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**MORPHOMETRY AND BIOPHYSICAL CHARACTERISTICS OF
TURF-BANKED LOBES AND TERRACES, KLUANE LAKE,
YUKON TERRITORY**

By

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A Thesis Submitted to the School of Graduate Studies in Partial Fulfillment of the
Requirements for the Degree of Master of Science.

Department of Geography

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ABSTRACT

The distribution, morphometry and biophysical characteristics of turf-banked lobes and terraces are described from a small subarctic alpine plateau (1300-1900 m a.s.l.) overlooking Kluane Lake in the southwest Yukon Territory, Canada. Observations on the distribution of lobes and terraces at this site indicate that the main controlling factors are the complexity of the topography and the properties of snow cover. Morphometric analysis of 85 lobes subdivided into five different slope orientations indicates a morphogenetic underpinning in which lobe form remains consistent (length-to-width ratio below unity) at different scales and between aspects, however, morpho-biophysical correlations could not provide an explanation for this. Nonparametric and multivariate parametric statistical tests indicate significant inter-aspect differences in the dimensions and biophysical characteristics of the lobes. These appear to be related to differences in site-specific factors. Measurements made along certain transects reveal a definitive downslope trend in the size of lobes. This organization is developed as a result of downslope gradients of various biophysical factors, primarily soil moisture and frost-susceptible soil (silt and clay), which are created by slopewash processes.

RÉSUMÉ

Les caractéristiques de distribution, morphométrie et biophysiques des lobes et des terrasses gazon-encaissés sont décrites pour un plateau alpin subarctique (1300-1900 m a.n.m.) près du lac Kluane, dans le sud-ouest du Territoire du Yukon, Canada. Les observations sur la distribution des lobes et des terrasses à ce site indiquent que les facteurs de contrôle principaux sont la complexité de la topographie et les propriétés de la couverture de neige. L'analyse morphométrique de 85 lobes subdivisés en cinq orientations différentes de pente indique un soutien morphogénétique où la forme de lobe demeure constant (taux de longueur-à-largeur au-dessous de l'unité) à différentes échelles et entre les aspects. Cependant, les corrélations morpho-biophysiques ne pouvaient pas fournir une explication pour ceci. Les essais multivariables statistiques paramétriques et non paramétriques indiquent des différences significatives d'inter-aspect dans les dimensions et les caractéristiques biophysiques des lobes. Ceux-ci semblent être liés aux différences dans des facteurs site-spécifiques. Les mesures faites le long de certains transects en descendant la pente indiquent une tendance définitive dans la taille des lobes. Cette organisation est développée en descendant la pente en raison des gradients de divers facteurs biophysiques, l'humidité primaire du sol, et un sol (vase et argile) susceptible au gel, qui sont créés par des processus de lavement de pente.

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CHAPTER 1

INTRODUCTION AND STUDY OBJECTIVES

1.1 INTRODUCTION

Hundreds of papers have been written on the process of solifluction in a wide range of periglacial environments and in a variety of laboratory experiments (Harris, 1981, 1987; Matsuoka, 2001). Despite these contributions, there has been very little advancement in the development of predictive models of periglacial slope evolution, especially in the context of modeling landforms. The ultimate goal in studying solifluction is to link both form and process, quantitatively, and in a comprehensive manner. In order to achieve this we must first develop quantitative measures of form and combine these with process measurements into computer-based models. At present, the development of comprehensive periglacial slope models is restricted by the lack of form-based information.

A common geographical approach, but one largely untried in studies of solifluction, is to search for organization, pattern and covariation of landform elements through the evaluation of measurements from a substantial spatial sample. Statistical treatment of these data is used to uncover complex relationships and explore the relative importance of different variables on landform development. Relationships derived from such studies can be used to develop and refine hypotheses, which can then be tested by process-based studies on a smaller collection of landform elements. This type of approach is particularly effective in exploratory work and as a tool for supporting,

refining, or refuting hypotheses about the origin and development of solifluction landforms.

Within this context, a study was initiated in April 2000 on a subarctic alpine plateau in the southwest Yukon Territory (Figure 1), in order to examine turf-banked solifluction lobes and terraces, two of the most common and distinct solifluction landforms in alpine periglacial environments. One of the most striking features of this site is that there appears to be a strong contrast in the distribution and morphology of these landforms according to aspect. In terms of periglacial landform development, aspect becomes an increasingly important factor when the climate is continental with a high incidence of clear skies and a significant proportion of precipitation falls as snowfall. At the study site, for example, the local northeasterly wind regime coupled with topographic effects traps snow on leeward slopes and greatly reduces its thickness and uniformity on exposed slopes. The main focus of this study is to describe the distribution, morphology and biophysical characteristics of turf-banked solifluction lobes and terraces, and to explore how and why these differ according to aspect. The main quantitative focus of this study is the lobes, while a more qualitative approach is applied in the investigation of the terraces. The specific objectives of this study are to:

- 1) Describe the morphology and distribution of the lobes and terraces,
- 2) Identify relationships between the morphometric parameters and biophysical variables measured at the lobes in order to begin to understand the modern environmental controls on lobe form,

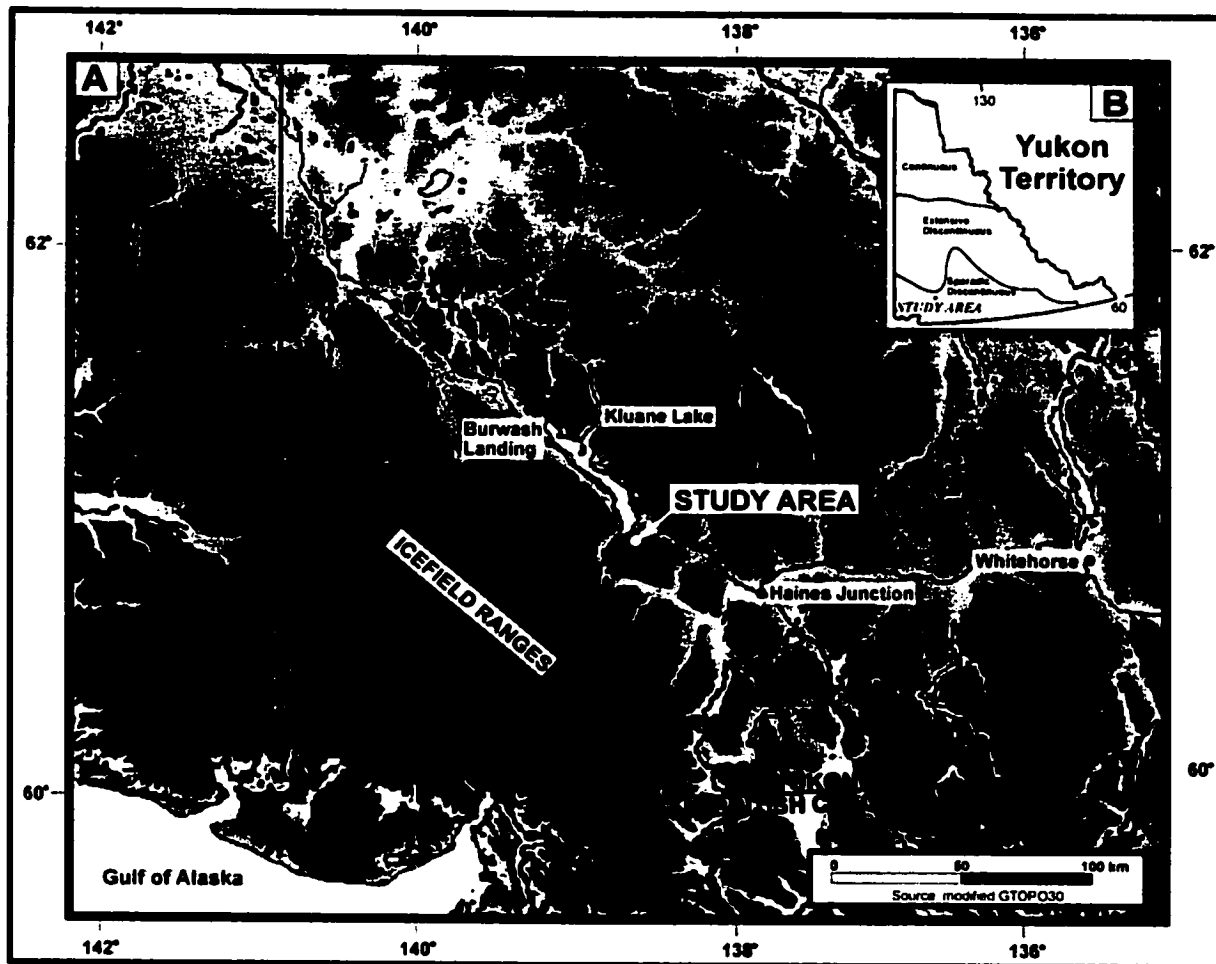


FIGURE 1: Location of A) study area and B) location with respect to generalized permafrost zones according to Heginbottom (1995).

- 3) Test for significant inter-aspect differences in the morphometric and biophysical characteristics of the lobes in order to begin to understand the controls on lobe size, and
- 4) Test for significant differences between the biophysical characteristics of areas with lobes and those devoid of lobes.

Measurements were made of lobe morphometry and biophysical characteristics. Parallel biophysical measurements were made on the adjacent non-lobed terrain. Data were analysed using multivariate statistical methods in order to explore complex multidimensional relationships. For the terraces, the main investigative methods involved observations in the field and aerial photographic interpretation.

1.2 TERMINOLOGY IN THE LITERATURE

1.2.1 Solifluction processes

Solifluction is considered to be the most important and widespread process of mass wasting in periglacial environments (Washburn, 1979; Harris, 1981; Lewkowicz, 1992; French, 1996). It is a process that occurs in both non-permafrost and permafrost environments, but is particularly favored in permafrost zones, where movement is restricted to the active layer. Solifluction in permafrost environments is often regarded as a flow-type movement in which active layer material exhibits characteristics of a viscous fluid in its downslope motion (e.g., McRoberts, 1978).

Despite wide use of the term 'solifluction', an unequivocal definition has yet to be accepted. The term was coined by Andersson (1906) to describe the slow downslope movement of saturated soil in cold regions. Brown (1974) defined solifluction as "slow, downslope movement of saturated, nonfrozen earth material behaving apparently as a viscous mass, over a surface of frozen material". Subsequent studies have shown that slow mass movements in cold regions include several processes that do not necessarily require saturated conditions. In the modern sense, it is generally accepted that solifluction is resolved into three components: frost creep, gelifluction, and plug-like movement. All three components are related to thaw consolidation of ice-rich soils.

French (1996) proposes a definition of solifluction that is distinguished according to the presence of permafrost and the resultant effect on the vertical movement profile. In the active layer of permafrost slopes, solifluction is resolved into frost creep, gelifluction and plug-like flow, and the vertical velocity profile is generally convex downslope (e.g., Mackay, 1981). Conversely, on slopes not underlain by permafrost, solifluction consists only of frost creep and gelifluction, and the vertical velocity profile is concave downslope (e.g., Williams, 1966). According to the *Glossary of Permafrost and Related Ground-Ice Terms* (ACGR, 1988) one component of solifluction can be creep of frozen ground (e.g., Savigny and Morgenstern, 1986). A more detailed discussion of solifluction components follows.

