Canada - France
Pipeline - Ground Freezing Experiment:
Phase IX

Fourth Thaw

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Energy, Mines and Resources Canada

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Foreword

This report describes findings from the fourth thaw period of the Canada-France pipeline ground freezing project. The Canada-France project comprises a team of Canadian and French scientists, engineers, technicians and graduate students. The on-site assistance of M.A. Dupas and M.B. Dumoulin are particularly noted, and the smooth cooperation with Laboratoire Central des Ponts et Chaussées and the Centre de Geomorphologie of the CNRS is of fundamental importance to the project. The project as a whole is supervised by a scientific committee. The members and their affiliations are listed below.

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1 Introduction

1.1 Scope of this Report

This report examines the observations made during the thaw period of the fourth freeze cycle of this project. Particular attention is given to the surface heave observations , soil micromorphology, and the irreversible displacement of the pipe.

The data for all phases of the Canada-France pipeline ground freezing experiment (including the period covered by this report) has recently be collected into a database available as an open file report. As a result of this, a review of results from all sensors is not included. Instead, this report concentrates on analyses of data for this and previous thaw periods which have not been reported previously.

1.2 Test Facility

The frost heave experiment is carried out at the "station de gel" at the Centre de Geomorphologie, C.N.R.S., Caen, France. The totally enclosed temperature controlled test facility was described in detail by Burgess et al. (1982) when the experiment was initially set up, and after additional instrumentation was added by Carleton University's Geotechnical Sciences Laboratories (1986).

The facility consists of a refrigerated hall 18 m long by 8 m wide and 5 m high. An 18 m long by 27 cm. in diameter

uninsulated steel pipeline was buried in initially unfrozen soil at a depth of 30 cm., and transects a frost susceptible silt and non-frost susceptible sand. Thus a boundary of soil types common in permafrost terrain has been simulated in this experimental facility (Burgess, 1985). The base of the trough of the facility is 1.75 m deep and has been specially prepared for the experiment in order to isolate the thermal and hydraulic regimes and to carefully control experimental conditions.

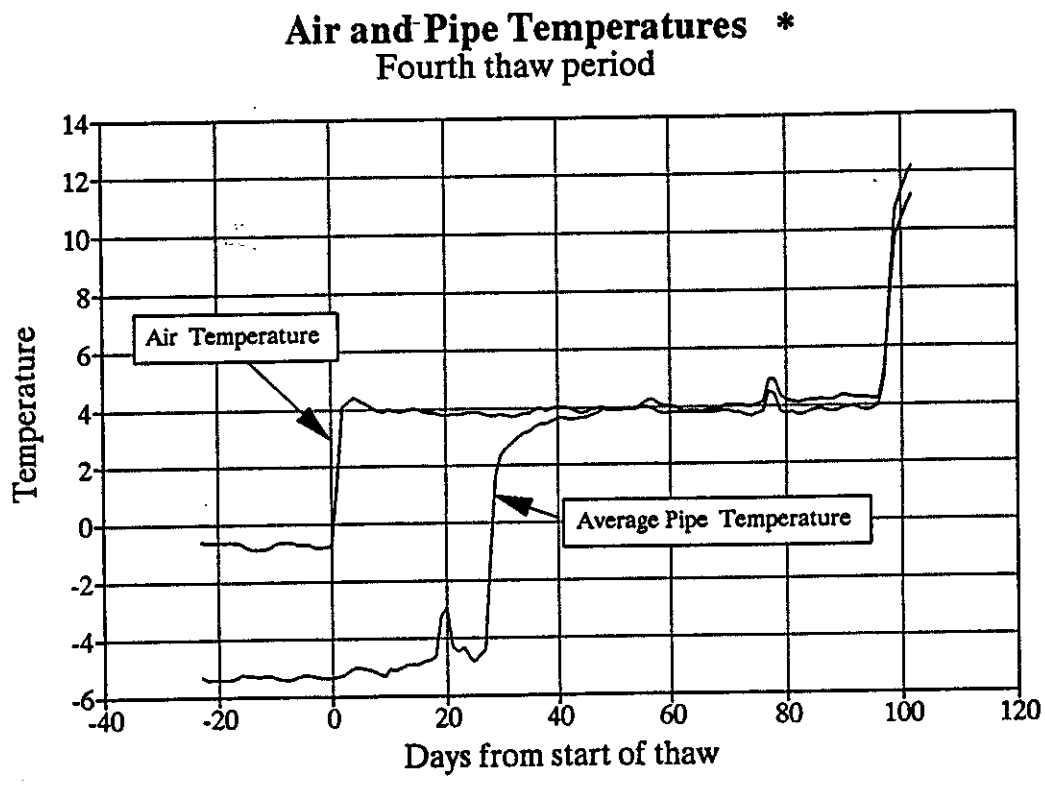
The experiment is instrumented to monitor the thermal and hydrological regimes. A network of thermistors and thermocouples monitor thermal regime while tensiometers and piezometers are used to monitor the hydrological regime. Additional instrumentation consisting of glotzl and petur cells are used to monitor total soil pressure Periodic optical level surveys permitted monitoring of total heave, with telescoping heave tubes and a magnet sensing device used to measure heave within soil layers.

1.3 Soil Characteristics

The pipeline has been buried in a frost susceptible silt (Caen silt) and a non-frost susceptible sand (SNEC). The silt is eolian in origin and composed of about 3 to 10 percent sand (2.0 to .076 mm), 75 to 85 percent silt (0.076 to 0.002 mm) and 10 to 20 percent clay (<0.002 mm). It has low plasticity (<15%) and can be designated as ML by the Unified Soil Classification System.

1.4 General conditions

The temperature conditions for the fourth thaw period were somewhat different that for previous cycles (Figure 1). Pipe temperature was maintained below freezing (-5.25°C) for the first 27 days of surface thaw, following which pipe temperature was maintained at 4°C. The water table was maintained at 90 cm beneath the soil surface, as in the past.



* Smoothed Daily Averages

Figure 1

2 Observations During the Fourth Thaw Cycle

2.1 Progression of thawing.

Figure 2 shows the progression of the thaw front adjacent to the pipe axis, as determined from the thermistor data. Figure 3 shows the latest date on which freezing temperatures were observed for different depths in both sand and silt. The higher thermal diffusivity in saturated sand relative to silt, as well as the high excess ice content in the silt, resulted in greater depth of freezing in the sand. During the thawing process however, the same factors were responsible for more rapid thawing in the sand. The

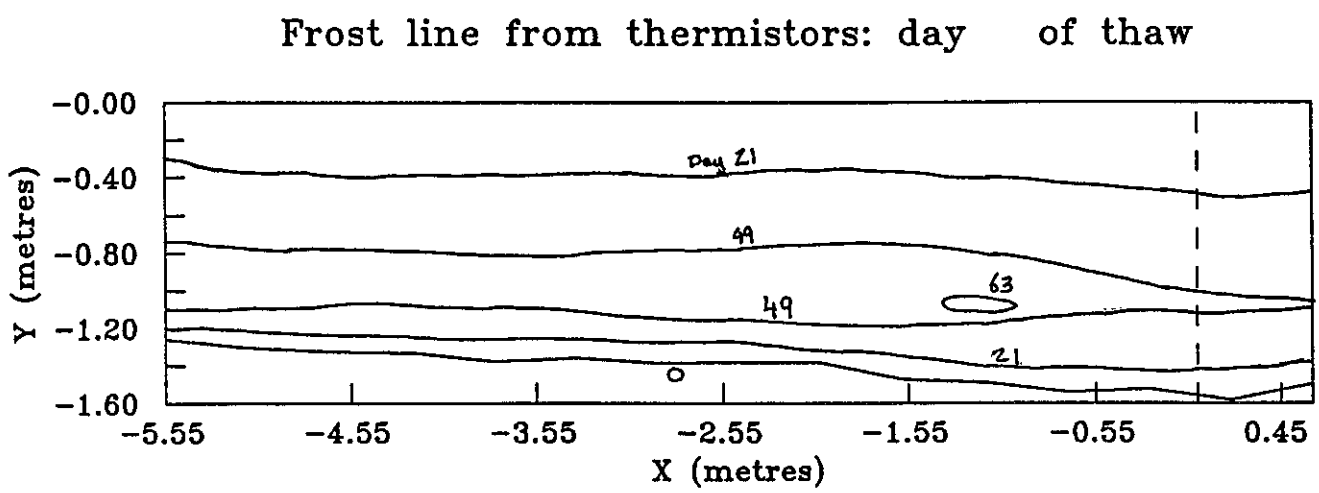


Figure 2

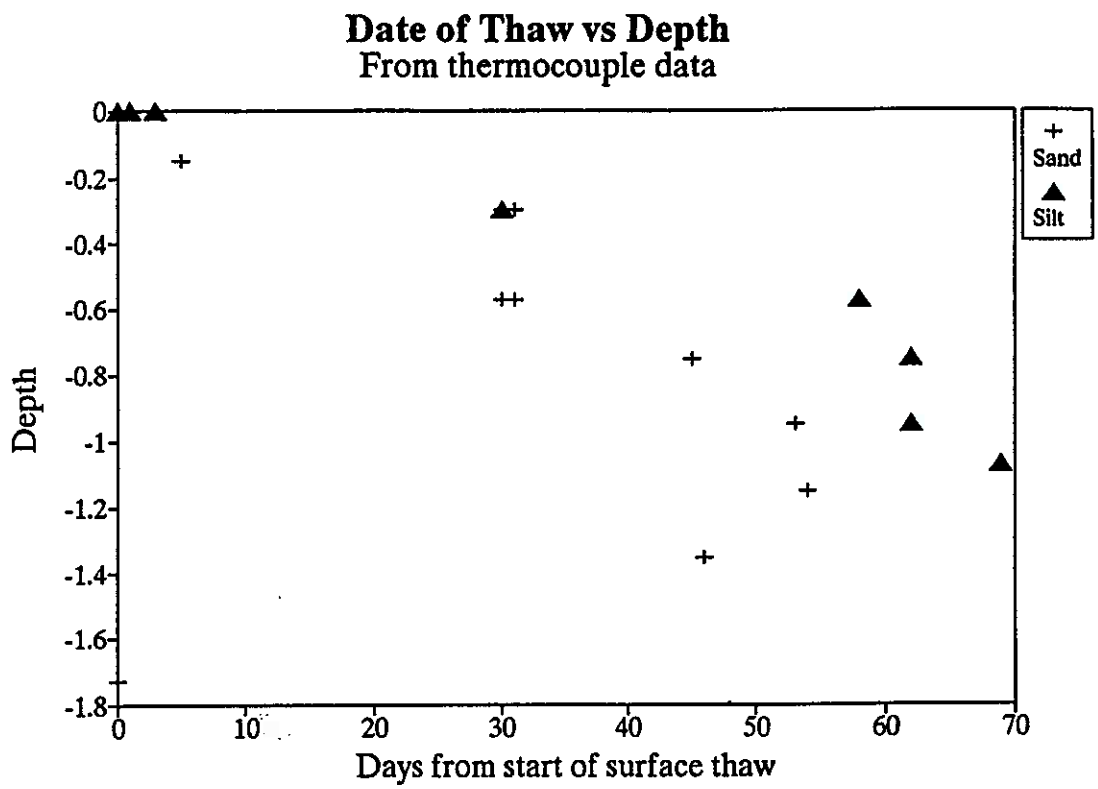
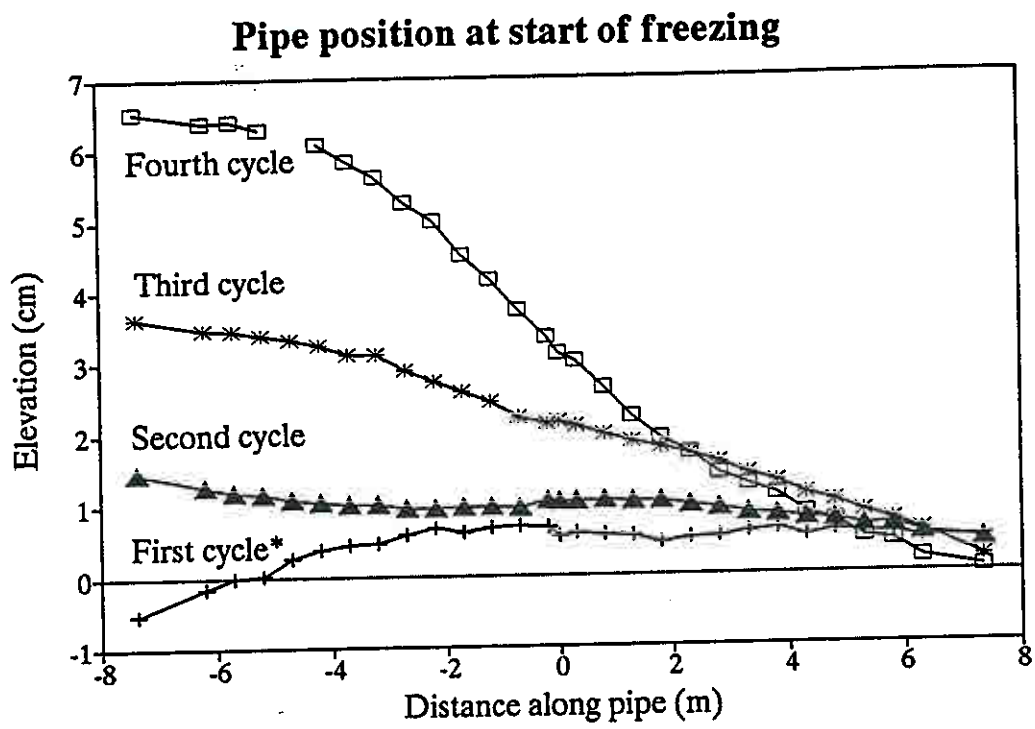


