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**AN EXPERIMENTAL STUDY ON THE INFLUENCE OF
CLIMATIC FLUCTUATIONS ON SOLIFLUCTION,
FOSHEIM PENINSULA, ELLESMERE ISLAND, N.W.T.**

by

© Shawne Clarke

**A thesis submitted in conformity with the requirements
for the degree of Master of Arts
Graduate Department of Geography
University of Ottawa**



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Abstract

A field experiment, involving direct manipulation of surface microclimate, was undertaken in the continuous permafrost zone to examine the influence of climatic fluctuations on solifluction rates and movements throughout the active layer. Movements and soil temperature were measured continuously from 1993-1997 using five electro-mechanical meters and thermocouple cables on an 8° colluvial slope in Hot Weather Creek valley, Ellesmere Island. Natural variation of movement among the years and the meters was measured until summer of 1996 when surface climatic treatments (surface warming, wetting, a combination of these two, and cooling) were performed. The longer-term effects of the treatments were monitored until August 1997.

Near-surface rates of movement and volumetric transport rates ranged between 0.8 and 1.9 cm yr⁻¹ and between 42 and 82 cm³ cm⁻¹ yr⁻¹ respectively, during the pre-treatment period. The warming and cooling treatments were successful in manipulating active layer depths, however the impact of the wetting treatments was not clear due to the high amounts of precipitation that were received in 1996. The two meters that were warmed recorded larger amounts of both near-surface movement (3.0 and 2.9 cm yr⁻¹) and volumetric transport (185 and 108 cm³ cm⁻¹ yr⁻¹) during treatments than the other meters, where near-surface movement ranged from 1.6 to 2.0 cm yr⁻¹ and volumetric transport was from 66 to 78 cm³ cm⁻¹ yr⁻¹. Ice lenses at the base of the active layer surrounding the warmed meters were thawed, releasing moisture and causing greater settlement and forward movement. Higher levels of moisture resulted in greater volumetric transport at the experimental site. For example, movement in 1996 at the control meter was greater than that recorded in 1994 and 1995, even though the depth of thaw was shallower. Considerable near-surface movement (2.0 to 4.1 cm yr⁻¹) and volumetric transport amounts (105 to 180 cm³ cm⁻¹ yr⁻¹) in 1997 are attributed primarily to a lag effect of high moisture levels in 1996. In the dry environment of the Fosheim Peninsula, moisture is the primary controlling factor on amounts of solifluction, with air temperature influencing moisture availability and distribution within the soil, and ice lens formation.

Near-surface measurements alone do not provide an accurate picture of solifluction in areas with two-sided freezing ("cold" permafrost) because there can be substantial variation in movement rates at depth. In addition, multi-year average rates potentially hide a considerable range of annual variability and do not allow for the examination of a relationship between climatic fluctuations and annual movement. In particular, the sequence in which warm, cool, wet and dry years occur influences the distribution of moisture within the active layer and the depth of thaw, and as a result, the total movement. Further study of the link between current climate and movements in areas of two-sided freezing is required to assist in palaeoclimatic reconstructions based on solifluction movements.

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Chapter 1. Introduction

1.1 Objectives

Although a considerable literature exists concerning solifluction, details of the processes responsible for movement in an area of two-sided freezing remain unclear. In addition, few data are available concerning inter-annual variability of volumetric transport and the role that fluctuations in climate may play in causing variability in movement through the soil profile.

An experimental site was established in 1992 on the Fosheim Peninsula, Ellesmere Island, in order to continuously monitor solifluction in an area of two-sided freezing. A detailed examination of the process of solifluction in terms of both inter- and intra-seasonal movements was planned, to better understand its various components. Climatic treatments carried out in 1996 were performed in order to examine their influence on movement.

1.2 Definitions and descriptions

1.2.1 Solifluction

Solifluction is considered to be one of the most important and widespread mass movements in the active layer in permafrost environments (Washburn, 1980; Mackay, 1981; Egginton and French, 1985; Lewkowicz, 1992a; Åkerman, 1996; French, 1996). It is a process of mass wasting which occurs in non-permafrost, discontinuous and continuous permafrost zones. Although the activity of this process in non-permafrost and discontinuous zones is discussed below, the focus of this thesis is on solifluction in the continuous permafrost zone.

The term solifluction was first used in 1906 by Andersson to describe "the slow flowing from higher to lower ground of masses of waste saturated with water" (*in* Harris, 1981). Since that time,

many authors have interpreted and redefined the term. After considering closely the meaning of each specific term used in the definition and reviewing the interpretations of other authors, Harris (1981) summarized his findings by defining solifluction as "the slow downslope flow of water saturated sediments due to the combined effect of gelifluction and frost creep". French (1996) wrote that in addition to gelifluction and frost creep, plug-like flow should be included within the definition of solifluction where conditions of two-sided freezing exist.

In contrast, both McRoberts and Morgenstern (1974) and Williams and Smith (1989) defined solifluction in terms of form, rather than genetic origin. Williams and Smith (1989) believed that for the purposes of their discussion, sufficient uncertainty exists as to the processes which are responsible for the creation of these forms, that it is useful to restrict the term to the forms themselves.

For the purposes of this thesis, a modified version of Harris' definition is used to define solifluction: the slow downslope movement of unfrozen sediments due to the combined effect of frost creep, gelifluction and plug-like movement. The word "saturated" has been omitted as, although it is recognized that moisture is a required condition for the occurrence of solifluction (Washburn, 1967), it is not clear whether saturation is a necessary condition (Williams and Smith, 1989) for all the components of movement (e.g., frost creep).

1.2.2 Frost creep

Frost creep is described as the ratchet-like downslope movement of particles produced by frost heaving of the ground and subsequent settling upon thawing - the heaving being predominantly normal to the slope and the settling more nearly vertical (Washburn, 1967; Benedict, 1970; French, 1993). Frost creep is not restricted to permafrost areas as its occurrence is only dependent on the freeze-thaw cycle (Lewkowicz, 1988). Some of the primary variables which influence rates of creep in an area of one-sided freezing include the frequency of freeze-thaw cycles, slope angle, moisture available for heave and the frost-susceptibility of the soil (French, 1996). As a result of detailed study

in an area of two-sided freezing, Mackay (1981) found that heave, an element of frost creep, was a year-round slope process. Not only was heave detected during the fall freeze-up period, but also throughout the rest of the year as moisture either percolated downward or was redistributed within the active layer, forming new ice lenses. It is widely accepted that frost creep in an area of one-sided freezing results in a concave downslope movement profile as movement decreases rapidly with depth (e.g., Washburn, 1980; Mackay, 1981; French, 1996) (Figure 1-1A). In an area of two-sided freezing, it is much more difficult to distinguish movement attributable solely to frost creep (Lewkowicz, 1988). In addition, movement which occurs as a result of frost creep in an area of two-sided freezing may be quite different from that observed in an area of one-sided freezing (see section 1.2.5 Plug-like movement). If it were possible for it to operate in isolation, frost creep in an area of two-sided freezing could result in a concave-convex profile (Figure 1-1A).

1.2.3 Gelifluction

As described by Washburn (1967, 1980), gelifluction is the slow downslope flow of saturated soil associated with perennially frozen ground. Gelifluction is most likely to occur in areas where the downward percolation of water is restricted (generally due to a frozen soil layer) and the melting of ice lenses results in excess porewater pressure which reduces the frictional strength of the soil (Harris, 1987b; French, 1993). These ice lenses form as a result of ice segregation, and upon melting, supply more water than can be contained within the thawed pore spaces. The pressure from consolidation of the thawing soil is therefore applied to the porewater and as a result, the frictional strength of the soil is decreased and downslope movement of soil can occur, even on slopes with very low gradients (McRoberts and Morgenstern, 1974). Additional water, that could increase the likelihood of the occurrence of gelifluction, is sometimes supplied by meltwater runoff from accumulated snow or from rainfall in the late spring or early summer months (Price, 1991). Williams and Smith (1989) suggested that excess porewater pressures may not be adequate to explain the occurrence of gelifluction and recent experimental results from Harris *et al.* (1995) support this view. In laboratory simulations of one-sided freezing, Harris *et al.* (1995) concluded that movement in the form of

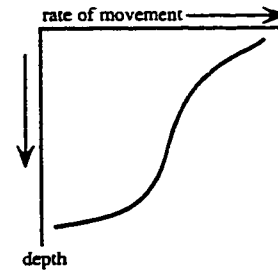
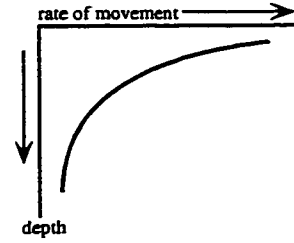
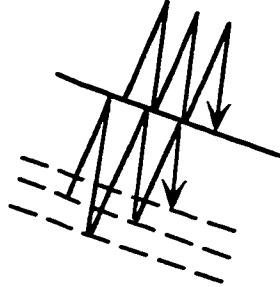
Figure 1-1. Solifluction processes and resultant vertical velocity profiles.

A) Frost creep

(i) one-sided freezing



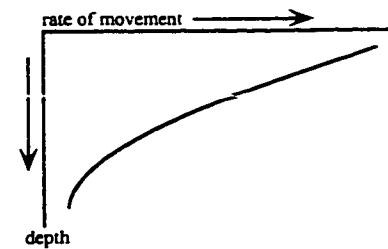
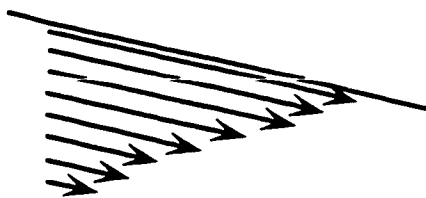
(ii) two-sided freezing



B) Gelifluction

(i) one-sided freezing - same as two-sided freezing.

(ii) two-sided freezing

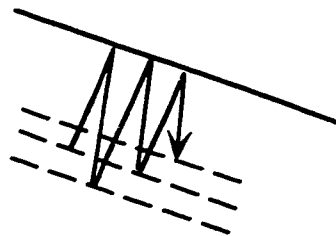


C) Plug-like movement

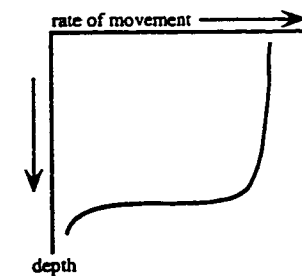
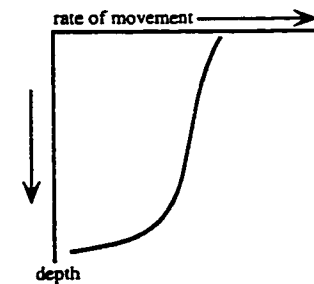
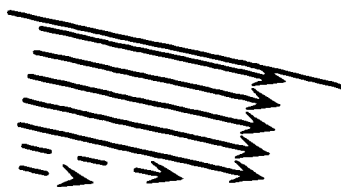
(i) one-sided freezing - has not been recorded.

(ii) two-sided freezing

(a) settlement of entire active layer



(b) shear at base of active layer



———— ground surface
 - - - - - base of active layer

viscous flow occurred while moisture contents of the soil were high during thaw but that traditional slope stability analysis could not explain the stress-strain relationships which they recorded.

Due to the need for a water supply for the initiation of gelifluction, the majority of movement in an area of one-sided freezing occurs during the spring melt season. According to Mackay (1981), in an area of two-sided freezing, most movement occurred in late summer, as by that time, the ice-rich zone at the base of the active layer is thawing. French (1996) referred to gelifluction as "classic" solifluction and described it as laminar in nature. Washburn (1980) expressed uncertainty as to whether movement occurs as a result of flow or by sliding along discrete shear planes, or a combination of the two processes. Regardless of the precise mechanism of movement, gelifluction, as defined herein, generally results in a concave downslope movement profile (Price, 1991; French, 1996), whether active in an area of one- or two-sided freezing (Figure 1-1B).

1.2.4 Plug-like movement

In addition to frost creep and gelifluction, Mackay (1981) discussed a "plug-like" movement which occurred as a result of frost creep late in the summer when the active layer had attained its greatest depth. During summer, the refreezing of thaw water at the base of the active layer increased the amount of ice lensing and caused additional frost heave to occur. When the thawing front reached the ice-rich basal zone, a downslope settling of the entire active layer occurred. Sliding of the relatively undisturbed active layer occurred along the top of the permafrost table (Mackay, 1981). The movement was characterized by a convex downslope movement profile (Figure 1-1C). While Mackay attributed plug-like movement to the settlement component of frost creep, other authors (e.g., Rein and Burrous, 1980; Lewkowicz, 1988; Williams and Smith, 1989; Lewkowicz and Clarke, 1998) referred to zones of shearing at the base of the active layer and high porewater pressures, suggesting a greater similarity to gelifluction. If plug-like movement is considered to occur as a result of frost creep, the vertical velocity profile due to frost creep in an area of two-sided freezing will be concave-convex downslope (Figure 1-1C). There does not appear to be any mention in the literature of the

shape of the velocity profile due to frost creep in an area of two-sided freezing if plug-like movement is considered to be separate from frost creep.

For the purposes of this thesis, plug-like movement is regarded as a separate component of solifluction.

1.2.5 Thaw consolidation

Thaw consolidation is described by Taber (1943, *in* Harris, 1981) as a loss of soil strength which occurs as a result of the thawing of ice-rich soils. When thaw proceeds at a rate greater than possible drainage of the resultant water, a portion of the consolidating soil particles transfer their weight to the pore water, thus reducing the normal stress and resulting in a reduction of soil strength (Morgenstern and Nixon, 1971; Williams and Smith, 1989). French (1996) noted that it is likely that thaw consolidation is the common mechanism behind the process continuum which exists between slow and rapid mass movements. Gelifluction is regarded by many geotechnical engineers as one form of thaw consolidation (French, 1996). A combination of two factors determines the slope instability which may occur as a result of thaw consolidation: rate of thaw and properties related to consolidation of the soil (Williams and Smith, 1989).

1.2.6 Differentiation between frost creep and gelifluction

Even though frost creep and gelifluction are theoretically described as two separate processes, the term solifluction is used by many authors to refer to the downslope movement occurring as a result of a combination of these two processes (e.g., Harris, 1981; Lewkowicz, 1988; Åkerman, 1996; French, 1996). This is primarily due to the difficulty in differentiating in the field between the two types of movement. It is particularly difficult in areas of two-sided freezing to distinguish between gelifluction, frost creep and plug-like movement, as defined here, occurring during the thaw season. As Lewkowicz (1988) concluded, "...it appears that at present it is more valid to lump together measurements of frost creep and gelifluction in continuous permafrost areas". Greater clarity in

future publications would also help others to understand whether a movement is being described as sliding, settling or flowing, each of which has particular geomorphic significance.

1.3 Contemporary solifluction research

1.3.1 Measurement techniques

Various methods have been used to measure current rates of solifluction. Surface movement has been monitored using painted stones, pegs and cone targets (e.g., Washburn, 1967; Jahn, 1978; Åkerman, 1996). Vertical displacement of the ground due to frost heave has been measured using a displacement transducer (Matsuoka, 1994) and a heavemeter (Mackay *et al.*, 1979 in Mackay, 1981). To measure ongoing subsurface movement, flexible plastic tubes (e.g., Mackay, 1981; Harris, 1987b), buried columns (Benedict, 1970; Jahn, 1978; Åkerman, 1996), electrical resistance strain gauges (e.g., Williams, 1957; Matsuoka, 1993; Yamada and Kurashige, 1996) and aluminum foil stripes (e.g., French, 1974; Egginton and French, 1985; Åkerman, 1996) have been used to monitor variations with depth. Recently, Lewkowicz (1992a) devised a solifluction meter that measures soil movement at several depths within the active layer.

1.3.2 Measurement difficulties

There are several difficulties that arise when measuring solifluction rates. There is some concern regarding the ability to apply findings from one study to another if different methods of measurement have been used (Benedict, 1970). In situations where only surface measurements are collected and there is no information on the movement profile, it may be difficult to fully understand the subsurface processes which are occurring. The relative importance of solifluction as a mass movement will also not be clear without knowing precisely the volume of soil that is being moved. Flexible plastic tubes used in subsurface measurements may be too rigid to accurately reflect movement at different levels (Mackay, 1981), nevertheless, they can provide a relatively good indication of volumetric transport (e.g., Mackay, 1981; Price, 1991). There is, however, likely to be a

certain amount of displacement of the tube in an upslope direction in reaction to a downslope force applied elsewhere along the tube. In addition, a tube cannot monitor the heave of soil which may occur in the soil profile (Jahn, 1978). Many of the techniques for measuring subsurface movement (e.g., buried columns, foil stripes) allow only for a single set of measurements to be made upon excavation of the equipment.

1.3.3 Rates of movement

Surface rates of solifluction vary considerably as shown by a review of the literature (Table 1-1). Surface rates of movement range from 0.4 - 12.0 cm/year in permafrost areas, and 0.0 - 8.0 cm/year in non-permafrost areas. In a review of studies from polar, subpolar and alpine environments, Benedict (1976) found that the median maximum velocity for lobes and terraces was 3.0 cm/year whereas for patterned and undifferentiated slopes the value was 2.6 cm/year. The relative importance of frost creep and gelifluction varies spatially and temporally, depending on the prevailing environmental conditions (Harris, 1981) (Table 1-2).

Table 1-1. Selective review of solifluction rates in permafrost and non-permafrost areas.

Permafrost Studies

Study Author	Location	Surface Rate (cm/yr)	Slope (°)	Reference
Jahn, 1960	Spitsbergen	1.0 - 3.0	3 - 4	French, 1996; Washburn, 1980.
Jahn, 1961	Spitsbergen	5.0 - 12.0	7 - 15	French, 1996; Washburn, 1980.
Barnett, 1966	Baffin Island, NWT	.75 - 5.2	5	Harris, 1981.
*Williams, 1966	Schefferville, Québec	9.8	4 - 16	Williams, 1966.
Washburn, 1967	Mesters Vig, Greenland	.9 - 3.7	10 - 14	Washburn, 1980.
†Benedict, 1970	Colorado Rockies	.4 - 4.3	5 - 18	Benedict, 1970.
French, 1974	Sachs Harbour, Banks Island, NWT	1.5 - 2.0	3	French, 1996.
Jahn, 1976	Spitsbergen	2.0 - 4.0	11	Harris, 1981.
Mackay, 1981	Garry Island, NWT	.4 - 1.0	1 - 7	French, 1996.
Egginton & French, 1985	Eastern Banks Island, NWT	0.6	<10	French, 1996.
Price, 1991	Ruby Range, Yukon Territories	0.53 - 2.05	14 - 18	Price, 1991.
Matsuoka & Moriwaki, 1992	Sør Rondane Mountains, Antarctica	<0.1 - 1.5	10 - 20	Matsuoka & Moriwaki, 1992
Åkerman, 1996	Spitsbergen, Svalbard	stripes 1.4 - 2 steps .9 - 2.2 lobes 3.3 sheets 4.3	2 - 25	Åkerman, 1996.
Lewkowicz & Clarke, 1998	Fosheim Peninsula, Ellesmere Island	1.7 and 3.1	-	Lewkowicz and Clarke, 1998.

* Located in discontinuous permafrost zone. † Permafrost may be present.

Non-permafrost Studies

Study Author	Location	Surface Rate (cm/yr)	Slope (°)	Reference
Rapp, 1960	Kärkevagge, Sweden	4.0	15	French, 1996.
Rudberg, 1962	Tärna area, Sweden	.9 - 1.8	5	French, 1996; Washburn, 1980.
Rudberg, 1964	Norra Storfjäll, Sweden	.9 - 3.8	5	French, 1996; Washburn, 1980.
Harris, 1973	Okstindan, Norway	0.0 - 6.0	4 - 17	Harris, 1973.
Gamper, 1983	Swiss Alps	1.5 - 6.5	--	Gamper, 1983.
Smith, 1992	Canadian Rockies, Alberta	0.1 - 1.17	12 - 32	Smith, 1992.
Rapp & Åkerman, 1993	Kärkevagge, Sweden	3.1	16	Rapp & Åkerman, 1993.
Matsuoka, 1994.	Akaishi Range, Japan	8.0	29	Matsuoka, 1994.

Table 1-2. Selective review of primary influences on solifluction.

Study Author	Location	Primary Influence on Solifluction
Benedict, 1970	Colorado Rockies, USA	↑ soil moisture, ↑ mvmt* ↑ slope gradient, ↑ mvmt
Harris, 1973	Okstindan, Norway	↑ soil moisture, ↑ mvmt ↑ slope gradient, ↑ mvmt ↑ vegetation, ↓ mvmt ↑ winter frost heave, ↑ mvmt
Washburn, 1980	review of literature	↑ soil moisture, ↑ mvmt ↑ slope gradient, ↑ mvmt ↑ silt-size sediment, ↑ mvmt
Dyke, 1981	Spence Bay area, NWT	↑ soil moisture, ↑ mvmt
Harris, 1981	review of literature	↑ soil moisture during thaw, ↑ mvmt
Gamper, 1983	Swiss Alps	↑ vegetation, ↓ mvmt ↑ early snow cover, ↓ mvmt ↑ duration of snow cover, ↓ mvmt
Egginton & French, 1985	Eastern Banks Island, NWT	↑ soil moisture, ↑ mvmt ↑ location on slope, ↑ mvmt
Lewkowicz, 1988	review of literature	↑ soil moisture, ↑ mvmt ↑ vegetation, ↓ mvmt ↑ slope gradient, ↑ mvmt ↑ silt-size sediment, ↑ mvmt
Price, 1991	Ruby Range, Yukon Territories.	↑ soil moisture during fall freeze-up, ↑ mvmt
Smith, 1992	Canadian Rockies, Alberta	↑ elevation, ↓ mvmt ↑ slope gradient, ↑ mvmt
Åkerman, 1996	Spitsbergen, Svalbard	↑ air temperature when process is active, ↑ mvmt ↑ content of fines in soil, ↑ mvmt ↑ soil moisture, ↑ mvmt ↑ vegetation, ↓ mvmt
Matsuoka, 1994	Akaishi Range, Japan	↑ short-term frost heave cycles, ↑ mvmt
Kirkby, 1995	model	↑ active layer depth, ↑ mvmt ↑ slope gradient, ↑ mvmt ↑ soil moisture during thaw, ↑ mvmt
French, 1996	review of literature	↑ soil moisture, ↑ mvmt ↑ vegetation, ↓ mvmt

* mvmt = movement

↑ = increased

↓ = decreased

1.3.4 Primary influences on solifluction rates

There has been a great deal of research to determine the primary influences on solifluction rates. According to Table 1-2, the primary environmental factors affecting movement are soil moisture, slope gradient, vegetation and soil texture. Although much of the literature concerns itself

with the evaluation of the relative importance of each of the factors, none of them operates in isolation. Inevitably, one factor acts as an influence on another, so it is difficult to assess an absolute order of importance.

1.3.4.1 Soil moisture

Soil moisture can have different sources, ranging from the meltwater from snow or ice lenses, to the infiltration of summer precipitation. Washburn (1967) stated that it is almost axiomatic that higher moisture in the soil promotes gelifluction and frost creep. By comparing movement rates in dry and wet sectors that have otherwise similar characteristics, Washburn (1967) determined that soil moisture, on slopes with a gradient between 10 and 14°, played a larger role than both slope gradient and the presence or absence of vegetation. He suggested that there is a boundary moisture condition for gelifluction, below which the process does not function.

Relatively high moisture levels are a prerequisite for solifluction, as it is the build-up of porewater pressures and loss of cohesive strength (McRoberts and Morgenstern, 1974; Bennett and French, 1991) and frost heave (Harris *et al.*, 1993) which are at the root of gelifluction and frost creep respectively. The amount of moisture that is available for ice segregation during freeze-up is therefore an important variable (Price, 1991). Mackay (1981) emphasized the influence of two-sided freezing in the formation of ice lenses. As the freezing fronts advance from both above and below during autumn, moisture is drawn towards them and subsequently freezes, resulting in the presence of ice lenses near the surface and near the base of the now-frozen active layer.

The thickness of these ice lenses depends primarily on the moisture supply (Harris, 1981). There are four major factors that influence the amount of ice segregation during soil freezing: (1) pore size of the soil; (2) moisture supply; (3) rate of heat extraction; and (4) confining pressure (Harris, 1987b).

Variations in the amount of snow cover, as well as rainfall received, are important causes of temporal variability in solifluction rates (Washburn, 1967) (see section 1.3.4.7.2 Precipitation).

1.3.4.2 Soil texture

A second important environmental control is the textural composition of a soil (Washburn, 1980; Dyke, 1981; Harris, 1981). Solifluction affects a wide range of sediments, ranging from alluvial silts and clays to glacial diamictons and screes (Harris, 1987b). Certain characteristics of grain size need to be considered. Silts and clays have a higher porosity than sands and gravels, yet they have lower permeability due to their small pore sizes. Due to their low porosity, sands have a lower saturation water content than clays (Harris, 1987a). For the most part, sands have a higher frictional strength than clays, but have a lower cohesion (Harris, 1987a).

In laboratory simulation experiments, Harris *et al.* (1993) determined that the most significant component in determining a soil's potential for high rates of solifluction was its silt and clay content. Susceptibility of a soil to ice segregation increases as the pore size decreases (Harris, 1987b): soils with a higher content of fine material encourage the formation of ice lenses during freezing, which causes both frost creep upon thawing and lowers the resistance of the soil to shear stress (Dyke, 1981). Silts and clays tend to retain water more than coarser grained soils, decreasing the rate of drainage during thaw (Harris *et al.*, 1993) and increasing the soil's susceptibility to flow by plastic deformation or liquefaction (Dyke, 1981). Harris (1981) found, however, that there is no correlation evident between soil granulometry and movement rates as any evidence of this relationship is likely obscured by other controlling factors.

1.3.4.3 Slope gradient

Solifluction can occur on very low-angled slopes (as low as, or even lower than 1°), but once the angle surpasses approximately 25°, more rapid mass movements tend to take place (Harris, 1981). The role of slope gradient in the rate of solifluction movement seems uncertain. It has been

suggested that solifluction rates may decrease with increased slope, as this allows for the downslope flow of water, reducing the potential for ice segregation and subsequently, frost heave (Smith, 1987). However, the majority of authors seem to indicate that slope plays a secondary role in increasing solifluction rates, and that for the most part, its effects are masked by other more important factors (Dyke, 1981; Harris, 1981; Hirakawa, 1989; French, 1996).

1.3.4.4 Vegetation

Vegetation plays contradictory roles in influencing rates of solifluction. It can act to retain moisture, thereby encouraging solifluction, but at the same time it can have a binding effect on soil surfaces (Bennett, 1970; Price, 1991). By limiting surface movement, a greater relative degree of subsurface movement may occur (French, 1996). According to Harris (1981), one of the primary factors which influences the vertical velocity profile is the thickness of the vegetation layer. A loss of vegetation can result in deeper soil freezing in non-permafrost areas, resulting in higher rates of solifluction (Van Vliet-Lanoë, 1993). Certain geomorphic forms that are present due to solifluction may be affected by vegetation. Vegetation may act to restrict groundwater flow from the riser in some solifluction lobe features, resulting in the formation of segregation ice, and subsequently, increased frost heave (Dyke, 1981). The presence of striping can be attributed to differential movement of the soil: finer grained unvegetated sections move twice as rapidly as the coarser, well-vegetated parts (Egginton and French, 1985).

1.3.4.5 Slope aspect

Slope aspect may indirectly influence rates of solifluction as it may affect vegetation, snow accumulation, air temperature and rates of evaporation (Price, 1991; French, 1996; Young *et al.*, 1997).

1.3.4.6 Permafrost

Climate acts as a control on solifluction rates primarily through its influence on the permafrost. In areas lacking permafrost, freezing of the ground is one-sided and occurs in a downward direction. In frost-susceptible soils, this results in a concentration of ice lenses near the ground surface (Mackay, 1981; Lewkowicz, 1988). The concentration of lenses tends to decrease with depth. In a one-sided freezing environment, movement tends to decrease with depth resulting in a concave downslope profile (Lewkowicz, 1988; Harris *et al.*, 1993; French, 1996).

Within the continuous permafrost zone, there is almost always two-sided freezing. Two-sided freezing results in more soil movement than in one-sided freezing for the same surface velocity, due to the greater depth at which processes take place (Woo *et al.*, 1992). Mackay (1981) discussed extensively many of the factors which influence solifluction in areas of two-sided freezing. Ice lenses form at both the top and bottom of the active layer, although they are likely to be more extensive at the base in part due to the downward percolation of meltwater during the spring and summer months which enriches the ice layer at the base of the active layer. The initial formation of segregation ice occurs during the fall and winter, as water is attracted to the freezing fronts. With the presence of the two freezing fronts, unfrozen water is trapped and will therefore eventually be transformed into ice (Price, 1991). Mackay (1981) described how the thawing of the upper active layer does not result in a large amount of consolidation or downslope movement as there is much less excess ice present there than near the bottom of the active layer. The majority of movement occurs later in the summer when the active layer has attained its greatest depth, resulting in the thawing of the ice-rich basal zone. Sliding of the relatively undisturbed active layer then occurs along the top of the permafrost table (Mackay, 1981). It is most likely that the profile will be convex downslope, as the majority of movement occurs along the base of the active layer where the ice lenses melt (French, 1996; Lewkowicz, 1988; Mackay, 1981). Even though the surface may move more than soil at depth, most of the differential movement occurs at the base of the active layer.

1.3.4.7 Climatic controls

1.3.4.7.1 Air temperature

Air temperature influences solifluction in several different ways. Firstly, the number of freeze-thaw cycles can affect movement due to frost creep (French, 1996). Air temperature plays a large role in determining whether freezing of soil is one- or two-sided in nature. Åkerman (1996) attempted to establish correlations between various air temperature indices and rates of solifluction. He found that for each specific solifluction feature, there was a given monthly air temperature that provided a very good correlation, while the other months and the mean summer temperature showed weak or very poor correlations. Movement at each feature correlated best with the mean temperature of the month in which it was most active (see section 5.3.1 A 22-year study: Åkerman (1996)).

Air temperature plays a direct role in determining the depth of thaw in any given year and the sum of thawing degree days can provide an indication of thaw depths (Egginton and French, 1985; Lewkowicz and Clarke, 1998). As previously discussed, in an area of two-sided freezing, the ice-rich zone is located at the base of the active layer. Rates of movement are influenced by whether the active layer is sufficiently deep to thaw this ice-rich zone, and perhaps even the ice-rich upper permafrost (Egginton and French, 1985; Price, 1991; Kirkby, 1995; Åkerman, 1996; Lewkowicz and Clarke, 1998).

1.3.4.7.2 Precipitation

The amount of precipitation and its form also influence solifluction rates. Washburn (1967) found that there was a high correlation between a rain period and higher solifluction movement rates. Snow on the ground surface can act in different ways to influence solifluction. The meltwater can infiltrate into the soil and help to increase porewater pressures and the formation of ice lenses. In an area with one-sided freezing, an early snowfall can lessen the depth of ground freeze. Its insulative and reflective properties can delay the thawing of the ground beneath it in the spring, potentially postponing soil consolidation and percolation of water down to the base of the active layer (Gamper,

1983). Åkerman (1996) indicated that the number of rainy days may play a greater role in influencing rates of movement than the amount of precipitation received.

1.3.5 Solifluction features

Certain geomorphic features develop as a result of solifluction. The most conspicuous of these is the solifluction lobe, yet the most common feature is the solifluction sheet, a uniform sheet of locally derived surficial materials (French, 1996). Other forms include terraces, alternating stripes of coarse and fine sediment, braking blocks and ploughing blocks (Lewkowicz, 1988; Åkerman, 1996; French, 1996). An extensive literature describes the morphology and the processes involved in the formation of solifluction features (e.g., Washburn, 1980; French, 1996). As this thesis focuses on the solifluction process rather than its form, solifluction features are not discussed at length here. In addition, features are absent from the study site location.

1.3.6 Solifluction experiments and models

Various experiments and models have been designed in order to closely examine different components of solifluction. Rein and Burrous (1980) manipulated the location of primary ice lensing in a soil profile experiment in order to examine its influence on soil displacement during thaw. Kirkby (1995) proposed a model for gelifluction rates in order to make inferences concerning the interpretation of Holocene rates of gelifluction as well as to predict likely directions of future change due to global warming. He concluded that active layer depth is the driving force behind solifluction rates. A series of laboratory experiments have also been performed (Harris, 1993; Harris *et al.*, 1993; Harris *et al.*, 1995, Harris and Davies, 1996) to examine the significance of a variety of elements such as climatic influences, soil texture, moisture contents, undrained shear strengths and porewater pressures.

1.4 Past solifluction rates and palaeoclimatic reconstruction

1.4.1 Measurement techniques

Solifluction lobes form in moist areas where the amount of gelifluction is higher than frost creep (French, 1996). Over time, solifluction lobes move downslope, burying the surface organic layer. Trenches excavated across solifluction lobes are used in palaeoclimatic reconstruction. Inferences about past solifluction rates, soil development and climate have been made by determining the rate at which lobe fronts have moved in the past. Hirakawa (1989) used a bed of volcanic ash at a solifluction lobe in Iceland as a marker having an absolute date in order to obtain its rate of movement. Other reconstructions have been attempted using the radiocarbon age of organic layers buried within solifluction lobes to determine their past rates of advance (e.g., Benedict, 1970; Alexander and Price, 1980; Dyke, 1981; Matthews *et al.*, 1986; Rapp and Åkerman, 1993).

1.4.2 Rates of movement and palaeoclimatic significance

Table 1-3 provides a selective list of studies in which the authors have examined rates of solifluction in the light of their potential use for palaeoclimatic reconstruction. It is apparent that there are no universal conclusions concerning the relationship between climate and solifluction rates. As stated by Harris (1993), the relationship between climate and solifluction rates may be quite complex and a direct relationship between temperature and rates may not exist.

1.4.3 Measurement difficulties

Although radiocarbon dating has been used to generate many estimates of past rates of solifluction at a variety of locations (Table 1-3), reservations about the interpretation and use of this method still exist. Benedict (1976) suggested that past rates of movement should be compared with current rates at the same location in order to help calibrate them with climate. Alexander and Price (1980) indicated that much care should be taken before climatic inferences are made based on this type of reconstruction. Matthews *et al.* (1986) listed the most important issues which they felt needed

Table 1-3. Selective review of solifluction lobe movement and palaeoclimatic inferences.

Study Author	Location	Oldest Date	Average Rate of Mvmt (cm/yr)	Link to Climate	Reference
Costin <i>et al.</i> , 1967	Snowy Mtns, Southeast Australia	2980 ± 180 ¹⁴ C yrs BP	0.16	Currently inactive lobes formed in conditions colder than present.	Benedict, 1976.
Everett, 1967	West Greenland	1695 ± 140 ¹⁴ C yrs BP 935 ± 120 ¹⁴ C yrs BP	0.12 0.18	No speculation regarding climatic significance.	Benedict, 1976.
Benedict, 1970	Colorado Rockies	2340 ± 130 ¹⁴ C yrs BP 2470 ± 110 ¹⁴ C yrs BP	0.19 0.34	Movement slow during an interstade and glacial maximum; rapid movement when moisture plentiful at beginning of a big freeze.	Benedict, 1970.
White & Mottershead, 1973	Ben Arkie, Northern Scotland	5145 ± 135 ¹⁴ C yrs BP	> 0.17	Cold and wet conditions increased movement.	Benedict, 1976.
Hamilton, 1974	Northern Alaska	2670 ± 180 ¹⁴ C yrs BP 2075 ± 130 ¹⁴ C yrs BP	0.08 0.11	Colder temperatures increased movement.	Benedict, 1976.
Worsley & Harris, 1974	Okstindan, Norway	2480 ± 90 ¹⁴ C yrs BP 2550 ± 80 ¹⁴ C yrs BP	0.12 0.11	Colder temperatures increased movement.	Dyke, 1981.
Ellis, 1979	Okstindan, Norway	4750 ± 130 ¹⁴ C yrs BP	-	Climatic deterioration increased movement.	Ellis, 1979.
Alexander & Price, 1980	Ruby Range, Yukon T.	2800 ± 140 yrs BP	0.37 - 1.02	Increased movement may reflect higher temperatures or precipitation or both.	Alexander & Price, 1980.
Dyke, 1981.	Spence Bay area, NWT	2210 ± 60 ¹⁴ C yrs BP 2170 ± 80 ¹⁴ C yrs BP 1360 ± 50 ¹⁴ C yrs BP	0.13 - 0.67 0.18 - 1.25 0.13	Worldwide rate similarities may indicate climate is not a dominant determinant factor.	Dyke, 1981.
Gamper, 1983	Swiss Alps	4700 yrs BP	0.5 - 3.0	Colder temperatures and less snow increased movement.	Gamper, 1983.
Reanier & Ugolini, 1983	Brooks Range, Alaska	6610 ± 100 ¹⁴ C yrs BP	0.32	Little change in movement throughout Holocene.	Reanier & Ugolini, 1983.
Matthews <i>et al.</i> , 1986	Jotunheimen, Norway	4470 ± 120 ¹⁴ C yrs BP	0.84	Climatic deterioration increased movement.	Matthews <i>et al.</i> , 1986.
Smith, 1987	Canadian Rockies, Alberta	3500 ± 100 ¹⁴ C yrs BP	0.35 - 1.5	Colder temperatures increased movement.	Smith, 1987.
Hirakawa, 1989	Iceland	~ 7000 yrs BP	0.32 - 0.4	Climatic deterioration increased movement.	Hirakawa, 1989.
Matthews <i>et al.</i> , 1993	various studies			Climatic deterioration increased movement.	Matthews <i>et al.</i> , 1993.

to be addressed in order to advance the use of solifluction lobe dating: a better understanding of the processes involved in lobe development and of their relationship to climatic change, improved dating control, and an increased awareness of the differential sensitivity of sites.

1.5 Thesis Research

With this research, it is hoped that the influence of climatic fluctuations on solifluction rates and processes in a high arctic environment will be clarified by examining data from an experimental site established at Hot Weather Creek, Ellesmere Island. When comparing rates of solifluction worldwide, consideration must be given to the environment from which the readings have been obtained. Many of the study sites are in subarctic, alpine or arctic maritime areas, where climatic influences may have different effects than in the high arctic. There is a paucity of research reported in the literature involving areas subject to two-sided freezing. More studies in continuous permafrost regions, examining movement at depth and testing for a greater number of variables, are required in order to more accurately determine the impacts of the various environmental controls on solifluction rates. This would lead to the development of theory that would permit more accurate prediction of rates and palaeoclimatic reconstruction.

The main objectives of this research are: (1) to examine in detail solifluction in terms of inter- and intra-annual variability in movement through the soil profile and (2) to determine the influence of fluctuations in air temperature and precipitation on solifluction rates and processes in an area of two-sided freezing. The following hypotheses were established in order to achieve these objectives:

- (1) Higher precipitation results in increased volumetric transport.
- (2) Increased depth of thaw results in increased volumetric transport.

In order to test both of these hypotheses, an experimental site was established in 1992 at Hot Weather Creek. Five solifluction meters (Lewkowicz, 1992a) and thermocouple cables were installed on a planar portion of an 8° colluvial slope. The acquisition of continuous soil movement and ground temperature data began in August 1993. During the summer of 1996, four meters underwent manipulation while the fifth acted as a control (meter C). One meter was artificially warmed (meter B), a second was cooled (meter E), a third was wetted (meter D) and a fourth was simultaneously warmed and wetted (meter A).

Hypothesis 1 was tested by observing how the rates of solifluction at meters A and D compare to those at the other meters. A comparison of inter-year variations was also made by examining movements at the meters for the two years prior to and the year following the wetting treatment.

Hypothesis 2 was tested at meters A, B and E by monitoring movement as with hypothesis 1. Measurements were also made at all of the meters of moisture content, *in situ* shear strength, porewater pressure and meter heights above the ground surface in order to provide greater detail of the soil conditions surrounding each meter.

Chapter 2. Study Site

The experimental site is located in the valley of Hot Weather Creek (79°58'N, 84°28'W) on the Fosheim Peninsula, Ellesmere Island (Figure 2-1).

2.1 Climate

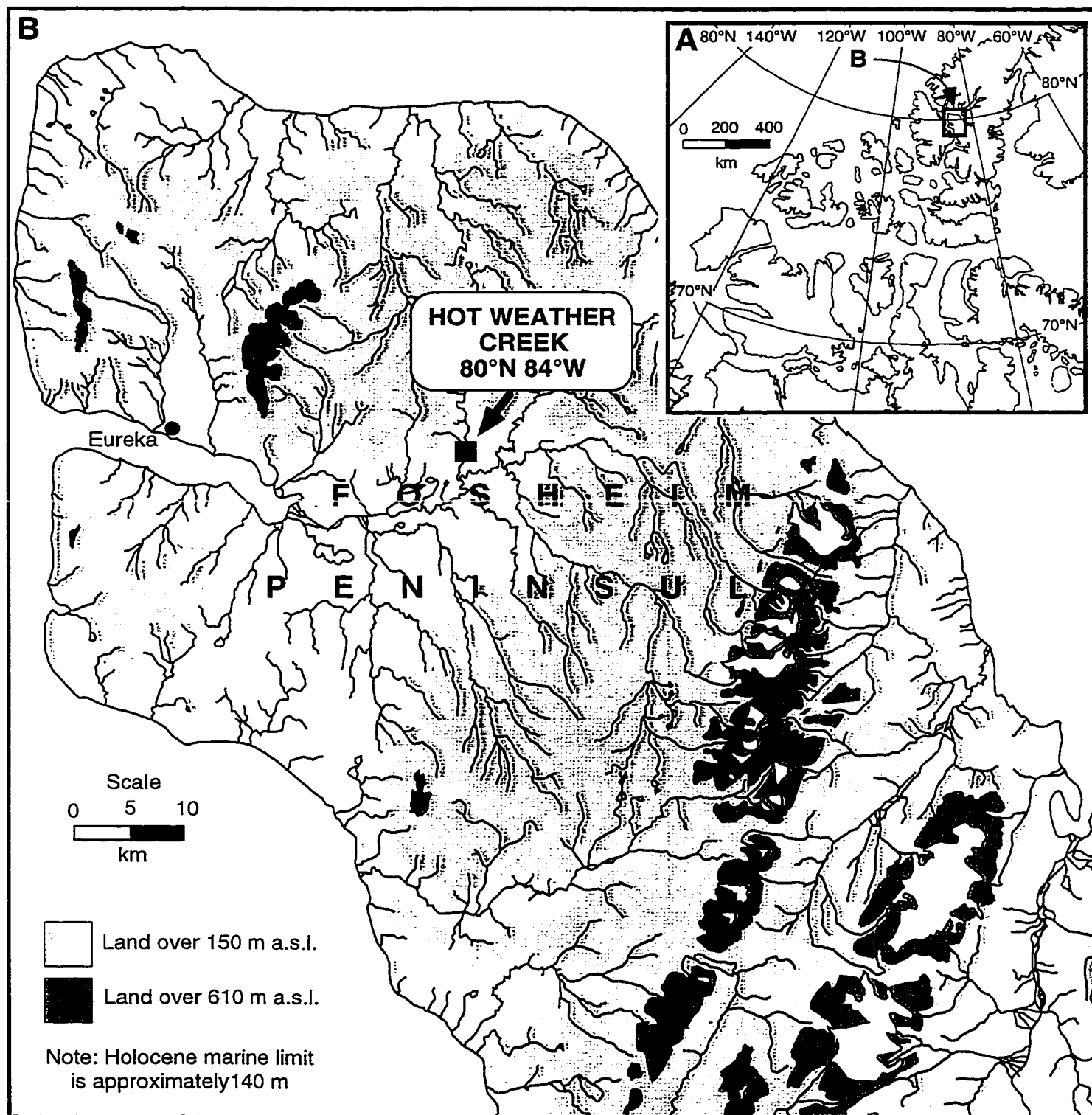
The Fosheim Peninsula is surrounded by a series of mountain ranges which tend to act as a barrier to disturbances coming from the Arctic Ocean and from Baffin Bay (Edlund and Alt, 1989). This contributes to the existence of a very dry region with warmer than normal summer temperatures for latitude 80°N. A year-round Atmospheric Environment Service (AES) weather station in Eureka has recorded the following data for the period 1951-1980: mean annual temperature -19.7°C; February mean temperature -38°C; July mean temperature 5.4°C; and mean annual precipitation 64 mm (AES, 1984).

The experimental site location is approximately 25 km east of Eureka, separated by Black Top Ridge (~800 m) and a broad, rolling, vegetated lowland (Edlund *et al.*, 1989). Due to its location inland away from the direct influence of the Slidre Fiord, Hot Weather Creek experiences temperatures which are 2-3° C warmer than Eureka in summer (Taylor, 1994). Other studies have demonstrated that conditions at Hot Weather Creek are both slightly warmer and wetter than at Eureka (e.g., Edlund *et al.*, 1989; Lewkowicz, 1992b; Lewkowicz and Wolfe, 1994).

2.2 Active layer and permafrost

Active layer depths range from approximately 0.5 to 0.9 m at different sites and considerable inter-annual variation may also occur at a single site. For example, at various locations near the study

Figure 2-1. Location of study site on the Fosheim Peninsula, Ellesmere Island.



slope, the maximum depth of the 0°C isotherm varied by up to 20 cm between 1995 and 1996. According to deep borehole temperature measurements recorded at a location just east of Hot Weather Creek, the permafrost is approximately 500 m thick (Taylor *et al.*, 1982 *in* Lewkowicz, 1992b). Given that the mean ground temperatures at the depth of zero annual amplitude are approximately -17°C, two-sided freezing of the active layer occurs (Lewkowicz, 1992b).

2.3 Bedrock and Quaternary history

The Quaternary history of the Fosheim Peninsula is not fully understood (Bell, 1996; Hodgson, 1985). It is likely that the limited expansion of the ice caps during the last glaciation was due to the hyper-aridity of the region (Bell, 1996). During this glaciation, the interior lowland of the Fosheim Peninsula was occupied by the sea (Bell, 1996). This large shallow basin, now exposed, contains a detailed sedimentary record. According to Bell (1996), the maximum Holocene marine limit was likely established by 10.6 ka BP. It is uncertain whether ice during the last glaciation can account for the amount of emergence which has been observed. It is possible that tectonic activity (England, 1992 *in* Bell, 1996) or glacio-isostatic depression, as a result of more than one ice cap (Hodgson, 1985) could be responsible for a portion of the uplift. Radiocarbon dating of shell samples (*Portlandia arctica*) indicates that the deglaciation of the Fosheim Peninsula began by 9560 ± 90 BP (Bell, 1996).

The surficial materials of the Hot Weather Creek basin are primarily weathered and colluviated bedrock, but marine, estuarine and deltaic sediments were deposited in the central and southern sections of the basin (Hodgson *et al.*, 1991). The Holocene marine limit in the Hot Weather Creek area is approximately 145 m asl (Bell, 1996). Consequently, the experimental site, at an elevation of approximately 120 m, was below sea level during or immediately following the last glaciation. Many plateau areas above the marine limit are dominated by weathered bedrock and till

(Bell, 1996) and over time, till has soliflucted downslope, so that some is found on the experimental slope site.

