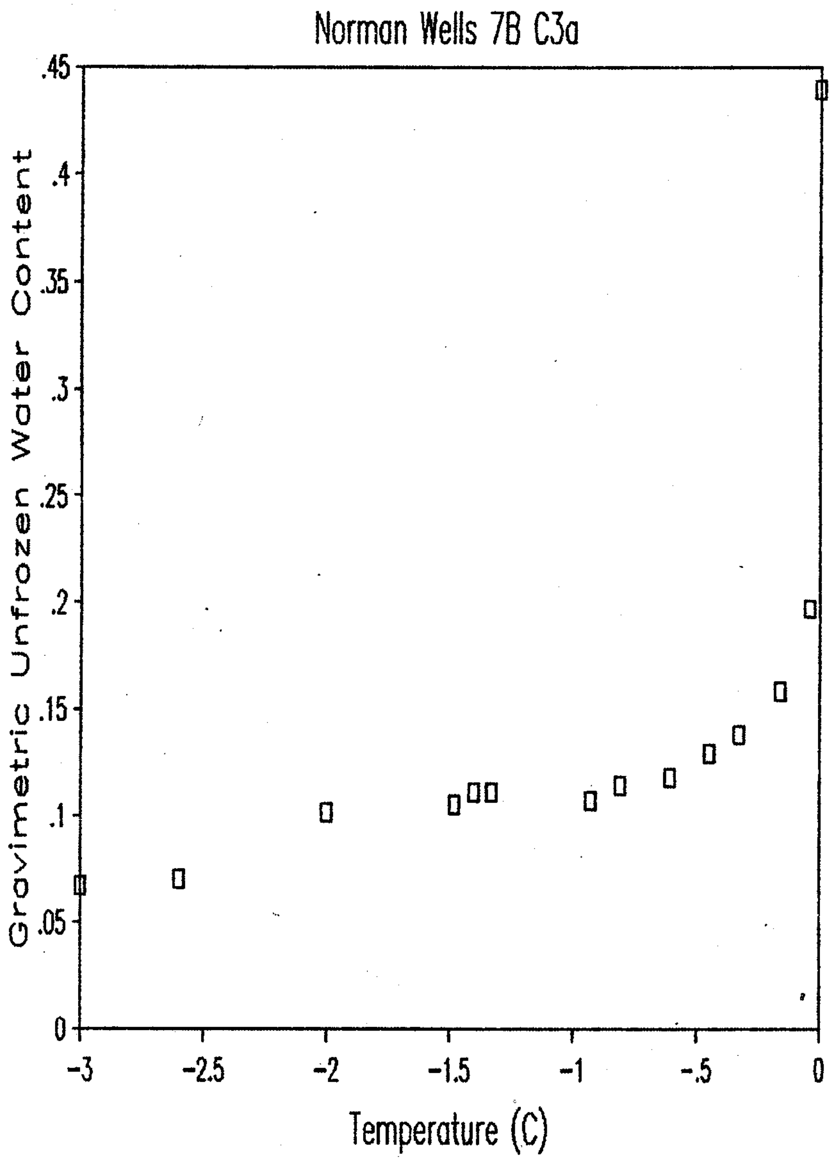
Norman Wells 7B C3a

pb = 1.184
w = 0.4830
θ = 0.5718
pt = 1.756

Temp.	Ka	θ	w
23.00	29.72	.5140	.4342
-10.60	6.25	.0667	.0563
-7.30	6.25	.0667	.0563
-5.40	6.53	.0751	.0634
-4.43	6.25	.0667	.0563
-3.49	6.46	.0730	.0616
-3.00	6.67	.0792	.0669
-2.60	6.79	.0827	.0699
-2.00	8.11	.1201	.1015
-1.48	8.27	.1245	.1051
-1.33	8.51	.1310	.1106
-1.40	8.51	.1310	.1106
-.93	8.35	.1267	.1070
-.81	8.67	.1352	.1142
-.61	8.83	.1395	.1178
-.45	9.34	.1528	.1290
-.33	9.76	.1634	.1380
-.16	10.74	.1875	.1584
-.04	12.74	.2331	.1969
.00	30.12	.5201	.4393


Norman Wells 7B C3a
Ka
35
30
25
20
15
10
5
-9
-7.5
-6
-4.5
-3
-1.5
0
Temperature (C)


Norman Wells 7B C3a
Volumetric Unfrozen Water Content
.4
.35
.3
.25
.2
.15
.1
.05
-3
-2.5
-2
-1.5
-1
-.5
0
Temperature (C)


Norman Wells 7B C3a
Gravimetric Unfrozen Water Content
0
.05
.1
.15
.2
.25
.3
.35
.4
.45
-3
-2.5
-2
-1.5
-1
-.5
0
Temperature (C)

Norman Wells 7B C5a

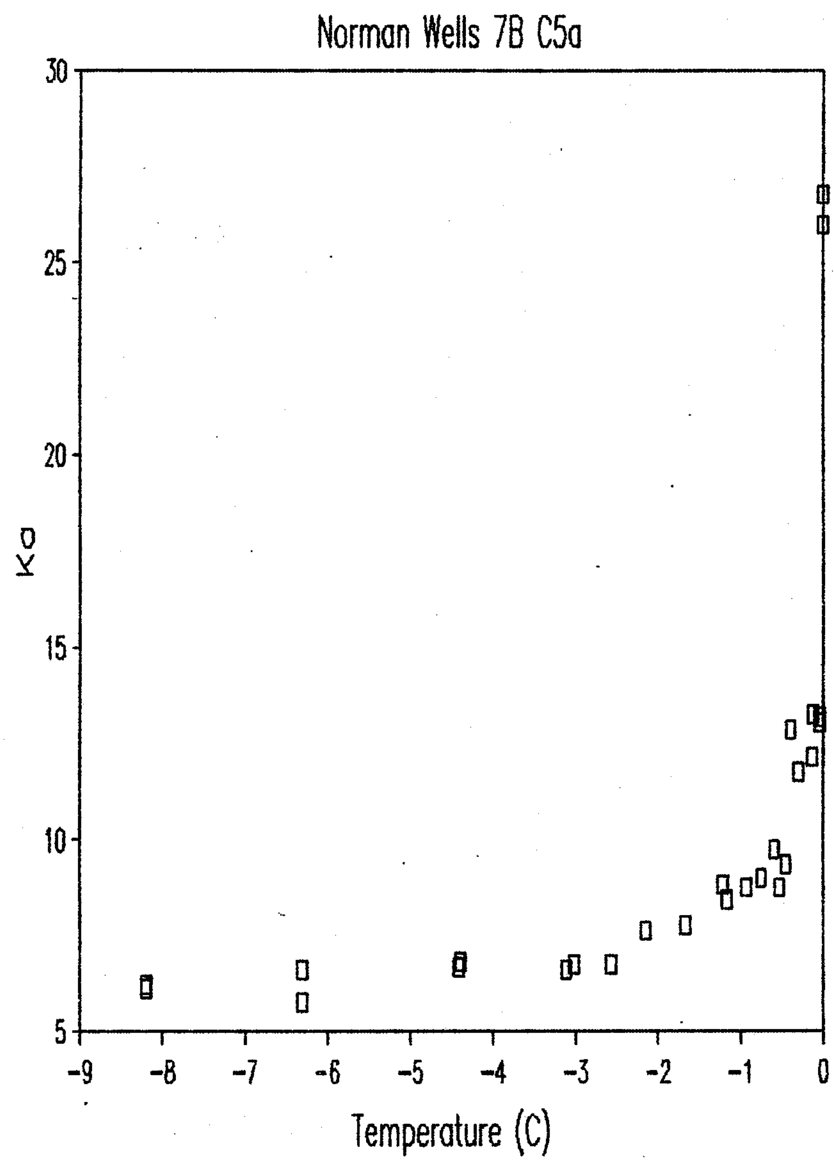
pb = 1.2488
w = 0.4241
θ = 0.5250
pt = 1.7783

Temp.	Ka	θ	w
.00	26.77	.4704	.3767
-.04	13.04	.2396	.1918
-.12	13.24	.2438	.1953
-.39	12.84	.2353	.1884
-.53	8.75	.1374	.1100
-.93	8.75	.1374	.1100
-1.22	8.83	.1395	.1117
-2.15	7.64	.1071	.0858
-3.02	6.76	.0819	.0656
-4.42	6.67	.0792	.0634
-6.30	5.77	.0521	.0417
-8.20	6.11	.0625	.0500
-10.70	5.64	.0480	.0385
.00	25.96	.4585	.3672
-.04	13.17	.2424	.1941
-.13	12.15	.2201	.1763
-.30	11.77	.2116	.1694
-.45	9.34	.1528	.1223
-.59	9.73	.1627	.1303
-.75	9.00	.1439	.1153
-1.17	8.43	.1288	.1031
-1.67	7.77	.1107	.0887
-2.57	6.75	.0816	.0653
-3.11	6.60	.0771	.0618
-4.40	6.82	.0836	.0670
-6.30	6.60	.0771	.0618
-8.20	6.23	.0661	.0529