Figure 3

greatest excess ice concentration was in the silt near the base of the frozen layer. This was due to the prolonged period that the frost line remained stable, allowing significant ice segregation there. As a result, thawing from below was much slower in the silt than in the sand. In particular, it can be seen that a small frozen body persisted near the base of freezing in the silt for an extended period (Figure 3). It can be seen from Figure 2 that this body was close to the sand-silt transition, suggesting that this particular location was influenced by the proximity of the sand as a heat sink and source of water for ice segregation.

2.2 Pipe displacement

Figure 4 shows the pipe shape at the start of the four freeze cycles, as determined from optical levelling of the pipe survey rods. The pipe is increasingly being displaced upward, primarily within the silt section. This is the result of the combined effect of two factors. Firstly, frost heave is approximately radial to the pipe (since the pipe is a sink for soil heat), while settlement is essentially vertical (since it is governed primarily by gravity). Secondly, bending stresses on pipe relax at the beginning of the thaw, with the loss of soil uplift resistance on thawing. This



* Datum for first cycle was different than for subsequent cycles: Position is approximate only.

Figure 4

allows upward pipe movement in those sections of the pipe where this reduces the overall stress in the pipe.

Figure 5 shows the shape and elevation of the pipe for selected days of the thaw period. While the overall movement of the pipe is downwards due to thaw settlement, uplift is apparent in the sand near the transition, and at the end of the pipe in the silt. In both cases, the uplift is due to the reduction in uplift resistance of the soil. In the sand, uplift reduces pipe stresses in the region of uplift, while in the silt, stresses are increased in the region of uplift, while stresses decline in the region of

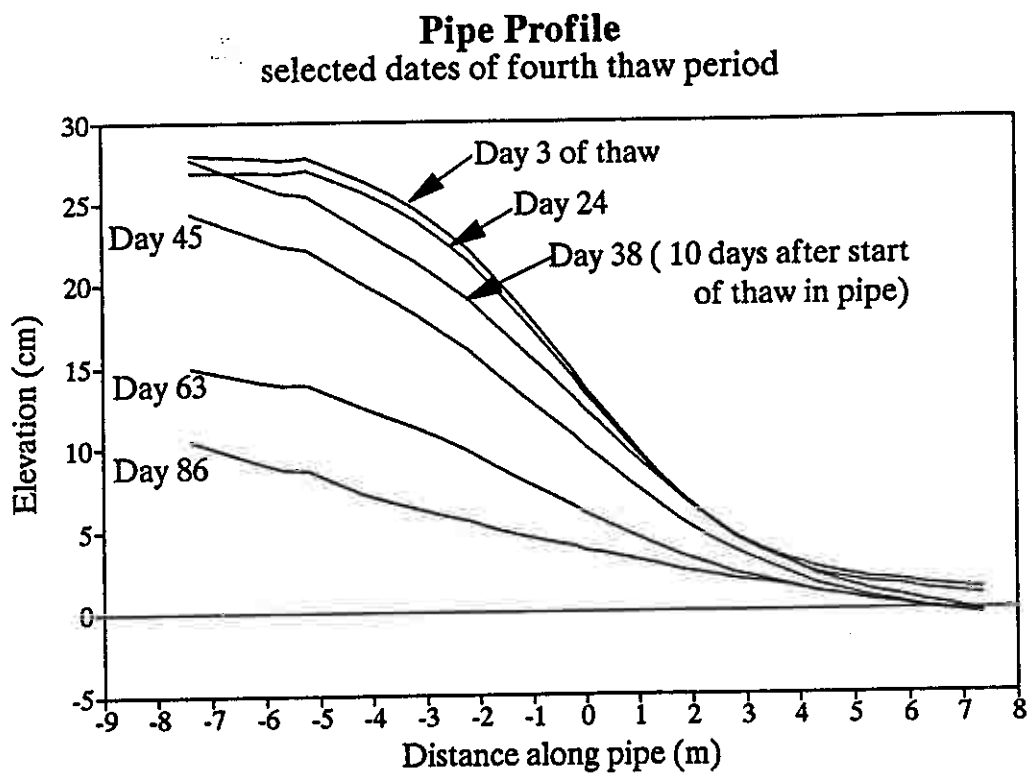


Figure 5

peak strain closer to the transition.

Figure 6 shows the elevation time series for selected pipe survey rods in the sand near the sand-silt transition. From the start of surface thaw, all points show a gradual decline in elevation. From the start of thaw around the pipe, however, pipe uplift is apparent in the three rods 0.8, 1.8, and 3.3 m from the transition. Uplift peaks about 10 days after the initiation of thaw

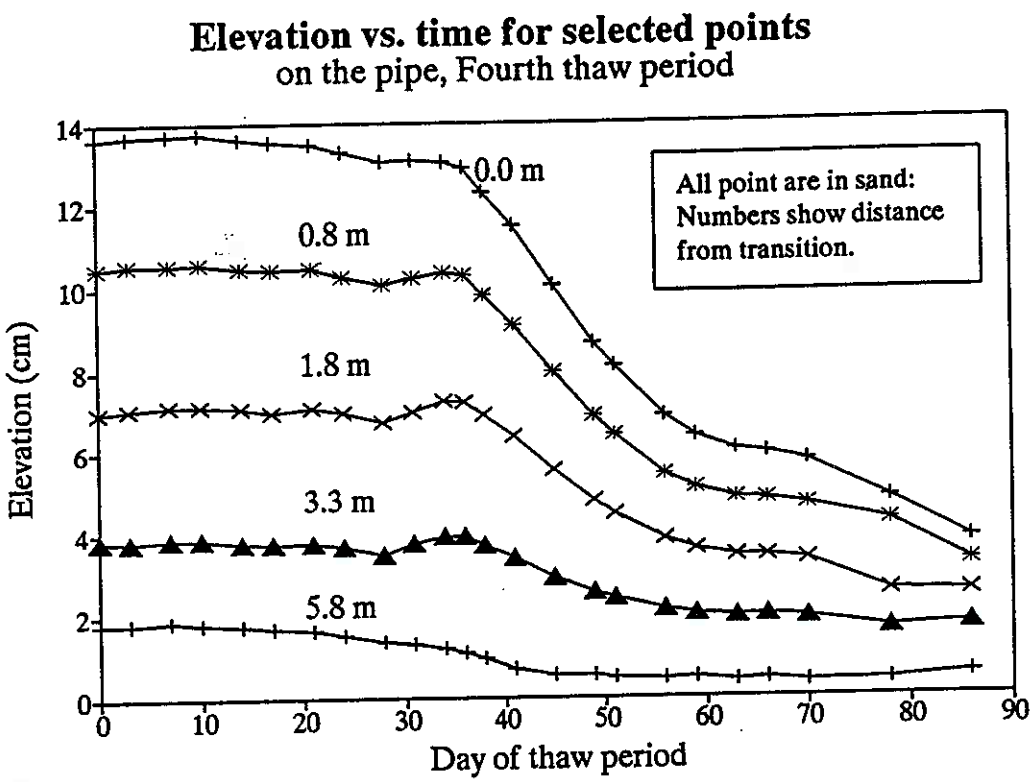


Figure 6

around the pipe. Figure 7 shows the behaviour of the same rods during the third thaw: in that period, the uplift behaviour can be observed in all rods, with peak uplift 1.8 m from the transition about 10 days after the onset of thaw.