Bedrock in Hot Weather Creek consists of poorly consolidated sandstone with minor shale and coal layers of the upper Cretaceous-lower Tertiary Eureka Sound Group (Hodgson *et al.*, 1991). Horizontally bedded, poorly lithified sandstone and coal are exposed in a meander bend 200 m upstream of the experimental site and almost certainly underlie it. The experimental site is therefore composed of a variety of materials.

2.4 Vegetation

Warm summer temperatures are primarily responsible for the study area being classified as an “enriched prostrate shrub” bioclimatic zone (Edlund and Alt, 1989). This classification refers to areas within the Queen Elizabeth Islands which display the greatest density and diversity of vascular plant species. The actual distribution of this diverse vegetation on the Fosheim Peninsula is greatly influenced by micro- and meso-scale moisture conditions (Edlund and Alt, 1989).

2.5 Study slope

The experimental site is situated on an 8° planar portion of a colluvial slope (Figures 2-2a and 2-2b). A topographic map of the slope is shown in Figure 2-3. The site is approximately 8 m above Hot Weather Creek itself and 25 m below the level of the plateau (Figure 2-4a). The solifluction meters were placed relatively close together (Figure 2-4b) in order to ensure that similar conditions (e.g., slope angle, soil texture, moisture) existed at each site. At the same time, a distance of at least 4 m was left between the meters in the hope that the climatic treatments would affect only the meter designated. The number of movement blocks and thermocouples installed at each meter are noted in Figure 2-4b.

Figure 2-2. Experimental site, Hot Weather Creek valley, 1996.

- (a) Location of experimental site. Note the snowbanks upslope which contribute runoff for more than one week in the spring. [June 10, 1996].



- (b) Experimental site. The effect of the polyethylene on plant growth is visible. [August 9, 1996].

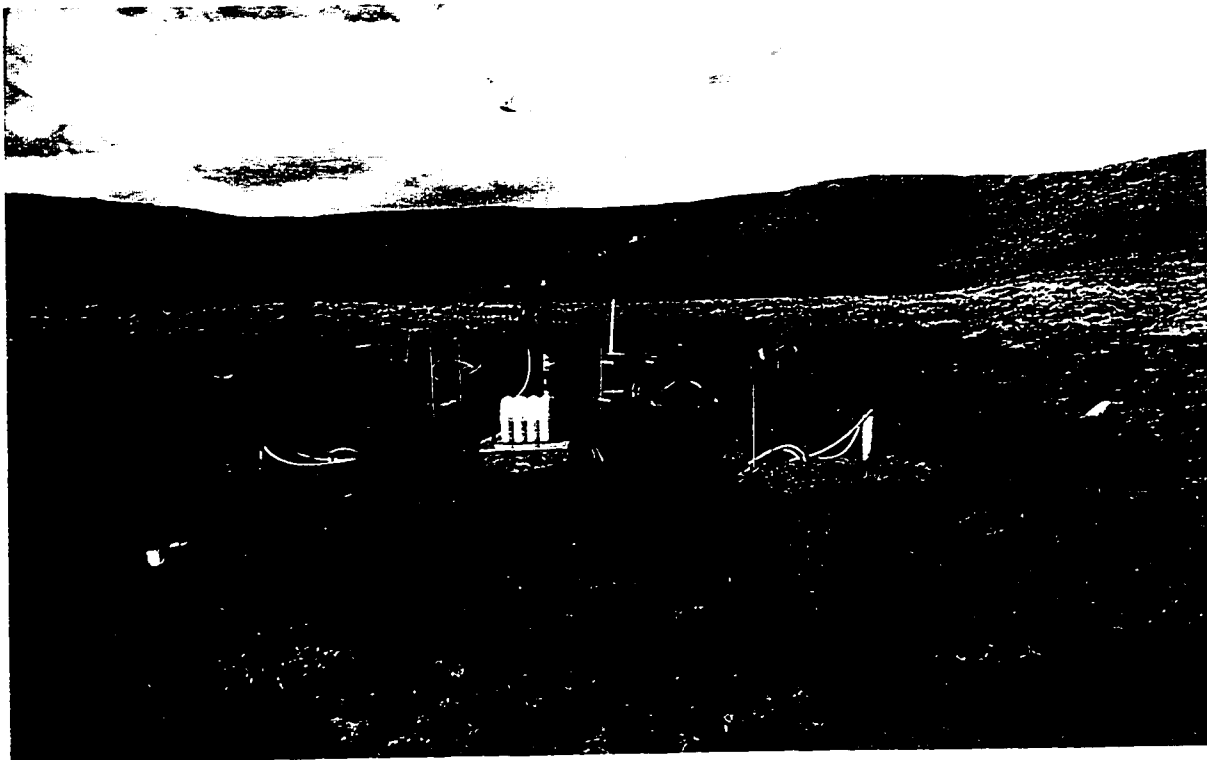


Figure 2-3. Topographic map of experimental site slope.

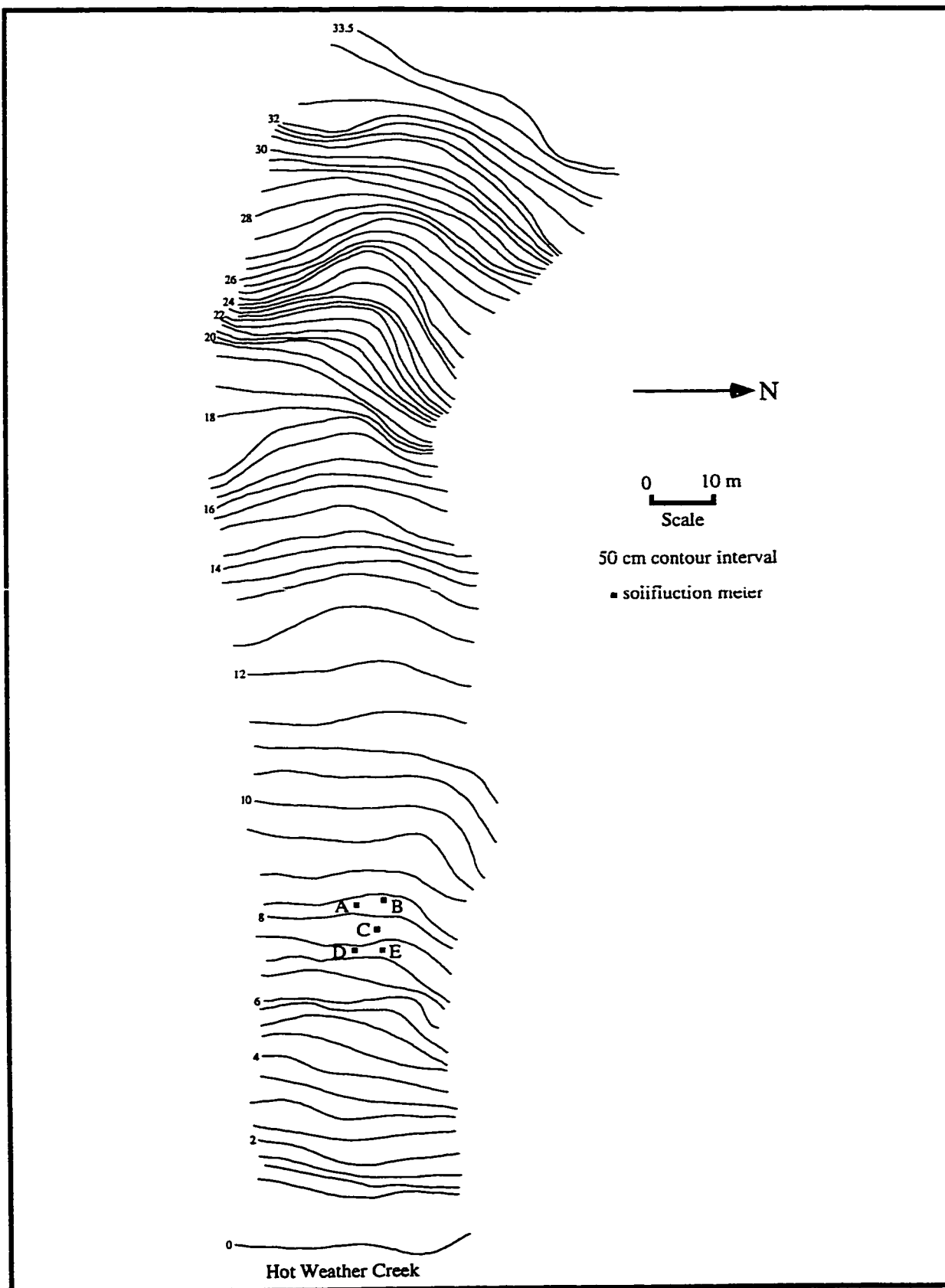
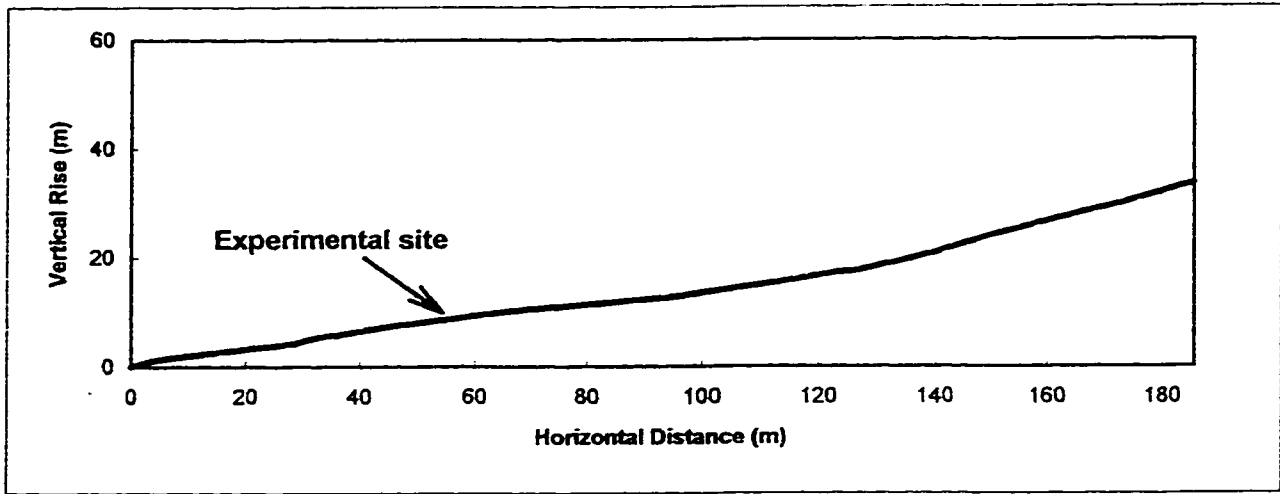
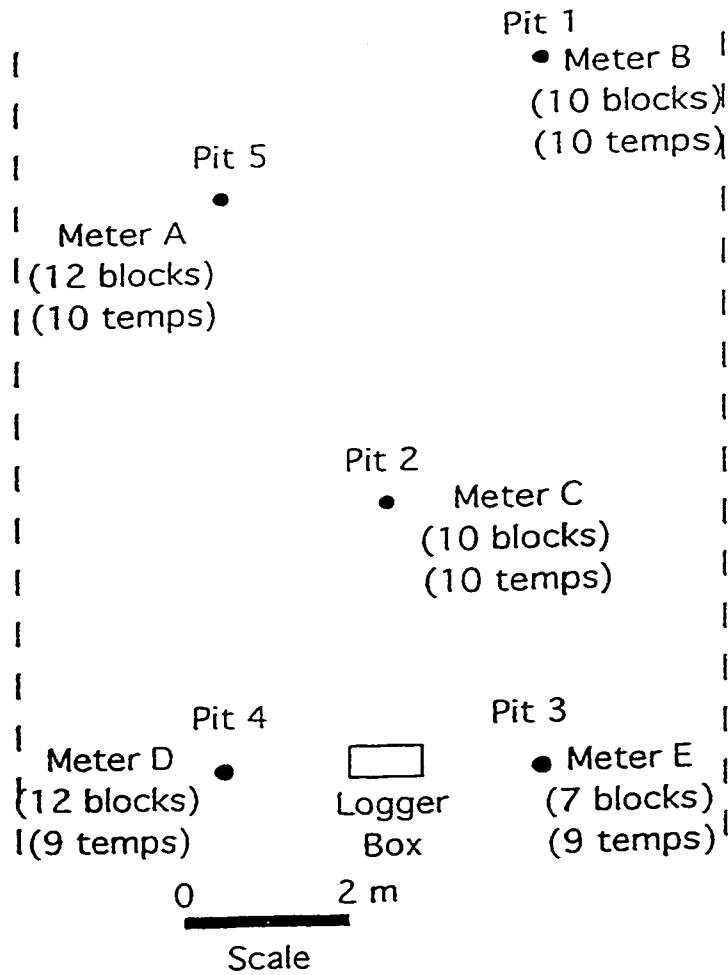


Figure 2-4. Experimental site location.

(a) Slope profile.



(b) Layout of experimental site.



When the meters were initially installed between June 30 and July 3, 1992, a borehole log was kept at each of the meter sites to record variations in visible ice content and soil texture (Figure 2-5). At that time, thaw depths at the sites ranged between 40 and 47 cm. The logs indicated that the zone between 40 and 50 cm depth contained about 5% visible ice lenses. In this region of two-sided freezing, this percentage reflects the relatively ice-poor section of the active layer profile which is situated between the two freezing fronts. Below this zone, the percentage of visible ice lenses rose to about 30-40% between about 50 and 140-180 cm. The uppermost part of this section was the ice-rich base of the active layer. This ice-rich layer blended into the top of the perennially frozen soil beneath (see Mackay, 1981). In holes where the soil texture became coarse at depth, there was no visible ice. These zones, ranging between 155 and 220 cm, were well below the potential active layer depth and therefore had no influence on solifluction.

Soil samples were taken within the top 80 cm at each hole, as well as from two pits dug in 1996, in order to ascertain texture and Atterberg limits. These analyses helped to determine whether possible differences in soil characteristics between the meters were a variable to be considered in the overall analysis of solifluction rates at the experimental site. The soil at the site is a very poorly sorted sandy silt (Shepard, 1954 *in* Gardiner and Dackombe, 1983) (Figure 2-6) with a low organic matter content. The mean silt content is 55%, the mean sand content is 38% and the average clay content is 7%. Atterberg limit tests indicate, however, that even though the soil is a sandy silt, it behaves in a similar manner to a low plasticity clay (Table 2-1). The mean liquid limit is 29%, while the mean plasticity index is 12%. Except for one sample (96 2-1), the soil characteristics are quite uniform (Table 2-1), and therefore variations in soil characteristics do not need to be considered in this study.

Based on three frost-susceptibility classification systems which categorize according to percentage of fines in a sample (German, Swiss and Norwegian), the soil at the experimental site is highly frost susceptible (Behr, 1981; Fetz, 1981; Sætersdal, 1981).

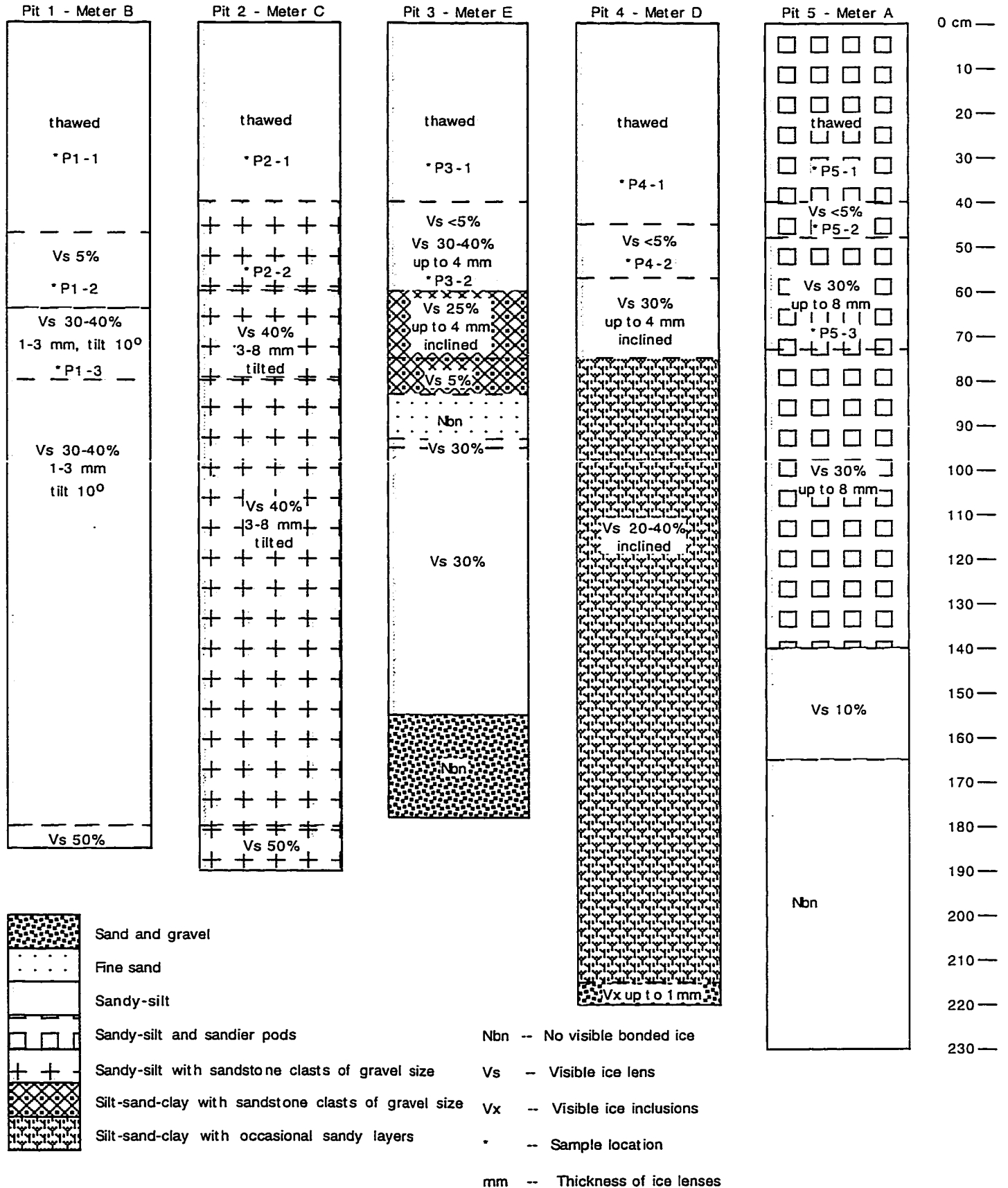


Figure 2-6. Textural properties of samples from the experimental site.

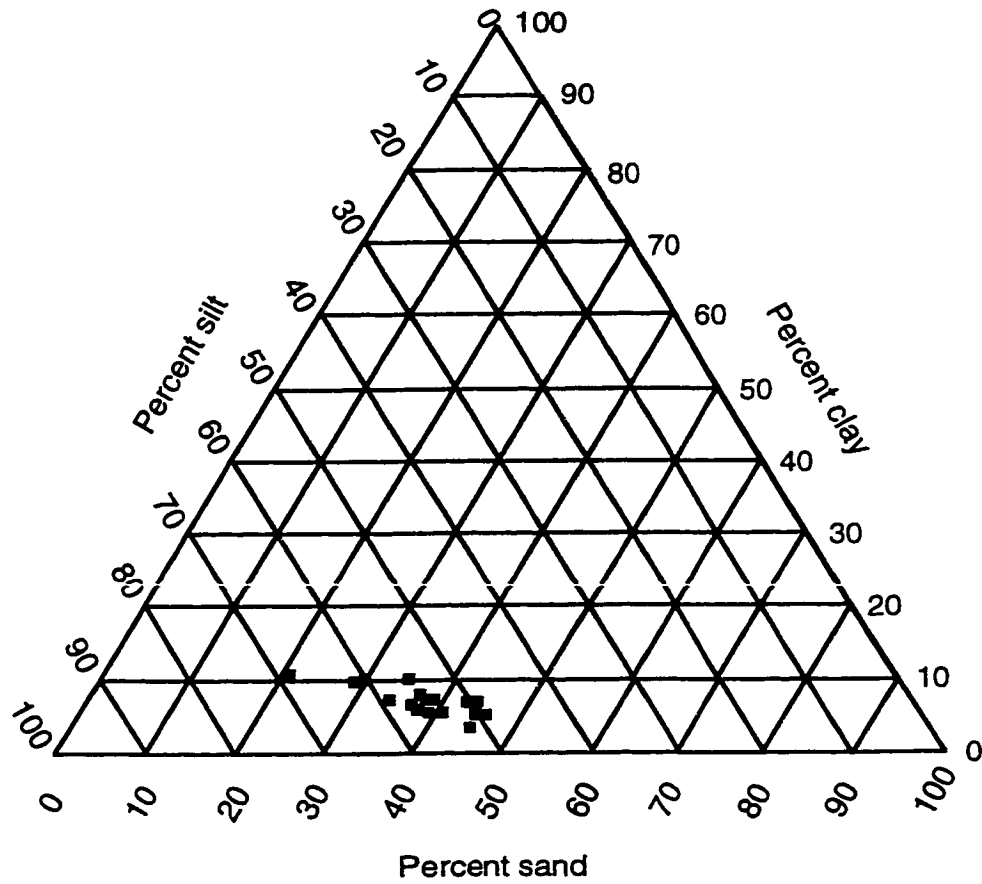


Table 2-1. Soil texture and Atterberg limits.

Sample #	Graphic mean (phi)	Graphic standard deviation (phi)	Graphic skewness	Graphic median (phi)	*	% sand	% silt	% clay	Organic matter (%)	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)
Meter A												
P5-1	4.18	2.24	0.26	3.79	1	35.9	57.2	6.9	7.5	30.0	17.9	12.1
P5-2	4.69	2.39	0.08	4.56	3	29.5	60.6	10.0	8.7	32.3	18.8	13.4
Meter B												
P1-1	4.10	2.34	0.28	3.65	1	39.0	54.0	7.0	7.8	27.0	17.6	9.4
P1-2	3.90	2.33	0.32	3.40	2	44.9	49.5	5.6	7.2	26.9	16.6	10.3
P1-3	3.73	2.09	0.34	3.40	2	45.8	50.6	3.7	6.5	25.5	16.5	9.0
96 1-1	4.31	2.57	0.05	4.20	3	37.1	54.3	8.7	9.4	31.5	16.8	14.7
96 1-2	3.80	1.97	0.35	3.40	4	41.3	53.4	5.3	6.5			
96 1-3	3.83	2.27	0.33	3.33	2	45.5	48.7	5.8	6.1	27.7	16.5	11.2
Meter C												
P2-1	4.12	2.20	0.30	3.67	1	37.0	56.3	6.7	7.9	28.9	18.0	10.8
P2-2	4.37	2.37	0.13	4.17	1	34.4	58.2	7.4	9.1	32.2	18.4	13.9
Meter D												
P4-1	4.37	2.44	0.12	4.17	1	38.6	54.7	6.7	9.0	30.4	17.5	12.9
P4-2	4.03	2.43	0.26	3.60	1	43.6	48.7	7.7	8.5	27.8	16.9	10.9
Meter E												
P3-1	4.28	2.19	0.29	3.85	1	29.7	60.6	9.8	7.9	28.3	18.7	9.7
P3-2	4.05	2.44	0.21	3.73	1	42.3	50.0	7.7	7.6	29.6	16.8	12.8
96 2-1	5.02	2.28	0.02	4.98	3	21.6	68.1	10.1	10.5			
96 2-2	4.05	2.11	0.31	3.60	2	38.4	56.4	5.1	5.1	27.6	17.1	10.5
96 2-3	4.51	2.46	0.13	4.30	1	35.1	55.3	9.6	7.7	33.5	17.9	15.6
Mean						37.6	55.1	7.3	7.8	29.3	17.5	11.8
S.D.						6.2	4.9	1.8	1.3	2.3	0.8	1.9

- * 1 - very poorly sorted, fine-skewed;
2 - very poorly sorted, strongly fine-skewed;
3 - very poorly sorted, near-symmetrical;
4 - poorly sorted, strongly fine-skewed.

The study slope is relatively well vegetated (55% cover), largely as a result of late-lying snowbanks upslope. A vegetation survey (Goldsmith and Harrison, 1976; Wein and Rencz, 1976) was conducted directly adjacent to the experimental site. The dominant species were *Dryas integrifolia*, *Salix arctica* and a variety of mosses.

The specific location of the experimental site was chosen primarily as it was a site which could be manipulated climatically. The section of the slope was mesic without being too wet. If the experiment had been established in an area that was subject to extreme conditions, it would have been difficult to effectively manipulate conditions in order to simulate climatic fluctuations. It was also desirable to have a location situated on a moderate slope, where meters could be placed far enough apart to not be influenced by treatments at another meter, yet close enough that the pre-existing conditions (i.e., slope, drainage, soil texture) were the same.

The experimental site was logistically good for daily treatments as it was situated close to a base camp. Its proximity to an automated weather station was also beneficial, as much climate data was made available.

Chapter 3. Methodology

3.1 Field methods

In order to test the hypotheses related to the aims of the study, the experimental site was established by Dr. A.G. Lewkowicz in 1992. Four different areas within the site underwent climatic treatments in the summer of 1996, and a fifth acted as a control.

3.1.1 Solifluction meters

Each of the solifluction meters (Lewkowicz, 1992a) consisted of a series of identical assemblies inserted in a PVC tube. The bases of the tubes were frozen into the permafrost, with the tops extending above the surface between 12 and 40 cm. Soil movement was measured at 8 cm intervals, beginning at a depth of 2 cm below the surface and extending as low as 90 cm. Meters A and D measured to a depth of 90 cm, meters B and C extended down to 74 cm, and meter E measured to a depth of 50 cm.

At each 8 cm interval, a pair of wooden blocks (4x4x4 cm) was installed downslope of the tube. The blocks were centered at the depths mentioned below, so they actually extended 2 cm above and 2 cm below the noted depth. These blocks were attached to either end of a metal rod which moved freely with the soil, and pulled out a flexible stainless steel rack as movement occurred. Each rack acted to turn a pinion gear attached to a precision potentiometer (Bourns Model 3590, 10 turn, 1k Ω) inside the PVC tube, and thereby altered its electrical resistance. Shielded copper-constantan thermocouple cables were installed next to each of the solifluction meters and recorded temperatures at a range of depths between the surface and 150 cm depth. The potentiometer and thermocouple connecting wires were buried just below the ground surface and extended to a central monitoring box. There, most of the thermocouples were connected to a Campbell Scientific AM416 relay multiplexer which was powered separately by a 12-volt battery cell (BP25). The multiplexer was connected to a Campbell Scientific 21X datalogger. The potentiometer wiring was linked to the datalogger by use of

two multiplexers. These multiplexers were powered through the datalogger by two 12-volt rechargeable batteries which were, in turn, linked to a solar cell. The thermocouples that monitored surface and air temperatures were connected directly to the datalogger. The datalogger was grounded by a copper pipe which was buried in the soil outside of the monitoring box. Data was stored on a Campbell Scientific SM712 solid state memory module.

The five meters were originally installed between June 30 and July 3, 1992. In early August 1993, it was decided to dig out the pits and re-set them in view of the severe settling of the blocks at the meters. The resetting of the blocks at all the meters to a depth of 8 blocks was completed by August 7, 1993. Those below were left untouched. Between August 5-10, the thermocouples for ground temperature monitoring were installed in CPVC pipes next to each solifluction meter using a water-jet drill to create the holes into the permafrost.

The following is a summary of the movement sensors and thermocouple cables in the soil at the experimental site. The numbers correspond to the average depth (in cm) below the ground surface.

Movement sensors

Meter A - 2, 10, 18, 26, 34, 52, 50, 58, 66, 74, 82, 90

Meter B - 2, 10, 18, 26, 34, 52, 50, 58, 66, 74

Meter C - 2, 10, 18, 26, 34, 52, 50, 58, 66, 74

Meter D - 2, 10, 18, 26, 34, 52, 50, 58, 66, 74, 82, 90

Meter E - 2, 10, 18, 26, 34, 52, 50

Thermocouple cables

Meter A - surface, 10, 26, 42, 50, 58, 66, 74, 100, 150

Meter B - surface, 10, 26, 42, 50, 58, 66, 74, 100, 150

Meter C - surface, 10, 26, 42, 50, 58, 66, 74, 100, 150

Meter D - surface, 10, 26, 42, 50, 58, 66, 100, 150

Meter E - surface, 10, 26, 42, 50, 58, 66, 100, 150

The data logger began to acquire ground temperature and soil movement data continuously in August 1993. The natural variation of movements among the meters was measured prior to climatic treatments being performed. There was some loss of data in March-April 1994, but data acquisition was continuous from then on so that two full years of information are available for comparison. Prior to June 1, 1996, the sensors were scanned every hour and data were output as six hour averages. On June 1, the reading frequency of the meters and thermocouples was changed to every five minutes with data output as one hour averages. On August 9, 1996, the readings were changed back to a one hour frequency with six hour average outputs for the subsequent autumn and winter periods.

Due to difficulties with the datalogger equipment as a result of excess humidity in the monitoring box, 3 periods of 1-8 days exist (June 30-July 4, July 12-13, July 25-August 2) when no data were collected during the summer of 1996. It is believed, however, that these small gaps are not vital to data analysis as missing movement and temperature data can be interpolated.

On June 10, 1997, the site was revisited to ensure the satisfactory operation of equipment and to download data obtained since the previous August. The datalogger reading frequency was once again changed to every five minutes with output as one hour averages.

It was decided that the greatest benefit would be gained from the experiment if the meters were carefully excavated on the final visit in August 1997. At that time, the location of each set of measurement blocks relative to their exit slot from the meter could be determined and this would serve as a basis of comparison to the datalogger readings.

An extreme precipitation event which occurred less than one week prior to meter excavation resulted in very moist soil conditions and the walls of any pit dug were subject to collapse. The meters were therefore excavated from the top down, and during this process, each set of blocks' distance away from the meter and its height above or below its exit slot was measured. The pair of blocks was then removed in order to allow access to the next set below. A special instrument, based on a profile gauge was constructed in order to easily and accurately measure the vertical position of the extended rack along its length without disturbing its position in the soil. Each set of blocks was then manually manipulated just prior to removal to ensure that an appropriate response was being registered at the datalogger. Two sets of blocks (C-50 and C-58) did not respond to the manipulation and it was felt that their racks were no longer properly on the potentiometer gear.

As many blocks as possible were measured and removed at each meter. At meters A, C and D, it was possible to measure blocks as deep as 74 cm, whereas at meter B, it was only possible to measure down to the 66 cm blocks. All blocks at meter E were measured, as the deepest set were only at 50 cm.

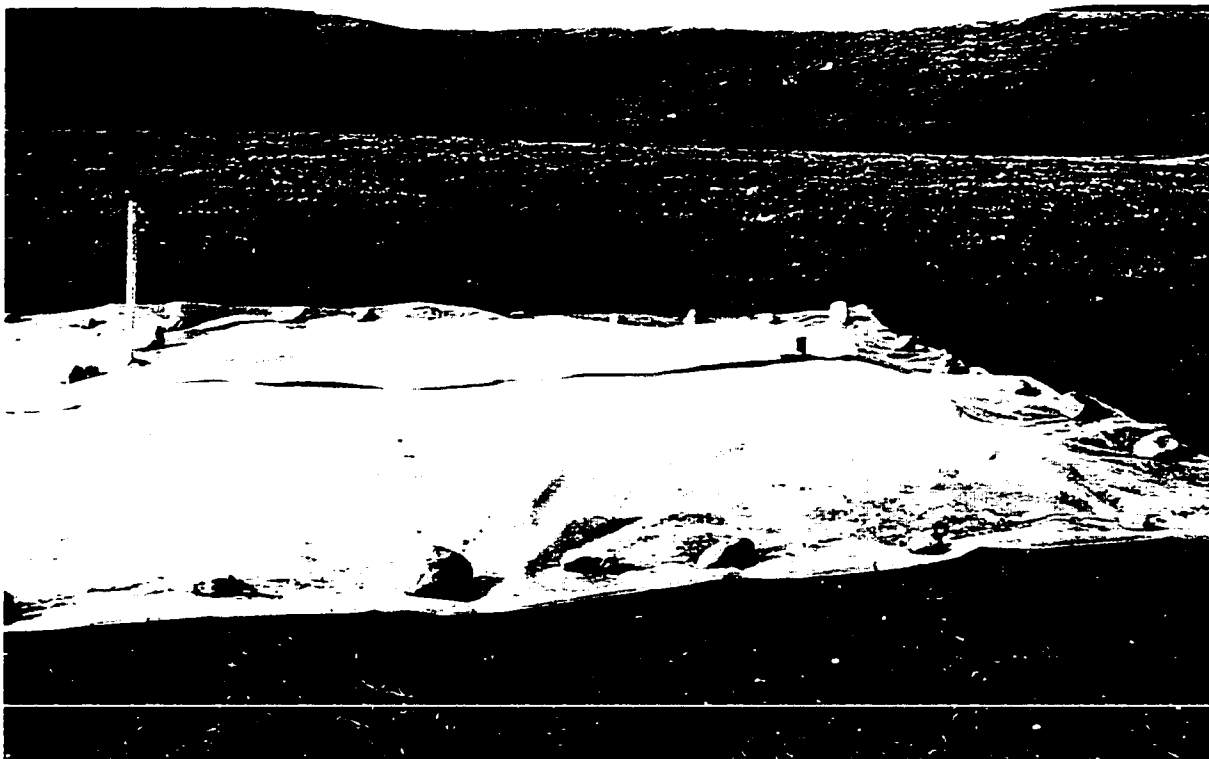
3.1.2 Climatic treatments

During the summer of 1996, one meter was warmed using polyethylene (meter B) (Figure 3-1a), one wetted by manual watering of the slope (D) (Figure 3-1b), one treated to a combination of these treatments (A) (Figure 3-2a), one cooled by shading (E) (Figure 3-2b), and the last left as a control (C). Due to the especially late and long spring run-off period, the treatments were not started until early July, when upslope snow had melted and the ground had begun to dry out.

Warming treatments were initiated at meters A and B on July 8. A single piece of transparent polyethylene was stretched out to cover the area surrounding both meters. The polyethylene was approximately 4.35 m wide and 8.70 m long. Small wooden stakes were inserted into the ground underneath the plastic in order to keep it about 15 cm off the ground. Slits were cut into the plastic in

Figure 3-1. Climatic treatments, 1996.

(a) Meter B – warming treatment.



(b) Meter D – wetting treatment.

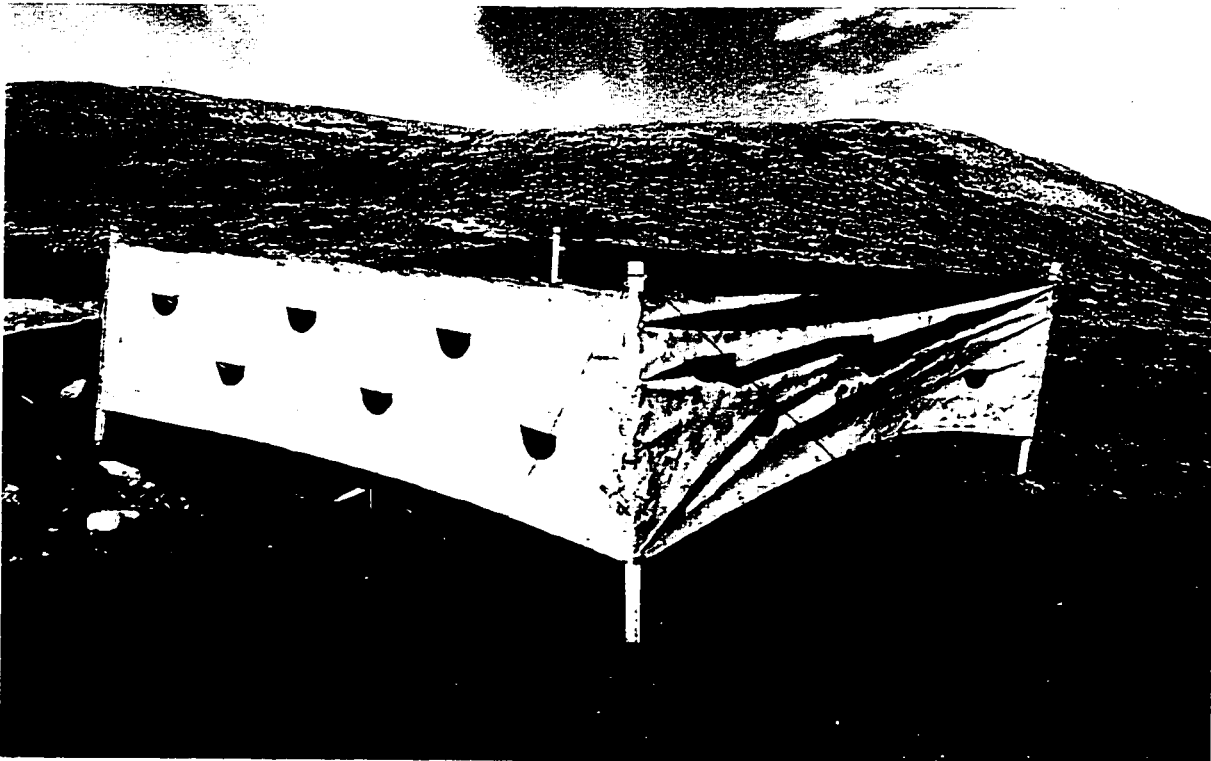


Figure 3-2. Climatic treatments, 1996.

(a) Meter A – warming and wetting treatment.



(b) Meter E – cooling treatment.



order for the solifluction meters and piezometer tubes to stick through. The outside edges of the plastic were held down with small rocks. The polyethylene remained in place until August 9, 1996.

A 4 m² area directly upslope of each of meters A and D was submitted to wetting treatments. At each meter, a 20 litre collapsible plastic container filled with water was attached to a garden soaker hose and placed 2 m upslope. The hose was approximately 4 m in length and was made of a material that allowed for the slow permeation of water along its length. This ensured that the water applied to the slope infiltrated into the soil rather than flowed downslope. Water from Hot Weather Creek was measured and used to fill the plastic containers. It was found that the permeability of the hoses decreased substantially as air temperatures approached the freezing point. When almost no water was observed to be seeping from the hoses, water was slowly poured manually directly onto the plots.

The initial plan was to apply 20 litres of water to each site twice a day in order to produce a significant change in the moisture contents of the plots. Due the lengthy spring run-off period, in addition to higher than average precipitation levels and considerable cloud cover, the ground surface remained moist throughout much of the summer. As a result, decisions were made on a daily basis as to the amount of water that should be applied to each of the two plots based on surface water conditions. The primary aim was to avoid the development of surface runoff as a result of overwatering. At meter A, the presence of the polyethylene cover reduced the evaporation of water into the air, so that the soil surface tended to have some pooling of water. Very little surface pooling occurred at meter D. For this reason, less water overall was applied to meter A. The amount of water applied to meter A (568 litres) was the equivalent of 142 mm of precipitation, while that applied to meter D (613 litres) was equivalent to 153 mm. Average annual precipitation for Eureka is 64 mm (AES, 1984).

Meter E was chosen as the meter to be cooled as its deepest movement measurement blocks were shallower than those of the other meters. A nylon insulation shield was erected around the meter on July 5 in order to keep direct solar radiation from the meter and the area directly

surrounding it. The 4 x 4 m square vertical shield was held in place with four 1.5 m stakes which were hammered into the ground and anchored with pegged wires. The shield reached a height of 1.2 m, with the base 20 cm above the ground. The inside of the shield was black in order to help reduce the reflection of incoming solar radiation to the plot, whereas the outside surface was spray-painted white in order to reflect solar radiation away from the plot. Air circulation across the plot area was promoted by leaving the bottom 20 cm open and by having several small flaps cut into each side of the canopy. Due to the continuously low angle of the sun at the study location, it was not necessary to cover the plot from above. The shield was taken down on August 9, 1996.

3.1.3 Associated measurements

Throughout the summer of 1996 and on two dates in 1997, measurements were made of meter angles, meter heights above ground surface, *in situ* shear strength, soil moisture content and porewater pressure. Meter angles, meter heights and *in situ* shear strength were also measured sporadically in 1993, 1994 and 1995.

3.1.3.1 Meter angles

The angle at which each meter was positioned was determined regularly over the summer. A Smartlevel electronic level with a precision of 0.1° was placed on the surface of the solifluction meter cap to determine this reading. As the meters were being excavated in 1997, angle measurements were made along the length of each meter in order to assess the shape of the meter deformation which may have occurred since original installation. This data helped to determine to what degree flexing of the meter itself was responsible for changes in the readings of the blocks.

3.1.3.2 Meter heights

A ruler was used to regularly measure the height of each of the meters above the ground surface in the middle of the left hand and right hand sides of the meter caps. Since the meters themselves were fixed in the permafrost, these data indicated whether heave or thaw settlement of the

soil surrounding them had taken place. The difference of both the height left and right from the previous measurement was calculated, and these two numbers were averaged to obtain the change from the previous measurement. If there was obvious pushing up of soil on one side of the meter, this was noted and the difference from the previous measurement included only the change in height from the undisturbed side.

3.1.3.3 *In situ* shear strength

In situ shear strength was determined approximately every five days using a Geonor shear vane. The shear vane measurements were taken about 1 m away from each solifluction meter location. Measurements were made at 8 cm intervals down through the thawed layer at depths equivalent to the depths of the solifluction meter blocks, until the frost table was reached. If the last vane measurement depth was more than five cm above the frost table, one more reading was taken directly above the frost table. Normally, five sets of measurements were made at each meter and frost table depths were also recorded. The first three times measurements were taken in 1996, only three repetitions were undertaken as the ground was still very moist and efforts were being made to minimize the impact of human disturbance at the meter sites.

3.1.3.4 Soil moisture content

At the same time as soil strength was measured, a Soiltest auger was used to obtain samples for moisture content analysis. The auger was inserted into the ground at a location close to each of the solifluction meters and samples were taken at the same 8 cm intervals as the shear strength readings and the measurement blocks. Each sample weighed approximately 20 g. The samples were placed into sealed plastic bags, after which they were weighed as soon as possible, usually later the same day, to an accuracy of ± 0.1 g. The bags were kept sealed and were stored for later laboratory analysis.

3.1.3.5 Porewater pressure

A piezometer tube was inserted into the ground close to each of the solifluction meters on July 6, 1996. The rigid PVC tubes (approximately 92 cm long and 4 cm in diameter) were pushed down to the frost table into pre-augered holes. Between July 7 and August 9, the depth of water in each of the tubes was checked about every 4 days. A ruler was inserted into the tube to determine the depth to the frost table from the top of the tube. From this, the height of the tube above the ground and the height of the water in the tube above the frost table were subtracted in order to derive the depth of the water in the tube below the soil surface. After each set of measurements, the tubes were pushed down to the top of the current frozen layer. When needed, the tubes were pulled out of the ground and any soil within was removed before being re-inserted. The tubes were left in the ground over the winter of 1996-97, and measurements were made at the time of the second visit in 1997.

3.1.3.6 Soil samples

Two small trenches measuring approximately 85 cm (length) x 40 cm (width) x 60 cm (depth) were dug in August 1996 in order to sample soil texture (Table 2-1). The first trench was located about 3 m upslope of meter B and the second, about 3 m downslope of meter E.

3.1.4 Climate data

An Atmospheric Environment Service (AES) automated weather station is located at Hot Weather Creek and provided most of the climate data during the study period (1993-1997). However, technical difficulties during 1996 resulted in incomplete data collection between June 1 and August 2. With the exception of the rain gauge, the station was again functioning from August 3, 1996 until July 29, 1997, at which time the program was changed to allow for longer-term monitoring without the need for annual maintenance.

Additional measurements of precipitation and temperature were made in the vicinity of the study site during 1996.

3.1.4.1 Precipitation data

Between May 10 and July 31, 1995, no data are available from the Hot Weather Creek weather station, therefore data from the AES station in Eureka (AES, 1995) were used (Table 3-1).

During the summer of 1996, a manual rain gauge was set up at the Hot Weather Creek camp and a tipping bucket rain gauge was established at a site approximately 1 km downstream from the experimental site. The data acquired from the tipping bucket gauge were used for precipitation values for the experimental site between June 1 and August 8.

In 1997, the copper barrel-shaped funnel of the rain gauge attached to the automated weather station was found on the ground at the end of July and it was not possible to tell at what point between June 10 (first visit to the site in 1997) and July 29 this occurred. As a result, there were no reliable precipitation data from Hot Weather Creek after June 9, 1997. The data from the AES station in Eureka (AES, 1997) were therefore used.

Table 3-1. Summary of available precipitation data, 1993-1997.

Year	Julian Day	Date	Source
1993	1 - 172	Jan. 1 - June 21	HWC weather station*
	173 - 365	June 22 - Dec. 31	HWC weather station*
1994	1 - 169	Jan. 1 - June 18	HWC weather station
	170 - 365	June 19 - Dec. 31	HWC weather station
1995	1 - 129	Jan. 1 - May 9	HWC weather station
	130 - 212	May 10 - July 31	AES Eureka
	212 - 365	Aug. 1 - Dec. 31	HWC weather station
1996	1 - 152	Jan. 1 - May 31	HWC weather station
	153 - 221	June 1 - Aug. 8	tipping bucket rain gauge, site B
	222 - 366	Aug. 9 - Dec. 31	HWC weather station
1997	1 - 160	Jan. 1 - June 9	HWC weather station
	161 - 365	June 10 - Dec. 31	AES Eureka

* Data has been quality controlled by Bea Alt and provided to the author.

Only precipitation data from the summer months (June, July and August) is considered in this analysis. During the colder months when precipitation falls in the form of snow and does not necessarily melt immediately into the rain gauge of the HWC automated weather station, it is possible

that snow is redistributed by wind, or that a substantial amount is lost through sublimation. It is also possible that the rain gauge freezes during the winter, as between October 1 and March 31, zero precipitation was recorded over a four-year period (1993-1997). Although a snow sensor was in place to record snow depth, it did not function properly.

3.1.4.2 Air temperature data

Three thermocouple cables were inserted in six-gill temperature shields to measure air temperature at 50 cm above ground and at 2 different locations 10 cm above ground at the experimental site in 1993. These were connected to the datalogger at the experimental site. One of the 10 cm air temperature sensors was placed so that it would be positioned underneath the polyethylene sheet once the warming treatments began in 1996. The 50 cm sensor functioned from installation date on August 12, 1993 until November 21, 1996, while the 10 cm sensors only functioned from July 14, 1996 to August 4, 1997. Gaps exist in the data from 1996 due to malfunctioning of the datalogger equipment during 3 periods of 1-8 days.

During the summer of 1996, three Hobo XT temperature loggers were installed in gill shields on poles at screen height to measure air temperature at the experimental site, at a site approximately 300 m north of the site (site A) and at a third location 1 km downstream (site B). Although the Hobo at the experimental site did not function during the entire summer, the other two Hobos recorded air temperature data between June 1 and August 2.