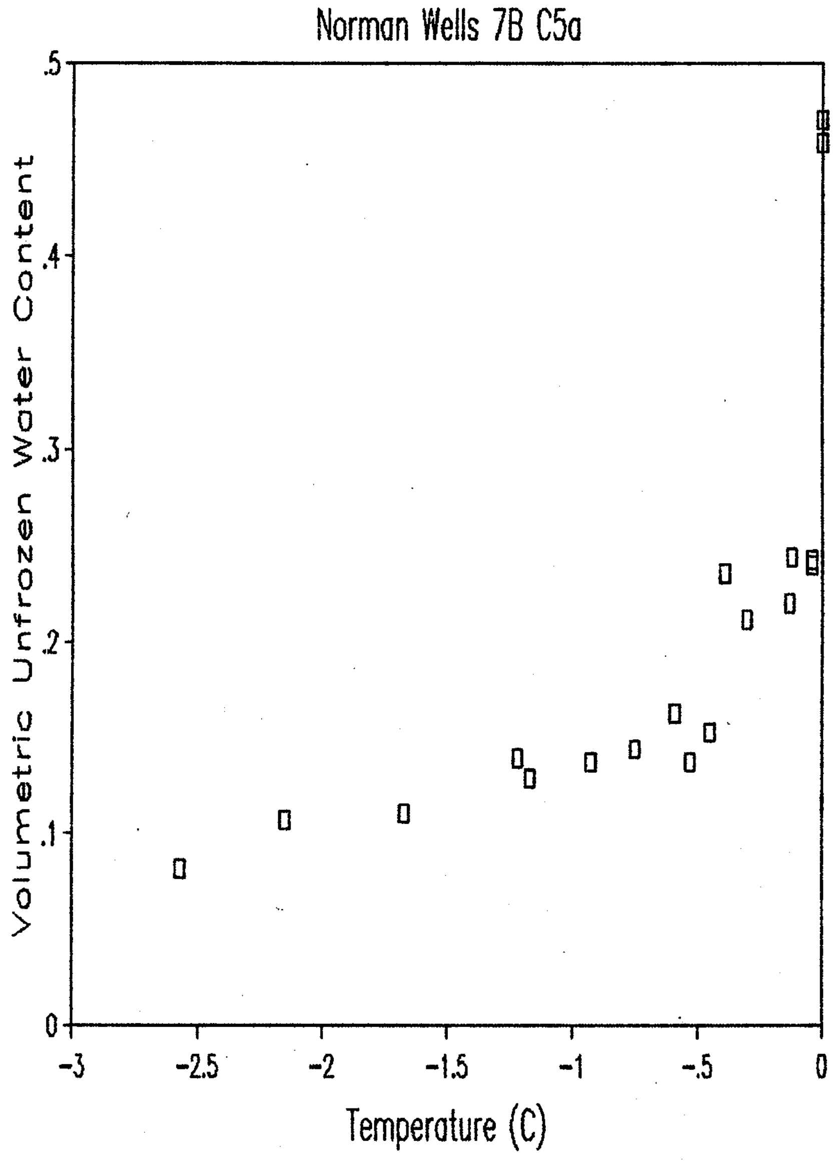
pb = 1.2128
w = 0.3580
θ = 0.4342
pt = 1.6500

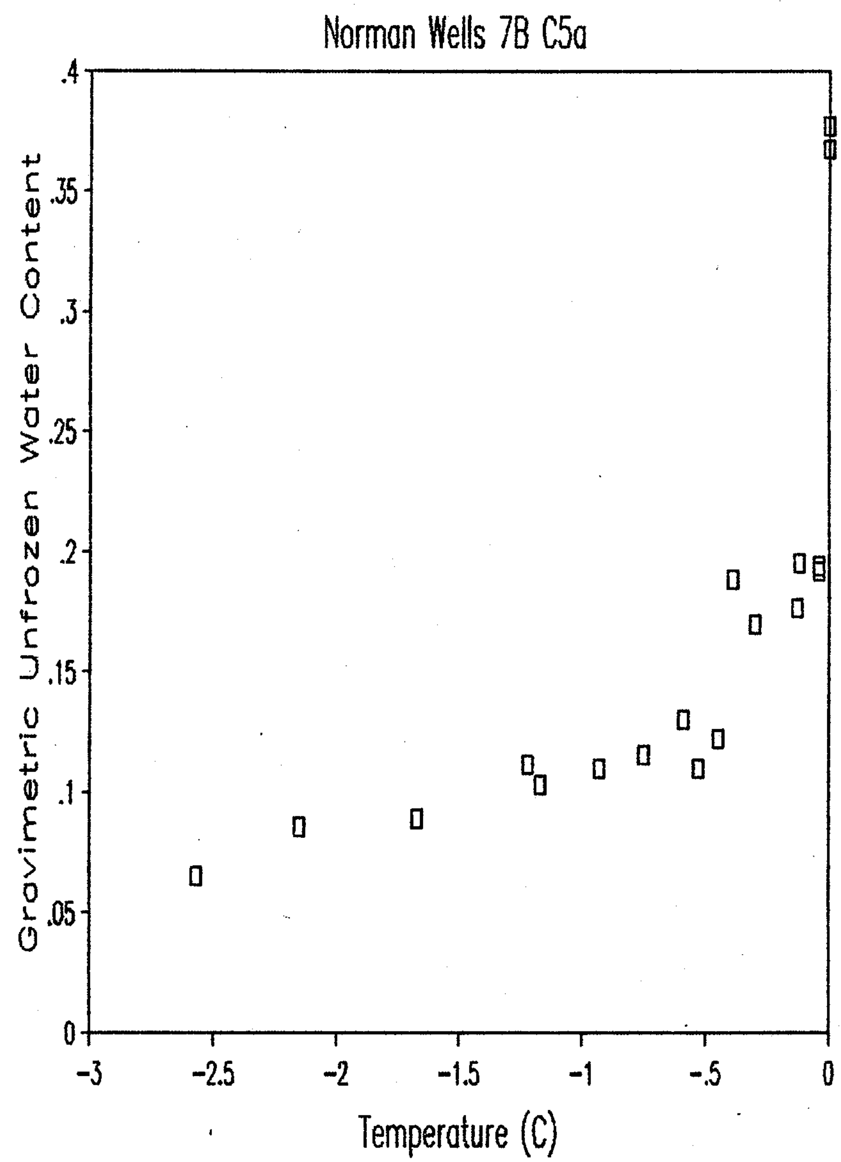
-4.15	6.90	.0860	.0709
-4.40	6.66	.0789	.0651
-5.20	7.15	.0932	.0768
-6.20	6.84	.0842	.0694
-6.85	6.96	.0877	.0723
-7.80	6.64	.0783	.0646
-8.60	6.82	.0836	.0689
-10.10	6.82	.0836	.0689
-3.60	7.74	.1099	.0906
-2.96	7.87	.1135	.0936
-2.62	8.01	.1174	.0968
-2.33	8.28	.1248	.1029

