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UNIVERSITY OF ALBERTA

Stratigraphy, Sedimentology and Microclimate of Turf-Banked Solifluction Lobes, Macmillan Pass, NWT.

BY

© T. Monique McIlhargey

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment for the degree of **Master of Science**

DEPARTMENT OF GEOGRAPHY

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DEPARTMENT OF GEOGRAPHY

January 27, 1993

Monique McIlhargey
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Dear Monique:

This letter will serve as formal permission for you to reproduce Figure 5.1 (page 62) from my dissertation as part of your M.Sc. thesis. As I indicated in my e-mail message of yesterday, the figure was used within a paper presented in <u>The Albertan Geographer</u> and you may wish to cite that paper rather than dissertation. Up to you. Regardless, thanks for [illegible] permission.

I have also included a recently published review of dated solifluction lobe deposits in North America. Note that these refer in particular to sites where it is possible, or almost possible, to develop activity chronologies. Hope it is some use. The spare copy is for Peter.

Have you any plans to make a presentation at the WCAG in Kamloops come March? If so then perhaps you can tell me more about your research and findings. Peter has told me a little but I would be delighted to hear the whole story. Why not make a presentation?

Good luck with your writing. It must be going well, if you have begun to worry about your illustrations.

Yours sincerely,

Dan

Dan Smith

ABSTRACT

Various physical and climatological parameters were investigated on three turf-banked solifluction lobes 13 km east of Macmillan Pass, NWT. Sedimentological and stratigraphic characteristics were examined on three lobes at 1650 ± 20m a.s.l. Sedimentological analyses of lobe material were compared to those of material from a control site located within 300m of the lobe sites. Lobe sites and parent slope materials were compositionally similar, however, reworking by periglacial processes produced different stratigraphic sequences in the lobes. The White River tephra deposit, radiocarbon dated at 1250 BP (Lerbekmo *et al.* 1975), was buried in the lobes and was a chronological marker. Sediment reworking was confirmed by analyses of macrofabric in the horizons above the tephra. Based on these analyses, one lobe was deemed to be inactive. The other two lobes were predominantly the result of gelifluction.

East-facing sites experienced more extreme temperature swings than those on north-facing slopes. Parent slopes responded more quickly to changing atmospheric conditions than did the solifluction lobe material. The lower slope gradient relative to the parent slope, moisture retention, and thick vegetation on the lobes have established a positive feedback perpetuating lobe development. Climatic conditions over the 1992 - 93 period were not conducive to periglacial mass-wasting processes capable of generating solifluction lobes of the dimensions of the study lobes. It is hypothesized that the lobes developed under climatic conditions during the Holocene and have been active at some time between 1250 BP and present. An experimental remote sensing technique utilizing ultra sonic depth sensors to record changes at the lobe front was evaluated. Systematic and random error of the sensors produced inconclusive results.

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I would like to thank Pete Kershaw for giving me the opportunity to do research in northern Canada. I would like to thank my committee for believing in my ability at a critical time. I am especially indebted to Martin Sharp, who, through his patience, guidance, and many edits, oversaw the completion of this thesis to its final format. As well, Dave Halliwell has been the source of many fruitful discussions on technical wizardry and microclimate and has always made the time to help me when I have been in an academic fix. Thanks for all your help.

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Goals in life are not usually achieved entirely as a solo effort. From the very beginning, my parents have believed in me and loved me. Mom and Dad, Thank-you. You have always encouraged me to do my best, no matter what it is I was doing. Thanks Dad, for always answering my seemingly long string of Whys? since I was little and encouraging me to have an inquisitive mind. At home, Smudge and Clover have lightened some of the darkest days by just being themselves. By far, the person most responsible for making me stick it out to the end was my husband Jim. When things got stormy, you were the eye of the storm. Your love, patience, hugs and support have help me endure the roller-coaster ride. Thanks Jim.

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GENERAL INTRODUCTION

BACKGROUND

Purpose

Mass wasting in periglacial environments is an important geomorphological agent. Since A.L. Washburn's (1967) benchmark paper on the phenomenon in Greenland, there have been numerous attempts to quantify solifluction and related processes using various techniques (cf. Benedict 1970; French 1974; Gamper 1981; Eggington and French 1985; Smith 1985; and Price 1991).

North American studies of mass wasting have been carried out in the Arctic (Dyke 1981; Mackay 1981; Friend 1988), Quebec (Morin and Payette 1988) Rocky Mountains (Benedict 1970, 1976; Smith 1985), Ruby Range, Yukon (Price 1970, 1971, 1991), and Alaska (Reanier and Ugolini 1983). The purpose of this thesis was to document the character of solifluction in the Selwyn Mountains, NWT, Canada. The aims of the investigation were twofold.

Chapter 2 analyzes solifluction lobe sedimentology and stratigraphy. Various physical characteristics of the sediment were analyzed to aid interpretation of fabric data. Macrofabric was analyzed using the eigenvalue method. While this is the standard method for glacigenic fabric analyses, the method has received little attention with regard to periglacial sediments. While many studies have used various dating techniques to determine past rates of movement (cf. Benedict 1970; Smith 1985; Morin and Payette 1988), only a few studies have tried to determine *past* processes (eg. Harris 1972). In this chapter, physical characterization of the sediment and fabric analysis determined possible genesis of the turf-banked forms under study.

Chapter 3 compares the microclimate of three study lobes and a control site to provide a microclimatic record of present site conditions. Subsurface temperatures of the parent slope and lobes were investigated. Previously used methods to measure movement i.e. stone markers, foil pillars, dowel pillars and inclinometer tubes have various errors associated with them. (cf. Anderson and Cox 1978; Smith 1993). In an effort to reduce error, a new remote sensing distance sensor was employed to monitor the movements at the front of the lobes. An evaluation of the experimental non-invasive technique is included. Initially, correlation between movement and microclimate was to be examined, however, problems with the movement data set prevented this.

Together, the two chapters provide physical and climatic evidence to characterize solifluction movement in the Macmillan Pass area. Despite the lack of reliable contemporary movement data, the subsurface temperature measurements and physical characteristics of the sediment presently at the site provided evidence of processes presently at work. The aim was to compare contemporary processes to those active in the past as manifested in the clast macrofabric.

Terminology

The periglacial terminology and corresponding definitions used throughout the thesis are those proposed by Washburn (1967) and subsequently adopted by Harris (1981) and Smith (1985, 1987a,b,c, 1992). Because the study area is located within the discontinuous permafrost zone (Kershaw and Kershaw 1983), presence or absence of permafrost as opposed to merely deep seasonal freezing is difficult to determine. In addition, it has been hypothesized that the presence of solifluction sheets - that is, broad expanses of debris moving downslope over a wide area as opposed to solifluction lobe forms which are lobate or linguoid in shape - is an indication of widespread permafrost while lobe forms occur in both permafrost and non-permafrost sites (Harris 1981). Therefore, solifluction is used in its broadest sense, that is, as it was originally defined by Andersson (1906)

> "This process, the slow flowing from higher to lower ground of masses of waste saturated with water ..., I propose to name solifluction"

The term solifluction encompasses a number of geomorphic processes and therefore, features are polygenetic. Presence of ground ice (whether seasonal or permanent) is required for certain mechanisms to work. A complex interaction between frost creep, gelifluction (or flow) and plug-like flow or slip results. Separation of these components is a much simpler task in theory than in practice. Frost creep was first described by Washburn (1967) as

> "ratchet-like downslope movement of ground and subsequent settling upon thawing, the heaving being predominantly normal to the slope and the settling more nearly vertical".

Frost cycles produce continuous displacement of soil. Frost action can be either perennial, seasonal or diurnal. The second component, gelifluction, is thaw-induced downslope flow of soil. Water released upon thawing coats individual soil particles reducing the frictional strength. This causes an overall reduction of shear strength and failure results. Plug-like flow (Mackay 1981) is movement of a coherent plug over a thin basal shear zone usually due to the thawing of an ice lens at the base of the active layer. Such slip is episodic.

STUDY SITE

Background

This study was conducted at a site 13 km east of the Continental Divide, on the border between the Selwyn and Mackenzie Mountains of the Northwest Territories (63°14'N ; 130° 02'W) 4 km south of the Canol Road (Figure 1.1). The study lobes where located southwest of the Tsichu River Airstrip and abandoned meteorological station (1974-1982).

Three turf-banked solifluction lobes and one control site at 1650 ± 20m a.s.l. were chosen. The control site was a fluvial terrace altitudinally located 20-40m below the study lobes. The terrace was largely comprised of imbricated gravels with little matrix. It was similar in morphology and size to the study lobes and thus, it was hypothesized that it would be subjected to a similar micro-environment. Climatic variations were thought to be minimal because the control was located within the same altitudinal belt and within close proximity to the

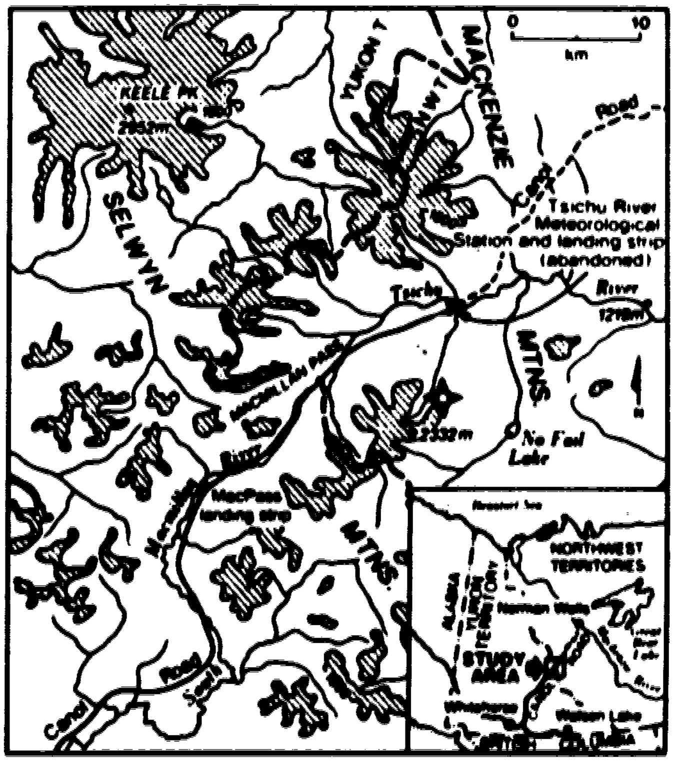


Figure 1.1 Location of the study area located along the Canol Road, Macmillan Pass, Northwest Territories. ◆ indicates site of study lobes.

study lobes. Selected study lobes displayed minimal differences in elevation, morphological development and slope gradient. Surficial materials were diamicton and glacially reworked felsenmeer.

The study area falls within the boundary of the White River east lobe tephra deposits (Lerbekmo pers. comm. 1993). This event has been ^{14}C dated with various organic samples found immediately above and below the tephra deposit. The eruption has been determined to occur between 1175 and 1390 BP with a mean of 1250 BP (Lerbekmo *et al.* 1975). Stratigraphic location of the tephra within the soil column provides a readily available chronostratigraphic reference horizon in the study lobes and on the parent slopes. Presence of a surficial tephra horizon as well as a tephra deposit at depth on the lobes confirms deposition has occurred above the buried horizon since 1250 BP. Soil columns with only a surficial tephra layer have not been overridden within the last 1250 years although the areas themselves may be moving downslope. While solifluction may have been present throughout the Holocene, the lack of organic layers below the buried tephra layers prohibits any inferences being made about movement and deposition of slope material prior to 1250 BP.

Two east-facing lobes, a north-facing lobe and a north facing control site were studied. Different orientations were chosen to determine if there were any microclimatic variations which in turn, affected moisture content. Moisture content has a significant effect on lobe morphology (cf. Washburn 1967, 1979; Harris 1981). The lobes were identified as East I (EI) and East II (EII) (east-facing solifluction lobes), North I (control) and North II (NII) (north-facing solifluction lobe). Study sites were located within 300m of each other (Figure 1.2). On each lobe, the long axis, width, parent slope angle, riser angle and tread angle were identified (Figure 1.3). Lobes of various sizes were located on moderately steep slopes (Table 1.1). Both North II and East II were the leading, downslope portions of a solifluction sheet (Figure 1.4 b,d). East I was an individual lobe form. The control site (fluvial terrace) was topographically similar in size and shape to EI (Figure 1.4 a,c). A gully collected water immediately upslope of the North II lobe and wound around eroding into the west side of the lobe. Water continued to flow throughout the 1992 summer season. An ephemeral stream was present at the East I lobe up to 15 June but had dried up by 23 July when the site was again checked.

Vegetation

Vegetation in the study area varied from lichen-heath to forb-meadow tundra. East II and North II were dominated by herbaceous vegetation. Graminioids, *Carex* spp., *Eriophorum* spp., *Geum* spp. were present. Vegetation of the control and East I tended to include more woody plant types composing a sparser cover than on the other study lobes. Small-scale frost sorting was evident on tread surfaces. *Cassiope tetragona* was the dominant species while *Salix* spp. and *Betula glandulosa* were also present at East I and North I. East I and the control were snow free on the tread surface by 7 June 1992. NII and EII were

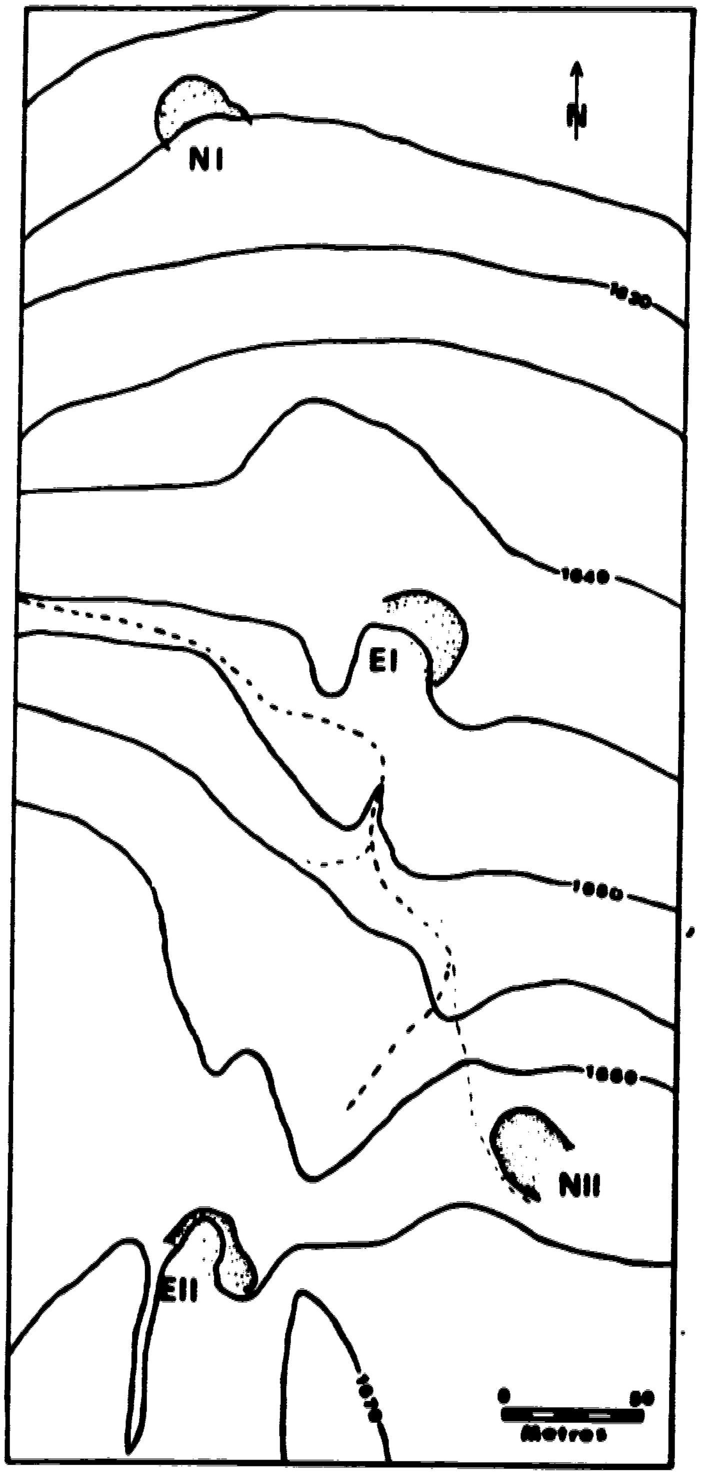
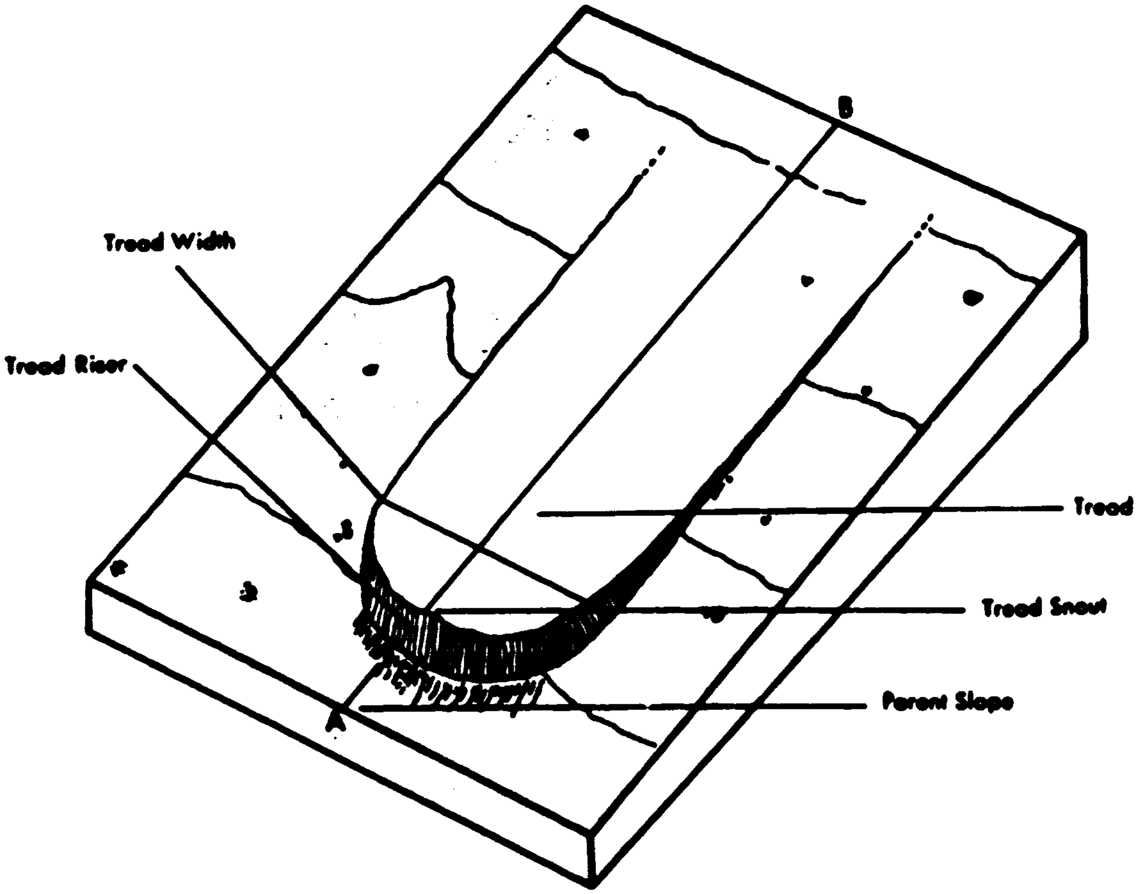


Figure 1.2 Relative location of the study lobes and the control site located 1650 ± 20m a.s.l. Dashed line indicates location of ephemeral stream.

a) Solifluction Lobe Terminology



b) Longitudinal Section

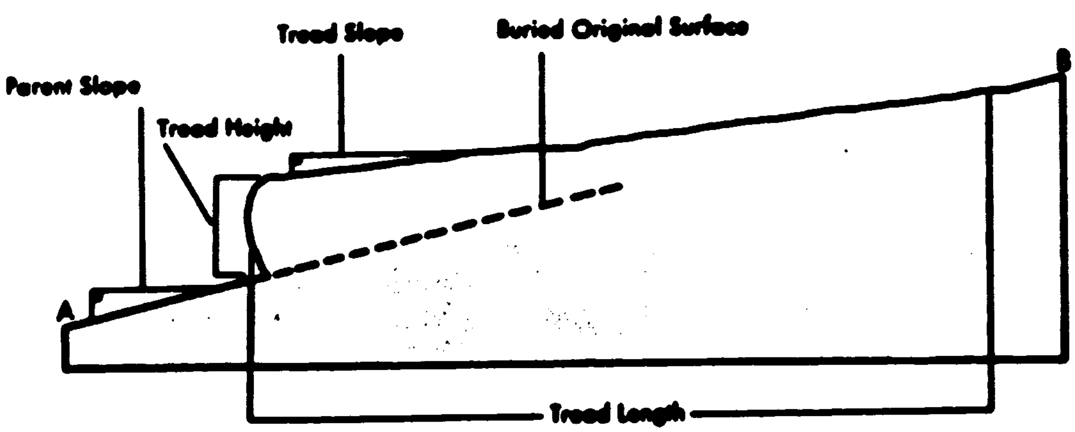


Figure 1.3 Different morphological compenents of solifluction lobes. Reproduced with permission from D. Smith (1985).

Site Label	Parent Slope °	Riser Angle °	Tread Angle °	Length metres	Width metres
Control (NI)	23	45	20	11.5	22
North II	26	31	9	18.4	34.5
East I	16	58	11	12.9	27.0
East II	14	44	21	16.8	27.0

Table 1.1 Morphometric parameters of study lobes and control site.

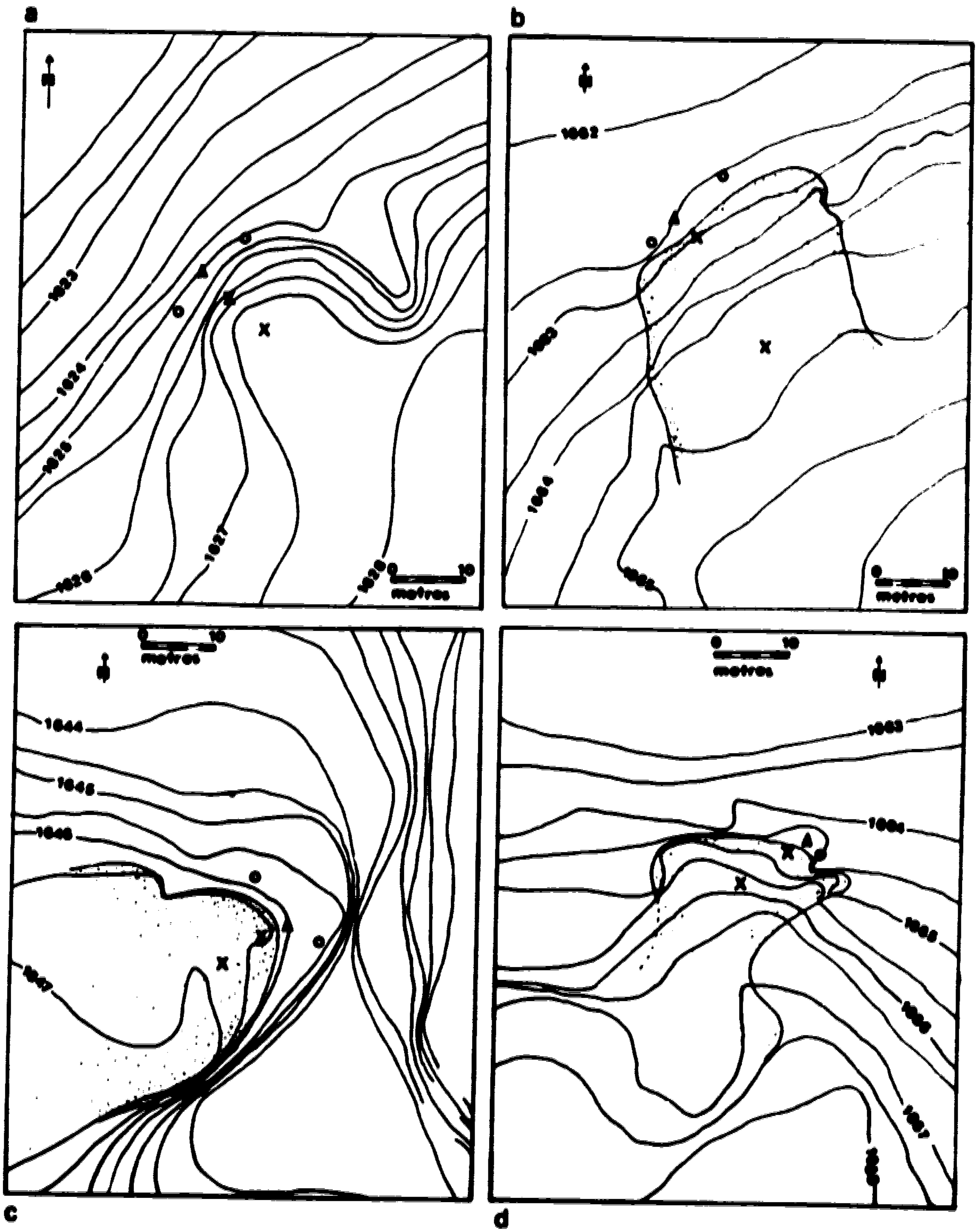


Figure 1.4 Individual topographical form of: a control site b North II c East I d East II. Contour interval .5m. ▲ = microclimate station ● = location of UDG x = subsurface temperature points. Maps were produced with a plane table.

not snow free until sometime after 15 June 1992. Vegetation patterns correspond to the areas of snow accumulation. Areas of late-lying snowpack had higher biomass than those that were exposed to the elements.