On June 10, 1997, two Hobos were set up at the experimental site to measure air temperature up until the date when the meters were excavated from the site in August. Of the two Hobos, one functioned and recorded temperature until August 4.

In order to establish an air temperature record for the experimental site between 1993 and 1997, the various sources of data were examined. Whenever possible, data collected directly at the

experimental site was used (Table 3-2). The most complete record was that recorded by the temperature shield positioned at 50 cm height (Ta 50 cm). From August 12, 1993 to June 30, 1996, air temperatures at Ta 50 cm were used, except for a 2-week period in summer 1994, when the values appear to be inaccurate as they fell as low as -18°C . This drop in temperature was not reflected in surface temperature data at the experimental site meters, or at the automated weather station; therefore the weather station values were used for this period instead.

Table 3-2. Summary of air temperature data used for the experimental site, 1993-1997.

Year	Julian Day	Date	Source
1993	224 - 365	Aug. 12 - Dec. 31	Ta 50 cm
1994	1 - 215	Jan. 1 - Aug. 3	Ta 50 cm
	216 - 231	Aug. 4 - Aug. 19	HWC weather station
1995	232 - 365	Aug. 20 - Dec. 31	Ta 50 cm
	1 - 365	Jan. 1 - Dec. 31	Ta 50 cm
1996	1 - 182	Jan. 1 - June 30	Ta 50 cm
	183 - 208	July 1 - July 26	Hobo site A
	209 - 221	July 27 - Aug. 8	Hobo site B
	222 - 326	Aug. 9 - Nov. 21	Ta 50 cm
	327 - 366	Nov. 22 - Dec. 31	HWC weather station
1997	1 - 162	Jan. 1 - June 11	HWC weather station
	163 - 216	June 12 - Aug. 4	Hobo @ site

Due to the relatively frequent gaps in the record from the experimental site during the summer of 1996, data from the Hobo temperature loggers at sites A and B were used between July 1 and August 8. Given that site A was only 300 m from the experimental site, data from the Hobo at that location were used until July 26, at which time the Hobo was moved elsewhere. For the remaining 13 days, data from the Hobo at site B were used.

Air temperature values from Ta 50 cm were once again used until November 21, 1996, at which time the thermocouple cable ceased to function. Data from the automated weather station were then used until a Hobo was set up at screen height on June 12, 1997 at the experimental site. The Hobo remained in place until excavation of the site was completed on August 4.

The daily Ta 50 cm values represent an average of the 4-times daily averages (0, 600, 1200 and 1800 hours) output by the datalogger at the experimental site (1 hour sampling frequency). Between June 1 and June 30, 1996, the daily values represent an average of hourly averages from the datalogger, as the sampling frequency at the site was increased to every 5 minutes for the summer period.

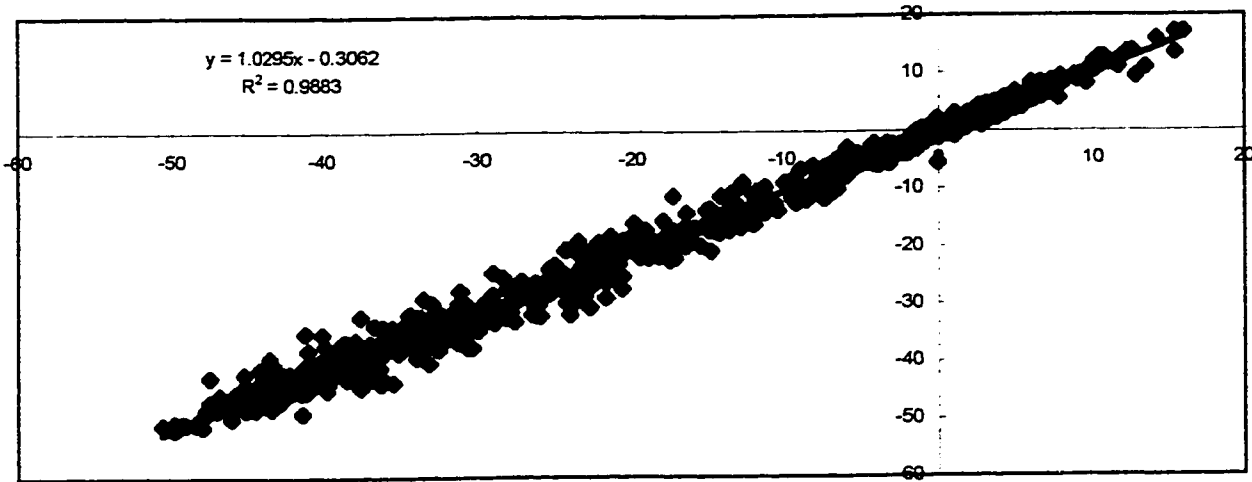
Daily temperature values from both the automated weather station and the Hobo temperature loggers represent an average of the daily maximum and minimum temperatures sampled on an hourly basis.

Air temperature values, from the days when both Ta 50 cm at the experimental site and the automated weather station were available, were compared between 1993 to 1996 in order to determine their similarity. Data from 763 days were plotted and a best-fit line was drawn (Figure 3-3a). In order to focus on the warm periods when air temperature variations are most critical, temperatures $> -5^{\circ}\text{C}$ were plotted separately ($n=228$) and a linear equation was fitted (Figure 3-3b). A good correlation existed between the Ta 50 cm values and those from the automated weather station, therefore gaps in the Ta 50 cm record were filled with data from the weather station (corrected using the linear equation), except when Hobo records were available. Some of the scatter that is apparent around the best-fit lines may be attributable to slight differences in the format of data output between the weather station and the data logger at the experimental site.

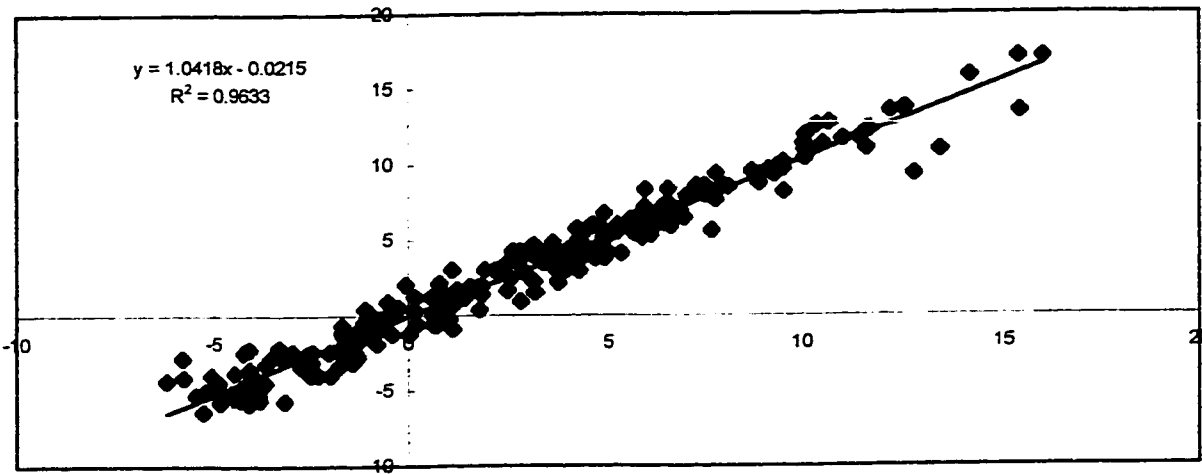
Hobo data from 1996 were plotted against available Ta 50 cm values ($n=42$) (Figure 3-3c). Once again, a good correlation existed; therefore, Hobo data were corrected using the linear equation and used to complete the record for the summer of 1996.

During the summer of 1997, it was assumed that the Hobo set up at the experimental site would have had a similar relationship to the Ta 50 cm data as the previous year's Hobos. It was not

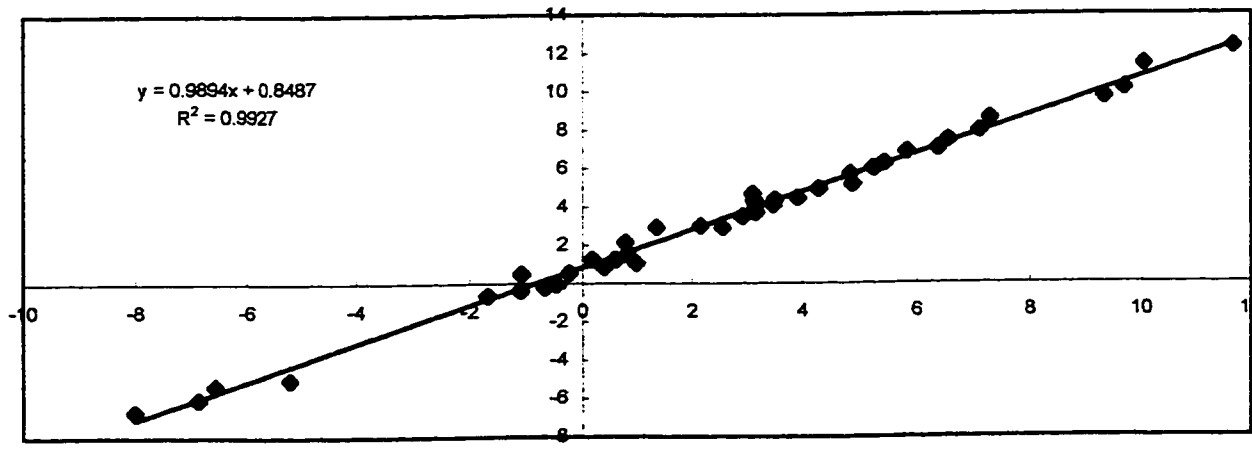
a) Automated weather station (x) vs. Ta 50 cm (y) air temperatures, 1993-1996 (degrees C).



b) Automated weather station (x) vs. Ta 50 cm (y) air temperatures >-5 degrees C, 1993-1996.



c) Hobo site A 1996 (x) vs. Ta 50 cm (y) air temperatures, 1996 (degrees C).



possible to make a direction comparison, as the Ta 50 cm monitor ceased to function in November 1996. The Hobo data were therefore corrected using the same linear equation as was used for the Hobo 1996 data.

Given that individual air temperature values are not being examined, it is felt that this air temperature record is adequate for purposes of determining general trends over the 5-year period between 1993 and 1997.

3.2 Laboratory methods

3.2.1 Soil moisture content

The first group of soil samples analyzed (from August 9, 1996) were weighed in the laboratory to determine the amount of moisture lost since the initial weighing in the field. These were then heated for twelve hours at approximately 110°C. After this period of time, the samples were re-weighed, then replaced in the oven for another twelve hours to determine whether a second twelve-hour baking period was necessary to completely dry out the samples. The weight of the samples was virtually identical after the second baking so it was decided that one twelve hour period was sufficient drying time. The equation used to calculate the moisture content of the samples was as follows:

$$\text{Moisture content} = \frac{[A-B] + [D-E]}{[E-C]} \times 100$$

where A is the initial sample weight in the field;

B is the weight of the sample in the laboratory when initially re-weighed;

C is the dish weight;

D is the weight of the sample in the dish before baking;

E is the weight of the sample in the dish after baking.

All other soil samples from 1996 and 1997 were processed in the same manner.

3.2.2 Soil organic matter content

A total of 17 samples were analyzed, first for organic matter content, then for particle size. The organic matter content of the soil samples was determined using the loss-on-ignition method as outlined by Kalra and Maynard (1991). A 20-25 g sample was initially dried at 105°C and weighed, before being heated to 500°C for 2 hours to burn off any organic material in the sample. The samples were then re-weighed, and the percentage of weight lost was calculated.

3.2.3 Particle-size analysis

3.2.3.1 Particles > 63 microns

Wet-sieving was performed to determine the portion of each sample larger than silt and clay (> 63 microns). A series of 5 sieves with mesh sizes ranging from 1000 to 63 microns (0 to 4 Ø) was used to categorize the sand-size particles. The samples contained no particles > 1000 microns.

After the organic matter was removed from the samples, they were re-crushed with a small amount of water using a rubber pestle to ensure complete disaggregation of the particles. More water was then added and the sample was blended for 2 minutes before being poured onto the nest of sieves. Deionized water was run through the sieves until it emerged from the bottom sieve clear, meaning that no clay or silt fraction remained in the sieves. The amount remaining in each sieve was dried and weighed to determine the breakdown of the portion of the sample > 63 microns.

3.2.3.2 Particles < 63 microns

A slightly modified version of Gullentops' discontinuous subtraction method (unpublished), based on Stokes' Law of the settling velocities of particles of different size and modified from the pipette method of granulometric analysis, was used to categorize the clay and silt portion of the samples. The water, mixed with silt and clay, that washed through the sieves was evaporated, and the total weight of silt and clay was determined. Each sample was then mixed with 20 ml of dispersant (sodium pyrophosphate at a concentration of 10 g/L) before being poured into a 1-litre decantation

cylinder. Enough water was added to fill the cylinder to the 1-litre mark and the entire cylinder was shaken to ensure a thorough mixing of the solution. Six 50-ml samples were taken from near the base of the cylinder at pre-set time intervals (0, 4'18", 12'12", 38'15", 1h50'48" and 4h34'24"). These times represent the settling times for the different sizes of silt. After the final sample was taken, all that remained in suspension was the clay portion. Each sample was dried in the oven at 105°C for 12 hours and weighed (minus the fraction of dispersant in each sample - 0.1g). To determine the portion of sample in each silt-size class, the following calculations were made:

(sample 1 - sample 2) x 20 = portion (g) between 32 and 63 microns;

(sample 2 - sample 3) x 20 = " " " 16 and 32 microns;

(sample 3 - sample 4) x 20 = " " " 8 and 16 microns;

(sample 4 - sample 5) x 20 = " " " 4 and 8 microns;

(sample 5 - sample 6) x 20 = " " " 2 and 4 microns;

(sample 6) x 20 = portion (g) less than 2 microns.

As each sample was only 50 ml, each value was multiplied by 20 as the volume of the entire solution was 1 L. The weight of each sieved or decanted portion was added together and the percentage that each represented of the whole sample was calculated.

3.2.4 Atterberg limits

The liquid and plastic limits of the soil samples taken from the experimental site were determined using the methods set out by ASTM D 4318-93. These limits, commonly known as Atterberg, are expressed as % moisture content and reflect the boundary limits of soil consistency. The dry sample preparation method was used as the samples were no longer at their natural water content. The multipoint liquid limit method using 3 values was performed to ensure precision in the results. A linear regression line was fit by computer. When the line fit poorly at the 25 "taps" value, both a linear and polynomial curve were employed and the average moisture content at 25 was used.

Two samples (96 1-2 and 96 2-1) did not have sufficient soil remaining after particle-size analysis to perform the Atterberg tests.

3.3 Data analyses

3.3.1 *In situ* shear strength

Some conversion of the shear strength values was necessary to take into consideration increased resistance with depth due to friction on the sides of the shear vane shaft. The conversion formulae, which were previously derived empirically by A.G. Lewkowicz, are as follows:

Values from:

$$2 \text{ cm: } S - 0.007 \times 2 \times S$$

$$10 \text{ cm: } S - 1.4 \times 0.079 \times S$$

$$18 \text{ cm: } S - [1.4 \times (0.2524 - 0.11091 \times \text{Log } (18)) \times \text{Sum } (10 \text{ cm value : } 18 \text{ cm value})]$$

↓

$$58 \text{ cm: } S - [1.4 \times (0.2524 - 0.11091 \times \text{Log } (58)) \times \text{Sum } (10 \text{ cm value : } 58 \text{ cm value})]$$

where S is the value obtained at that particular depth.

Once the values were adjusted, the mean figure for each meter was calculated and profiles were constructed.

3.3.2 Thaw strain

Thaw strain ratios were calculated using the increase in meter height above the ground surface as an indicator of the settlement which had occurred as a result of the melting of ice lenses in the soil. The following equation was used:

$$(\text{meter height change/thaw depth increase}) \times 100 = \text{thaw strain}$$

The ratio was calculated for each date in 1996 when meter height was measured, and therefore change in meter height could be determined. Each ratio was plotted against the range of soil depths which thawed during that time period.

3.3.3 Active layer thaw depths

Active layer thaw depth values were calculated based on temperature data from the thermocouple probes at the experimental site. The calculations began as soon as the sensors at 10 cm depth began to indicate temperatures $>0^{\circ}\text{C}$. For every sensor at each meter, a mean daily temperature value was calculated. Except during the summers of 1996 and 1997, the mean was based on six-hour averages output from the datalogger 4 times per day. During the summers of 1996 and 1997, the daily mean was calculated based on hourly averages from the datalogger.

For each day during the thaw period, the mean daily temperature values for every depth at each meter were plotted against the probe depth in the soil profile. A 5th order polynomial equation was fitted to the points, and the value for the y-intercept was noted, as it corresponded to the location of 0°C on the graph. If a temperature value at either the top or bottom of the profile acted to greatly distort the shape of the curve but was not itself one of the values closest to the 0°C isotherm, it was disregarded and the line was plotted without using that particular value. The daily calculations were continued until significant freeze-back began from the surface downward and it became impossible to plot a single line that would accurately represent two-sided freeze-back.

The series of daily values for the depth of 0°C at each meter were plotted and represent the progression of thaw through the soil profile. There were a small number of occasions when the predicted depth of thaw was less reliable. Meters D and E did not have temperature sensors at 74 cm, so a considerable distance existed between the sensors at 66 cm and those at 100 cm. The prediction of the depth of 0°C once thaw reached this range was therefore less accurate. There were also two

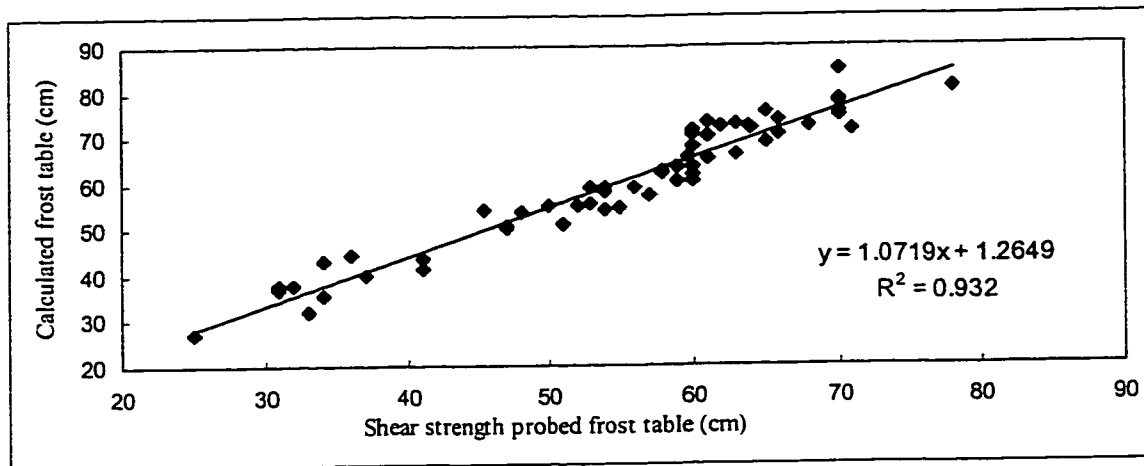
periods of time when the probes at 50, 58 and 66 cm at meter A were not functioning. From August 11 to September 2, 1993, the calculations at meter A did not use values between 50-66 cm. From June 22 to August 6, 1994, it was felt that insufficient data were available to predict the thaw depth, and gaps, therefore, exist in the data. Similarly, gaps exist in the thaw depth values plotted for meter D in 1997, as the 58 and 66 cm temperature probes did not function from July 2 to July 21.

For the 3 brief periods in 1996 when no soil temperature data was available due to datalogger malfunction, the increase in thaw depth was distributed linearly between the beginning and end of each period.

Frost table depths were recorded whenever shear strength measurements were taken, based on the depth to which the instrument could be pushed into the soil. Each frost table value is a mean based on 5 individual probe depths. The measurements were taken on 3 days in 1994 and on 1 day in 1995. These earlier values are based on one set of 5 readings taken for the entire experimental site. The measurements in 1996 were based on a set of 5 readings at each individual meter, taken on a regular basis over the summer (approximately every 5 days). One set of readings was recorded at each meter on July 30, 1997.

In order to help assess the accuracy of the calculated thaw depths, they were compared to shear strength probe depths by plotting calculated thaw depths for the days when probe depths were available versus probe depths. Figure 3-4 shows that the probed thaw depths were noticeably shallower than the calculated depths. This was probably due to thaw settlement, as the calculated depths were based on data from temperature sensors which were anchored in the permafrost and which remained fixed as the soil profile both heaved and settled. It was decided to apply a correction factor to the calculated depths so that they would better reflect the probed thaw depths.

Figure 3-4. Shear strength probe depth vs. calculated frost table depths, 1994-1997.



The values for each meter were plotted separately in order to determine the most accurate equation for the trend at each. A best fit line, either linear or polynomial, was fit to each set of points. These equations are noted below, where x is calculated thaw depth and y is the corrected thaw depth. The correction factors were only applied to calculated thaw depths below 30 or 35 cm. When thaw depths were shallower than 30 or 35 cm, the equations did not accurately reflect the trend in the difference between calculated and probed thaw depths, and therefore the annual thaw depth graphs do not include these values.

Meter A

$$y = -0.00939x^2 + 2.02607x - 33.25024 \quad r^2 = .986 \quad x > 35 \text{ cm}$$

Meter B

$$y = 1.0206x - 5.56499 \quad r^2 = .995 \quad x > 35 \text{ cm}$$

Meter C

$$y = 0.94099x + 1.49518 \quad r^2 = .977 \quad x > 35 \text{ cm}$$

Meter D

$$y = -0.00236x^2 + 0.99858x + 2.85549 \quad r^2 = .961 \quad x > 30 \text{ cm}$$

Meter E

$$y = .88074x + 1.44428 \quad r^2 = 0.915 \quad x > 35 \text{ cm}$$

It was difficult to arrive at a satisfactory equation for meter E, as the thaw depths in 1996 were very shallow, so there were few points available for a line to fit through. In order to improve the accuracy of the correction factor, the probed values representing the entire experimental site from 1994 and 1995 were included with meter E's 1996 values and a line was plotted using all of the values.

The correction equations were then applied to the calculated thaw depths for each meter. It is believed that the application of the correction equations also helped to improve the accuracy of the values from meters D and E at the point when thaw depths fell between 66 and 100 cm.

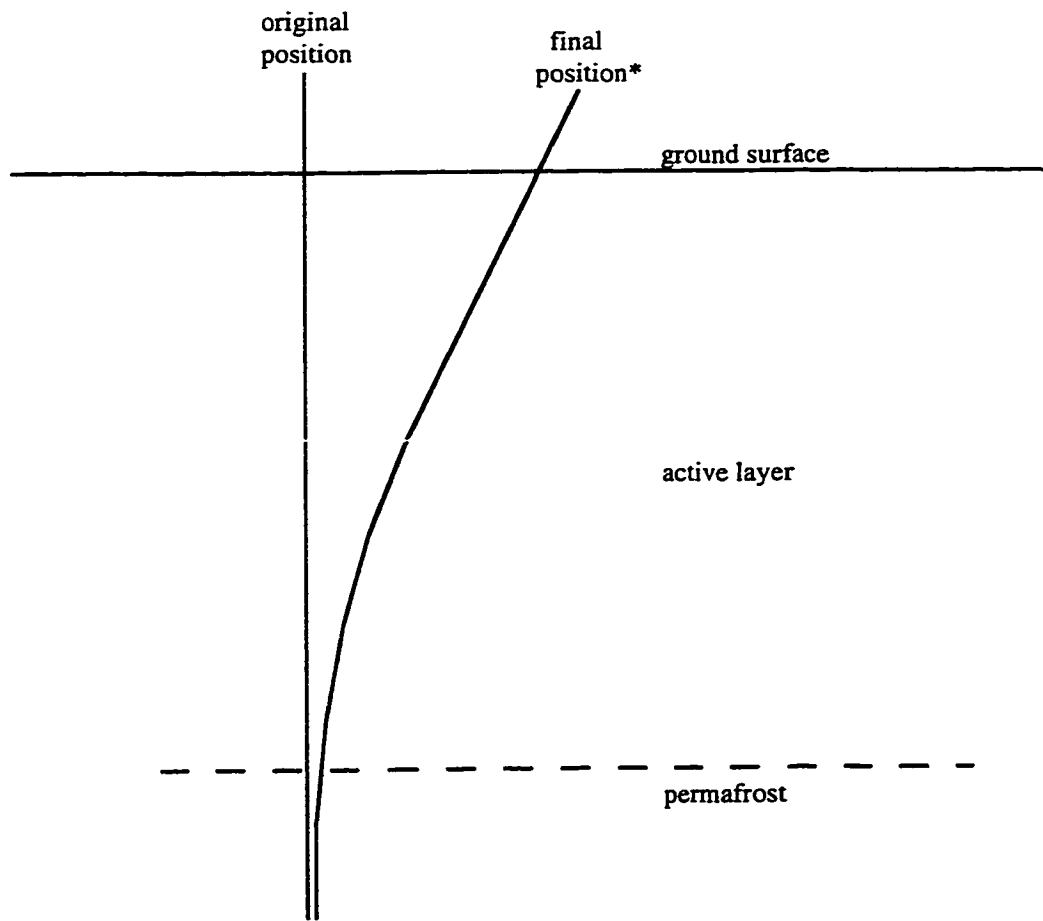
3.3.4 Meter angles

Based on angle measurements from the meter caps, it was determined that the meters had experienced tilting since their installation in 1992, even though the base of each meter was frozen in permafrost. As a result, the movement data did not reflect the full amount of downslope movement, and may have at times even indicated a retrograde movement. Two elements were examined: the shape of the meter deformation and the temporal distribution of the angle change.

Based on angle measurements obtained during excavation of the meters in 1997, it was assumed that the meter bend started at a depth of 82 cm (approximately 8 cm deeper than the average thaw depth) and that the curvature was split into five sections, after which the meter angle remained constant (Figure 3-5). For ease of calculation, the five sections of angle change were assumed to be 8 cm, the same distance as between the measurement blocks.

The correction factor through time was based on a line fitted through a plot of the 1996-97 readings. A linear equation ($y = -0.002497x + 171.589802$) with an r^2 value of 0.83 was fitted to the 1996-97 angle values for all the meters at the experimental site. The 5 measurements from 1993-

Figure 3-5. Final shape of meter deformation.



*For purposes of the diagram, the change in angle is assumed to be 25 degrees. Actual changes in meter angle were considerably less.

1995 were not directly considered when determining the appropriate correction factor, as it was uncertain where the measurements were taken on the meter.

As the change in meter angle appeared to have been relatively evenly distributed over the entire period and there was no pattern in the residuals, a correction factor based on a change of 0.0025° per day at the top of the meter was added to the movement data. Based on the shape of meter deformation, the angle correction factor was distributed through the profile in the following manner:

2 - 42 cm - same angle change as the top of the meter;

50 cm - $4/5$ of angle change;

58 cm - $3/5$ of angle change;

66 cm - $2/5$ of angle change;

74 cm - $1/5$ of angle change;

82 cm or lower - no change in angle since installation.

The next step involved calculating the angle at which each meter was tilted at each individual set of blocks over time. The original equation was based on angle measurements taken from all of the meters. To determine the most appropriate y-intercept for each meter, the final angle measurement at each meter and the date on which it was taken were substituted into the equation and it was solved. The resultant value was then used as the y-intercept for that particular meter. To determine the angle of the meter at a particular set of blocks on any day over the study period, the predicted value from the linear equation was used to calculate the top angle, then the deformation through depth was calculated.

3.3.5 Soil movement data

Movement data from the datalogger were downloaded automatically to a memory module which was subsequently downloaded directly to a computer.

3.3.5.1 Potentiometer calibration

Each rack, pinion gear and potentiometer set was calibrated in the laboratory prior to installation in the field in 1992 and calibration coefficients were established (Lewkowicz, 1992a). The raw movement data from the datalogger were adjusted using the appropriate coefficients.

3.3.5.2 Initial and final block positions

In order to determine the movement of the measurement blocks in 1996 and 1997, it was necessary to reconstruct movement over the entire period during which the meters were operating (1993-1997). At the end of fieldwork in 1997, the meters were excavated and final physical measurements of the movement blocks were taken. No measurements were made when the blocks were originally installed, but it is known that each pair was positioned at a right angle to the meter, and each was less than 10 cm away from the meter.

The initial position of each set of blocks in 1993 was calculated using the final set of physical measurements and datalogger readings (Figure 3-6). Knowing the final horizontal distance that the blocks were away from the meter (D) and the height either above or below the exit slot at the meter (H), it was possible to calculate the direct distance (C) from the exit slot to the measurement blocks using basic geometry. The final reading from the datalogger (DLF) also corresponded to this distance. Given that the datalogger value did not necessarily start at zero, it was usually not the same value as the actual distance between the blocks and the exit slot. The difference between these values was calculated, and was added on to the initial 1993 datalogger value. This new value represents the original distance of the blocks from the meter.

3.3.5.3 Interpretation of movement data

3.3.5.3.1 Problem

When the solifluction meter was originally designed, it was assumed that the movement recorded would be relatively straightforward: heave (extension of the rack), settlement back to the

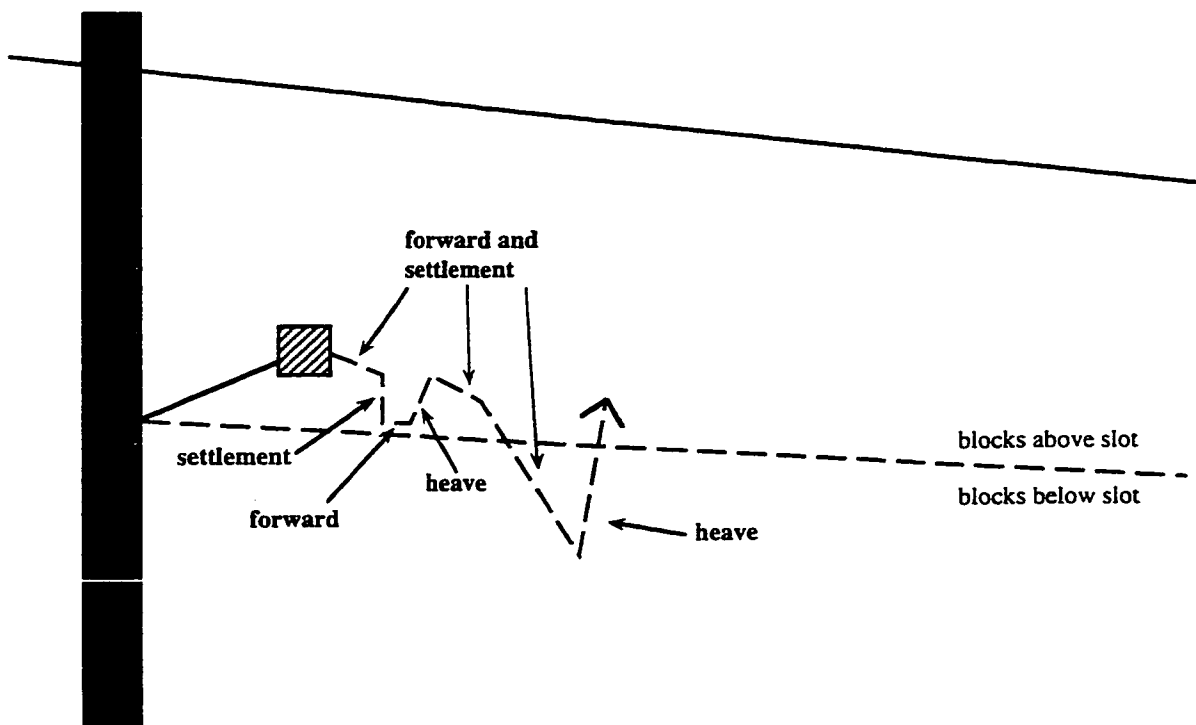
original level (retraction) and forward movement (extension). The depth of the measurement blocks at the end of the annual cycle was expected to be roughly the same as at the start. It was found that annual fluctuations in air temperature, thaw and freeze-up dates and precipitation played a large role in determining the importance of each individual element of solifluction (heave, settlement, forward movement). The relative importance of each varies significantly year-to-year, resulting in a movement that was much more complex than anticipated. An example of two years of movement data is shown in Figure 3-7, together with the actual movement that could have produced it. It is significant that heave at different times may be represented as extension or retrograde movement.

3.3.5.3.2 Solution

As the meter was only capable of measuring the resultant of a 2-dimensional movement, the data representation of movement was not a clear portrayal of the actual movement of the blocks. All of the directions of movement noted in Figure 3-8 would be reflected in the data as an increase in distance from the meter. Therefore, in order to arrive at a satisfactory analysis, it was essential to determine the position of the measurement blocks relative to their exit slot at the meter throughout the record (1993-1997). The initial block position, which was previously calculated, was used as the starting point for the reconstruction of movement. Calibrated movement data, corrected for the gradual change in meter angle over time, were graphed and carefully examined. It was important to compare the movement and temperature data of each individual set of blocks to that of the other blocks at the same meter in order to look for patterns through the soil profile which would help with interpretation. Other information which was used to help determine the direction of movement included: air temperature, soil temperatures, precipitation, meter height relative to the ground surface, porewater pressure, soil shear strength and soil moisture content.

Figure 3-7. Actual movement of blocks versus data representation of movement.

Actual movement of blocks



Data representation of movement

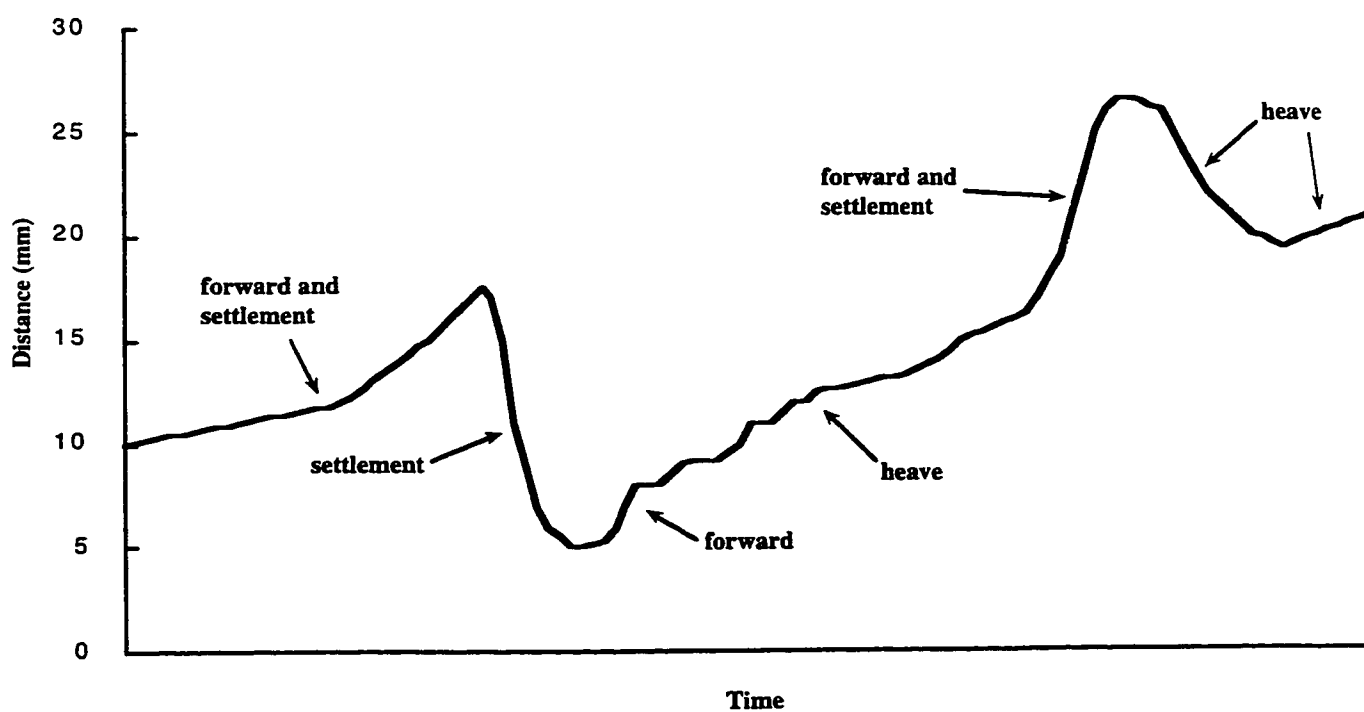
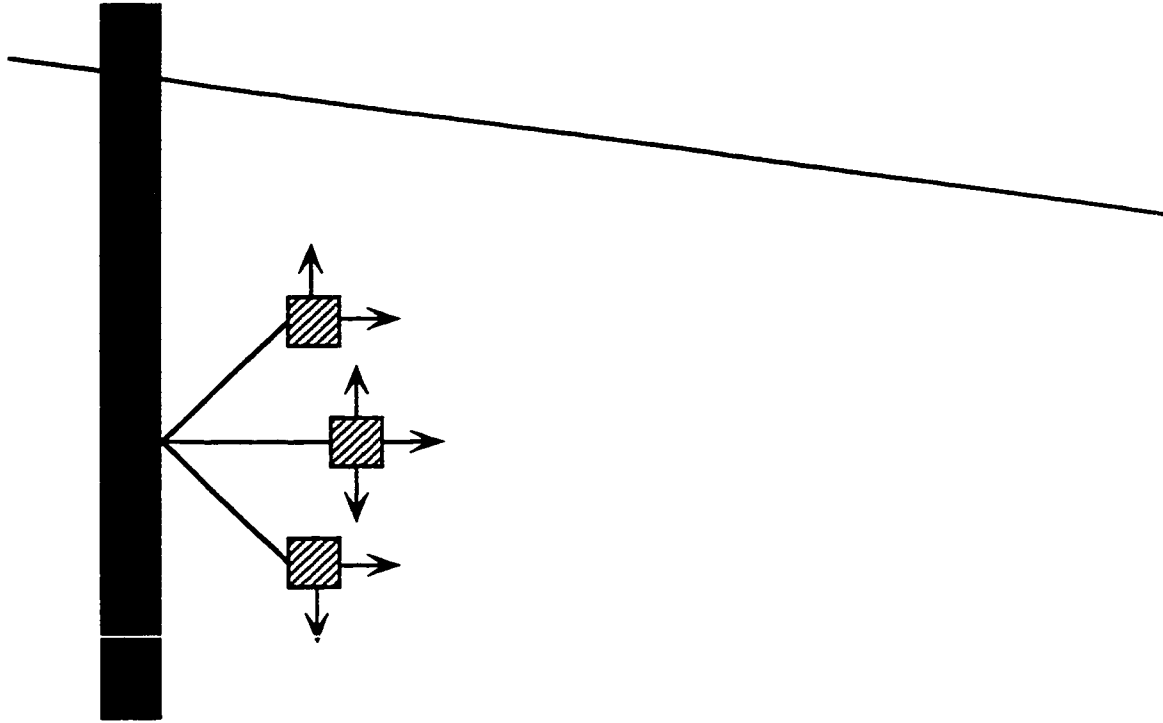


Figure 3-8. Possible movements resulting in an increase in block distance away from the meter.



3.3.5.3.3 Methods

3.3.5.3.3.1 Movement interpretation

Between 1993 and the start of climatic treatments in 1996, it was possible to assume that the same variables (e.g., air temperature, precipitation) affected each meter and that the blocks likely responded in a similar manner at each meter. Nevertheless, each meter was examined individually, as part of the purpose of the measurement period prior to the administration of climatic treatments was to assess the natural variation of movements among the meters. After the start of treatments, it was necessary to consider each meter individually.

A number of steps were taken in order to ascertain the direction of movement of the measurement blocks. Each year's movement was divided into several segments, based on changes in slope of the movement data line. These same segments of time were examined on graphs of soil temperature, air temperature and thaw depths. Starting from a position level with the exit slots in August 1993, it was possible to retrace the location of the blocks either above or below the slot. One key element which helped in this process was the fact that major heave occurs during the freeze-up period through the entire soil profile and that this would be reflected as a change (either increase or decrease, depending on the position of the blocks) in the movement values. It was possible to use this information of block location relative to the slot to help interpret the direction of movement at other periods of time. Table 3-3 indicates how the position of the blocks relative to the exit slot influenced the values recorded by the datalogger.

Table 3-3. Change in datalogger values according to block location and type of movement.

Block location	Datalogger values	Possible movement directions
above exit slot	increasing	forward, heave, forward/settlement
	decreasing	settlement
below exit slot	increasing	forward, settlement, forward/settlement
	decreasing	heave

One of the first things examined was whether increasing or decreasing air or soil temperatures were associated with either increasing or decreasing movement values. It was important to note whether a sudden change in the trend of movement values was marked by a temperature peak or trough or by a precipitation event.

It was also helpful that forward movement (whether combined with settlement or not) was always associated with increasing values, whether the blocks were above or below the exit slot. Therefore, if a meter had blocks that were both above and below the slot and they were all indicating increasing values, an element of forward movement was almost certainly involved.

In 1996, the measurements of meter height above the ground surface were used to determine the occurrence of ground heave or settlement over the course of the summer. Measurements of porewater pressure, soil shear strength and soil moisture content were used to examine whether conditions conducive to forward movement were present.

3.3.5.3.3.2 Difficulties

There were 3 different factors which may have held back forward movement of the measurement blocks after thaw depths indicated that they were no longer in soil that was frozen. First, due to the size of the measurement blocks (4x4x4 cm), it was possible that the tops of a pair of blocks were in thawed soil, but that the bases were still frozen in. Second, the design of the meters was such that the excess length of rack inside the main tube extended downwards. If water had entered the tube, it was possible that the tail-end of the rack was frozen in ice at a depth lower than the blocks, thus restricting potential forward movement. Third, the thermocouple cables monitoring soil temperature were set up in a manner that they were anchored in permafrost. As a result of heaving and settlement of the soil, the depth at which each thermocouple was monitoring varied over time. They were not necessarily located at exactly the same depths as the measurement blocks.

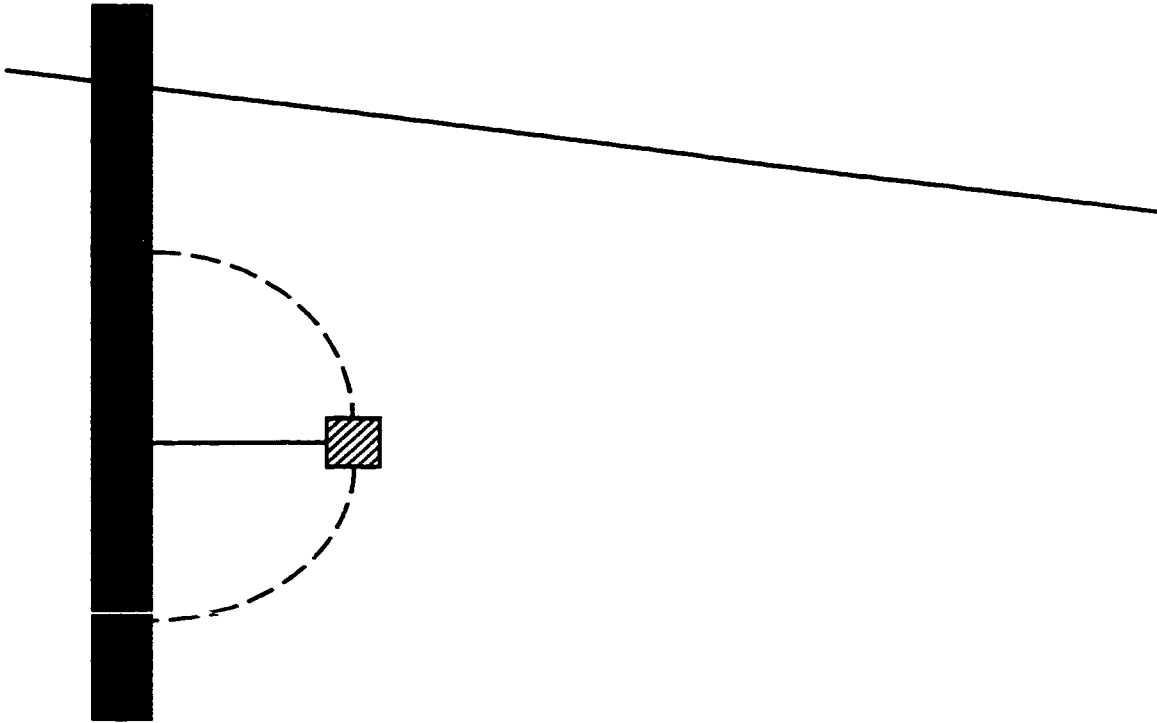
3.3.5.3.3 Movement reconstruction, 1993-1997

From the graphs drawn using the calibrated, angle-corrected movement data, individual points were chosen from each line where a noticeable change in slope occurred. The datalogger value for that point was determined and it was converted to a distance value using the same correction that was used to find the blocks' start position. This value represented the distance between the exit slot and the blocks at a particular time, however, it did not provide an indication of where they were specifically situated along an arc of equi-distant points surrounding the exit slot from the meter (Figure 3-9).

For each set of blocks, a diagram was hand-drawn on graph paper, using a ruler, a compass and a protractor. Both the initial and final block positions were marked on the diagram (Figure 3-10). The origin (0,0) represented the location of the exit slot on the meter. The first value representing movement from the initial block location was determined, and an arc representing all the possible directions of movement that could have produced this reading was drawn using a compass. When drawing the arc, the origin was used as the pivot point, as the exit slot was the location around which the blocks themselves pivoted. Based on the available information mentioned above, the direction of movement (heave, settlement, forward) was determined and the appropriate angle at which to draw a line representing movement was calculated (see Appendix A for a detailed example). A straight line was then drawn from the initial block location to the point where it intersected the arc.

Using this method, a series of arcs and lines were drawn, reproducing the approximate movement that took place at each set of measurement blocks from 1993 to 1997. Once a diagram was completed, x and y coordinates were determined for each point, and graphs indicating the horizontal and vertical movements of each set of blocks through the soil profile were created (see Appendix B). From the hand-drawn diagrams, it was also possible to determine approximate block positions on any specific day over the study period. As it was decided to discuss results on an annual basis from January 1 to

Figure 3-9. Arc of equi-distant points surrounding exit slot from meter.



December 31, the position of each set of blocks on January 1 of each year was determined and movement profiles were graphed.

3.3.5.3.3.1 Movement angles

The angle at which each line was drawn was based on 3 factors: slope angle, type of movement and meter angle. For purposes of discussion, angles will be referred to as x° up or down, using a flat horizon as a reference point of 0° . The slope angle was constant at 8° (down) and forward movement was considered to occur at the same angle (i.e. parallel to the site slope). Given that heave occurs normal to the slope, it was considered to occur at 82° (up). Settlement was considered to occur at 94° (down), as it takes place at an angle approximately between vertical (90° , down) and normal (98° , down) to the slope (Washburn, 1967). As was often the case during mid- to late-summer, it was difficult to distinguish between forward movement and settlement as they often occurred simultaneously. The relative importance of each was assessed and an angle between 8° (down) and 94° (down) was chosen.