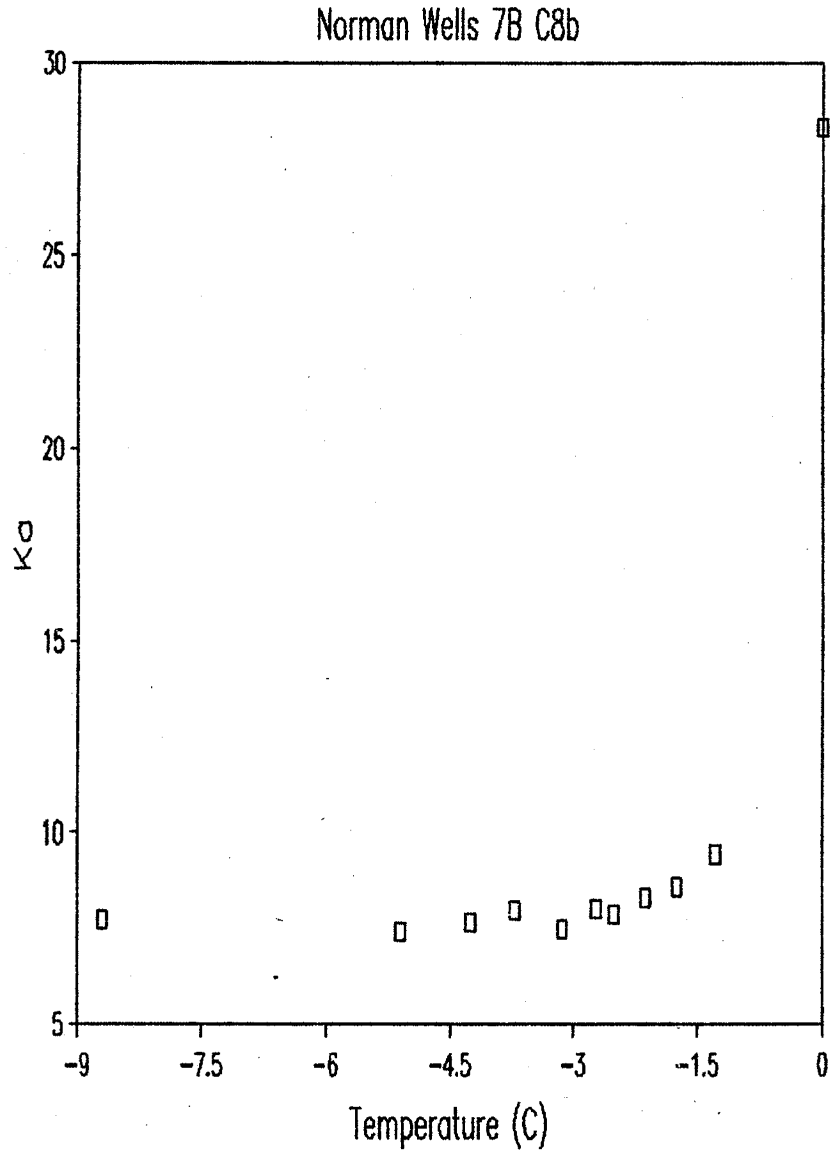
-1.97	8.85	.1400	.1154
-1.61	9.29	.1515	.1249
-.98	10.50	.1817	.1498
-.89	10.50	.1817	.1498
-.62	11.47	.2047	.1688
-.30	15.26	.2847	.2348
-.28	14.98	.2793	.2303
-.21	15.35	.2864	.2362
-.03	17.92	.3333	.2749
2.50	31.62	.5433	.4479



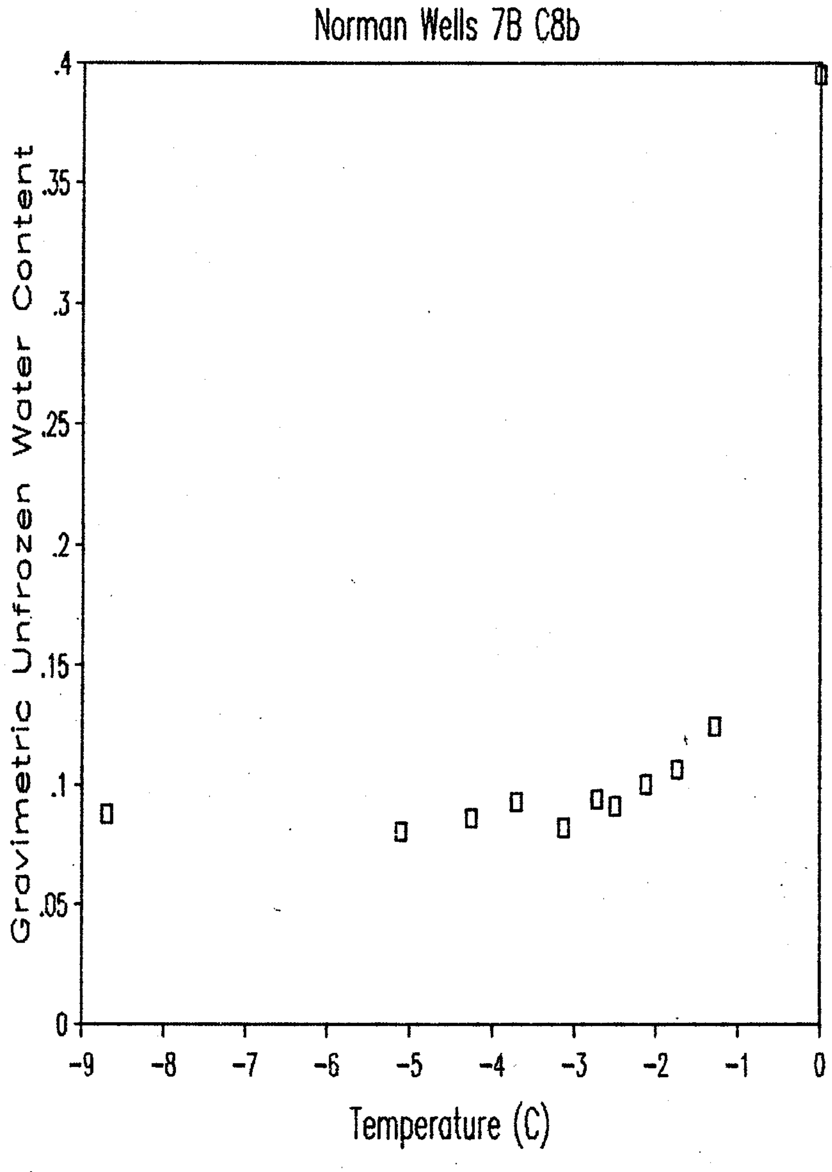
Norman Wells 7B C5a
30
25
20
15
10
5
Ko
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
Temperature (C)


Norman Wells 7B C5a
Volumetric Unfrozen Water Content
Temperature (C)
0
.1
.2
.3
.4
.5
-3
-2.5
-2
-1.5
-1
-.5
0


Norman Wells 7B C5a
Gravimetric Unfrozen Water Content
0
.05
.1
.15
.2
.25
.3
.35
.4
-3
-2.5
-2
-1.5
-1
-.5
0
Temperature (C)



Norman Wells 7B C8b
30
25
20
15
10
5
Ka
-9
-7.5
-6
-4.5
-3
-1.5
0
Temperature (C)

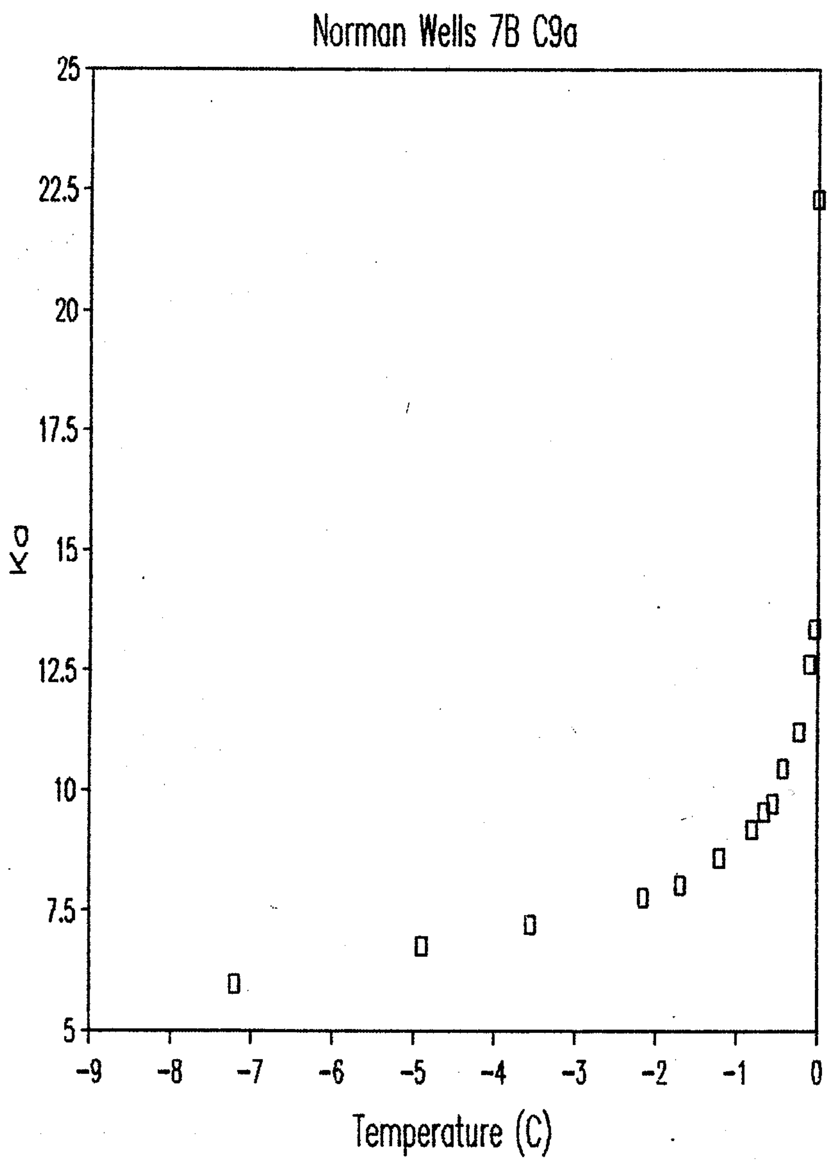


Norman Wells 7B C8b
Gravimetric Unfrozen Water Content
.4
.35
.3
.25
.2
.15
.1
.05
0
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
Temperature (C)