Climate

The area is classified as a subarctic alpine area (Kershaw 1976). Climatic data were collected by AMAX with the assistance of Atmospheric and Environment Services Canada from October 1974 to August 1982. Mean annual temperature for this period was -7.7°C. Frosts occurred throughout the growing season; however, mean daily temperatures were above freezing from late May to mid-September. Average annual precipitation in the valley was 490mm with snowfall of 294cm (Kershaw and Kershaw 1983).

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CHAPTER TWO

STRATIGRAPHY AND SEDIMENTOLOGY OF TURF-BANKED SOLIFLUCTION LOBES

INTRODUCTION

Three dimensional analyses of macrostructure in various glacigenic depositional environments have been used to infer palaeoflow direction and possible depositional processes involved (eg. Mark 1973; Mills 1977; Dowdeswell and Sharp 1986). Comparable systematic analyses have not been used to document the character of solifluced material. While many studies have determined past rates of movement and present processes (eg. Alexander and Price 1980; Caine 1981; Smith 1985; Price 1991; Matsuoka and Moriwaki 1992), little has been done to determine processes that have contributed to the present solifluction lobe morphology. Analysis of solifluction micro- and macro-fabrics has usually been limited to orientation data only (Harris and Ellis 1980; Harris 1981) or alternatively, dip data have been analyzed separately (Benedict 1970, 1976). With a combined analysis of orientation and dip measurements, probable genesis of solifluction lobes can be inferred.

Using the terminology of Smith (1985), solifluction is the combined result of frost creep and gelifluction (flow). Mackay (1981) considers 'plug-like flow' a third process operating on periglacial slopes. The different solifluction processes should produce identifiable fabrics because the processes cause reorientation in one distinctive direction. Frost heave mechanisms cause the reorientation of clasts perpendicular to the freezing front. As the freezing front progresses down into the soil, freezing penetrates below the stone faster than the surrounding soil because the rock material is a better heat conductor. Decreased pore water pressure near areas of freezing causes moisture to be drawn to the base of the stones from the surrounding soil. Accumulation of ice pushes the stone in the path of least resistance, upwards. As thawing occurs, fines fill the void left by the thawing ice at the base of the stone and the stone will maintain its frost-heaved position (eg. Taber 1930; Beskow 1935). Therefore, downslope movement dominated by frost creep would cause the long axis to be oriented vertically or near-vertically without a preferred orientation.

Gelifluction, the slow flow of thawed water-saturated soil with reduced or no shear strength, results in deformation by shear. Gelifluction occurs when moisture contents are sufficient to allow the soil to deform plastically (Washburn 1967). Ellipsoidal objects will be rotated at different rates as the object is transported in a viscous fluid. The rotation rate is lowest when the object is oriented parallel to the shear plane (Glen *et al.* 1957). Therefore, it is most likely to find the long axis of a clast parallel to the shear plane. Shear stress imparted on the matrix during gelifluction would result in orientation of the long axis parallel to the local slope.

It has been well-documented that solifluction movement decreases with depth. Profiles of movement range from concave downslope to convex downslope (Washburn 1967; Benedict 1970; Harris 1972; Smith 1985; Price 1991).

Segregation ice and the thickness of vegetation have been identified as the two factors which control profile form (Price 1991). Maximum shearing is likely to occur where segregation ice is thickest prior to thaw (Harris 1981).

For comparative purposes, fabric analysis was restricted to the top 20cm of soil. This was done despite higher rates of shear strain at depth which would have a great effect on reorientation in regard to gelifluction. Analysis was restricted to the top 20cm because: 1) pebbles from different lobes were surrounded by similar matrix (less than 2.00mm) material, and 2) reorientation by frost creep would be concentrated in the uppermost layers of the soil column. Washburn (1967) found that frost creep accounted for 75% of lobe develpment in Greenland. Therefore, it was important to document this evidence in the macrofabric. Surface layer moisture contents in mid-summer were much higher than those in the desiccated B and C horizons. The fine-grained soil of the Ah horizon would entrain water which had likely migrated to the freezing front the previous fall. Hence, segregated ice development and subsequent thaw would be highest in the surficial layer. Discrete differences in preferred orientation and dip of the clasts at a shear zone would be an indication of plug-like flow (Nelson 1985).

The physical characteristics of the frozen ground within which frost heave, gelifluction and slip occur provide key information to determine which process is likely to prevail. Differences in the fabric reflect small variations in texture and lateral inflow of water (Van Vliet-Lanoe 1985). To aid interpretation of the fabric information, several physical characteristics were investigated. Trenches were dug along the long axis of the lobe to expose the internal stratigraphy.

Stratigraphic logs were made of the exposed soil horizons and the tephra horizon was traced throughout the length of the lobes. This ash, radiocarbon dated at 1250 BP (Lerbekmo *et al.* 1975), provides a chronological marker. Presence of buried ash - representing a former land surface - divides the facies above the tephra from those below. Sediment above the marker layer has been deposited by some mass-wasting process during the last 1250 years.

Increased organic content at depth indicated incorporation of organic material as the lobe overrode the former land surface. This provided further evidence of recent movement. Sufficient moisture has been reported as the most important limiting factor for solifluction to occur (Washburn 1967; Benedict 1970). Therefore, soil samples were collected from all horizons in all the soil pits to determine if there were any significant moisture differences among the three study lobes and the control site.

Gelifluction is strongly influenced by grain-size (Washburn 1967). It was therefore necessary to determine the particle size of the matrix which was defined as the less than 2.00mm fraction. Fine sand, silt and clay-size particles have large surface areas for a given volume allowing large quantities of water to be adsorbed. Conversely, coarse sand-size particles are too large to allow close packing. Surface area is reduced and the large voids allow much more drainage. This has the combined effect of reducing moisture content in these types of soils.

Proportions of various sized particles are related to the plasticity index which determines how a soil will behave under certain moisture conditions. The liquid limit marks the upper moisture boundary that a soil will behave platically. Above the liquid limit, soil moves like a viscous liquid. The plastic limit is the lower moisture boundary of plastic deformation. Below this limit, the soil no longer behaves as a plastic material. The plasticity index is the difference between the upper liquid limit and lower plastic limit. It is an indication of the range in moisture contents at which soil can deform plastically. Gelifluction can occur at any moisture content above the plastic limit. Below these limits, frost creep can still be an important clast reorientation mechanism. Frost creep preferentially moves large clasts forward unlike gelifluction, which does not discriminate between sizes.

Water retention due to the lack of drainage in finer grained soils provides the necessary moisture for saturated flow (gelifluction) and frost creep. Increased moisture has been documented to cause increased rates of movement (Jahn 1967; Gamper 1981). Moisture availability during the autumn has been cited as the primary factor in soil movement rates in the Colorado Front Ranges (Benedict 1970). However, which process is contributing to the increased movement documented at some sites compared to other similar sites (gelifluction or frost-creep) is still debated (Smith 1987). With the combined analyses of macrofabric and physical characteristics, the process that has dominated deposition of sediment in the lobe form may be inferred. This study assesses the present geomorphological characteristics of the site and relates these characteristics to the macrostructure of the three solifluction lobes.

METHODS

Field Methods

Trenches approximately 1.5m in length, 0.75m in width and deep enough to expose all soil horizons were dug approximately 3m east of the long axis on North II and 3m south of the long axis on the east-facing lobes. Trenches were dug approximately 5m west of the long axis on the control site. One trench was dug on the prolobe area, one was dug into the riser and at least one was dug into the tread. Depending on the morphology of the lobe, additional trenches spaced equally apart were dug further upslope on the tread. The trenches continued down into the parent material until no further evidence of weathering zones was present. Full descriptions and depth of each horizon were recorded. Soil samples were collected for laboratory analyses from all horizons in each pit in the period 5-7 August 1992 for laboratory. Clast density was estimated volumetrically using criteria outlined by Day (1983:72).

Orientation data were collected from three trenches on each study lobe. Trenches located on the riser, midtread and tread were chosen systematically to allow comparison of data between similar parts of the three lobes. Each sample consisted of 50 pebbles located within the near-surface layer (0-20cm) of each trench. Clasts with an a-axis between 2 and 30cm with an a:b axis ratio of 2 or greater were used. Azimuth (A) of the long axis and dip (D) of each clast were recorded with a Brunton compass. Sources of error associated with Brunton compass measurements include: 1) local magnetic attraction of stones 2) compass out of level 3) weak needle magnetism and 4) problems determining the long axis of stones. Therefore, care must be taken when interpreting the data.

Laboratory Analyses

Soil samples were analyzed for pH using Fischer litmus paper. Samples were air dried to determine moisture content using a dry weight basis. Organic content was estimated by loss on ignition at 550°C for four hours (McKeague 1978). Determination of sand and silt-size proportions was completed with the use of dry sieving followed standard procedures (American Society for Testing Materials. 1985: D422-63). The fine silt and clay-size fraction was determined with a Sedigraph 5100. Liquid and plastic limits were determined using the <425μm fraction according to standard procedures (American Society for Testing Materials. 1985: D4318-84).

Data Analysis

Analysis of Variance (ANOVA) was performed on some of the physical characteristics of the sediments to determine if any significant differences were present in two contexts:

1) spatially within the same soil layer in the different lobes

2) between different soil layers within the lobes

Differences among the lobes would indicate that lobes may have evolved differently. Significant differences between soil horizons indicate a horizon upon which shearing and/or deformation would likely occur. Beskow (1935) empirically derived classes of frost susceptible and non-frost susceptible soils. Generally, he determined that soils heaved differently depending on particle size distributions. Frost action increased rapidly from zero in coarse sands to a maximum in the fine silts. As the clay content is increased, frost action slowly declines. This definition is quite broad and its has been found that soils that do not meet this criterion are frost susceptible. Because all of the soils under investigation fell within Beskow's (1935) frost susceptible range, relative frost susceptibility was estimated to gain an understanding of soil behaviour. Caine's (1978) criteria to estimate relative frost susceptibility were used. Caine determined that sand content is inversely proportional to frost susceptibility. Therefore, analysis of variance was done on the sand-size fraction to determine if there were any significant differences in frost susceptibility among the sites. In addition, ANOVA was performed on the moisture contents as this variable affects the behaviour of the soil. Finally, analysis of variance was done on the organic matter content to determine if spatial differences were significant.

Fabric data were analyzed using the eigenvalue method according to procedures outlined by Nelson (1985). This method is advantageous because it is three-dimensional and accounts for both orientation and dip instead of treating the two measurements separately. The analysis provides information about any preferred orientation and the strength of the clast fabric. Second, this method has been used by Nelson (1985) in periglacial fabric analysis and shows promise as a means to better identify such fabrics. Raw data were plotted on Schmidt nets and contoured at 2 standard deviations (Kamb 1959). Azimuthal values were then rotated such that "north" was in the downslope direction. To ensure a standard plane of reference, dip values were rotated into the local slope inclination as suggested by Nelson (1985). The eigenvalue method treats individual observations as unit vectors. The orientation matrix is derived by summing the matrices which are the product of each measured axis and its transpose in cartesian coordinates. The eigenvectors (V_1, V_2, and V_3) of this matrix correspond to three orthogonal principal axes of the data sample. Eigenvector V_1 is the direction of maximum clustering while V_3 refers to direction of minimum clustering. The normalized eigenvalues (S_1, S_2, and S_3) summarize the fabric strength or degree of clustering about the respective eigenvectors. Testing for randomness shows that when $n=50$ S_1 values greater than 0.51 and S_3 values of less than 0.17 are significantly different than random at the 95% confidence interval. This method has several advantages over other circular tests pertinent to this study, namely:

1) it is rotationally invariant with respect to orientation measurements. That is, the test outcome will not vary if the data are rotated. Azimuthal values will change but the statistics associated with the direction of maximum clustering will remain the same.

2) it is independent of the shape of the distribution. However, care must be taken in interpreting results because the method cannot cope adequately with some multimodal distributions (Woodcock and Naylor 1983). Comparison of the data on an equal area plot to the computed eigenvector will allow identification in situations where this would be a problem (Woodcock 1977).

For a more detailed discussion of the advantages and disadvantages of equal area zonal tests and circular parametric tests, the reader is referred to Woodcock and Naylor (1983).

With the use of the eigenvalue method, analysis of the preferred orientation and dip simultaneously allowed inference of processes involved in the reworking of material. Strength of the fabric as well as the shape of the distribution provide insight into the processes at work. The shape parameter is a measure of the distribution. Mathematically, it is $((Log\ S_1/S_2)/(Log\ S_2/S_3)$. Shape values ≥ 1.0 are clusters while values from $0 < 1.0$ are girdles. Strong clusters indicate one dominant orientation. Girdles would indicate similar dips but more variable orientations. Benedict's 1970 study determined the path the material was taking as it progressed downslope. It was hoped that with macrofabric information, the depositional environment under which the sediment was deposited could also be inferred. Physical characteristics of the sediment and lobe morphology had to be examined to aid interpretation of *how* the pebbles were moved downslope.

RESULTS

Stratigraphy

Soil horizon development varied among the lobes. Within each lobe, horizon development was parallel to the local slope through the length of each lobe.

Tephra was absent in the soil profile at the control site (Figure 2.1). The lack of this horizon indicates that following deposition, the tephra was eroded. Surficial material within the control site consisted of weakly-imbricated fluvial gravels (Figure 2.2). The imbricated gravels and lack of matrix less than 2.00mm indicate that removal of the tephra was by fluvial action. Pedogenic development was poor, usually limited to a shallow Ah layer superimposed on the imbricated gravels. The gravel layer prevented further excavation into underlying layers. The fluvial gravels were markedly different from the sediment found in the lobe sites.

Material in the lobes contained larger quantities of fines, tephra layer(s) and fewer pebbles than the control site. Pedogenic development was more advanced with the expression of a B horizon at some locations (Figure 2.3).

The tephra layer was near the surface at the prolobe and upper tread areas but was buried deeper at the riser/midtread area of North II and East II. Soil development was most advanced in these two lobes.

Two full soil profiles were present in the riser/midtread positions on North II. Buried humus was present. Unfortunately, due to the lack of financial

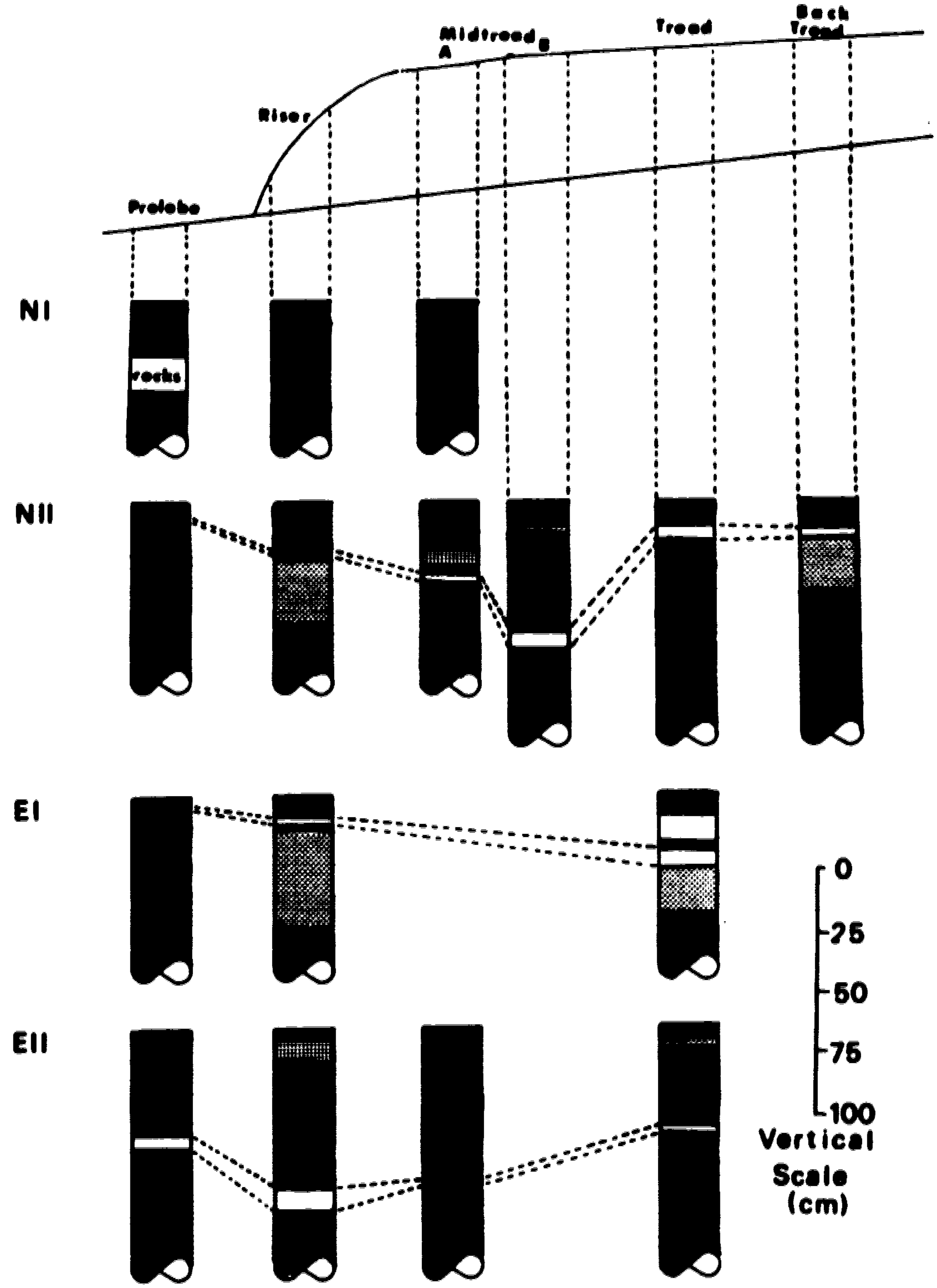

Figure 2.1 Longitudinal profile through solifluction lobe. Soil layer development within soil pits. Dashed line traces location of tephra deposit throughout length of lobe. □ = Tephra ■ = Ah ▒ = B ■ = C

Figure 2.2 Example of gravel - cobble material found within the control site.

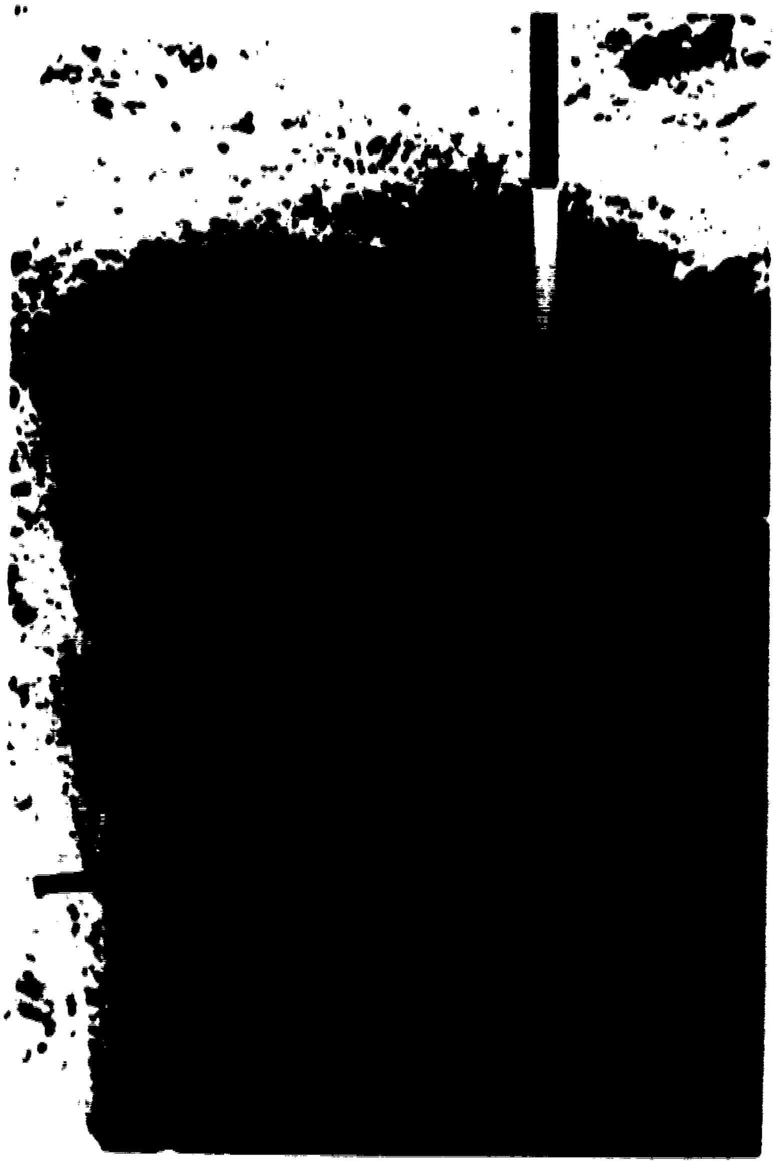

Figure 2.3 Well-developed soil horizon found in North II site. Notice layering between Ah, tephra, B and C horizons at this locale. Arrow indicates location of deformed tephra layer.

resources, dating of any of the buried organic material at this site was not possible. This lobe was the largest of those studied. It was located on the steepest slope (26°) but had the lowest riser (31°) and tread (9°) angles. Pits had to be sunk at least a metre on this lobe to reach unweathered material. Therefore, a large volume of sediment has been deposited on top of the parent slope at this site during the last 1250 years. North II consistently had the thickest surface organic accumulations.

Stratigraphically, there were differences in the sediment at the East II site. Pedogenic development was more advanced on the lobe than on the prolobe. The prolobe area consisted of a tephra layer at 45cm depth located between two C horizons. This contrasted with the lobe stratigraphy where both Ah and B horizons were developed. Surficial organic accumulation was thin throughout.

At East I, tephra remained near the surface throughout the length of the lobe and two White River layers were found in the tread. No other volcanic deposits were present in the study area, so the buried layers indicate overriding of a former surface. Surficial organic accumulation was moderate.

Soil Characteristics

Some trends were apparent in the spatial and vertical differentiation of the physical characteristics. Generally, the organic content of the soils at depth increased towards the front of the lobe and then fell again in the prolobe area. This corresponded to a decrease in pH towards the snout of the lobes indicating incorporation of organic material as the lobe advanced. The pH values decreased downslope on the two east facing sites. NII was the exception having a consistent reading of 4.5 from the tread to the prolobe at all depths. The pH of tephra layers at all locations, and at all depths, remained consistent at 4.5 (Table 2.1).

Moisture Content

No spatial trend was evident in the moisture content although it varied among soil horizons. Buried Ah, Ah and tephra had the highest moisture contents. Lowest moisture was found in the C horizons and the desiccated B horizons, which were usually located between surface Ah horizons and buried Ah or C horizons (Table 2.1).

Overall, EI had the highest moisture content followed by EII and NII, with the control site having the lowest values. There was no significant difference between the moisture content of the Ah horizons of North II and the control site, despite a large difference in the mean values (64.4% versus 36.6% respectively). This was due to the small sample sizes. There was a significant difference in the tephra horizon moisture content of the three lobes. All the C horizons had similar moisture contents. Generally, this indicates that the moisture content was similar at depth (C horizons) but significantly different in the near the surface layers of the three lobes (Table 2.2).

Ah horizons had variable moisture contents (mean 45.5±18.7%) as did B horizons (11.7±7.0%). The reason for the variability in the moisture contents of the Ah horizons was that they were located at the surface below organic mats of

Lobe	Trench	Layer	Moisture Percent	Organic Percent	pH
NII	3	Ah bur	42.93	30.24	4.5
NII	4	Ah bur	30.12	16.94	4.5
NII	5	Ah bur	30.42	14.57	4.5
EI	1	Ah	22.96	12.07	4
NII	1	Ah	60.50	30.21	4.5
NII	2	Ah	66.71	47.89	4.5
EII	3	Ah	28.44	11.87	4.5
NI	3	Ah	40.66	11.19	3.5
NII	4	Ah	66.10	13.95	4.5
NII	5	Ah		16.47	4.5
NI	2	Ah	32.76	10.71	3.5
EI	1	Tephra	32.50	4.22	4.5
EII	1	Tephra	24.79	4.32	4.5
EI	2	Tephra	39.04	10.12	4.5
EII	2	Tephra	24.76	5.66	4.5
NII	2	Tephra	37.53	1.77	4.5
EII	3	Tephra	25.60	5.29	5
NII	3	Tephra	38.09	5.43	4.5
NII	4	Tephra	42.10	5.16	4.5
EI	3	Tephra	34.77	3.31	4.5
EI	3	Tephra2	34.18	6.44	4.5
NII	5	Tephra2	35.73	4.88	4.5
EI	1	B	16.29	6.32	4.5
NII	1	B	9.63	4.04	4.5
EI	2	B	9.63		4
EII	2	B	9.06	6.00	5
NII	2	B	6.88	3.57	4.5
EI	3	B	12.57	5.14	4.5
NII	3	B	9.47	6.30	4.5
EI	4	B	28.77	18.19	5
NII	4	B	7.52	8.66	4.5
NII	5	B	4.82	3.45	4.5
EI	1	C	9.16	7.49	4.5
NII	1	C	6.70	10.84	4.5
EI	2	C	6.70	3.45	4
NI	2	C	8.44	3.13	4.5
NII	2	C	11.89	5.47	4.5
EI	3	C	5.54	4.13	5
EII	1	C1	15.19	8.45	5
EII	2	C1	14.25	6.28	5
EII	3	C1		4.21	5
NII	3	C1	15.90	4.13	5
EI	4	C1	14.05	4.28	5.5
NII	4	C1	10.51	5.40	4.5
NII	5	C1	9.53	3.59	4.5
EII	1	C2	15.60	5.74	5
EII	2	C2	11.38	4.18	5
EII	3	C2		5.00	5
NII	3	C2	8.79	5.54	5
EI	4	C2	16.13	4.80	5.5
NII	4	C2	4.76	4.60	4.5
NII	5	C2	8.70	4.08	4.5

Table 2.1 Moisture percent by dry weight, organic content and pH of all study sites by horizon.