3.3.5.3.3.2 Meter angles

As previously discussed, the meters experienced gradual bending between 1992 and 1997. It was therefore necessary to consider the angle at which the meter was bent when drawing the line representing movement as the y-axis in the diagram (representing the meter) remained constant. It was assumed that meter bending began on the date of initial installation in 1992. Using the previously mentioned correction equation with the appropriate y-intercept value for each meter, meter angles were calculated for the dates on which movement was first recorded each year. The change in angle from the previous measurement was appropriately distributed along the length of the meter (see section 3.3.4 Meter angles). For the purpose of simplification, these angles were assumed for the period of a year. For example, if the meter was completely upright (90° , up), heave would take place at 82° (up), settlement would be at 94° (down) and forward movement would be at 8° (down). If the

top of the meter was at an angle of 84.6° , heave (between 2 and 42 cm) would occur at 87.4° (up) ($90^\circ - (84.6^\circ - 82^\circ)$), settlement would be at 88.6° (down) ($90^\circ - (86^\circ - 84.6^\circ)$) and forward movement would be at 2.6° (down) ($0^\circ - 84.6^\circ - 82^\circ$). In this manner, the movement of the blocks in the diagram was relative to the y-axis, which represented an annually changing meter angle.

3.3.5.3.3.3 Difficulties

It was not possible to reconstruct movement for 10 sets of measurement blocks. All of the blocks which were originally located at a depth of 2 cm were either partially exposed at the ground surface or suspended in the air. These values were therefore not included in the analysis as the datalogger values did not fully reflect the movement which occurred. Potentiometers at meter A (10 cm) and meter C (50 and 58 cm) malfunctioned, so that although it was possible to measure their final location during excavation, data logger values were not available to calculate their initial position. It was not possible, therefore, to determine the total distance that they had moved.

Difficulties were encountered when drawing the diagrams for the 34 and 42 cm blocks at meter B. In 1995 and 1996, virtually no heave was recorded at these blocks during the freeze-up period, but it was not possible to complete the reconstruction of movement without including some degree of heave. Although it was impossible to determine annual movement, the total amount of movement over the study period was calculated, and these figures were included in the final profile.

During the reconstruction of movement, it was occasionally necessary to modify the angle at which movement occurred in order to arrive at a point on the arc that was drawn the required distance away from the exit slot. Given that the blocks would not have moved in a series of straight-line movements, it is likely that slight differences in the path of movement may have been responsible for the required angle modification. Changes to the angle of movement were usually only necessary once or twice per set of blocks over the entire study period and appeared to have little overall impact on the final pattern of movement. On several occasions, small modifications were made to either an angle or

direction of movement when drawing the diagrams, and this had this had very little effect on the remainder of the diagram.

In August 1993, the blocks between 2 and 58 cm were re-set due to the severe pulling down which had occurred since 1992. The blocks below 58 cm were not re-set as they were not yet thawed. It was therefore possible to assume that they were located below the slot at the start of continuous monitoring in 1993. Nevertheless, several diagrams for each of these sets of blocks were drawn with initial positions ranging from 5 mm above to 20 mm below the slot in order to determine which scenario best-fit the series of movements which occurred. At meters B, C and D, the initial position was determined to be 5 mm below the slot and at meter A, 10 mm below. Meter E had no blocks deeper than 50 cm.

3.3.5.4 Summary of meter corrections

As a result of the above corrections, a degree of error is present in the final movement values. For example, some quantitative error was introduced when it was assumed that the upper section of each meter had a linear bend. When drawing the graphs for each set of blocks, qualitative interpretation of the available data was required in order to establish a movement record. Nevertheless, associated information combined with recurring patterns of movement helped to lessen the introduced error. In addition, changes in the interpretation of small segments of movement had little impact on the overall pattern of movement of each set of measurement blocks.

The potentiometers read to a precision of <0.1 mm and the movement data is probably correct to ± 1 mm. Due to the sampling and read-out frequency of the data, the timing of movement is accurate within < 1 day. There is confidence, therefore, that the movement record established is an accurate depiction of movement which occurred at the experimental site between 1993 and 1997.

Chapter 4. Results

The focus of the thesis is on solifluction during 1996, the year in which climatic treatments were undertaken, and 1997, when possible lag effects may have influenced solifluction processes. The results of movement and associated measurements during these two years are presented in this chapter. In addition to these results, data from 1993-1995 were available and were examined for purposes of comparison. Although these results are not discussed at length in this chapter, they are presented in the tables and figures together with the 1996 and 1997 values.

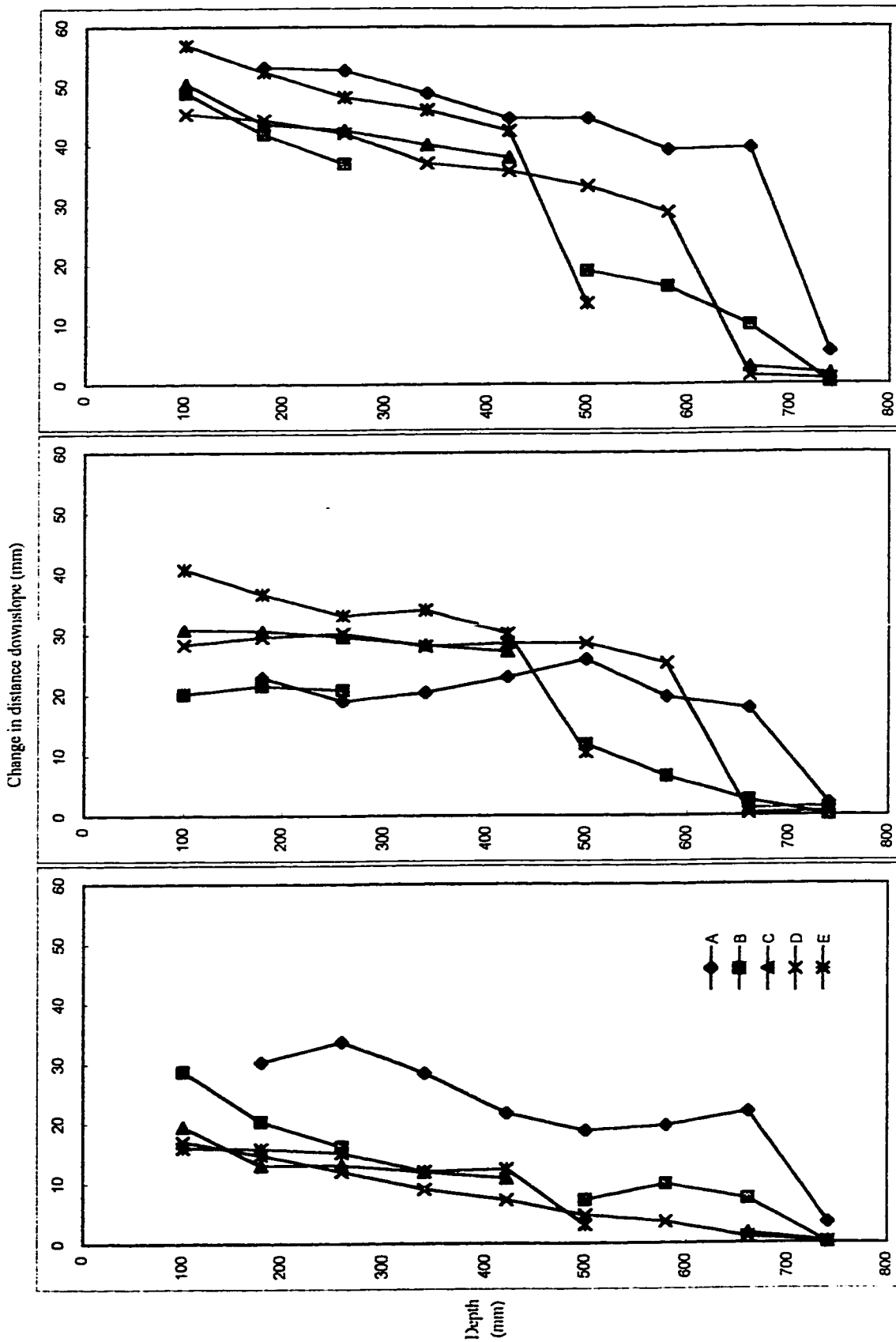
4.1 Movement

One year of movement corresponds to one calendar year (January 1 - December 31). In this manner, the time period is fixed rather than being subject to annual variation (e.g., a time period based on the start of thaw or heave). This also places the heave associated with late summer freeze-up in the same time period as the variables likely to have had the greatest impact on it: the previous summer air temperatures and precipitation. Movement is divided into 2 components: horizontal (downslope) and vertical (heave or settlement). The 1993 and 1997 values are not based on a full year of data as the logger began collecting data on August 11, 1993 and the meters were excavated between August 1-3, 1997.

4.1.1 Downslope movement

In 1996, the blocks at Meter A indicated greater amounts of downslope movement than those at the other meters at all measured depths (Figure 4-1a). The maximum amount of movement recorded was at 26 cm depth (34 mm), while movement at the other meters ranged between 12 and 16 mm at the same depth. Very little movement was measured at 66 cm depth, only 1 to 7 mm at meters B, C and D, whereas meter A indicated 22 mm. Meter A also recorded 3 mm of movement at 74 cm, while C and D had <1 mm each. Note that the deepest measurement blocks at meter E are located at a depth of only 50 cm.

Figure 4-1. Annual downslope movement, 1996-1997.



a) 1996 downslope movement.

b) 1997 downslope movement.

c) 1996-1997 combined downslope movement.

The blocks at meter B indicated greater amounts of movement than at meters C, D and E at all depths recorded. The maximum recorded amount was at 10 cm depth (B - 29 mm; C - 20 mm; D - 17 mm; and E - 16 mm). Movement at meters B, C, D and E was greatest at the top of the profile and decreased with depth (with the exception of B-50 cm). Meter A demonstrated a much less consistent decrease with depth, as movements at 26, 58 and 66 cm were greater than those recorded immediately above these depths.

The amount of downslope movement measured in 1997 was greatest at meter E in the upper and middle sections of the soil profile, ranging from 41 mm at 10 cm to 30 mm at 42 cm (Figure 4-1b). The depth of maximum movement varied between the meters: A - 50 cm, B - 18 cm, C - 10 cm, D - 18 cm and E - 10 cm. Meter A demonstrated the least amount of movement at 26, 34 and 42 cm, but movement decreased much less with depth: at 66 cm, meter A measured 18 mm of movement, whereas meters B, C and D had 3, 1 and <1 mm, respectively. At 74 cm, meter A recorded 2 mm, while meters C and D recorded slightly greater movements (2 and 1 mm) than they had at 66 cm depth.

Movement decreased much less consistently with depth in 1997 than in 1996, as similar amounts were recorded at each meter between the depths of 10 and 42 cm. Meter D measured similar amounts of movement to a depth of 58 cm (ranging from 30 mm at 18 cm to 25 mm at 58 cm), while movement at meter A remained relatively constant down to 66 cm (ranging from 26 mm at 50 cm to 18 mm at 66 cm). Due to excavation of the meters, the 1997 data represent a minimum amount of downslope movement as it is probable that further forward motion and/or settlement would have occurred during the month of August.

The total movement for 1996 and 1997 combined indicates that in the upper and middle sections of the soil profile, there were similar amounts of movement at each meter (Figure 4-1c). Between a depth of 10 and 42 cm, the average total movement at all the meters combined was 45 mm,

with a standard deviation of only 6 mm. Below 42 cm, however, there are large variations in the amounts of total movement. Meter A recorded much greater total movement below 42 cm, ranging from 45 mm at 50 cm to 5 mm at 74 cm. In comparison, meter B recorded only 19 mm at 50 cm and virtually no movement at 74 cm.

4.1.2 Vertical movement

The two elements which make up the vertical component of movement, heave and settlement, occur as a result of the phase transition of moisture in the soil. Based on the coordinates derived from hand-drawn graphs, total annual amounts of heave and settlement were separated out from the movement data for each set of measurement blocks. The annual mean values at meter E will tend to be higher than those of the other meters as it did not have measurement blocks deeper than 50 cm, and therefore no values deeper than 50 cm were included in the calculation of the mean. At the other meters, these values tended to be very small, which served to bring down the mean values.

4.1.2.1 Heave

Mean total heave was calculated for each depth measured in 1994 and 1995 (Table 4-1). In 1994, very little variation in heave was recorded between 10 and 50 cm, with values ranging from 13 to 19 mm. The amount of heave dropped rapidly below 50 cm, with only 1 mm recorded at a depth of 66 cm. Similarly, values remain relatively high between 10 and 58 cm (between 18 and 28 mm) in 1995, followed by a rapid decrease below 58 cm.

During 1996, the largest sum of heave movements occurred at a different depth at each meter: meter A - 26 cm (33 mm), meter B - 50 cm (28 mm), meter C - 34 cm (47 mm), meter D - 42 cm (44 mm) and meter E - 10 and 18 cm (46 mm) (Table 4-1). Between the depths of 10 and 42 cm, meter E recorded the greatest amounts of heave (42 - 46 mm) except at 34 cm, where meter C showed a slightly greater amount (47 mm). Meter B had the least amount of heave between the depths of 10 and 26 cm (18 - 25 mm). The amount of heave at blocks above 66 cm was considerably less at meter

Table 4-1. Total annual heave, 1993-1997 (mm).

Numbers in brackets represent the percentage of total heave which occurred during fall freeze-up.										
1993*	10	18	26	34	42	50	58	66	74	Mean
A	-	29	21	28	27	44	45	0	0	24
B	16	15	19	-	-	47	25	0	0	17
C	6	10	22	35	47	-	-	10	0	19
D	8	12	23	25	34	41	52	11	0	23
E	8	17	24	28	47	26	-	-	-	25
1994	10	18	26	34	42	50	58	66	74	Mean
A	-	18 (100)	12 (92)	16 (94)	21 (90)	26 (96)	10 (80)	0	0	13
B	11 (55)	7 (57)	13 (85)	-	-	17 (94)	5 (100)	-	0	9
C	19 (79)	19 (84)	14 (79)	16 (81)	18 (83)	-	-	0	0	12
D	22 (77)	21 (86)	17 (82)	14 (86)	15 (87)	14 (93)	13 (100)	3 (0)	0	13
E	17 (82)	6 (83)	10 (70)	11 (82)	21 (71)	20 (100)	-	-	-	14
Mean	17	14	13	14	19	19	9	1	0	
1995	10	18	26	34	42	50	58	66	74	Mean
A	-	35 (57)	13 (100)	24 (100)	19 (100)	29 (100)	16 (100)	0	2 (0)	17
B	9 (22)	18 (72)	17 (100)	-	-	18 (100)	4 (100)	-	0	11
C	42 (62)	19 (58)	20 (100)	21 (100)	21 (100)	-	-	8 (100)	4 (0)	19
D	26 (69)	27 (70)	18 (100)	11 (100)	11 (100)	20 (100)	35 (100)	6 (100)	0	17
E	33 (79)	32 (75)	22 (95)	27 (100)	24 (100)	23 (100)	-	-	-	27
Mean	28	26	18	21	19	23	18	5	2	
1996	10	18	26	34	42	50	58	66	74	Mean
A	-	32 (100)	33 (100)	33 (100)	18 (100)	0	8 (100)	16 (100)	13 (54)	19
B	23 (100)	25 (100)	18 (100)	-	-	28 (100)	11 (100)	21 (100)	0	18
C	43 (81)	40 (68)	38 (71)	47 (75)	42 (79)	-	-	0	0	30
D	33 (76)	31 (74)	36 (67)	37 (68)	44 (66)	41 (71)	41 (76)	0	0	29
E	46 (83)	46 (70)	45 (60)	42 (67)	46 (67)	0	-	-	-	37
1997*	10	18	26	34	42	50	58	66	74	
A	-	0	0	3	0	0	0	3	10	
B	0	0	0	-	-	0	0	0	0	
C	0	0	0	0	0	-	-	5	17	
D	0	0	0	0	0	2	0	3	14	
E	0	0	0	0	2	0	-	-	-	
*Totals do not reflect a full year, therefore fall freeze-up heave as a percentage of total heave was not calculated.										
1993 - August 11-December 31; 1997 - January 1-August 2.										

A than at meters C and E (0 - 33 mm), but meter A recorded heave at a greater depth than at any other meter (13 mm at 74 cm). Overall, there appears to be little pattern of total heave evident through each individual profile as values neither decreased nor increased consistently with depth.

If only heave recorded during the 1996 fall freeze-up is considered, the effect is to decrease the total amount of heave recorded at meters C, D and E for the year (Table 4-1). It has no impact on meter A and B values, as they only recorded heave during the fall. No single meter indicates the greatest amount of heave at all depths. Maximum heave recorded ranges from 38 mm at 10 cm (meter E) to 7 mm at 74 cm (meter A).

Very little heave was recorded in 1997 because the meters were excavated prior to the major freeze-back period in late summer. A small amount of heave (2 - 3 mm) occurred between 34 and 50 cm at 3 of the meters (A, D and E), while slightly greater heave was recorded at 66 cm (3 - 5 mm) as well as at 74 cm (10 - 17 mm) at meters A, C and D. All heave recorded in 1997 took place during the summer.

4.1.2.2 Settlement

Mean settlement was calculated for each depth measured in 1994 and 1995 (Table 4-2). The pattern of settlement was similar both years, although the values were much greater in 1995 than in 1994. In both years, settlement between 10 and 42 cm remained relatively constant, ranging between 9 and 11 mm in 1994 and between 35 and 39 mm in 1995. Peak settlement values were recorded at a depth of 50 cm (17 mm in 1994 and 40 mm in 1995), below which settlement decreased relatively rapidly.

During 1996, settlement values at meter A were much greater than at any of the other meters, ranging from 50 mm at 18 cm to 14 mm at 74 cm (Table 4-2). The only exception occurred at 50 cm, where meter B had 22 mm of settlement versus 19 mm at meter A. While values at meter B were

Table 4-2. Total annual settlement, 1993-1997 (mm).

	10	18	26	34	42	50	58	66	74	Mean
1993*										
A	-	8	3	10	5	14	16	1	0	7
B	6	6	6	-	-	13	7	0	0	5
C	0	1	5	11	13	-	-	8	0	5
D	0	2	6	7	10	11	14	0	0	6
E	0	6	7	7	14	22	-	-	-	9
1994										
A	-	13	7	8	10	17	4	0	0	7
B	0	2	7	-	-	8	0	0	0	2
C	11	13	8	9	11	-	-	0	0	7
D	15	16	18	12	11	10	10	0	0	10
E	10	1	6	6	13	23	-	-	-	10
Mean	9	9	9	9	11	17	5	0	0	
1995										
A	-	49	44	46	43	42	20	16	0	32
B	41	36	31	-	-	35	3	-	0	25
C	45	32	35	41	38	-	-	26	0	31
D	29	30	22	20	27	32	43	20	0	25
E	38	47	41	39	39	52	-	-	-	43
Mean	38	39	35	37	37	40	22	23	0	
1996										
A	-	50	33	41	41	19	30	19	14	31
B	11	22	21	-	-	22	17	4	0	14
C	12	1	1	2	1	-	-	0	0	2
D	2	2	2	2	1	0	0	0	0	1
E	1	2	2	1	1	0	-	-	-	1
1997*										
A	-	13	25	27	7	11	22	1	0	13
B	7	7	5	-	-	12	16	12	0	8
C	45	35	41	48	52	-	-	4	0	32
D	23	25	28	27	35	37	35	5	0	24
E	47	43	42	48	54	23	-	-	-	43

*Totals do not reflect a full year. 1993 - August 11-December 31; 1997 - January 1-August 2.

usually much lower than those at meter A, meter B also registered much greater settlement below 10 cm than at meters C, D and E. At 10 cm, meters B and C measured almost identical values (11 and 12 mm, respectively). Other than at 10 cm depth, settlement values at meters C, D and E were very small. The maximum value at both D and E was 2 mm. Although the maximum value recorded at each meter occurred in the upper 18 cm of the profile, there is little pattern of settlement evident through the remainder of the profile.

As noted previously, 1997 values do not reflect the entire amount of settlement that would have occurred during that summer. Nevertheless, considerable settlement was recorded at all of the meters in the period prior to excavation. Down to a depth of 42 cm, meter E recorded the highest settlement values, ranging from 54 mm at 42 cm, to 42 mm at 26 cm. The only exception occurred at 34 cm, where meter C had the same amount as meter E (48 mm). The greatest amount of settlement at each meter occurred at greater depths than in 1996: meter A - 34 cm (27 mm), meter B - 58 cm (16 mm), meter C - 42 cm (52 mm), meter D - 50 cm (37 mm) and meter E - 42 cm (54 mm). Overall, the settlement values at meters C, D and E were much greater than those at meters A and B. The one notable exception occurred at 66 cm, where meter B recorded 12 mm, compared to meters A, C and D which had 1, 4 and 5 mm, respectively. Once again, there is no apparent pattern of settlement through the soil profiles, although overall, the greatest amount of heave (1996) and settlement (1997) occurred at meters C, D and E and the least at meters A and B.

4.1.2.3 Net vertical movement

The net change in vertical position from January 1 of one year to January 1 of the following year was calculated for each set of measurement blocks by subtracting the total settlement for a given year from the sum of heave movements (Table 4-3). A positive value indicates that the net vertical movement was upward (heave), whereas a negative value indicates a net downward movement (settlement). In 1994, there is very little variation in the mean net change between 10 and 58 cm, ranging between 5 and 8 mm of net movement upward. With the exception of the value calculated

Table 4-3. Net change in vertical position, 1994-1997 (mm).

Net change: positive - heave, negative - settlement.										
1994	10	18	26	34	42	50	58	66	74	Mean
A	-	5	5	8	11	9	6	0	0	6
B	11	5	6	-	-	9	5	-	0	6
C	8	6	6	8	6	-	-	0	0	5
D	7	5	-1	2	4	4	3	3	0	3
E	6	5	4	6	9	-3	-	-	-	4
Mean	8	5	4	6	8	5	5	1	0	
1995	10	18	26	34	42	50	58	66	74	Mean
A	-	-14	-31	-22	-24	-13	-4	-16	2	-15
B	-32	-18	-14	-	-	-18	0	-	0	-13
C	-3	-13	-15	-21	-18	-	-	-18	4	-12
D	-3	-3	-4	-9	-15	-11	-9	-14	0	-8
E	-4	-15	-19	-12	-15	-29	-	-	-	-16
Mean	-11	-13	-17	-16	-18	-18	-4	-16	2	
1996	10	18	26	34	42	50	58	66	74	Mean
A	-	-18	0	-8	-23	-19	-22	-4	0	-12
B	12	2	-3	-	-	6	-6	17	0	4
C	32	39	36	45	41	-	-	0	0	28
D	31	30	34	36	43	40	41	0	0	28
E	45	44	44	41	45	0	-	-	-	36
1997*	10	18	26	34	42	50	58	66	74	Mean
A	-	-13	-25	-23	-7	-11	-22	2	10	-11
B	-7	-7	-5	-	-	-12	-16	-12	0	-8
C	-45	-35	-41	-48	-52	-	-	0	17	-29
D	-23	-25	-28	-27	-35	-35	-35	-2	14	-22
E	-47	-43	-42	-48	-51	-23	-	-	-	-42

*Totals do not reflect a full year: 1997 - January 1-August 2.

for a depth of 58 cm, net change in vertical position remains relatively constant between 10 and 66 cm in 1995 (ranging between 11 and 18 mm of net movement downward).

In 1996, meter E recorded the greatest net movement upward between 10 and 42 cm, ranging from 41 to 45 mm. No change in vertical movement was recorded at 50 cm. With the exception of the blocks at 26 cm, meter A demonstrated the greatest amount of net downward movement, ranging from 18 mm at 18 cm to < 1 mm at 74 cm. The maximum amount of net downward movement was recorded at a depth of 42 cm (23 mm) at meter A. Overall, of the blocks at meters C, D and E which recorded vertical movement, all indicated net upward movement of at least 30 mm. In contrast, only 1 set of blocks at meter A (26 cm) and 4 at meter B (10, 18, 50 and 66 cm) recorded net upward movement, with amounts ranging between < 1 mm and 17 mm.

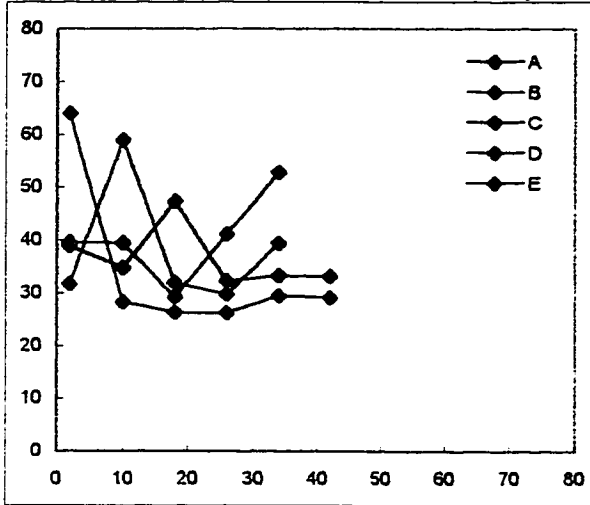
The 1997 net vertical movement values do not include the entire thaw period or the fall freeze-up. It is still valuable, however, to compare the results recorded between the meters. Between 10 and 58 cm, all blocks indicated a net movement downward, with meters C and E recording the greatest amount of settlement between 10 and 42 cm (35 to 52 mm). Meter D recorded the most settlement at 50 and 58 cm (35 mm). With the exception of meter B at 66 cm, meters A and B demonstrated smaller amounts of net downward movement than meters C, D and E.

4.2 Associated measurements

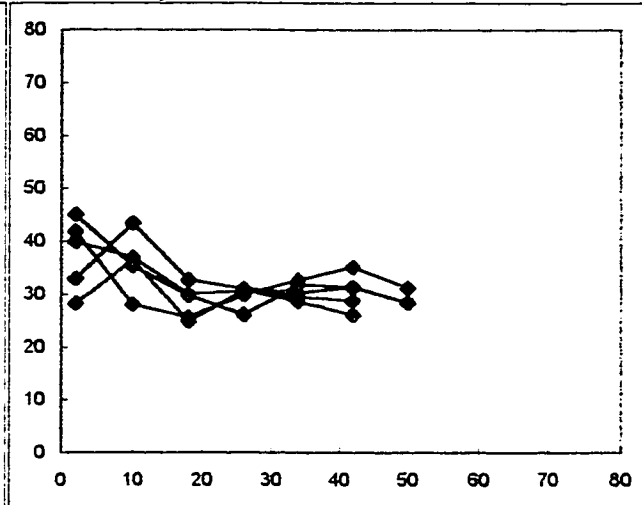
4.2.1 Soil moisture content

Samples were taken at regular intervals through the thawed soil profile at each meter throughout the summer of 1996, as well as just prior to excavation in 1997. The results of moisture content analysis are presented in Figures 4-2 and 4-3. Figure 4-2 allows for a comparison of the values between the meters on each sample day. Throughout 1996, the majority of samples taken from below 10 cm at each meter had a moisture content between 25 and 35%. The average moisture

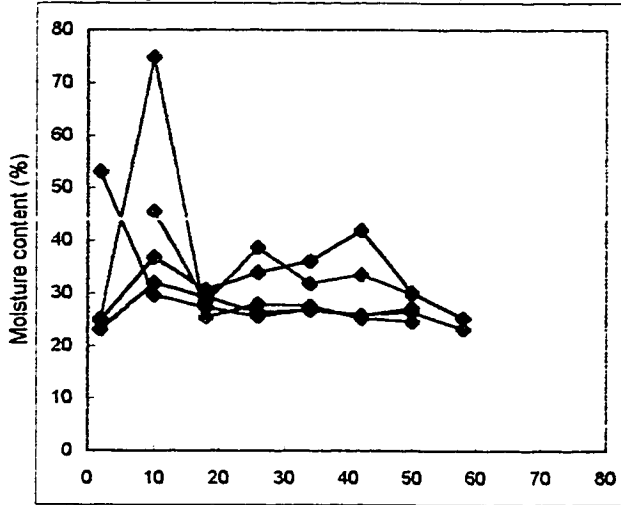
a) June 30, 1996 (Meter A too wet to sample)



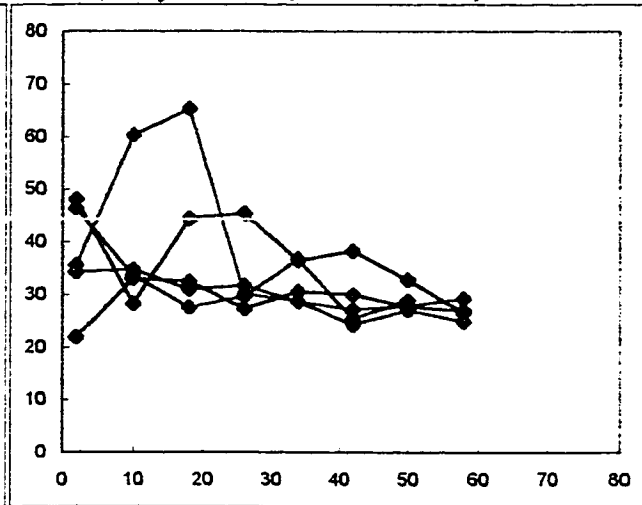
b) July 7, 1996



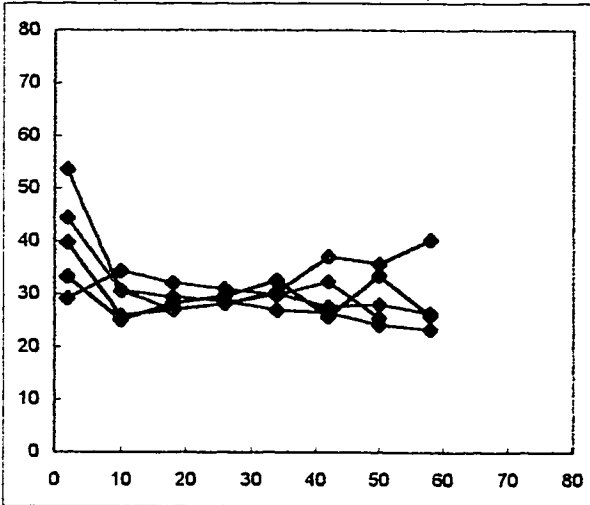
c) July 14, 1996 (A and D wetted)



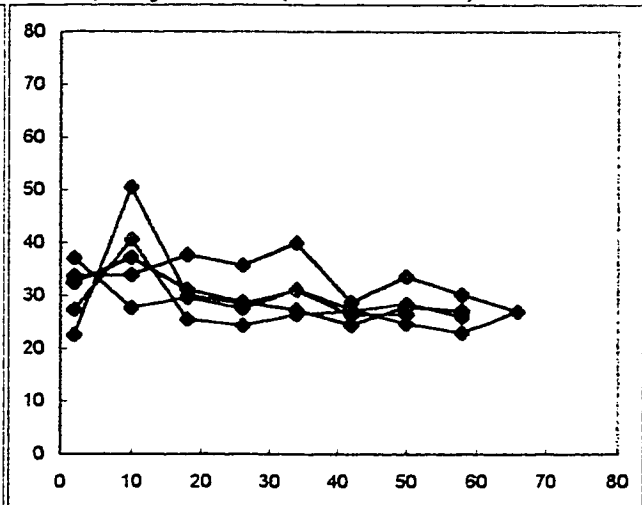
d) July 18, 1996 (A and D wetted)



e) July 23, 1996 (A and D wetted)

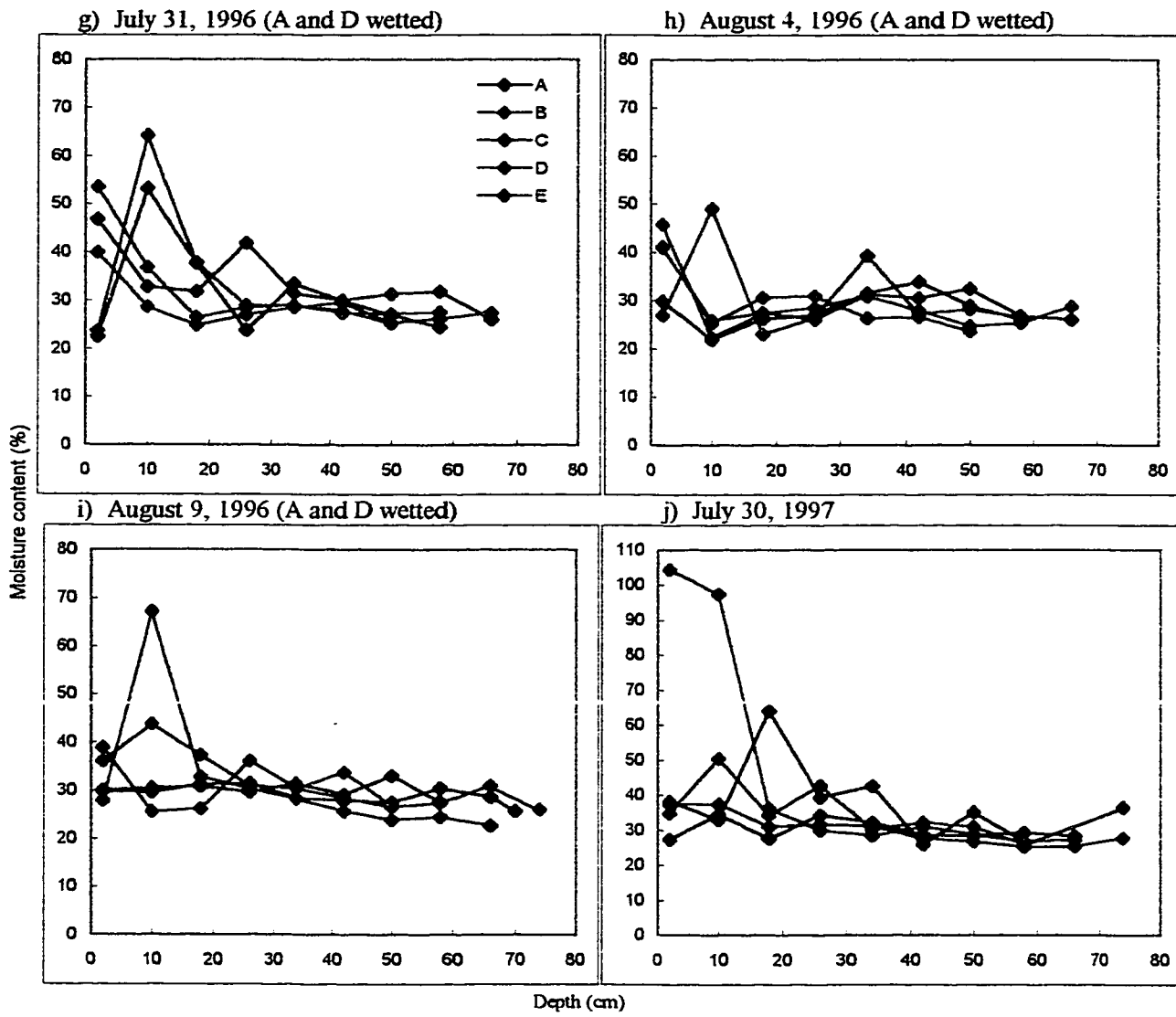


f) July 27, 1996 (A and D wetted)



Depth (cm)

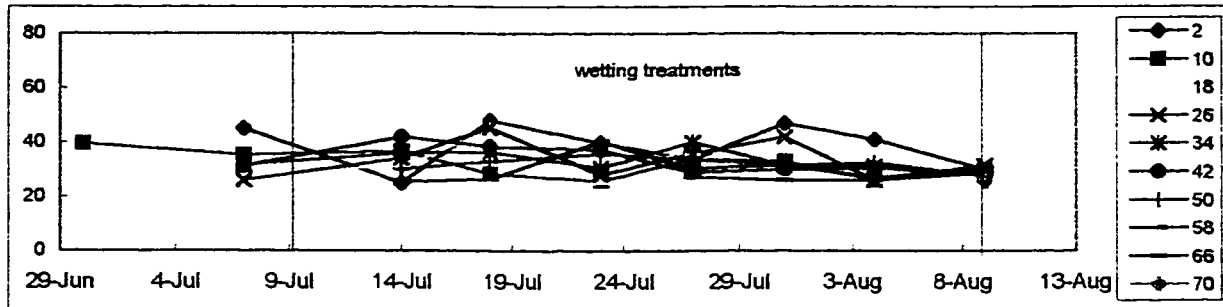
Figure 4-2. Soil moisture content, variation between meters, 1996-1997.



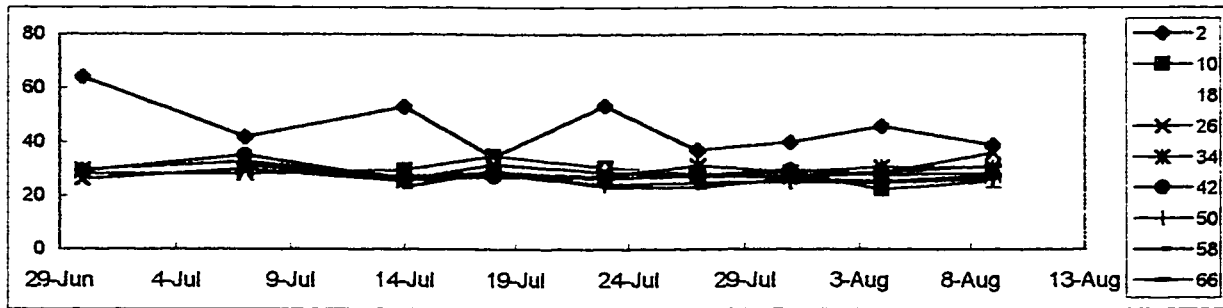
Please note difference in y-axis scale in Figure j.

Figure 4-3. Soil moisture content: trend over time, 1996.

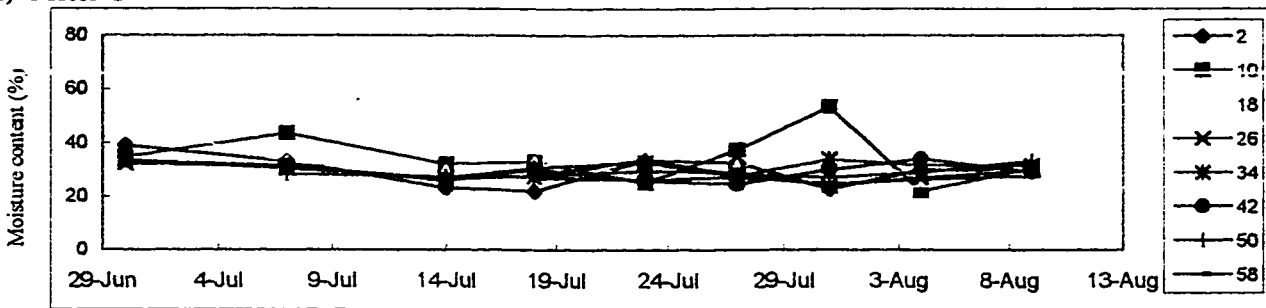
a) Meter A



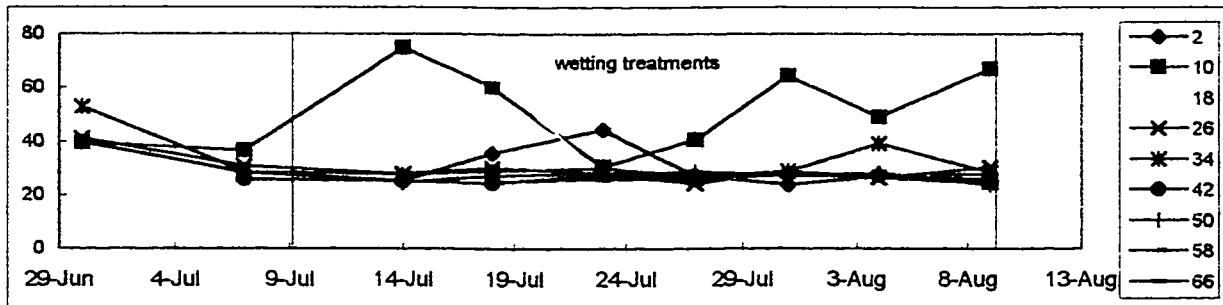
b) Meter B



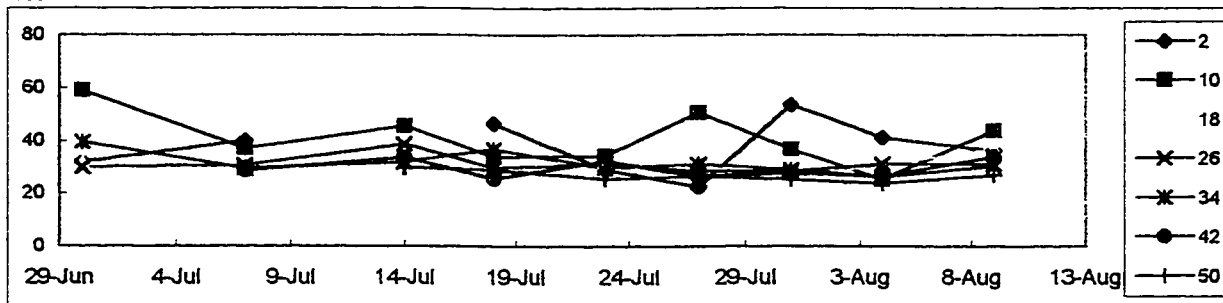
c) Meter C



d) Meter D



e) Meter E



Note: Legend values represent depth (cm).

content of all values in 1996 and 1997 was 32.0% with a standard deviation of 9.2. Figure 4-3 illustrates the lack of variation in moisture at each meter during the summer of 1996.

On June 30, 1996, the values at each meter were quite variable ranging from, at meter B for example, 64.0% at 2 cm to 26.2% at 26 cm (Figure 4-2a). Moisture contents were less variable on July 7, with an overall trend to decreasing values with depth (Figure 4-2b). Wetting treatments began at meters A and D on July 8, 1996 and continued through the summer until August 8. In addition, the area surrounding meters A and B was covered with a polyethylene sheet during this same period. The moisture content values at these meters may, therefore, have been influenced by these treatments.

The profiles of moisture content values from soil samples taken between July 14 and August 9, 1996 show a similar trend (Figures 4-2c through 4-2i). At 10 cm depth, the value at meter D was much greater throughout the summer than both the values at the same meter and those at the other meters, with a maximum reached on July 14 of 75%. On July 18, the value at 18 cm at meter D was also much higher than elsewhere (65%). There are, however, two exceptions: July 23, when the value at D-10 was within range of values at the other meters at the same depth (25 - 34%); and July 27, when meter E had a higher moisture content than meter D (51 versus 41%).

Between July 14 and July 31, meter A had the highest moisture content values below 18 cm more frequently than at any other individual meter, particularly between 42 and 58 cm. On the dates sampled, values ranged from 25% at 58 cm on July 14 to 45% at 26 cm on July 18.

On several sample dates, the moisture content at 2 cm was considerably higher than at greater depth in the soil profile (July 14 (B), July 18 (A and E), July 23 (A, B and D), July 27 (B), July 31 (A, B and E), August 4 (A, B and E) and August 9 (B)).

The results from July 30, 1997 were similar to those from 1996 (Figure 4-2j). Meter D had much higher moisture content values at 2 and 10 cm than any of the other meters (104 and 97%, respectively). Meter A had the highest values at 18, 34 and 50 cm, and also the second highest value at 26 cm. The overall average for the samples from that day was 36%, which is slightly higher than the overall average of all samples (32%).

4.2.2 *In situ* shear strength

In situ shear strength of the soil was measured at regular intervals within the soil profile at each meter throughout the summer of 1996, as well as just prior to excavation in 1997 (Figure 4-4). Throughout 1996, a similar trend with depth was maintained at each meter (Figure 4-5). The highest shear strength values occurred at either 2 or 10 cm, with the exception of B-50 and D-50 on July 13 and D-50 on July 23. The maximum values recorded at each meter were as follows: meter A - 39 kPa (10 cm, July 27), meter B - 43 kPa (August 4, 2 and 10 cm), meter C - 55 kPa (August 9, 2 cm), meter D - 36 kPa (August 9, 10 cm) and meter E - 52 kPa (July 31, 2 cm). The lowest values occurred at either 26 or 34 cm, with the exception of E-42 on July 18 and B-65 on July 23 and July 27. The minimum values recorded at each meter were as follows: meter A - 9 kPa (26 cm, July 13), meter B - 6 kPa (26 cm, August 4), meter C - 3 kPa (34 cm, June 30), meter D - 9 kPa (26 cm, June 26) and meter E - 4 kPa (34 cm, July 7).

Shear strength values increased with depth below the minimum values recorded at either 26 or 34 cm, with numbers approaching the maximum values recorded at 2 and 10 cm (Figure 4-5). When the active layer depth was sufficient to record a measurement at 66 cm, this value generally showed a decline in the shear strength from that recorded at 50 or 58 cm. On four days (July 18, July 27, July 31 and August 9), the deepest recorded value at meter B showed a relatively sharp increase in shear strength over the measurement 8 cm above, possibly because partially frozen sediment was sampled.

Figure 4-4. *In situ* shear strength: variation between meters, 1996-1997.