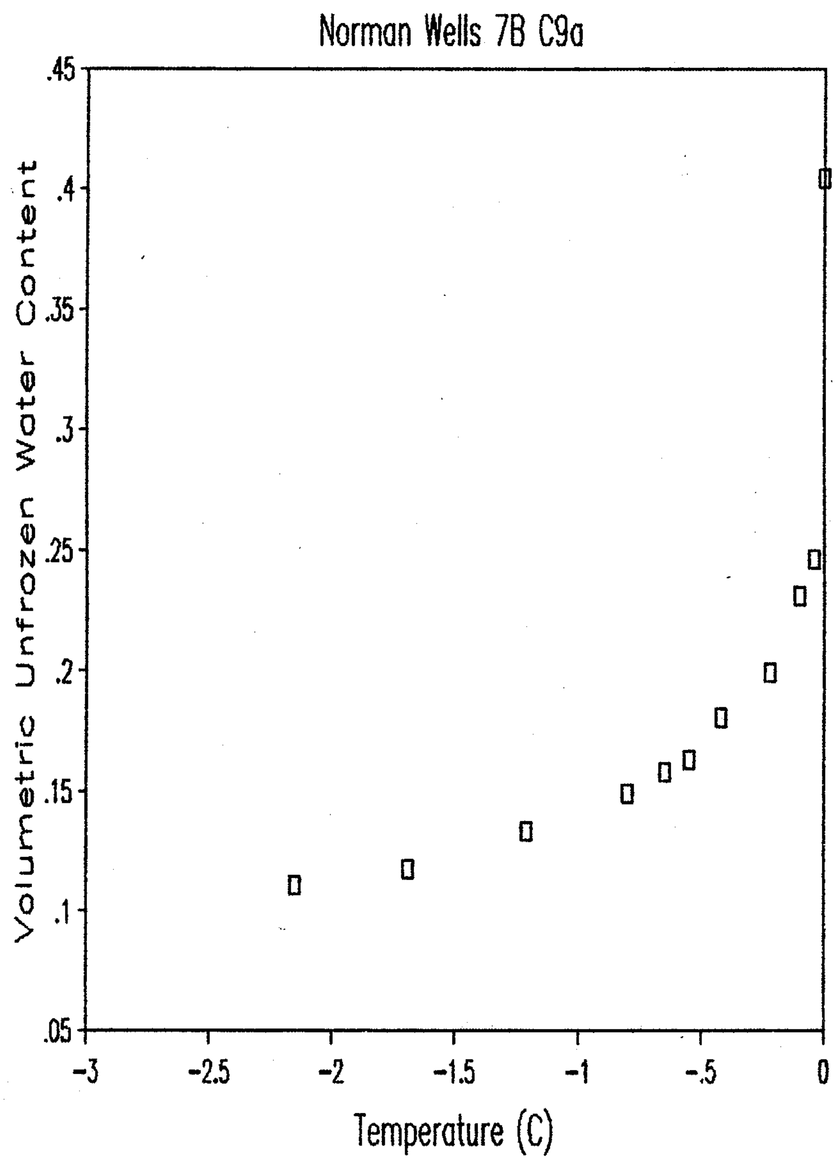
Norman Wells 7B C9a

pb = 1.5009
w = 0.2899
θ = 0.4351
pt = 1.9360

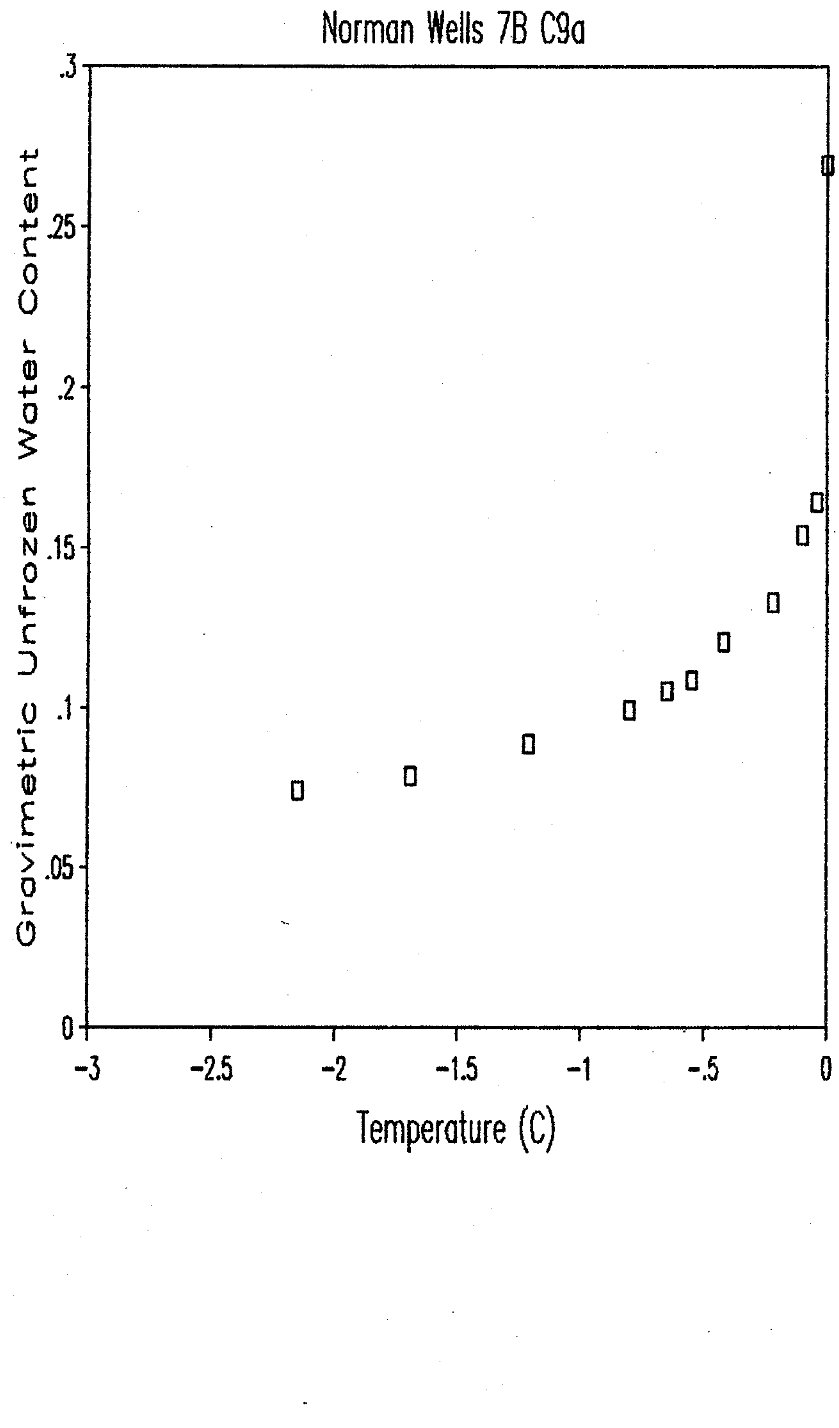
Temp.	Ka	θ	w
.00	22.30	.4042	.2693
-.04	13.36	.2464	.1642
-.10	12.63	.2307	.1537
-.22	11.23	.1991	.1326
-.42	10.46	.1807	.1204
-.55	9.74	.1629	.1086
-.65	9.55	.1581	.1054
-.80	9.20	.1491	.0994
-1.21	8.60	.1334	.0889
-1.69	8.02	.1177	.0784
-2.15	7.77	.1107	.0738
-3.55	7.22	.0952	.0634
-4.90	6.76	.0819	.0545
-7.20	5.97	.0582	.0388
-10.40	6.38	.0706	.0470



Norman Wells 7B C9a
Ko
25
22.5
20
17.5
15
12.5
10
7.5
5
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
Temperature (C)