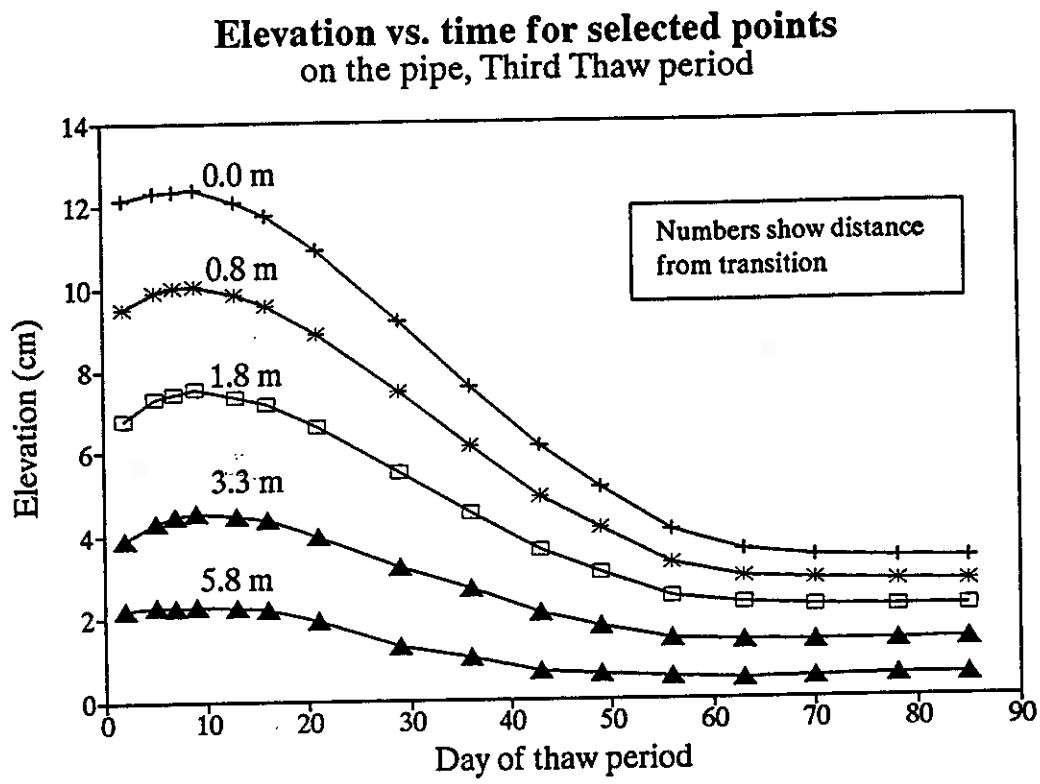


Figure 7

Maximum pipe uplift during the second, third, and fourth thaw periods is shown in Figure 8. This was calculated as the maximum elevation experienced during the thaw period minus the pipe elevation prior to the start of thaw (or, in the case of the fourth thaw, prior to the start of pipe thaw). In all three cases, the zones of pipe uplift are at the end of the pipe in the silt, and near the transition in the sand. Uplift was greatest at the end of

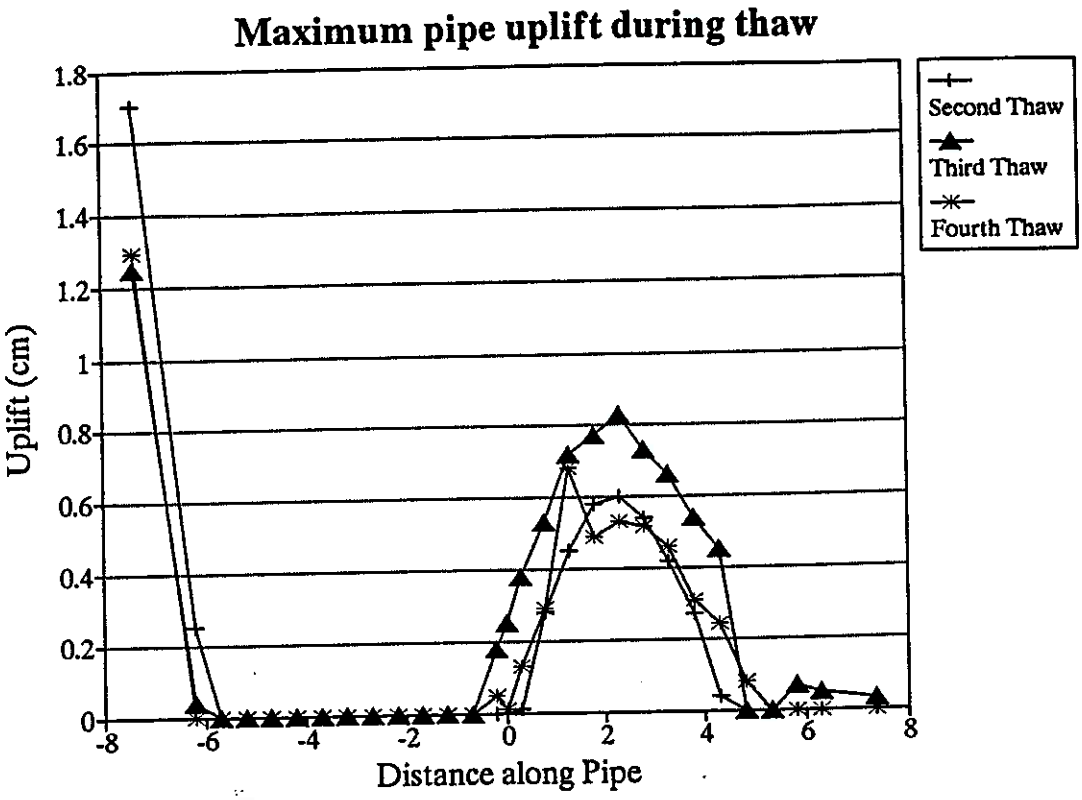
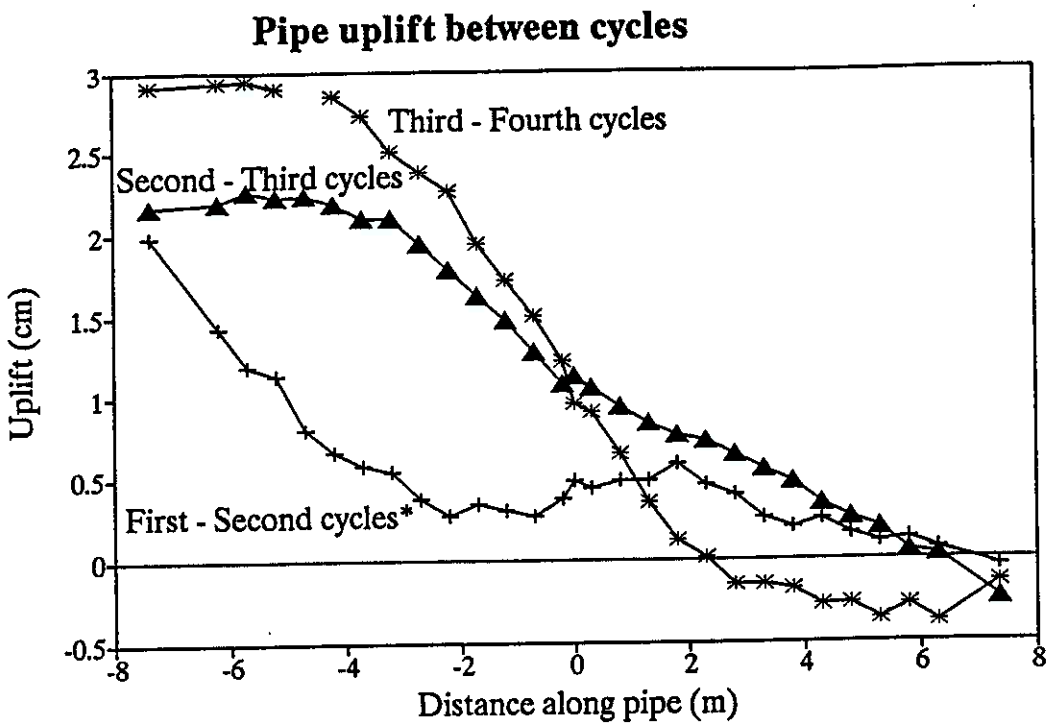


Figure 8

the pipe in all cases. Near the transition, uplift was greatest for the third thaw: the delayed thaw around the pipe during the fourth thaw makes it impossible to conclude about the magnitude of uplift in the fourth thaw relative to the magnitude of uplift in the previous cycles.

Figure 9 shows the amount by which the pipe was shifted upwards in each freeze-thaw cycle (calculated as the difference in position between cycles). It is clear that the process has accelerated with each cycle, due to the lower uplift resistance in each cycle. The lower resistance is the result of the shallower soil cover on the pipe with each movement, as well as the



* Datum for first cycle was different than for subsequent cycles: Position is approximate only.

Figure 9

development of cracks in the soil directly over the pipe.

2.3 Pipe stress

Figure 10 shows the profile of stress in the pipe for selected dates during the thaw period. During the period of surface thaw with freezing temperatures maintained in the pipe, stresses along the pipe reduced slightly (by 10 to 15%) in the zone between the points of peak stress, while the ends of the pipe experienced a slight increase in stress (Figure 11).

Following the initiation of thaw around the pipe, stresses near the transition (where stresses reach a peak in the freezing