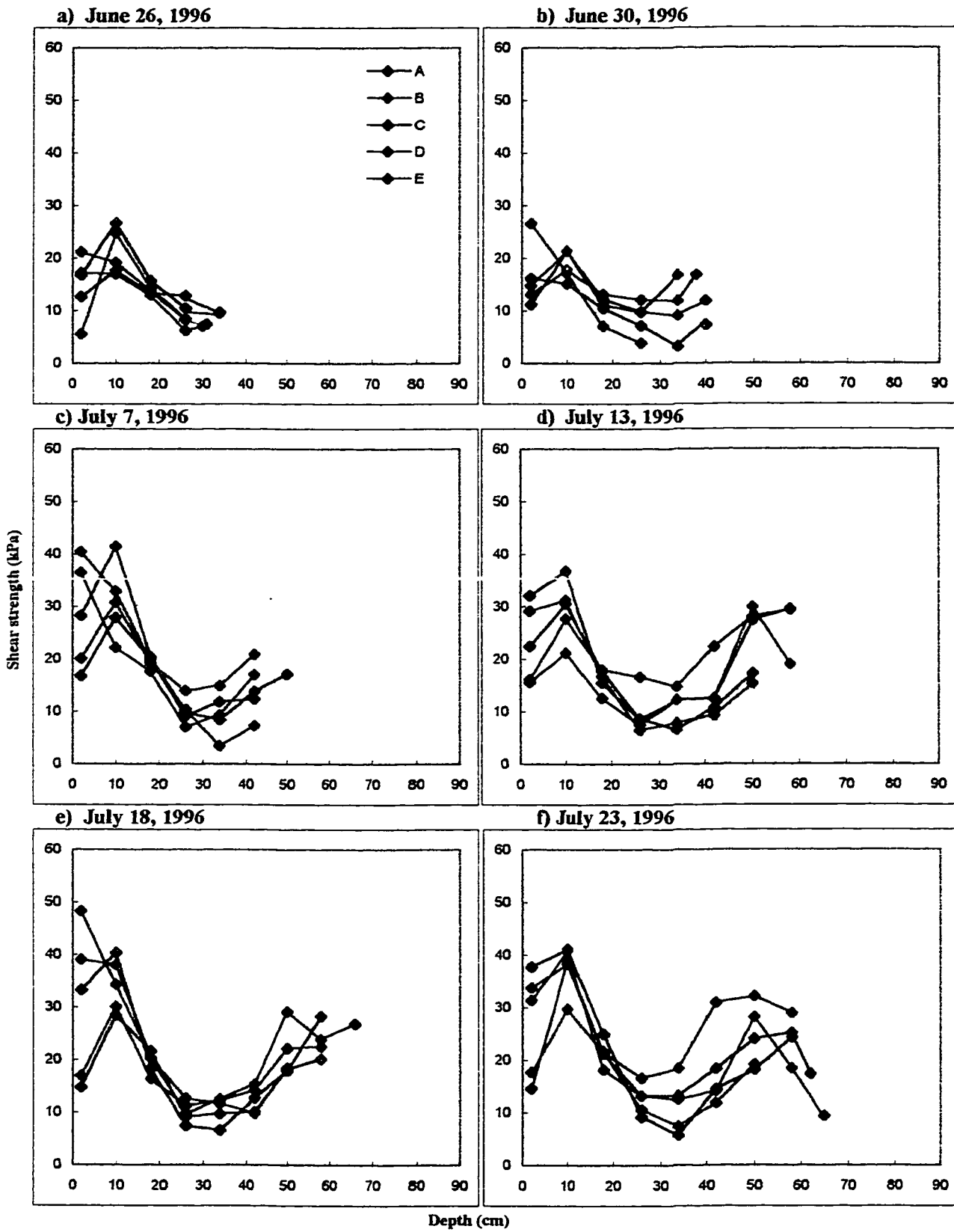


Figure 4-4. *In situ* shear strength: variation between meters, 1996-1997.

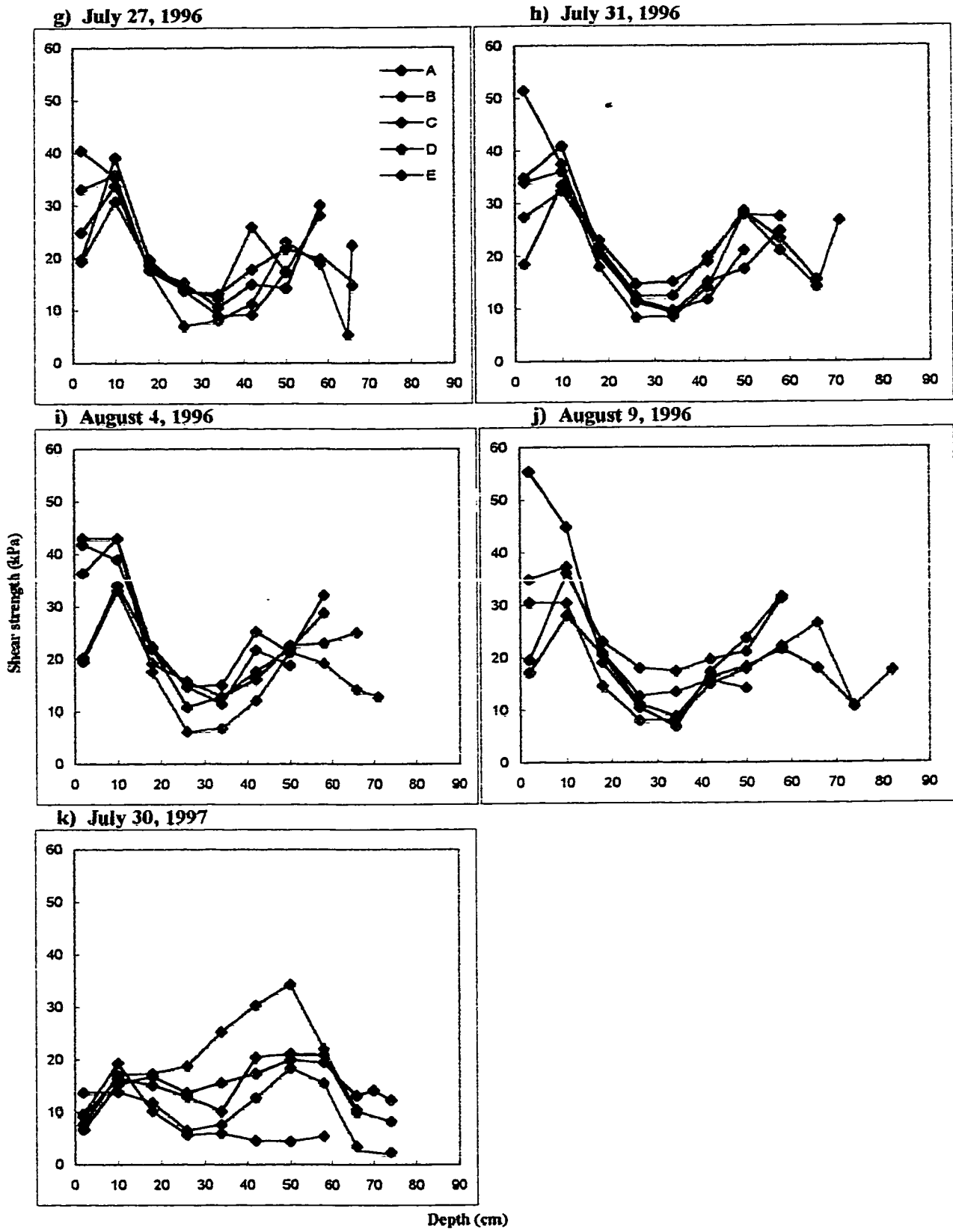
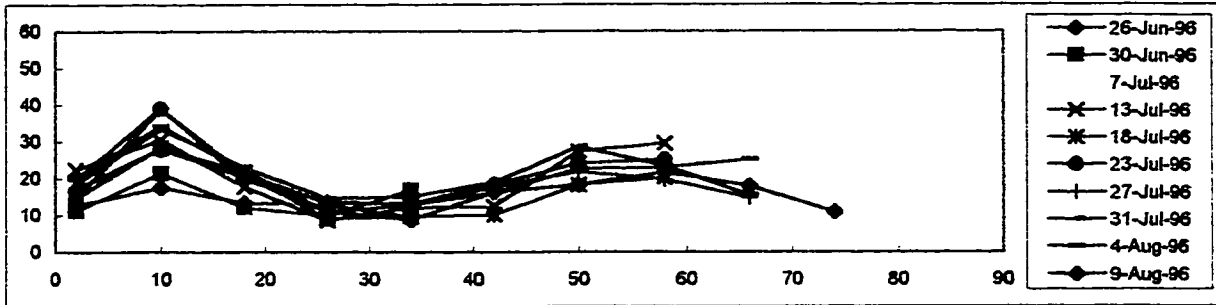
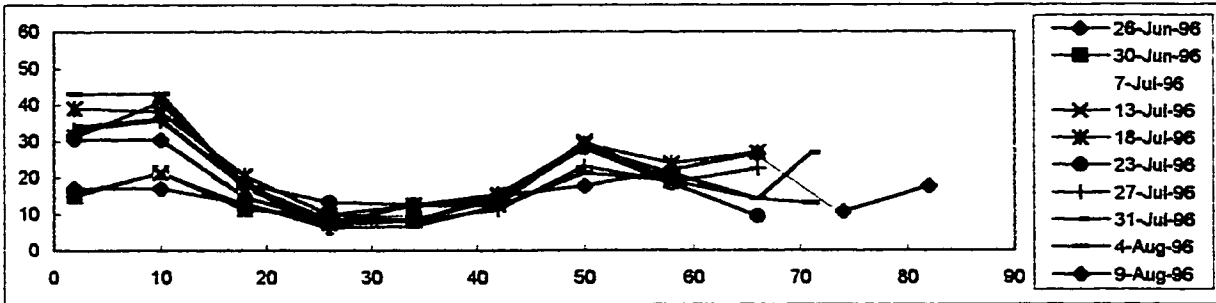


Figure 4-5. *In situ* shear strength: trend with depth, 1996.

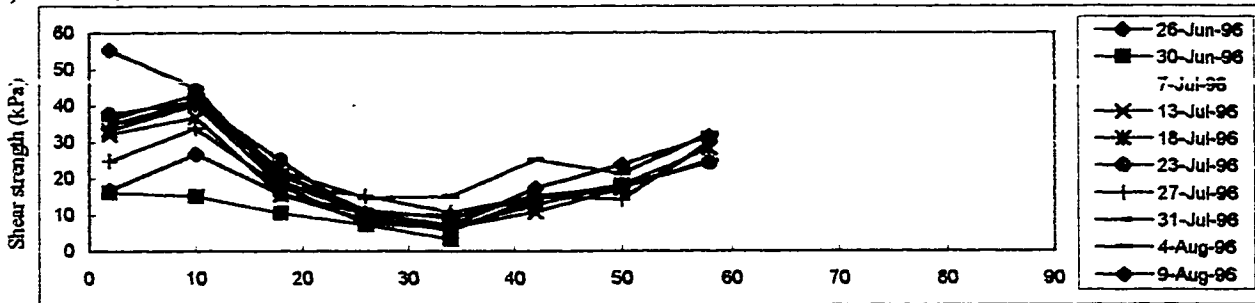
a) Meter A



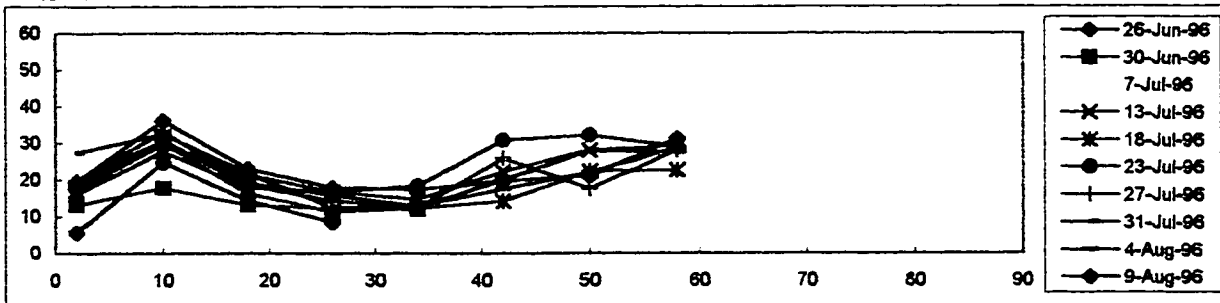
b) Meter B



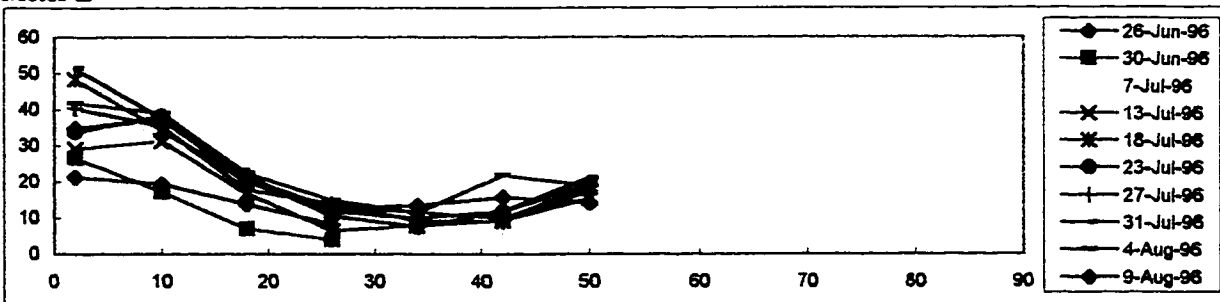
c) Meter C



d) Meter D



e) Meter E



Depth (cm)

The lack of change in shear strength over the summer of 1996 is illustrated in Figure 4-6. A very slight hardening trend is visible at meters C, D and E, but unlike other years when surface values exceeded 100 kPa, low values show that a surface crust did not form over the course of the summer.

On July 30, 1997, *in situ* shear strength values recorded were very low, probably as a result of a major precipitation event that occurred on July 27: 9 (2 cm) to 21 kPa (50 cm) at meter A; 2 (74 cm) to 18 kPa (50 cm) at meter B; 7 (2 cm) to 20 kPa (50 cm) at meter C; 8 (2 cm) to 34 kPa (50 cm) at meter D; and 4 (50 cm) to 19 kPa (10 cm) at meter E (Figure 4-4k). The pattern that was evident in 1996 was not as clear. The shear strength values recorded at 2 and 10 cm were lower relative to the other measurements in the soil profile. The values at meter D increased to a depth of 50 cm (34 kPa), after which point they decreased significantly (8 kPa at 74 cm). In contrast, the values at meter E decreased below 10 cm (19 kPa) and stayed below 6 kPa through the remainder of the active layer.

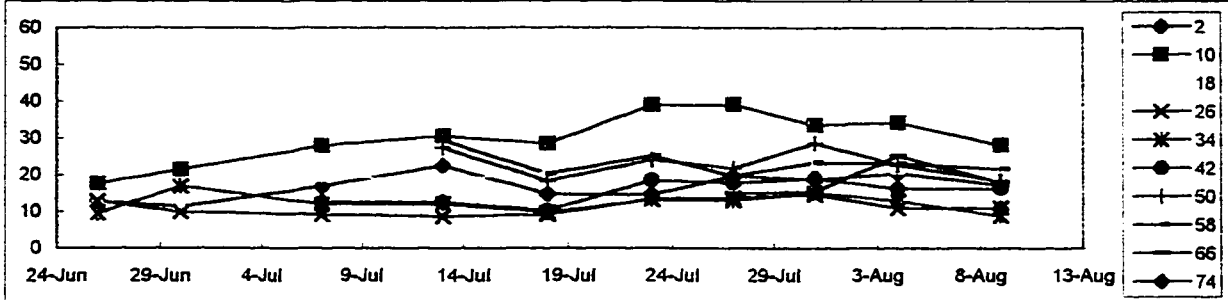
For purposes of comparison, shear strength values from Meter C recorded on July 31, 1996 were contrasted to values from earlier years (Figure 4-7). Prior to 1996, a single set of measurements was taken from a position near the center of the experimental site, rather than a set at each individual meter. Nevertheless, the values should be representative of the general trend in strength at the meters. Consideration should also be given to the fact that the measurements were recorded at different times during the summer and that, as a general rule, shear strength increases over the summer. Overall, the values in 1996 were much lower than those from previous years. Only the measurements recorded in June 1993 during spring thaw and those from below 34 cm in July 1995 are similar to those from July 1996. Even then, the 1995 measurements indicate the presence of a rigid surface crust as values were almost 120 kPa near the surface.

4.2.3 Porewater pressure

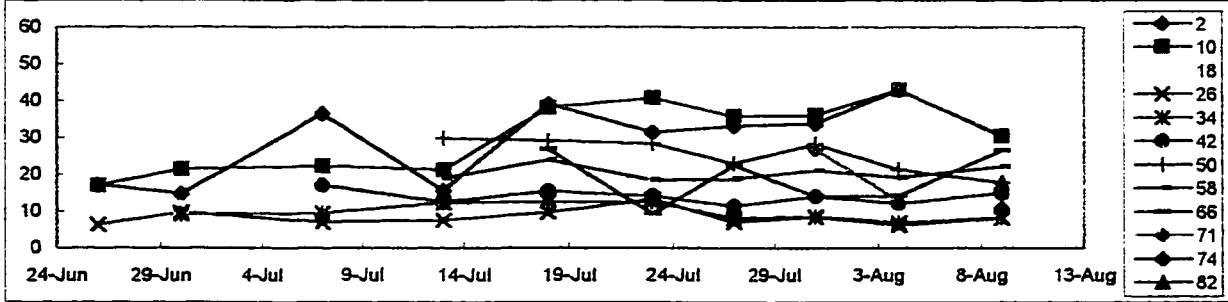
The distance below the ground surface of water in piezometer tubes was measured regularly during the summer of 1996 and twice in 1997 (Figure 4-8). The initial readings were taken on July

Figure 4-6. *In situ* shear strength: trend over time, 1996.

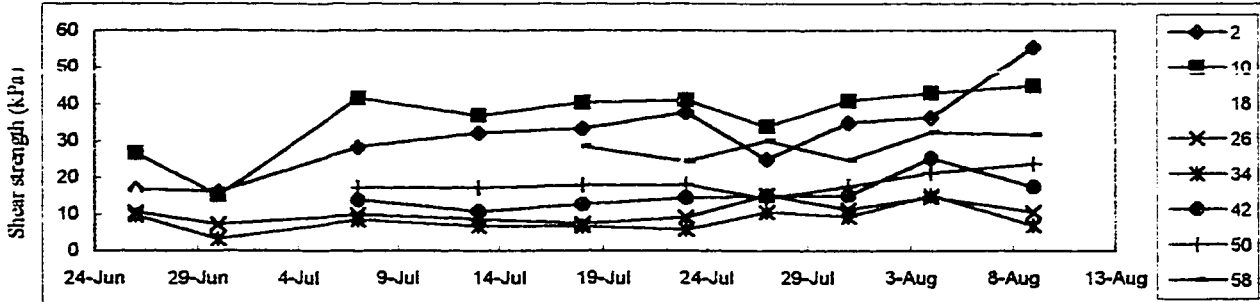
a) Meter A



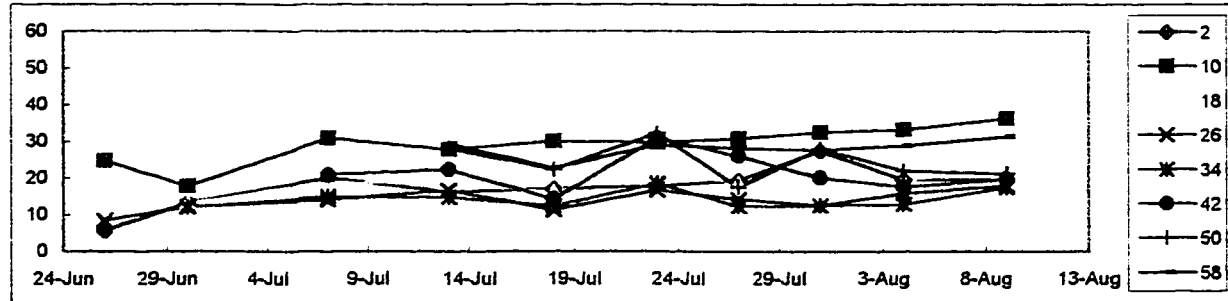
b) Meter B



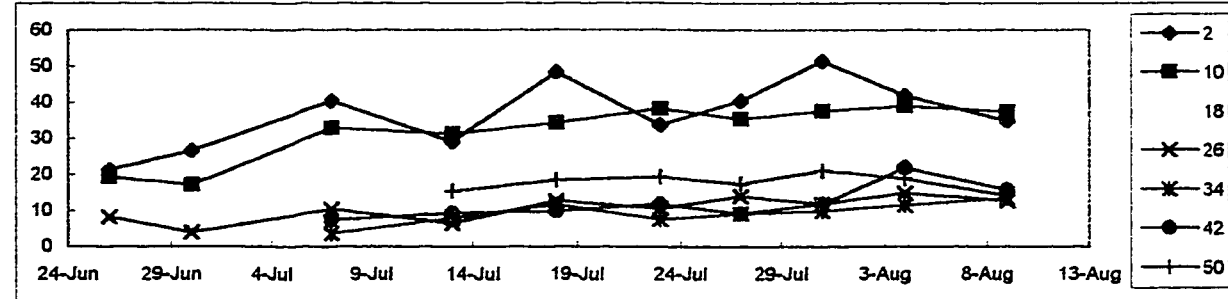
c) Meter C



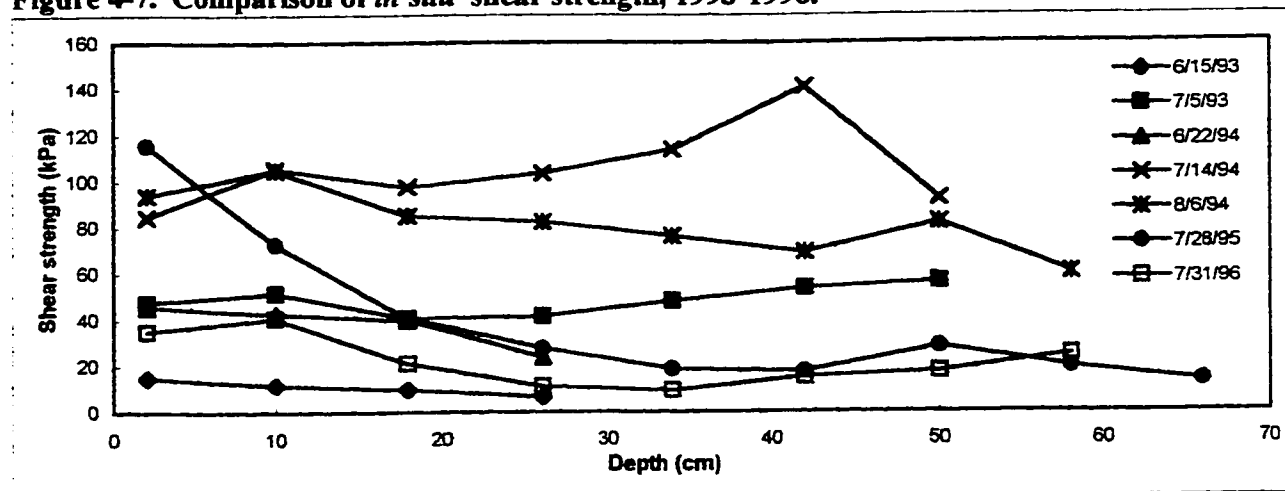
d) Meter D



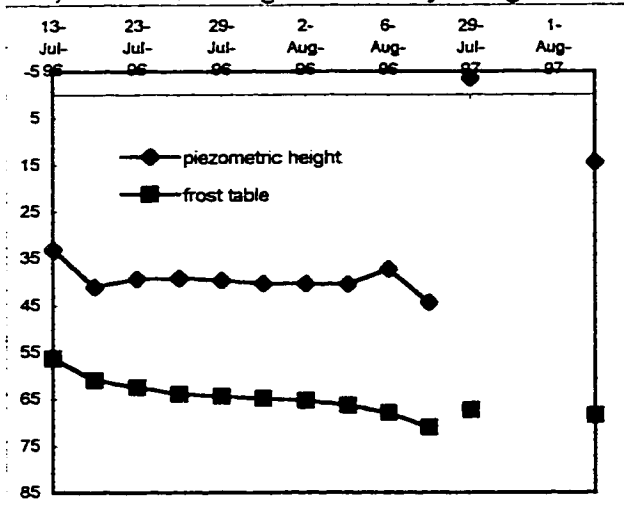
e) Meter E



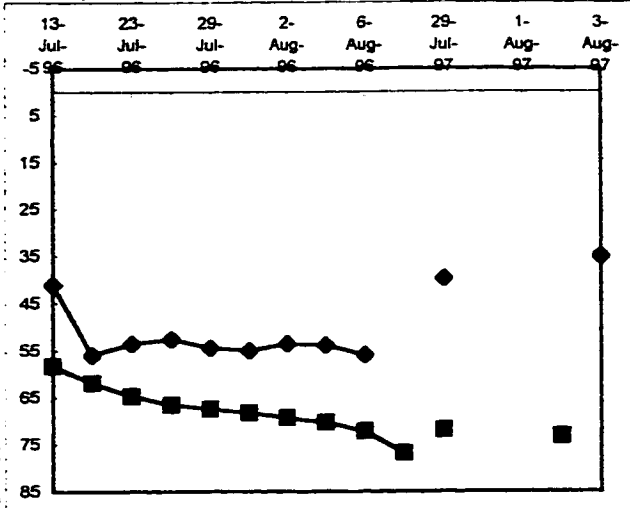
Note: Legend values represent depth (cm).

Figure 4-7. Comparison of *in situ* shear strength, 1993-1996.

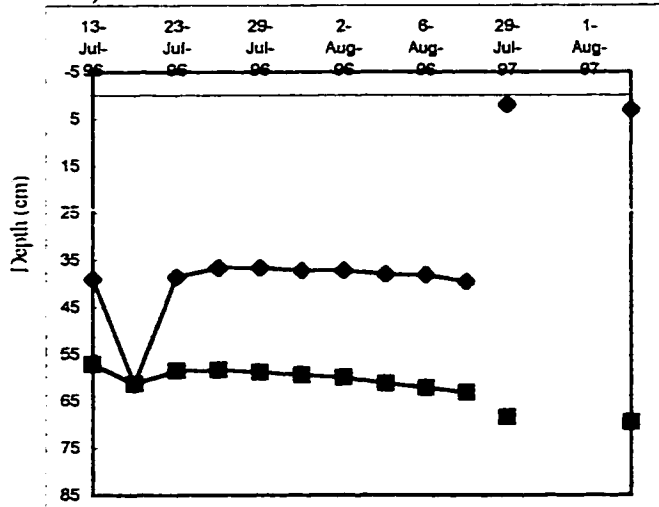
a) Meter A, wetting treatment July 8-Aug. 9, 1996.



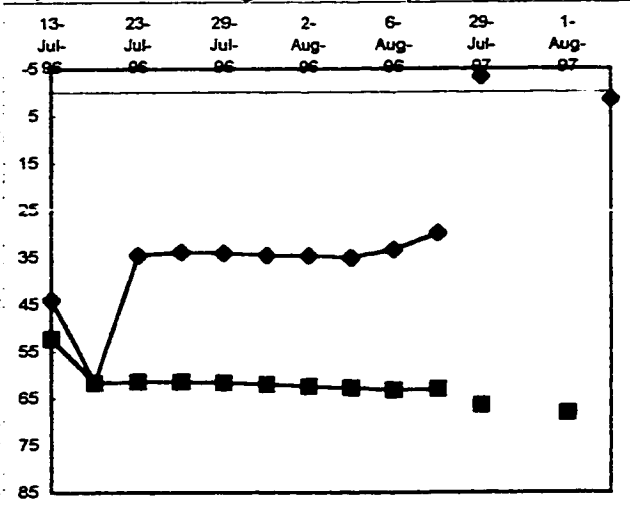
b) Meter B



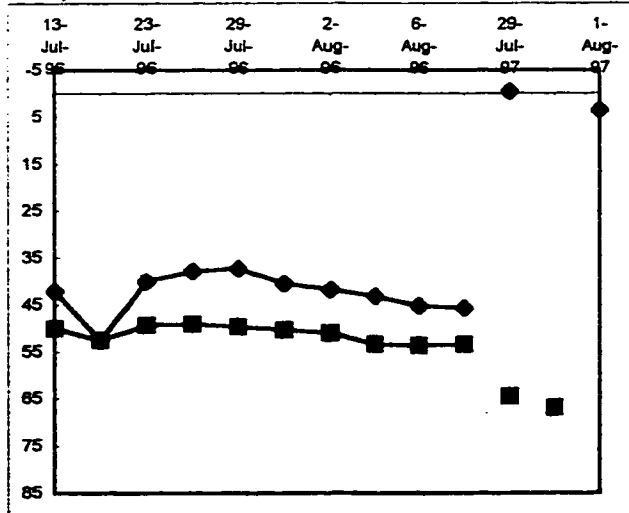
c) Meter C



d) Meter D, wetting treatment July 8-Aug. 9, 1996.



e) Meter E



13, one week after insertion of the tubes into the ground. Water levels in the tubes on that day ranged from 33 cm from the ground surface at meter A to 44 cm from the surface at meter D. Five days later on July 18, there was no water in the tubes at meters C, D and E. Water was present 56 cm down from the surface at meter B and 41 cm from the surface at meter A. Between July 23 and August 9, the depth of the water level below the ground surface in each tube showed only small changes: meter A - 37.3 to 44.3 cm; meter B - 52.7 to 56 cm; meter C - 36.6 - 39.5 cm; meter D - 33.4 to 35.1 cm; and meter E - 37.3 to 45.7 cm. However, the increase in thaw depth over the period means that the distance between the frost table and the water level increased (except at meter E, where the distance decreased slightly over the period due to a very small change in thaw depth).

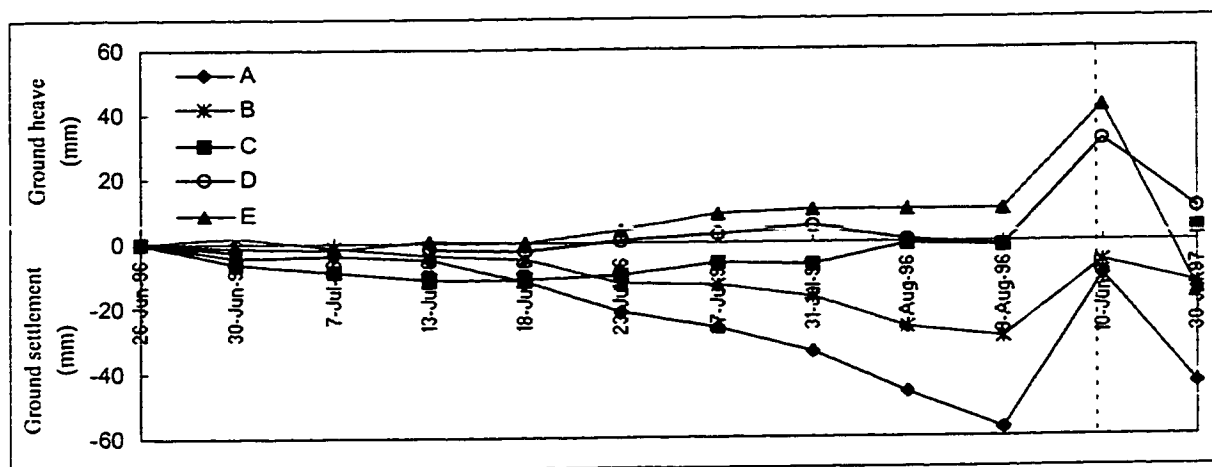
In 1997, the first water level measurements were made 2 days following a record rainfall event at Eureka (20.8 mm in 24 hours, AES). Water levels in the piezometer tubes at A, D and E were above the ground surface (3.5, 3.3 and 0.5 cm), while the level at meter C was only 2 cm below the surface. The water level in the tube at meter B was 39.8 cm below the surface. Within 2-4 days, a second measurement was made at each tube, just prior to meter excavation. Meter B had an increase in water level (change of 4.7 cm), while all others showed a decrease in water level between 1.1 and 18 cm.

4.2.4 Meter heights

The height of the top of each meter above the ground surface was measured regularly throughout the summer of 1996 and on two days in 1997 (Figure 4-9). This measurement provides information on the timing and amount of heave or settlement at each meter. During the summer of 1996, soil surrounding the two meters that were subjected to warming treatments (A and B), behaved very differently than that around the other meters. Between June 26 and July 13, only a small amount of change in meter heights was recorded at each meter. Meter E indicated a net decrease in the height of the meter (1 mm), which suggests that heave occurred. The other meters all indicated a net increase in meter height (meter A - 5 mm, meter B - 4 mm, meter C - 12 mm and meter D - 2 mm),

which suggests that settlement occurred. Between July 13 and July 18, meter heights remained virtually unchanged, except at meter A, where there was an increase of 7 mm. Between July 18 and the final measurement on August 9, both meters A and B had a continuous increase in height above the ground surface, ending the period with a net increase of 59 and 30 mm, respectively. Meters C and D recorded both small fluctuations in meter height over the period and both ended with a small net increase of 2 mm. After July 18, the height of meter E decreased until July 31, where it remained until August 9. Net decrease in the height of meter E was 10 mm.

Figure 4-9. Change in distance between ground surface and top of meters, 1996-1997.



Between August 9, 1996 and June 10, 1997, the height of each meter decreased substantially due to the large amount of heave as a result of fall freeze-up: meter A - 47 mm, meter B - 24 mm, meter D - 33 mm and meter E - 32 mm. Due to a thick basal ice layer surrounding it, the height of meter C was not measured on June 10, 1997. Final meter height values were recorded just prior to excavation. Increases in meter height compared to the June 10 elevation ranged from 57 mm at meter E to 7 mm at meter B.

4.3 Maximum thaw depths

In 1996, the maximum depth of thaw varied considerably at each meter (Figure 4-10). Meters A and B thawed more than 70 cm (72 and 79 cm, respectively), whereas meter E thawed to a depth of only 54 cm. The thaw depths at meters C and D were between these values, recording thaw depths of 64 and 66 cm, respectively.

The meters were excavated in 1997 prior to the date when maximum thaw depths would have been obtained, therefore the depths of thaw on July 31 are considered. The variation between the meters was relatively small: meter E recorded the shallowest thaw depth (67 cm), while meter B had thawed the greatest amount (72 cm).

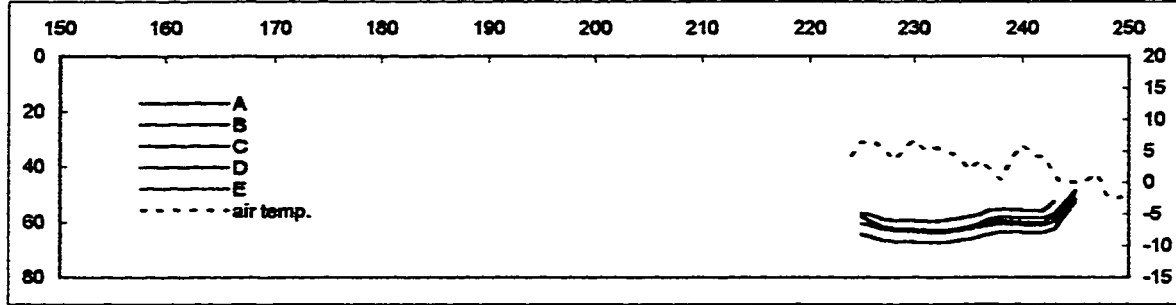
4.4 Rates of thaw

Due to the manner in which correction factors were applied to thaw depths, rates of thaw were considered only once the depth of thaw was greater than 35 cm (> 30 cm at meter D). A considerable amount of time separates the days on which the greatest rate of thaw (cm/day) at each meter was recorded in 1996: meter A - 4.4 cm/day (June 29); meter B - 2.8 cm/day (June 27); meter C - 2.1 cm/day (July 9); meter D - 3.3 cm/day (August 10); and meter E - 2.0 cm/day (August 4) (Figure 4-11). The average rates of thaw at meters A and B were very similar at 0.9 and 1.0 cm/day, respectively. Meters C and D were much less, averaging 0.6 and 0.8 cm/day each, while meter E had an average thaw rate of only 0.4 cm/day.

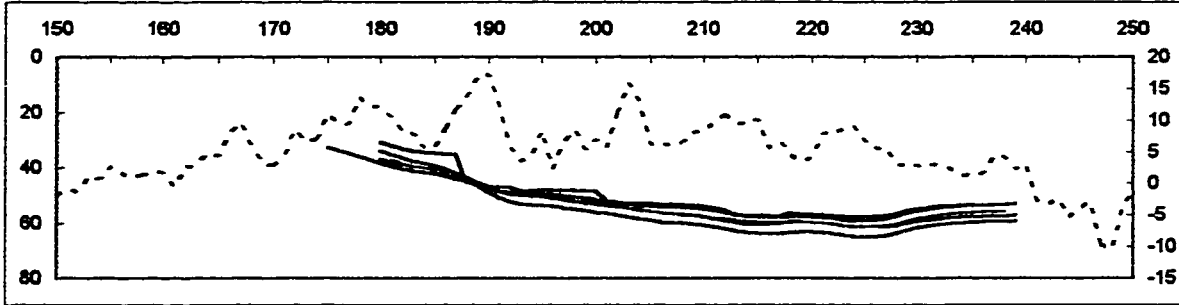
There are two periods during the summer when, as a result of datalogger malfunction, no soil temperature data were recorded (June 30-July 4 and July 25-August 2). During these periods, the change in thaw depth was evenly distributed, therefore the thaw rate does not accurately reflect daily fluctuations.

Figure 4-10. Summer thaw depths and air temperature, 1993-1997.

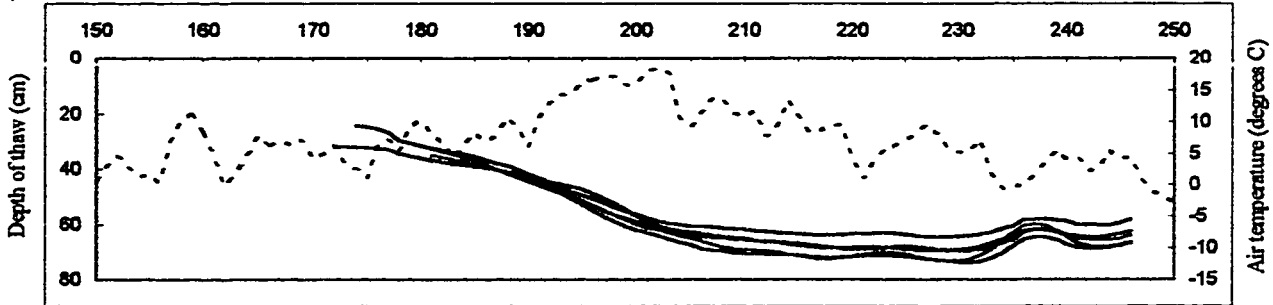
a) 1993



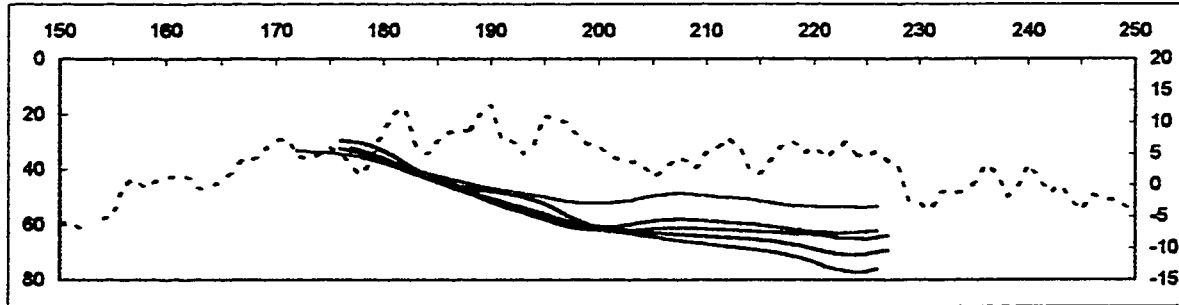
b) 1994



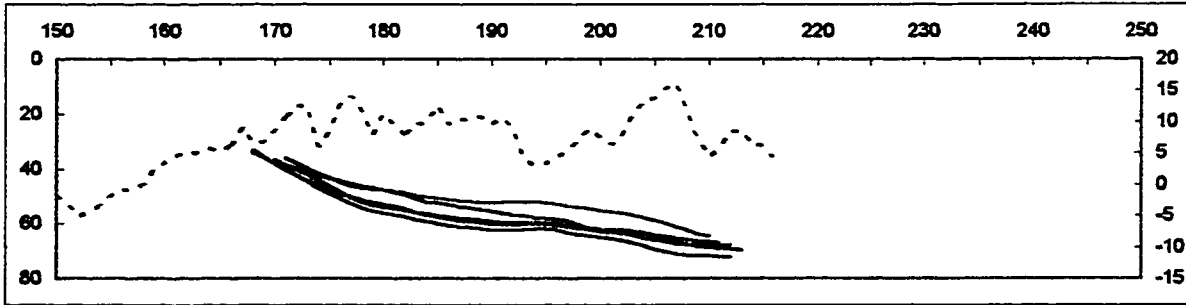
c) 1995



d) 1996



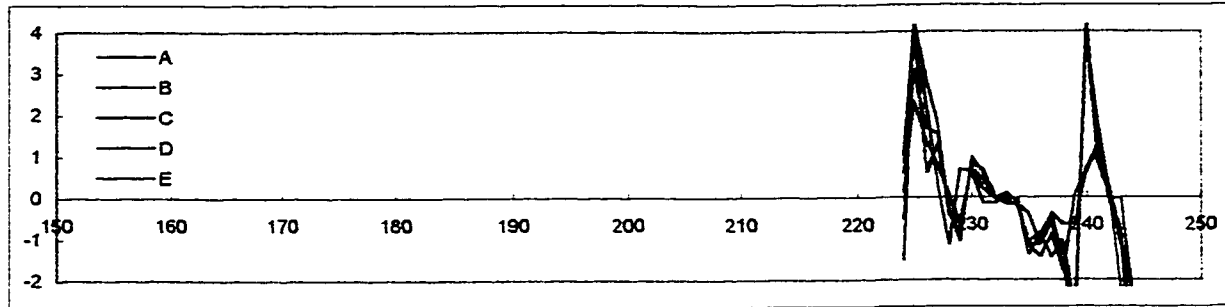
e) 1997



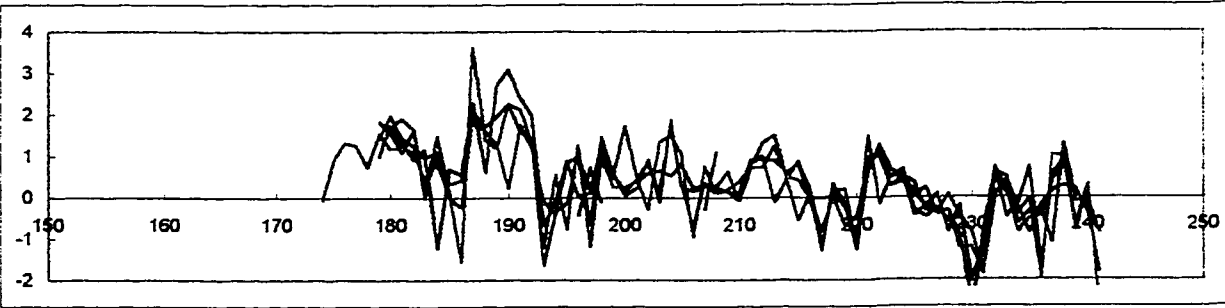
Julian days

Figure 4-11. Rates of thaw, 1993-1997.

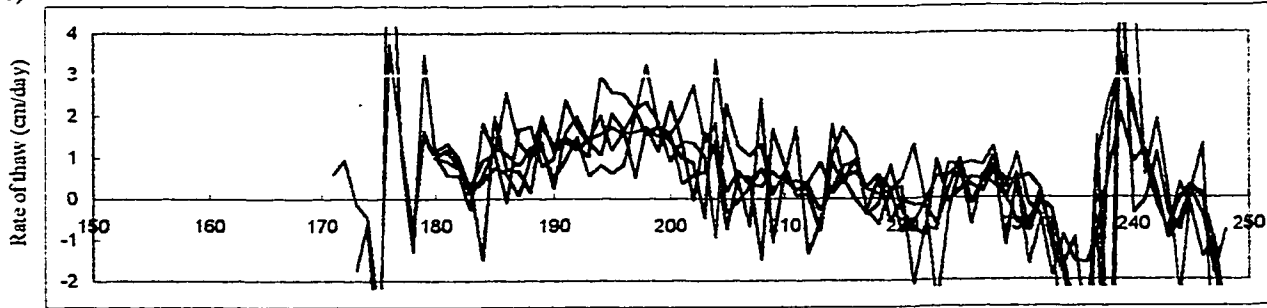
a) 1993



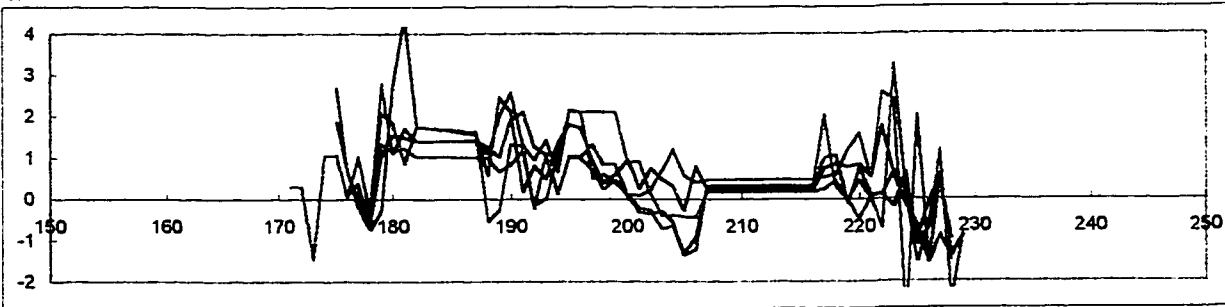
b) 1994



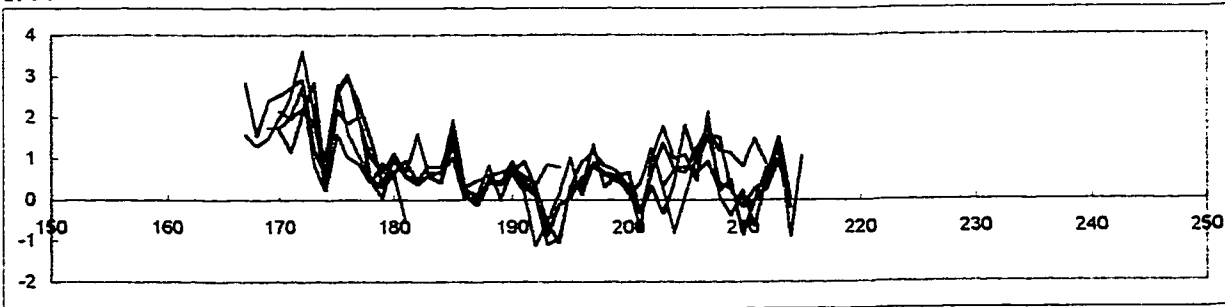
c) 1995



d) 1996



e) 1997



Julian days

4.5 Thaw strain

The thaw strain ratio at meter A in 1996 remained low (< 6%) until the thaw depth reached 56 cm and the ratio increased to 15% (Figure 4-12). Thaw strain values were very high (up to 85%) while the frost table deepened from 60 to 66 cm. Further deepening of the frost table resulted in a decrease of the ratio to 24%.

At meter B, the thaw strain ratio remained very low until the thaw depth reached 62 cm and the ratio increased to 27%. A maximum value of 49% was attained when the frost table deepened between 68 and 70 cm, after which point the ratio again dropped below 5%.

The highest thaw strain ratio (12%) at meter C was attained while the frost table was between 35 and 40 cm. As the frost table deepened, the values were either less than 5%, or were negative values, as a certain amount of freeze-back occurred from the bottom upward. Meters D and E also sustained freeze-back after July 18, and therefore the thaw strain values were not valid.