1.2.2 Frost creep

As defined by Washburn (1967), frost creep is the "ratchet-like downslope movement of particles as the result of frost heaving of the ground and subsequent settling upon thawing, the heaving being predominantly normal to the slope and the

settling more nearly vertical". Frost creep can be subdivided into diurnal frost creep and annual frost creep, depending on the duration and intensity of the freeze-thaw period (*cf.* Matsuoka, 1994). Needle ice creep is a special kind of diurnal frost creep that occurs when surface material is lifted by needle ice and then settles upon thawing. Frost creep can be distinguished geographically according to the presence or absence of permafrost and the resultant effect on the distribution of ice lenses. In non-permafrost sites, which are influenced by one-sided freezing, frost heave occurs predominantly near the surface where the bulk of ice lenses accumulate. Conversely, in permafrost sites, which are influenced by two-sided freezing, ice lenses form both near the surface and near the base of the active layer. Meltwater from near surface ice lenses or surface water may re-freeze at the base of the active layer and induce a late-summer heave (Mackay, 1981).

1.2.3 Gelifluction

The term 'gelifluction' is used to describe the component of solifluction that occurs mainly during the thaw period. The *Glossary of Permafrost and Related Ground-Ice Terms* (ACGR, 1988, p.39) defines gelifluction as "the slow downslope flow of unfrozen materials on a frozen substrate". Saturation during the thaw period due to thawing soil ice or surface water may induce soil deformation and reduce the strength of the soil to a pre-failure strain level (Harris *et al.*, 1995). If the rate of pore water generation exceeds the discharge capacity of the soil, excess pore water pressure will develop and downslope movement will occur by gelifluction. Since frozen ground forms an effective barrier to free drainage, the main control on the timing of gelifluction is the drainage conditions. In non-permafrost areas the soil becomes freely drained (under-drained) in early summer following the disappearance of frozen ground. In permafrost areas the persistence of a frozen substrate prevents free drainage and promotes late-

summer gelifluction. Distinction of the gelifluction component in the total soil movement is often difficult because it may be confused with the other solifluction components.

1.2.4 Plug-like movement

Plug-like movement only occurs on slopes underlain by permafrost. The term was originally proposed by Mackay (1981) to describe late summer sliding along a thawing ice-rich basal zone at the top of the permafrost. Similar motion has been described by Egginton and French (1985) where sliding also took place along discrete zones higher in the active layer. The reason plug-like movement occurs only in permafrost environments is because of two-sided freezing (permafrost), and its effect on the distribution of ice lenses in the active layer (*cf.* Mackay, 1981). In non-permafrost areas and the discontinuous permafrost zone, freezing is from the surface downward. Water migrates upward to the freezing plane, resulting in ice lenses forming preferentially in the upper few centimeters of soil. Movement is therefore restricted to the upper few centimeters of soil, resulting in a concave downslope velocity profile.

In areas affected by two-sided freezing, two freezing planes propagate through the soil during freeze-up: one from the top of the permafrost (upfreezing) and one from the surface (downfreezing). The two freezing planes force moisture in the active layer to migrate towards either plane resulting in a dessicated middle zone. Consequently, the resulting ice lenses are distributed along both the top and base of the active layer. During the summer thaw period, the ice content along the base of the active layer is augmented by downward moisture migration. The base of the active layer is therefore ice-rich. In late summer, when the maximum depth of seasonal thaw is attained, the release of excess water from the thawing basal ice-rich zone can induce movement in a

plug-like manner; the overlying active layer materials sliding relatively undisturbed over the deforming ice-rich basal zone.

1.2.5 Solifluction landforms

Solifluction processes often produce distinct landforms. In some cases these landforms may develop into a catena of solifluction phenomena (Benedict, 1970; Ballantyne and Harris, 1994). The Russian literature on solifluction is unique in that it distinguishes two types: (i) cover solifluction and (ii) differential solifluction (Yershov, 1998). Cover solifluction is "movement of ground that occurs more or less uniformly and rather slowly" (Yershov, 1998, p. 206). Also, cover solifluction does not produce the appearance of flow on the slope. In contrast, differential solifluction "shows itself on the surface in the typical landforms of micro- and mesorelief: solifluction lobes, terraces, stripes, etc." (Yershov, 1998, p. 207).

Studies of solifluction landforms have included a wide range of features such as lobes, terraces, sheets, braking blocks (boulders), ploughing blocks (boulders), non-sorted steps, sorted steps, non-sorted stripes, and sorted stripes. Most studies focus on the lobes, terraces, sheets, and stripes, probably because of their abundance on arctic and alpine slopes. Excluding stripes, the lobes, terraces and sheets have several common attributes such as riser height, tread length and tread width. More often than not, the plan shape is irregular and asymmetric, reflecting the complexity with which such forms develop. The sediment along the tread portion is typically a diamicton (Washburn, 1979), the properties of which may vary considerably for features on the same slope. The riser or front commonly contains a concentration of large clasts (Williams and Smith, 1989). Forms may occur on slopes ranging from a few degrees

(e.g., Mackay, 1981) to more than 20° (e.g., Smith, 1987). Further distinction can be made between turf-banked and stone-banked forms where the former have vegetation present along the riser and are poorly sorted, while the latter do not have vegetation along the riser and generally show better sorting.

Despite considerable attention, consistent terminology for differentiating solifluction lobes, terraces and sheets is lacking. Attempts to standardize solifluction terminology have failed to use geometry to classify form and, therefore, there is still some ambiguity in their definition. For example, the *Glossary of Permafrost and Related Ground-Ice Terms* (ACGR, 1988, p. 78) offers the following definitions that, in the authors' opinion, fail to differentiate between the three landforms according to consistent measures (i.e., dimensions, process, and/or locational measures):

lobe – an isolated, tongue-shaped feature, up to 25 m wide and 150 m or more long, formed by more rapid *solifluction* on certain sections of a slope showing variations in gradient; commonly has a steep (15°-60°) front and a relatively smooth upper surface. Fronts covered by a vegetation mat are called 'turf-banked lobes' whereas those that are stony are called 'stone-banked lobes'.

sheet – a broad deposit of nonsorted, water-saturated, locally derived materials that is moving or has moved downslope. Stripes are commonly associated with solifluction sheets.

terrace – a low step, or bench, with straight or lobate front, the latter reflecting local differences in rate of flow. A solifluction terrace may have

bare mineral soil on the upslope part and 'folded under' organic mat in both the seasonally thawed and the frozen soil. Those covered by a vegetation mat are called 'turf-banked terraces'; those that are stony are called "stone-banked terraces.

In addition to the confusion within the above definitions, there is also a lack of clarity in review publications. For instance, Harris (1981, p.126), states that "there appears to be no sharp boundary between lobes and terraces". Matsuoka (2001) provides a detailed compilation of form-process measurements on various solifluction landforms from differing periglacial environments. However, he too does not resolve the ambiguity in definitions.

Another problem is in our understanding of the development and evolution of solifluction lobes, terraces and sheets. For example, Benedict (1970, p.166) states that turf-banked solifluction lobes and terraces "form where downslope movement is impeded". However, as any kitchen experimenter can tell you, when a viscous fluid such as olive oil or maple syrup is impeded in its downslope translation, it tends to diverge around the impediment, producing a concave (crescentic) downslope form rather than a lobate form. Although over simplified, this example illustrates one of the fundamental gaps in our understanding of the development of solifluction lobes, terraces and sheets. As such, it has become increasingly important to look for analogues in other disciplines. One discipline that holds promise in terms of process and form is fluid mechanics, especially analysis of experiments performed with viscous fluids on inclined surfaces. Solifluction is much more complex in terms of its multiple movement components, but the behavior of viscous fluids on inclined surfaces produces remarkably similar forms. By

examining such analogue forms and process it may be possible to begin to develop hypotheses as to the development, movement, and evolution of solifluction landforms.

The following discussion is intended to provide a brief review of potential analogues in the fluid mechanics literature for lobe, terrace and sheet forms. This discussion of each form is followed by a review of the main characteristics of turf-banked and stone-banked morphologies. The specific terminology used in this study is presented in Section 1.3.

1.2.5.1 Lobate forms

Lobes occur singly as bulbous, parabolic-shaped features, with curved or slightly v-shaped fronts in plan form, oriented with their central downslope axis approximately orthogonal to the local contour. Lobate phenomena on inclined surfaces invariably result from the physical manifestation of localized instability (*cf.* Buckmaster, 1977). Instability occurs when viscous flow is accelerated due to an increase in the local slope angle or a reduction in the surface tension or frictional forces between the translating fluid and the substrate. Accelerated flow becomes channelized and results in movement occurring most rapidly along the central downslope axis of the lobe where edge effects are negligible. In viscous fluids, the shape of the lobe is a function of the viscosity and surface tension (Huppert, 1982). In order to preserve the lobe form, downslope movement along the lobe front must equal that of the tread. Movement occurs in a circulatory motion along the advancing front in a manner analogous to a caterpillar-track (e.g., Veretennikov *et al.*, 1998).

Considering that solifluction, particularly in permafrost settings, exhibits characteristics of a viscous fluid in its downslope movement (Brown, 1974; McRoberts, 1978), the above description of viscous fluids on inclined planes implies that solifluction lobes are localized pockets of fast moving debris relative to the adjacent terrain (differential solifluction in the sense of Yershov). Surprisingly, only a few field studies have shown that this is in fact true because most studies focus only on the feature and not its movement relative to adjacent areas. A few notable exceptions to this are studies by Benedict (1970), Price (1973) and Gengnian *et al.* (1995), which have shown that the upper tread surface of turf-banked lobes typically moves much faster than the lobe front or adjacent terrain. Benedict (1970) was also able to distinguish the greatest rate of movement and the channelizing of movement towards the central downslope axis (p.181). The slow rate of advance along the lobe front is problematic if the fluid mechanics analogy is correct. However, stratigraphic studies from turf-banked lobes loosely support this analogy and indicate that contemporary short-term studies of the rate of advance of the lobe front misrepresent the average rate of movement of the entire feature. Evidence from buried organic-rich horizons extending back from the lobe front indicates that more often than not, movement is analogous to a caterpillar-track (e.g., Benedict, 1966; Worsley and Harris, 1974; Alexander and Price, 1980; Elliot, 1996; Matsuoka, 2001). Elliott (1996, p.471) describes this phenomenon as 'soil inversion' and suggests that "near-surface sediments probably dam up behind the vegetation mat forcing the lobe to roll over and thereby invert the soil profile".

1.2.5.1.1 Turf-banked lobes

Turf-banked lobes are the most widely distributed solifluction landform (Benedict, 1976). They have been reported from most periglacial environments, but are probably

best developed in alpine regions where debris-channelizing influences (vegetation, material and topography) are most variable (Harris, 1981). Turf-banked lobes possess several measurable morphometric attributes including an upper tread length, width and angle, and the riser or snout height and angle. The turf cover is believed to play an important role in restraining downslope movement along the riser and also in restricting heat and moisture exchanges with the atmosphere. In the only morphometric study on turf-banked solifluction lobes to date, Smith (1987), at sites in the Canadian Cordillera, reports the following average values ($n = 58$): tread angle 21° , riser height 0.4 m, tread length 2.6 m and a tread width 4 m.