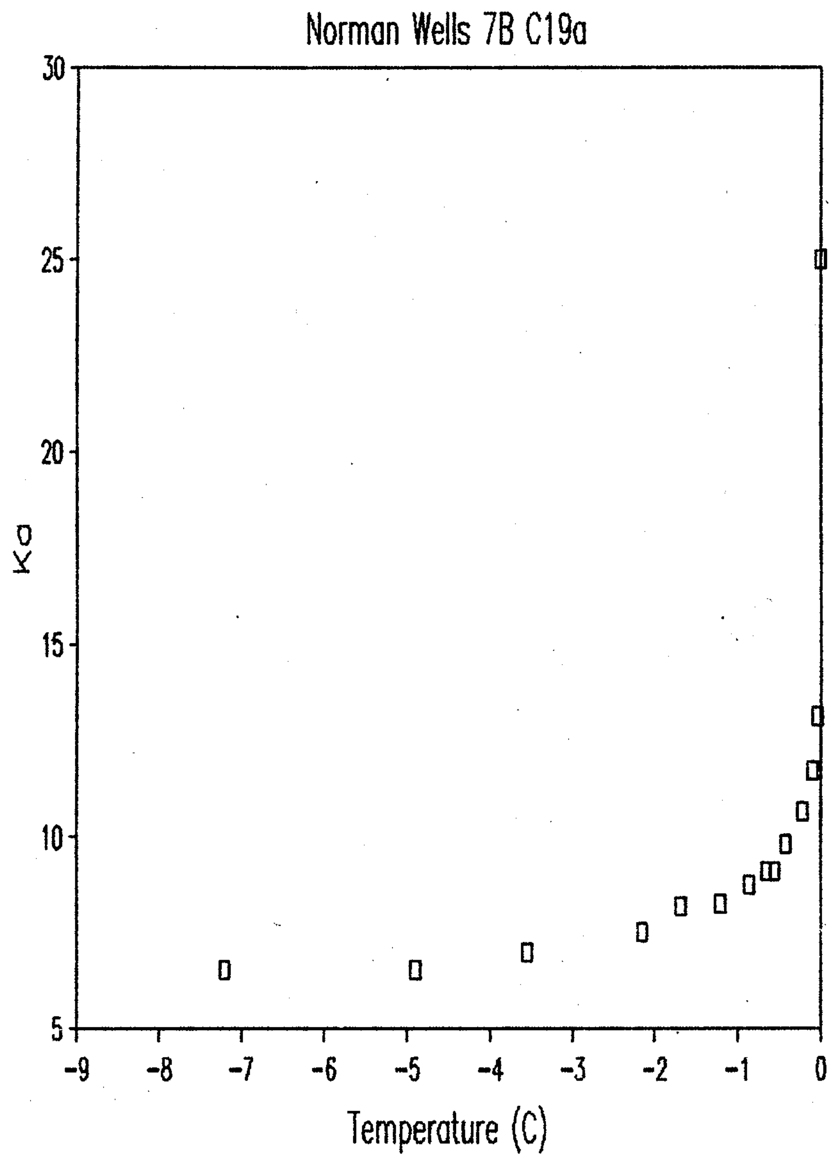
Norman Wells 7B C9a
Volumetric Unfrozen Water Content
.45
.4
.35
.3
.25
.2
.15
.1
.05
-3
-2.5
-2
-1.5
-1
-.5
0
Temperature (C)


Norman Wells 7B C9a
Gravimetric Unfrozen Water Content
.3
.25
.2
.15
.1
.05
0
-3
-2.5
-2
-1.5
-1
-.5
0
Temperature (C)

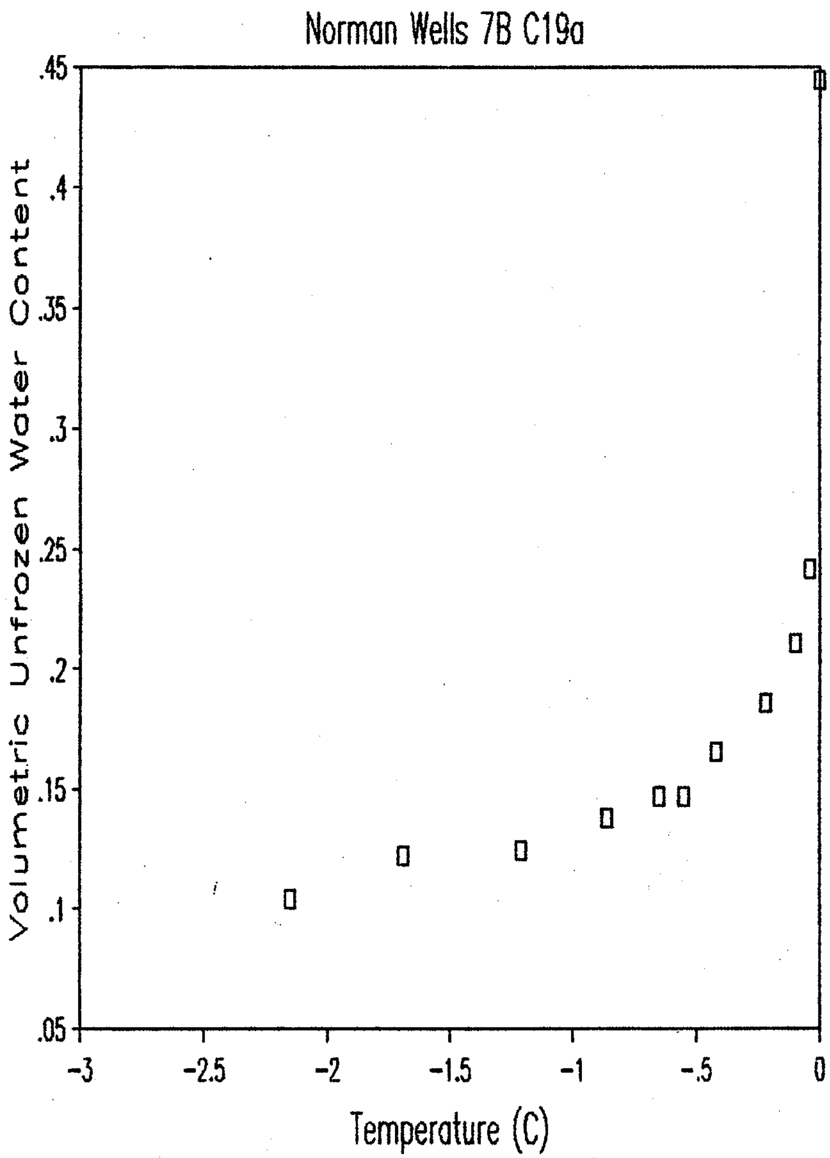
Norman Wells 7B C19a

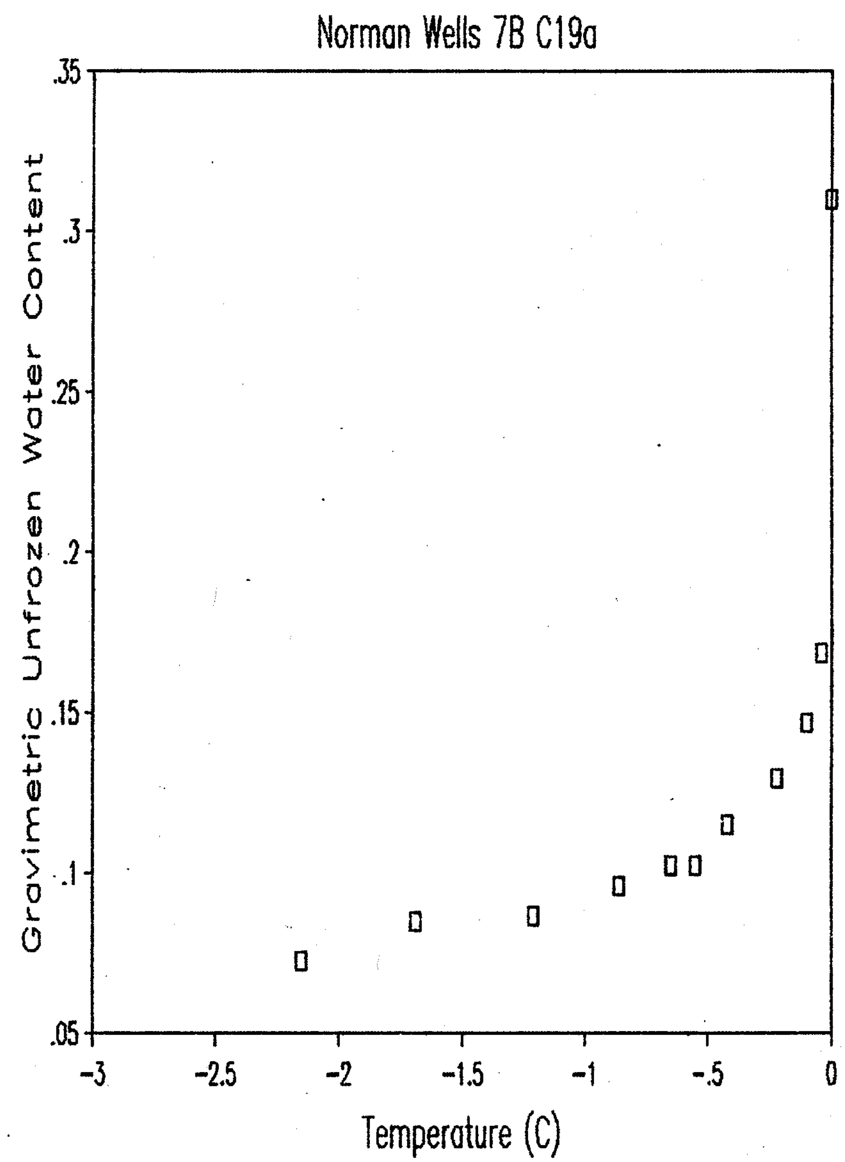
pb = 1.4352
w = 0.3182
θ = 0.4567
pt = 1.8919