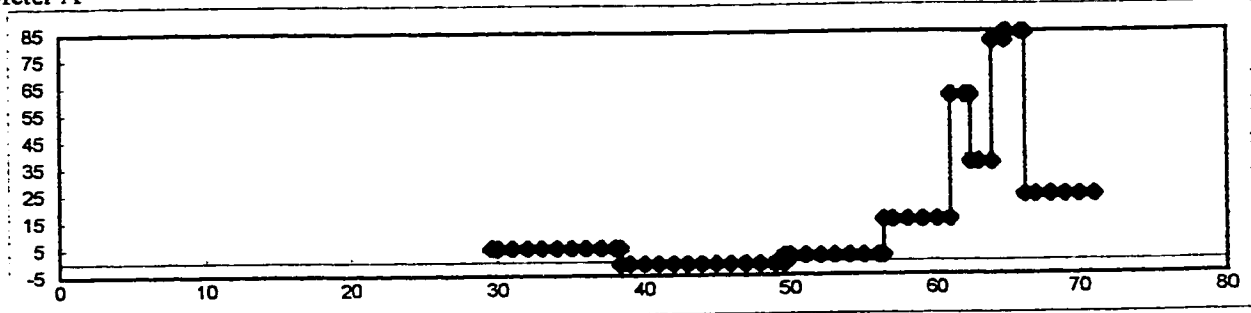
4.6 Climate data

4.6.1 Precipitation data

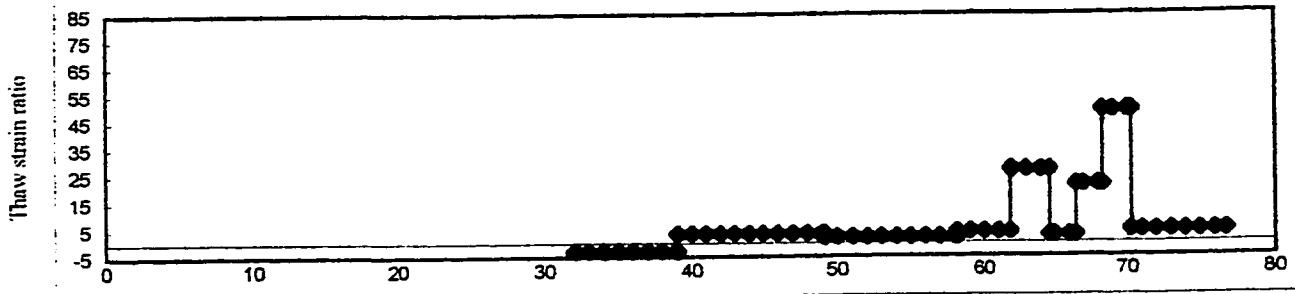
Amounts of summer precipitation varied considerably year-to-year (Table 4-4). Although in 1994, there were the same number of days with precipitation as in 1996, no more than 5 mm was received on a single day (Figure 4-13a). The summer of 1995 was relatively dry, with both a low number of days with precipitation, as well as a low total amount received. One large precipitation event of note occurred on August 21, when 13 mm was received (Figure 4-13b). The summer of 1996 was notable for the total amount of precipitation received (78 mm) and the total number of days with precipitation (30), as well as the magnitude of one of the precipitation events (Figure 4-13c). On June 24, after three of the previous four days had received precipitation, almost 15 mm of precipitation

Figure 4-12. Thaw strain ratios, 1996.

a) Meter A



b) Meter B



c) Meter C

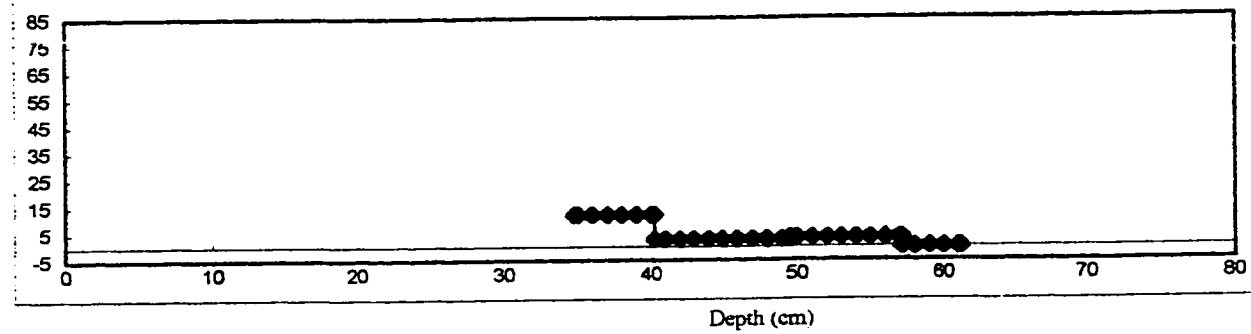
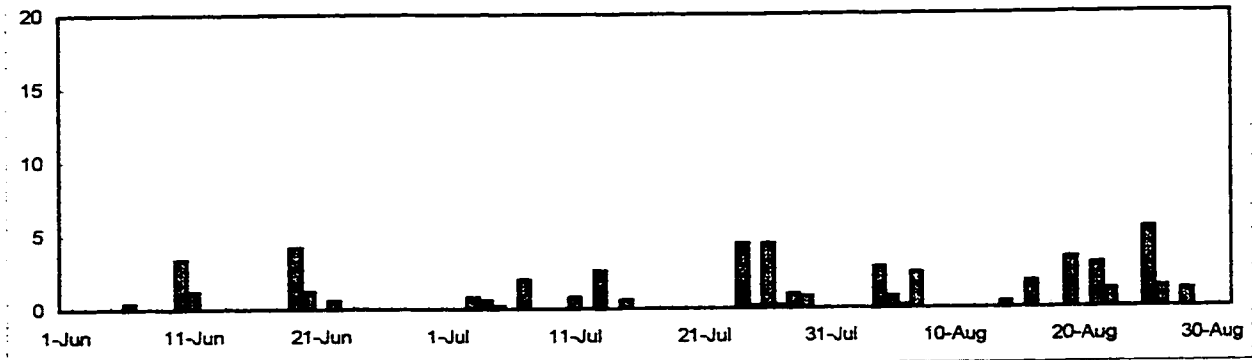
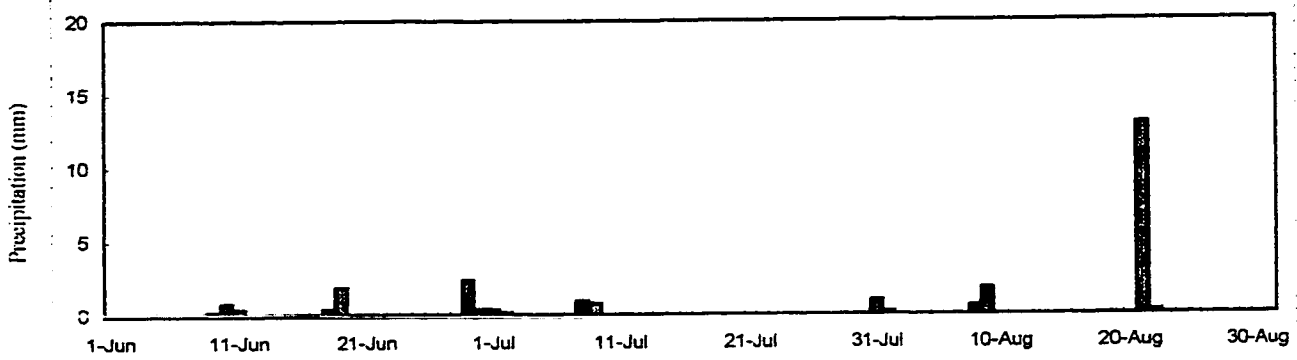


Figure 4-13. Summer daily precipitation totals, 1994-1997.

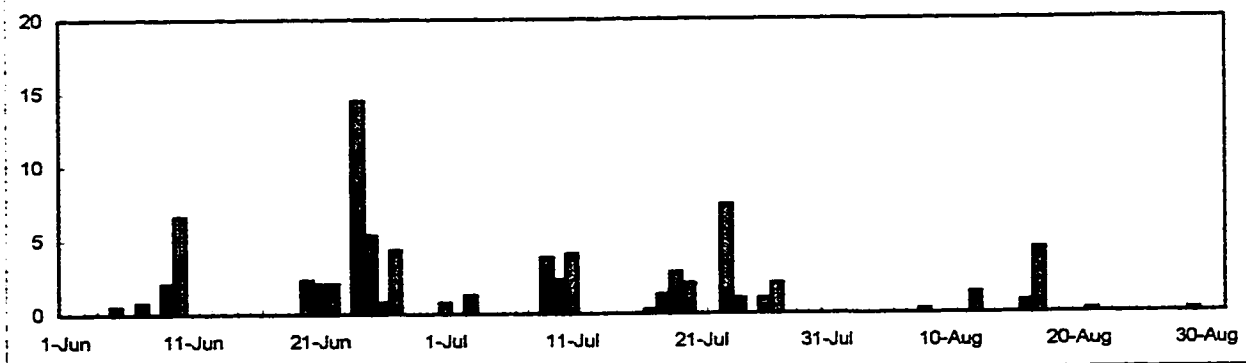
a) 1994



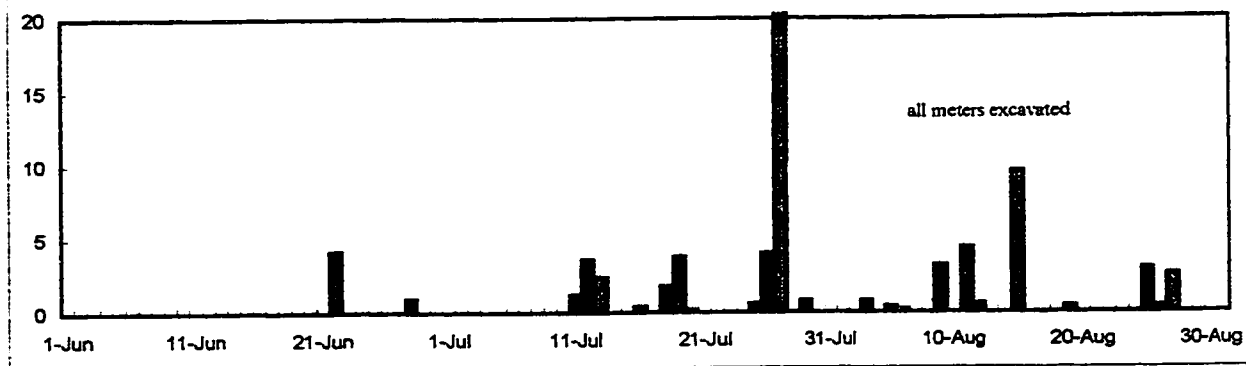
b) 1995



c) 1996



d) 1997



fell, followed immediately by three more days when up to 5 mm of precipitation was recorded. Although the total number of days with precipitation was not high in June and July 1997, a very large rainfall was recorded on July 27 (21 mm) (Figure 4-13d).

Table 4-4. Summary of summer precipitation, 1993-1997.

Monthly values (mm)	1993	1994	1995	1996	1997
June	6.4	11.0	6.5	41.1	5.6
July	16.4	18.6	3.4	30.0	39.6
August	5.4	24.0	15.8	7.3	0.8*
Total	28.2	53.6	25.7	78.4	46.0
Number of days with precipitation					
June	5	6	7	11	3
July	8	13	5	13	11
August	4	11	5	6	1*
Total	17	30	17	30	19

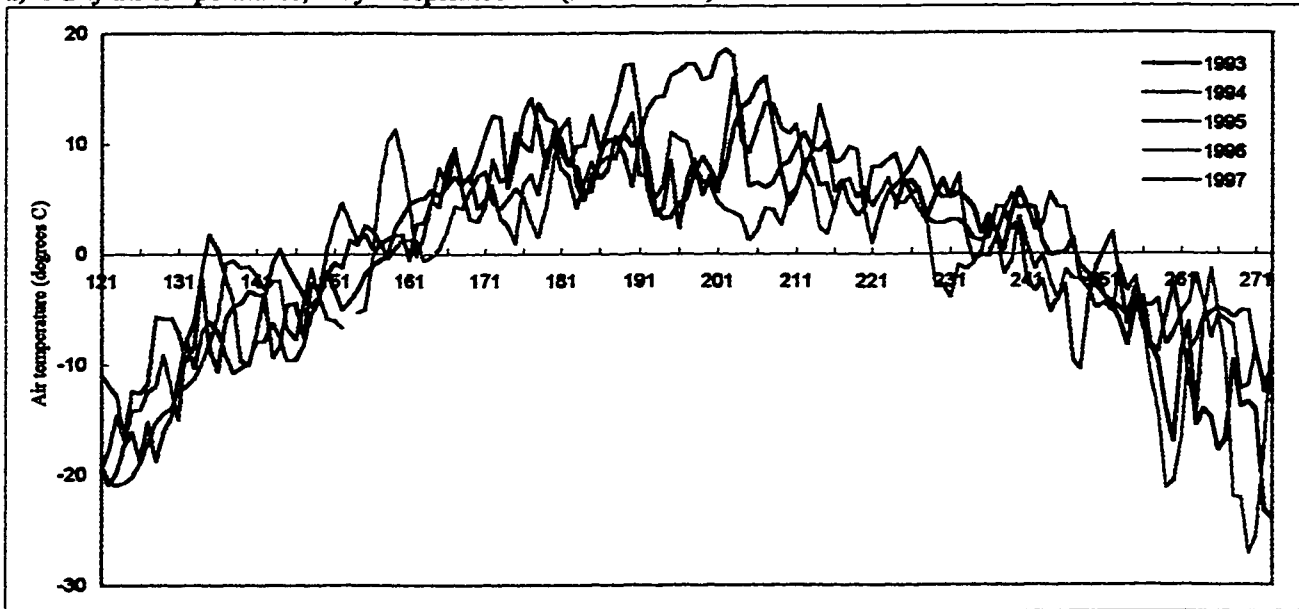
* Only includes precipitation received up to August 3.

4.6.2 Air temperature data

Air temperature values from the period just before thaw to just after freeze-up (May 1-September 30) are presented in Figure 4-14a. The mean annual temperatures between 1994 and 1996 (the three years with a complete record) were the same at -19°C (Table 4-5), however the mean summer (June, July, August) temperature was much lower in 1996 than in 1994 or 1995 (3.9°C versus 6.1 and 7.6°C , respectively) (Figure 4-14b).

Air temperatures were recorded at a height of 10 cm above the ground at two locations at the experimental site during 1996: just below the sensor located at 50 cm height situated in the middle of the site; and between meters A and B, underneath the polyethylene sheet used for warming treatments. These values were examined in order to help assess the success of the warming treatments. Although the warming treatments started on July 8 (JD 190), neither of the 10 cm height thermocouples functioned until July 14. Between that day and August 9 (JD 222), when the polyethylene sheet was removed, it is evident that the warming treatment had an impact on the near-surface air temperatures as the sensor at the warmed location had a mean temperature for the period

a) Daily air temperatures, May 1-September 30 (JD 121-273).



b) Mean monthly air temperatures.

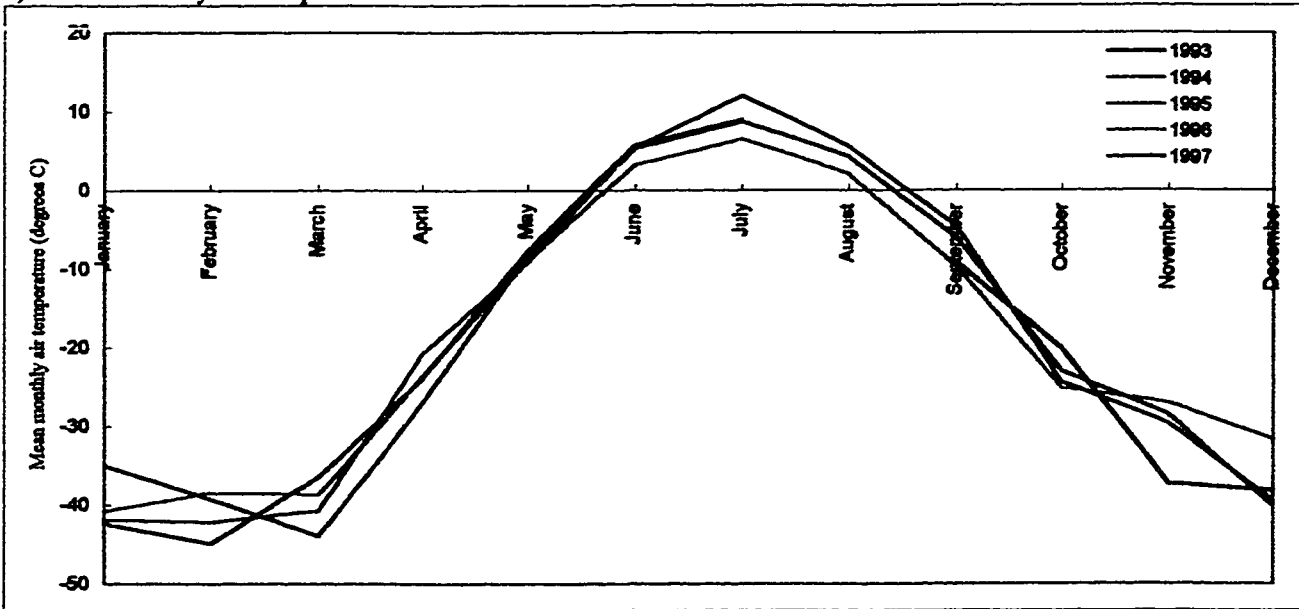


Table 4-5 Mean air temperatures

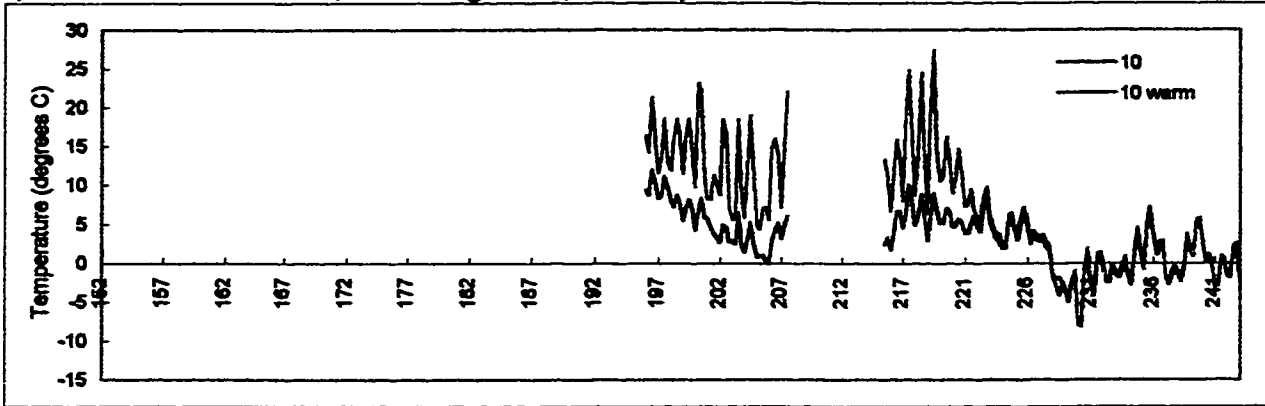
	1994	1995	1996
Annual mean air temperature	-19.41	-19.15	-19.36
Summer mean air temperature (June, July, August)	6.08	7.64	3.88

of 13.0°C versus a mean of 5.4°C at the other sensor (Figure 4-15a). When the 10 cm air temperature values (Ta 10 cm) were plotted against the temperature values from the “warmed” location (Ta 10 cm W) (Figure 4-15c), the values from underneath the sheet were much greater, as shown by the equation of the best-fit line. The significant amount of scatter which is evident around the line is likely due to the impact of meteorological variables, such as solar radiation and wind, which could either heighten or lessen the effect of the polyethylene sheet.

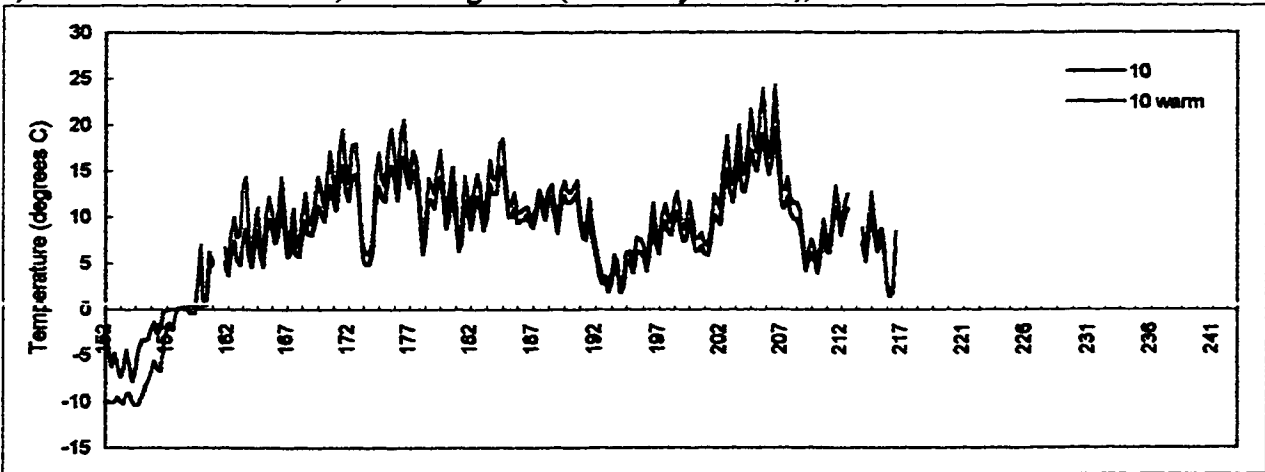
The temperatures at the two 10 cm monitors were examined immediately following the removal of the warming treatment (Figure 4-15a) as well as for the summer of 1997 (Figure 4-15b) in order to verify that the differences in temperature recorded during the treatment period in 1996 could not be attributed to any other variable. Following removal of the warming treatment in 1996, the temperatures at the two monitors were very similar, although the Ta 10 cm W values remained slightly higher. During the summer of 1997, a fairly constant relationship existed between the two sets of values, with temperatures recorded at Ta 10 cm W slightly higher than those from Ta 10 cm (Figures 4-15b). This could be due to slight differences in height of the monitors as a result of animal disturbance, or due to differences in the underlying vegetation cover. Between June 1 and June 9 (JD 152-160), the relatively large differences between the 10 cm values (Figure 4-15b) are likely due to differences in snow cover.

Ground surface temperatures recorded at each meter were also used to help assess the impact of the climatic treatments (Figure 4-16a). During the treatment period in 1996, the average ground surface temperatures at the two warmed meters (A and B) were both greater than 11°C, while meters C and D (control and wetted) both had average ground surface values of approximately 5.5°C (Table 4-6). Meter E (cooled) had the lowest average ground surface temperature at 4.5°C. After treatments had finished on August 9, the differences in ground surface temperatures rapidly diminished, and

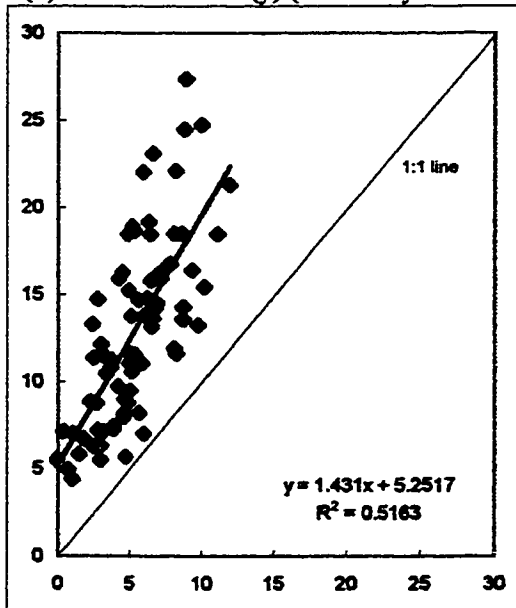
a) Ta 10 cm vs. Ta 10 cm W, June 1-August 31 (Julian Day 152-243), 1996.



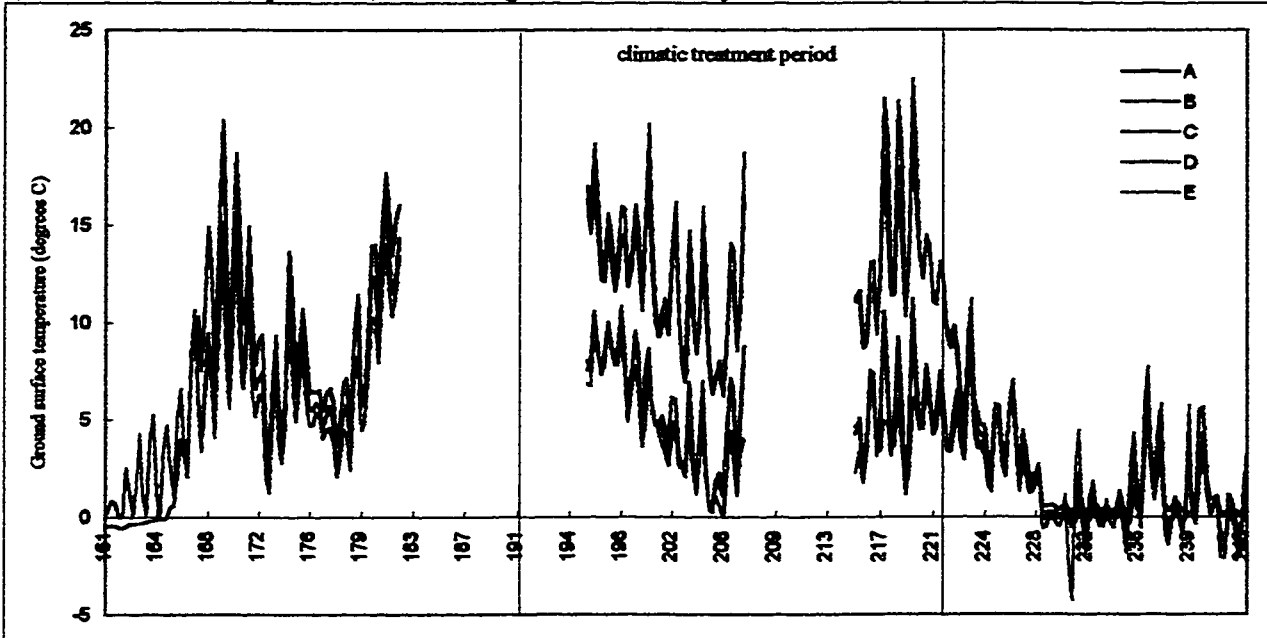
b) Ta 10 cm vs. Ta 10 cm W, June 1-August 31 (Julian Day 152-243), 1997.



c) Ta 10 cm (x) vs. Ta 10 cm W (y) (Julian day 196-222), 1996



a) Ground surface temperatures, June 9-August 31, (Julian Day 161-244), 1996.



b) Ground surface temperatures, June 10-July 31 (Julian Day 161-212), 1997.

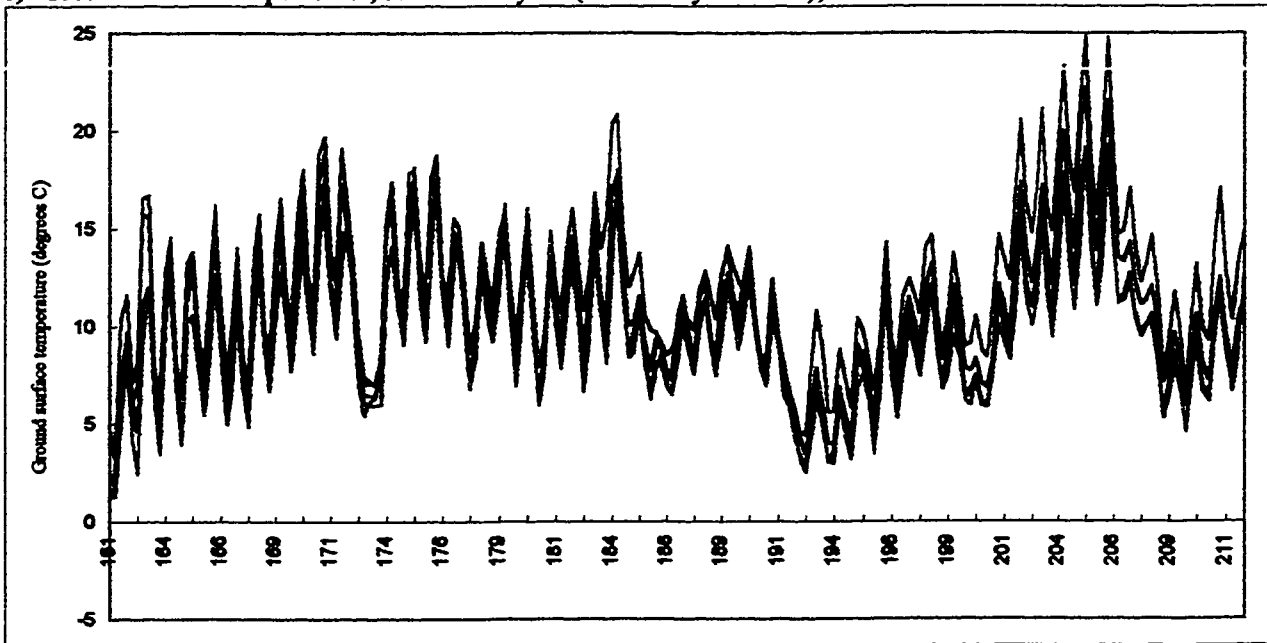


Table 4-6. Mean ground surface temperatures (degrees C)

	1994	1995	1996	1996	1996	1997
Julian Day	161-243	161-243	190-222	223-244	190-244	161-212
A	7.54		11.92	1.93	6.60	11.03
B	7.89	9.45	12.84	1.67	6.88	12.18
C	7.80		5.52	1.39	3.32	9.69
D			5.64	1.17	3.25	10.36
E	8.25	10.25	4.50	1.76	3.04	9.56

average temperatures for the remainder of the month ranged between 1.2 and 1.9°C (Figure 4-16a and Table 4-6).

Between June 10 and July 31, 1997, the average ground surface temperatures at meters A and B remained slightly warmer than at the other meters (Figure 4-16b and Table 4-6). Their average temperatures were 11.0 and 12.2°C respectively, while those at meters C, D and E were 9.7, 10.4 and 9.6°C, suggesting that there was either a lag effect from the climatic treatments or that the sensors were not positioned exactly the same relative to the ground surface.

4.7 Summary

Movement and temperature were successfully monitored between 1993 and 1997 at the experimental site. When climatic treatments were performed in the summer of 1996, cooler and wetter conditions than normal were experienced. The warming treatments were particularly effective in altering active layer conditions, as indicated by increased thaw depths at the two meters subjected to the treatment, due to the cool air temperatures which predominated throughout the summer. The effectiveness of the wetting treatments in substantially increasing moisture levels in the soil surrounding two of the meters is not clear due to the high amounts of precipitation received in 1996. Moisture content values remained high throughout the summer with little variability over time or between the meters. However, lower water levels were recorded in 1996 and 1997 at the meter which received the least amount of moisture input in 1996.

In situ shear strength remained low at all the meters throughout the summer, exhibiting little variability as thaw depths increased. In addition, there was no surface crust development.

Only the meters which were warmed had thaw strain ratios greater than 15, with both showing high ratio values as thaw advanced to depths between 60 and 70 cm.

In 1996, all the meters recorded greater amounts of movement than in previous years, including 1995, when thaw depths were greater. The two warmed meters recorded higher amounts of movement than the other three, with the meter which was also wetted indicating by far the greatest amount of movement. As a result of high moisture availability in 1996, large amounts of heave occurred during fall freeze-back. This led to large amounts of settlement and movement at all the meters in 1997, particularly at the meters which had shallower thaw depths in 1996. Overall, the results indicate large variability in horizontal and vertical movements, both year-to-year and between the meters, as a result of fluctuations in climatic conditions.

Chapter 5. Discussion

5.1 The importance of methodology

Solifluction consists of several processes which result in movements which have both a vertical and horizontal component. Many different methods, which vary significantly in complexity and frequency of measurement, have been used to measure solifluction. The method of measurement chosen influences the level of detail obtained and the overall value of the results. In addition, net downslope movement is the resultant of both vertical and horizontal displacements, and these separate components should be examined in order to fully understand the processes which are responsible for movement.

5.1.1 Surface measurements versus measurements at depth

By far the most common displacement measured is surface motion downslope, both because measurement is easy and because it can provide an estimate of the geomorphic work being performed by solifluction. Surface or near-surface rates of downslope movement are measured using techniques such as painted stones, pegs, and cone targets. Of the studies which use these methods, some examine net downslope displacement of surface markers over a given period of time (e.g., French, 1974), while others incorporate the vertical component of movement at the surface by measuring change in position with the use of a theodolite (e.g., Washburn, 1967).

In order to compare movement at the experimental site with that found at other locations, near-surface movement was considered (Table 5-1). With the exception of meter A, for which the 18 cm blocks were used, near-surface values are represented by data from the 10 cm blocks. Near-surface rates of movement recorded at the experimental site of between 0.8 and 4.1 cm/yr are comparable to those found in other studies in areas of permafrost (see Table 1-1).

Table 5-1. Annual near-surface rates of movement (cm/yr)

	1994	1995	1996	1997†	Mean
A*	1.1	1.4	3.0	2.3	2.0
B	1.1	1.9	2.9	2.0	2.0
C	1.3	1.0	2.0	3.1	1.9
D	1.1	0.8	1.7	2.8	1.6
E	1.2	1.1	1.6	4.1	2.0
Mean	1.2	1.2	2.2	2.9	1.9

*Values from meter A are from blocks at 18 cm depth, whereas those from B, C, D and E are from 10 cm.
 †Values are considered to be a minimum amount of movement for the year, as meters were excavated in early August.

However, if only near-surface measurements had been examined at the experimental site, significant differences in movement downslope at depth between the meters would have gone unnoticed. For example, in 1996, although the near-surface movement at meter A is approximately the same as that found at meter B, movement at a depth of 66 cm is almost three times greater than meter B (Figure 4-1a). In 1997, meter A recorded the second lowest amount of near-surface movement, yet it had the greatest amount of downslope movement at both 66 and 74 cm (Figure 4-1b).

The movement profiles for 1996 and 1997 combined indicate that in the upper and middle sections of the soil profile (10-42 cm), there were very similar amounts of movement at each meter (Figure 4-2). Even though the timing and primary process responsible for movement varied among the meters, it is only at depth in the profile that significant differences in movement are evident. A much more accurate assessment of the importance of solifluction in terms of sediment transport is obtained by measuring movement through the entire active layer.

5.1.2 Measurements of vertical movement

The use of plastic tubes, buried columns and most surface markers does not allow for precise measurement of change in vertical position within the soil profile. This movement occurs largely due to changes in the physical state and quantity of water within the soil as a result of seasonal and environmental fluctuations. Information on changes in vertical position can help to indicate the

importance of different elements of solifluction (i.e., frost creep versus gelifluction). It can also help to reveal possible impacts of climatic fluctuations, such as thawing of ice lenses at the top of the permafrost. This is important as the resulting subsidence may affect measurements of active layer depth (see Leibman, 1998).

Measurements of net vertical movement at the experimental site for 1994 and 1995 indicated that different climatic conditions must have affected the meters over the two years, as virtually all the measurements blocks in 1994 recorded a net movement upward, whereas in 1995, almost all indicated a net movement downward. A likely scenario is that more moisture remained in the soil until freeze-back in the fall (1994) and increased heave left the blocks in a position higher in the soil profile than the previous year. The following summer (1995), temperatures were warm enough to thaw beyond the previous year's thaw depth, causing a significant amount of settlement.

In 1996, it is evident from changes in vertical position within the soil profile that meters A and E were subjected to very different conditions. In the near-surface, the blocks at meter A showed a net decrease in height of 18 mm, while those at meter E recorded a net increase of 44 mm. Thaw depths at meter E remained relatively shallow (54 cm) and little settlement occurred. High levels of precipitation resulted in large amounts of heave during freeze-back. Enhanced thaw depths at meter A (72 cm) resulted in the thawing of the ice-rich layer at the base of the active layer which led to large amounts of settlement in the soil profile. The heave during freeze-back did not cause sufficient upward movement in the soil to overcome the large amount of settlement.

5.1.3 Annual averages versus annual variability

Most other methods of measuring solifluction which provide information on movement at depth, and therefore of volumetric transport (e.g., flexible plastic tubes, buried columns), allow only for a single set of measurements to be made upon excavation of the equipment. As a result, they do

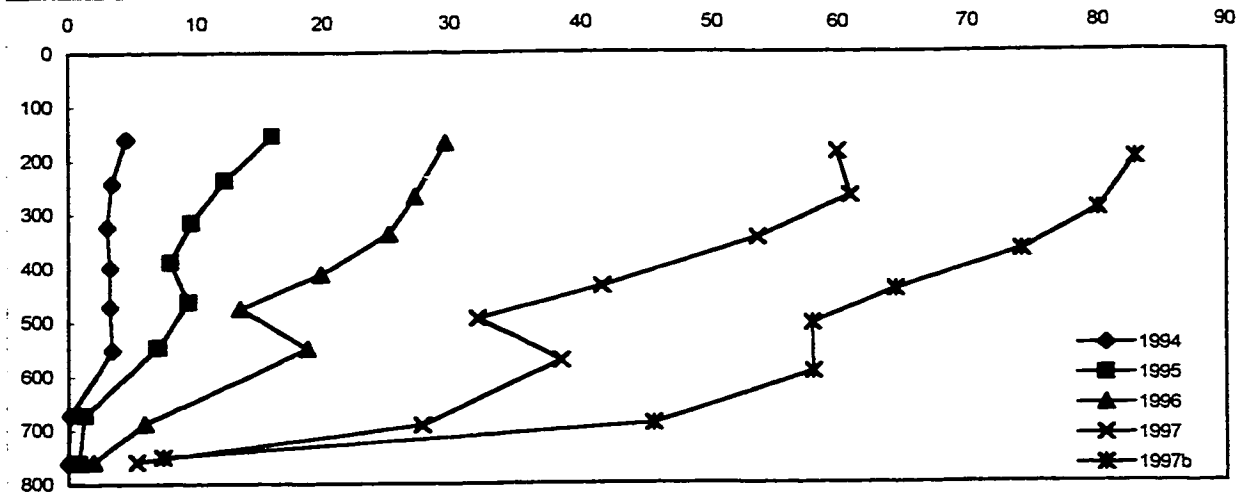
not provide a good indication of annual variability of movement, nor do they effectively allow for an examination of changes in vertical position, either at the surface or at depth.

The meters used in this study allowed for continuous monitoring of the various processes which constitute solifluction, down to a depth of 90 cm. Each set of measurement blocks was able to react in the vertical and horizontal planes as an individual unit to pressures acting on it. It was thus possible to construct a series of movement profiles over time for the 5 meters studied and to examine the manner in which the blocks have been transported both vertically and horizontally within the active layer (Figure 5-1). These profiles provide a more accurate portrayal of annual movements than if a final set of movement data were divided into a series of equal periods of time and amounts. It would not be possible to examine relationships between movement and climatic fluctuations without having information on the variability of annual movements. For example, the total of 1996-1997 downslope movement at the experimental site does not provide a clear indication of the movement occurring year-to-year, particularly in the upper and middle sections of the soil profile, as all five meters showed similar movement between 10 and 42 cm (Figure 4-2). Different processes over the two years produced similar outcomes at all five meters in this section of the profile, when, in fact, significant differences in *annual* movement existed among the meters (Figures 4-1a and 4-1b). At a depth of 26 cm, meter A recorded 34 mm of movement downslope in 1996 but only 19 mm in 1997, while meter E recorded 15 mm of movement in 1996 and 33 mm in 1997.

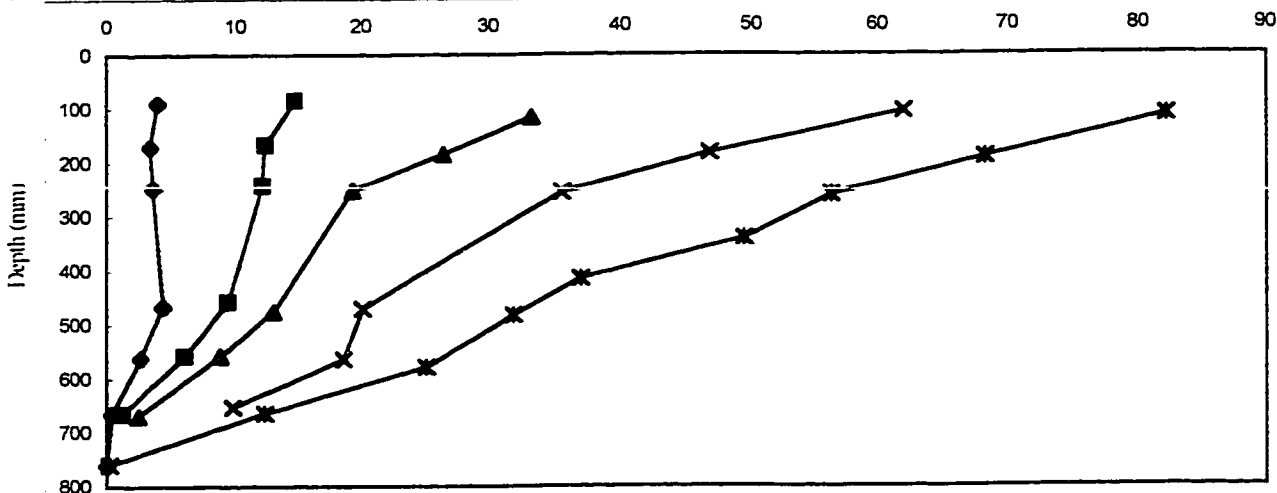
The first observations of variability in annual volumetric transport in an area of two-sided freezing were calculated based on the vertical velocity profiles. Considerable variability is evident in the amount of sediment transported downslope each year (Table 5-2). Since the deepest measurement blocks at meter E were only at a depth of 50 cm, movement between 58 and 74 cm was assumed to be the same as at meter B from 1994-1995 and 1997. In 1996, the depth of zero movement at meter E was assumed to be 50 cm, as the depth of thaw was only 54 cm. Values for 1997 reflect a minimum

Figure 5-1. Annual movement profiles, 1994-1997.

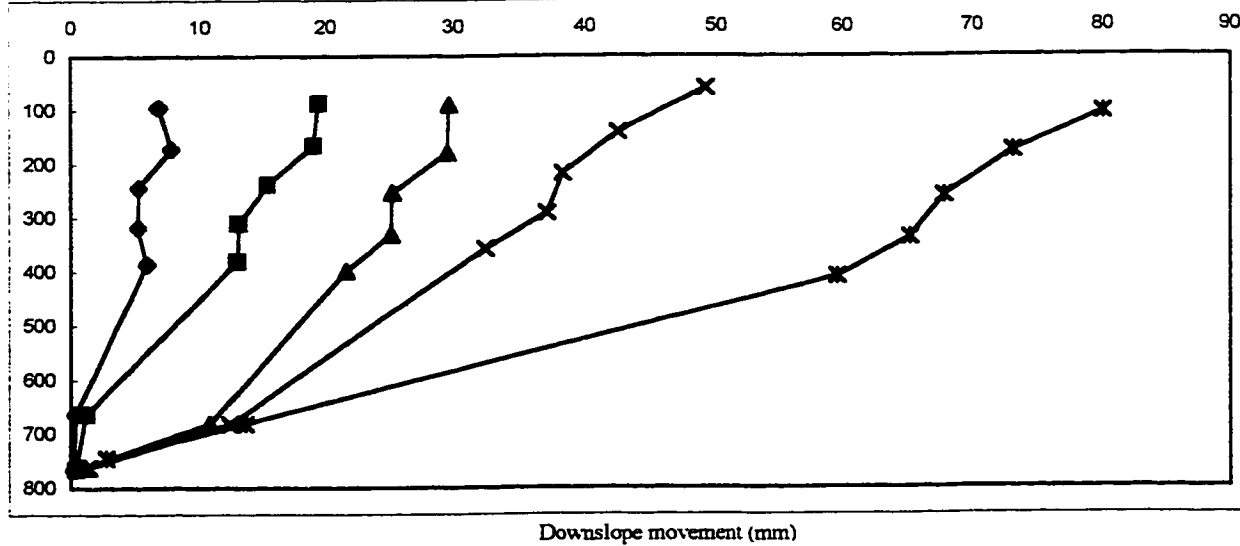
a) Meter A (warmed and wetted).



b) Meter B (warmed).

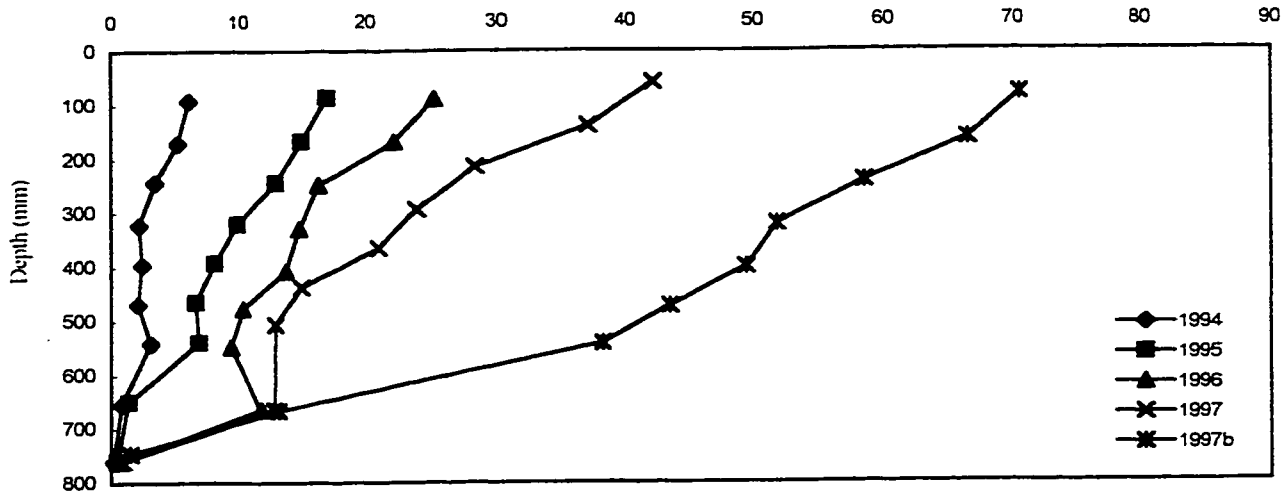


c) Meter C (control).