	Lobe	n	Mean	F	p
Ah	NI	2	36.606		
	NII	3	64.43	2.38	N.S.
Tephra	EI	4	35.1		
	EII	3	25.0		
	NII	4	38.2	7.67	.011358
B	EI	4	17.3		
	NII	5	7.66	1.632	N.S.
C	EI	5	10.3764		
	EII	4	14.0987		
	NII	8	9.5991	.4539	N.S.

Table 2.2 Summary of Analysis of Variance comparing moisture percentage among study sites when $n \geq 2$. N.S. = not significantly different at $p < 0.05$.

varying thickness. Extremely high moisture contents recorded at North II ranged from 60.50% at the prolobe to 66.10% on the tread. These high values correspond to Ah horizons that were located immediately below thick organic mats (Figure 2.1). The variability in the moisture content of the B horizons was largely due to the high values recorded at East I. B horizons at this site corresponded to samples with increased organic content due to the lobe overriding a former land surface. Tephra samples had high moisture contents (mean 33.5±6.0%) in comparison to those of the lower desiccated B and C horizons (11.7±7.0% and 10.73±3.2% respectively). Analysis of variance performed among all the different soil horizons yielded a significant difference. All possible pairs were subsequently analyzed. ANOVA results of pairings with the buried Ah layers are suspect. There was no significant moisture content difference between the buried Ah layer and the B and C horizons, but a significant difference was recorded between the buried Ah layer and the surficial Ah layers. It was expected that no significant difference would be found between the buried Ah and surficial Ah horizons due to very similar mean moisture contents (33% and 34% respectively). A difference was recorded because the buried Ah horizon had a large variance and small sample size (n = 3). Therefore, these results were discarded. Significant differences at $p < 0.05$ were present between all of the other horizons (Table 2.3).

Organic Content

Organic content varied throughout the soil column. Ah horizons had the

Site	n	Mean	F	p
Buried AH	3	34.39		
Ah	7	45.45		
Tephra	11	33.56		
B	10	11.67		
C	7	9.19		
C_1	6	13.24		
C_2	6	10.89	8.9013	3.2E-07
C	7	9.19		
C_1	6	13.24		
C_2	6	10.89	1.335	N.S.
Buried Ah	3	34.49		
Ah	7	45.45	6.495	.0315
Ah	7	45.45		
Tephra	11	33.56	9.535	.0007
Ah	7	45.45		
B	10	11.67	7.039	.0137
Ah	7	45.45		
C_{all}	18	10.73	24.9486	1.5E-07
B	10	11.67		
Tephra	11	33.56	62.154	1.5E-07
B	10	11.67		
C_{all}	18	10.74	3.5435	.0119
C_{all}	18	10.73		
Tephra	11	33.56	5.394	.02633
Buried Ah	3	34.49		
C_{all}	18	10.73	3.8402	N.S.
Buried Ah	3	34.39		
Tephra	11	33.56	1.4681	N.S.
Buried Ah	3	34.39		
B	16	11.67	1.0837	N.S.

Table 2.3 Summary of Analysis of Variance comparing moisture percentage between different horizons. No signicant difference was found among the sub-groups of C horizons, and therefore, they were lumped together as one category for the remainder of the analysis. N.S> = not significantly different at $p < 0.05$.

highest organic contents (mean 19.8±11.5%) followed by B horizons (mean 5.6±2.1%), tephra samples (mean 5.2±2.1%) and C horizons (mean 5.2±1.7%). Significant differences were found between the Ah horizons and all others. Tephra, B and C horizons did not have significantly different organic contents (Table 2.4).

Organic matter percentages displayed a similar pattern among the lobes. Ah horizons in NII had the highest accumulation of organic material with a mean of 27.5 %. Overall, in the lower soil strata (B and C), EI had the highest organic content and the control site the lowest. There was no significant difference in organic content among the lobes in the tephra, B and C horizons although slightly higher organic percentages at depth in east-facing sites indicate incorporation of organic material as the parent slope was overridden. There was a significant difference in organic content in the Ah horizons between NII and the control site (Table 2.5).

Textural Characteristics

<u>Frost susceptible soils</u>

Sediments within the lobes ranged from silty-clay loam to stony sand-clay loams (Table 2.6). All of these soils fall within Beskow's (1935) frost susceptible range. The textural character of the greater than 2.00mm fraction was similar among the same horizons of different lobes (Figure 2.4). Within each lobe, the Ah, buried Ah, and tephra had no significant difference in sand content.

Site	n	Mean	F	p
Buried Ah	3	20.58		
Ah	8	19.51		
Tephra	11	5.15		
B	9	5.56		
C	7	5.75		
C_1	7	4.76		
C_2	6	4.81	3.473	.0046
C	7	5.75		
C_1	7	4.76		
C_2	6	4.81	.0118	N.S.
Buried Ah	3	20.58		
Ah	8	19.51	3.651	N.S.
Ah_{all}	11	19.80		
Tephra	11	5.15	31.103	3.3E-06
Ah_{all}	11	19.80		
B	9	5.56	31.592	2.4E-05
B	9	5.56		
C_{all}	20	5.08	1.4474	N.S.
Tephra	11	5.15		
B	9	5.56	.3051	N.S.
C_{all}	20	5.08		
Tephra	11	5.15	1.4702	N.S.
Ah_{all}	11	19.80		
C_{all}	20	5.08	45.772	2.8E-07

Table 2.4 Summary of Analysis of Variance comparing organic percentages between different horizons. No significant difference was found among the sub-groups of C horizons or Ah horizons and therefore, they were lumped togther as one category respectively. N.S. = not significantly different at $p < 0.05$.

	Lobe	n	Mean	F	p
Ah	NI	2	10.9		
	NII	4	27.56	7.34946	.03506
Tephra	EI	4	6.02		
	EII	3	5.09		
	NII	4	4.31	.85263	N.S.
B	EI	3	7.21		
	NII	5	4.48	.00542	N.S.
C	EI	5	4.77		
	EII	7	5.31		
	NII	8	5.45	2.2515	N.S.

Table 2.5 Summary of Analysis of Variance comparing organic percentage among study sites by soil horizon when $n \leq 2$. N.S. = not significantly different at $p < 0.05$.

Lobe	Trench	Horizon	Clast Volume*	Sand	Silt	Clay
NII	3	Ah bur	2	12.81	70.35	13.83
NII	4	Ah bur	2	18.04	64.04	18.77
NII	5	Ah bur	2	13.29	68.53	17.18
NII	1	Ah	1	6.31	83.73	8.30
EI	1	Ah	2	29.81	48.29	21.44
NII	2	Ah	1	3.87	95.34	0.29
NI	2	Ah	1	4.01	64.85	30.05
NI	3	Ah	1	4.19	74.84	19.29
EII	3	Ah	1	58.85	31.88	10.88
NII	4	Ah	2	19.82	61.59	18.75
NII	5	Ah	2	28.41	56.80	15.83
EII	1	Tephra	1	18.06	65.79	15.26
NII	2	Tephra	1	12.07	81.81	6.12
EII	2	Tephra	1	52.23	36.36	11.96
EI	2	Tephra	1	16.59	71.02	11.37
NII	3	Tephra	1	9.88	83.17	6.74
EII	3	Tephra	1	7.97	81.85	8.13
EI	1	Tephra	1	10.91	57.81	31.11
EI	3	Tephra	1	6.51	84.59	8.90
NII	5	Tephra2	1	6.08	87.48	5.29
EI	3	Tephra2	1	8.85	60.18	30.95
NII	1	B	3	49.86	30.80	19.45
EI	1	B	2	30.67	46.22	23.10
NII	2	B	3	59.35	31.45	8.40
EII	2	B	2	68.75	16.81	14.02
EI	2	B	3	48.98	26.78	24.80
NII	3	B	3	54.80	29.13	14.05
EI	3	B	2	33.89	32.79	32.29
NII	4	B	3	69.30	14.88	15.46
EI	4	B	1	12.04	36.08	52.08
NII	5	B	3	80.81	11.04	7.92
EI	1	C	3	63.88	23.80	11.99
NII	2	C	3	37.80	39.07	22.41
NI	2	C	3	61.71	27.31	10.46
EI	2	C	3	45.47	27.91	26.74
EI	3	C	3	65.04	26.24	7.79
EII	1	C1	2	47.25	38.88	14.73
EII	2	C1	2	63.82	17.45	18.39
NII	3	C1	2	28.67	42.27	28.75
EII	3	C1	2	61.09	21.26	16.92
NII	4	C1	2	40.38	36.80	23.00
EI	4	C1	2	19.12	43.94	37.09
NII	5	C1	2	38.65	38.21	24.34
EII	1	C2	2	42.74	37.08	18.05
EII	2	C2	3	54.88	24.79	19.37
NII	3	C2	3	52.76	29.00	16.88
EII	3	C2	3	56.20	25.05	18.39
NII	4	C2	3	50.77	33.70	14.89
EI	4	C2	2	28.90	30.84	30.82
NII	5	C2	3	40.51	34.89	24.85

Table 2.6 Particle size of ≤ 2.00 mm fraction and volumetric clast content of horizon samples from each study site. * after Day (1983:72): ≥ 2.00 mm where 1 = less 15% volume, 2 = 15-35% volume, 3 = 35-60% volume.

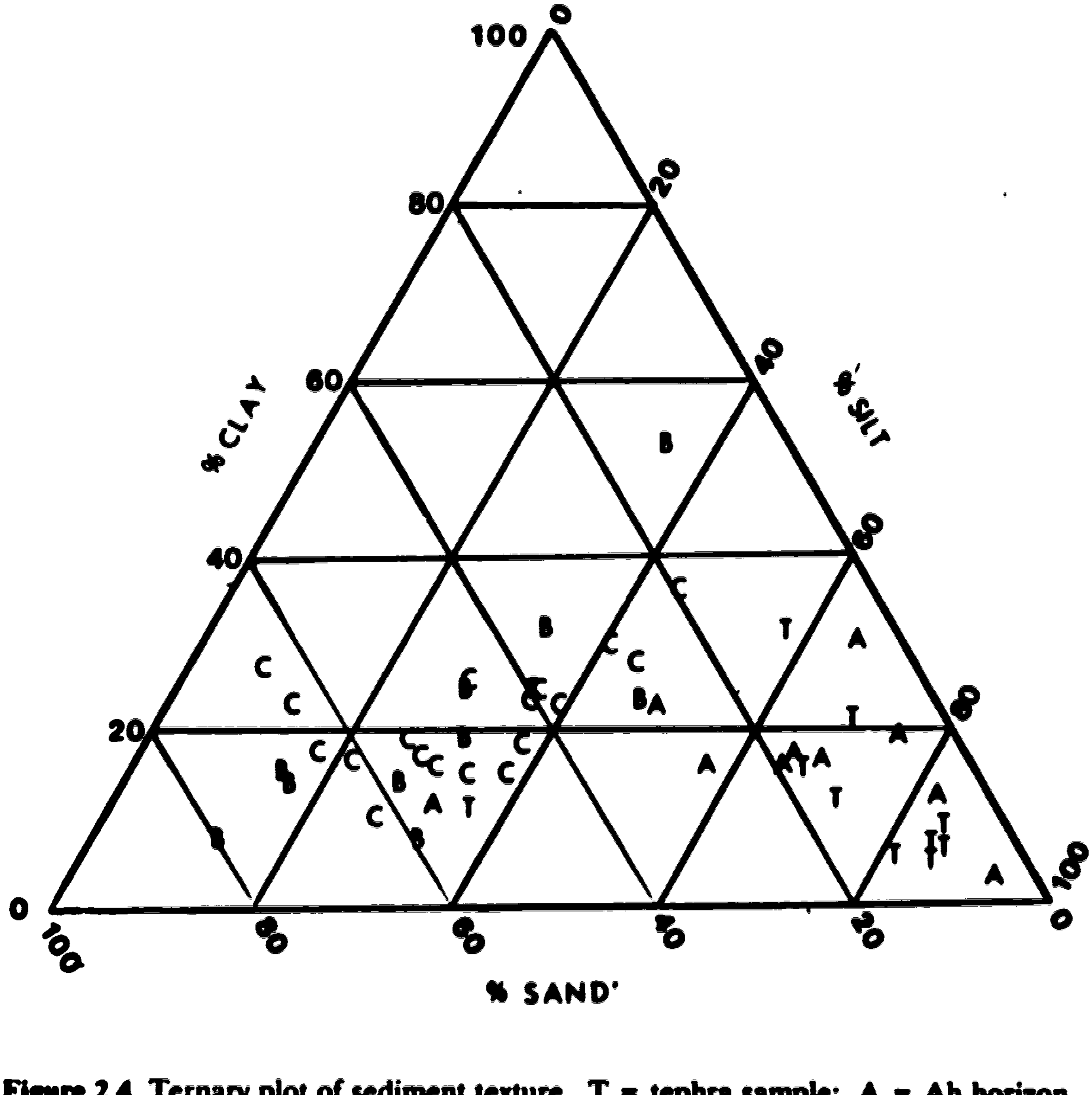

Figure 2.4 Ternary plot of sediment texture. T = tephra sample; A = Ah horizon sample; B = B horizon sample C = C horizon sample. Note how the Ah and tephra samples plot on the right of the diagram and the B and C samples are concentrated on the left.

However, there were significant textural differences among the rest of the horizons within each lobe (Table 2.7). Sand fractions in the B and C horizons had means of 50.6±20.7% and 47.2±13.5% respectively. This contrasted with Ah horizons which had varying sand contents averaging 19.2±18.7%. Clay contents in the Ah horizons tended to be more homogeneous than their sand contents, having a mean of 21.6±9.5%. Despite differences among the different horizons, sediments were not significantly different among the lobes (Table 2.8). Overall, there was a general trend of increasing proportion of fines towards the snout of North II. No change in textural character was identified in East II sediments. East I displayed a decrease in fines towards the lobe snout.

Clast density increased near the riser of EI. This pattern is similar to that reported by Everett (1967) in the Tasersiaq Area, West Greenland. East II and North II did not display any noticeable differences in clast density along the length of the lobe.

Index Properties

Because no significant differences were found between textural characteristics of the same horizon on each lobe, representative samples from each horizon were selected at random for determination of Atterberg limits. The range in plasticity indices for all of the samples was less than 11 percent (Table 2.9). These indices are similar to those reported for solifluction sediments by Washburn (1967) at Mesters Vig, Northeast Greenland, and Smith (1985) in the southern Canadian Rockies. Sediments in the Ah horizon had liquid limits with a

Horizon	n	Mean	F	p
Buried Ah	3	14.715		
Ah	8	19.16		
Tephra	10	14.917		
B	10	50.604		
C	5	54.862		
C_1	7	42.682		
C_2	7	46.366	5.1332	.0002
C	5	54.862		
C_1	7	42.682		
C_2	7	46.366	.277	N.S.
Buried Ah	3	14.72		
Ah	8	19.16	3.599	N.S.
Ah_{all}	11	19.2		
Tephra	10	14.2	.0032	N.S.
B	10	50.604		
C_{all}	19	47.245	2.3495	N.S.
C_{all}	19	47.25		
Ah_{all}	11	17.9	63.4	1.9E-09
Ah_{all}	11	17.95		
B	10	50.6	9.92	.005
B	10	14.92		
Tephra	10	50.60	20.6	.0003
C_{all}	19	47.25		
Tephra	10	14.92	87.81	3.4E-11

Table 2.7 Summary of Analysis of Variance comparing sand content as a measure of frost susceptibility among different horizons. N.S. = not significantly different at $p < 0.05$.

	Lobe	n	Mean	F	p
Ah	NI NII	2 4	4.1018 14.605	8081.2	.0082
Tephra	EI EII NII	4 3 3	10.738 26.087 9.3202	.8664	N.S.
B	EI NII	4 5	30.844 62.782	14.524	.0052
C	EI EII NII	5 6 8	44.203 54.264 41.334	.9277	N.S.

Table 2.8 Summary of Analysis of Variance comparing sand content as a measure of frost susceptibility among the lobe by horizon when $n \geq 2$. N.S. = not significantly different at $p < 0.05$.

Lobe	Trench	Horizon	Liquid Limit	Plastic Limit	Plasticity Index
NI	3	Ah	53.8	50.6	3.3
EII	3	Ah	48.4	40.7	7.7
NII	4	Ah	77.5	74	3.5
NI	2	Ah	49.4	44.5	4.9
NII	3	Buried Ah	107	106	1
NII	3	Tephra	NP	NP	NP
EI	3	Tephra	NP	NP	NP
EI	3	Tephra2	NP	NP	NP
NII	3	B	38	35.5	2.5
EI	3	B	31.5	27	4.5
EI	3	C	16.5	NP	NP
NII	3	C1	29.8	25.7	4.1
EII	3	C1	33.3	23.3	10
EII	3	C2	37.2	29	8.2
NII	3	C2	26	21.5	4.5

Table 2.9 Atterberg limits for selected samples. Values reported are in percent. NP = non plastic.

mean of 57.3±13.7%. Plastic limits were similarly high (mean 52.5±14.9%) resulting in a mean plasticity index of 4.85±2.02%. The buried Ah horizon had extremely high limits (liquid limit 107; plastic limit 106) which resulted in a very narrow plasticity index of 1%. All of the tephra samples were non-plastic despite clay-size fractions averaging 24.3%. Highest plasticity indices were in the C horizons (6.70±2.49%) corresponding to sediments with more diverse particle size composition.

The most plausible explanation of the radically different behaviour of the Ah and tephra soil horizons was the shape of the particles. Particle size analysis in its various forms (sieving, sedigraph techniques) assumes spherical particles (Gee and Bauder 1986). However, the tephra shards were prism-like in shape unlike the locally derived material that is more spherical. It is also important to note that the tephra shape lead to loose packing creating more pore space and the highest moisture contents. The different behaviour of the soils determines which processes predominate at a microscale level. Rounded, non-sorted particles will encourage gelifluction while well-sorted, prism-shaped tephra will be non-plastic providing a slip plane for overlying layers. As the top 20cm was used for fabric analysis, it was important that the Ah horizon was plastic in nature.

Clast Fabric

Most of the raw fabric data plotted as girdles at the poles (Figure 2.5). Raw values produced weak fabrics indicated by S_1 values ranging from .4989 to

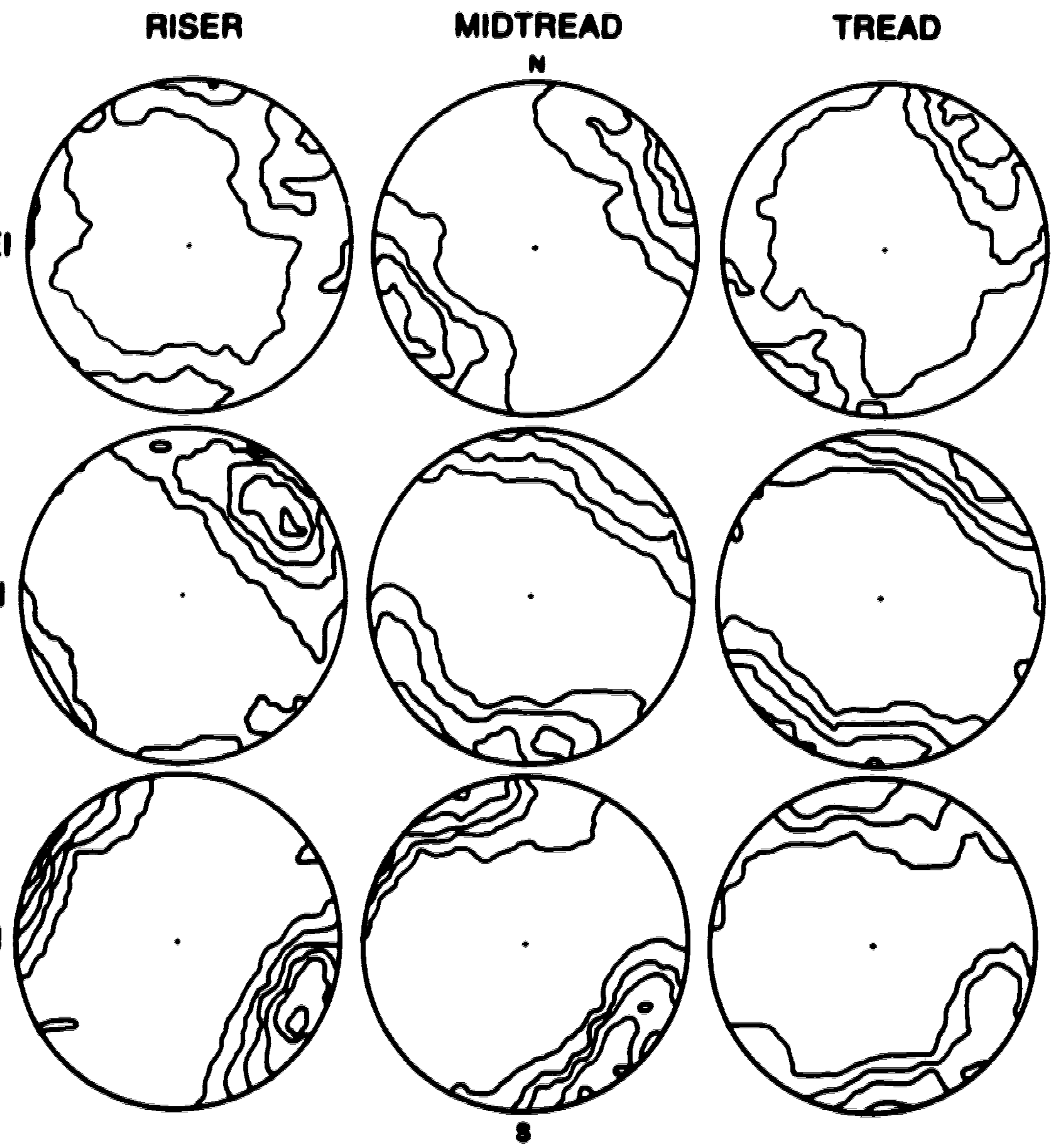

Figure 2.5 Equal area plot of raw fabric data from East I, East II and North II lobe. Data are plotted on the lower hemisphere. Contour interval is 2σ.

.7356 (Table 2.10). Transforming 'north' into the downslope direction and rotating dip values ensured a standard plane of reference, and thus allowed comparison between the three sites (Figure 2.6). After rotation into the local slope, there was an increase is S_1 values and a corresponding decrease in S_3 values at all points on both east lobes and the tread position of the NII lobe compared to the raw data values for these locations. This resulted in higher strength parameter values (Log S_1/S_3). The rotation allows the data to be compared to the local slope rather than arbitrarily to the horizontal. Because all fabric strengths (Log S_1/S_3) increased with rotation, Nelson's (1985) recommendation to rotate the data to a standard plane of reference provided a better framework for analysis. Therefore, this data transformation was adopted for analysis (Appendix A).

By plotting S_3 and S_1 values, all of the fabrics plot together in one area (Figure 2.7). If plotted on stretched x and y axes, fabric results from the tread and midtread of East I and North II plot together as clusters throughout the graph (Figure 2.8). It is difficult to determine if the risers plot together due to the small sample size (n=3). The eigenvalues associated with these fabrics are weaker than previously documented (Nelson 1985). However, in discussing Nelson's 1985 study, Mills (1993) cited Nelson describing his solifluction fabrics coming from "optimal settings" producing "strong fabrics" and that "fabrics coming from other solifluction sites might not be as strong" (p.23). Strength of the fabrics under investigation are similar to those reported for undeformed lodgement till

	Lobe	Location	Azimuth	Dip	S1	S3	Strength Log(S1/S3)	Shape (Log S1/S2)/ (Log S2/S3)
Raw	EI	RISER	48	8.246	[illegible]	0.12	1.42	[illegible]
Fabric	EII	RISER	46.8	21.183	0.8633	0.0857	2.08	0.8237
	NII	RISER	119.3	7.906	0.7366	0.0648	2.43	1.183
	EI	MID	237.7	1.458	0.8673	0.1386	1.36	[illegible]
	EII	MID	204.8	2.217	0.838	0.0739	2.15	0.8886
	NII	MID	146.5	2.392	0.8826	0.0888	2.12	1.12
	EI	TREAD	226.7	0.811	0.5377	0.1467	1.29	0.7228
	EII	TREAD	205.9	3.156	0.8831	0.0511	2.86	0.4867
	NII	TREAD	346	0.612	0.5875	0.1008	1.77	0.8571
Rotated								
Fabric	EI	RISER	342.8	5.3	0.5467	0.053	2.38	0.1648
	EII	RISER	341.3	9.4	0.6743	0.0406	2.81	0.4422
	NII	RISER	340.3	1.56	0.7086	0.0542	2.57	0.7285
	EI	MID	165.7	1.1	0.7378	0.0527	2.64.	0.9124
	EII	MID	394.3	0.089	0.8518	0.0182	3.86	0.236
	NII	MID	183.2	0.913	[illegible]	0.085	2.33	0.6428
	EI	TREAD	156.5	2.5	0.588	0.0645	2.21	0.3126
	EII	TREAD	320.4	0.363	0.8802	0.0209	3.46	0.3088
	NII	TREAD	26.5	5.5	0.6086	0.0696	2.17	0.4157

Table 2.10 Summary of eigenvalue statistics for raw and rotated fabrics.