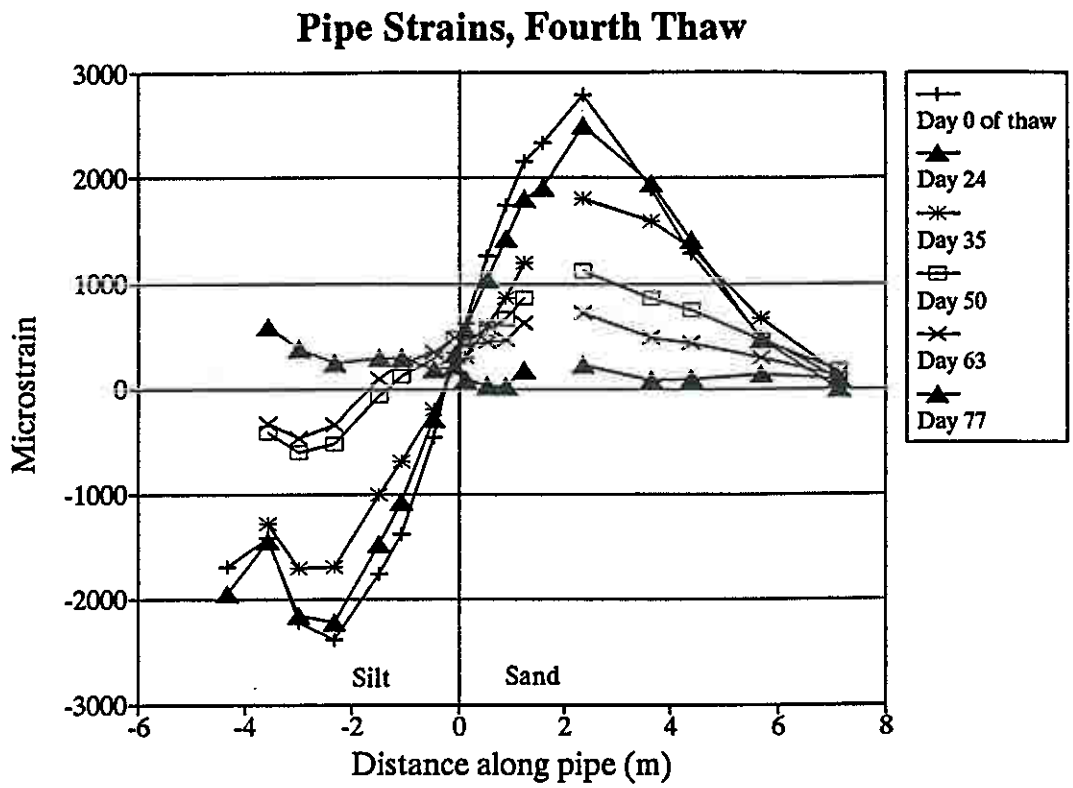


Figure 10

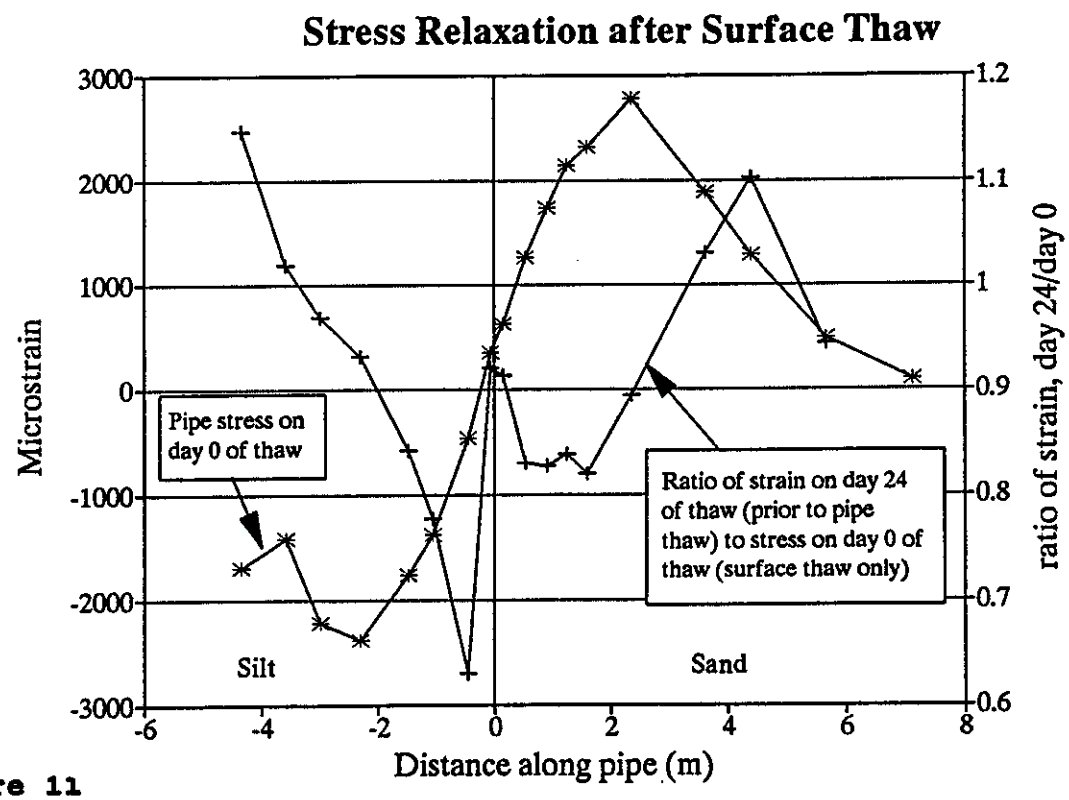


Figure 11

phase decline rapidly (approximately exponentially) with time (Figure 12). Stress at the end of the pipe increases significantly, to a level higher than that experienced during the freezing phase near the transition (Figure 13). The strain gauge 4.3 m from the transition fails at a level of approximately 2600 microstrain. This gauge was originally installed third from the end of the pipe: the two closer to the end failed after the second freezing cycle.

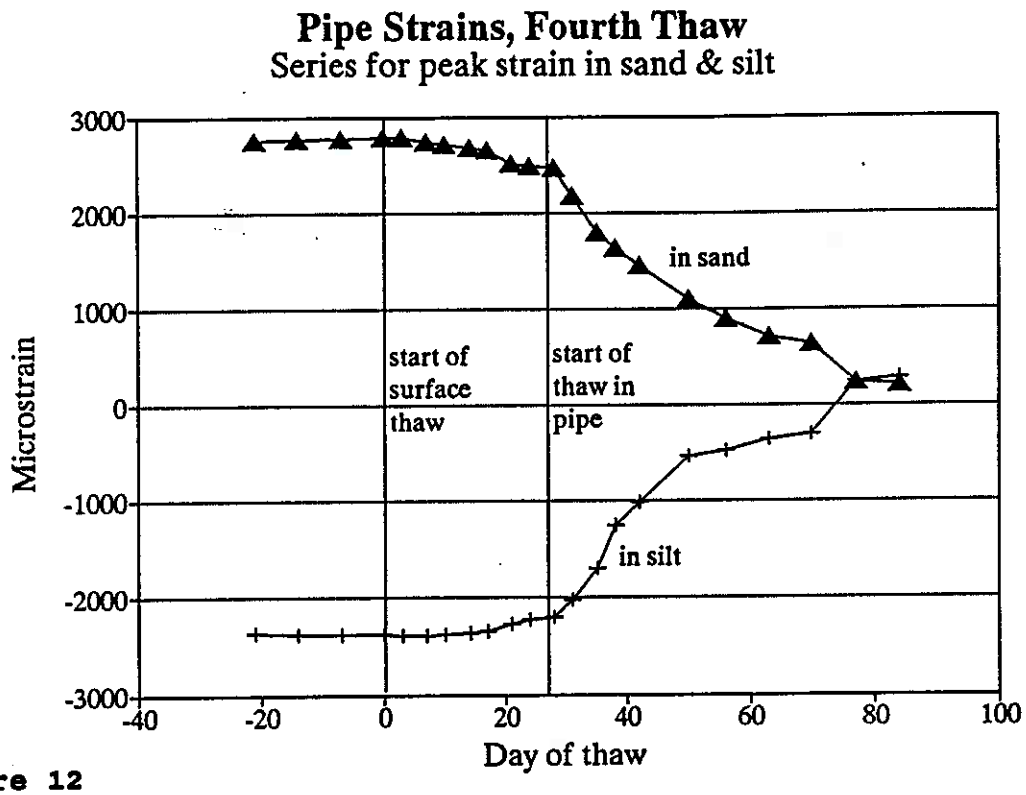


Figure 12

Strain behaviour at the end of the pipe was significantly different during the first thaw period. However, differences in thermal and soil conditions between the first and fourth thaw periods limit the usefulness of comparisons between them. Strain

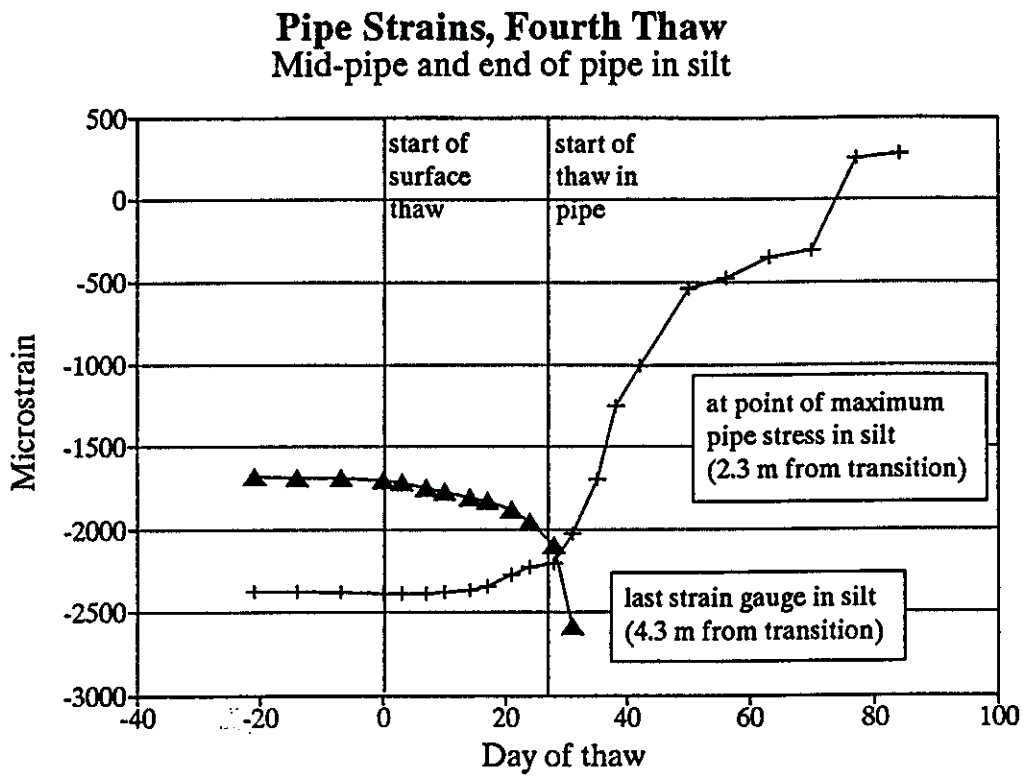


Figure 13

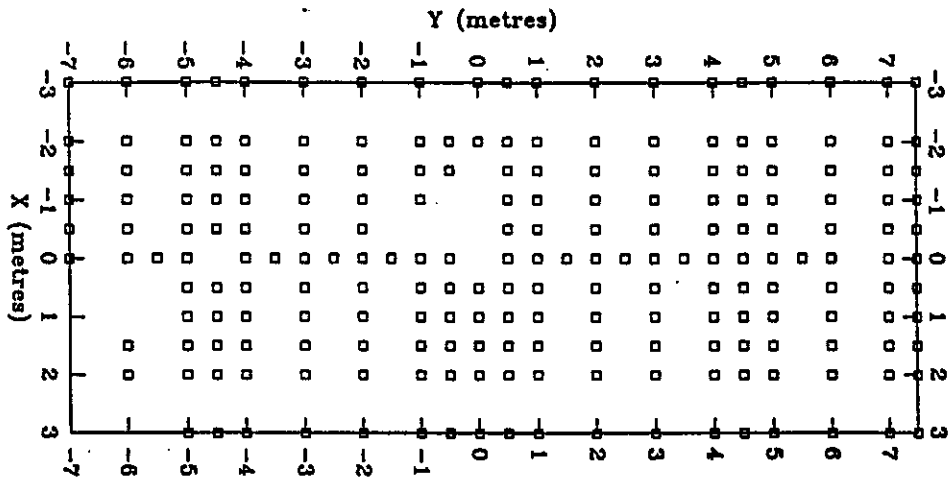
gauge data is not available for the second and third thaw periods.

2.4 Surface Levelling

The shape of the soil surface was recorded by optical survey of a grid of fixed points on the soil surface 0.5 m and 1 m apart (Figure 14) approximately once every two weeks during the thaw period. Manipulation of this data can reveal features of the spatial and temporal variation of the soil behaviour during the experiment. In this section, results for two simple manipulations of the surface heave data are presented:

- Total settlement, or the change in elevation from the start

of thaw.



Position of survey grid markers

Figure 14

- The changing spatial distribution of the rate of settlement over time.