Temp.	Ka	θ	w
.00	25.00	.4445	.3097
-.04	13.14	.2417	.1684
-.10	11.72	.2104	.1466
-.22	10.66	.1856	.1293
-.42	9.83	.1652	.1151
-.55	9.11	.1468	.1023
-.65	9.11	.1468	.1023
-.86	8.77	.1379	.0961
-1.21	8.26	.1242	.0865
-1.69	8.18	.1220	.0850
-2.15	7.53	.1040	.0725
-3.55	6.99	.0886	.0617
-4.90	6.54	.0754	.0525
-7.20	6.53	.0751	.0523
-10.40	5.57	.0459	.0320



Norman Wells 7B C19a
30
25
20
15
10
5
Ka
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
Temperature (C)


Norman Wells 7B C19a
Volumetric Unfrozen Water Content
.45
.4
.35
.3
.25
.2
.15
.1
.05
-3
-2.5
-2
-1.5
-1
-.5
0
Temperature (C)

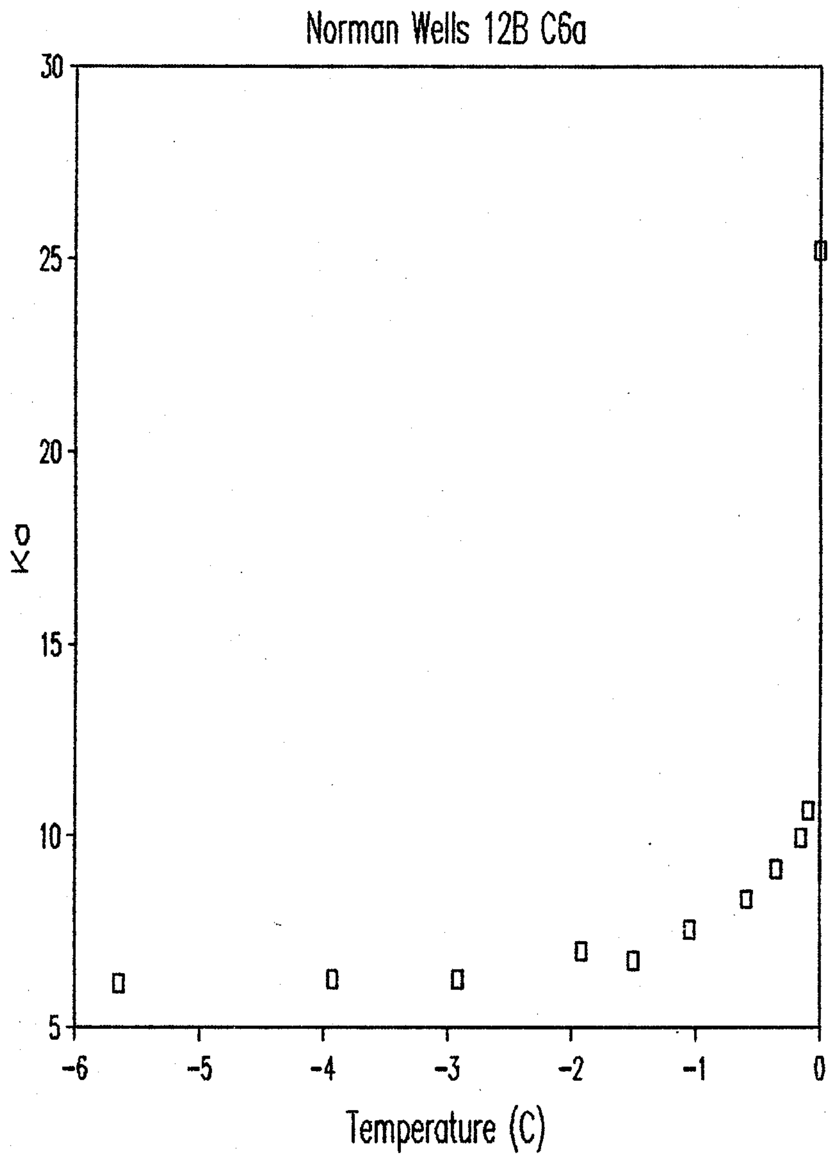


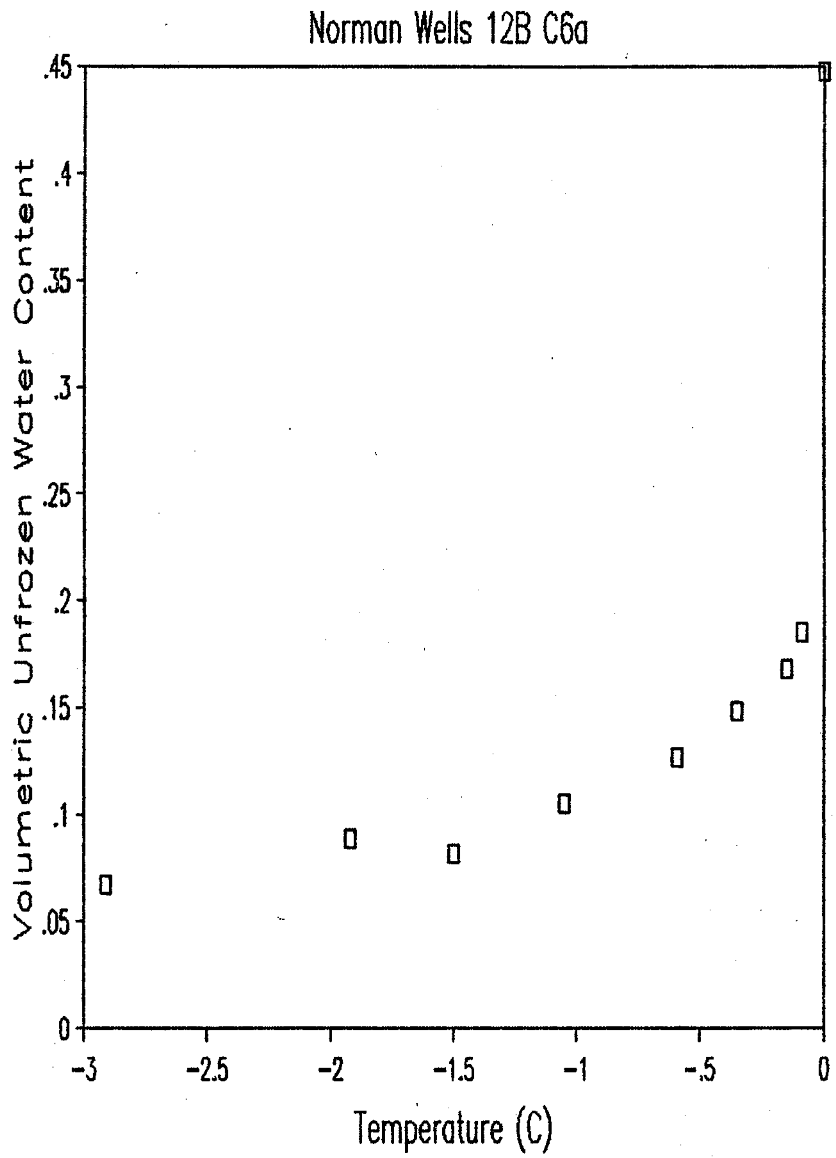
Norman Wells 7B C19a
Gravimetric Unfrozen Water Content
.35
.3
.25
.2
.15
.1
.05
-3
-2.5
-2
-1.5
-1
-.5
0
Temperature (C)