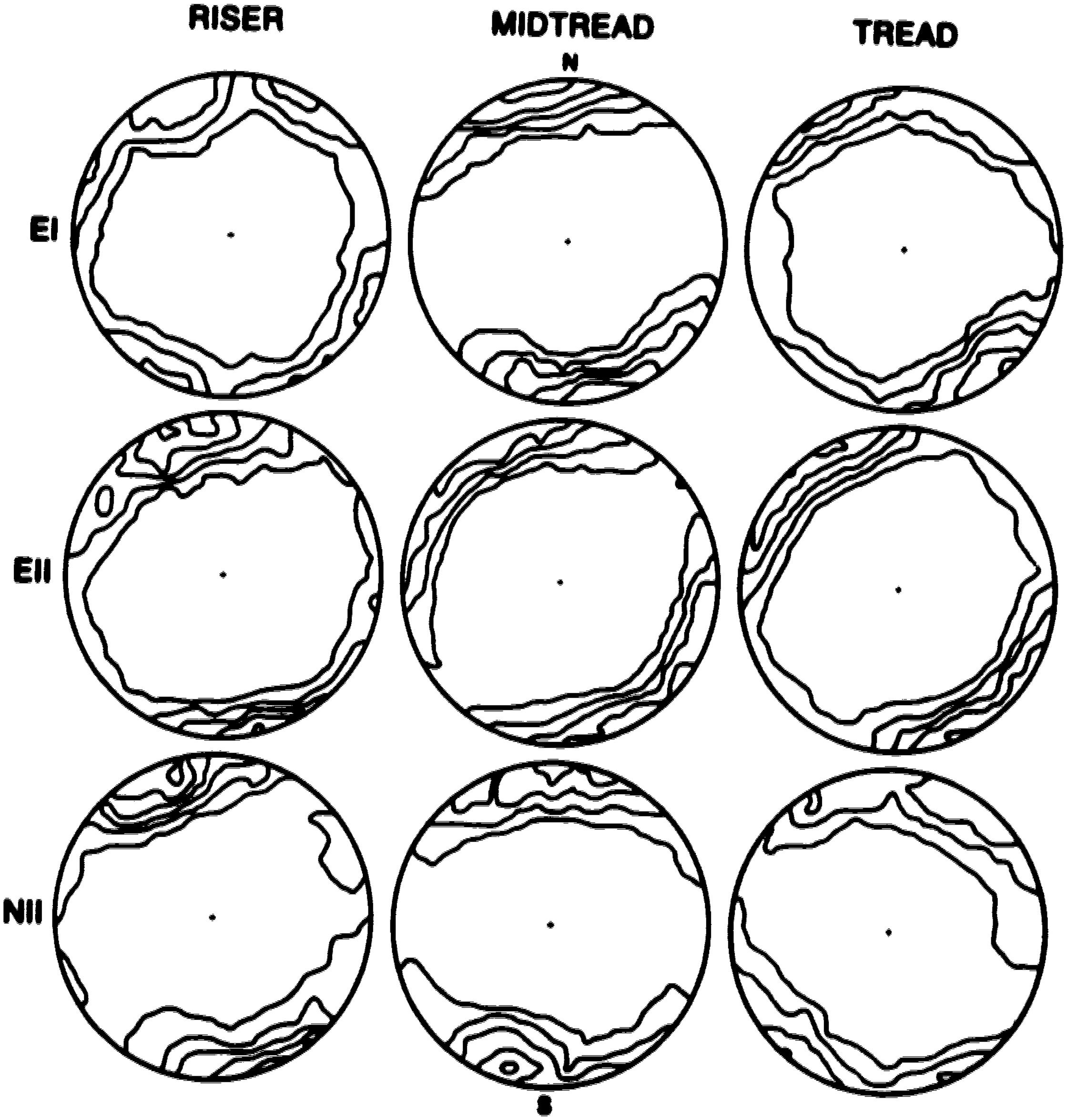

Figure 2.6 Equal area plot of transformed fabric data from East I, East II and North II lobe. Data are plotted on the lower hemisphere. Contour interval is 2σ.

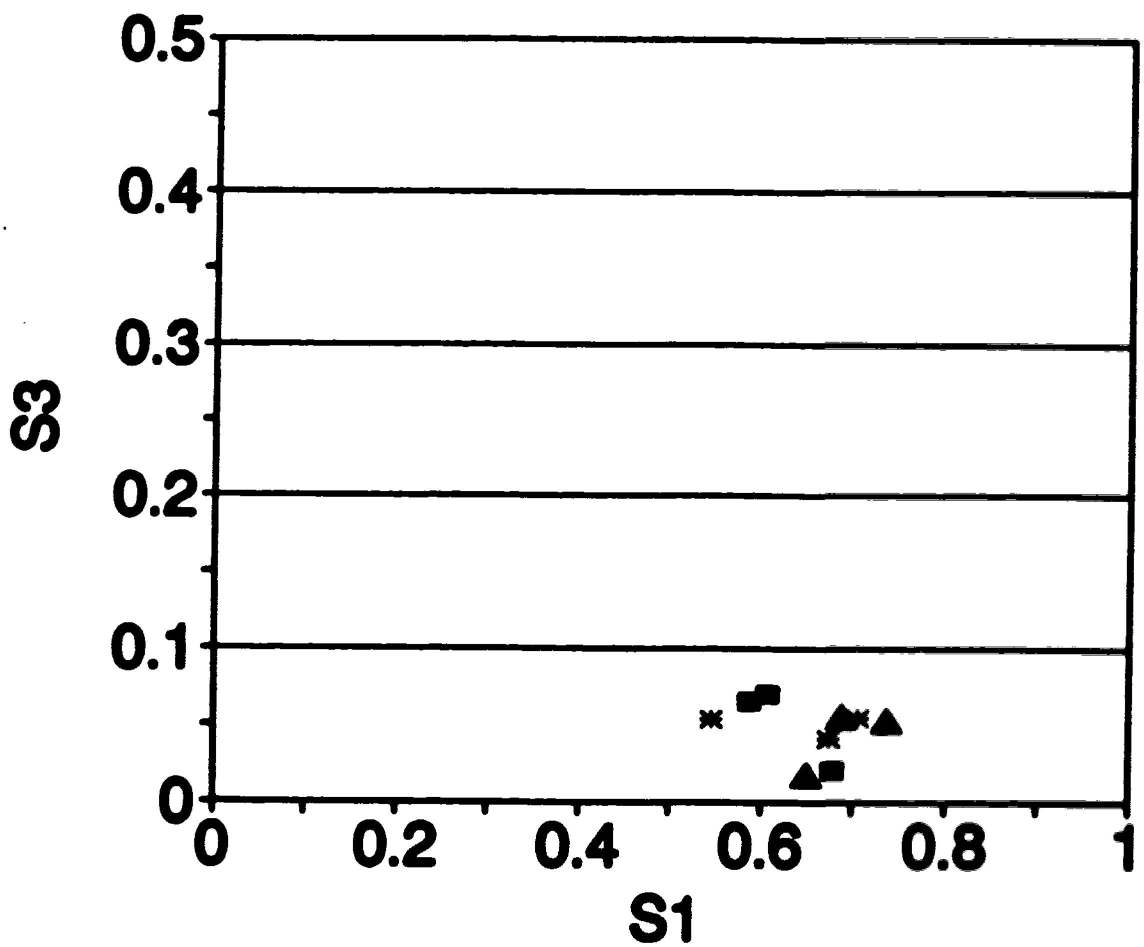

Figure 2.7 Plot of S_1 versus S_3 for transformed data. $S_1+S_2+S_3 = 1.0$. Therefore, $S_3 \ngtr S_{1\,min}$ * = riser position; ▲ = midtread position; ■ = tread position.

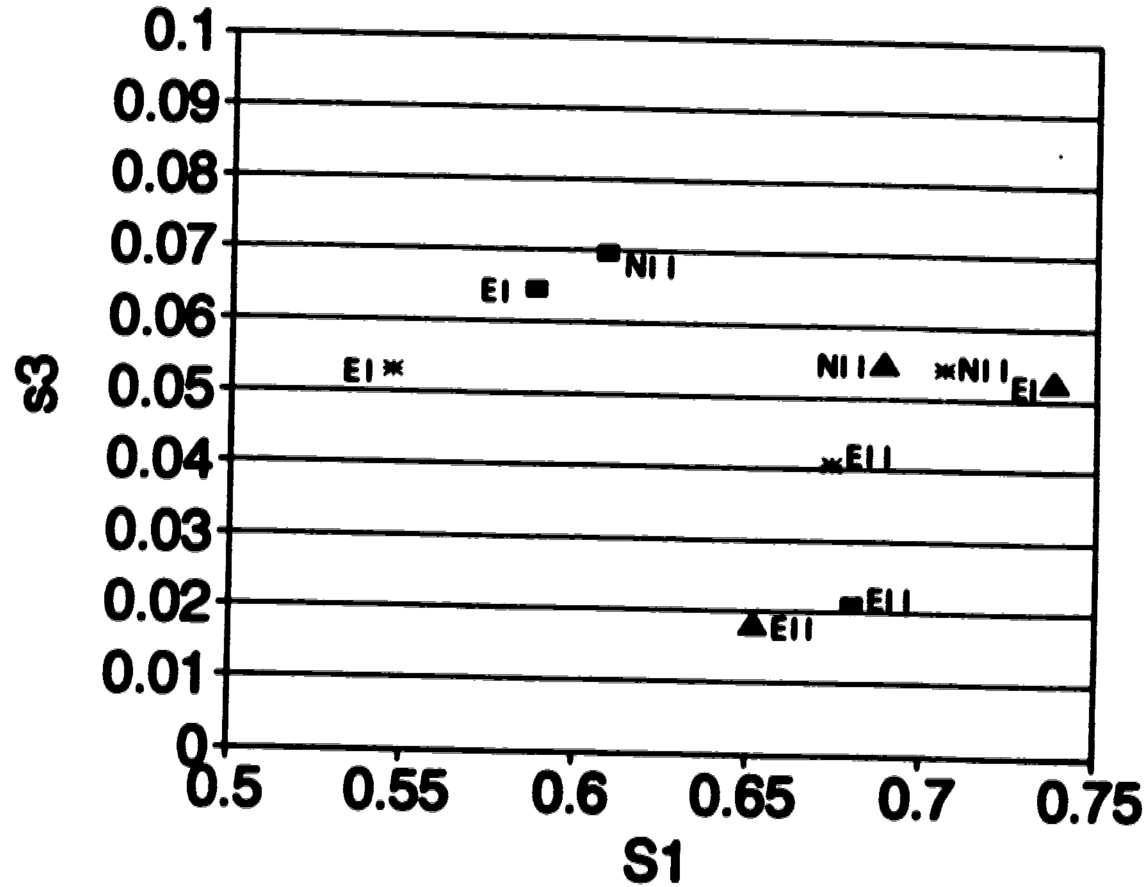

Figure 2.8 Plot of S_1 versus S_3 for transformed data on stretched axes. * = *riser* position; ▲ = midtread position; ■ = tread position.

(Dowdeswell and Sharp 1986).

East II clasts were sub-horizontal relative to the parent slope. This lobe had high fabric strengths, with the very low S_3 values. These small values indicate that reorientation has been the result of predominantly one process (represented by the S_1 value) unlike the other two sites. As the S_1 values are high, there was only one predominant mode of reorientation. Horizontal clasts indicate the predominance of gelifluction over frost creep in the reorientation of stones. The tread fabric at all three sites was a girdle indicating horizontal alignment. Stones at the tread location are migrating towards the long axis of the lobe from the outer edges (Benedict 1970). Therefore, they have not yet been perfectly aligned with the fastest flowing central part of the lobe.

East I lobe had the weakest fabrics on the riser. S_1 values ranged from .5467 at the riser, to a high of .7378 at the midtread position and .5880 at the tread position. The low value associated with the riser position was likely due to inclusion of some fabric from the parent material. The trench straddled the boundary and clasts were measured throughout the pit. It is, however, instructive to note the progression of weak fabric at the riser, a strong fabric midtread, and a weak fabric upslope in the tread position.

On the North II tread, the increase in S_1 strength was almost solely due to a decrease in S_3 values. That is, the dip of the data was essentially removed. Conversely, S_1 of the fabric at the riser and midtread of North II declined after rotation. This occurred despite an increase in the strength parameter (Log S_1/S_3).

This indicates that at these two locations, clast reworking has not occurred relative to the local slope. The North II lobe had a large difference between the parent slope angle and tread angle (15°). East I and East II had differences of 5° and 7° respectively. Therefore, reworking had likely occurred due to external factors (i.e. frost action).

Strength of the fabric at different locations was different for all three lobes. Therefore, each lobe must be analyzed separately to explain individual form.

DISCUSSION

Physical Characteristics

The imbricated gravels at the control site indicate fluvial deposition rather than any periglacial process. The morphology of this lobate form was the result of fluvial erosion. Lack of any buried tephra at the North I site indicates that no movement has occurred here during the last 1250 years or that following tephra deposition, the tephra was eroded by fluvial action before it could be buried. In addition, the lack of any buried Ah or humus layers indicates that the lobate form has not overridden the parent slope. Similarly, absence of a tephra deposit on the surface indicates that tephra deposits at this site were likely eroded fluvially as the present day ephemeral headwaters of a mountain stream are located approximately 30m downslope. The mountain stream has cut its way down through approximately 15m of diamict. The stream has continued to erode the steep north valley side preserving the control site on the gently sloping south valley wall.

At North II and East II, the buried tephra proves that burial of the parent slope has occurred within the last 1250 years. Movement and deposition of material may also have occurred prior to the White River eruption. The depth at which the tephra was located at the riser and midtread positions indicates a progressive piling up of debris towards the snout of the lobe. To determine how material was moved, it was necessary to examine the other evidence.

The increase in fines towards the front of North II agrees with the results of Benedict (1970). As gelifluction does not discriminate on particle size there must be another process at work on the slope. North II was located on a 26° slope with an ephemeral stream cutting into the lobe on the west side. In addition, luscious vegetation on this site and the presence of a late lying snowpack indicates that there was sufficient moisture to wash the fines downslope (Jahn 1967). North II had high moisture and organic contents due to the large number of Ah soil samples taken from this lobe which skewed the overall distribution. However, North II sediments had the lowest moisture and organic contents at depth (B and C horizons). The low organic content indicates that no new organic material has been incorporated into the lobe. Homogeneous pH at this site could be an indication that leaching has occurred and any pH differences resulting from incorporation of surface organics in the lower horizons has been removed. The removal of fines, low moisture and organic contents at depth and the thick surface organic accumulation indicates that the NII lobe is stationary or moving slower than the east-facing sites. This was further confirmed by the low riser angle of 31° compared to 44° and 58° on the east-facing sites.

East II had very pronounced burial of tephra at the riser and midtread. The tephra deposit was thickest at the riser. This sample location corresponded to the deepest tephra burial along the length of the lobe. Up to 60cm of sediment had been deposited on top of the White River ash. Therefore, movement has been present at this site during the last 1250 years. This site had the second highest moisture contents in the B and C horizons. No spatial pattern was identified in organic content of various horizons at this site.

Tephra was present near the surface on East I. There were no buried tephra layers in the riser and midtread of East I. In addition, no tephra was identified within the matrix material of the B horizons where increased organic contents were present. The lack of buried tephra could be explained by: 1) no overriding of parent material has occurred since 1250 BP i.e. the lobe under investigation formed prior to 1250 BP; or 2) the surficial tephra deposit on the parent slope was removed by fluvial or eolian action before the lobe advanced. Due to the presence of tephra presently on the parent slope, the latter explanation seems unlikely. The high organic content of the B horizons indicates that organic material has been incorporated at depth at some time. However, it is difficult to determine at what time burial occurred. There were two thick tephra layers found in the tread. While it appears as if the lobe front has not recently advanced, recent surficial overriding has occurred upslope on the tread.

At East I, there was an increase in coarse-textured material towards the front of the lobe. Coarser material may have been preferentially moved forward by frost creep processes. This sorting of material has been reported with regard to stone-banked terraces (Everett 1967). Due to the presence of active frost sorting processes on the tread surface, frost action appears to be the likely cause of increase in coarse-textured material downslope. The increase in clast density in the riser of the EI lobe provides further evidence of active frost sorting. Stones move faster downslope largely due to the predominance of frost action on steeper slopes (Benedict 1970). The stone front terraces are overridden when the slope gradient decreases.

Particle size of all soil horizons for all sites fell within the frost-susceptible range (Beskow 1935). This indicates that entrainment of water and subsequent frost-heave would be possible at all depths at all sites. There was no significant difference in the estimated relative frost susceptibility according to the criteria outlined by Caine (1978). However, Ah and tephra samples behaved quite differently. All tephra samples were non-plastic while the Ah horizon had a low plasticity index. Evidence suggested the tephra layer could have provided a convenient slip plane upon which the Ah horizon was transported downslope. In addition, C horizon sediments had the highest plasticity index indicating that they would be most likely to deform, due to thawing of ice in the overlying sediments. This process is referred to as thaw consolidation (Taber 1930). This occurs because of the loss in strength of soils subjected to rapid thawing and slow drainage. Water released by melting ice lenses cannot be expelled, so that in the process of consolidation, some of the load is transferred to the pore water causing a loss in strength.

Clast Fabric

All lobe treads displayed similar characteristics and therefore, have probably undergone similar processes. As previously documented, clasts dip upslope (Benedict 1970). However, the dip recorded at all lobes approximates horizontal when rotated into the local slope. The near horizontal/upslope dip indicates that gelifluction (with some imbrication) was at work on these slopes. Field moisture conditions were well below the plastic limit suggesting lack of moisture for gelifluction to occur. However, Atterberg limits were determined for the <425μm fraction where as moisture content was determined on a dry weight basis for the whole particle size range of soil including some clasts. Therefore, field moisture conditions were comparable to the plasticity index moisture contents.

Eigenvalues and eigenvectors for the midtread position of the study lobes indicated that there was a transition in the fabric from that found farther upslope in the tread position. On each lobe, there was a decrease in the S_3 values at the midtread. The decrease in S_3 values indicated a more homogeneous reworking mechanism. At the midtread, movement tended to be aligned directly downslope (Benedict 1970). In addition, the stones continued to tend towards horizontal in this position at all three lobes. These reorientations indicated that gelifluction was active. Flow occurred from areas of high to low potential energy which was directly downslope, along the long axis of the lobe. Frost action would not produce this azimuthal preference. The strongest midtread fabric was found on East I.

Both east lobes had weak girdles in the riser position. There were slight downslope dips and large scatter in the data. These riser fabrics displayed the lateral spreading of material at the lobe front due to lack of resistance and increased frost action. The effect of frost action reorienting the stones may be a function of the lack of gelifluction rather than an increase in frost activity. The fabric on the tread of East I indicates reorientation by gelifluction and yet, frost sorting is well developed on the surface. Therefore, the apparant increase in frost creep at the lobe front may be the result of decreased lobe motion. Conversely, the riser position on North II had the closest clustering of all riser fabrics in the study area indicating strong preferred orientation and lack of lateral spreading. Using the same argument as above, the predominance of gelifluction indicates that this lobe was the most active. However, many of the physical characteristics of this lobe indicate that it is stationary. A second explanation for the lack of frost action reworking the stones on the riser could be the extremely thick (15cm) organic layer. This surficial layer insulated the ground from frost. Microclimatic investigations determined that this site was warmer than the other sites (Table 3.1). Dip on the NII lobe was horizontal. The strength of NII fabric suggests viscous flow was the mode of downslope transport at the lobe snout.

Inter-lobe Comparisons

East I had the highest moisture contents, spatially differing organic contents, sparse woody vegetation and a general sorting of particles throughout the lobe length. Tephra remained near the surface throughout the length and no buried tephra layers were identified. Clasts were horizontal relative to the parent slope. Clasts tended to be preferentially moved forward as indicated by the increase in clast content at the riser. As the trenches were located to the "east" of the long axis, the movement of clasts towards the long axis on the tread and divergence of material at the lobe snout duplicated the evolution reported by Benedict (1970). The lobe had the low (Log S_1/S_3) at the tread and riser. Similarly, the high S_1 was offset by an increase in the S_3 value at the midtread. The shape of the distribution tended towards a cluster at the midtead. The difference in the fabric suggests the East I lobe has evolved differently from the other two study lobes. The scatter in the preferred orientation indicated the clasts were no longer solely reworked by gelifluction at the riser position. These characteristics combined with the presence of frost sorting on the surface indicated that this lobe had a component of frost-creep reorienting the stones.

The North II lobe fabric was slightly different. After rotation, S_1 and S_3 values decreased at the riser and midtread positions. However, S_1 values increased in relation to S_3 values. This is not indicative of frost creep which would cause S_3 values to rise in relation to S_1. Dip angle at the riser was low compared to the other two sites. At the midtread position, the fabric was parallel to the long axis and nearly horizontal. It was at these particular locations where two complete soil profiles were found on North II. The distinct divisions between the soil horizons indicated that the upper soil profile moved *en masse*. Some deformation was present in the tephra layers. This indicated that this layer was likely the shear plane upon which the sediment was transported downslope. Fabric measurements from the lower soil profile may have confirmed this "plug-like" flow. At the tread, the clasts were oriented away from the long axis. This does not conform to Benedict's (1970) flow pattern. As tread fabric plotted in the subgroup with East I riser and tread (i.e. high S_3 values in relation to S_1 values), it was concluded to have been formed by the same reworking processes. That is, frost creep has recently reworked surficial sediment on the tread. Coupled with homogeneous pH, thick surface organic accumulation, and low moisture and organic contents in the B and C horizons, the North II site was concluded to be inactive at this time except for some localized post-depositional frost action.

Stones in East II tended to have the same preferred orientation as those of EI. Fabric strength (Log S_1/S_3) throughout the lobe was the highest of all sites. This lobe had the second highest moisture contents providing sufficient moisture for gelifluction. Despite similar vegetation on North II, East II had a thin organic accumulation. This thin accumulation as well as the fabric suggests this lobe is presently active. Unlike NII, pH decreased downslope although organic content did not show any discernible trend. The complex interaction of mineralogy, humus and groundwater make it difficult to infer genesis based solely on pH.

However, North II was similar in mineralogy and vegetation to East II and did not display this trend. Therefore, it is possible that the difference in soil characteristics between these lobes was related to groundwater and leaching. It is possible that the present moisture conditions are responsible for the activity of these lobes.

CONCLUSIONS

This study has concluded that within a very small range of geotechnical, elevational and morphometric parameters, solifluction can evolve differently producing similar macrofabrics. Van Vliet-Lanoe (1985) has determined that changes in the organization of the fabric in periglacial environments are largely due to the lateral inflow of water. The flow of water is affected by the slope gradient and aggregation of soil particles. In a later study, Van Vliet-Lanoe (1988) concluded that the polygenetic origins of many periglacial landforms produce very similar fabric. Mills (1993) has determined that fabric strength is the best criteria to distinguish different fabrics. However, fabric data alone cannot determine depositional environment. Other lines of evidence were necessary to infer different origins.

All fabrics in the study area were similar in shape i.e. girdles. There was some range in the strength values. Fabric strength was much weaker than that reported by Nelson (1985) and was similar to that reported for undeformed lodgement till (Dowdeswell and Sharp 1986). However, Nelson's (1985) study differed from the present one in a few respects. First, the locations of his study fabrics were concentrated on the midtread and tread. It was in this location where the strongest fabrics were found in this study. Second, Nelson's study consisted of eight samples from "optimal settings" and "fabrics in other solifluction sites may not be as strong" (Mills 1993 p.23). Therefore, the fabric strengths in this study may be more typical of solifluction deposits. Further studies to obtain more fabric measurements from solifluction environments will provide more information about the fabric characteristics. Third, rotation of fabric into the local slope does not always lead to an increase in fabric strength. Morphometric parameters appeared to influenced the rotation. These morphometric characteristics in turn influence the depositional environment. As well, post-depositional reworking due to frost action reoriented stones according to the penetration of the frost line which mirrors the surface angle. Which reference plane is correct is a difficult problem to resolve.

The three lobes in this study have similar fabrics throughout their lengths. Inclusion of other lines of evidence suggests sediment has been deposited primarily by gelifluction but post-depositional reworking has occurred in some instances.

East I fabric suggests gelifluction was the predominant mode of deposition. The lowest S_1 values of the entire study were found on the tread and on the riser. The physical characteristics of this lobe and visible presence of frost sorting on the surface indicated that frost creep was responsible for the scatter in these fabrics.

East II fabric suggests that deposition has been accomplished almost exclusively by gelifluction. S_1 and S_3 values were very similar through the length of the lobe. Soil characteristics were similar throughout. The thin surficial organic accumulation as well as a 44° riser angle suggest that this lobe continues to flow.

North II fabric had similar strengths to those of the east-facing sites. However, rotation into the local slope resulted in a decrease in the S_1 values of the midtread and riser fabrics. Many of the physical characteristics suggest this lobe is presently inactive although some reworking of surface materials due to frost creep may be present at the tread. Previous movement at NII appears to have been plug-like in nature.