Cumulative settlement

Settlement of the soil surface can be extracted from the surface survey data (Figure 15), by examining the change in elevation from the start of thawing. As the surface has become increasingly uneven with repeated freeze-thaw cycles, the shape of the surface during a thaw period is less a record of the actual pattern of thaw consolidation and settlement than a cumulative history of the segregation/consolidation and thaw settlement that

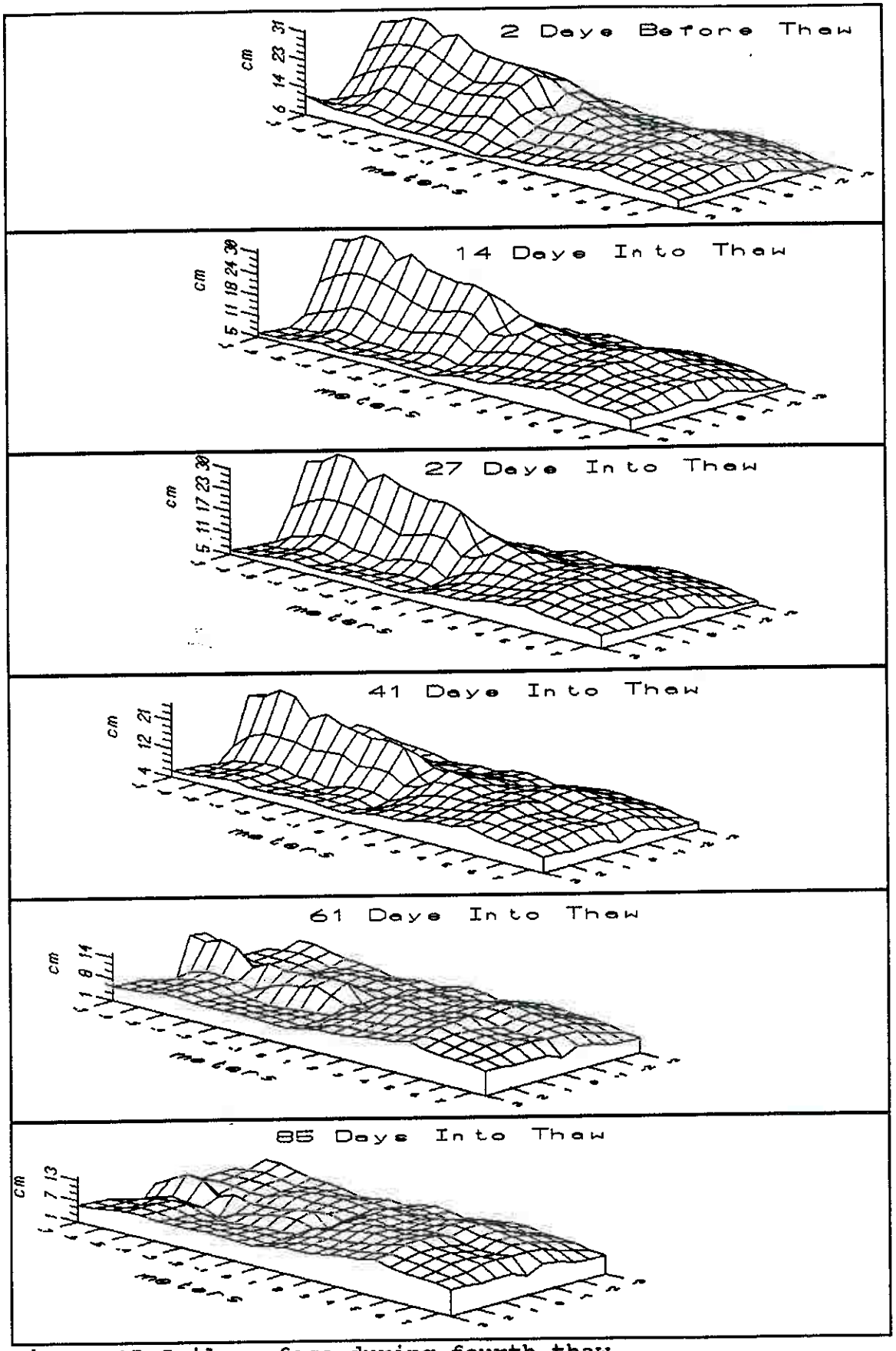


Figure 15 Soil surface during fourth thaw

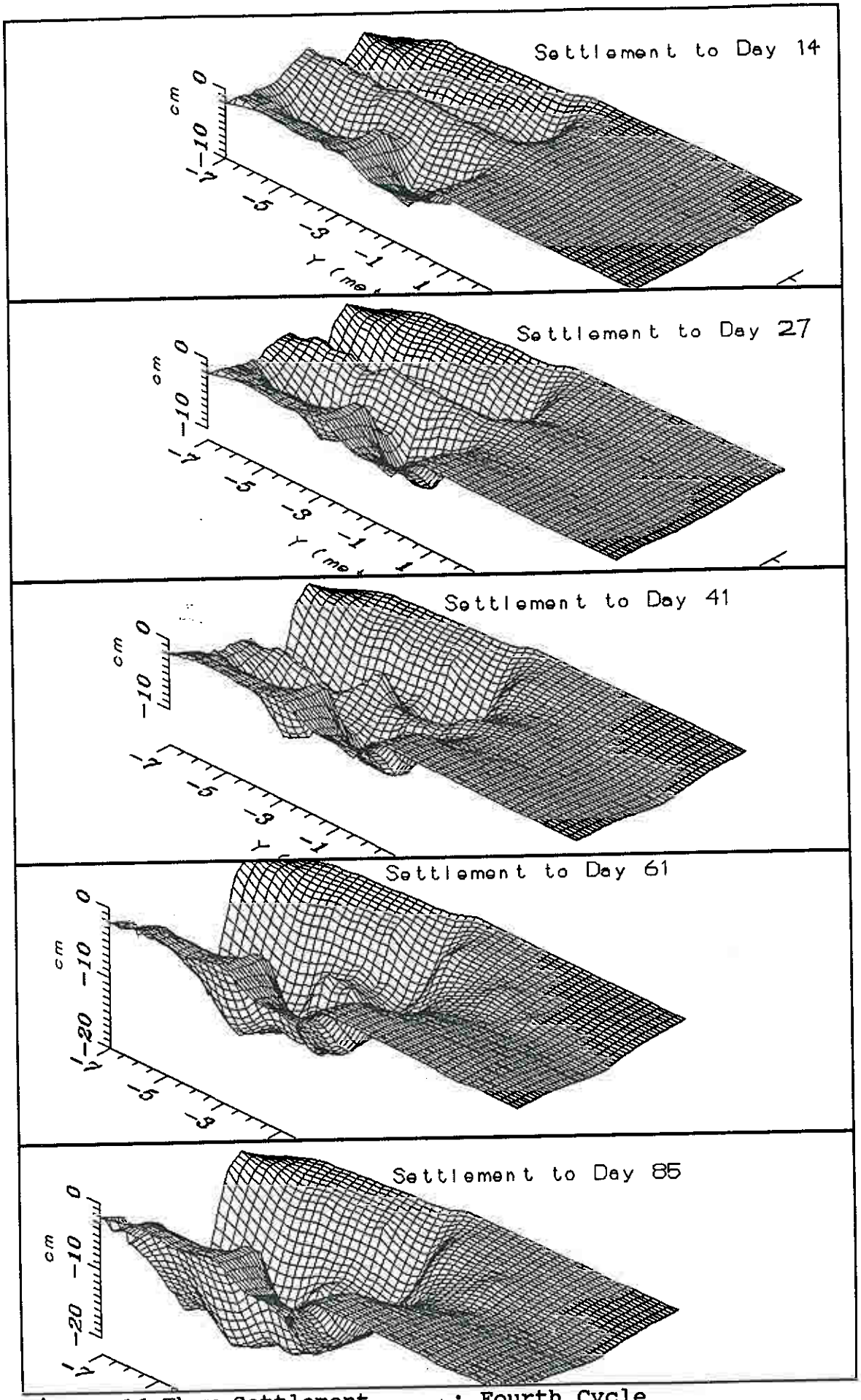


Figure 16 Thaw Settlement : Fourth Cycle

has occurred from the beginning of the experiment. Figure 16 shows the cumulative settlement of the soil for different dates of the freeze cycle. The dominant features of the series are the settlement adjacent to the pipe in the silt section prior to initiation of thaw in the pipe, followed by settlement beneath the pipe once thaw was initiated there. Almost no settlement occurs in the sand, except directly adjacent to the pipe.

Settlement rates over time.

The changing spatial distribution of the rate of settlement over time was calculated by examining elevation changes between dates within the survey record. Figure 17 shows the spatial variation in settlement rate calculated for different periods of the thaw. The dominant features of the series are :

- the rate of settlement is initially high throughout the silt section (except over the pipe and at the margins);
- following this settlement continues adjacent to the pipe, though at a reduced rate;
- with the onset of warm temperatures in the pipe, the rate of settlement is highest immediately below the pipe.
- the rate of settlement peaks in the period 43-63 days after the initiation of surface thaw (14-34 days after thaw around the pipe).

This pattern shows that the rate of soil thawing and the spatial distribution of ice within the soil combine to determine the spatial pattern of thaw settlement.

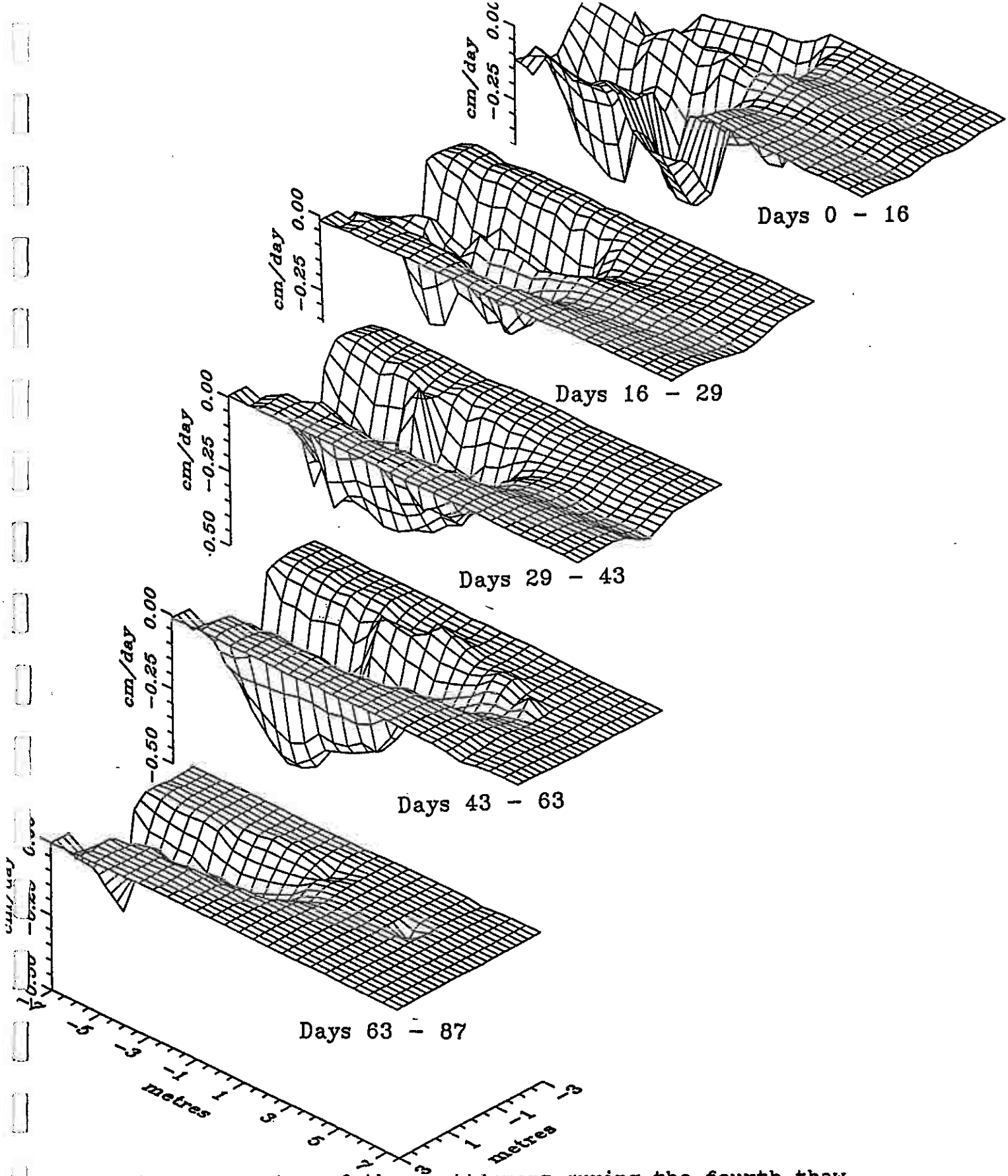


Figure 17 Rates of thaw settlement during the fourth thaw.