1.2.5.1.2 Stone-banked lobes

Stone-banked lobes are also common in alpine periglacial environments although they occur less frequently than turf-banked lobes. They are morphometrically similar to turf-banked lobes, but they are characterized by much stronger sorting of large clasts towards the downslope margins due to the lack of vegetation cover. Benedict (1970, p.176) defines stone-banked lobes as "lobate masses of rocky debris underlain by relatively stone-free, fine-textured, moving soil". Quinn (1987) further differentiates between stone lobes and stone-banked lobes, where the former has no fines while the latter do. The development and process of downslope movement is thought to be similar to that of turf-banked lobes. Frost creep is considered to be more important than gelifluction (Benedict, 1970) due to the increased activity of diurnal frost heave (*cf.* Matsuoka, 1996), and because gelifluction is only significant in fine-grained soils where high pore water pressures are more likely to develop. Van Steijn *et al.* (1995) suggest that the stone banks are progressively overridden by the fine-textured, moving soil, but frost sorting along the front continually re-establishes the stone banks. Hall (1981), from

a site on Marion Island in the southern Indian Ocean, reports average values for parent slope angle of 13° , tread angle of 4° , riser height of 0.3 m, and tread length of 0.9 m. Grab (2000) from a site in the High Drakensberg, reports average values for the frontal bank width of 4.4 m, length of 2.4 m, height of 1 m and a riser angle of 26° .

1.2.5.2 Terrace forms

For the purpose of this study, the term 'terrace' is broadly used to describe relatively straight-fronted, bench-like features that align with their front and longest dimension roughly parallel to, or up to several degrees at angle to the local contour. In the context of viscous flow, they can be distinguished from lobes by the lack of edge effects that produce a distinct curved front in plan view, and are suggestive of uniform movement across the leading edge. Evidence from experiments with viscous fluids translating down an inclined plane suggests that straight-fronted, or terrace-like forms are quasi-stable and difficult if not impossible to maintain on moderate to steep gradients (e.g., Buckmaster, 1977). Results indicate that uniform movement across a straight-front contact line is sensitive to small perturbations along the advancing front and lateral edge effects, ultimately leading to the development of a single lobe or a series of lobes or fingers extending downslope (e.g., Huppert, 1982). As the gradient decreases, a series of lobes may merge into a more straight-fronted feature as a result of dispersive forces within the snout.

The discussion above provides some suggestion of the form-process relationship of solifluction terraces. It implies that solifluction terraces are either (1) quasi-stable translational features prone to breakdown into lobes or multiple fingers, (2) decelerating dispersive phenomena resulting from a decrease in slope gradient, or (3) not analogous

to viscous phenomena. Although there are numerous photographic examples of solifluction terraces located at the base of slopes where the gradient decreases (e.g., Washburn, 1979 p. 206; Repelewska-Pekalowa and Pekala, 1993, p. 262), and of fingering instabilities (e.g., Ballantyne and Harris, 1994, p.116; Price, 1973, p. 236), there is insufficient evidence from process-based and stratigraphic studies on solifluction terraces to indicate whether the fluid mechanics studies provide an accurate analogue. A further problem in our understanding of terrace development is that of erosion along the front of the terrace riser. Since solifluction terraces often exhibit features closely resembling cryoplanation or nivation landforms such as a persistent snowbank along base of riser, there is a crucial need of data from measurements of riser advance or retreat.

1.2.5.2.1 Turf-banked terraces

Turf-banked terraces have been described as long step-like features with their longest dimension arranged approximately parallel to the local contour (Washburn, 1979) or at angles of up to several degrees (Benedict, 1970; Stocker, 1973). They are characterized by vegetation cover along the riser and typically also have vegetation along the tread surface. They exhibit many of the same morphometric attributes as lobes (i.e., an upper tread length, width and angle; and the riser or snout height and angle), however because movement is believed to be more uniform (*cf.* Benedict, 1976), they do not develop a distinct curved front at right angle to the contour. There is currently insufficient evidence, process-based or stratigraphic, to indicate if movement is analogous to the turf-banked lobes (i.e., caterpillar-track).

1.2.5.2.2 Stone-banked terraces

There are very few mentions of stone-banked terraces in the solifluction literature. They have been described in Colorado by Benedict (1970) and in the Venezuelan Andes by Pérez (1987). It is apparent that the feature identified as a stone-banked terrace in Benedicts' (1970) study is collectively formed by a series of stone-banked lobes (fingers) moving faster than the adjacent terrain (cf. Benedict, 1970, p.202). One reason which may account for the rarity of stone-banked terraces is that the potential for uniform movement across non-vegetated debris slopes (a necessary condition for the formation of a terrace feature according to Benedict, 1976), is very low as a result of variability of the material, moisture supply and underlying bedrock morphology.

1.2.5.3 Sheet forms

In the context of viscous flow, the term 'sheet' suggests uniform laminar or stable flow. Although the term does not account for morphology, it has been used to describe fluid advance over a dry surface and coating flows (cf. Buckmaster, 1977; Hocking, 1990). If we consider a form-based definition of sheets, it is difficult to distinguish them from the terraces. Instead, it may be more useful to characterize sheets as featureless (similar to cover solifluction in the sense of Yershov) and restrict use of the term to steady flow of a viscous fluid in which no forms develop.

Despite some of the problems in clearly defining the plan form of sheets, there are some qualitative aspects which can be used to distinguish them from lobes and terraces. One way is to restrict the use of the latter two terms to differential solifluction

landforms in which the dimension of their expression on the surface is considerably less than the lateral extent of the slope. In contrast, sheets may be considered as covering solifluction landforms, which possess a riser extending for nearly the entire width of a given section of slope. Typically, this type of expression is more common in the high arctic where environmental controls (e.g., topography, wind, vegetation cover, moisture and soil properties) tend to be more uniform across slopes (*cf.* Harris, 1981). It may be difficult to apply the term 'sheet' to alpine areas where these controls are more spatially irregular.

1.2.5.3.1 Turf-banked sheets

According to the literature on solifluction landforms, turf-banked solifluction sheets result from extensive gelifluction and frost creep in relatively homogeneous materials on wide uniform slopes. They are most common in the high arctic where solifluction operates uniformly (French, 1976). They may occur at angles as low as 1-3° and produce relatively uniform expanses of smooth terrain (French, 1996). Sheets often terminate downslope with a distinct step or riser. In plan view, the riser may produce a relatively linear edge (*cf.* Washburn, 1979, p.206) or an irregular edge as a result of local variations in topography or moisture supply. At a site in West Spitsbergen, Åkerman (1996) describes sheets terminating over a flat surface of raised beach deposits below a system of well-developed talus cones. The height of these sheets averages 0.65 m and their longest dimension extends for up to several tens of kilometers (Åkerman, 1996).

1.2.5.3.2 Stone-banked sheets

Stone-banked sheets have been described primarily in South America (e.g., Francou, 1988; Van Steijn *et al.*, 1995; Francou and Bertran, 1997). The sheets are integral in the development of stratified slope deposits through processes such as needle-ice, frost creep, gelifluction and frost sorting of clasts (Francou and Bertran, 1997). Stratification in sheets generally produces the following key characteristics as outlined by Van Steijn *et al.* (1995): 1) grading of coarse fractions (coarsening upward) as a result of frost sorting, 2) a surficial pavement of stone stripes, 3) a layer of heterogenous, matrix-rich, clast-supported or matrix-supported material, and 4) a lower level of openwork clasts. The morphometry of stone-banked sheets is not well documented, but Van Steijn *et al.* (1995) indicate that the length of stone-banked lobes is on the order of a few meters while that of sheets is several tens of meters.

1.3 TERMINOLOGY USED IN THIS STUDY

For the purpose of this study, turf-banked solifluction features are first subdivided into lobate or terrace forms, and these are further subdivided into simple or complex forms. Examples of each are given in Figure 2. Because there is considerable difficulty in distinguishing between the lateral boundaries of some slopes at the study site, the term 'sheet' is not used in this study. For the lobes and terraces, the following definitions are used:

Turf-banked solifluction lobe: a discrete, more-or-less symmetric feature, with a convex shape in plan view extending downslope, aligned with its central axis at right angle to or up to several degrees at angle to the local contour, elevated above the local parent slope with a step-like appearance in profile, having complete or partial vegetation cover along the front (a.k.a. riser) and tread surface respectively, and undergoing or

having undergone downslope displacement by frost creep, gelifluction and/or plug-like movement.

Turf-banked solifluction terrace: a more-or-less straight fronted feature in plan view, often with poorly discernible lateral margins, aligned parallel to or up to several degrees at angle to the local contour, elevated above the local parent slope with a step-like appearance in profile, having complete or partial vegetation cover along the front and tread surface respectively, and undergoing or having undergone downslope displacement by frost creep, gelifluction and/or plug-like movement.

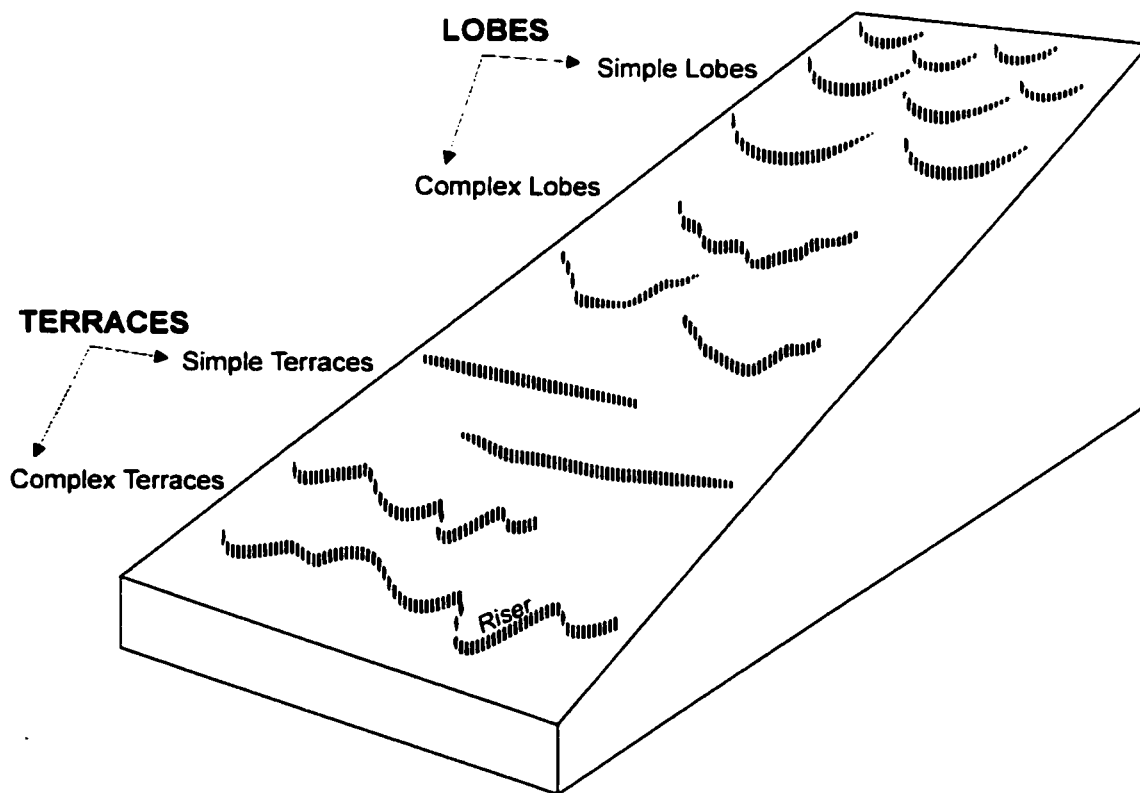


FIGURE 2: Examples of the morphometry of turf-banked solifluction lobes and terraces, and the simple and complex subcategories.