Along the long axis of each lobe, there were slight shifts in the mass-wasting processes. On the S_1 versus S_3 plot of eigenvalues, treads of EI and NII plotted as a sub-group. Tread areas on these two lobes appeared to have been affected by frost creep. At the midtread position, horizontal clasts and fabric clustering indicated homogeneous reworking. It is this location which is usually considered the fastest moving (Washburn 1967; Benedict 1970; French 1974; Harris 1981). Therefore, fastest movement at the study site was the result of gelifluction. Gelifluction was the dominant process of deposition. At the riser, lateral spreading and slight downslope dip indicated that gelifluction, and frost creep (and some free falling due to gravity from the dislodgement of material) contributed to the east-facing lobe fronts.

This study used a spatially based sampling scheme. Future studies should include fabrics from different depths at the same location. This would allow the identification of slip episodes by distinct changes in the orientation of the clasts. Plug-like flow could be identified by a significant change in the preferred clast orientation from one soil layer to another (Nelson 1985). Plug-like flow is the *en masse* movement of a soil mass due to the thawing of an ice-rich layer at the base of the active layer (Mackay 1981). Failure occurs along a shear plane due to a reduction in shear strength. Failure along a discrete plane may be a function of particle size distribution, depth of seasonal frost, and water content differences.

Identification of fossil solifluction deposits should include eigenvalue analysis of the fabric. However, the present author agrees with the findings of Nelson (1985) and Mills (1993) that fabric should not be the sole criterion for identification of solifluction deposits. This is the second eigenvalue method fabric study of solifluction fabric. Obviously, further investigation of solifluction fabric must be completed to distinguish solifluction fabric from other sedimentary environments.

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CHAPTER THREE

MICROCLIMATE AND AN EVALUATION OF A NEW TECHNIQUE TO MEASURE THE MOVEMENT OF SOLIFLUCTION LOBES

INTRODUCTION

Presence of permafrost or deep seasonal freezing is the main characteristic of periglacial slopes (Harris 1981). Formation and rates of movement are controlled mainly by climatic factors (Benedict 1976; Washburn 1979; Nesje *et al.* 1989). Recent solifluction studies have concentrated on ^{14}C dating of buried organic layers. These layers are usually interpreted as former ground surfaces which have been overridden by the advancing lobe front as it moves downslope. Assuming no new carbon has been incorporated into the buried organic layer, the date at which any point along the length of the lobe was overridden can be determined. The rate of frontal advance can then be determined for different time periods (cf Alexander and Price 1980; Friend 1988; Smith 1993). This method has been used to infer past climatic conditions. Highest movement rates have been hypothesized to correspond to periods of deteriorated climatic conditions (Gamper 1981; Nesje *et al.* 1989). However, Eggington and French (1985) and Price (1991) reported increased measured movement on solifluction lobes due to plug-like flow that was initiated by increased thaw of the active layer due to warmer than usual summer temperatures. Other workers have determined that cold, humid periods resulted in increased moisture content which were responsible for enhanced solifluction activity (Morin and Payette 1988). Locally, forest fire activity has been found to promote solifluction in Northern Quebec (Filion *et al.* 1991). The different local interpretations of enhanced lobe development illustrate the complex relationship between solifluction development and palaeoclimatic conditions. The ambiguity associated with proxy climatic inference from ^{14}C dating may be eliminated with research into contemporary climatic conditions.

Since the early 1970s, few recent studies have been directed towards investigations of contemporary microclimate of solifluction lobes (Washburn 1967; Benedict 1970; Harris 1972). Because soil freezing due to climatic conditions is the controlling factor of periglacial mass-wasting, a full investigation into air and subsurface temperatures of three turf-banked lobes and a control site was carried out.

Microclimate stations were established at all four study sites during the 1992 summer field season. A full year of subsurface temperature measurements was obtained for the East II site. It was hoped that microclimatic conditions could be compared to movement rates. However, the experimental remote sensing technique used to determine rates of movement produced inconclusive results. Therefore, an evaluation of the technique follows the results of the study of the subsurface thermal regime.

Previous research on rates of solifluction movement has relied on estimates of movement through proxy sources. Contemporaneous observations at the time of actual motion have never been made (Williams and Smith 1989). Some researchers have stated that the majority of movement occurs early in the thaw season during snowmelt when the soil is saturated and able to flow (Gamper 1981; Nesje *et al.* 1989). Contrary to this, other scientists have stated that most movement can occur during episodic events in summer or fall freeze-up (Benedict 1975; Price 1991; Matsuoka and Moriwaki 1992).

There are three approaches to the quantification of movements produced by solifluction processes. In previous studies, surveying of surface targets or measurements based on changes in the positioning of painted stone networks have been used (Eggington and French 1985; Smith 1987b). Measurement of changes in the distribution of inserted vertically positioned material have been achieved with inclinometer tubes (Smith 1985, 1987b; Price 1991), foil pillars (Eggington and French 1985; Gamper 1981), and dowel pillars (Gamper 1981; Smith 1987b). The third method is radiocarbon dating of buried organics (Benedict 1976; Smith 1987a; Morin and Payette 1988; Nesje et al. 1988). Errors associated with the first two physical measurement techniques have been discussed at length by Anderson and Cox (1978). In addition, Smith (1993) has reviewed many of the techniques used for the determination of solifluction movement rates. A summary of the biases and errors associated with these methods is now presented.

Painted stone networks have a marker incorporation period of up to four years (Smith 1993). In situ marked surface particles may not be moving during any one particular year due to climatic, vegetational and locational parameters as well as stone morphology. Selected marked stones will move at different rates according to their size and shape. Markers placed on the lobe surface are not initially subjected to the same processes as stones that are marked in situ. Until marker incorporation, stone networks have been reported to overestimate movement by up to 300% (Caine 1981). This surface method of measurement can also be prone to disturbances due to human influences (French 1974).

Installation of vertically aligned materials such as foil and dowel pillars causes initial disturbance errors. Jahn (1989) reported that wooden dowels require a 3-4 year initialization period. These monitoring devices have different thermal and physical characteristics from the surrounding soil and react differently to changing climatic and physical conditions (Smith 1987b). Foil pillars have higher thermal conductivity and lower heat capacity than surrounding soil. Changes in thermal characteristics cause changes in the natural thawing and freezing cycles. Movement of water towards the freezing front produces frost heave, over-saturation of the soil, and discrete icy layers required for plug-like flow. Presence of foreign material in the soil upsets the natural thermal conditions which have a direct effect on water flow through the soil.

Deformation of inclinometer tubes has provided the most detailed view of subsurface movement. However, tubes tend to curl because of their inherent shape and the process of manufacture (Price 1970). Vertical curvature of the tubes occurs as pressure is applied on one side of the tube. The opposite side easily deforms in a convex motion possibly overestimating the actual movement. Long-term inclinometer monitoring in the Ruby Range produced almost exclusively convex-concave downslope profiles (Price 1991) which may be partly due to the technique employed. In addition, upslope movements have been recorded due to drying of the soil (Anderson and Cox 1978). Like other subsurface techniques, inclinometer tubes require a 3-4 year stabilization period (Smith 1993). Results from tubes like those from other vertically inserted materials, are biased due to different heat fluxes and changes in the natural pattern of water migration near the inserted material.

Due to the effects of the initial disturbance, long term study is required to acquire accurate motion results (Smith 1992). Therefore, duration of the study is a consideration. It has been reported that measurement error can exceed actual rates of movement in studies of less than ten years duration (Anderson and Cox 1978). In addition, methods recording subsurface movement (i.e. foil and dowel pillars and inclinometer tubes) are ultimately discontinued when the site is excavated to obtain final readings.

Radiocarbon dating of buried organics in solifluction lobes to document past movement and reconstruct Holocene climates is common. While this technique can provide useful insights into past movements, cryoturbation can redistribute organic material and hence, dating of layers or structures within lobes can be complicated. (Alexander and Price 1980; Smith 1985). Furthermore, calibration of the mean residence time of buried organic material must be established to accurately document movement rates (Smith 1993).

To eliminate installation-generated errors and determine when the maximum movement occurred, a technique was devised to record movement remotely. Campbell Scientific sonic depth sensors (UDGs) were used to measure the distance between the lobe front and the sensor. These sensors were connected to the same CR10 datalogger which was set up near each lobe front. The sensors have a 1.0mm resolution (Campbell Scientific Canada Corp. 1989). The depth gauges emit an ultrasonic wave at the reflecting surface within a 12° cone. The time it takes the sonic wave to return to the sensor can be translated into a distance. Any movement of the lobe was documented as a change in the distance measured. Distance measurements at a point were recorded six times daily at 0400, 0800, 1200, 1600, 2000 and 2400 hours.

The single point measurements were subject to errors due to interference at the time of the reading. Field studies measuring reflection from snowpack accumulation have determined a root-mean-square error of less than 2.00cm (Goodison *et al.* 1988). Therefore, it was determined that ±2.5cm was the true accuracy of the sensors over a snowpack. Sources of errors associated with measurement over a snowpack included blowing snow/snowfall events and changes in the density of surface snow (Goodison *et al.* 1988). During precipitation events, there is interference from the snowflakes (or rain drops) as they pass through the area through which the acoustical signal is travelling. This causes the signal to be scattered. The second source of error is related to how the signal bounces back from the target. Light, fluffy snow bounces a weak signal back to the UDG because much of its energy is absorbed. As well, the surface roughness is much greater than that of hard packed snow. Therefore, hard packed snow will bounce back more accurate and stronger signals. Errors have not been quantified for the method proposed here. Certainly precipitation events did occur, although these were relatively short-lived compared to snowfall and drifting snow. Although the accuracy of the sensors in this application was largely unknown, it was hoped that the possible cause and effect between climatic conditions and periglacial mass-movement could be identified.

The objectives of this study were twofold. First, subsurface thermal regime was monitored for characterization and comparison of the control, east and north-facing lobes in the Macmillan Pass area. The full year record of East I provided a full record of freezing and thawing. Second, this study evaluated a new remote sensing method using Ultra Sonic Depth Sensors directed at the snout of the lobes. It was expected that application of the technique would identify morphological change at a particular point. It was hoped new data on the timing of morphological change at the lobe front would be gained.

METHODS

Field Methods

Automated data collection equipment was installed on the control and EI sites on the 12 and 13 June 1992 respectively. NII and EII were instrumented on 27 and 28 July respectively. All data were recorded on Campbell Scientific CR10 dataloggers with power supplied by a 12V gel-cell battery. Batteries were kept charged with a 4W solar panel.

Microclimate stations were installed in front of all three lobes and the control site (Figure 3.1). Air and subsurface soil temperatures were collected during the 1992 summer season with one site overwintering (EII) to collect year-round data. Measurements were taken at 10 minute intervals at all locations. Hourly and daily mean temperatures were calculated from 6 and 144 observations. Minimum and maximum temperature for each 24 hour period were also output. Subsurface temperatures on the study lobes and the control site were taken using thermocouples which were installed at the beginning of the season at -5, -20, and -50 cm depths. Thermocouples were fixed to 2cm-diameter wooden dowels and inserted into the ground. Wooden dowel was used because it has thermal characteristics more similar to soil than metallic rods. Care was taken to ensure that the dowels fitted snugly into the holes. Vegetation and surficial material were packed against the dowelling to ensure that sensible heat was not transferred downwards along the dowel. Thermocouples were attached to the dowel in such a way as to ensure contact with the soil. This was important to ensure that accurate soil temperatures were measured.

To produce an accurate record of the distance between the sensor and the reflecting surface on the solifluction lobe riser, ultra sonic depth sensors were

Figure 3.1 Sample instrumentation of study sites.

positioned directly at the lobe snout at a slight angle from horizontal and carefully anchored with guy wires to reduce the potential for movement. Use of ultra sonic depth gauges requires a measurement of air temperature to calculate the density of the air in order to compute the distance to the target. Air temperature was taken 1.5m above the ground approximately 1.5m from the lobe front half way between the UDGs. Campbell Scientific Ultrasonic Depth Sensors were positioned approximately 3m to the left and right of the microclimate stations in the area immediately in front of each lobe (Figure 3.1).

Despite the care taken to ensure accurate data collection, there were sources for errors. First, calculation of the distance was dependent upon another independent variable, air temperature. Second, the sensor recorded the closest object in its path. Measured distance could have varied when tall standing vegetation such as *Betula glandulosa* and *Carex* spp. were blown over to within the 12° cone. Third, while the sensors were anchored into the ground, it was possible that the parent slope which the solifluction lobes were overriding moved as well. This could result in a change of the angle of the sensor which would cause it to measure a different point. Fourth, diurnal variations were present in the data. Problems arose when the sun heated the units. This pressurization of the sensor head caused a diaphragm within the sensor to stick, resulting in erroneous readings (Campbell Scientific Newsletter 1992). The problem was prevalent in the early morning, usually with the 0800 hours reading. However, it was common for the erroneous reading to occur at 1200 hours and to a lesser extent 1600 hours. The malfunction did not occur on overcast days but occasionally happened throughout the day and into the evening when clouds passed overhead. Together, the four sources of error caused inaccurate readings from low to high frequency in magnitude. Combined, the errors produced a data set in which no discernible pattern was evident.

Data Analysis

Systematic error in the data could not be corrected because the junction reference temperature in the datalogger was not stored. This value determines temperature differences along the length of the individual circuit connectors on the datalogger board. If it is measured, any discrepancies present can be traced to the individual circuit the thermocouple is attached to and corrected (Halliwell 1992). In an effort to reduce the systematic error inherent in each observation, the observations were averaged over a longer time period so that the positive errors would be cancelled out by the negative errors. Temperature data were reduced to mean, maximum, and minimum daily temperature. Out of range errors in the temperature data were removed manually from the data set.

The full subsurface temperature record at different depths in East II allowed the identification of the zero-curtain effect. This is the effect of latent heat of fusion of ice. It takes $4.2J/g^{-1}$ to cool 1 gram of water 1°C at 15°C while $334J/g^{-1}$ of heat must be extracted to freeze 1 gram of water (Williams and Smith 1991). This causes ground temperature to remain at or near 0°C for an extended period of time while freezing and thawing occurs. As the moisture content of the soil increases, the zero-curtain effect increases (Washburn 1979). The zero-curtain effect was identified by the periods during which the subsurface temperature remained constant at 0±0.450°C.

The raw distance values from the UDGs were measured on an angle (Θ). It was necessary to convert the values to a true horizontal distance to measure the true motion. Therefore, the cosine of Θ was taken to convert the distance measured on the angle to a horizontal value (Figure 3.2). These converted values were then subtracted from the manually measured distance from the sensor to the lobe surface yielding a change in distance from zero (ΔD). All graphs were produced using the transformed data set. Anomalous values associated with diurnal heating which caused the sensor to malfunction were manually removed from the data set and deleted values were interpolated.

RESULTS

Temperature

Full temperature records are contained in Appendix B. North II microclimate data were collected from 27 July 1992 until 23 August 1992 while East II data were collected from 28 July 1992 until 31 July 1993. Due to the late installation, no thaw period was recorded at the North II site. Consequently, thawing-degree-day and freezing-degree-day totals for the full record period could not be compared among the sites. Generally, this meant that absolute

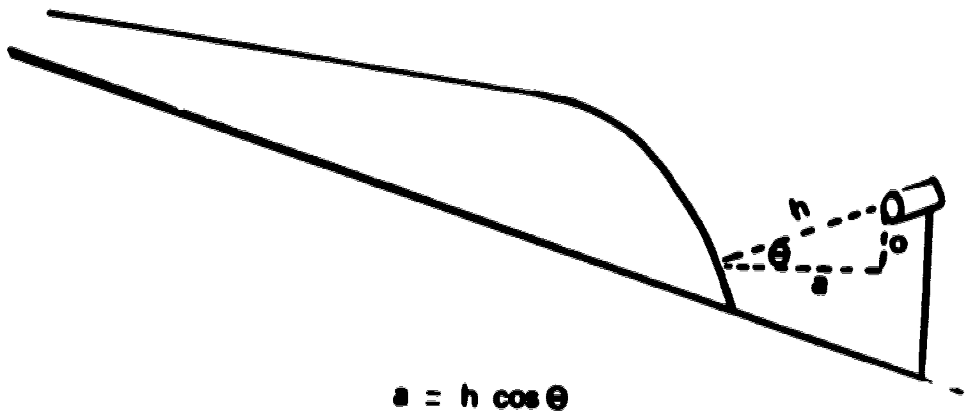

Figure 3.2 Derivation of horizontal distance from the Ultra Sonic Depth Sensor to the lobe front.

temperature values from only East I and the control site could be compared for the majority of the thaw season.

A complete subsurface temperature record was collected in the East II lobe for 8 of the 9 sample points. Unfortunately, due to animal damage, air temperature data were not recorded between 3 October 1992 and 21 June 1993. Additionally, the -5cm depth thermocouple at the prolobe failed on 1 October 1992 and was not re-excavated and repaired until 17 May 1993.

Temperature measurements were analyzed in three contexts: 1) variations with depth 2) variations within the lobes and 3) variations among the lobes. The separate analyses allowed characterization of thermal characteristics of the study sites. The summer temperature records of the control, East I and North II sites and the full year record of East II were compared.

Temperature variation with depth

The lowest mean annual temperatures for the full year record at East II were found at -20 and -50cm on the tread. The mean annual temperature decreased with depth on the tread and was below 0°C at -20cm and -50cm. The tread temperatures were approximately 1.2°C below the mean annual temperatures for the same depths on the riser during the 1992-1993 season. Mean annual temperatures at -20cm and -50cm depths on the riser at East II were lower than -5cm depth. The lack of temperature measurements at -5cm on the prolobe precluded any analysis of mean annual temperature at this location (Table 3.1).

Temperature at a depth of -50cm continued to decline at EII through the

Time Period	Site	Depth	Prolobe	Riser	Tread
13 June - 27 July 1992	Control	-5	7.872	7.965	7.555
		-20	5.109	5.115	3.87
		-50	1.648	2.428	0.802
	East I	-5	6.678	4.245	7.694
		-20	3.624	1.714	2.913
		-50	2.385	0.116	0.839
28 July - 23 August 1992	Control	-5	6.128	7.965	7.555
		-20	5.137	5.115	3.87
		-50	1.648	2.428	0.802
	East I	-5	6.758	6.294	6.701
		-20	5.547	5.173	5.395
		-50	4.61	3.444	4.26
	North II	-5	7.153	6.394	4.477
		-20	7.398	5.573	5.156
		-50	6.659	4.326	3.807
	East II	-5	6.889	7.799	5.869
		-20	7.261	6.673	4.419
		-50	6.491	5.289	4.959
28 July 1992 - 30 July 1993	East II	-5	N.A.	0.537	0.473
		-20	0.744	0.992	-0.638
		-50	0.674	0.732	-0.931

Table 3.1 Mean subsurface temperatures for specified periods.

autumn until 19 January 1993 when it stabilized at the riser (Figure 3.3) and tread (Figure 3.4). Winter temperatures on the riser at all depths were quite similar. Differences in the mean annual temperature were largely due to differences recorded during the summer periods. Winter temperature on the tread at -20cm closely followed that of -5cm. Very little time lag was present. Extreme high and low temperatures on the prolobe were recorded at the near surface (-5 cm) until the thermocouple failed 1 October 1992 and again after 17 May 1993 when it was repaired. Temperature on the prolobe at -50cm was almost identical to that of -20cm throughout the winter (Figure 3.5).

Mean summer subsurface temperature profiles at the other three sites were similar to East II. There was a general decrease in temperature at depth, however, some -5cm mean summer temperatures were lower than -20cm because the monitoring period included the beginning of the freeze-back. The smallest subsurface thermal gradient between -5cm and -50cm occurred at East II when the full year temperature record was averaged. Subsurface gradients were largest during the 13 June to 27 July 1992 period (≥0.089°Ccm^{-1} at East I and ≥0.122°Ccm^{-1} on the control). As heat penetrated into the soil on the lobe sites, the subsurface gradient decreased to ≤0.062°C on East I between 28 July and 23 August 1992. This contrasted with the control site which maintained a large subsurface gradient (≥0.100°Ccm^{-1}) between 28 July and 23 August (Table 3.1).

Intra-lobe comparisons

No freeze-back was recorded for the East I, North II and control sites. Freeze-back to a depth of 50cm on East II occurred first by 25 September 1992

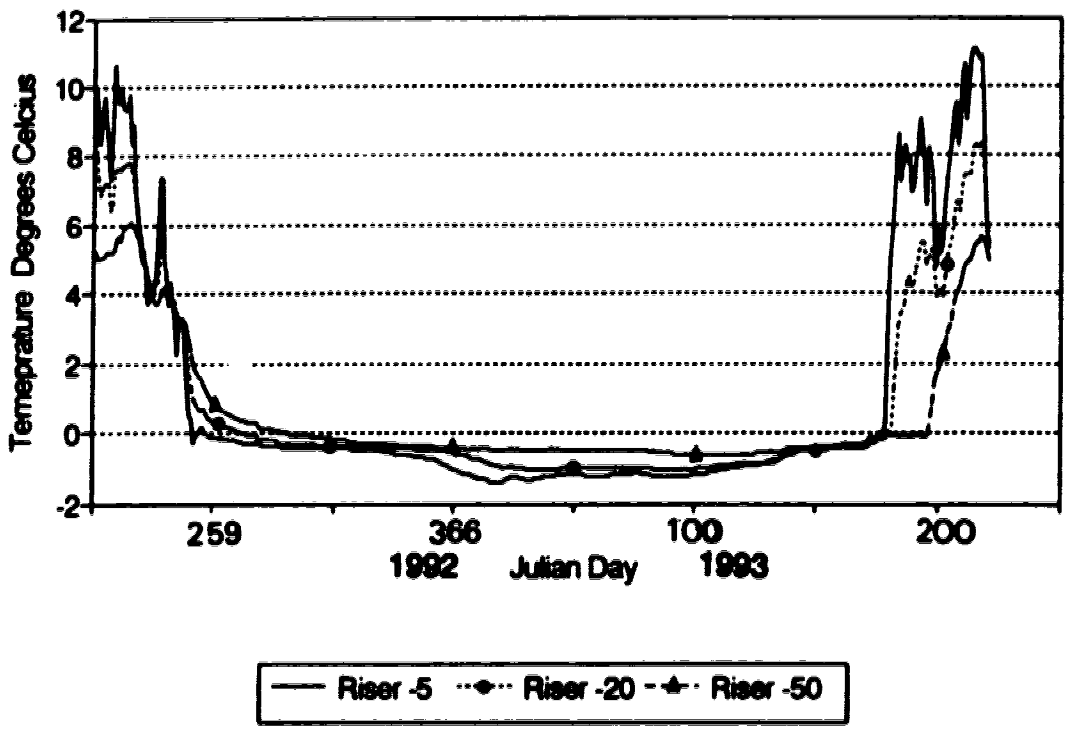

Figure 3.3 **Subsurface temperature record of the riser of East II. 27 July 1992 - 30 July 1993.**

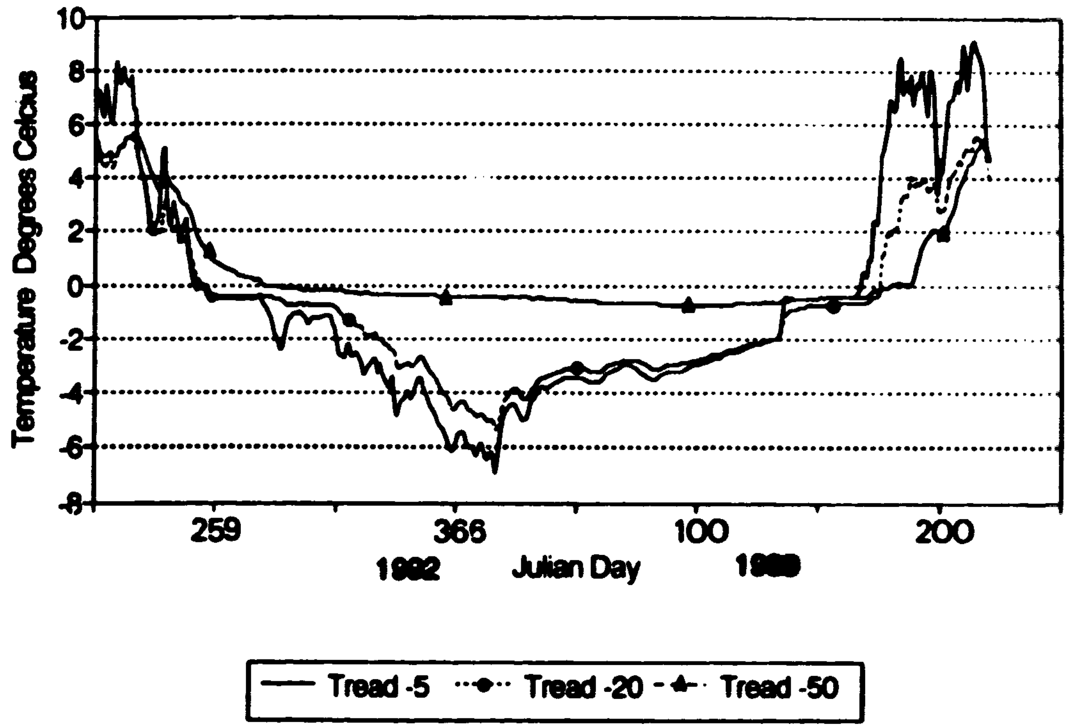

Figure 3.4 Subsurface temperature record of the tread of East II. 27 July 1992 - 30 July 1993.