3 Soil Microstructure

The thermodynamic conditions within frozen ground at temperatures just below 0 C are such that there are continuing translocations of water, ice and the displacement of particles (Williams, 1982). The dynamic nature of frozen ground expresses itself in both micro and macromorphological changes which take place as a function of freeze-thaw cycling. The continuing internal deformation of frozen soil produced by small movements of ice, moisture and soil particles which collectively may produce creep (Williams, 1986) is thought to have caused an increasing heave susceptibility of the frost susceptible soil used in the experiment.

Micromorphological observations performed at the termination of the fourth thaw cycle reveal microstructural evidence of internal movement and reorganisation of soil fabric components. The resultant fabric type is believed to be responsible for the reported changes in permeability (Dallimore, 1984) and for increasing the frost heave potential of the soil.

3.1 Soil Sampling

Two undisturbed soil sample blocks of Caen silt were taken from a soil profile along the B B-axis located at a distance of 1 m from the side of the pipe (Figure 18). The first sample (Zone 1) is located at a depth of between 27 to 33 cm. below surface which corresponded to the position of the -0.5 C isotherm at the

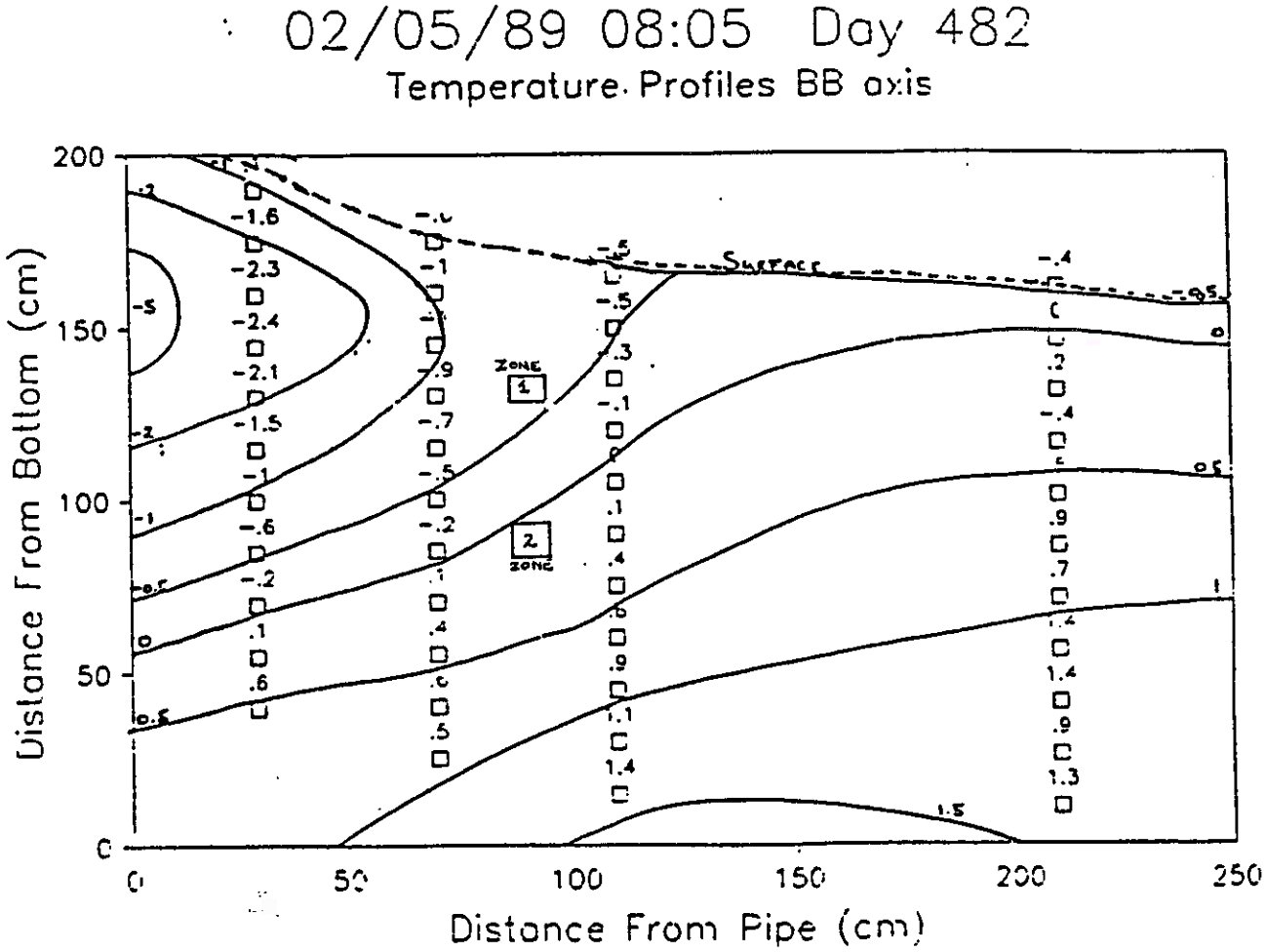


Figure 18

end of the fourth freeze cycle. The second sample (Zone 2) was taken from a depth of between 59 to 69 cm. below surface, a depth which corresponded to the maximum depth reached by the 0 C isotherm at the termination of the fourth freeze cycle. Soil samples from these two zones were allowed to air dry prior to shipment back to laboratories in Canada.

Soil sample preparation consisted of using one half of the specimens to conduct grain size analysis, sedimentation and mineralogical analysis of the clay size fraction. The second half of each specimen was impregnated with plastic resins from which

thin sections were prepared for the purposes of micromorphological analysis.

3.2 Mineralogy of Clay-Size Fraction

Samples of the clay-size fraction were separated by sedimentation. Scanning electron microscopy and X-ray diffraction analysis were carried out on oriented samples by allowing a suspension of the clay to dry slowly on glass slides. It was felt that from an understanding of the constituent clay mineral present, possible inferences could then be made regarding the development and arrangement of the soil fabric.

Electron micrographs for suspensions of clay taken from Zone 1 and Zone 2 were produced at both 1,000 x and 5,000 x magnification. A comparison of the relative abundance of clay size particles present in Zone 1 and Zone 2 is presented in Plate 1

Plate 1

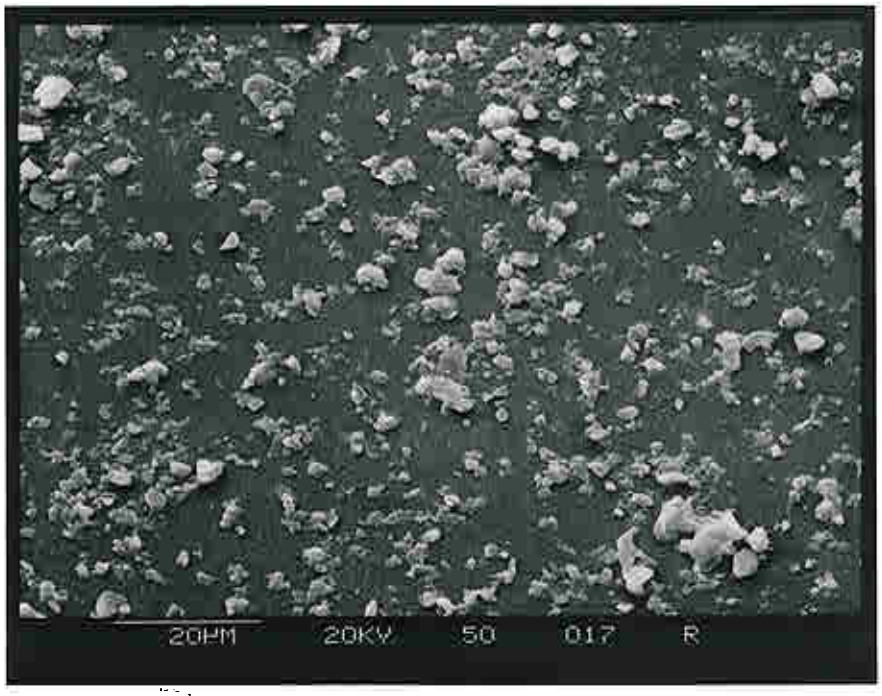


Plate 2

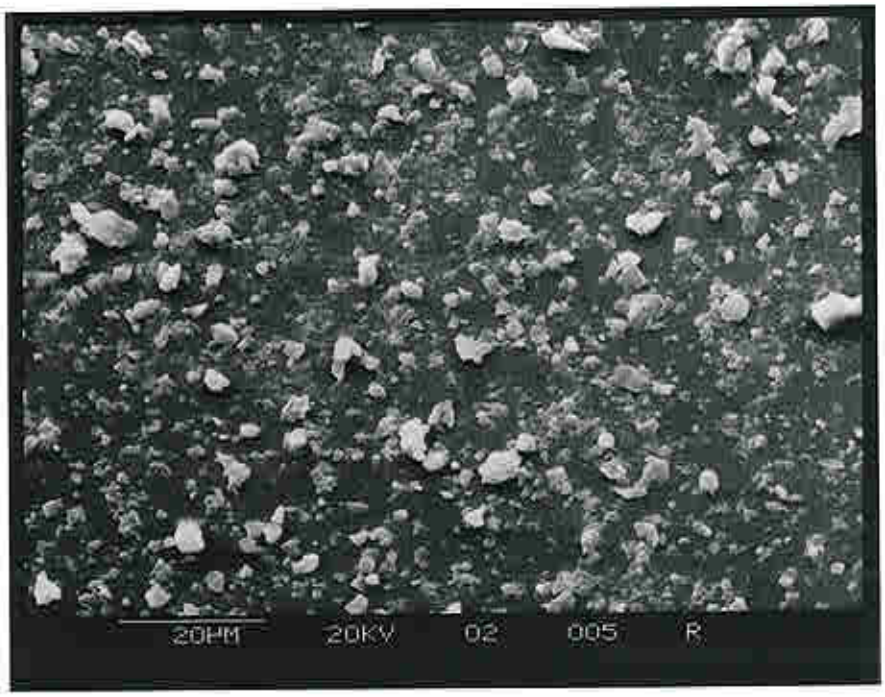


Plate 3

Plate 4

(1,000 x) and Plate 2 respectively. It would appear that there is a higher percentage of fines present in Zone 2 (59 - 69 cm below surface).

Micrographs produced at 5,000 x magnification for Zone 1 (Plate 3) and Zone 2 (Plate 4) reveal the presence of different mineral types in the clay size faction. Prominent in both plates is the well crystallised plate-shaped, six-sided clay mineral kaolinite, and some rounded grains of the mineral quartz distinguished by conchoidal fractures. Also present in both plates are irregular flake-shaped aggregates which appear as stackings of units without regular outlines. It was hoped that X-ray analysis would reveal the identity of these irregular masses.