Given the above definitions, it is clear that the main distinguishing factor between a lobe and a terrace in this study is the presence (absence) of a plan shape convexity. Since the local contour may induce a plan shape convexity, to be considered a lobe the convexity must be at an angle to the local contour (Figure 2). Although this was rarely the case in this study, it may have led to some incorrect classifications because the identification of the local contour was based on the author's judgement. For the simple and complex sub-categories of the above, the main distinguishing factor is that the former are smoother and regular, while the latter have plan form irregularities such as fingers (see Figure 2). These characteristics suggest that the more irregular (complex) features have resulted from irregular rates of solifluction within the parent feature either during its inception or as a secondary process thereafter. Smoother, more regular (simple) shapes indicate a localized discrete occurrence of differential solifluction in the sense of Yershov (1998). In cases where the fingers exhibit well-defined lateral margins, these may be considered as discrete lobes.

1.4 FACTORS AFFECTING THE RATE OF SOLIFLUTION

The role of various factors affecting the rate of solifluction has been examined or reviewed by numerous authors (e.g., Benedict, 1970; Price, 1973; Washburn, 1979; Dyke, 1981; Harris, 1973, 1981, 1987, 1993; Gamper, 1983; Egginton and French, 1985; Lewkowicz, 1988; Smith, 1992; Åkerman, 1996; Matsuoka, 1994, 1996, 2001; Kirkby, 1995; French, 1996). These studies and reviews suggest that soil properties, soil moisture, soil thermal regime, slope gradient, vegetation and snow cover are some of the most important biophysical factors affecting the rates of movement.

1.4.1 Soil properties

Various soil properties affect solifluction including texture, porosity, hydraulic conductivity, and index properties. Texture is important in terms of the soils' frost susceptibility and the development of ice lenses. Generally, coarse to medium sands are non-frost susceptible, whereas fine sands, silts and all but the most dense clays are frost susceptible (Harris, 1981).

Porosity is generally high for clays and silts, but due to their small pore sizes, their hydraulic conductivity is lower than sands and gravels; therefore less water is required to saturate sands than clays. As the result of the lower saturation limit, sands deform more readily than finer particles at low moisture contents and are thus more susceptible to gelifluction-type displacements.

The soil index properties determine its behavior at different moisture levels. Moisture levels coinciding with, or exceeding the soil's plastic limit result in plastic deformation, also referred to as pre-failure strain by Harris *et al.* (1995). Moisture levels coinciding with, or exceeding the soils' liquid limit result in viscous flow-type displacements. Both the plastic and liquid limits of solifluction soils are typically very low, owing to low amounts of cohesive material. French (1996, p.154) provides a good summary of index properties from various periglacial environments.

1.4.2 Soil moisture

Soil moisture is probably the most important factor affecting not only the occurrence and rate of solifluction, but also the relative contributions of frost creep,

gelifluction and plug-like movement. Washburn (1967) observed significantly higher rates of movement on 'wet' slopes, compared to lower rates on 'dry' slopes. By comparing movement on slopes with similar gradients and vegetation cover, Washburn determined that soil moisture is more important than both slope gradient and the presence or absence of vegetation cover.

Soil moisture controls the behavior of soil during the thaw period. Often, moisture contents exceed the soil's liquid limit and the soil behaves as a viscous fluid (e.g., Price, 1970). At high moisture levels, the increase of porewater pressure and reduction of effective stress result in a decrease of shear strength and promote downslope movement by gelifluction or plug-like movement. Soil moisture is also a prerequisite for all three solifluction components in that the amount of moisture available for ice segregation during freeze-up is critical for the development and thickness of ice lenses, which, upon thaw, initiate instability and promote downslope movement.

Soil moisture distribution in solifluction lobes has been examined by Benedict (1970) and Harris (1977). Benedict (1970) noted a strong relationship between the groundwater level and the rate of movement on different solifluction landforms; higher rates occurred where groundwater levels were at or near the ground surface. Harris (1977) noted that the released soil moisture from ice lenses caused liquefaction and enhanced downslope movement by frost creep.

1.4.3 Soil thermal regime

The soil thermal regime influences the rate of solifluction in many ways. One of the most important implications relating to solifluction is the rate of thaw and the process

of thaw consolidation (*cf.* Morgenstern and Nixon, 1971). In thaw consolidation, the rate of thaw determines the rate of release of frozen soil water and the development of excess porewater pressure necessary for soil flow (Harris, 1981). When thaw occurs at a rate greater than the rate of porewater drainage, some of the consolidating soil particles transfer their load to the porewater, thereby decreasing the effective stress (*cf.* Terzaghi, 1943). If drainage is impeded by an underlying frozen substrate, the soil may become undrained and solifluction may occur under total stress conditions as opposed to effective stress conditions.

Another important element of the soil thermal regime relates to the frequency, duration and depth of freeze-thaw cycles and their effect on the type of frost heave. Matsuoka (1996) has shown that frequent diurnal freeze-thaw cycles may result in rapid downslope displacement of the near surface debris by frost creep (diurnal frost creep). The difference in the frost duration affects the depth at which ice lenses develop during freeze-up, thereby controlling the depth of movement. Recent work by Yamada *et al.* (2000) in seasonally frozen ground has shown that seasonal freeze-thaw cycles can result in frost creep occurring up to 95 cm at depth in solifluction lobes in Japan.

1.4.4 Slope gradient

Solifluction can occur on low-angled slopes of only a few degrees (e.g., French, 1974; Washburn 1979) to several tens of degrees. Rapp (1960) noted that rapid mass movements tend to take place at gradients in excess of 25° (*cf.* Harris, 1981). Several models have been developed to characterize the dependence of movement on slope gradient (Higashi and Corte, 1971; Washburn, 1979; Williams and Smith, 1989; Matsuoka, 1998), the simplest of which gives surface velocity V_s by:

$$V_s = C \tan \theta \quad (\text{eq. 1})$$

where C is the heave amount and θ is the slope angle.

Washburn (1967) noted a linear relationship between gradient and the rate of movement, but Harris (1972) showed that there is no apparent relationship between the sine of the gradient and the rate of movement for turf-banked solifluction lobes. In the context of vegetated slopes, Harris (1987) states that the "initiation of instability and subsequent movement velocities depend more on the ice content of the thawing soil and its rate of thaw than on slope gradients". However, on non-vegetated slopes, Higashi and Corte (1971) and Matsuoka (1998) show that movement is proportional to the second power of the slope gradient.

1.4.5 Vegetation

Like snow cover, vegetation (dead and living) has an important insulating effect on the ground thermal regime because it has a much lower thermal diffusivity than the underlying mineral soil which restricts penetration of temperature waves (Harris, 1987; Riseborough and Burn, 1988). This is particularly the case in areas where the ground is covered by a thick organic mat that acts as a thermal and moisture buffer. These properties are crucial in preventing short-term freeze-thaw cycles and therefore, diurnal frost creep. Gamper (1983) showed that movements in solifluction lobes in seasonally frozen ground are controlled by vegetation cover and by the depth of seasonal freezing; the greatest movement occurring on vegetation-free treads. Harris (1973) reported a similar trend.

the greatest movement occurring on vegetation-free treads. Harris (1973) reported a similar trend.

Vegetation also has an important binding effect on the soil, although it has yet to be quantified for solifluction processes. For example, Price (1973), at a site in permafrost, found that in certain turf-banked solifluction lobes the movement profile was convex downward, indicating greater differential movement at depth. After twenty years of monitoring, Price (1991) found evidence to suggest that movement occurs between the surface organic mat and the underlying frozen ground. He also mentions that excavations of lobe risers often reveal roots trailing upslope.

1.4.6 Snow cover

Snow cover is a crucial factor in the soil thermal regime. Several studies have shown that snow cover is important in insulating the ground from low winter air temperatures (e.g., Gold *et al.*, 1972; Nicholson and Granberg, 1973; Harris, 1974; Gamper, 1983). The timing and duration of snow cover affect rates of freezing and thawing which in turn affect the distribution of ice lenses, as well as the availability of moisture during the thaw period. Persistent snow patches in particular favour solifluction on the areas downslope. For example, Harris (1977) recorded high groundwater levels on a solifluction slope below a persistent snow patch.

Several qualitative relationships have been observed between snow and solifluction landforms. For example, Benedict (1970), at a site in the Colorado Front Range, noted that turf-banked lobes are best developed along meltwater drainage routes that pass through winter snow-free areas, and that turf-banked terraces and stone-banked lobes occupy snow-accumulations slopes. Price (1974) noted that

depending on the orientation, snowmelt occurs later on larger lobes, thereby preventing the development of a significant vegetation community and reducing the inclination of the lobe riser.

1.5 THESIS RESEARCH

As stated in Section 1.1, the main objectives of this study are to:

- 1) Describe the morphology and distribution of the lobes and terraces,
- 2) Identify relationships between the morphometric parameters and biophysical variables measured at the lobes in order to begin to understand the modern environmental controls on lobe form,
- 3) Test for significant inter-aspect differences in the morphometric and biophysical characteristics of the lobes in order to begin to understand the controls on lobe size, and
- 4) Test for significant differences between the biophysical characteristics of areas with lobes and those devoid of lobes.

Eight morphometric parameters were used to evaluate lobe morphometry: tread length (TL), tread width (TW), tread angle (TA), riser height (RH), riser angle (RA), length-to-width ratio (TL:TW), height-to-length ratio (RH:TL) and height-to-width ratio (RH:TW). Fifteen biophysical factors, or variables were examined, which, as outlined in the preceding discussion, are either directly or indirectly related to the processes of

solifluction. The variables are: presence/absence of permafrost, snow depth (SD), parent slope (PS), organic mat thickness (OM), late-summer thaw depth (THL), and the soil moisture at 40 cm below ground surface (S40) and at 80 cm (S80), soil liquid limit (LL), soil plastic limit (PL), percent gravel (%GR), percent sand (%SD), percent silt (%ST) and percent clay (%CL). Some combinations of the soil variables were also examined in the statistical analyses. These include the combined percent clay and silt (%STCL) and the combined percent sand and gravel (%GRSD).

In view of the fact that there have been very few studies that have addressed similar objectives, the development of research hypotheses was not pursued. However, several fundamental research questions were developed from the objectives:

- 1) What is the distribution of turf-banked solifluction lobes and terraces at the study site?
- 2) What is the morphometry of turf-banked solifluction lobes and terraces at the study site? How does the morphometry compare with other studies?
- 3) What is the distribution of permafrost at the study site? Is this a factor in the distribution of lobes and terraces?
- 4) What are the effects of differential snow cover across turf-banked solifluction lobes and terraces at the study site?
- 5) Is there a catena of solifluction landforms?

- 6) Are there significant relationships between the morphometric parameters from the lobes? How do these compare at different spatial scales and with other studies?
- 7) Which biophysical variables relate best to the morphometric variables from the lobes? Are relationships the same for pooled data and for data subdivided by aspect?
- 8) Can the morphometric and biophysical characteristics of lobes be classified according to aspect? If so, which variables best distinguish among classes?
- 9) Are there significant differences between the biophysical characteristics of sites with lobes as opposed to sites devoid of lobes? If so, which variables best discriminate between these groups?