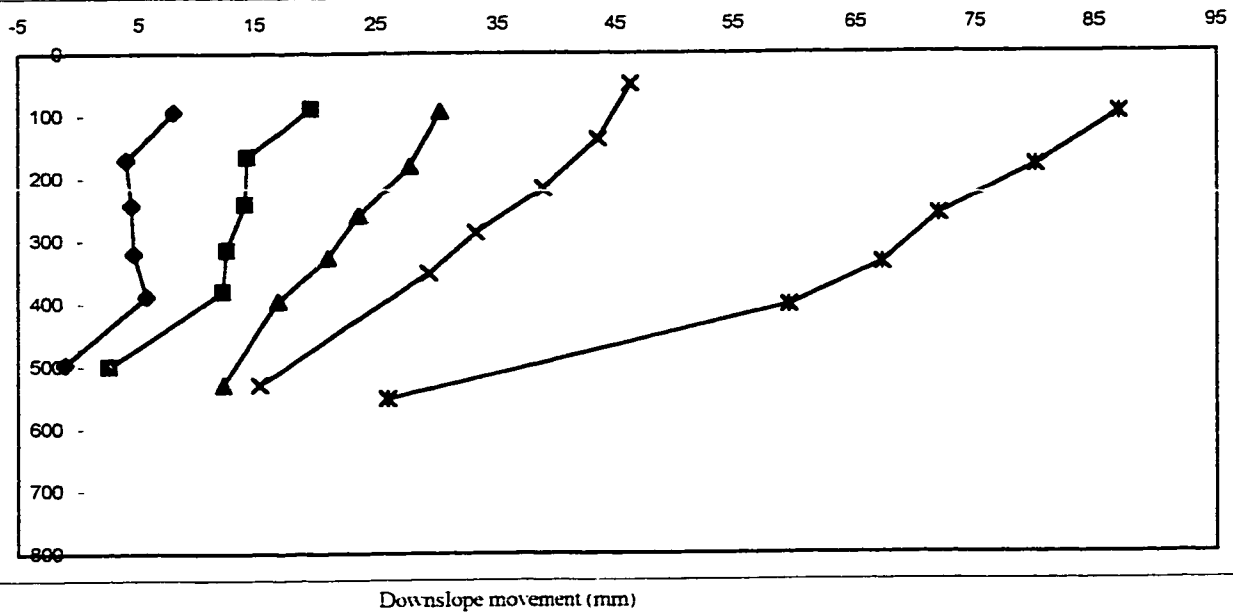


Note: Legend values represent positions as of January 1, except "1997b" which represents positions on August 1.

d) Meter D (wetted).



e) Meter E (cooled). Note slight difference in x-axis scale.



Note: Legend values represent positions as of January 1, except "1997b" which represents positions on August 1.

amount of displacement as the meters were excavated in early August before downslope movement would likely have finished for the year.

Table 5-2. Summary of volumetric transport at experimental site, 1994-1997 ($\text{cm}^3 \text{cm}^{-1} \text{yr}^{-1}$)

(Numbers in brackets represent maximum thaw depth in cm)

	1994	1995	1996	1997†	Mean	1996 as % of 1994	1996 as % of 1995
A	50.2 (58)	81.6 (65)	184.7 (72)	152.3 (68)	117.2	368	226
B	47.0 (60)	57.8 (70)	107.8 (79)	104.7 (72)	79.3	229	187
C	59.3 (65)	70.2 (74)	77.9 (64)	160.4 (69)	91.9	131	111
D	48.6 (62)	42.2 (70)	65.8 (66)	176.3 (67)	83.2	135	156
E*	50.4 (62)	54.5 (74)	69.2 (54)	179.7 (67)	88.5	137	127
Mean	51.1	61.2	101.1	154.7	92.0		
S.D.	4.3	13.5	44.4	26.9			

*Values for 1994-1995 and 1997 assume the same movement as at meter B between 58 and 74 cm depth.

†Values reflect a minimum amount of displacement as meters were excavated in early August.

The amount of sediment transported downslope is much less variable among the meters in 1994 and 1995, before they were subjected to climatic treatments. In 1996, meter A (warmed and wetted) had approximately 2.5 times ($185 \text{ cm}^3 \text{cm}^{-1} \text{yr}^{-1}$) the volume transported at meters C (control), D (wetted) and E (cooled) (78 , 66 and $69 \text{ cm}^3 \text{cm}^{-1} \text{yr}^{-1}$, respectively). Although it recorded much less movement than meter A, meter B (warmed) nonetheless also had a higher volumetric transport ($108 \text{ cm}^3 \text{cm}^{-1} \text{yr}^{-1}$) than meters C, D and E.

In 1997, meters C, D and E recorded the greatest volume transported (between 160 and 180 $\text{cm}^3 \text{cm}^{-1} \text{yr}^{-1}$), while meter A had only slightly less ($152 \text{ cm}^3 \text{cm}^{-1} \text{yr}^{-1}$). Meter B recorded a much lower volume than the other meters ($105 \text{ cm}^3 \text{cm}^{-1} \text{yr}^{-1}$). Overall, however, less variability exists among the meters in 1997 than during the treatments of the previous year.

The recorded volumes in 1994 and 1995 are, for the most part, comparable to those recorded by Benedict (1970), Bennett and French (1991) and Price (1991), which range between 19 and 67 cm³ cm⁻¹ yr⁻¹ (see below Table 5-3). The values larger than 100 cm³ cm⁻¹ yr⁻¹ measured in 1996 and 1997 are even greater than the maximum volume recorded by Williams (1966) in northern Québec (134 cm³ cm⁻¹ yr⁻¹). These studies do not, however, report on annual variability of volumetric transport. Mean annual figures could potentially hide a much broader range of values. Similarly, having only mean annual volumetric transport values available for each meter at the experimental site (Table 5-2) would have revealed little of the significant differences which occurred during the study period.

5.2 Solifluction in an area of two-sided freezing

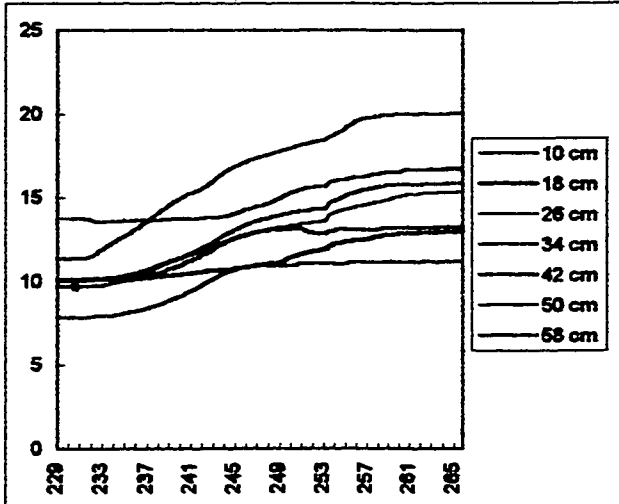
5.2.1 Types of movement

Several different processes fall within the definition of solifluction. Given the limited data available concerning areas subject to two-sided freezing, particularly in the High Arctic, one goal of this study was to identify movements which occur as a result of these processes in this area. Although as a result of the complexity of solifluction and the limitations of the instrumentation, a detailed examination of intra-seasonal movements was not performed, it is possible to distinguish different types of motion.

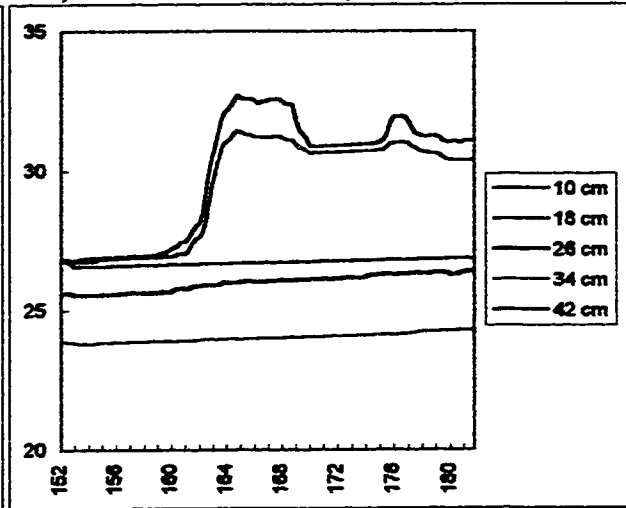
5.2.1.1 Annual frost heave

During fall freeze-back every year, a period of heave is evident at each meter at all the measurement blocks which had thawed during the preceding summer. For example, in 1994, the blocks at each meter began to record heave on about August 20 (JD 232), when the air temperatures started to decrease towards 0°C (Figure 5-2a). Freeze-back began from the base of the active layer, as deeper blocks (50 and 58 cm) indicated heave slightly earlier than those at shallower depths. By about September 22 (JD 265), heave appeared to have ended and no movement was recorded at any depth until the following spring. Although heave has elsewhere been detected within the frozen

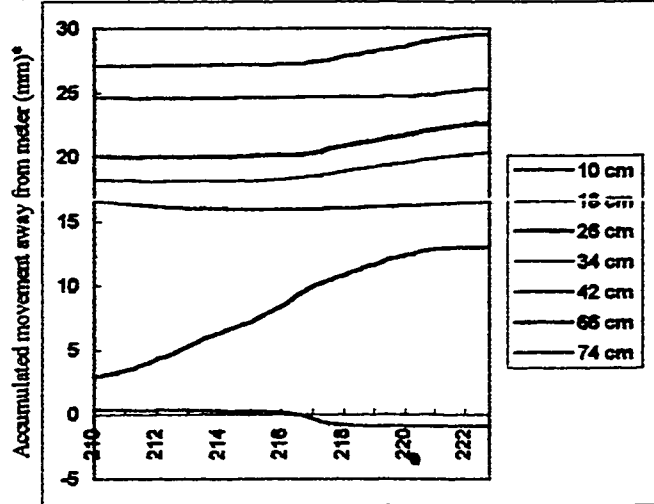
a) Annual frost heave, meter B, 1994.



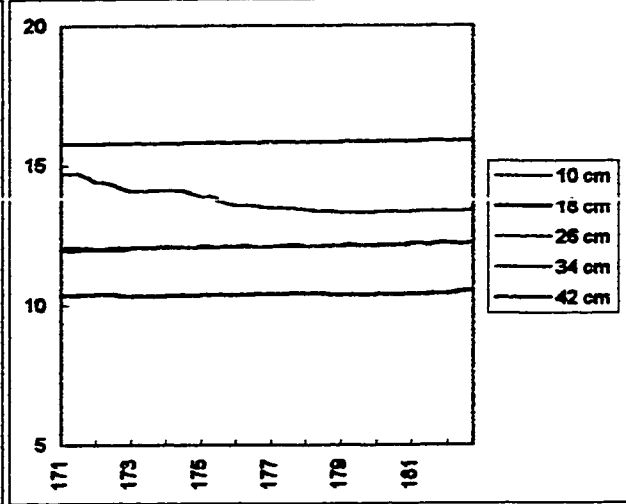
b) Short-term frost heave, meter C, 1995.



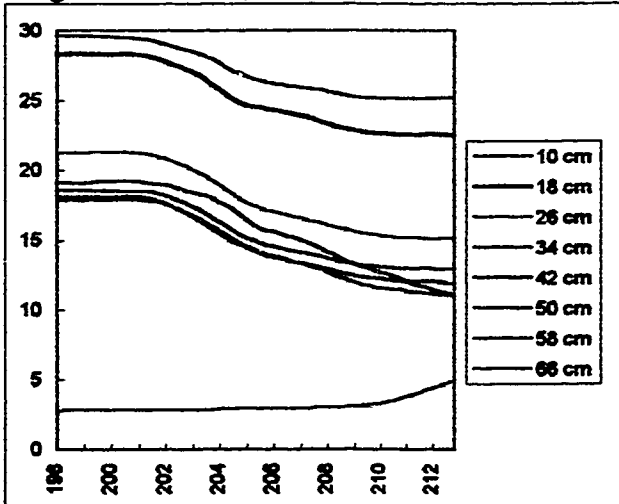
c) Mid-summer heave at depth, meter C, 1995.



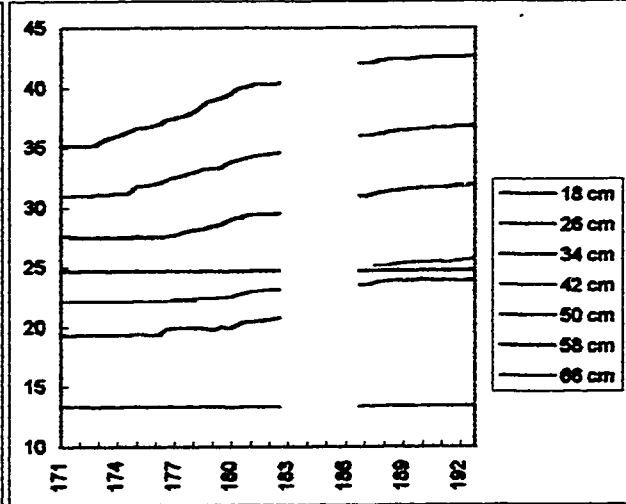
d) Shallow settlement, meter E, 1994.



e) Plug-like settlement, meter D, 1995.



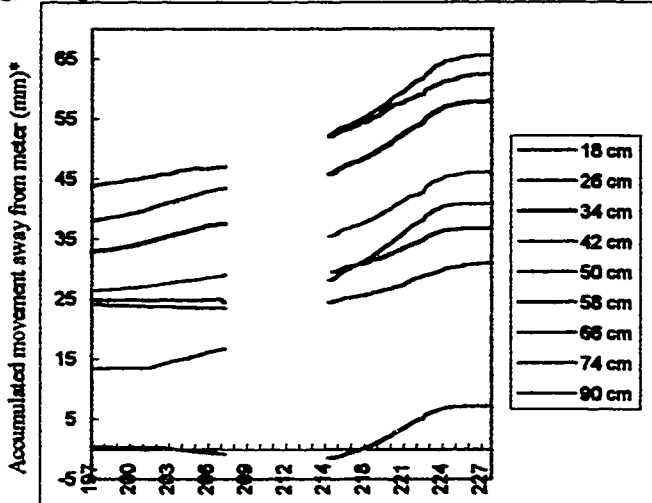
f) Gelifluction, meter A, 1996.



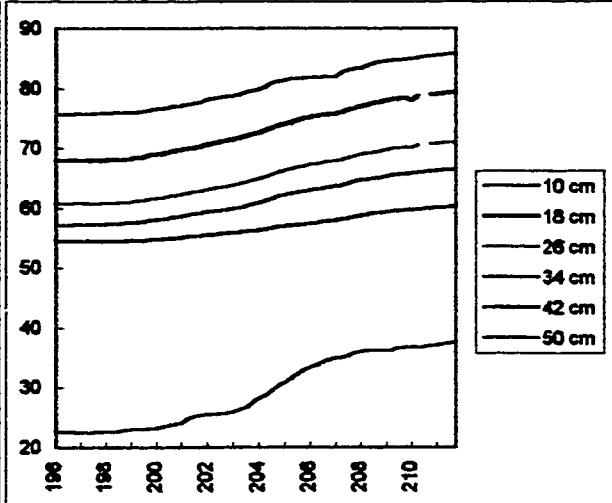
Julian Days

*Note: Values represent accumulated distance away from the meter. Direction of movement does not necessarily reflect actual movement up and down.

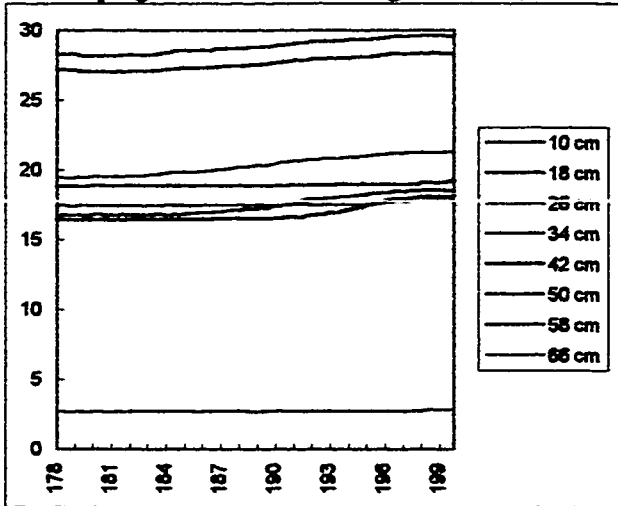
g) Plug-like movement, meter A, 1996.



h) Plug-like movement, meter E, 1997.



i) Shallow plug-like movement and gelifluction, meter D, 1995



Julian Days

*Note: Values represent accumulated distance away from the meter. Direction of movement does not necessarily reflect actual movement up and down.

active layer during winter (Mackay, 1983; Lewkowicz, 1992a), a lack of movement between fall freeze-up and spring thaw was typical during the study period at the experimental site.

5.2.1.2 Short-term frost heave

In addition to the annual cycle, short-term frost heave cycles, similar to those discussed by Matsuoka (1994), were detected at the experimental site (Figure 5-2b). In 1995, the mean daily air temperature had gone as high as 11°C by June 8 (JD 159), before dropping down just below 0°C on June 11 (JD 162). As a result, thawed soil surrounding the near-surface blocks (10 and 18 cm) refroze and heaved upward. This pattern of movement was repeated when near-surface soil once again thawed and refroze on June 25 (JD 176).

5.2.1.3 Mid-summer heave at depth

As discussed by Mackay (1981), frost heave was detected at depth at the site during summer thaw. Around August 4, 1995 (JD 216), the depth of thaw at meter C was about 71 cm when approximately 4 mm of heave was recorded at the 74 cm blocks as a result of the refreezing of meltwater which had percolated downward to the base of the active layer (Figure 5-2c). This meltwater resulted from high air temperatures between July 29 and August 3 (JD 210 and 215), which caused an increase in thaw depth and melting of ice lenses.

5.2.1.4 Settlement

As a result of two-sided freezing, the top section of the active layer in winter has a lower ice content than the bottom section (Mackay, 1981), but some lensing does still occur near the surface. A small amount of settlement was recorded at shallow depth during the spring thaw at meter E in 1994 (Figure 5-2d). The blocks at 10 cm depth settled approximately 3 mm while mean daily air temperatures remained above 4°C between June 20 and 28 (JD 171 and 179). The 18 cm blocks did not indicate any settlement during this time. Given that no surface heave was recorded previously

that spring, settlement must have occurred due to thawing of lenses formed near the surface the previous fall.

Because settlement as a result of thawing of ice lenses near the base of the active layer generally occurs during the summer at the same time as other downslope movements, it was difficult to isolate specific instances when it occurred. However, between about July 19 and 29, 1995 (JD 200 and 210), a relatively large amount of settlement (approximately 20 mm) occurred at all the measurement blocks between 10 and 58 cm at each meter (Figure 5-2e). At the time, mean daily temperatures remained consistently above 10°C and thaw depths ranged between 60 and 70 cm. Given that settlement took place at the same time throughout the active layer, it could be said to be “plug-like” in nature as referred to by Mackay (1981), even though there was virtually no element of forward motion.

5.2.1.5 Gelifluction

Although difficult to differentiate from other movements, what appears to be a relatively clear example of gelifluction can be seen in 1996 at meters A, B and C (Figure 5-2f). Between June 20 (JD 172) and July 8 (JD 190), the thaw depth increased from approximately 28 to 50 cm, yet relatively little settlement was recorded at each meter (5 mm), implying that there were few ice lenses at this depth in the active layer. However, a relatively large precipitation event (14 mm) which occurred on June 23, and which closely followed three consecutive days of precipitation between June 19 to 21 (JD 171 to 173) (approximately 2 mm per day), would likely have provided sufficient moisture to initiate gelifluction (see Washburn, 1967 and Price, 1991). Forward movement occurred initially between 10 and 18 cm, then was recorded progressively at greater depth as thaw became deeper.

5.2.1.6 Plug-like movement

As a result of the warming and wetting treatments in 1996, meter A appears to demonstrate plug-like movement precisely as described by Mackay (1981) (Figure 5-2g). Moisture from thawed

ice lenses of upper sections of the active layer and from the wetting treatments percolated downward to the base of the active layer and refroze, as evidenced by heave which occurred mid- to late July at a depth of 74 cm. Warming treatments served to increase the thaw depth beyond 70 cm in late July causing high thaw strain values (see Figure 4-13) and measurement blocks between 18 and 74 cm all recorded similar downslope movement from August 2 (JD 215) until about August 14 (JD 227), suggesting a plug-like movement.

Due to being cooled in 1996, the active layer at meter E remained relatively shallow (54 cm). As a result, even though the experimental site was kept intact until only early August 1997, the thaw front at meter E had already descended below the previous year's permafrost table. On July 16, 1997 (JD 197), when the depth of thaw measured about 54 cm, the blocks at meter E began to demonstrate a plug-like motion which appeared to be a combination of settlement and downslope movement (Figure 5-2h). Movement began at the same time between 10 and 50 cm, likely as the soil moved along a shear plane created by the thawing of ice lenses at the base of the previous year's active layer and similar to movements described by Egginton and French (1985).

Plug-like movement which began a few days later at meter A, and shortly thereafter at meters C and D, probably occurred as a result of the downwards percolation of the large amount of precipitation which fell between July 18 and July 27 (JD 199 and 208). It is not known exactly how much rain fell at Hot Weather Creek on July 27, but a record 20.8 mm was recorded at Eureka on that day. Measurements of water level in the piezometric tubes recorded two days after the event indicated that the water table was approximately level with the ground surface at all the meters except meter B. Increased moisture likely decreased strength sufficiently at the base of the active layer to cause shear.

Although when Mackay (1981) first discussed plug-like movement, it was as a result of the melting of ice lenses at the base of the active layer, Egginton and French (1985) indicated that it may

also occur at other depths within the active layer along discrete zones where ice lenses formed and subsequently thawed. At meter D in 1995, there appears to be an example of this type of shallow plug-like movement (Figure 5-2i) (all of the meters show an indication of the same movement, however it is best demonstrated at meter D). Forward movement began on about July 1 (JD 182) when blocks between 10 and 34 cm started to record similar motion at the same time. Between July 1 and 17 (JD 182 and 198), the depth of thaw increased from approximately 38 to 50 cm and air temperatures ranged between 4 and 17°C. Initially, blocks between 10 and 34 cm appeared to move together as a unit, however as thaw progressed, movement seemed to more closely resemble gelifluction with movement along discrete shear planes, as eventually blocks at 42 and 50 cm depths began to record similar movement. Due to the low amount of precipitation received in July, it is likely that moisture as a result of thaw was more important in initiating movement. As in most cases, an examination of soil micromorphological characteristics would help to determine whether movement was as a result of flow or by sliding along a shear plane.

5.2.2 Vertical velocity profiles

Theories and study findings concerning the shape of vertical velocity profiles and the processes responsible vary somewhat, due primarily to differences in study location (one-sided versus two-sided freezing) and vegetation (e.g., Williams, 1966; Benedict, 1970; Mackay, 1981; Egginton and French, 1985; Price, 1991). Differences in the interpretation of terminology regarding movement mechanisms also leads to confusion when profile shapes are attributed to particular processes, but these processes are defined differently.

Figure 5-1 illustrates the shape of the vertical velocity profiles at the experimental site meters between 1994 and mid-1997. For purposes of this discussion, only the shape of the final profiles at the time of excavation in 1997 will be considered, as they allow for the passage of the maximum possible amount of time since installation of the meters. In addition, given that the measurement blocks were physically measured during the excavation process, these final values are considered to

be somewhat more accurate than the intermediary profiles which relied upon interpretation of values from the datalogger.

The profiles at meters C, D and E are very similar in shape. Although no measurements lower than the 50 cm blocks were made at meter E, it is assumed that the base of the profile differs only perhaps in its more rapid decrease in movement below 50 cm, due to a shallow thaw depth in 1996. At all three meters, the profiles demonstrate a slightly convex downslope form. Meter B differs only in that its profile resembles more of a straight line than a convex shape. In contrast, the profile at meter A is convex-concave downslope. The profile is convex downslope between 18 and 66 cm, then becomes slightly concave at the base where movement decreases rapidly.

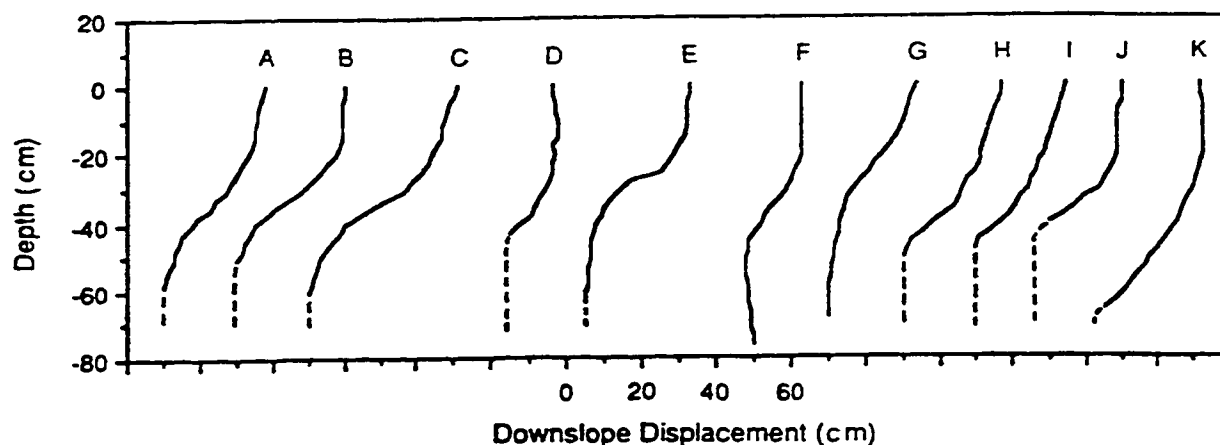
The profile at meter A differs from the others due to the warming and wetting treatments in 1996. The large amount of plug-like shear and settlement that occurred at the base of the active layer had a significant effect on the profile shape. Although it appears as though plug-like movement (whether in the form of settlement en masse or shearing) is relatively common, it is perhaps only responsible for large amounts of movement in years that are either marked by extreme thaw depths or excessive precipitation, as suggested by both Egginton and French (1985) and Price (1991).

Overall, the profiles are similar to that found by Lewkowicz and Clarke (1998) for both an excavated hose column and two solifluction meters, all situated within 100 m upslope of the experimental site. The measured hose column differed only in the upper section of the profile from a proposed model which demonstrated shearing in a thin zone directly above the base of the active layer. This type of plug-like movement has been identified at the experimental site (Figure 5-2g). In addition to the shearing at the base of the active layer, the profiles at the experimental site also show a decrease in movement at depth near the base due the effect of plug-like settling of the soil after the thaw of ice lenses either at the base of the active layer or at the top of the permafrost (Mackay, 1981).

An examination of the profiles at the experimental site confirms the suggestion made by Lewkowicz and Clarke (1998) that other processes are active in shaping the upper section of the profile. The processes demonstrated to be active at the experimental site which would better allow the modelled profile to correspond to the actual movement profile are frost creep (at the surface) (Figure 5-2b), gelifluction (Figure 5-2f), and possibly shallow plug-like movement (Figure 5-2i).

In the Ruby Range, Yukon Territories, the processes described by Price (1991) which shape the velocity profiles, are very similar to those active at the study site. These profiles demonstrate greater differential movement at depth than near the surface (Figure 5-3). The two primary differences at the sites monitored by Price are: (1) a thick vegetation mat which resists internal shearing and minimizes frost creep effects at the surface and (2) a lack of movement at the base of the active layer. If the velocity profiles that he recorded were modified to reflect these differences, they would be virtually the same as those found in this study, suggesting that many similar processes are active.

Figure 5-3. Vertical velocity profiles from the Ruby Range, Yukon Territories (from Price, 1991).



5.2.3 Volumetric Transport

Overall, the rates of volumetric transport calculated at the experimental site are higher than most recorded in other studies (Table 5-3). If maximum thaw depths and rates of surface movement are compared, it appears that the major source of difference between the values from the experimental site and others must be the shape of the velocity profile.

Table 5-3. Selective review of volumetric transport rates.

Author	Location	Mean annual surface mvmt (cm)	Maximum depth of mvmt (cm)	Mean annual volume (cm ³ cm ⁻¹ yr ⁻¹)	Reference
Rudberg, 1964	Sweden	5 max	70	39	Harris, 1981.
Williams, 1966	Québec	9.8 max	105	114	Harris, 1981.
Benedict, 1970	Colorado	2.4 max	50	59	Harris, 1981.
Harris, 1977	Norway	1.6 max	65	26	Harris, 1981.
Mackay, 1981	Garry Island	0.5	57	15	Mackay, 1981.
Bennett & French, 1991	Melville Island	0.9-2.4	30-53	20.3	Bennett & French, 1991.
Price, 1991	Yukon	0.5-2.1	48-63	19-67	Price, 1991.
Clarke, 1998	Ellesmere Island	A - 2.0	82	117	This study.
		B - 2.0	74	79	
		C - 1.8	74	92	
		D - 1.6	74	83	
		E - 2.0	74	88	

For example, the maximum average annual surface movement recorded by Williams was 9.8 cm and the maximum depth of movement was 105 cm, while at the experimental site, the maximum near-surface movement recorded in any year was 4.1 cm and the maximum depth of movement was between 74 and 82 cm. Even with these differences, the similarity in volumetric transport can be explained by the fact that the vertical velocity profiles recorded by Williams were primarily concave downslope, while those at the experimental site are convex.

It is interesting to note the high volumetric transport values recorded at the experimental site given the generally dry nature of the Fosheim Peninsula. Although lower rates are found in the area, local slope conditions are mesic. Volumetric transport at the experimental site is larger than that reported by Bennett and French (1991) on Melville Island throughout the study period (1994-1997).

An examination of the profiles at the two sites suggests that there is less decrease in velocity with depth on Melville Island (Bennett and French, 1991), therefore differences in maximum recorded depth of movement (30-53 cm versus 74-82 cm) must be largely responsible for greater movement at the experimental site.

Lower volumetric transport reported by Mackay (1981) on slopes which demonstrate convex downslope velocity profiles appears to be due to a combination of factors, such as shallower thaw depth and slower surface movement than at the experimental site.

5.3 Movement variability versus climatic fluctuations

5.3.1 A 22-year study: Åkerman (1996)

Given the considerable variability in annual rates of solifluction that exists, it is important to assess the impact that climatic fluctuations have on movement. The 22-year study completed by Åkerman (1996) examined the relationship between solifluction and creep rates and selected climatic variables at a variety of small-scale periglacial surface features in West Spitsbergen. He found that mean annual surface displacement rates varied from 0.9 cm at sorted steps to 6.8 cm in talus creep. The mean rates of movement of solifluction sheets and lobes were 4.4 and 3.5 cm, respectively. Åkerman found that a good correlation did not exist between mean annual temperature and annual rates of movement at solifluction sheets and lobes, even during periods when air temperature varied regularly (seven consecutive years with average temperatures below normal) and irregularly (five-year period with a temperature trend from 2.5°C above normal to 2.5°C below normal). He found that for each specific solifluction feature, there was a given monthly air temperature that provided a very good correlation, while the other months and the total summer mean temperature showed weak or very poor correlations. Movement at each feature correlated best with the mean temperature of the month in which it was most active, and the smaller and shallower the form, the earlier and shorter the duration of activity. For example, the movement of solifluction lobes correlated best with July mean

temperature ($r^2=.53$), whereas solifluction sheets correlated best with August mean temperature ($r^2=.69$). The movement of sheets was found to be dependent on the release of moisture upon thawing of ice lenses at the base of the active layer, which only occurred with at least an August mean air temperature of 3.3°C.

Åkerman also found that increased periods of time with greater moisture availability related to increased rates of movement. Maximum snow depth in May and June correlated well with surface displacement of solifluction sheets ($r^2=.85$). In addition, a long, cool spring resulted in greater movement than a short warm one, as it prolonged the length of the melt period, and thus, the period during which greater amounts of moisture were present. Similarly, the number of rainy days appeared to be of greater importance than the amount of precipitation received.

Overall, it was found that the monthly data, combining several factors, such as monthly mean air temperature, degree days in May-June, thaw index and monthly mean ground temperature, provided the best correlation between climate and rates of surface movement of solifluction sheets and lobes (Åkerman, 1996), although little detail as to the specifics of these combined factors was provided in the report.

Åkerman's work (1996) is valuable as a long-term study which compared rates of movement of many forms under varying climatic conditions. However, the data available concerning movement at depth were limited, and therefore the relationships studied were restricted to the utilization of surface rates of displacement. As discussed above, an examination of surface rates is not necessarily effective in detecting differences in movement at depth. Åkerman also used the term "process", but unfortunately was not more specific as to which element of solifluction was particularly affected, other than referring to shallow or deep processes. It appears from this paper that movement was correlated only with climatic conditions from the same year, whereas perhaps it would have also been useful to examine movement in relation to the previous year's conditions.

5.3.2 Experimental site

Two variables emerge in the literature as key factors influencing annual rates of solifluction: moisture (primarily its availability during fall freeze-up and its distribution in the active layer) and depth of thaw (e.g., Washburn, 1967; McRoberts and Morgenstern, 1974; Harris, 1981; Egginton and French, 1985; Bennett and French, 1991; Price, 1991; Åkerman, 1996; Lewkowicz and Clarke, 1998). Measurements made in association with the solifluction meters at the experimental site can be examined in order to help determine the role played by moisture and depth of thaw during the study period.

Before closely examining the differences in volumetric transport between the meters in 1996 and 1997, it is important to compare the values of the meters in the two years prior to the climatic treatments (Table 5-2). In 1994, the volume transported at each meter is similar, with a mean of $51.1 \text{ cm}^3 \text{ cm}^{-1} \text{ yr}^{-1}$ and a standard deviation of only $4.3 \text{ cm}^3 \text{ cm}^{-1} \text{ yr}^{-1}$. In 1995, the differences between the meters are larger, with a mean of $61.2 \text{ cm}^3 \text{ cm}^{-1} \text{ yr}^{-1}$ and a standard deviation of $13.5 \text{ cm}^3 \text{ cm}^{-1} \text{ yr}^{-1}$. By the beginning of 1996, the cumulative movement at meter D was a bit less than that of the other meters (Figure 5-1). The differences in amounts transported could be as a result of several factors as slight natural variations in movement rates, thaw depths or profile shapes may exist between the meters. There are not, however, significant pre-existing natural differences, as the meters are located within close proximity of each other and soil properties at each meter are similar. It is more likely that a certain element of error was introduced during the interpretation stage of data analysis, and thus the distribution of movement between years could be slightly inaccurate. It should be noted, however, that interpretation of movement in 1996 and 1997 was facilitated by the measurement of additional variables and therefore should reflect a greater degree of accuracy.

5.3.2.1 1996 movement

Climatic treatments at the experimental site between July 8 and August 9, 1996 potentially affected the moisture of the soil surrounding each meter in three ways: meters A and D respectively

had total equivalents of 142 and 153 mm of water applied to the soil surrounding them; meters A and B were covered by a polyethylene sheet which prevented much of the natural precipitation from penetrating directly into the soil surface surrounding them; and the polyethylene sheet likely also acted to lower surface evaporation rates. In addition, it is possible that meter C may have received slightly increased amounts of precipitation due to its position a few metres downslope of the edge of the polyethylene sheet.

Even though the soil surrounding meters A and D received considerable amounts of water as part of the wetting treatments, moisture content values do not clearly reflect the treatments as, with a few minor exceptions, moisture content values remained remarkably consistent throughout the summer at each meter (Figures 4-3 and 4-4). Only the moisture level at 10 cm at meter D remained consistently high during the treatment period, ranging between 31 and 75%. Drying out of the upper sections of the profiles due to evaporation at the meters which were not subjected to wetting, which is normally expected as the summer progresses, did not occur. Moisture content values were greater than the mean liquid limit (29%) on more than half of the days when samples were taken.

The lack of clear differences in moisture contents between the meters is primarily due to the climatic conditions during the summer of 1996. At Eureka weather station, 58 mm of precipitation were recorded between June 1 and August 31, whereas the 30-year mean (1951-1980) is 29 mm (AES, 1984). At Hot Weather Creek, which usually receives approximately 25% more precipitation than Eureka (Lewkowicz and Wolfe, 1994), 78 mm fell during the summer. The mean summer air temperature (June 1-August 31) at Eureka during 1996 was 1.9°C, while the 30-year mean is 3.5°C. Mean summer air temperatures during 1994 and 1995 at Hot Weather Creek were 6.1 and 7.6°C, respectively, while in 1996, the mean was 3.9°C. The high level of precipitation kept moisture levels relatively high in the active layer throughout most of the summer, as demonstrated by the water levels in the piezometer tubes (see Figure 4-9). In addition, low air temperatures probably reduced

evaporation rates. These high amounts of precipitation likely acted to weaken the potential signal of the wetting treatments.

As would be expected with moisture contents around the liquid limit (see Harris, 1996), measurements of *in situ* shear strength recorded low values (between 6 and 55 kPa, with a median value of 17 kPa) (Figure 4-5), particularly compared to those in previous years (Figure 4-8). Although meters C, D and E indicated a very slight strengthening trend towards the beginning of August, there was not a significant change. Possibly as a result of the wetting treatments, the near-surface strength of meters A and D were slightly lower than the values at meters B, C and E. Upon examining the data closely, however, a clear relationship did not exist between moisture contents and shear strength values from 1996 and 1997. In addition, neither shear strength nor moisture contents varied as depth of thaw progressed.

Although moisture content values revealed little difference between the meters, water levels were highest above the frost table at meters A (warmed and wetted) and D (wetted) and lowest at meters B (warmed) and E (cooled). The level at meter B may have been lower due to lack of direct precipitation, however it is not certain why the level at meter E remained lower than at the other meters. A shallow depth of thaw may have had an influence as the ice-rich zone at the base of the previous year's active layer did not provide moisture to the active layer because it remained frozen.

The two meters that were warmed (A and B) both recorded larger amounts of movement than the other meters, as greater thaw depths allowed for the thawing of ice lenses at the base of the active layer, thus resulting in greater settlement and forward movement (Table 5-2). However, in addition to warming, meter A was subjected to wetting treatments and recorded a much larger amount of movement than meter B due to the occurrence of plug-like shearing, as well as greater settlement, at the base of the active layer. Nonetheless, meters C, D and E received greater amounts of precipitation than meter B (as a result of precipitation and/or climatic treatments), yet recorded less movement.

The impact of the large differences in thaw depth (i.e., thawing of the ice-rich zone) between meter B and meters C, D and E (79 cm versus 64, 66 and 54 cm, respectively) was sufficient to overcome the effect that greater moisture may have had, particularly given the similarity in moisture content values between the meters due to the overriding impact of high precipitation levels.

Measurements of meter height above the ground surface suggest that much of meter A's movement in 1996 may have occurred as a result of soil settlement at depth, as increased thaw depth (72 cm) allowed for melting of an ice-rich zone. Between June 26 and August 9, soil surrounding meter A settled approximately 58 mm, whereas that surrounding meter E heaved approximately 10 mm and both meters C and D remained virtually unchanged. It is unclear why meter B recorded only 30 mm of settlement, given that it had a slightly greater thaw depth (79 cm) than meter A. It is perhaps because less moisture was available to percolate downwards for mid-summer frost heave at the base of the active layer, and as a result, less settlement and downslope shearing occurred as thaw depth increased. Nevertheless, much of meter B's movement is also attributable to soil settlement at depth.

Even though meter D was subjected to wetting treatments and had a slightly greater thaw depth than meters C and E, it recorded the lowest amount of movement of all the meters. When treatments finished on August 9, meter D recorded a very high moisture content at 10 cm, yet had the lowest moisture values between 34 and 66 cm. Its shear strength values were slightly higher than those of the other meters between 18 and 42 cm. The moisture content results suggest that the wetting treatments were ineffective in increasing moisture levels, yet on the same day in August, meter D recorded a higher level of water in the piezometer tube than the other meters (Figure 4-9). The same pre-existing conditions which led meter D to have the lowest amounts of movement in 1994 and 1995 may have also influenced its movement in 1996. It should be noted, however, that the amount of volumetric transport at meter D in 1996, as a percentage of 1994 and 1995 movement, falls within the range or is greater than the percentages calculated for meters C and E (Table 5-2).

Amounts of movement in the upper section of the active layer at meter E (cooled) are similar to those recorded at meters C and D. A large drop in movement between 42 and 50 cm suggests that a zone of shear may have existed between those depths. Volumetric transport was less at meter E than at the other meters (except meter D) due to its shallow depth of thaw.

It is difficult to assess the pattern of movement through the profile at meter C (control) as the measurement blocks at 50 and 58 cm did not function. The greater volumetric transport in 1996 than 1995 indicates, however, that the cool wet conditions of 1996 combined to have greater impact on movement than the warm dry conditions of 1995.

Due to the availability of much moisture during fall freeze-up, large amounts of heave were recorded at each meter, particularly at meters C, D and E. Although overall, the amount of heave seems to be only weakly associated with the number of days of freeze-back at the experimental site between 1994 and 1996, the long duration of freeze-back in 1996 (14-32 days) likely served to help promote the growth of ice lenses.

The impact of the climatic treatments and natural climatic conditions on moisture distribution and thaw depths at the solifluction meters determined patterns of movement in 1996. Overall, high natural moisture levels (due to high precipitation amounts, a large total number of days with precipitation and low air temperatures) lowered shear strength values and led to elevated porewater pressures, thus providing conditions potentially suitable for both gelifluction (Washburn, 1967) and plug-like movement, while warming treatments increased thaw depths, promoting increased settlement and forward movement.

5.3.2.2 1997 movement

High volumetric transport in 1997 is related to the large amounts of heave experienced in 1996, precipitation received in July and warm air temperatures. Very high levels of precipitation in

July decreased soil strength and increased porewater pressure, providing conditions conducive to both gelifluction and plug-like shear at all the meters. Due to the excavation of the meters in early August, the 1997 data represent a minimum amount of downslope movement as it is probable that further forward and/or settlement would have occurred during the month.

The largest amount of downslope movement of the measurement blocks in 1997 was at meter E in the upper and middle sections of the soil profile, ranging from 41 mm at 10 cm to 30 mm at 42 cm. Potential frost creep at meter E was high in 1996, as total heave for the year was at least 42 mm down to a depth of 42 cm. As a result of the cooling treatment in 1996, meter E had the shallowest thaw depth, therefore ice lenses which formed at the base of the active layer were at a shallower depth than at the other meters. Due to relatively warm air temperatures, these lenses thawed in July, resulting in large amounts of settlement and creating a zone of shear around a depth of 50 cm (see Figure 5-1). The precipitation event in late July, when depth of thaw at meter E had increased to approximately 64 cm, likely resulted in the creation of another narrow zone of shear below 50 cm, although a lack of measurement blocks makes it impossible to determine exactly what occurred.

The profiles of movement at meters A and D also indicate zones of shear as plug-like movement appears to have been generated in large part by the high amounts of precipitation which fell near the end of July. Even though thaw depths at meters A and D were similar at the time (approximately 68 cm), the location of the shear zone at meter D appears to have been influenced by the depth of its ice-rich zone. Greatest shear at meter D occurred between 58 and 66 cm: precipitation which percolated to the base of the active layer likely added to that provided by the thawing of ice lenses to create a zone of low strength (see Figure 4-5k) susceptible to plug-like shear. Meter D also experienced a relatively large amount of settlement due to the thaw of the ice-rich zone at the base of the previous year's active layer.

At meter A, the area of greatest shear was situated just below 66 cm. Because very little settlement was recorded below 58 cm in 1997 and the 1996 thaw reached a depth of approximately 72 cm, it does not appear that significant melting of the ice-rich zone occurred. Nevertheless, the precipitation which fell apparently provided sufficient moisture to promote plug-like shear at the base of the active layer. It is possible that had the meters been left intact for the remainder of August, meter A would have recorded greater movement as a result of further settlement and possible plug-like movement, providing that air temperatures were sufficiently warm to increase thaw depths as far as its ice-rich zone.

Meter B recorded the greatest thaw depth in both 1996 and 1997, yet had the lowest combined amount of downslope movement during those years. This suggests that the lower amounts of moisture that it received in 1996 had a greater impact on movement over the course of the two years than did the deeper thaw. Like 1996, however, measurements of moisture content and shear strength recorded on July 30, 1997 show that meter B had similar values to the other meters, yet water level in the piezometric tube was 40 cm below the ground surface, whereas at all the other meters, it was at ground surface level. The velocity profile indicates no obvious zone of shearing, yet as with meter A, it is possible that meter B would have recorded greater movement in August as a result of thawing of an ice-rich zone, if it had not been excavated.

It is again difficult to determine the possible location of a shear zone at meter C without data from 50 and 58 cm blocks. Nevertheless, given that downslope movement decreases from 29 mm at 42 cm to 1 mm at 66 cm, a shear zone must be situated somewhere in between, probably around a depth of 64 cm, the maximum depth of thaw in 1996.

It is interesting to note that in 1996, higher rates of thaw at meters A and B due to the warming treatments resulted in greater thaw depths, and subsequent settlement and downslope movement, whereas in 1997, the slightly higher thaw rates at the same meters were likely due to the

fact that the ice content of the active layer which had had a chance to thaw by the beginning of August was lower at meters A and B than at meters C, D and E, due to the deeper thaw in 1996. As a result, higher thaw rates in June and July in 1997 were associated with less movement.

5.3.2.3 Overall findings

The study findings suggest that, in this dry environment, moisture is the primary controlling factor on amounts of solifluction. As discussed by Edlund *et al.* (1990), the two sources of soil moisture in the region are precipitation and ground ice. High levels of precipitation during summer (such as in 1996 and 1997) lead to greater amounts of downslope movement, potentially both in the current year, as well as the following year (providing moisture is available during fall freeze-up). Sufficiently deep active layers can result in the thawing of ice-rich zones at the top of the permafrost resulting in greater settlement and forward movement.

Volumetric transport rates in both 1996 and 1997 are higher than amounts calculated for 1994 and 1995 (Table 5-2). Even though the air temperatures experienced at meters C, D and E were cooler in 1996 than in 1994 or 1995, and as a result, thaw depths were shallower (Table 5-2), movement at each meter was higher than in those previous two years as a result of very high amounts of precipitation. The warming treatments at meters A and B served to further increase movement in 1996 due to the thaw of the ice-rich zone at the base of the active layer. The extremely high amounts of volumetric transport in 1997 are a result of high precipitation in both 1996 and 1997, as well as warm air temperatures in 1997 which ensured sufficient thaw to at least start the melting of ice lenses situated at the base of the 1996 active layer.

Air temperature is important in terms of the manner in which it influences moisture availability. Cooler temperatures may decrease levels of evaporation (see Harris, 1993) or prolong the thawing of snow in the spring (see Åkerman, 1996), thus increasing potential for the maintenance of high moisture levels. In addition, a cool summer, resulting in a shallower active layer, will

position the zone of primary ice lensing at a lesser depth in the active layer, thereby increasing the likelihood that the ice-rich layers will be thawed again sooner than if they were at a lower depth in the profile.

However, as found by Åkerman (1996), warm summer air temperatures and deeper thaw increase the likelihood of thawing of the base of the active layer and the top of permafrost, which, depending on the amount of time since they were last thawed, could be very ice-rich (Lewkowicz and Clarke, 1998), resulting in increased movement as a result of both settlement and shearing. It has been demonstrated that the two sources of soil moisture in the region are precipitation and ground ice, and that in warmer years, the ground-ice-controlled regime prevails (Edlund *et al.*, 1990). The full impact of air temperature is, to a large extent, determined by antecedent moisture conditions.

Air temperature also influences the formation of ice lenses in the soil profile, as a longer freeze-up period promotes greater ice lens formation (Washburn, 1980).