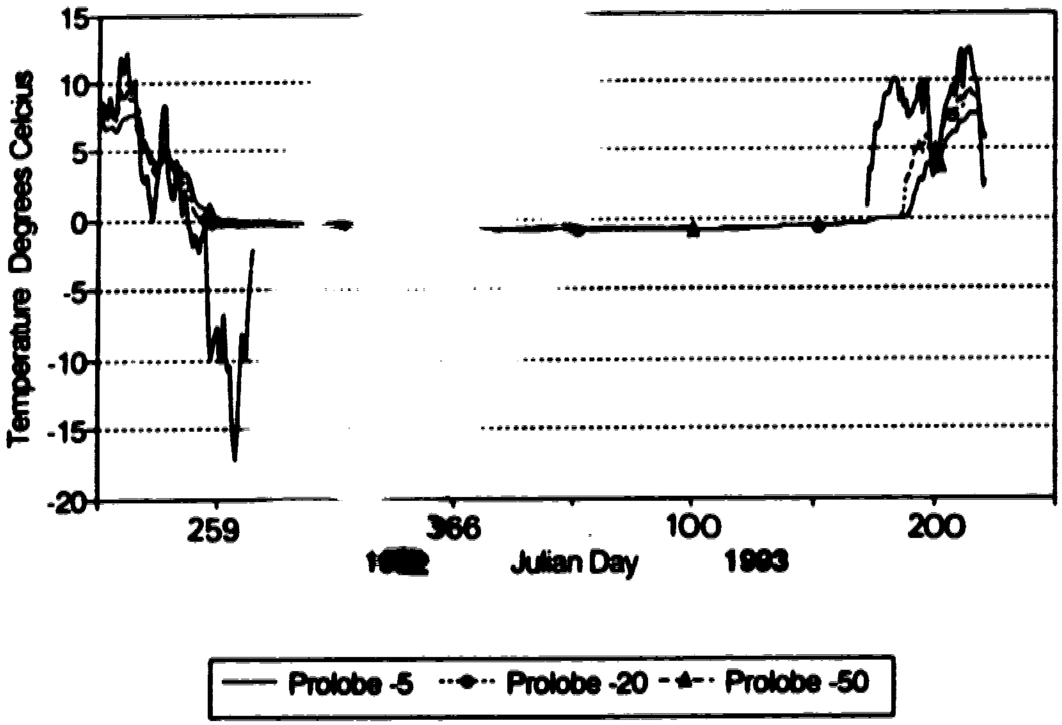

Figure 3.5 Subsurface temperature record of the prolobe of East II. 27 July 1992 - 30 July 1993.

on the prolobe, by 13 October on the tread, and 11 days later on the riser. The average rate of freezing between -5cm and -50cm was 2.05cm/day on the prolobe, 1.25cm/day on the tread and 1.07cm/day on the riser.

The fast freezing on the prolobe area of East II was related to the lack of a zero-curtain effect. The absence of this effect at the prolobe location - while it was present on the tread - suggests different physical conditions at the time of freezing. The relatively thin surficial organic layer on the prolobe allowed heat to be extracted sooner and faster than on the better insulated (i.e. thicker organic accumulation) lobe areas. Over the course of the growing season, the prolobe area dried while the tread maintained its moisture. Measured moisture content on the prolobe was slightly less than on the lobes (Table 2.1). This slight difference does not seem large enough to account for the difference in thermal regimes measured. However, moisture samples were taken in mid-summer and samples taken later in the summer may have reflected a larger moisture difference as drying continued. Assuming this to be true, the lack of moisture on the prolobe allowed the frost line to penetrate quickly.

On the tread, the thicker insulating organic layer (Figure 2.1) prohibited the ground from drying during the summer, and caused increased moisture retention. It has been reported that high moisture content reduces local freezing due to latent heat released upon freezing (Rouse 1982). The removal of latent heat is shown by the zero-curtain effect. Freezing was retarded when temperature on the tread hovered just below 0°C for 5 days at -5cm and for 28 days at -20cm.

The slow freezing on the riser cannot be explained by the subsurface moisture content because it was drier than the tread. No zero-curtain effect was identified here. Because temperature remained between 0°C and -2°C, throughout the winter, removal of heat from the ground appeared to be restricted by the presence of an early snowpack drifting against the lobe front. The high moisture and lack of insulating snow on the tread decreased the mean annual temperature there. Mean annual temperatures were approximately 1.2°C and 0.8°C on the riser and prolobe respectively.

The tread was the coldest and the riser the warmest during the 1992-1993 season on East II. This pattern has been documented previously (cf. Benedict 1970; Harris 1972; Price 1991). However, the mean subsurface summer temperatures (including the same time period for East II) indicated that the prolobe was the warmest area. The fact that East II showed the same pattern during the summer period indicates that full year monitoring at all sites would have determined the riser to be the warmest location.

At North II and East II, tread areas had the lowest mean summer temperatures (Table 3.1). Prolobes had highest mean summer temperatures at all three lobe sites. This pattern was present regardless of the orientation of the lobes indicating a colder micro-environment on the lobes. The tephra and C horizons (which comprised a large volume of the sediment in the soil column in both the lobes and parent slopes) had lower moisture contents on the prolobe areas than on the lobes (Table 2.1) More energy is required to heat up saturated soil than dry soil, so dry soils (i.e. prolobe areas) will heat up faster, producing an overall higher mean summer temperature.

Inter-lobe comparisons

All three lobes recorded similar air and subsurface temperatures. North II and East II had virtually the same air and subsurface temperatures. These two lobes recorded the lowest mean summer temperatures on the tread. Mean summer temperatures on East I were slightly different. These lower temperatures at depth at the East I site could be the result of installation effects. However, tread temperatures of the three lobes were quite comparable. Therefore, the larger thermal gradient on the riser and prolobe of East I may be the result of more severe microclimate. This hypothesis is supported by the presence of active frost sorting on this lobe. Temperatures on East I on the riser and prolobe were approximately 2°C lower than temperatures at -50cm on North II and East II.

Overall, the control site had a less variable microclimate than the lobes (Figure 3.6). Air and near-surface temperature (-5cm) maxima were lower and minima were higher confirming there were smaller temperature ranges than at the East I and East II sites during the same time period. A larger subsurface gradient was identified at the control site compared to the lobe sites. Higher -20cm and lower -50cm temperatures were recorded for the prolobe, riser and tread at the control site compared to the east-facing sites (Figure 3.7).

Penetration of the thaw front on the prolobe, riser and tread at the control and east-facing sites was from the surface down. There was no record of thaw at North II because the site was instrumented after the completion of thaw. The zero-curtain effect was present during thaw in the lobes. Thaw proceeded rapidly at the control site. The zero-curtain effect was minimal at this site, with all three

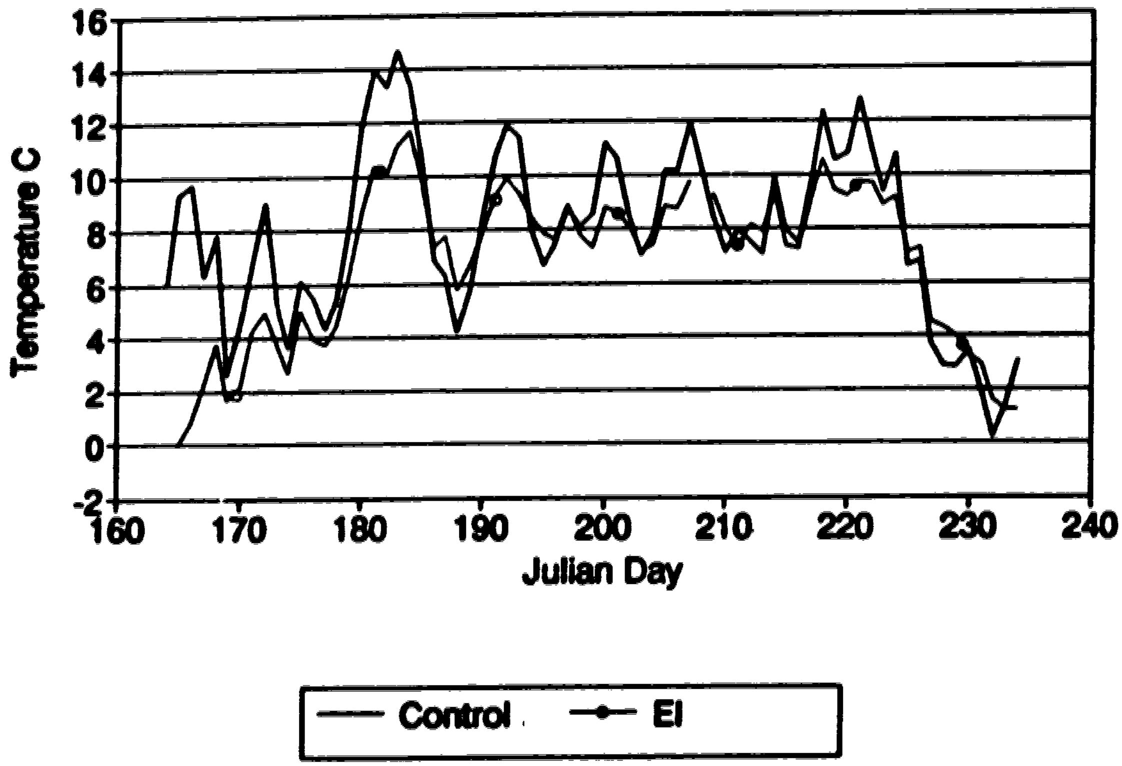

Figure 3.6 Comparison of mean daily air temperature for the control and East I for the period 13 June 1992 - 23 August 1992. Julian Day 160 = 8 June 1992.

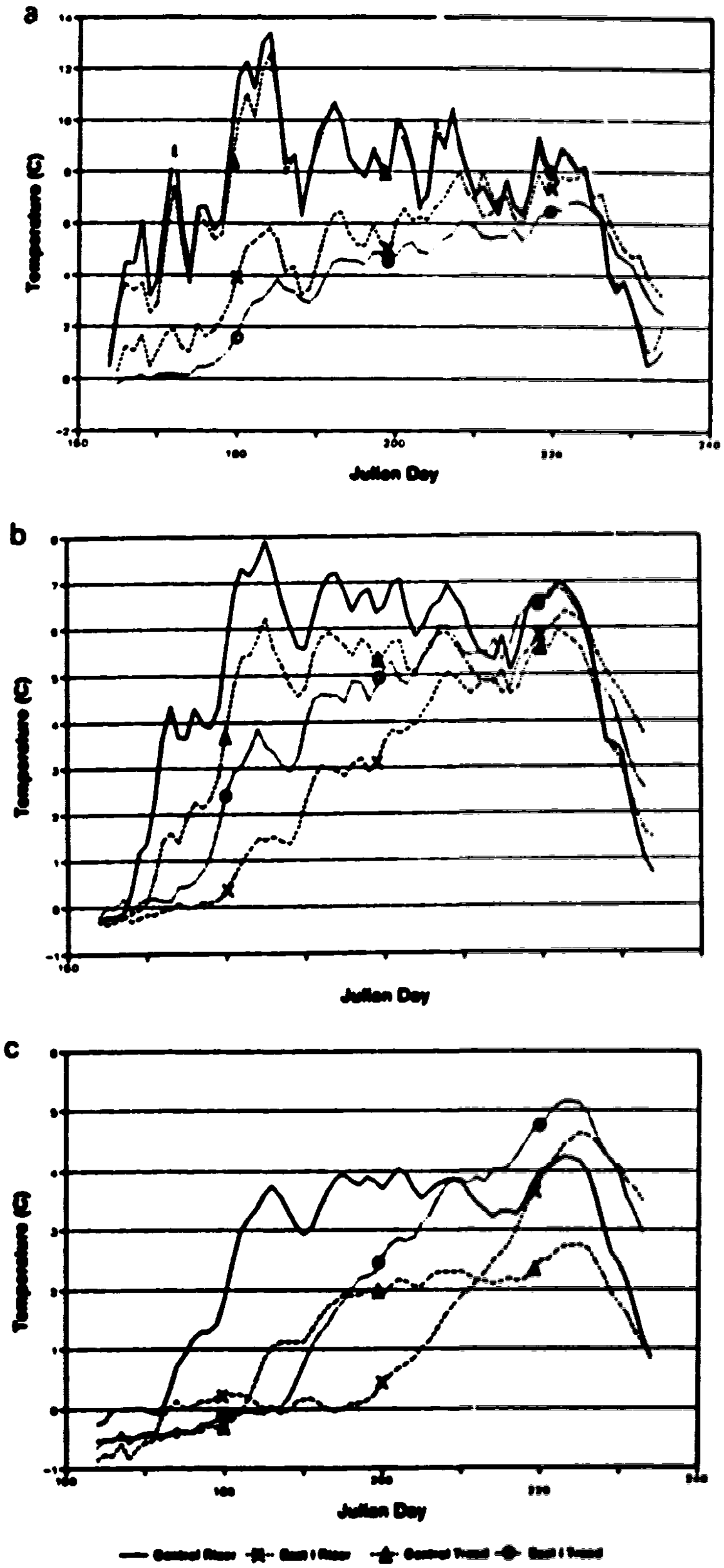

Figure 3.7 Comparison of riser and tread subsurface daily mean temperatures of the control and East I for the period 13 June - 23 August 1992. Julian day 160 = 8 June 1992. a = -5 cm depth b = -20 cm depth c = -50 cm depth.

locations thawing to a depth of -50cm within 9 days of one another. This rapid thaw contrasted with that at the east-facing sites. Neither east-facing site thawed until the middle of July and the zero-curtain effect lasted up to 49 days at -20cm on EI. No zero-curtain effect was identified at -20cm depth on the tread of East II but it was present at -50cm depth. The extended presence of the zero-curtain effect on the east-facing sites indicates that the control site and lobes had markedly different thermal fluxes due to varying water contents (Table 3.2).

Unfortunately, only freeze-back was recorded for East II. Similar thaw patterns on East I and East II indicate that freeze-back may have been similar. However, moisture supply at that time period was unknown and inferences about the freeze-back on the other three sites would not be tenable.

Movement

Movement was recorded for the control site and East I from 12 and 13 June 1992 respectively until 23 August 1992. Movement records were collected for the North II and East II sites from the 27 and 28 July 1992 respectively until 23 August 1992. Repositioning of the sensors on the control and East I sites was required after returning to the field on 24 July 1992 after a 2½ week absence.

All of the movement records showed large amounts of scatter. The manually measured distance was subtracted from the UDG measurements to determine a change in distance (ΔD). Regression equations were calculated to determine the overall ΔD of recorded movements. The total change in distance was determined as the y intercept (in all cases 0) minus the calculated regression

		Date Thaw initiated	Date Thaw complete	Total Duration Days
Prolobe -5				
	Control	< 12 June		N.A.
	EI	< 13 June		N.A.
	EII	< 21 June		N.A.
Prolobe -20				
	Control	< 12 June	16 June	> 5
	EI	< 13 June	25 June	> 13
	EII	27 May	5 July	40
Prolobe -50				
	Control	< 12 June	24 June	> 13
	EI	< 13 June	29 June	> 17
	EII	31 May	8 July	40
Riser -5				
	Control	< 12 June		N.A.
	EI	thawed		N.A.
	EII	thawed		N.A.
Riser -20				
	Control	< 12 June		N.A.
	EI	< 13 June	28 June	> 17
	EII	21 May	8 July	49
Riser -50				
	Control			N.A.
	EI	12 June	18 July	49
	EII	6 June	15 July	40
Tread -5				
	Control	< 12 June		N.A.
	EI	< 13 June		N.A.
	EII	13 June	19 June	7
Tread -20				
	Control	< 12 June	19 June	8
	EI	< 13 June	24 June	12
	EII	24 June	24 June	0
Tread -50				
	Control	24 June	30 June	7
	EI	19 June	17 July	30
	EII	7 June	7 July	31

Table 3.2 Summary of thaw periods of Control, East I and East II lobes. Control and EI values are 1992 data. EII values are 1993 data.

value of the distance for 23 August 1992. In almost all cases, the regression line was found not to be significantly different from zero at the 95% confidence interval. In cases where the regression did have a significant slope, r^2 values were low.

Control

For the period 12 June 1992 - 23 August 1992, thirteen days of data were lost because sensors were knocked down at the control and EI sites (11-24 July). Scatter in the recorded values made it difficult to determine movement rates. During the initial period at the control site, there was little movement producing horizontal lines on the graph with slopes which were not significantly different from zero at the 95% confidence level. On 24 July 1992, both UDGs located to the east and west of the lobe centre were repositioned. Following repositioning, the east sensor recorded radical change in the distance measured. Possible sources of the measurement were: 1) herbaceous components of the plant cover interfering with the signal, and 2) the sensor was not stationary. This could change the angle at which the sensor was positioned which would result in the measurement being made on a different point on the lobe (Figure 3.8).

East I

Significant scatter was initially present in the results from both the north and south sensor on East I. On 24 July 1992, the north sensor was repositioned accounting for the large increase in the distance measured. The regression equation for the south sensor indicated approximately 20mm of movement during the measurement period. Similarly, 30mm of movement on the north side from

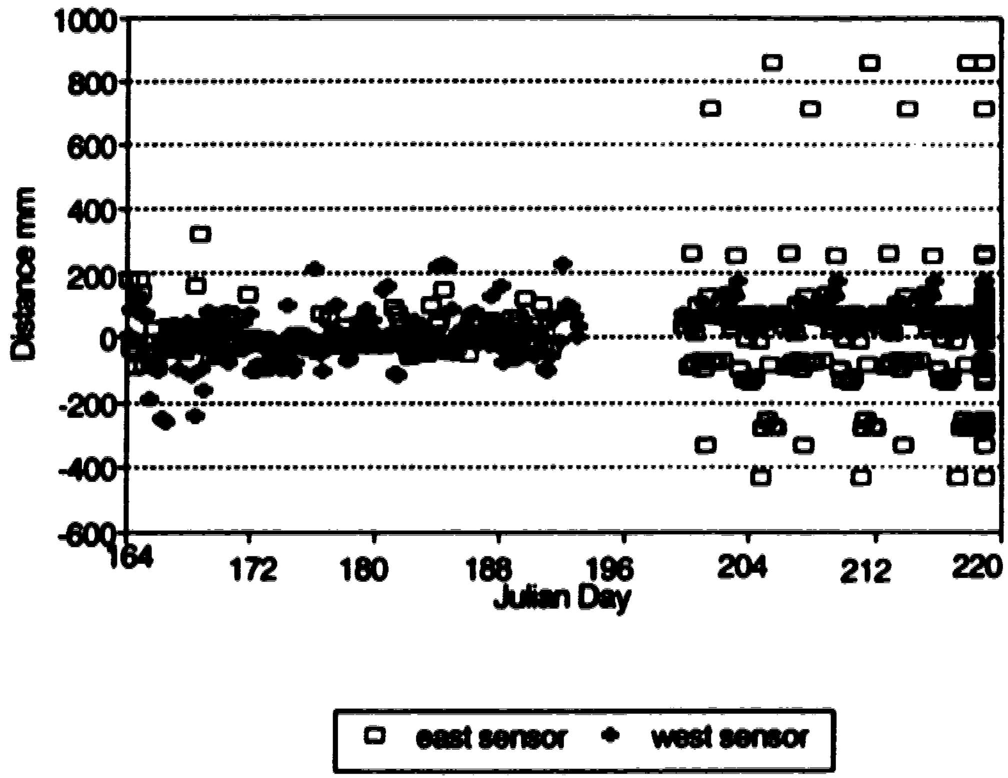

Figure 3.8 Measured movement for Control site. 12 June 1992 - 27 August 1992.

13 June until 2 July 1992 was determined using the regression equation. The recorded movement of these two sensors was similar in magnitude to the errors determined for measurement over a snowpack (Goodison *et al.* 1988). Following repositioning, the north sensor recorded rapid change in distance (ΔD) during two distinct time periods. The cause of the changes in distance measured is probably movement of the sensor head (Figure 3.9).

North II

North II UDGs did not measure any change in distance on the east or west side. Regression lines fit to the observations had slopes which were not significantly different from zero at the 95% confidence interval. Data points were scattered with no apparent trends (Figure 3.10).

East II

East II recorded the largest ΔD of the three lobes. Regression analysis indicated that there was approximately 250mm of movement over 24 days. While the regression relationship is stronger than that for any of the other lobes (r-squared 0.3581), the amount of scatter makes the magnitude of movement seem questionable (Figure 3.11). A possible explanation for the decrease in distance measured could have been a change in the angle of the sensor head due to subsidence and thaw around the stake on which the sensor was mounted. It was calculated that only a 7.3° rotation in the angle of the sensor from the vertical would account for 25cm of movement assuming a 44° riser angle. The effects of wind and thaw consolidation around the base of the pole upon which the UDG was mounted could easily account for this change in angle. Therefore, the sensor

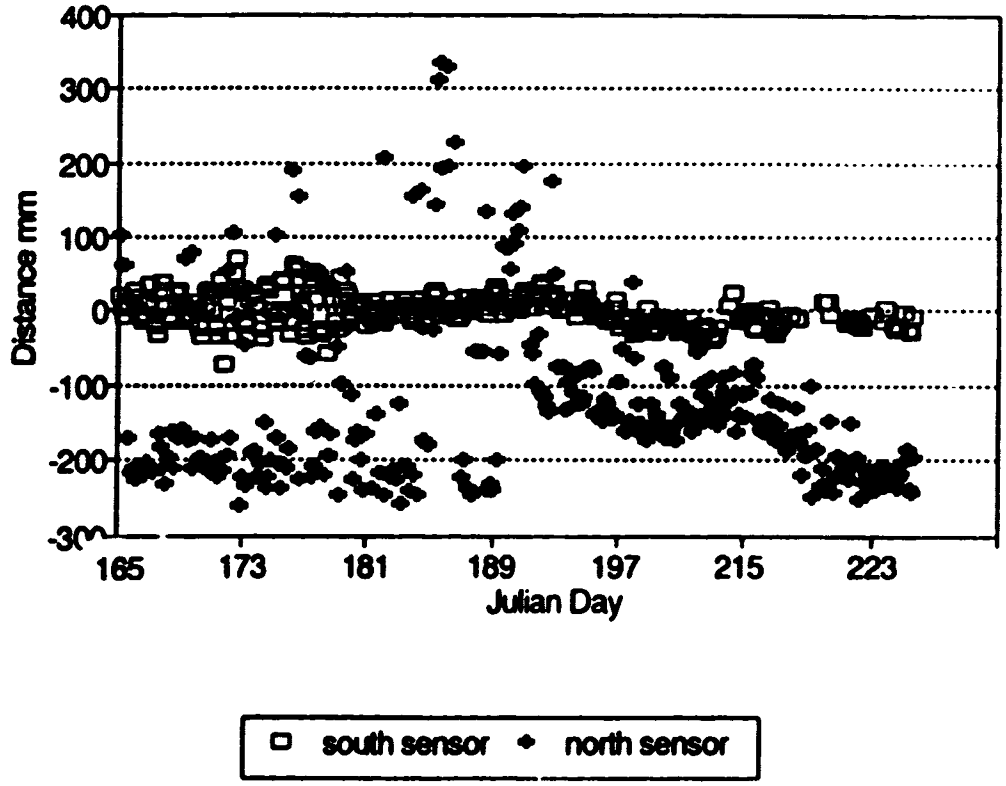

Figure 3.9 Measured movement for East I site. 13 June 1992 - 27 August 1999.

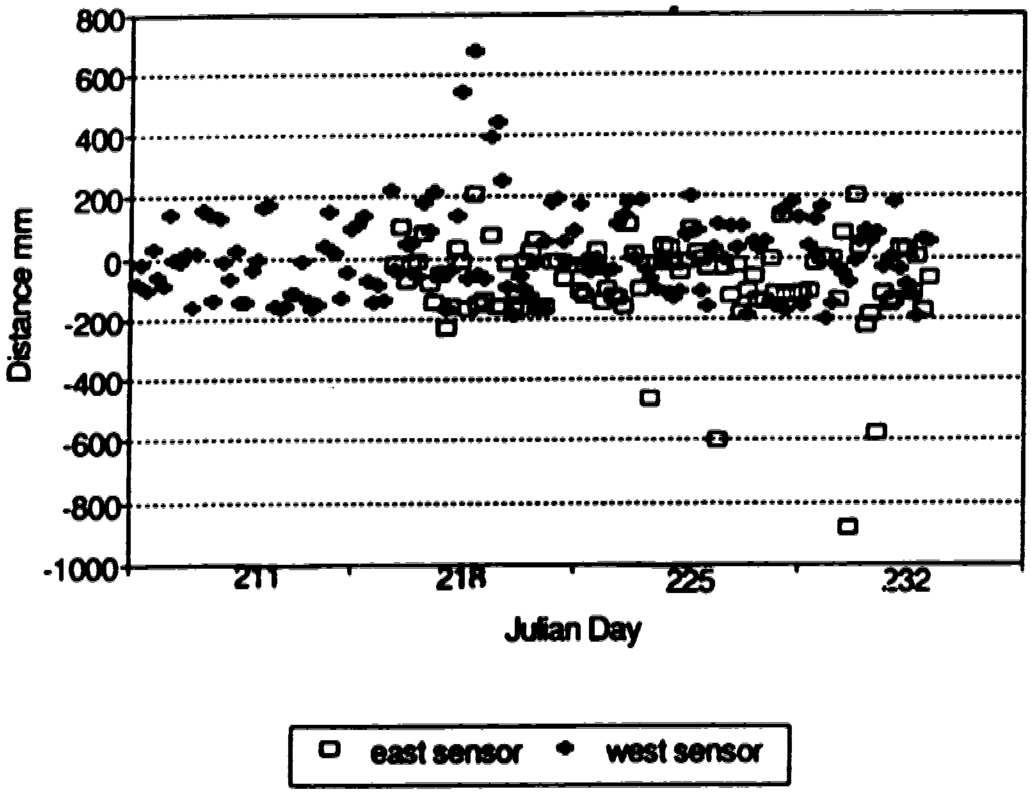

Figure 3.10 Measured movement for North II site. 22 July 1992 - 27 August 1992.