CHAPTER 2

THE STUDY AREA

2.1 INTRODUCTION

The research area is located in the Kluane Range of the St. Elias Mountains at the south end of Kluane Lake on a broad alpine plateau west of Outpost Mountain (Figure 3). The plateau lies between 1300 and 1900 m a.s.l., and is approximately 7 km from the Kluane Lake Research Station of the Arctic Institute of North America (AINA). The plateau is divided into two main watersheds separated by a long northwest/southeast trending ridge (Figure 4). The smooth glaciated slope on the east side is predominantly northeast-facing and is dissected by several deep valleys. The west side is a deep and undulating bowl-shaped basin with fairly complex topography and a steep backscarp. Treeline is relatively abrupt and occurs locally at 1380 m a.s.l., and is followed by shrub willow and tundra zones at higher elevations. Willows extend to 1480 m and tundra extends to 1900 m. Tundra vegetation is dominated by mosses on north- and east-facing slopes and sedge communities on west- and south-facing slopes. Periglacial features are widespread and diverse. Active layer depths measured in a new CALM grid (Circumpolar Active Layer Monitoring) established in 1999 on the west side of the plateau averaged 55 cm (S.D. = 12) and 59 cm (S.D. = 14) in 2000.

2.2 CLIMATE

The climate of the Kluane Lake region is very complex but exhibits mainly a continental regime (Taylor-Barge, 1969; Wahl *et al.*, 1987; Harris and Prick, 2000). The

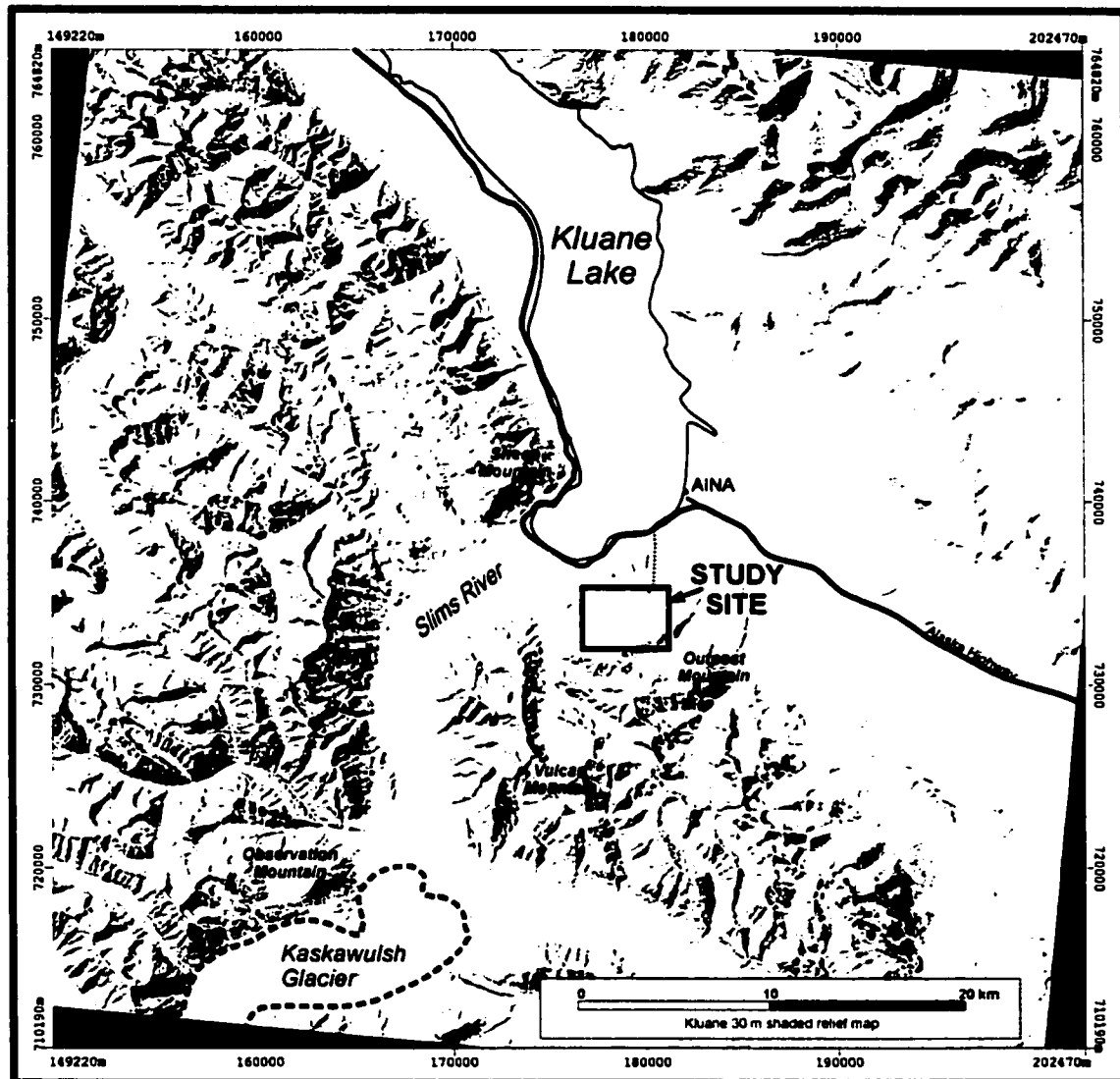


FIGURE 3: Shaded relief map of the location of the study site. The relief map is derived from a 30 meter elevation model.

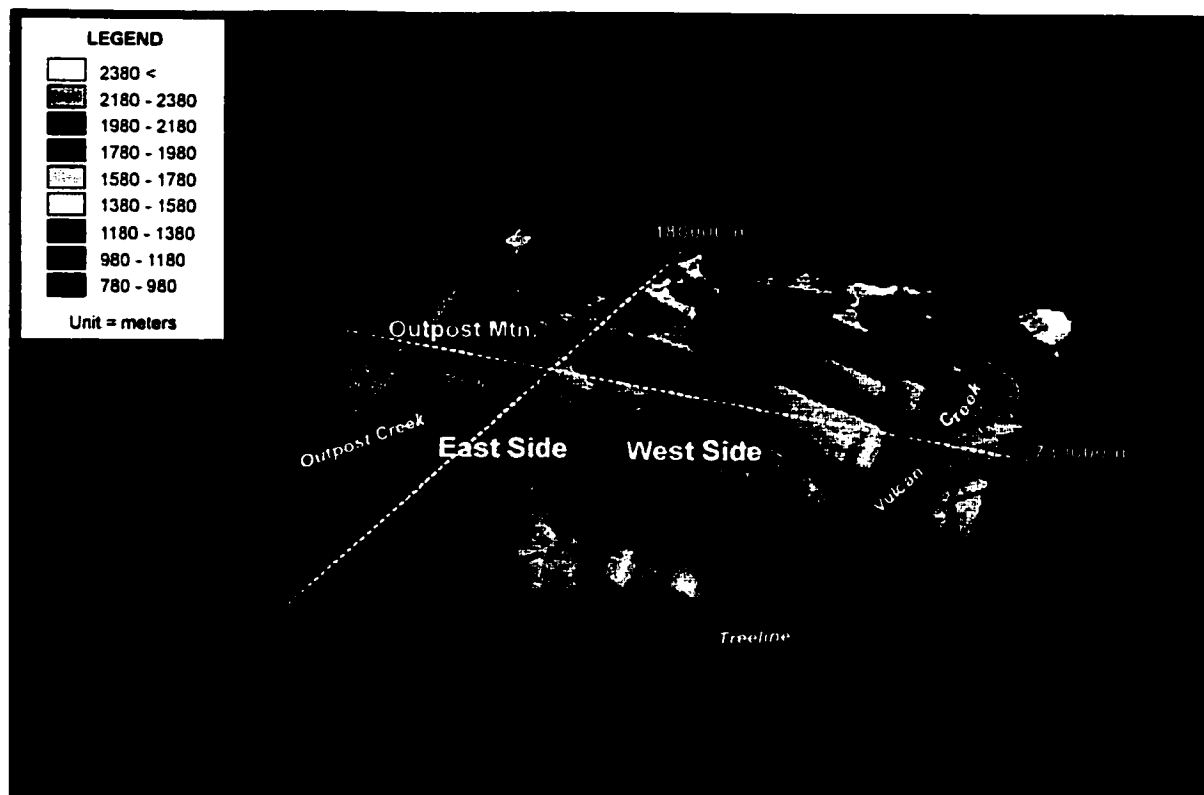


FIGURE 4: 3D perspective view of plateau. Image derived from a 30 m DEM. *Note the bowl shaped topography of the west side of the plateau and the smoother east side.

St. Elias Mountains exert considerable influence on the regional climate (Taylor-Barge, 1969), effectively forming a barrier to the warm moist systems emanating from the Gulf of Alaska further to the west. Frontal effects over the mountains are usually dissipated by subsidence before reaching the vicinity of Kluane Lake. The result is an extreme precipitation gradient from the Gulf coast to Kluane Lake. For example, Yakutat, Alaska on the coast typically receives approximately six times the amount of precipitation of that received at Kluane Lake. Thus, the Kluane region is characterized by an intense rain shadow effect as a result of orographic uplift induced by the mountains (Taylor-Barge, 1969). Although infrequent, the Kluane Lake region periodically experiences high

magnitude pluvial events that cause widespread landsliding and flooding (e.g., Clague and Evans, 1988). Notable events occurred in 1968 and 1988 when landsliding resulted in closure of the Alaska Highway for several days.

There is no long-term climate record for the study site at this time. The nearest permanent monitoring stations are at Burwash Landing (806 m a.s.l.) and Haines Junction (599 m a.s.l.), approximately 50 and 60 km away from the field site, respectively (Figure 1). Sporadic meteorological data are available from Nickling (1976) and Sawada (1996) at the Slims River Valley, and an eight-year record (1972-1980) is available from the Arctic Institute of North America's Kluane Lake Research Station (786 m a.s.l.). Temperature and precipitation data from some of these sites are given in Figure 5.

Overall, precipitation data from Haines Junction, Burwash Landing and Kluane Lake indicate that precipitation is dominated by snowfalls. Rainfall occurs from April to August with a peak in mid-summer (Figure 5). At the study site, snowfall is possible at any time of the year. During the 2000 field season persistent precipitation occurred at the plateau study site wherein rainfall occurred on 12 days between July 28 and August 14. This contributed to debris flow activity at lower elevations along the northern margin of the study site and possibly in the occurrence of an active-layer detachment on the east side of the plateau (see Section 2.3).