At the experimental site, precipitation and air temperature combined to determine amounts of volumetric transport, and depending on the combination of the two (e.g., cool moist, warm moist, etc.), the timing and the primary process responsible (i.e., frost creep, gelifluction, plug-like movement) varied. When examining the impact of climatic fluctuations on rates of movement, it is important to compare rates with conditions from the previous year(s), in addition to those of the current year. Consideration must also be given to the sequence in which warm, cool, wet and dry years occur, as various combinations will differently influence the distribution of moisture within the active layer, the depth of thaw, and as a result, the total movement.

The results of this study confirm the findings of other authors who highlight the importance of moisture and thaw depth and more specifically, the emphasis placed on moisture distribution by Harris (1981), Egginton and French (1985) and Bennett and French (1991). Results also indicate that

plug-like movement seems to take place, at least to some extent, in most years; it can occur either at a shallow location in the active layer or at depth, providing moisture is present to promote shearing (as a result of either thaw or precipitation) or at depth when thawing of ice lenses takes place, resulting in simultaneous plug-like settlement. Its importance in terms of sediment transport, however, is greatly enhanced with increased moisture.

The hypotheses outlined in the thesis research (see section 1.5) have been shown to be too simplistic in nature. Both precipitation and depth of thaw are linked to solifluction through their influence on moisture availability and distribution. If only precipitation or thaw depth is examined without reference to the other, only one source of moisture has been considered. More importantly, movement must be related to climatic conditions in both current and previous years as the same conditions in one year can produce different outcomes, depending on the antecedent moisture conditions (e.g., availability of moisture during fall freeze-back, depth of ice-rich zone).

The experiment itself was not entirely adequate to determine the impact of the climatic treatments on solifluction. The impact of the warming treatments was greatly enhanced due to the cool temperatures which prevailed during the summer of 1996, producing a scenario in which the contrast between the meters was perhaps too extreme. The wetting treatments had a questionable impact on the area surrounding the meters due to high precipitation values. Too small an area surrounding the meters may have been treated, providing the opportunity for the additional moisture to dissipate. The examination of data from previous years, however, helped to provide additional information on the influence of climatic fluctuations on inter-annual variability of solifluction.

In order to adequately assess the impact of climatic fluctuations on rates of solifluction, instrumentation must, at a minimum, be able to provide movement data on an annual basis, as year-to-year variability is too great for multi-annual averages to be useful. The data collected has also highlighted the importance of measuring both vertical and downslope movement through the entire

soil profile when considering the elements of solifluction in order to be able to accurately assess the importance of each type of movement. While the solifluction meters measured resultant movements, heave meters (Mackay *et al.*, 1979) installed next to each meter would have added vital information on vertical movement of the active layer.

A general pattern of variability in movement can be traced to annual climatic fluctuations, but a much longer record must be obtained and examined to be able to accurately predict rates of solifluction given a particular sequence of climatic conditions.

5.3.3 Palaeoclimatic implications

In order to make inferences about palaeoclimatic conditions based on past rates of solifluction, an accurate relationship between current conditions and rates must be established and as suggested by Åkerman (1996), this requires considerable care due to the complex manner in which climate and geomorphic processes interact. As discussed above, a long time series is required to ensure the accuracy of the relationship between climate and rates. Even then, attention must be paid to whether the effects of long-term change of climate have been assessed or merely the outcome of climatic variation. Prediction of solifluction rates based on climatic fluctuations is not necessarily transferable to the longer-term scale of climate change, as change would involve a new set of fluctuations within a changing set of boundary conditions (e.g., maximum and minimum air temperatures and precipitation values). If a range of movement rates associated with a particular “set” of possible fluctuations can be established, perhaps inferences about past climatic conditions can be made. A set of boundary conditions (i.e., moisture, temperature) above or below which solifluction does not occur could then perhaps also be determined.

As pointed out by Matthews *et al.* (1993), it must not be assumed that a particular response to change in one place necessitates an equivalent response in another location. For example, warm moist summers may enhance rates in one area while elsewhere, cool moist summers increase rates of

movement. Looking back at Table 1-3, the majority of studies which concluded that colder temperatures resulted in increased movement were conducted in areas where currently one-sided freezing occurs. Colder conditions, therefore, imply increased movement primarily due to deeper penetration of the freezing front (Harris, 1993) and possibly longer snowmelt periods. However, if temperatures were to decrease sufficiently that two-sided freezing were to become predominant, very different conditions would exist within the active layer and rates of movement would be influenced by other variables.

If unequivocal relationships can be established between current solifluction rates and climatic fluctuations, this information may be used to help identify palaeoclimatic boundary conditions within which solifluction was more or less effective in transporting sediment downslope. At this time, it appears that further study concerning current relationships between solifluction and climate in an area of two-sided freezing are required before inferences could be made concerning past climatic conditions based solely on rates of solifluction.

5.4 Application of findings

Due to the location of the study site in an area which has summer air temperatures which are more moderate than other locations at a similar latitude, the direct comparability of solifluction rates from the experimental site is somewhat restricted to other areas with relatively warm and dry conditions. Many of the processes which have been monitored, however, are active throughout permafrost areas which are subject to two-sided freezing. The impact of moisture (availability and distribution) on solifluction in areas of two-sided freezing is similar, even though fluctuations in climate may vary from site to site.

The importance of examining movement at depth and annual variability in order to assess the impact of climatic fluctuations on solifluction is applicable to all permafrost areas with two-sided

freezing. Given the nature of the processes which are active, climatic fluctuations may cause greater variability in volumetric transport in areas of two-sided freezing than those with only one-sided freezing. Where one-sided freezing is active, the ice-rich zone will always be near the surface, regardless of the penetration of the freezing front, whereas the location of the ice-rich zone in an area of two-sided freezing is much more variable, and hence the processes which are associated with the thawing of the ice-rich zone will also vary .

5.5 Limitations of findings and suggestions for future work

The primary limitation encountered during this study concerned the design of the equipment used. Although the solifluction meters were very effective in continuously monitoring movement and temperature at depth between 1993 and 1997 (except for brief periods with very high moisture levels in 1996), the nature of the data collected brought about certain difficulties which arose during the interpretation of the movement data. Even though the base of each meter was frozen in permafrost, a small amount of downslope tilt occurred between 1993 and 1997. This problem may be difficult to circumvent, however, given that the meters were specifically designed to remain stiff and immobile, yet bending still occurred, likely as a result of movement within the active layer and the top of the permafrost.

When the solifluction meter was originally designed, it was assumed that the movement recorded would be relatively straightforward, but movements proved to be much more complex than anticipated. The meter was only capable of measuring the resultant of a 2-dimensional movement, therefore the data representation of movement was not a clear portrayal of the actual vertical and horizontal movement of the blocks. A lengthy procedure was therefore required in order to interpret the movements over four years at each set of blocks. Although the data were examined in conjunction with a number of associated measurements to help with the interpretation, certain ambiguities existed in the data set.

Ideally, a new instrument will be designed which can differentiate clearly between horizontal and vertical displacements within the active layer a combination of more than one instrument may be used in order to accomplish this. Although regular measurements of meter height above the ground surface greatly aided data interpretation during 1996, continuous monitoring of vertical displacement throughout the study, perhaps similar to that recorded by Matsuoka (1994), would have been extremely beneficial. Given the opportunity, it would also be useful to test equipment under a variety of conditions in order to ensure that data is accurate and unambiguous.

There are several steps which would help in the determination of the spatial and temporal variability of solifluction and the impacts of climatic fluctuations. Greater comparability between studies should be sought, as a lack of consistency in what is being measured, the methods being used and the timing thereof makes it difficult for authors to directly compare findings and to benefit from the work of others (see Lewkowicz, 1988). Movements at depth must also be considered in order to fully appreciate both spatial and temporal variability.

Many authors have recognized the value of long-term studies (e.g., Washburn, 1967; Mackay, 1981; Egginton and French, 1985; Bennett and French, 1991; Price, 1991; Lewkowicz, 1992). This is particularly important when trying to establish relationships between movement and climatic fluctuations, as there are virtually an endless number of possible climatic sequences and long-term study is necessary in order to determine a pattern of response. In addition, many extreme conditions may not be encountered in the short term (e.g., Egginton and French, 1985; Price, 1991), and thus an inaccurate evaluation of movements could potentially be made.

An important feature of the solifluction meters used in this study was their ability to provide data on an ongoing basis in a non-destructive manner. This feature could help to promote the establishment of longer-term studies, as data for analysis is provided continuously. Ideally, monitoring in the field would be performed in conjunction with physical modelling in the laboratory.

Ongoing results from the field could be applied to models, at the same time as modelling results could help to interpret field measurements and perhaps allow for the replication of field conditions in order to more closely examine specific scenarios.

As noted by Harris (1996), physical modelling "...offers the opportunity to monitor the response of slopes and slope materials to repeated phase changes and enables investigators to control material properties, thermal regimes and hydraulic conditions". Up to this point, modelling performed by Harris and others (e.g., Harris *et al.*, 1993; Harris *et al.*, 1995; Harris and Davies, 1996) has focused on simulating solifluction in areas of one-sided freezing, although future work will be aimed at modelling solifluction in sites with two-sided freezing (Harris, 1996). This work would have the potential to greatly advance knowledge in terms of spatial and temporal variability: spatially, it is relatively easy to vary laboratory conditions to simulate various locations, and temporally, annual cycles of freezing and thawing can be shortened in order to recreate a greater number of climatic fluctuations.

In conjunction with continuous monitoring of solifluction at depth in the field and in the laboratory, it would also be important to perform more work on the micromorphology of soliflucted materials. Although some work of this nature has been completed (see discussion, French, 1996), it seems that sufficient uncertainty still exists as to the exact mechanisms (e.g., shearing, flow) which are active that more work of this genre would be beneficial in the study of intra-seasonal movement.

Chapter 6. Conclusions

Several conclusions can be reached regarding solifluction at the experimental site:

1. Near-surface rates of movement recorded at the experimental site of between 0.8 and 4.1 cm yr⁻¹ are comparable to those found in other studies in permafrost areas.
2. The following types of movement were identified at the experimental site: annual and short-term frost creep, mid-summer heave at depth, gelifluction and plug-like movement (both as a result of settlement and shearing).
3. Plug-like movement appears to take place in most years at the experimental site as it can occur either in the near-surface or at greater depth within the active layer, providing that moisture (due to thaw or precipitation) is present to promote shearing, or that ice lenses at the base of the active layer are thawing resulting in simultaneous settlement through the active layer. Its importance in terms of volumetric transport, however, is greatly enhanced with increased moisture.
4. In this dry environment, moisture is the primary controlling factor on amounts of solifluction. Air temperature is important in terms of the manner in which it influences moisture availability, its distribution within the soil and ice lens formation.
5. Depending on the combination of precipitation and air temperature, the timing and primary process responsible for sediment transport vary. Consideration must be given to the sequence in which warm, cool, wet and dry years occur, as various combinations will differently influence the distribution of moisture within the active layer, the depth of thaw, and as a result, the total movement.

The following conclusions can be reached concerning the impact of the climatic treatments:

6. There is clear evidence that the warming and cooling treatments were successful in manipulating active layer conditions in 1996, as maximum thaw depths ranged from 72 cm at meter A (warmed and wetted) to 54 cm at meter E (cooled). The control meter (C) thawed to a depth of 64 cm.
7. The impact of the wetting treatments is not clear due to the above-average precipitation that

occurred during the summer of 1996. This resulted in high moisture values at all of the meters and weakened the signal of the treatments. As a result, the two meters that were wetted (A and D) were not affected by significantly higher moisture content or piezometric values than the two that received natural levels of precipitation (C and E). The meter which did not directly receive natural precipitation, as a result of a side-effect of the warming treatment, nevertheless recorded similar moisture content values to the other meters, but did have lower piezometric values.

8. Higher levels of moisture resulted in greater volumetric transport at the experimental site. All of the meters recorded enhanced volumetric transport during the year when climatic treatments were performed, primarily as a result of the above-average precipitation that was received at the site. The two meters that were warmed recorded larger amounts of movement during treatments than the other meters, as ice lenses at the base of the active layer were thawed, releasing moisture and causing greater settlement and forward movement.
9. High volumetric transport at all of the meters in 1997 is related to the large amount of heave experienced in 1996, a large precipitation event in July and warm air temperatures which allowed for at least the start of thaw of the ice-rich zone at each meter.
10. Prior to climatic treatments, recorded volumetric transport rates in 1994 and 1995 ranged from 42 to 82 $\text{cm}^3 \text{cm}^{-1} \text{yr}^{-1}$ and are comparable to the mean annual values recorded in other studies. Mean values over the entire study period, however, were higher than most recorded in other studies, with a mean value at the control meter of 92 $\text{cm}^3 \text{cm}^{-1} \text{yr}^{-1}$. Differences in amounts transported are related to vertical velocity profile shape, maximum depth of movement and surface rates of movement.

The following conclusions can be reached concerning vertical velocity profiles at the experimental site:

11. The vertical velocity profiles at three of the meters (control, wetted and cooled) demonstrated a slightly convex downslope form. The profile of the meter that was warmed resembled more of a straight line, rather than convex shape. The profile of the meter that was both warmed and wetted

was primarily convex in shape, but with a slight concavity at the base. This profile differed from the others due to the large amount of plug-like shear and settlement that occurred at the base of the active layer during the summer during which treatments were applied.

12. The profiles are similar to those from meters and hose columns located upslope (Lewkowicz and Clarke, 1998) showing a decrease in movement at the base due to the effect of plug-like settling and shearing due to thaw of ice lenses either at the base of the active layer or at the top of the permafrost. A combination of frost creep (at the surface), gelifluction and shallow plug-like movement shape the upper section of the profile.

Several general conclusions can be made concerning the study of solifluction:

13. Near-surface measurements of solifluction do not provide an accurate examination of movement downslope at depth in an area of two-sided freezing. A much more accurate assessment of the importance of solifluction in terms of sediment transport is obtained by measuring movement through the entire active layer.
14. Mean annual movement values potentially hide a broad range of annual variability and do not allow for the examination of a relationship between climatic fluctuations and annual movement.
15. At this time, it appears that further study concerning current relationships in an area of two-sided freezing are required before palaeoclimatic inferences based solely on rates of solifluction can be made.
16. Long-term study, combined with physical modelling, will help in establishing patterns of spatial and temporal variability of solifluction as a result of climatic fluctuations.

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Appendix A

Movement of measurement blocks, 1993-1997:

Two examples of the interpretation process - Meters A and C, 26 cm

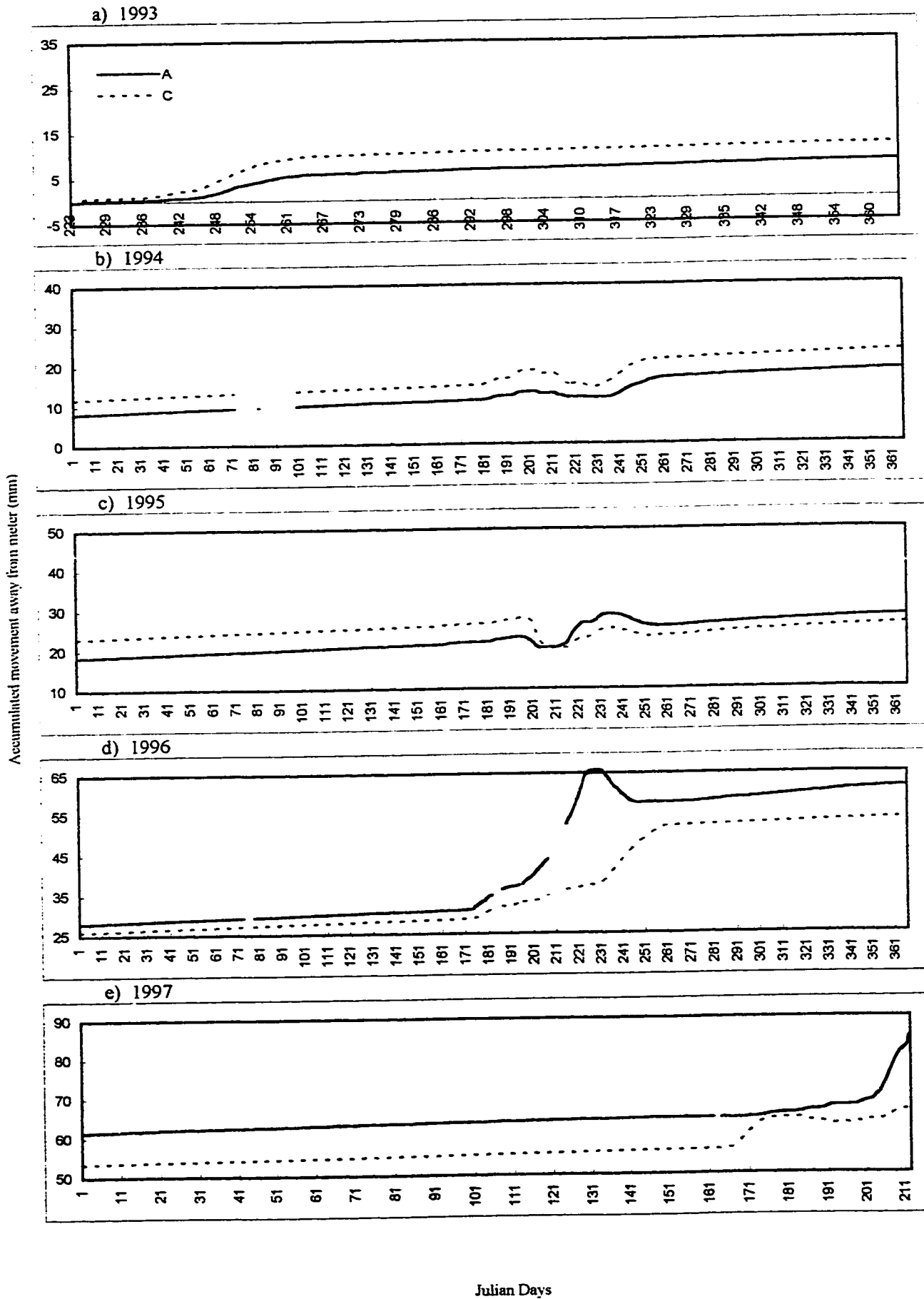
A detailed description of the interpretation of calibrated, angle-corrected movement data for two sets of measurement blocks is included. Between 1993 and 1995, the same climatic conditions affected the meters, and the blocks (both situated at a depth of 26 cm) responded in a similar manner. In 1996, meter A was warmed and wetted, while meter C was left as a control. The interpretation of both sets of blocks is included in order to illustrate the variation in movement data as a result of the treatments (Figure A-1). Except where specifically indicated otherwise, the description of movement relates only to the 26 cm measurement blocks at meters A and C.

Because the correction for the change in meter angle over the study period was applied on a daily basis throughout the year, an increase of .0044 mm in the movement data is apparent on days when no other movement was recorded. In the interpretation process, these increases were labelled as “forward tilt” and the movement was considered to be forward. In the interpretation below, forward tilt was assumed to take place when no other change in movement values was recorded.

The air temperature values used were mean daily figures from the record presented in the results.

The gaps in 1996 movement data were due to datalogger failure, however they were small enough that, with the help of the associated data, movement during these periods was interpolated.

Figure A-1. Calibrated, angle-corrected movement data, meters A and C, 26 cm, 1993-1997.154



Julian Days

Table 3-3 was reprinted from Chapter 3 in order to reiterate how the change in movement data varied depending on the measurement block location relative to the exit slot.

Table 3-3. Change in datalogger values according to block location and type of movement.

Block location	Datalogger values	Possible movement directions
above exit slot	increasing	forward, heave, forward/settlement
	decreasing	settlement
below exit slot	increasing	forward, settlement, forward/settlement
	decreasing	heave

Initial distance of the measurement blocks from their exit slot:

A26 - 28.1 mm, C26 - 13.1 mm

1993

- Day 218-219 - measurement blocks between 2 and 58 cm depth re-set at each meter, level to their exit slot; thaw depths approximately 60 cm.
- Day 223 - datalogger readings begin.
- Day 223-226 - air temperature increases to 7°C; 3 mm precipitation; active layer increases from approximately 58 to 63 cm; movement values increase; greatest increase in movement values occurs at depth; initial movement is settlement, therefore blocks now slightly below exit slot.
- Day 226-237 - air temperature drops to 2°C day 237; no precipitation; some re-freeze experienced at depth as the active layer depth decreases from approximately 63 to 61 cm; no change in movement values.
- Day 238-244 - air temperature falls to a level just above 0°C before climbing to 6°C on day 240, then falling below 0°C on day 244; no precipitation; freeze-back of the active layer from the base continues as the depth decreases to 57 cm; movement values increase; greatest increase in movement values occurs at depth; blocks move from just below to a position above exit slot; movement is heave.

- Day 244-263 - air temperature remains below 0°C; 5 mm of precipitation; freeze-back continues at depth; movement values increase; greatest increase in movement values occurs at depth; blocks are above exit slot; movement is heave as a result of fall freeze-back.
- Day 263-365 - no change in movement values.

1994

- Day 1-179 - air temperature rises as high as 14°C on day 178; active layer thawed to approximately 34 cm; no change in movement values.
- Day 180-193 - air temperature falls to 6°C by day 184, rises to 17°C on day 190, then starts to drop rapidly to 4°C on day 193; 4 mm of precipitation; active layer deepens rapidly to approximately 39 cm on day 183, where it remains until day 186 when it continues to deepen rapidly to 51 cm on day 193; movement values increase; movement decreases with depth; blocks are above exit slot; movement is forward.
- Day 194-198 - air temperature as low as 2°C on day 196, then fluctuates up and down between approximately 2 and 8°C; 3 mm of precipitation; active layer remains approximately 51 cm deep; movement values increase; the amount of movement appears to be similar through the active layer; blocks are above exit slot; likely that the warmth on day 190 released much moisture in the soil and it, combined with small amount of precipitation, percolated downward and refroze with cold temperatures on day 194; movement is heave from depth.
- Day 198-206 - air temperature rises to 16°C on day 203 then falls to 6° on day 206; 4 mm of precipitation fall on day 205; active layer becomes deeper until day 204, increasing to 57 cm, where it remains until day 206; relatively little change in movement values until day 203, when a sharp decrease in values begins, ending abruptly on day 206; movement occurs simultaneously through the active layer; blocks are above slot; movement is settlement which ceases when active layer depth becomes stationary.
- Day 206-211 - air temperature increases from 6 to 10°C; 6 mm of precipitation; slight deepening of thaw depths to 58 cm; no change in movement values.

- Day 211-217 - air temperature increases to 11°C on days 212 and 215 before decreasing to 6°C on day 216; 4 mm of precipitation; slight deepening of thaw depths to approximately 61 cm on day 215, followed by a slight freeze-back on day 217; movement values decrease rapidly with an abrupt end on day 217; movement begins and ends simultaneously through the active layer; blocks are above slot; movement is settlement which ceases when active layer depth experiences slight freeze-back.
- Day 217-224 - air temperature drops to 4°C then increases to 9°C; 3 mm of precipitation; active layer deepens slightly from 60 to 62 cm; virtually no change in movement values.
- Day 224-227 - air temperature decreases slightly to 6°C; no precipitation; thaw depths reach a maximum at approximately 61cm; movement values decrease; movement occurs simultaneously through the active layer; blocks are above slot; movement is settlement.
- Day 227-231 - air temperature drops to 3°C; 5 mm of precipitation; active layer indicates freeze-back as thaw depths rise to approximately 55 cm; no change in movement values.
- Day 231-260 - air temperature fluctuates between 1 and 5°C before rapidly dropping below 0°C on day 241; 13 mm of precipitation between days 231 and 240; active layer fluctuates slightly around 54 cm, before rapid freeze-back begins on approximately day 242; movement values indicate large increase; movement begins at depth; blocks are above exit slot; movement is heave as a result of fall freeze-back, with amounts of heave likely boosted due to precipitation received.
- Day 260-365 - no change in movement values.

1995

- Day 1-181 - air temperature rises as high as 10°C on day 180; active layer depth approximately 35 cm by day 181; no change in movement values.
- Day 181-196 - air temperature climbs gradually to 17°C on day 196; 3 mm of precipitation; active layer depth increases rapidly from 35 to 53 cm; blocks indicate slow gradual increase in value to day 196; movement begins at shallow depth and gradually becomes deeper; blocks are above slot; movement is forward.

- Day 196-210 - air temperature stays warm fluctuating between 9 and 19°C; no precipitation; active layer deepens from approximately 53 to 66 cm;

movement data:

A26 - very rapid decrease in values until day 204, then virtually no change in values between days 204 and 210; movement is settlement throughout - as level of blocks decreases relative to exit slot, movement values change from indicating a decrease to being relatively constant;

C26 - very rapid decrease in values until day 210; blocks remain above exit slot, therefore settlement is recorded as a decrease in movement values through entire period.
- Day 210-215 - air temperature fluctuates between 8 and 13°C; 1 mm of precipitation; active layer deepens slightly to approximately 68 cm;

movement data:

A26 - values show steady increase; blocks below slot; movement is continued settlement.

C26 - values remain almost unchanged; as blocks fall relative to exit slot, movement values change from indicating a decrease to being relatively constant; movement is continued settlement.
- Day 215-222 - air temperature remains between 9 and 11°C until after day 219, when it drops to 1°C on day 221; 2 mm of precipitation; active layer depth remains relatively constant until day 222 when a slight amount of freeze-back occurs; movement values indicate rapid increase, which lessens on day 222; blocks are below exit slot; movement is settlement and forward which decreases with colder temperatures at the end of the period.
- Day 222-233 - air temperature rises to 10°C on day 227 before falling to 2°C on day 233; no precipitation; active layer deepens slightly to approximately 69 cm on day 232; movement values increase very slowly until day 227 after which they increase rapidly, slowing on day 232; increase in movement begins and ends at the same time through the active layer; blocks are below exit slot; movement is settlement and forward which stops when air temperature decreases and active layer thaw ceases.
- Day 233-238 - air temperature decreases and falls below 0°C on day 236 before rising back to 4°C on day 238; 13 mm of precipitation on day 233; active layer indicates freeze-back with depth

decreasing from approximately 68 to 59 cm; no change in movement values; precipitation likely has little impact due to dry state of upper section of active layer as a result of low summer precipitation amounts.

- Day 238-252 - air temperature fluctuates between 2 and 6°C until day 246, after which it drops rapidly below 0°C; 8 mm of precipitation between days 246 and 247; active layer indicates small deepening to 65 cm until day 246, after which rapid freeze-back begins; blocks are below exit slot due to large amount of settlement; movement values decrease steadily; movement is fall freeze-back heave.
- Day 252-294 - air temperature drops from -4 to -32°C; movement values at C26 indicate a slight increase as blocks heave to a position higher than their exit slot.
- Day 294-365 - no change in movement values.

1996

- Day 1-172 - air temperature rises as high as 7°C on day 171; active layer depth approximately 30 by day 172; no change in movement values.
- Day 172-190 - air temperature drops from 6°C to just above 0°C on day 178, then climbs rapidly and fluctuates between 4 and 12°C - summer peak of 13°C reached on day 190; 25 mm of precipitation between day 175 and 178; active layer deepens rapidly from 32 to 51 cm; approximately 4 mm of settlement of ground surface around meters; movement values indicate increase; all blocks, whether above or below exit slot, indicate increase in value, therefore there must be an element of forward movement; movement appears to start at shallow level in active layer and to deepen gradually, likely promoted by precipitation; movement is forward and settlement.
- Day 190-195 - climatic treatments start; air temperature fluctuates between 5 and 11°C; 10 mm of precipitation between day 190 and 192;

A26: active layer deepens from 52 to 56 cm; movement values indicate a small increase; blocks below exit slot; only 2 mm of settlement of ground surface, therefore movement is primarily forward, triggered by precipitation.

C26: active layer deepens from 51 to 57 cm; movement values indicate a small increase; blocks above exit slot; only 2 mm of settlement of ground surface, therefore movement is primarily forward, triggered by precipitation.

- Day 195-205 - air temperature drops from 11°C on day 195 to 1°C on day 205; 14 mm of precipitation;

A26: active layer deepens from 56 to 62 cm; movement values indicate rapid steady increase; blocks below exit slot; 16 mm of settlement of ground surface; movement is settlement with a component of forward movement (all blocks indicate similar movement whether above or below slot).

C26: active layer depth remains approximately the same; movement values indicate small increase; movement appears to be slightly greater at depth; blocks above exit slot; 2 mm of heave of ground surface; movement is heave from depth, as precipitation percolates down to base of active layer and refreezes.

- Day 205-222 - air temperature fluctuates between 1 and 7°C with lows on days 214 and 215; 4 mm of precipitation;

A26: active layer deepens from 62 to 71 cm; movement values indicate rapid steady increase; blocks below exit slot; 37 mm of settlement of ground surface; movement is settlement and forward.

C26: Day 205-216 - active layer deepens slightly from 58 to 60 cm; movement values indicate increase; blocks above exit slot; 8 mm of heave of ground surface; movement is heave from depth as moisture percolates downwards and refreezes.

Day 216-222 active layer deepens from 60 to 63 cm due to slightly warmer air temperatures; movement values indicate small increase; blocks above exit slot; movement is settlement and forward.

- Day 222-230 - treatments end on day 222; air temperature falls from 6°C on day 222 to below 0°C on day 229; 7 mm of precipitation;
A26: freeze-back begins late in period as active layer depth decreases from 71 to 67 cm; movement values indicate steady increase until day 227 after which there is no change in movement values; blocks below exit slot; forward and settlement continue until day 227.
C26: freeze-back begins after day 227 as active layer depth decreases from 63 to 61cm; movement values indicate very slight increase until day 227 after which there is no change in movement values; blocks above exit slot; movement is forward and settlement.
- Day 230-260 - air temperature drops from -3 to -20°C; trace amounts of precipitation;
A26: active layer has rapid freeze-back; movement values indicate rapid decrease; blocks below exit slot; movement is heave.
C26: active layer has rapid freeze-back; movement values indicate rapid increase; blocks above exit slot; movement is heave.
- Day 260-366 - no change in movement values.

1997

- Day 1-167 - air temperature rises as high as 9°C on day 167; active layer depth approximately 32 by day 167; no change in movement values.
- Day 167-174 - air temperature rises to 13°C on day 172, then drops to 6°C by day 174; 4 mm of precipitation; active layer deepens rapidly from approximately 32 to 44 cm;
A26: no change in movement values.
C26: steady increase in movement values; movement begins simultaneously in upper section of active layer, then gradually deepens; movement begins only once thaw depth reaches 30-50 cm, when the active layer may have reached a critical lowering of stress, so that the soil starts moving together suddenly; blocks above exit slot; movement is forward as blocks both above and slightly below exit slot indicate an increase in movement values.

- Day 174-194 - air temperature rises to 14°C on day 177 and remains high until day 194 when it drops to 3°C; 7 mm of precipitation fall between days 192 and 194; active layer deepens rapidly between days 174 and 183 from 44 to 56 cm, after which the rate of thaw slows;

A26: very slow increase in movement values; blocks are below exit slot; movement is forward and settlement.

C26: Day 174-183 - very small increase in movement values; blocks are above exit slot; movement is primarily forward with a small amount of settlement.

Day 183-194 - decrease in movement values; blocks are above exit slot; movement is primarily settlement with a small amount of forward.

- Day 194-206 - air temperatures increases from 4 to 15°C; 9 mm of precipitation; active layer depths increase steadily from approximately 60 to 66 cm;

A26: movement values increase slowly, becoming much more rapid after day 202; blocks are below exit slot; movement is forward and settlement.

C26: movement values increase slowly; blocks are above exit slot; movement is forward and settlement.

- Day 206-212 - air temperature fluctuates between 7 and 15°C; 22 mm of precipitation; very small increase in active layer depths from 66 to 69 cm;

A26: movement values increase rapidly; blocks are below exit slot; movement is forward and settlement, due in large part to heavy precipitation on day 208.

C26: movement values increase steadily; blocks are above exit slot; movement is forward and settlement, due in large part to heavy precipitation on day 208.

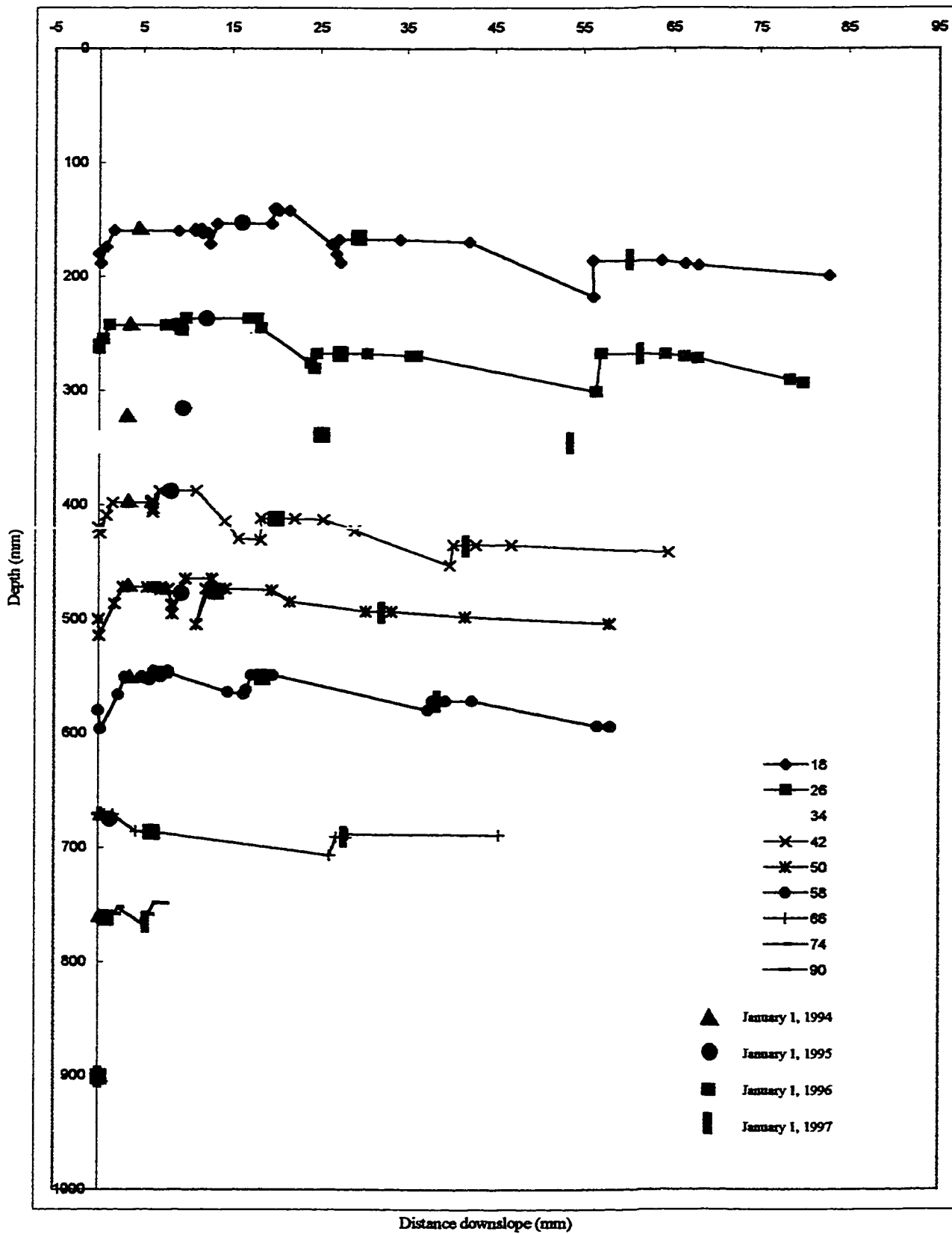
Final block positions:

A26 - 108 mm out from meter; 34 mm below exit slot; direct distance from exit slot to blocks - 113 mm.

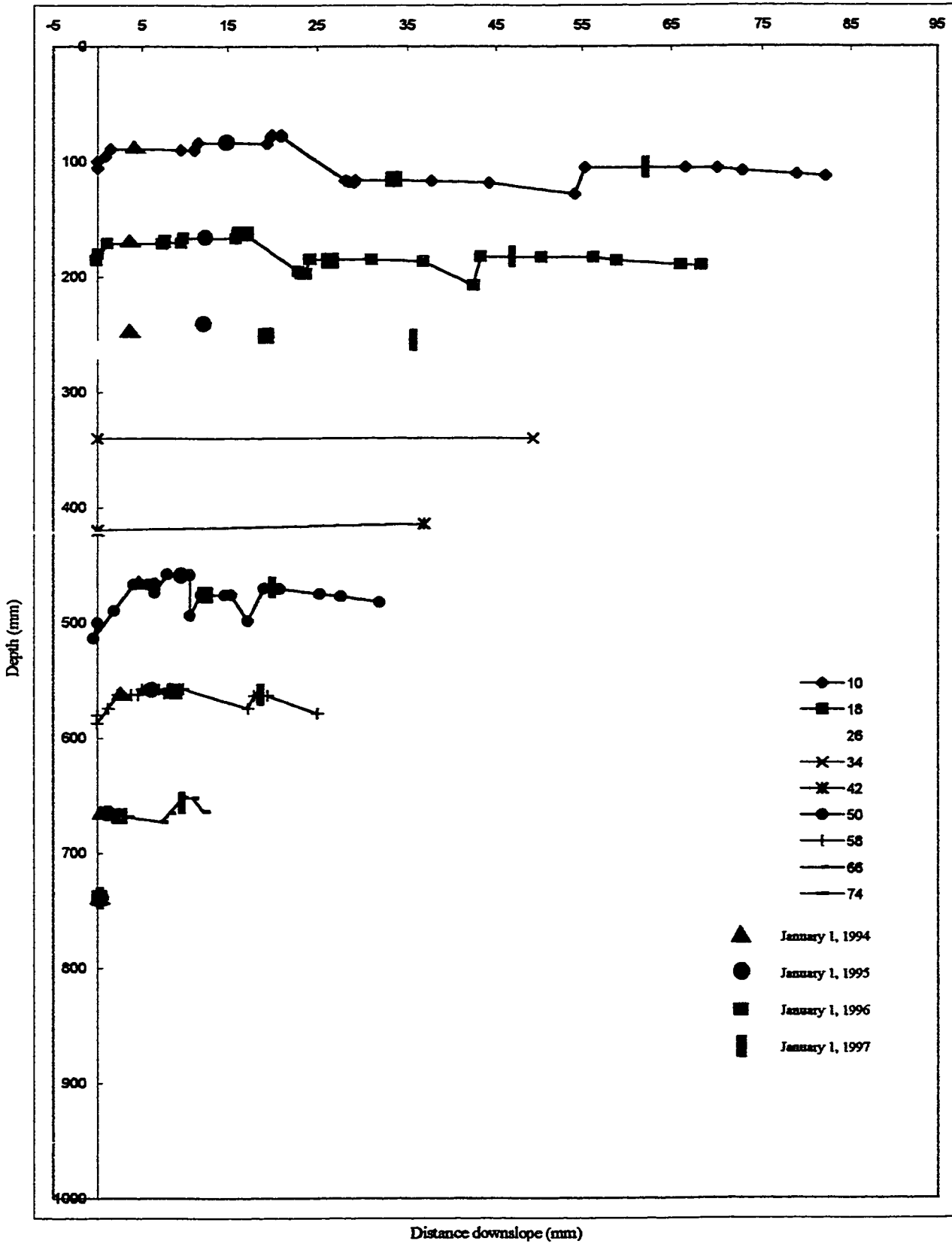
C26 - 81 mm out from meter; 1 mm above exit slot; direct distance from exit slot to blocks - 81 mm.

Appendix B. Movement of measurement blocks through soil profile,
August 1993-August 1997.

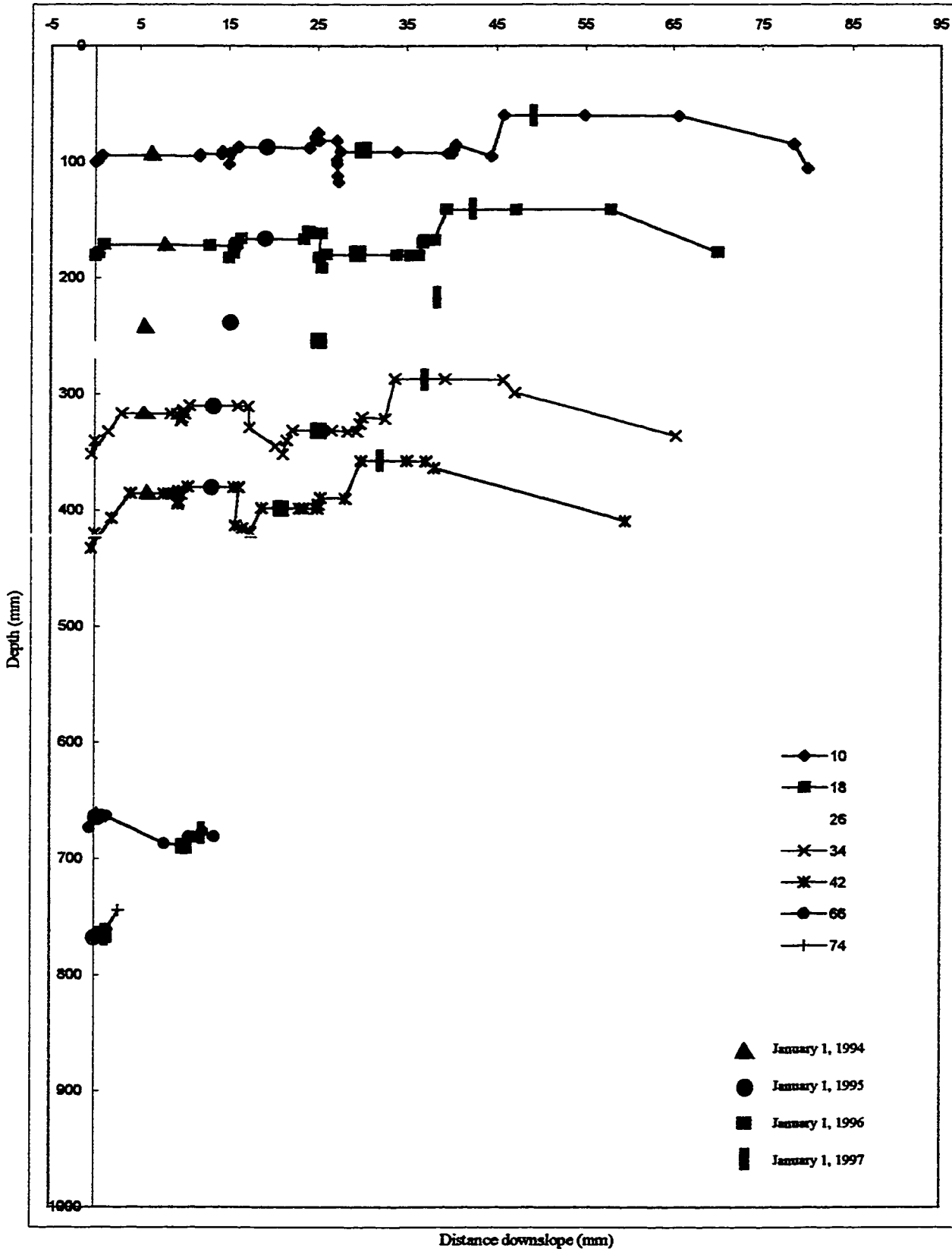
a) Meter A (warmed and wetted)



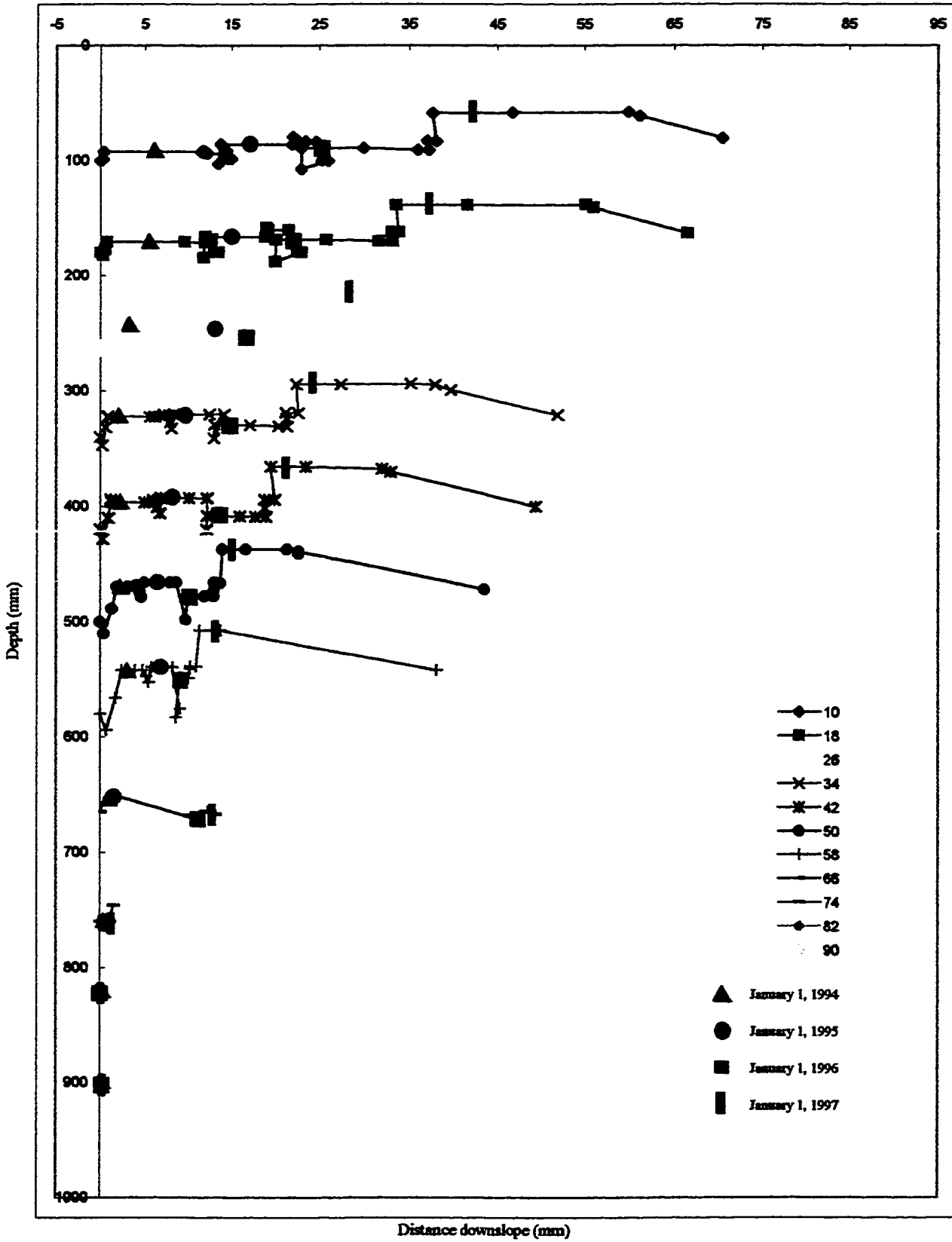
b) Meter B (warmed)



c) Meter C (control)



d) Meter D (wetted)



e) Meter E (cooled)