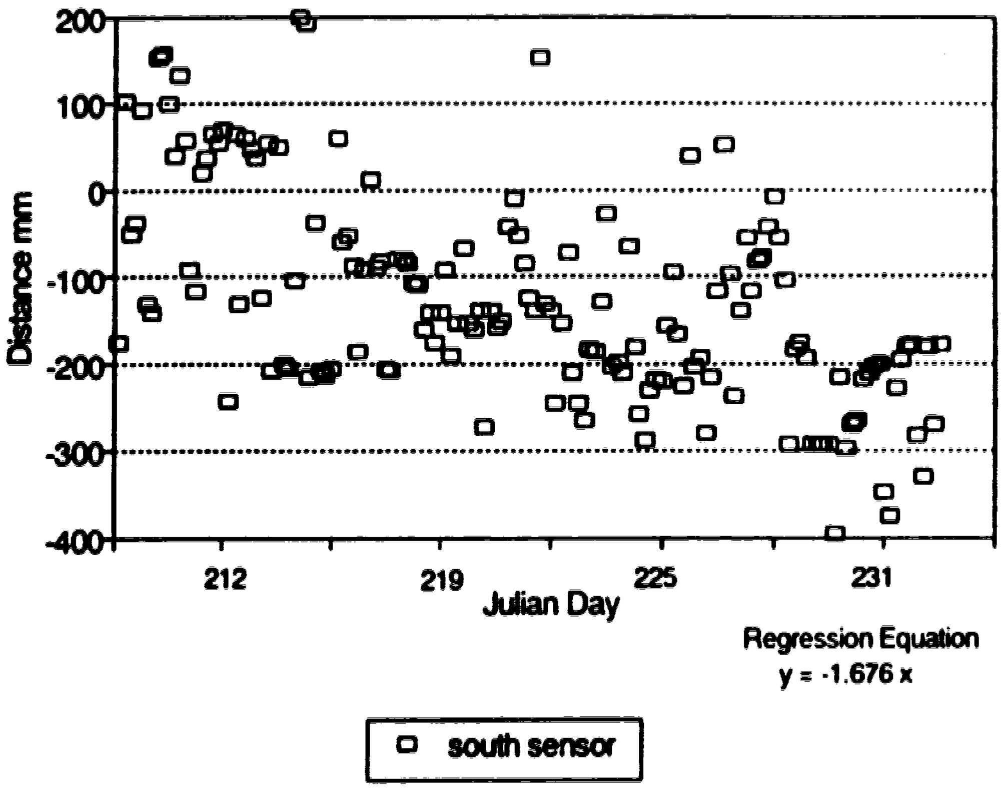

Figure 3.11 Measured movement for East II site. 23 July 1992 - 27 August 1992.

head continued to move throughout the 1992 summer season.

DISCUSSION

Temperature

Variations with depth

Penetration of frost was from the surface downwards at all locations on East II. This caused temperatures at depth to lag behind those near the surface. The pattern of mean annual temperatures decreasing with depth on the tread reflected the heat penetration. On the prolobe and riser, mean annual temperature did not necessarily decrease with depth. Lack of -5cm temperature measurements for most of the winter precluded any summary of the thermal regime at the prolobe. On the riser, extreme swings in -5cm temperature had the net result of decreasing the mean annual temperature. The near surface layer recorded these cycles while the soil at depth was insulated, especially during freeze-back. Winter temperatures on the riser at all depths were very similar. After thawing was complete, temperature at -5cm was the highest. This resulted in the non-linear temperature gradient at the riser.

Higher temperatures were recorded at -5cm compared to -20cm and -50cm depths at almost all sites between 13 June and 23 August 1992. This was the result of penetration of heat from the surface downwards. Temperature differences between -5cm and -50cm were highest for the control site and lowest for East II.

The control site had a larger thermal gradient compared to the lobe sites.

The control site consisted of washed fluvial gravels with high permeabilities facilitating rapid drainage which increased the sensible heat flux at the soil surface early in the thaw season. Upon drying, the heat capacity was reduced which allowed the temperature to rise quickly at the surface. At the same time, the thermal conductivity of the drying soil was reduced. Removal of water from the voids reduced the contact between the grains. The thermal conductivity of the soil constituents is quite different. Water a 0°C has a thermal conductivity of 0.56 $Wm^{-1}K^{-1}$ while air has a thermal conductivity of 0.025 $Wm^{-1}K^{-1}$. As drying occurred, energy transfer deeper into the soil was retarded due to the low thermal conductivity.

It took the control site riser an extended period of time to warm up to 0°C. The riser thawed quickly in the upper 20cm of soil after which heating then slowed considerably. This change in the sensible heat flux in the riser was likely due to drying. As thaw progressed, drying simultaneously reduced the thermal conductivity of the soil. At some depth between -20 and -50cm, the low thermal conductivity of the dry surface layers insulated the ground below from further heat penetration. On the tread, the fact that onset of warming occurred at -50cm before -5cm indicates that there was heat flux via soil water percolating from upslope. This was the only location which showed this trend. The gravelly material at the site would allow free drainage unlike the fine-grained material found in the three lobe sites. In addition, the presence of ground water could be partly responsible for the lack of heating at depth.

<u>Intra-lobe comparison</u>

The tread had lower subsurface summer temperatures on the control and lower subsurface mean annual temperatures on EII than the riser and prolobes for these two sites. It is hypothesized that the lower tread temperatures are the result of little or no snowpack on the tread surface. It has been reported that tread areas are swept free of snow permitting deeper frost penetration and lower winter temperatures (Washburn 1967; Harris 1972; Price 1991). The presence of frost leads to moisture migration during the freeze-back period. Slow gradual freezing allows sufficient time for water to migrate to the freezing front producing large ice lenses (Washburn 1968; Williams and Smith 1989). During thaw and subsequent warming, the large water contents from thawing ice lenses are retained by the fine grained soil. The increased heat capacity of the saturated soil retards heating. Therefore, summer subsurface temperatures are reduced.

The riser has previously been documented as the warmest area on solifluction lobes (Benedict 1970; Harris 1973; Price 1991). However, this was only true at the East II site. Benedict's study included winter data and should therefore, only be compared to a similar time period (i.e. East II). The full temperature record of East II indicates that freeze-back in the riser position was twice as slow as in the prolobe position. Riser areas were covered by a deep snowpack well into the onset of thaw during the 1992 season. This had the effect of insulating the ground from extreme swings in air temperature during the spring. It can then be inferred that the riser was likely insulated by snow or had a thicker snowpack early in the autumn while the prolobe and tread areas were exposed to the elements.

The other three sites had highest summer mean daily temperatures in the prolobe location. This contradicts Benedict's (1970) finding that the riser was the warmest location. The reason for the warm prolobe was related to the data collection period. The high temperatures on the prolobe were only present for the sites monitored during the summer period when the prolobes experienced drier conditions than the lobes. Lack of surficial organic accumulation allowed drying on the prolobes. As previously discussed, the sensible heat flux was higher at drier sites. It must be also noted that East II showed the prolobe area as the warmest site during the same time period. Therefore, further monitoring at other sites throughout the winter period would likely indicate that overall, the riser was the warmest location on the lobes.

Inter-lobe comparison

Despite the short duration, trends present in the North II and East II data sets correspond to results found for the same time period in the longer data sets for the control site and East I. Unfortunately, data for the freeze-back period at these two sites and thaw at North II were not available.

Throughout the summer period, East I and East II had lower maximum, higher minimum and lower overall mean subsurface temperatures than the North II lobe (Table 3.1). These east-facing sites also had higher overall moisture contents than the north facing sites. Increased water content retards soil heating in the spring period. It has been calculated that the largest portion of the soil heat flux during thaw is stored as latent heat (Halliwell and Rouse 1987). In this case, the different microclimate was the result of orientation and slope altering the angle of incidence of solar radiation. The differences in moisture due to microclimatic variations is supported because the lack of solifluction features on south or west-facing slopes due to increased insolation and drying (Smith 1985).

The temperature profiles at the control site were not significantly different from those at the other three sites. However, solifluction in any form was not developed here or within the immediate vicinity (<50m). Therefore, the basis for solifluction to occur in the study site was presumably the frost susceptible sediment texture, which allowed retention of water throughout the summer season. Upon freezing, ample moisture was available to migrate to the freezing front on the lobes. However, no correlation was found between sediment texture and movement rates - a condition previously documented by Harris (1981) and Smith (1985).

This study illustrates how variable moisture content can affect the temperature at different sites within close proximity to one another. The effect of different insolation due to orientation as a trigger mechanism to affect moisture content within the soil is largely unknown. The cause and effect relationship is difficult to pinpoint. Solifluction at this site appears to be near its climatic threshold because of the lack of features on south and/or west-facing slopes.

Movement

Scatter inherent in the movement data raises the question of their validity. North II values generated a horizontal line with scatter of 390mm throughout the 1992 summer period. This error is at least an order of magnitude larger than the maximum error reported by Goodison *et al.* (1988) for measurements over a snowpack. Potential sources for the error were: 1) within the sensor itself. The sensor may have not functioned properly mounted sideways. All previous field studies has mounted the sensor vertically usually to determine snow depth. 2) within the parameters used to calculate the measurements. This could be an error in the air temperature measurements. 3) the sensor position was affected by wind and insecure stabilizing cables; and 4) the scatter in part is the result of signals returning from other reflective surfaces (eg. vegetation). Pruning vegetation would remedy this problem, however, this could upset the natural transfer of energy into the soil. As large scatter was found at East I between 12 June and 7 July when the area was still covered with snow, it seems as if error due to vegetative interference was insignificant.

The period of highest movement on the control, East I and East II sites occurred during the warmest time of year after thawing of the upper 50cm of the soil was complete i.e. when plug-like flow would already have occurred. Therefore, the recorded movement was probably due to something else. Both of these sites had high moisture contents throughout the summer season. Presence of this water indicates that gelifluction could have continued on the parent slope throughout the measurement period causing a slight shift in the angle of the pole upon which the sensor was mounted. It was previously shown that a 7.3° change in angle would account for the total change in distance measured on East II. The continued decrease in distance measured was likely due to inadequately mounted sensors.

CONCLUSIONS

The subsurface thermal regime of the study lobes was quite similar. From the full temperature record of East II, it was determined that the tread areas were the coldest and the riser areas the warmest. The lobe forms were colder than their parent slope counterparts. Freezing and thawing on the lobe were prolonged compared to the prolobes. Furthermore, the zero-curtain effect was most pronounced on the lobes. Despite marginally different moisture contents between the prolobe and tread in mid-summer, temperature differences were concluded to be the result of lower moisture contents on the prolobe. Prolobe areas thawed and froze the fastest due to reduced heat capacity because of lower moisture contents. The control site was quite different from the lobes. The control site was drier than the other sites and consequently, thawing (and it can be inferred also freezing) regimes were altered.

Thaw progressed from the surface downward at all sites. Similarly, freezing occurred from the surface downward. Therefore, it is difficult to determine if the study site was an area of deep seasonal freezing rather than permafrost. The mean annual temperature between 1977-1983 (-7.7°C) indicates conditions favourable for solifluction. The interrelationships of particle-size, high moisture content, orientation, slope angle and vegetation create a positive feedback situation which may help to perpetuate lobe development. The cause and effect of heat inputs into the soil and warming causing drying is a complex one. Initially, local differences in moisture content resulting in enhanced lobe development are climatically driven (Benedict 1976; Morin and Payette 1988). Following establishment, the wetter lobes prevent further heating. This allows more moisture to be retained during the summer periods causing a further depression of mean annual temperatures.

The periods of freeze and thaw could not be attributed to increased movement due to inconclusive UDG results. Theoretically, this relationship of freeze/thaw to increased movement should be identifiable with this type of automated monitoring. However, any automated remote sensing technique must be evaluated for its robustness before it is employed in the field. Further study to gather empirical evidence of actual movement would be required to determine if these lobes are presently active.

This study has determined that measurements using ultra-sonic depth gauges have measurement errors that exceed movement. In addition, there was no control to determine if the location of the measurement equipment was stable. The automated technique could allow accurate results to be determined only after some of the questions about the technique are resolved. First, it must be determined if the sensors malfunction when mounted horizontally. Second, errors associated with measuring a vegetated surface must be determined. If these problems can be solved, any further studies using this technique must be mounted on bedrock. Because measurements made by the UDG are point measurements, the data from them is somewhat limited. Eggington and French (1985) reported variable rates of movement for different locations on the same lobes. The relatively cheap cost and simple instrumentation of traditional proxy techniques allows many more locations on the lobes to be instrumented to measure movement. In addition, many of the techniques quantify movement at depth. The UDG sensors do not have this capability. However, the main advantage remains that this method allows automated data collection.

Another possible remote sensing technique which may be more advantageous and less prone to errors would be a system which measures distance with laser technology. While more measurements of the morphology of the lobe could be taken, the major disadvantage like that of the UDG would be the inability of the method to measure the motion of particles in the way that the subsurface techniques do. Estimation of sediment movement at depth in the upslope portions of the lobe would not be possible. Therefore, it once again becomes a problem of comparability. Point measurements of the morphology of the lobe have never been compared to subsurface or surface target measurements. An investigation into the relationship of volumetric sediment transport to frontal lobe advance is required to allow comparison to other traditional techniques. Given the problems identified in this study, it is paramount that any measurement system used is mounted on bedrock.

Further investigations of using ultra-sonic depth sensors or similar techniques should suppress vegetation growth. Problems of drainage and the natural effect of vegetation on solifluction processes must be realized to ensure an undisturbed study. The best remedy may be to provide installation for long-term monitoring allowing comparison to other proxy techniques. Any further use of remote sensing devices to measure movement must be carried out in conjunction with proxy techniques. With further empirical evidence, possible relationships of volumetric sediment transport to morphological change at the front of the lobes may be determined.

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CHAPTER FOUR

CONCLUSIONS

Clast Fabric

Use of clast fabric measurements to infer depositional environment in solifluction deposits has produced some identifiable results. Macrofabrics were aligned with the local slope and were horizontal throughout the lobe length. Fabrics in this study were weaker than those previously documented for solifluction fabrics (Nelson 1985). Fabric strengths in this study were similar to those reported for undeformed lodgement till (Dowdeswell and Sharp 1986). This indicates that pebble reorientation in the study lobes did not produce such unimodal fabrics as that in the lobes in Nelson's (1985) study.

While the lobes had very similar fabrics, the stratigraphic and geotechnical evidence often pointed towards slight differences in genesis. This is not surprising as it has been reported that many different periglacial processes can contribute to similar fabric patterns (Van Vliet-Lanoe 1988). This was largely due to the fact that most periglacial forms are polygenetic in origin and separating the effects of different mechanisms on sediment is a difficult endeavour. The three lobes in this study have undergone similar processes.

Based on macrofabric analysis, it was concluded that all three lobes have been formed predominantly by gelifluction. The physical characteristics of East I suggest this lobe has experienced reworking of material by frost creep. Lines of evidence which suggested this were: the decrease in fines towards the snout, the increase in clast content towards the snout, visible frost sorting on the surface and the stratigraphic location of tephra within the lobe. The physical characteristics of East II did not suggest frost creep. There was no spatial sorting of the particle-size or clast content throughout the length, no visible frost sorting was evident and buried tephra layers were found. These characteristics suggested that sediment deposition was accomplished by gelifluction. The fabric at the North II midtread and riser suggested accelerated movement due to gelifluction relative to the east-facing lobes. However, many of the physical characteristics such as: washing out of fines, similar organic matter content in lower horizons throughout the length, thick surficial organic accumulation, and low riser angle, suggested the lobe was stationary. It is difficult to resolve these two seemingly different lines of evidence. A possible explanation for strong fabric reorientation could be that flow was plug-like in nature resulting in a stronger preferred orientation at the lobe riser compared to the other lobes.

Along the long axis of each lobe, dominant mass-wasting processes varied. Tread areas appear to have been slightly affected by frost creep. The plot of S_1 and S_3 eigenvalues (Figure 2.8) indicates that the treads from different orientations were affected similarly. Progressing towards the front, gelifluction became dominant at the midtread position. Fabrics at this location had low S_3 values indicating reworking by one mechanism. At the riser, fabrics continued to be dominated by gelifluction indicated by the horizontal dip of the clasts. Slight changes in the dip and preferred orientation as well as increase in clasts and sand-size particles at East I indicated frost creep has contributed to the lobe front (Everett 1967; Benedict 1970).

This study used a spatially based sampling scheme. The relationship of macrofabric and microfabric analyses to solifluction sediment has received little attention. Further investigations must include sampling at depth to detect evidence of plug-like flow. Further studies of solifluction fabric using the eigenvalue method will add to the data set allowing characterization of form and process based on the fabric.

Microclimate and Movement

Overall, the tread was found to be the coldest area in the study site while the prolobe area was the warmest. The subsurface temperatures of the lobes were lower than their prolobe (parent slope) counterparts. Subsurface temperature differences were the result of moisture content differences. Thaw progressed from the surface downward. Similarly, all freezing occurred from the surface downward indicating that the study site may only be an area of deep seasonal freezing rather than permafrost. Despite this, well developed solifluction lobes and sheets were present. Presence of solifluction sheets has been reported to occur only in areas with widespread permafrost (French 1974). However, microclimatic investigations do not support the presence of widespread permafrost. The North II and East II lobes were the leading downslope portions of large solifluction sheets. Therefore, the origin of the sheets may be from previous Holocene climatic conditions when permafrost was widespread.

While a comprehensive subsurface temperature data set was collected, no relationships could be found between climatic events and movement. This was largely due to questionable movement recordings. This study has determined that measurements using ultra-sonic depth gauges have measurement errors that exceed movement. The accuracy and resolution of the UDGs must be determined in this type of application (i.e. horizontally mounted over a vegetated surface) before any further studies are completed. In addition, it was found that a small change in the angle of the sensor head (7.3°) on East II could account for the amount of "movement" recorded there. Therefore, any further studies employing this method *must* be mounted on bedrock.

Inter-Lobe Comparisons

North II was concluded to be stationary at this time. The effect of northward orientation on solifluction lobe development is not known for the study area, but the microclimatic investigations showed a less severe environment than eastward orientation. It was obvious from the fabric as well as through the presence of two sets of soil horizons that North II had deformed in the past sometime after 1250 BP. However, many of the contemporary physical characteristics indicated there was no movement at present. North II was the only lobe in which fabric did not increase in strength after rotating parallel to the local slope. Lack of any frost sorting on the feature as well as no increase in coarse material forward discounts frost creep as the cause for this. Instead, the stones have likely been stationary since reworking by plug-like flow.

Both east-facing sites appear to be active at this time. However, the lobes have different vegetation, different spatial distribution of sand-size particles and stratigraphy indicating different processes at work. One of the East I UDG sensors recorded a movement trend similar in timing and magnitude to previous studies (cf. Benedict 1970; Mackay 1981). The continuous movement throughout the summer season is similar to that reported by Mackay (1981). Scatter was large but the overall trend of 20-30 mm could have been real. However, errors associated with UDG measurements over a snowpack have been determined to be ±2.5cm (Goodison *et al.* 1988). Therefore, none of the UDG results will allow any conclusions to be made about movement.

Summer temperatures were similar between these two sites. Therefore, different stratigraphic sequences may be the result of:

a) differences in other physical characteristics namely moisture which is related to parent slope, and summer insolation due to orientation

b) microclimate among the sites is significantly different. More complete microclimate data sets (i.e. including winter records) may show larger differences. East I was an open area and East II was quite sheltered. Consistently high snowfall (as was the case in winter 1991-92) would effectively bury East II, sheltering the ground from any extreme temperature swings. By contrast, East I would be swept free of snow on the tread and exposed to the elements.

The fast freezing and thawing and overall warmer temperature profile of prolobe compared to the lobes indicates that the lobes perpetuated themselves. Once established, colder subsurface temperatures resulted in enhanced periglacial processes. The date of origin of the lobes is unknown. However, due to the presence of buried White River ash, the lobes have been active at some point between 1250 BP and present.

Although the limitations of short-term monitoring were realized, this study was the first to document and characterize solifluction sediment in the Selwyn-Mackenzie Mountains, Northwest Territories. Interpretations of solifluction sediments should use as many lines of evidence as possible. It is obvious that the relationship of increased rates of solifluction movement to the periglacial processes at work is not fully understood. Further studies documenting the relationship between contemporary movement and contemporary climate may also shed some light on the complex interaction of the variables at work on periglacial slopes.

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APPENDIX A

Fabric Data for Lobe sites

Points   Rotated EI Trench 1 Prolobe/Riser   19-11-1993

Trend and Plunge of Grain Axes

249	4	349	33	181	6	68	2	336	6
338	29	111	13	30	0	345	9	295	11
91	4	293	1	331	10	347	13	279	11
210	12	129	4	157	7	29	6	14	3
334	15	339	13	121	2	337	41	86	9
84	33	123	6	181	11	214	2	101	6
104	3	338	22	336	13	194	2	286	5
118	7	207	3	211	7	67	16	193	6
316	5	41	17	229	7	21	10	310	12
33	6	47	10	201	40	335	13	155	15

Points   Rotated EI Trench 2 Midtread   19-11-1993

Trend and Plunge of Grain Axes

175	2	342	6	307	19	257	12	164	16
20	43	121	21	140	0	127	7	166	1
125	11	309	10	179	12	188	13	144	10
207	8	12	7	304	13	299	4	163	8
350	9	339	29	353	7	132	13	341	15
201	13	168	9	333	11	201	10	214	18
144	10	156	1	187	10	347	9	128	12
156	2	195	4	344	7	350	9	347	4
6	14	24	0	210	2	186	15	227	30
180	14	15	23	111	13	150	10		

Points   Rotated EI Trench 3 Tread   19-11-1993

Trend and Plunge of Grain Axes

278	42	299	14	35	1	215	3	340	10
220	0	147	1	231	10	167	1	265	11
0	13	59	15	127	13	180	16	200	30
140	13	269	10	164	3	12	5	21	8
310	1	327	62	50	16	348	5	348	0
246	5	241	4	144	12	116	12	10	6
138	5	142	12	162	12	131	11	121	30
153	3	136	6	355	17	130	11	323	14
139	8	318	8	150	35	26	5	206	0
265	6	126	12	34	3	163	12	264	12

50 Points Rotated EII Trench 2 Riser 19-11-1993

Trend and Plunge of Grain Axes

335	3	347	13	342	2	337	6	299	1
319	14	337	11	176	2	8	10	339	10
33	4	198	2	349	26	311	10	272	9
312	40	349	48	337	12	287	15	346	17
342	11	7	4	13	22	81	3	18	8
295	2	63	5	296	9	178	10	318	14
351	1	343	13	316	10	23	7	181	2
357	7	242	10	203	1	228	28	159	13
242	4	110	4	15	14	146	5	171	3
286	4	309	24	163	2	353	35	285	5

49 Points Rotated EII Trench 3 Midtread 19-11-1993

Trend and Plunge of Grain Axes

339	12	323	5	187	7	12	10	233	12
128	10	107	13	85	2	117	3	331	5
321	4	166	2	285	3	352	6	271	8
289	5	340	0	169	2	89	9	172	8
303	2	11	14	157	5	71	3	346	1
108	3	104	2	79	10	29	7	91	0
170	19	187	8	321	6	111	8	307	1
301	9	1	11	332	11	217	5	182	14
291	5	146	5	253	11	141	8	331	1
16	10	158	5	14	9	317	1		

49 Points Rotated EII Trench 4 Tread 19-11-1993

Trend and Plunge of Grain Axes

307	8	53	7	315	0	106	7	292	9
133	10	354	12	96	5	290	10	135	6
114	3	302	0	227	2	34	2	167	19
133	5	300	11	163	3	346	13	303	1
186	4	243	2	294	13	105	0	274	8
226	3	181	3	160	11	191	12	148	2
197	8	337	5	165	16	152	3	109	11
341	12	276	12	351	1	172	4	337	4
79	4	335	13	335	6	141	12	105	2
343	3	325	9	85	12	326	12		

Points Rotated NII Trench 2 Riser 19-11-1993

Trend and Plunge of Grain Axes

188	17	360	1	336	13	334	16	148	17
2	19	239	5	142	22	54	10	139	13
194	12	197	15	330	21	338	5	319	12
334	9	107	13	123	5	323	14	327	10
344	8	98	4	276	22	83	17	332	2
197	13	173	16	259	9	55	6	143	19
342	13	158	7	356	5	1	2	0	9
113	7	325	19	51	23	148	10	180	23
194	12	334	1	5	17	355	4	331	7
334	12	320	20	324	1	191	23	350	19

Points Rotated NII Trench 3 Midtread 19-11-1993

Trend and Plunge of Grain Axes

13	2	198	12	29	12	31	7	199	3
345	17	341	12	62	3	237	7	359	13
21	22	138	13	15	22	179	23	158	12
7	0	334	2	339	12	123	0	345	11
10	9	67	8	198	18	194	20	197	13
358	15	226	18	51	11	343	10	194	21
208	22	119	0	135	14	180	21	183	26
315	14	334	6	341	9	199	6	306	12
16	7	192	19	329	7	204	18	260	6
269	26	322	4	218	13	1	25		