Mean daily temperatures are very similar between the three stations with a minor lag in the onset of temperatures above 0°C at the Kluane Lake station. There is considerable difference in the Mean Annual Air Temperature (MAAT) over the period of record with the lowest values occurring at Burwash Landing (-4.4°C), followed by Haines

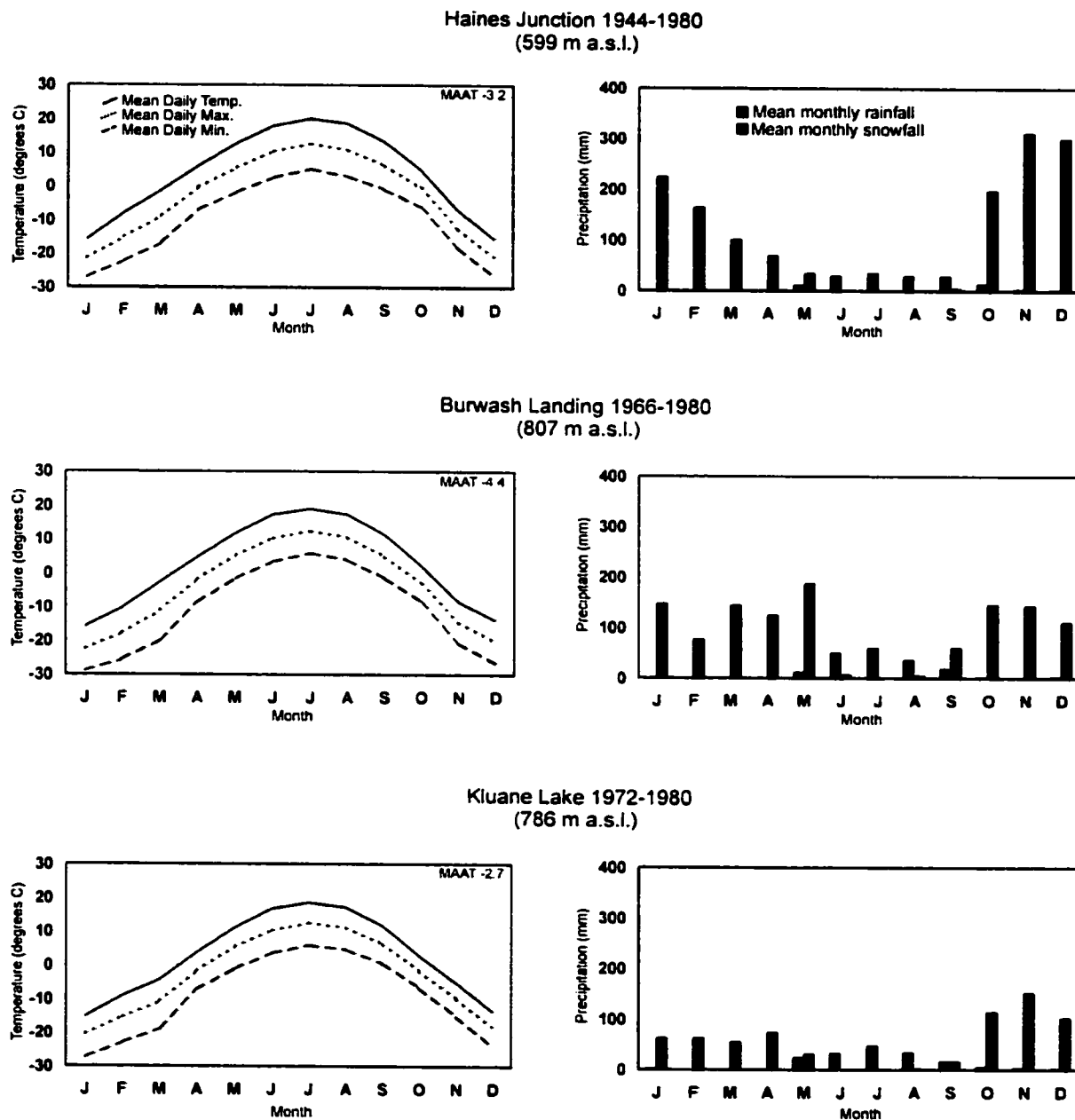


FIGURE 5: Average monthly air temperature and precipitation data from stations near the study site (source: Canadian Climate Normals, Atmospheric and Environment Canada, 1982).

Junction (-3.2°C) and Kluane Lake (-2.7°C). The higher MAAT at Kluane Lake is probably a result of lake effects.

Temperature inversions in the mountains of northern Canada preclude the simple use of lapse rates to estimate the MAAT on the plateau study site. For example, Taylor *et al.* (1998) have shown that valley-bottom temperature inversions can substantially influence permafrost distribution in the Mackenzie Valley near Norman Wells. It is possible that the records shown in Figure 5 are influenced by similar inversions, so that the MAAT of the study site may only be 1-2°C colder than at Kluane Lake, instead of the 5-6°C that might be expected due to the elevation difference. At this time, the only available data for the study site are ground surface temperatures from a south-facing slope at approximately 1860 m a.s.l. (Figure 6). The Mean Annual Ground surface Temperature (MAGT) for this slope during 2000-2001 was -2°C with a temperature range of 53°C (min. -18°C and max. 35°C). Large temperature waves occur frequently throughout the year (Figure 6), highlighting the importance of insolation on the surface temperature and suggesting little, if any, snow cover during winter on this slope. Nevertheless, since a thermal offset can be expected, even this suggests permafrost may be present on this slope.

2.3 PERMAFROST AND PERIGLACIAL FEATURES

Heginbottom (1995) shows the area as being within the sporadic discontinuous permafrost zone with low to medium ice content. However, in a more detailed study of the Kluane region S.A. Harris (1983) shows the study site as being within the continuous permafrost zone. On the east side of the plateau of Outpost Mountain, S.A. Harris (1987) reported values for the active layer depth along an altitudinal transect which showed a

strong relationship with supra-permafrost drainage, but not with the organic mat where this exceeded 2.5 cm in thickness. The values reported by S.A. Harris (1987) also indicated an anomalous relationship with altitude, being thinner between 823 and 910 m a.s.l. and deeper in the shrub tundra at 1310 m a.s.l.. However, this trend is questionable given the coarseness of the colluvial deposits at lower elevations (i.e., 823 to 910 m a.s.l.), which make accurate measurement of the frost table extremely difficult and highly subjective.

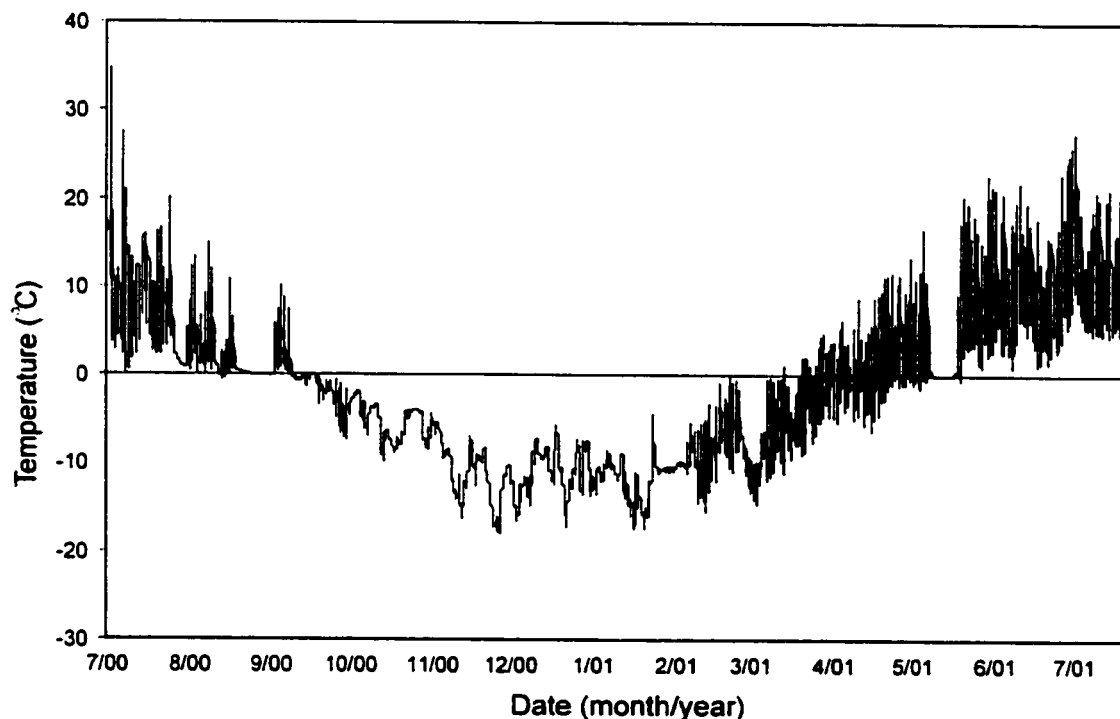


FIGURE 6: Ground surface temperature time series from a south-facing slope in the study site (~1860 m a.s.l.). The thermistor tip was located 2 cm below the ground surface.

The presence of active-layer detachment slides (ALDSs) and thermokarst ponds show that permafrost occurs on the plateau. The ALDSs occur on slopes between 13-18°. They range in length from 12-72 m and in width from 6-64 m. The morphology of

some of the slide scars suggests a complex failure history involving successive mobilization of discrete slide blocks. On one occasion, a recent (2000?) ALDS was modified by retrogressive thaw failure. The larger thermokarst ponds are located on the west side of the plateau and show no evidence of significant change in size over the last 60 years. Two smaller thermokarst ponds are located in a small saddle straddling the main divide between the east and west sides of the plateau. Surrounding these latter ponds is what appears to be a small network of thermal contraction cracks. The most recent pond to develop in the area has formed in the last 20-25 years and shows signs of active bank collapse.

In addition to the thermokarst ponds, other ground ice features observed on the plateau include seasonal frost mounds. These occur more frequently on north-facing slopes on the east side of the plateau where Hypnum moss is the dominant vegetation cover. On the west side of the plateau, seasonal frost mounds were observed in various states of decay along the meltwater drainage route of late lying snow on a scree slope.

Several other periglacial mass wasting features are present on the plateau. Block streams are found on some south-facing slopes along the northern margin of the west side of the plateau. Stratified scree deposits are found in a large box-canyon debris flow valley on the plateau side at elevations between 1100 and 1250 m a.s.l. (Harris and Prick, 2000). Poorly-developed stone-banked lobes occur below a series of a late-lying snow patches at approximately 1830 m a.s.l.. Several slush/debris flow chutes are found on a large scree slope along the southern boundary of the west side of the plateau. Several large active and inactive rock glaciers are also found at lower elevations in the region (e.g., Blumstengel and Harris, 1988; Johnson and Nickling, 1979).

Active patterned ground phenomena include (poorly developed) sorted circles, non-sorted circles, non-sorted steps, sorted stripes and sorted nets. The sorted forms occur predominantly at elevations above 1800 m a.s.l. where vegetation is thin or absent. The non-sorted forms occur at elevations as low as 1500 m and up to the limit of vegetation cover. The dimensions of the active stripes and nets are between 4 and 8 cm in width and diameter, respectively. Both appear to be active under the current climate regime as indicated by the displacement of matchsticks following clearance of a summer snowfall in August 1999. Their small size and poorly developed structure suggests that the dominant sorting mechanism is superficial freeze-thaw cycles, probably of frequent occurrence.

2.4 GEOLOGY

The southwest region of the Yukon Territory is dominated by two major physiographic regions - the St. Elias Mountains and the Yukon Plateau. Lying between these two features is the Shaskwak valley, a major fault oriented northwest by southeast. Structurally, the St. Elias Mountains form a geosyncline with the Kluane Range forming the eastern boundary (Muller, 1967). West of the boundary range of the St. Elias Mountains are the Icefield Ranges which are dominated by a glacial landscape. The Yukon Plateau lies to the northeast of the Kluane Range forming a geanticline. The two regions differ considerably in terms of geology. The St. Elias Mountains are composed of a wide variety of metasediments, metavolcanics and intrusive rocks whereas the Yukon Plateau is composed predominantly of granitic rocks (Muller, 1967). The Ruby Range is a small intrusive mountain group located near the western border of the Yukon Plateau. The range runs roughly parallel to the Shaskwak valley.