Norman Wells 12B C6a

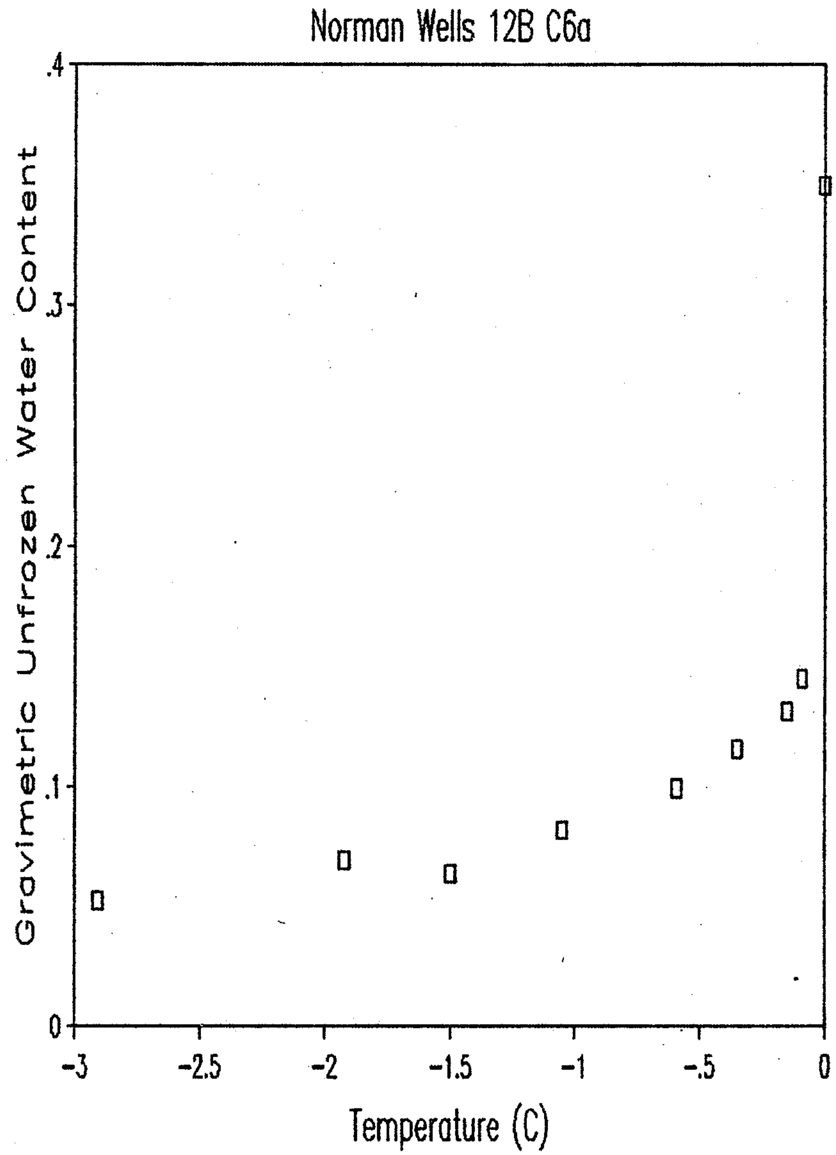
pb = 1.2811
w = 0.3751
θ = 0.4805
pt = 1.7616

Temp.	Ka	θ	w
.00	25.20	.4474	.3492
-.09	10.65	.1853	.1447
-.15	9.94	.1679	.1311
-.35	9.16	.1481	.1156
-.59	8.35	.1267	.0989
-1.05	7.56	.1049	.0818
-1.50	6.75	.0816	.0637
-1.92	6.98	.0883	.0689
-2.91	6.25	.0667	.0521
-3.92	6.25	.0667	.0521
-5.65	6.15	.0637	.0497


Norman Wells 12B C6a
30
25
20
15
10
5
Ko
-6
-5
-4
-3
-2
-1
0
Temperature (C)



Norman Wells 12B C6a
Volumetric Unfrozen Water Content
Temperature (C)
0
.05
.1
.15
.2
.25
.3
.35
.4
.45
-3
-2.5
-2
-1.5
-1
-.5
0

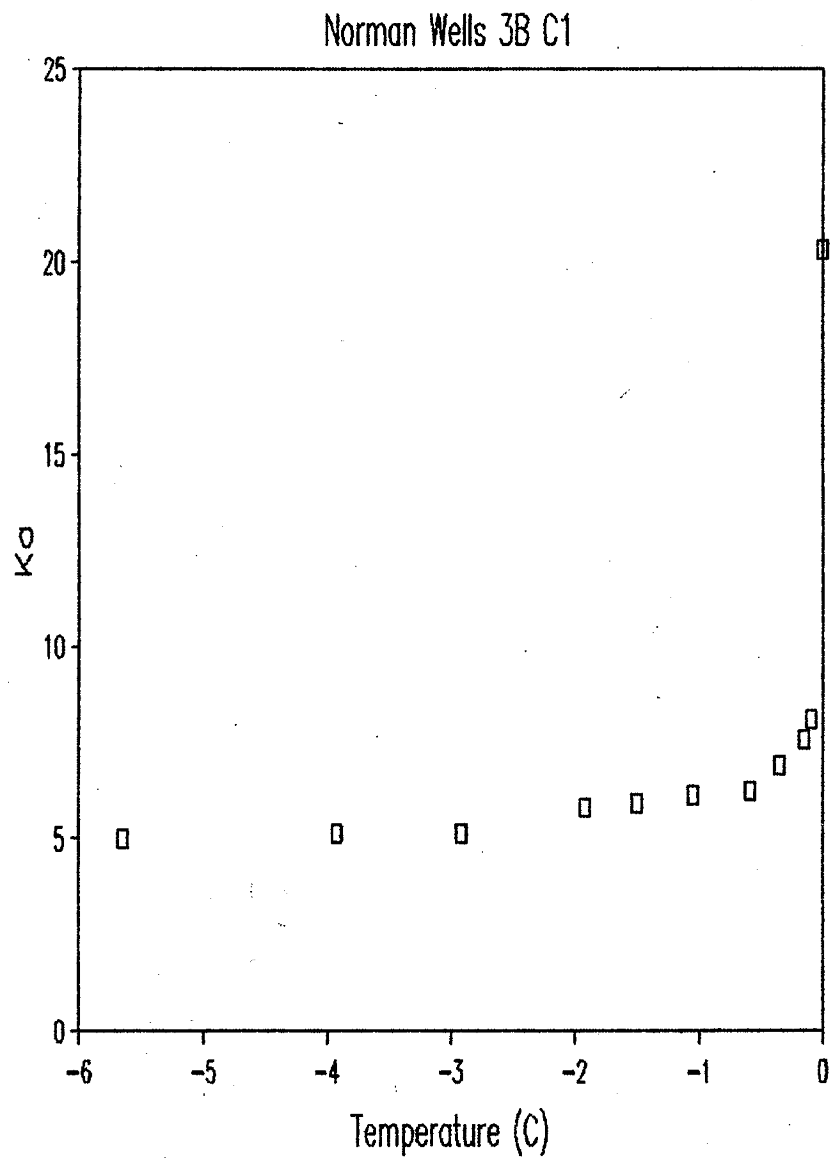


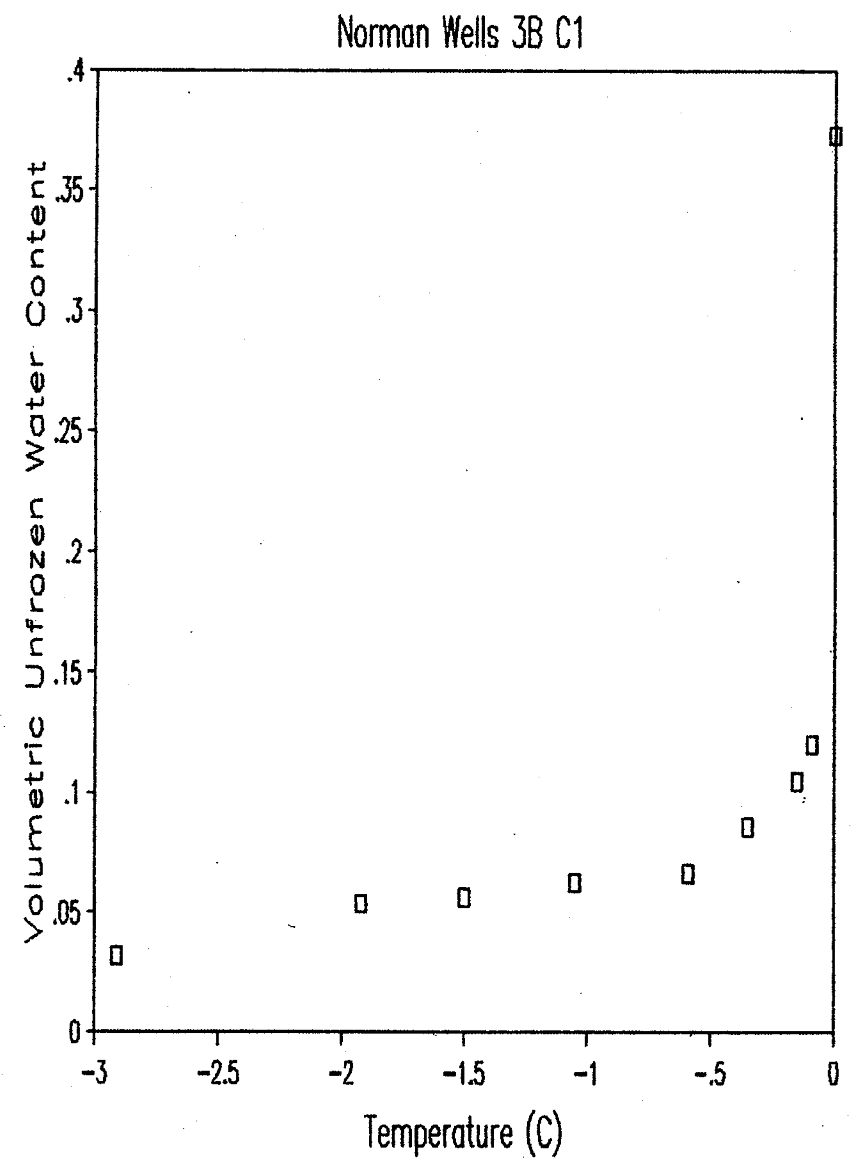
Norman Wells 12B C6a
Gravimetric Unfrozen Water Content
.4
.3
.2
.1
0
-3
-2.5
-2
-1.5
-1
-.5
0
Temperature (C)