A standard procedure involving three series of diffractograms was followed in the X-ray analysis of the orientated specimens. In the initial series two specimens prepared from the top and bottom of each zone were X-rayed as is (untreated), at relative humidity of 50% at 20 C. All the specimens produced the same X-ray diffraction patterns (Figure 19), thus inferring that the same minerals are present in both zones. For the second series a single specimen was saturated with 50/50 glycerol-water mixture and again X-rayed after overnight soaking. A final series was undertaken after this same specimen was heated to 400 C for one hour in a muffle furnace, cooled and X-rayed. According to the D-spacings produced by the three conditions (Figure 20), the clay minerals kaolinite, illite and smectite were present in Caen silt.

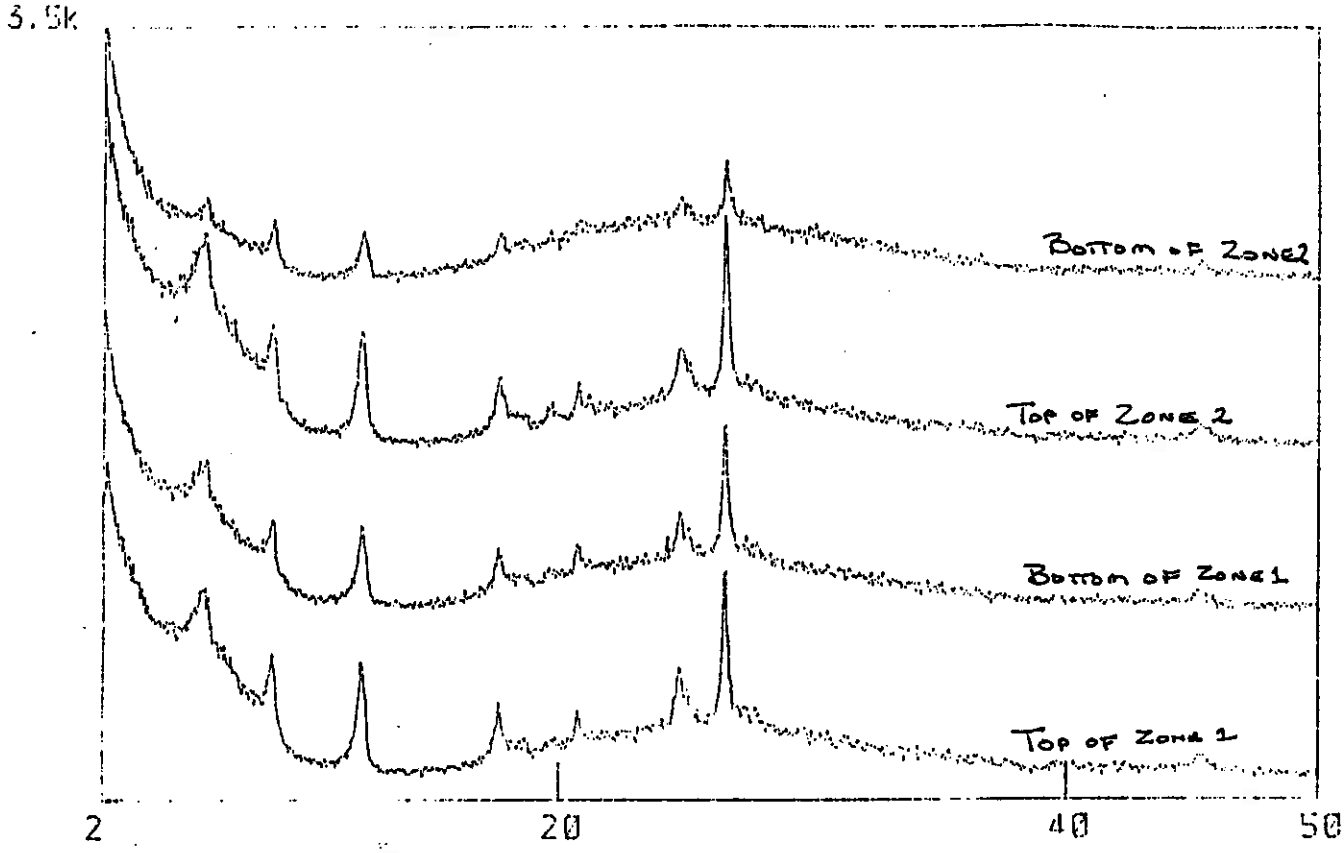


Figure 19 X-ray diffraction patterns for samples from top and bottom of zones 1 and 2.

3.3 Sample Preparation for Micromorphological Analysis

Soil thin sections (slides) were prepared from both samples after they had been impregnated with polyester resins. The theory of sample impregnation and thin section preparation is widely documented, having been described in detail by Osterkamp (1977), Fitzpatrick (1984) and Sheldrick (1984).

The soil micromorphology was described according to a glossary of micromorphological terminology produced by Howes and White (1990). Soil fabric descriptions were made from vertically

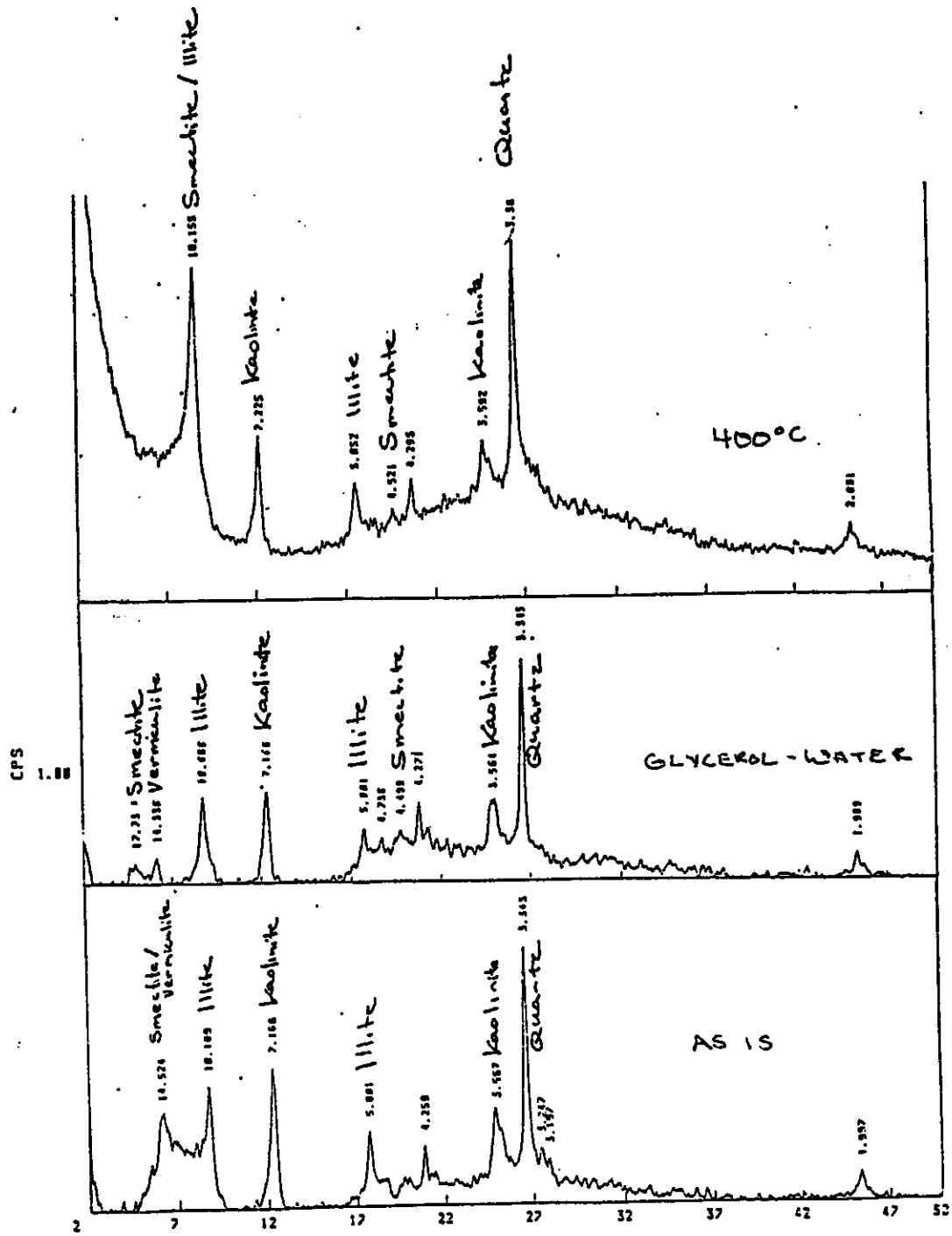


Figure 20 X-ray diffraction patterns for three sample conditions.

oriented thin sections at 25x magnification. Fabric description at 25x magnification provides an indication of the gross morphology that characterises the structures of the soil fabric (Fox 1979).

3.4 Observation and Discussion

Examination of the prepared thin sections reveal that a distinct granular fabric has developed in the samples taken from Zones 1 and 2. Plate 5 (Zone 1) shows finer colloidal material, clay accumulations (a) on the upper surface of a partially accommodated planar voids (b). This indicates accumulation above what was probably a former ice lens. Internal movement could be inferred from the tendency for accumulations to occupy voids left behind by segregated ice lenses.

Corte (1966) reported on separate experiments which involved cycles of freezing the soil from the top or from the bottom up and then thawing from the top. He inferred from the grain size analysis of the soil samples that during the freezing process there was a tendency for fine particles (<0.074 mm) to migrate to the freezing plane.

Plate 6 (Zone 1) shows iron oxide coatings on clay accumulations which have formed a series of bands (a) above a partially accommodated planar void (b). Here it is clear that preferential mobilisation of fines to surmount banded sediments and pressure stress accumulations adjacent to melted lenses are a major process (Bunting 1983). It is difficult to theorise whether these

assemblages of banded accumulations formed during one freeze-thaw cycle or represent the work performed by all four experimental freeze-thaw cycles.

Plate 7 (Zone 1) shows very thin infillings (a) beneath skeleton grains of the mineral quartz (b). Internal reorganisation of soil material can be inferred from the tendency for vertical or near vertical alignment of some of these skeleton grains (Fox and Protz, 1981). The upward movement of the larger skeleton grains (c) may have resulted from ice lenses or crystals of ice at the base of these grains. Thawing of the ice lenses and soil material adjacent to these skeleton grains would take place initially because of the higher thermal conductivity of the grains. The thawed finer material could slump into the space formerly occupied by the ice lenses, thus preventing the return of these grains to their original positions.

The near vertical or vertical alignment of these grains can be attributed to differential movement (French, 1976). The top of the grain would be captured by the advancing freezing front while the base remains unfrozen. Depending on the shear strength of the unfrozen soil, the axis of the skeleton grain may undergo rotation with the tendency being toward vertical alignment.

Plate 5.