The bedrock geology of the study area and study site is shown in Figure 7. At the study site, the bedrock geology is characterized by two main compositional groups: The Kluane Ranges Suite and Wrangell Lavas. Both groups are commonly exposed as valley-side and summit tors. The Kluane Ranges Suite, which formed during the late-early Cretaceous, consists of mid-gray, medium to coarse grained, biotite hornblende granodiorite with quartz diorite, quartz monzonite, and hornblende diorite (Kluane Ranges Plutonic Suite) (Gordey and Makepeace, 1999). The Wrangell Lavas are Miocene to Pliocene and younger and can be easily discriminated from the plutonic rocks from the Kluane Ranges Suite by their rusty red-brown appearance. The Wrangell Lavas consist of two main sub-groups: mafic to felsic volcanic rocks, and with local conglomerate (Gordey and Makepeace, 1999).

2.5 QUATERNARY HISTORY

Several Pleistocene glacial advances have entered the Shawkak valley, each progressively less extensive than the last. Evidence for pre-Pleistocene events in this area is very limited (Denton and Armstrong, 1969). Pre-Wisconsin drift can also be identified but not dated (Denton and Stuiver, 1967). Early Wisconsin drift deposits are believed to be widespread in the area, but are beyond the capability of radiocarbon dating (Denton and Stuiver, 1967).

Muller (1967) summarizes the Pleistocene glacial advances into three separate episodes: the Nisling, the Ruby and the St. Elias. Denton and Stuiver (1967) found evidence of four episodes: the Shawkak, the Icefield, the Kluane and Neoglaciation. Although Muller (1967) does not propose any dates for the advances, it is evident from

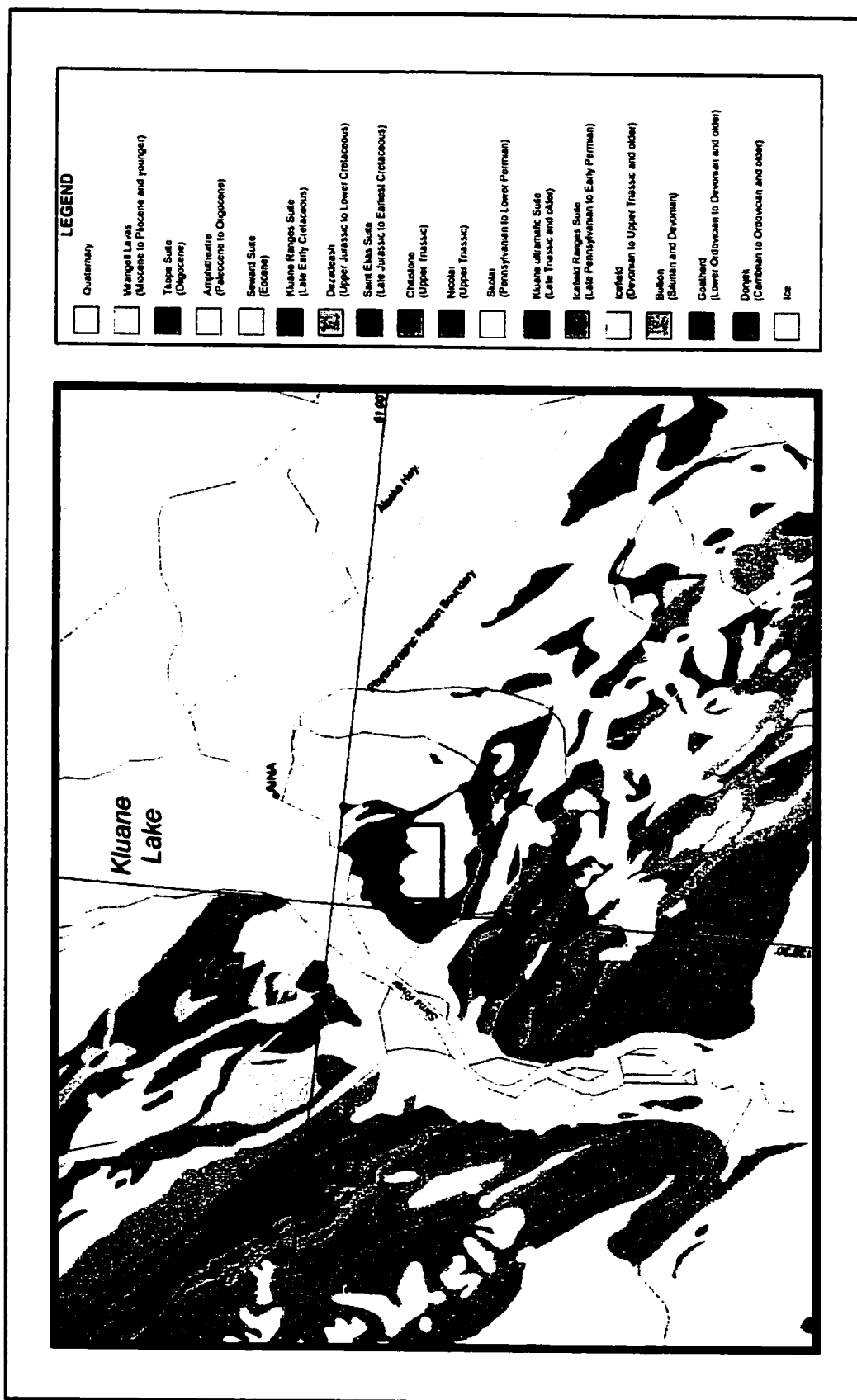


FIGURE 7: Bedrock geology of study area (modified from Gordey and Makepeace, 1999).

his discussion that these episodes correlate to the chronology proposed by Denton and Stuiver (1967): Nisling-Shakwak, Ruby-Icefield and St. Elias-Kluane.

According to Denton and Stuiver's (1967) recreation, the most extensive glacial advance in the Kluane area was the Shakwak (Middle Pleistocene, > 100,000 years B.P.) which extended north to the Nisling Range. Ice extended across the Ruby Range and flowed north-northwest and terminated at the Yukon Plateau physiographic region which was probably never glaciated (Denton and Stuiver, 1967). This glacial advance was followed by the Silver inter-glacial which lasted until 100,000 years B.P.. The next glacial advance was the Icefield advance which occurred at the onset of the late Pleistocene. The Icefield advance was not nearly as extensive as the Shakwak. The Boutillier Non-glacial interval followed and lasted until approximately 30,000 years B.P. (Denton and Stuiver, 1967). The most recent large-scale advance was the Kluane advance which occurred following the Boutillier Non-glacial from ~30,000 to 12,500 years B.P.. The Kluane glacial period was characterized by expanding cirque and valley glaciers but the Shakwak Valley is believed to have been ice-free during this period. The Slims Non-glacial interval ensued until the most recent period of activity referred to as the Neoglacial period, a.k.a., Little Ice age (in the sense of Matthes, 1939).

The Hypsithermal interval began after 8700 years B.P. (Rampton, 1981) and extended up to the Neoglacial. During this period the termini of many glaciers were up-valley from their current positions. Denton and Stuiver (1967) and Borns and Goldthwait (1966) proposed that the Kaskawulsh Glacier occupied a position more than 22 km up valley from its present position. During the Neoglacial several large glacier-dammed lakes formed south of the study area near Haines Junction. Neoglacial Lake Alsek

attained a maximum shoreline height of approximately 670 m a.s.l. (Clague and Rampton, 1982).

The limits of glaciation are not known for the study site at this time. Thus, the earliest date for the onset of ice-free conditions cannot be precisely determined. However, for areas no more than 15 km to the north and northeast of the study site, Muller (1967) shows the upper limit for the Shawkwak (Nisling) Glaciation to be between 1200-1700 m a.s.l.. If Muller's trimlines apply to the study site investigated here, this evidence suggests that some areas on the plateau may have been ice-free during the Quaternary. Given the cirque-like morphology of the west side of the plateau, it is possible that a small cirque glacier or snowfield occupied this portion of the plateau during the Icefield Glacial.

2.6 SURFICIAL DEPOSITS

The surficial deposits in the study area result from a wide range of high latitude mountain processes. The valleys contain a variety of unconsolidated glacial, glaciofluvial, glaciolacustrine and alluvial deposits. Mass wasting processes such as landsliding (Clague, 1981), debris flows/torrents (Harris and Gustafson, 1993), rock glaciers (Blumstengel and Harris, 1988), and talus slope accretion (Harris and Prick, 2000) contribute significantly to the surficial deposits. Active aeolian processes and loess accumulation are also ongoing in the area, particularly at lower elevations near the mouth of the Slims River Valley (e.g., Nickling, 1976).

The surficial geology on the broad alpine plateau of Outpost Mountain is characterized by various compositional categories including tills, alluvium and colluvium.

Field observations from unvegetated active-layer detachment landslide scars indicate that the bouldery soils of the active layer are matrix supported. Section descriptions from exposed river cuttings along the eastern margin of the study site indicate that the till cover is moderately deep (5-30 m) and locally variable (Denton and Stuiver, 1967). Stratigraphic observations from lower elevations along Outpost Creek indicated that the youngest drift sediments are from the Kluane Glaciation followed by ice contact stratified drift (Denton and Stuiver, 1967). These occur across the lower east side of the plateau along with some kame delta or terrace sediments (Rampton, 1981). The west side is predominantly colluvial sediments with some morainal deposits at lower elevations near Vulcan Creek (Rampton, 1981).

Cryosolic soils predominate at the plateau site where the active layer is < 1 meter thick. In non-permafrost zones within the study area the most frequently occurring soil types are brunisolic soils, which occur in the montane zones and regosolic soils, which predominate in the subalpine and alpine (Blood and Associates, 1975). Borns and Goldthwait (1966) identified a widespread paleosol at lower elevations in the study area which they termed the 'Slims Soil'. This paleosol formed in the Slims Non-glacial interval during the Hypsithermal when conditions were much warmer than present. White River tephra (~1200 year B.P.) overlies the Slims Soil sporadically at lower elevations.

2.7 VEGETATION

Three vegetation zones comprise the area around the study site: (i) a montane zone which occupies the valleys and lower slopes up to elevations of 1380 m a.s.l., (ii) a subalpine zone which extends from 1380 to 1480 m a.s.l., and (iii) an alpine zone above 1480 m a.s.l..

The montane zone consists predominantly of well-drained till and alluvium overlain by a mature white spruce (*Picea glauca*) community. Mosses (e.g., *Hypnum revolutum*) dominate the ground cover with thickness of up to 50 cm. Treeline occurs abruptly at ~1380 m a.s.l. above which there are some widely scattered stands of krummholz.

The subalpine zone is dominated by woody shrubs such as willow (e.g., *Salix glauca*, *Salix barclayi*), which show a gentle altitudinal transition from a dense structure to a more open and patchy structure at higher elevations. Hypnum moss is the dominant surface cover but sedge communities are also present and are more prevalent in well-drained areas.

The alpine zone is characterized by dwarf vascular plants. Communities comprise various constituents such as Lapland cassiope (*Cassiope tetragona*), fescue (*Festuca altaica*), dryas (*Dryas octopetala*) and willow (e.g., *Salix reticulata*) (Blood and Associates, 1975).