Norman Wells 3B Cl

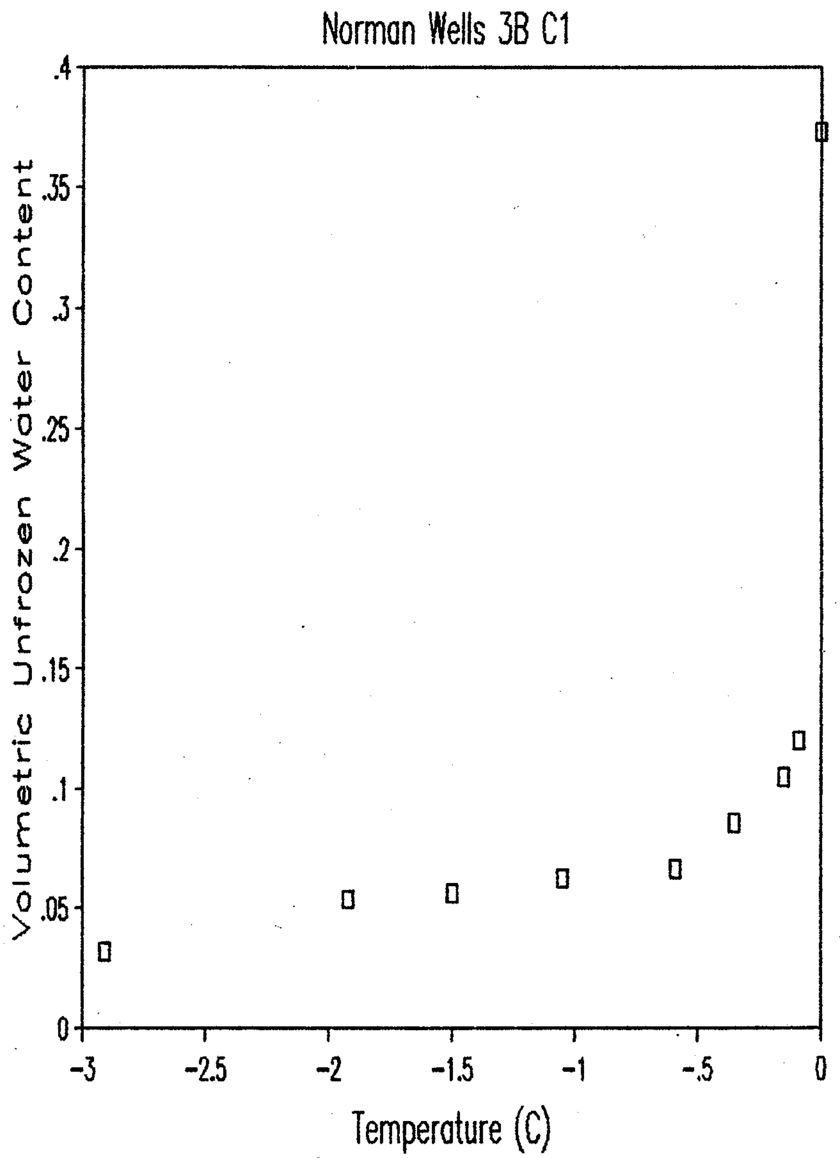
pb = 1.7000
w = 0.2087
θ = 0.3549
pt = 2.0556

Temp.	Ka	θ	w
.00	20.31	.3731	.2195
-.09	8.10	.1198	.0705
-.15	7.56	.1049	.0617
-.35	6.89	.0857	.0504
-.59	6.24	.0664	.0391
-1.05	6.11	.0625	.0367
-1.50	5.91	.0564	.0332
-1.92	5.82	.0536	.0315
-2.91	5.12	.0317	.0186
-3.92	5.12	.0317	.0186
-5.65	5.00	.0278	.0164

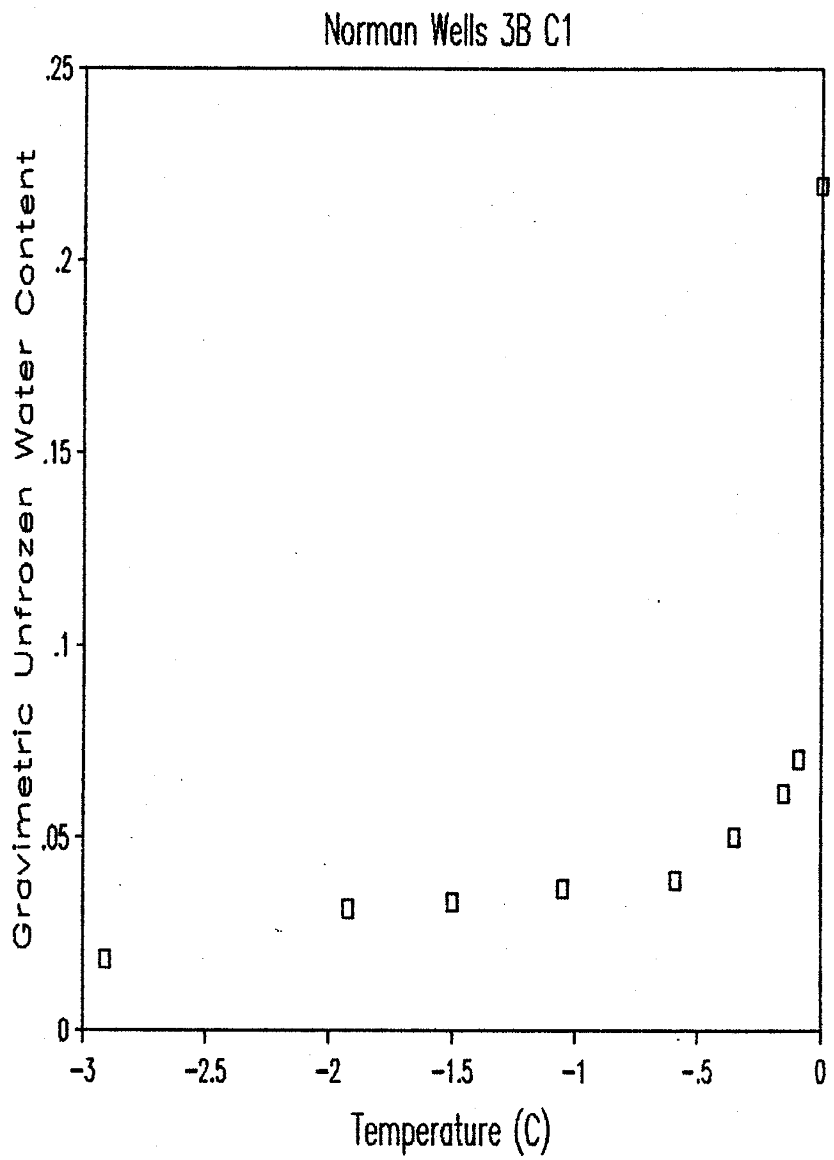

Norman Wells 3B C1
Ko
Temperature (C)
25
20
15
10
5
0
-6
-5
-4
-3
-2
-1
0



Norman Wells 3B C1
Volumetric Unfrozen Water Content
.4
.35
.3
.25
.2
.15
.1
.05
0
-3
-2.5
-2
-1.5
-1
-.5
0
Temperature (C)



Norman Wells 3B C1
Volumetric Unfrozen Water Content
.4
.35
.3
.25
.2
.15
.1
.05
0
-3
-2.5
-2
-1.5
-1
-.5
0
Temperature (C)


Norman Wells 3B C1
Gravimetric Unfrozen Water Content
Temperature (C)
.25
.2
.15
.1
.05
0
-3
-2.5
-2
-1.5
-1
-.5
0

Appendix II

Dielectric Constant-Water Content Data for Woodchips

Ka	θv
1.88	.0000
2.71	.0417
3.77	.0833
5.39	.1250
6.58	.1667
8.68	.2083
10.70	.2500
13.09	.2917
15.38	.3333
17.67	.3750
21.50	.4167
24.40	.4583
28.87	.5000
31.73	.5417
36.80	.5833
38.40	.5950
35.24	.5417
28.87	.5000
25.05	.4583
22.31	.4167
18.78	.3750
15.72	.3333
12.63	.2917
10.01	.2500
8.43	.2083
5.18	.1667
4.42	.1300

Ka	θv
4.42	.1300
4.51	.1500
5.68	.1833
7.22	.2167
7.69	.2333
9.47	.2667
11.28	.3000
13.57	.3333
15.55	.3667
18.40	.4000
20.70	.4333
24.40	.4667
27.04	.5000
30.53	.5333
34.22	.5667
37.86	.6000
45.11	.6333