Clay accumulations (a) on upper surface of a partially accommodated planar void (b). Zone 1; Plain Light; 25x

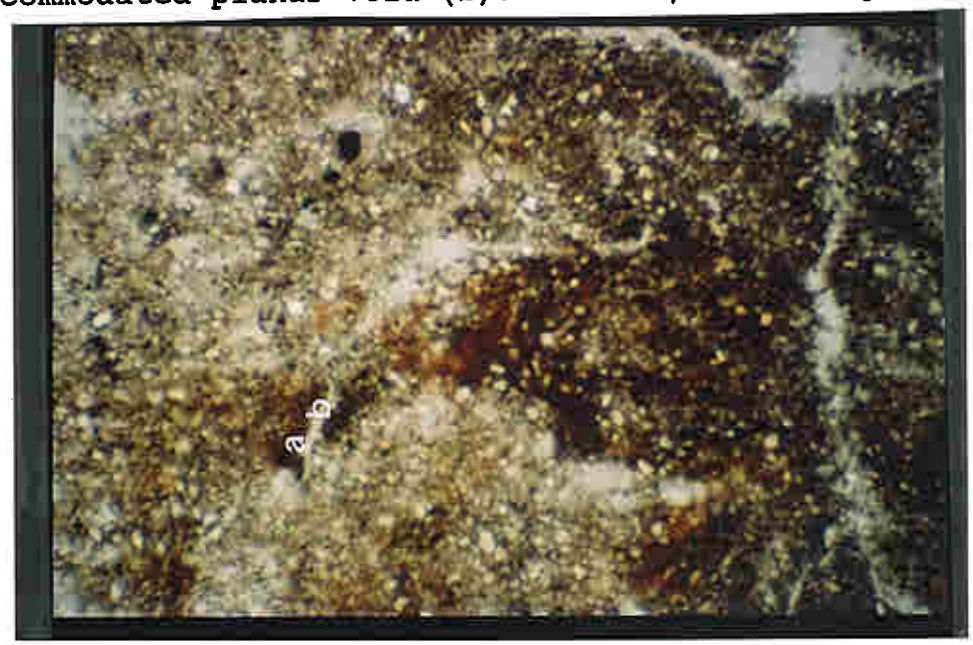


Plate 6.

Pressure stress accumulations (bands) of iron oxide coated clay (a), above partially accommodated planar void (b). Zone 1; Plain Light; 25x

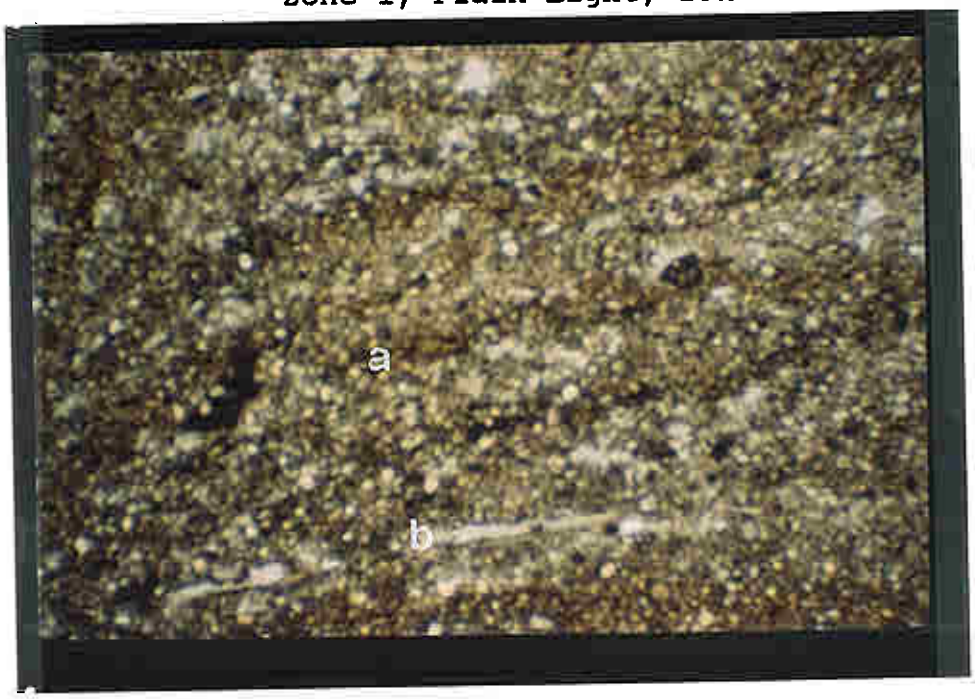


Plate 7.
Thin infilling (a) beneath skeleton grains (b).
Zone 1; Plain Light; 25x

Plate 8.

Dense granular structure of Zone 2. Plain Light; 25x.

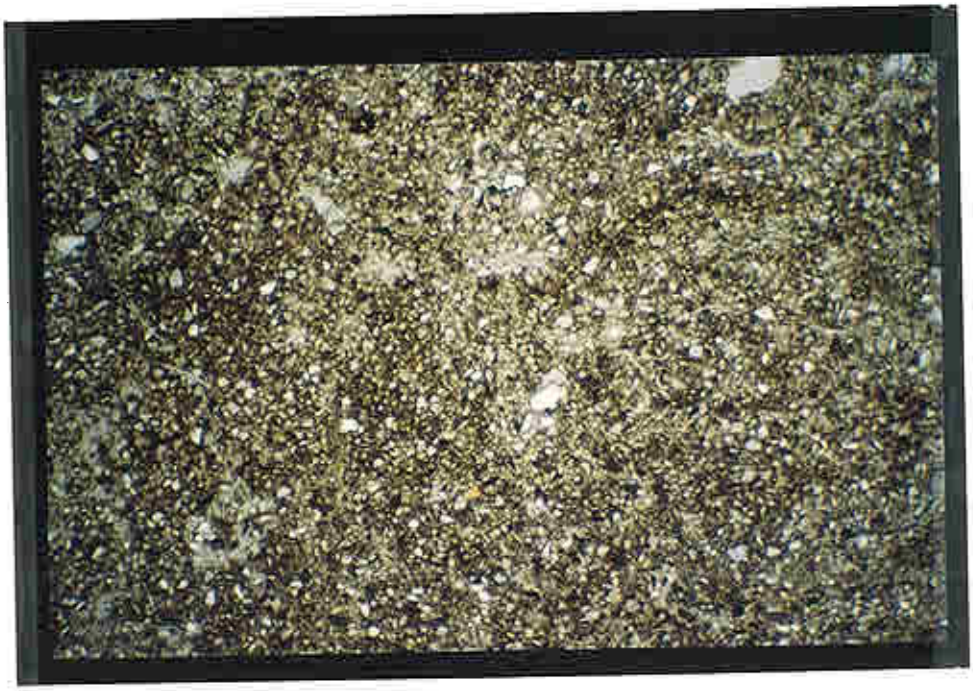


Plate 9

Granular structure of Zone 1. Plain Light; 25x.

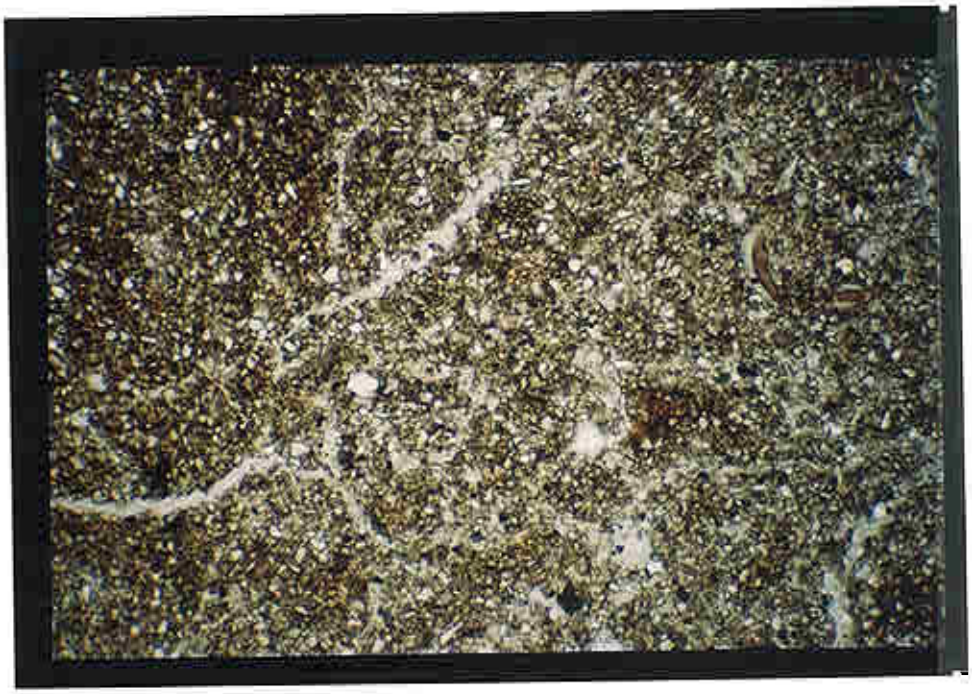


Plate 8 shows a much denser granular structure which characterises the soil taken from Zone 2 as compared to that of Zone 1 (Plate 9). Given the evidence presented in micrographs (Plates 1 through 4) it can be inferred that a much closer packing of the sand and silt grains has taken place. The clay minerals present in the void spaces which ordinarily have a flocculated orientation, collapsed during freezing to a more dispersed and denser structure (Chamberlain 1981). It can be theorised that some of the flake shaped aggregates which resemble stacking units observed in the micrographs (Plate 3) are the forms now assumed by some clay minerals (smectites) identified in the soil.

3.5 Conclusion: The Significance of Microstructural Genesis on the Performance of a Buried Chilled Pipeline

Microscopic observations performed on undisturbed frost susceptible soil samples adjacent to a buried chilled pipeline reveal the presence of new microstructural features. The translocation of water, ice, particles and small displacements associated with frost creep are collectively accountable for the ongoing microstructural genesis.

Table 1 indicates how, after each successive freeze/thaw cycle for two to four inclusive, the heave susceptibility of the Caen silt has continued to increase, albeit at a decreasing rate.

Table 1

Heave of Pipe in Caen Silt (Day 100)

Freeze Cycle	Heave (cm)	% Increase
Second	9.88	---
Third	10.77	9%
Fourth	11.40	5.8%

Given that both the carefully controlled thermal and hydraulic regimes for each of these freeze/thaw cycles have remained unchanged, it can be inferred that the reported changes in the soil's microstructure are accountable for the observed performance characteristics. Chamberlain and Gow (1979) have shown that the freezing and thawing of silt and clay slurries cause an increase in the vertical permeability and density at depth of their specimens. These changes were observed to alter

the frost heave potential of the soil from the first freeze/thaw cycles to the second and third cycles.

Dallimore (1984) reported similar findings for changes in hydraulic conductivity of Caen silt after performing detailed analysis of frozen and unfrozen sections of samples exposed to several freeze/thaw cycles. Unfrozen sections were observed by Dallimore to become less permeable after several thaw consolidation cycles, while conversely, the frozen soil sections experienced an increase in vertical permeability, from 8 x 10 cm to 3 x 10 cm .

Micromophological evidence indicates that distinct micro-fabric patterns have resulted from the cryogenic processes that are active in this soil adjacent to a buried chilled pipeline. The rearrangement of both the skeleton grains and plasma or f- members and f-matrix have resulted in a soil micro-fabric which changes as a function of position to freezing front. The observed micro-fabric patterns of Zone 1 (-0.5 isotherm) can be held accountable for the increased hydraulic conductivity which has been reported. Conversely the much more closely packed granular microstructure observed to occur just below the 0 C isotherm in Zone 2 would account for its decreasing hydraulic conductivity.

From this it is clear that the effects of microstructural

changes which affect frost susceptibility of soil needs to be determined after several freeze/thaw cycles in order to better evaluate soil/pipe interaction which occurs in situ in the field.

Additional micromorphological research, together with experimental studies are still required to assess what mechanisms induced by cryogenic processes will cause the distinct reorganisation of the microfabric reported in this report.

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