Points Rotated NII Trench 4 Tread 19-11-1993

Trend and Plunge of Grain Axes

194	11	103	22	23	19	49	12	7	22
344	5	347	7	25	0	3	5	97	9
59	20	13	19	266	7	335	7	241	17
227	9	17	4	257	9	341	7	218	15
30	0	90	10	138	2	43	20	24	20
27	9	85	38	29	16	75	24	206	23
227	8	37	20	313	66	137	1	163	4
212	2	78	10	171	15	319	9	329	17
237	11	29	15	1	18	231	6	236	14
309	16	334	9	205	20	337	1	62	7

. Points EI Trench 1 Prolobe/Riser

Trend and Plunge of Grain Axes

143	2	63	49	355	10	142	18	60	22
52	45	5	3	104	16	239	7	189	5
165	20	187	15	225	4	61	29	173	5
284	28	23	12	231	23	283	10	88	19
228	1	53	27	15	14	66	59	340	7
158	49	197	22	75	5	288	18	355	10
178	19	56	38	60	29	268	18	180	11
192	23	101	13	105	9	321	0	87	10
30	21	115	33	123	9	275	6	204	4
41	22	121	26	275	56	229	3	49	1

Points EI trench 2 mid tread

Trend and Plunge of Grain Axes

69	14	60	15	57	8	230	34	241	12
236	10	19	5	244	7	38	6	80	30
21	35	23	26	53	45	230	17	98	16
151	4	73	4	247	9	81	6	284	18
215	30	82	3	206	29	241	7	260	31
58	0	218	26	55	31	202	28	301	46
94	59	101	8	85	3	230	18	254	30
195	37	266	9	62	7	269	20	89	39
214	16	18	29	227	11	58	23	5	3
21	9	13	20	275	26	244	7	44	6

Points EI Trench 3 Tread

Trend and Plunge of Grain Axes

352	58	74	29	204	15	32	11	31	8
13	30	133	31	41	78	36	4	212	8
289	15	201	29	304	0	56	4	224	51
109	13	254	32	62	21	25	5	100	21
54	26	274	46	62	16	195	46	280	16
294	16	34	3	140	11	227	19	159	10
41	15	163	6	315	20	210	22	220	28
125	6	58	13	38	4	69	33	108	19
61	15	266	11	10	4	204	27	237	28
159	5	21	24	264	10	217	2	158	4

Points EII Trench 2 Riser

Trend and Plunge of Grain Axes

41	17	279	10	48	25	237	13	128	10
233	1	264	16	253	10	49	27	356	10
48	16	55	40	79	36	22	24	81	28
43	20	17	24	327	11	89	21	32	9
5	15	158	5	84	22	67	12	57	11
25	28	18	54	1	16	63	21	172	10
43	25	55	62	129	19	128	4	15	38
62	12	43	26	2	23	89	13	49	12
74	24	355	29	64	4	294	42	59	49
45	24	52	31	24	28	225	27	171	9

Points EII Trench 3 mid tread

Trend and Plunge of Grain Axes

45	26	207	10	189	12	236	33	177	9
29	19	232	16	77	28	253	22	32	9
253	21	171	11	43	9	207	8	139	3
258	4	244	8	137	17	177	22	27	6
299	26	337	22	52	15	13	15	37	15
194	24	355	19	354	11	187	5	262	4
173	27	46	14	350	12	247	3	44	9
151	16	235	16	325	4	38	25	360	5
183	17	155	23	175	7	283	19	203	13
217	9	58	6	157	14	68	0		

Points EII Trench 4 tread

Trend and Plunge of Grain Axes

193	6	180	17	72	10	263	22	145	18
119	21	8	14	309	16	223	9	41	27
21	14	293	16	180	1	231	30	221	8
352	7	280	12	171	14	38	11	27	2
178	5	233	33	160	6	175	25	171	16
19	4	19	9	112	11	227	2	229	11
240	2	186	3	247	17	162	2	211	5
342	9	49	11	46	3	57	15	331	2
176	4	232	1	77	2	58	10	212	2
201	20	189	13	34	12	223	10		

Points NII Trench 2 Riser 15- 7-1993

Trend and Plunge of Grain Axes

328	6	154	35	124	15	122	10	334	11
140	22	337	8	58	27	118	30	114	22
116	10	110	2	56	1	316	28	145	6
114	7	298	28	223	6	141	21	135	19
288	6	99	11	112	21	140	14	111	16
142	4	114	14	337	10	253	16	114	11
19	18	247	10	313	7	105	4	100	3
282	1	83	28	119	32	291	0	104	22
194	13	103	9	15	29	108	33	331	0
279	10	107	13	283	4	320	0	130	4

Points NII Trench 3 Midtread 14- 3-1994

Trend and Plunge of Grain Axes

333	25	338	11	169	11	351	30	159	26
125	6	121	11	22	26	17	16	139	13
161	1	278	10	155	1	319	0	158	35
7	23	114	21	119	35	123	23	125	12
150	14	207	15	338	5	334	3	337	10
138	8	6	5	191	12	123	13	334	2
348	1	119	23	275	9	324	2	323	49
125	9	114	17	121	14	339	17	86	11
156	7	332	19	109	16	344	5	40	17
269	49	102	19	358	10	1	48		

Points NII Trench 4 Tread 15- 7-1993

Trend and Plunge of Grain Axes

334	12	19	43	350	23	287	31	17	12
243	1	153	4	230	13	177	3	169	8
163	4	46	16	98	25	273	89	141	5
189	11	115	16	183	3	97	24	11	17
147	1	21	6	164	3	123	27	16	9
124	18	7	14	167	14	172	25	89	7
127	16	157	19	45	61	218	13	114	14
345	23	37	14	169	7	311	8	345	3
323	28	121	16	34	47	199	14	117	22
237	14	352	8	346	0	109	6	22	30

APPENDIX B

East II Temperature Record

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[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

North II Temperature Record

Julian Day	Mean Prolobe -5cm	Mean Prolobe -20cm	Mean Prolobe -50cm	Mean Riser -5cm	Mean Riser -20cm	Mean Riser -50cm	Mean Tread -5cm	Mean Tread -20cm	Mean Tread -50cm	Mean Wind m s-1
209	10.38	8.28	6.407	8.58	6.163	3.398	8.56	5.199	2.521	0.2
210	8.65	7.88	6.375	7.28	5.748	3.43	6.669	4.836	2.552	0.218
211	10.08	7.86	6.37	7.9	5.372	3.362	8.06	4.637	2.506	4.22
212	8.73	7.5	6.244	7.04	5.231	3.301	6.886	4.563	2.578	2.982
213	8.24	7.51	6.209	6.67	5.177	3.289	6.298	4.547	2.672	3.503
214	9.69	7.5	6.202	7.81	5.111	3.195	7.38	4.448	2.798	1.725
215	8.28	7.89	6.184	6.612	5.313	3.229	6.464	4.733	2.572	3.42
216	7.87	7.17	6.129	6.5	4.938	3.189	6.2	4.353	2.582	3.481
217	9.23	8.67	8.74	7.26	6.073	7.42	5.101	3.201	6.776	4.453
218	11.84	10.68	7.75	6.163	8.95	5.493	3.204	8.19	4.686	2.583
219	10.05	9.35	7.93	6.223	7.7	5.649	3.373	7.35	4.981	2.752
220	10.62	8.44	7.91	6.33	7.93	5.755	3.442	7.51	5.015	2.829
221	12.48	11.01	8.03	6.444	8.47	5.666	3.445	8.51	5.018	2.835
222	10.65	9.68	8.26	6.476	8.06	5.917	3.634	7.92	5.519	3.083
223	9.22	9.26	8.11	6.549	7.77	5.959	3.683	7.46	5.345	3.17
224	10.23	9.76	8.07	6.578	8.19	5.869	3.718	7.5	5.231	3.183
225	6.491	8.02	7.83	6.513	6.675	5.738	3.764	6.459	5.13	3.233
226	6.537	8.31	7.57	6.468	6.778	5.416	3.706	6.326	4.886	3.189
227	3.478	6.101	7.05	6.269	4.808	4.917	3.571	4.664	4.49	3.085
228	2.689	5.469	6.236	5.997	4.277	4.231	3.356	4.218	3.882	2.894
229	2.628	4.894	5.872	5.661	3.96	4.002	3.147	3.856	3.656	2.716
230	3.28	4.385	5.556	5.458	3.519	3.797	3.002	3.354	3.422	2.593
231	1.743	3.98	5.014	5.233	2.93	3.259	2.823	2.814	2.906	2.429
232	-0.179	3.316	4.632	4.942	1.89	2.762	2.564	2.123	2.622	2.202
233	1.009	3.485	4.286	4.725	1.894	2.303	2.32	2.304	2.346	2.025
234	2.265	4.34	4.167	4.573	1.983	1.938	2.059	2.977	2.28	1.862

East I Temperature Record

Julian Day	Mean [illegible] -5 cm	Mean [illegible] -20 cm	Mean [illegible] -40 cm	Mean [illegible] -5 cm	Mean [illegible] -20 cm	Mean [illegible] -40 cm	Mean [illegible] -5 cm	Mean [illegible] -20 cm	Mean [illegible] -40 cm	Mean Wind m s-1
164										
165	-0.824	-0.154	-0.103	0.272	-0.323	-0.671	2.329	-0.21	-0.040	3.342
166	0.825	0.135	-0.120	1.210	-0.280	-0.704	[illegible]	-0.085	-0.013	[illegible]
167	2.157	0.142	-0.100	1.844	-0.336	-0.79	4.793	-0.046	-0.530	2.730
168	3.777	[illegible]	-0.49	[illegible]	-0.173	-0.300	0.615	0.172	-0.302	[illegible]
169	1.674	-0.007	-0.107	0.446	-0.314	-0.034	2.360	-0.083	-0.585	2.12
170	2.105	-0.080	-0.130	1.025	-0.243	-0.077	3.163	0.100	-0.407	2.07
171	4.313	0.135	0.04	1.086	-0.171	-0.571	6.144	0.108	-0.407	1.300
172	[illegible]	0.105	0.080	1.917	-0.157	-0.541	6.073	0.170	-0.404	2.30
173	3.715	0.080	0.043	1.100	-0.072	-0.176	4.51	0.131	-0.435	2.404
174	2.40	0.04	0.085	1.030	-0.087	0.007	3.651	0.132	-0.443	2.320
175	4.503	0.100	0.154	2.074	0.085	0.135	5.700	0.42	-0.346	1.735
176	3.080	0.154	0.100	1.047	-0.044	0.013	4.042	0.402	-0.41	2.405
177	3.700	0.250	0.154	[illegible]	0	0.083	4.205	0.502	-0.374	2.071
178	4.46	0.440	0.103	2.321	0.080	0.130	5.222	0.604	-0.305	1.50
179	6.324	1.06	0.246	2.944	0.082	0.133	6.60	1.131	-0.267	1.377
180	8.65	2.175	0.280	4.043	0.105	0.173	11.13	1.750	-0.100	2.305
181	10.37	3.300	0.701	5.021	0.30	0.274	12.52	2.405	-0.073	1.046
182	10.02	4.06	1.302	5.300	0.670	0.237	11.46	2.94	-0.085	2.740
183	11.1	4.405	1.801	5.953	0.875	0.230	13.70	3.005	-0.05	2.001
184	11.00	4.823	2.300	5.01	1.247	0.211	14.05	3.412	-0.064	1.500
185	9.82	5.246	2.001	5.300	1.405	0.005	10.82	3.040	-0.065	1.437
186	7.4	5.005	2.005	4.140	1.440	0.000	7.06	3.404	-0.082	1.72
187	7.70	4.877	3.015	4.32	1.546	0.082	7.53	3.353	0.005	1.015
188	5.005	4.300	2.000	3.234	1.397	-0.005	4.005	3.053	0.025	1.003
189	6.725	4.404	3.014	3.470	1.34	-0.020	6.173	2.000	0.172	1.007
190	7.80	4.780	3.173	4.400	1.003	0.110	8.25	3.219	0.400	1.025
191	9.30	5.105	3.303	5.736	2.271	0.16	10.30	3.040	0.742	1.800
192	9.60	5.002	3.72	6.327	2.770	0.17	11.42	4.47	1.005	1.027
193	9.30	5.015	3.041	6.451	3.005	0.000	10.4	4.505	1.20	0.97
194	8.47	5.043	4.102	5.827	3.000	0.013	8.11	4.502	1.403	0.206
195	7.00	5.701	4.235	5.100	2.942	-0.035	7.16	4.581	1.632	0.220
196	7.85	5.63	4.220	5.105	2.015	0.000	7.01	4.42	1.005	0.243
197	8.83	5.807	4.20	5.823	3.074	0.075	8.63	4.054	1.000	0.302
198	7.04	5.001	4.300	5.251	3.302	0.004	7.24	4.047	2.105	0.36
199	7.34	5.504	4.290	4.025	2.817	0.135	6.043	4.446	2.21	0.277
200	8.63	5.740	4.329	6.102	3.60	0.240	9.05	4.730	2.275	0.303
201	8.66	5.000	4.405	6.300	3.504	0.425	9.56	5.141	2.505	0.308
202	8.13	6.002	4.546	6.151	3.703	0.540	8.19	5.271	2.754	0.2
203	7.16	5.773	4.597	6.246	3.747	0.672	6.626	4.004	2.046	0.301
204	7.43	5.005	4.438	6.161	3.003	0.745	7.32	4.007	2.046	0.302
205	8.07	5.04	4.403	6.63	3.005	0.845	9.04	5.003	2.077	0.301
206	8.75	6.005	4.023	7	4.108	1.017	9.30	5.377	3.112	0.2
207	8.82	6.307	4.81	7.35	4.405	1.143	10.04	5.500	3.205	0.214
208 M		6.042	5.021	7.96	4.600	1.365	10.63	6.040	3.506	1.300
209	9.30	6.004	5.113	7.19	5.040	1.500	8.73	6.025	3.753	1.600
210	8.00	6.405	5.651	6.002	4.852	1.746	7.72	5.913	3.000	2.300
211	7.3	6.102	4.800	6.254	4.75	1.676	6.000	5.400	3.005	3.302
212	8.15	5.06	4.846	6.362	4.506	1.865	7.76	5.423	3.700	3.106
213	7.8	5.887	4.704	6.942	4.757	2.141	7.35	5.401	3.073	3.000
214	8.34	6.004	4.072	6.000	4.000	2.27	10.05	5.476	3.040	1.805
215	7.30	6.100	4.005	6.244	4.004	2.400	7.12	5.705	4.000	3.007
216	7.24	5.004	4.705	5.004	4.6	2.506	7.54	5.344	4.007	3.30
217	9.00	5.001	4.6	6.001	4.736	2.767	8.35	5.052	4.071	1.300
218	10.6	6.444	4.704	7.00	5.207	3.033	11.05	6.232	4.254	2.102
219	8.46	6.025	4.072	7.20	5.40	3.330	9.03	6.305	4.405	1.325
220	8.25	6.722	5.100	7.41	5.670	3.507	8.07	6.540	4.040	2.404
221	8.77	6.707	5.242	7.00	5.874	3.846	10.11	6.000	4.704	1.004
222	8.71	6.004	5.313	7.72	6.002	4.007	8.54	6.004	4.82	2.100
223	8.02	6.05	5.301	7.70	6.104	4.227	8.53	6.040	5.070	2.000
224	8.2	6.720	5.305	8.05	6.340	4.432	8.31	6.777	5.16	2.350
225	7.12	6.45	5.324	7.02	6.200	4.516	6.807	6.542	5.157	2.700
226	7.3	6.105	5.104	7.17	6.176	4.024	7.22	6.237	5.102	1.800
227	4.501	5.56	4.000	6.146	5.001	4.502	4.215	5.055	4.005	3.117
228	4.305	4.040	4.500	5.405	5.441	4.405	4.071	4.000	4.011	3.047
229	3.807	4.422	4.132	4.005	5.005	4.307	4.040	4.021	4.382	2.216
230	3.274	4.235	3.000	4.711	4.005	4.140	2.005	4.304	4.105	4.306
231	2.504	3.60	3.045	4.735	4.007	4.054	2.105	3.777	3.943	4.402
232	1.507	3.104	3.205	3.004	4.200	3.613	0.574	3.100	3.513	4.270
233	1.253	2.701	2.000	3.300	4.001	3.654	1.301	2.771	3.350	3.111
234	1.300	2.350	2.60	3.104	3.601	3.401	2.130	2.340	2.605	1.436

Control site Temperature Record

Julian Day	Mean Probe +150 cm	Mean Probe -5 cm	Mean Probe -20 cm	Mean Probe -40 cm	Mean Floor -5 cm	Mean Floor -20 cm	Mean Floor -40 cm	Mean Tread -5 cm	Mean Tread -20 cm	Mean Tread -40 cm	Mean Wind m s-1
164	6.013	-0.124	-0.077	-0.185	[illegible]	-0.270	-0.254	0.853	[illegible]	-0.543	3.414
165	9.34	[illegible]	[illegible]	[illegible]	2.540	-0.234	[illegible]	2.81	[illegible]	-0.534	[illegible]
166	8.73	0.045	[illegible]	[illegible]	4.407	-0.188 M		3.041	-0.306	-0.516	2.165
167	6.304	[illegible]	-0.091	[illegible]	4.45	-0.130 M		3.414	-0.236	[illegible]	[illegible]
168	7.85	5.007	[illegible]	-0.048	[illegible]	0.311 M		[illegible]	-0.123	[illegible]	1.785
169	[illegible]	3.157	[illegible]	[illegible]	[illegible]	1.102 M		2.530	-0.043	[illegible]	[illegible]
170	[illegible]	[illegible]	[illegible]	-0.125	[illegible]	1.370 M		2.87	0.125	[illegible]	[illegible]
171	6.8	7.37	[illegible]	[illegible]	[illegible]	[illegible]	-0.057	[illegible]	[illegible]	-0.435	1.312
172	8.07	[illegible]	[illegible]	-0.107	[illegible]	[illegible]	-0.083	7.45	1.412	[illegible]	1.553
173	5.170	6.312	4.127	[illegible]	5.81	[illegible]	0.277	[illegible]	[illegible]	-0.427	[illegible]
174	3.047	4.43	3.134	[illegible]	4.137	[illegible]	0.714	3.715	1.373	[illegible]	[illegible]
175	6.147	7.28	[illegible]	[illegible]	[illegible]	[illegible]	0.914	[illegible]	[illegible]	-0.38	[illegible]
176	5.516	6.673	4.243	0.134	[illegible]	[illegible]	1.167	[illegible]	2.28	[illegible]	[illegible]
177	4.317	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.3	5.373	2.14	-0.376	[illegible]
178	5.457	[illegible]	[illegible]	[illegible]	[illegible]	3.877	[illegible]	[illegible]	2.343	[illegible]	[illegible]
179	[illegible]	9.02	[illegible]	[illegible]	[illegible]	4.314	1.414	[illegible]	[illegible]	-0.314	[illegible]
180	[illegible]	11.34	5.976	0.81	11.7	[illegible]	[illegible]	[illegible]	[illegible]	-0.272	1.674
181	[illegible]	12.45	7.85	[illegible]	[illegible]	[illegible]	[illegible]	11.84	[illegible]	[illegible]	[illegible]
182	13.27	11.07	7.19	1.537	[illegible]	7.31	[illegible]	10.15	[illegible]	[illegible]	2.77
183	14.71	[illegible]	7.23	[illegible]	[illegible]	7.17	[illegible]	11.84	5.442	0.176	[illegible]
184	[illegible]	13.02	7.47	[illegible]	[illegible]	7.42	[illegible]	12.57	5.767	0.474	[illegible]
185	10.61	[illegible]	7.84	2.123	[illegible]	7.81	[illegible]	10.77	6.247	[illegible]	[illegible]
186	[illegible]	[illegible]	[illegible]	2.130	[illegible]	7.41	3.753	7.82	5.01	[illegible]	1.07
187	6.304	0	[illegible]	1.85	8.65	[illegible]	[illegible]	8.72	5.105	1.124	1.954
188	4.177	5.730	[illegible]	[illegible]	6.545	[illegible]	[illegible]	[illegible]	4.79	1.127	[illegible]
189	[illegible]	[illegible]	5.105	1.741	[illegible]	[illegible]	3.08	8.15	4.54	1.121	2.045
190	8.42	[illegible]	5.361	[illegible]	8.56	5.575	[illegible]	8.03	4.775	1.116	1.510
191	10.70	10.55	[illegible]	2.113	10.04	6.243	3.048	[illegible]	5.445	1.331	2.050
192	[illegible]	11.25	7.12	[illegible]	[illegible]	[illegible]	3.384	10.7	5.0	1.521	1.974
193	11.45	10.76	7.28	[illegible]	10.05	7.16	3.671	[illegible]	5.825	1.710	1.632
194	[illegible]	[illegible]	7.05	[illegible]	8.56	7.19	3.852	8.55	5.787	1.787	1.231
195	[illegible]	7.76	[illegible]	2.910	8.13	6.81	[illegible]	8.07	5.045	1.913	1.295
196	7.43	7.52	6.017	2.811	7.79	[illegible]	3.637	7.9	5.403	[illegible]	1.779
197	[illegible]	[illegible]	[illegible]	2.841	[illegible]	6.746	3.758	[illegible]	5.784	1.911	[illegible]
198	8.12	8.19	[illegible]	3.017	8.14	[illegible]	[illegible]	8.27	5.645	[illegible]	[illegible]
199	8.56	8.12	[illegible]	[illegible]	[illegible]	6.341	3.817	[illegible]	5.234	1.87	[illegible]
200	11.2	10.47	[illegible]	2.810	[illegible]	6.476	3.702	8.77	5.457	1.814	[illegible]
201	[illegible]	8.97	6.915	3.185	8.57	[illegible]	[illegible]	8.14	[illegible]	2.051	1.9
202	8.53	[illegible]	[illegible]	3.34	[illegible]	7.87	4.03	8.34	5.753	[illegible]	[illegible]
203	7.82	6.851	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.126	2.145	[illegible]
204	7.87	7.48	5.76	[illegible]	7.87	[illegible]	[illegible]	7.33	5.075	[illegible]	3.579
205	10.16	[illegible]	6.444	[illegible]	[illegible]	[illegible]	3.544	[illegible]	5.385	2.857	[illegible]
206	10.11	[illegible]	6.734	[illegible]	[illegible]	[illegible]	3.672	[illegible]	5.705	[illegible]	1.853
207	[illegible]	[illegible]	[illegible]	3.415	10.31	6.570	3.772	10.52	[illegible]	2.28	1.010
208	10.19	[illegible]	6.851	3.510	[illegible]	[illegible]	[illegible]	[illegible]	5.911	[illegible]	2.353
209	8.5	8.42	6.63	[illegible]	[illegible]	[illegible]	[illegible]	7.83	5.67	2.3	[illegible]
210	7.14	7.28	[illegible]	[illegible]	7.85	6.417	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
211	[illegible]	[illegible]	[illegible]	3.341	7.45	[illegible]	3.812	[illegible]	5.128	[illegible]	4.713
212	7.52	7.11	[illegible]	3.315	[illegible]	[illegible]	[illegible]	7.11	[illegible]	2.144	[illegible]
213	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.36	6.615	4.861	2.136	[illegible]
214	[illegible]	7.9	5.841	3.130	7.84	[illegible]	3.215	[illegible]	[illegible]	[illegible]	[illegible]
215	7.86	[illegible]	6.130	[illegible]	[illegible]	5.84	[illegible]	6.711	[illegible]	2.135	[illegible]
216	7.5	6.777	5.321	[illegible]	[illegible]	[illegible]	[illegible]	6.447	[illegible]	[illegible]	[illegible]
217	8.81	[illegible]	[illegible]	[illegible]	7.42	5.53	3.27	7.34	[illegible]	2.144	1.34
218	[illegible]	8.54	[illegible]	[illegible]	[illegible]	6.311	[illegible]	[illegible]	5.21	[illegible]	1.637
219	[illegible]	8.11	7.12	3.813	8.34	[illegible]	3.701	[illegible]	5.5	[illegible]	1.151
220	10.77	[illegible]	7.13	3.87	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.47	2.515
221	[illegible]	8.21	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8.70	[illegible]	[illegible]	1.670
222	10.91	8.14	7.35	4.140	8.81	[illegible]	4.132	[illegible]	[illegible]	[illegible]	2.38
223	[illegible]	[illegible]	7.65	4.315	[illegible]	[illegible]	[illegible]	8.04	5.657	2.710	[illegible]
224	10.78	[illegible]	6.784	4.2	[illegible]	6.077	[illegible]	[illegible]	5.719	2.737	[illegible]
225	[illegible]	[illegible]	[illegible]	[illegible]	6.744	[illegible]	4.148	[illegible]	[illegible]	2.747	2.48
226	[illegible]	[illegible]	[illegible]	3.875	[illegible]	5.740	[illegible]	6.325	[illegible]	[illegible]	[illegible]
227	3.785	[illegible]	[illegible]	[illegible]	[illegible]	4.782	[illegible]	4.181	[illegible]	2.457	[illegible]
228	[illegible]	[illegible]	3.424	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.215	[illegible]
229	[illegible]	[illegible]	3.573	[illegible]	3.718	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
230	3.477	3.317	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.123	1.751	[illegible]
231	1.914	2.82	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.131	2.476	[illegible]	5.041
232	0.177	0.614	1.575	1.727	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
233	[illegible]	0.785	1.143	1.37	[illegible]	[illegible]	1.213	[illegible]	1.6	[illegible]	[illegible]
234	[illegible]	[illegible]	[illegible]	[illegible]	1.877	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.374