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

Field studies took place in two phases. In April and May 2000, twenty-four randomly distributed transects were laid out on slopes with differing orientations at elevations between 1500 to 1900 m (Figure 8). The distribution of solifluction lobes could not be ascertained on most transects at this time, thereby ensuring random sampling. The transects were marked by rock cairns at either end and at the midpoint. Systematic snow depth measurements were made at 10, 20 or 30 m intervals. In July and August 2000, the transects were re-acquired and measurements were made of the depth to frozen ground at the same intervals used for the snow surveys. When lobes were encountered during the re-acquisition of transects, measurements were made of the lobe morphometry and the biophysical variables. Because most lobes which intersected the transects were complex in form, simple lobes encountered for up to 70 meters off to one side of the transect were included. Parallel biophysical measurements were also made 1-2 m in front of each lobe, herein regarded as the non-lobe site. Unfortunately, because "selective availability" was still in operation at the time of fieldwork, GPS readings were insufficiently accurate to determine the exact location of the lobes and the altitudinal limits of the transects. Biophysical variables measured in the field include the parent slope, snow depth, late-summer thaw depth and organic mat thickness. Soil samples were obtained from each lobe and adjacent non-lobe site and analyzed for soil moisture at 40 and 80 cm depth, index properties (liquid and plastic limits), and particle size distribution (percent gravel, sand, silt and clay).

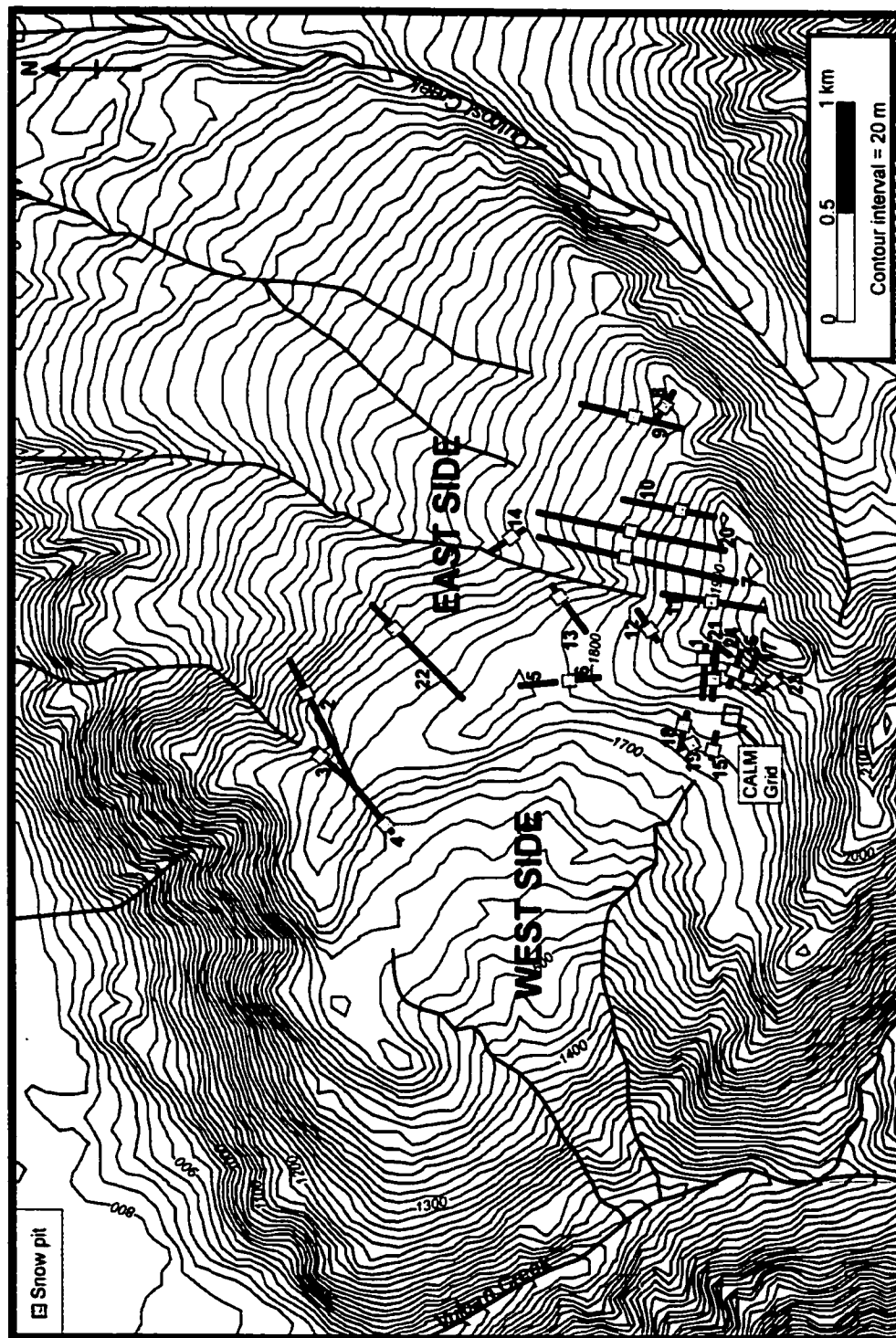


FIGURE 8: Contour map of study site showing the locations of the transects and snow pits.

* Note the smoother topography of the east side of the site.

3.2 FIELD METHODS

3.2.1 Turf-banked solifluction lobe morphometry

Because the boundaries of the terraces were often difficult to discern in the field, their morphometry could not be determined. As such, the main focus of the study became the lobes, which possess relatively distinct lateral boundaries. As discussed in Chapter 1 (Section 1.3), the solifluction lobes observed in this study fall into two broad groups: those that occur as discrete simple forms, and those that form irregular or complex multi-lobe forms (see Figure 2). In order to maintain consistency and enable comparison between different slope orientations, only those lobes meeting the specifications of the first group (simple) were included for measurement in the study. The sample is biased towards “ideally” shaped turf-banked solifluction lobes but this selection was essential in order to prevent confusion in the interpretation of the statistical analyses. In addition, there were three cases encountered on the transects where well-defined symmetric lobes were observed emerging from larger terrace-like parent features. These were included in the study because it was assumed that the lobes represented a location of differential solifluction on the parent feature.

The morphometry of individual lobes was examined by measuring the tread length (a-axis), tread width (b-axis), tread angle, riser height (c-axis) and riser angle (Figure 9). The methods used here are similar to, but modified from those used by Hall (1981) and Smith (1987). Before making any measurements, the dimensions of a lobe were determined somewhat subjectively by identifying the lateral margins of the lobe expression where it blended into the parent slope. These points were marked with flags.

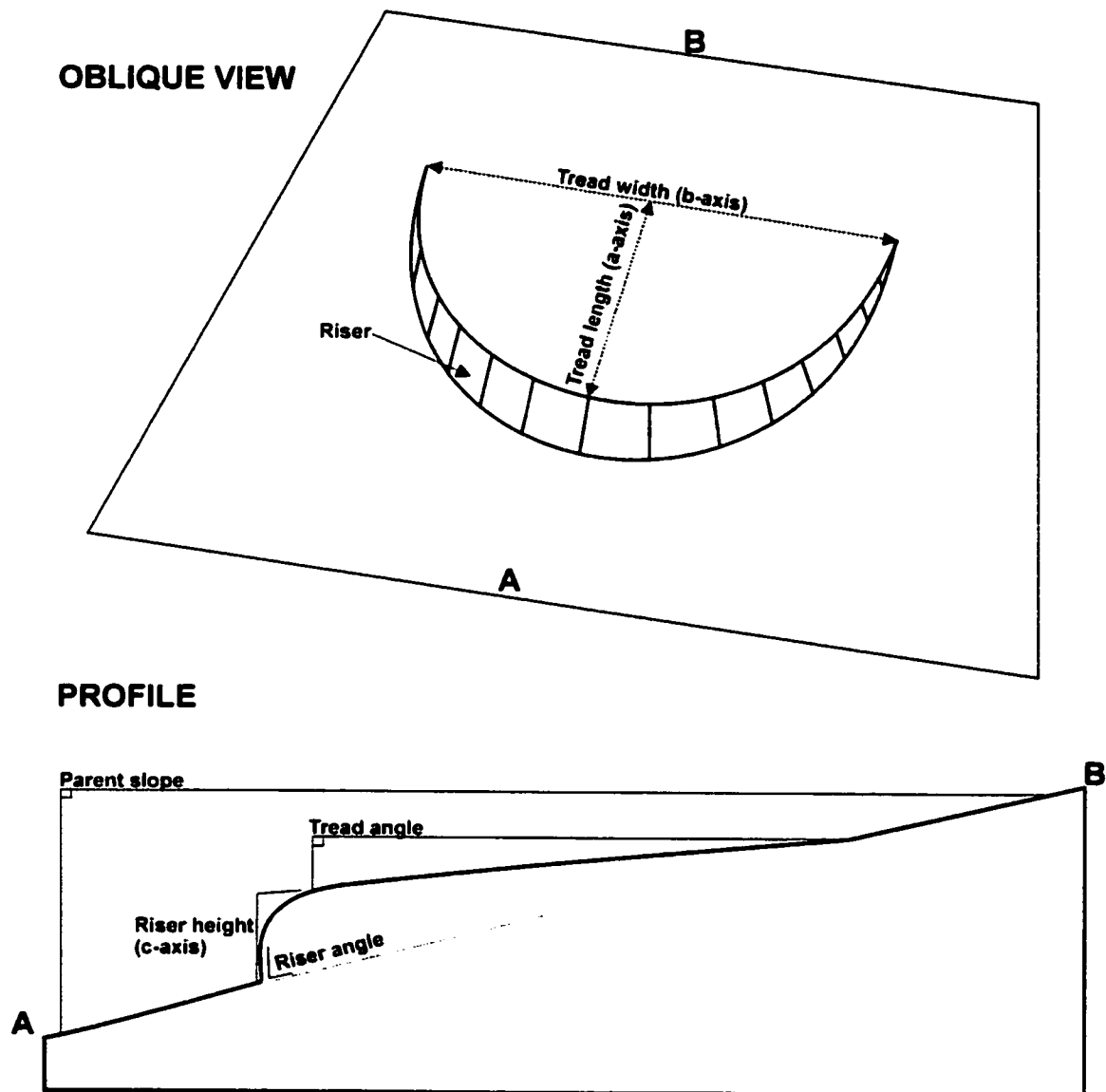


FIGURE 9: Diagram of morphometric parameters from lobes (modified from Smith 1987).

The a-axis of the lobe was then identified by the observer positioning himself between the two lateral flags and visually identifying the central axis. Flags were inserted in line with the a-axis at two points: the upslope limit of the tread and the riser. When turf-banked lobes were encountered emerging from a parent feature, the tread length was measured with respect to the initiation point on the parent feature.

Following the identification of the lobe limits, measurements were made of the tread length and width with a 30 m tape. Tread angle was measured along the central downslope axis with an abney level. Riser angle was measured along the central axis with a digital level relative to the local slope angle. When lobe risers exhibited an overhang, the reading was taken as 90°. The parent slope was measured with an abney level from below the riser to the upslope limit of the tread on the slope adjacent to the lobe. Riser height was measured along the central axis with a graduated staff and steel tape. The staff was placed in front of the riser and the steel tape was extended from the upper tread surface until it intersected the staff. The point of intersection on the staff was taken as the height.

3.2.2 Biophysical variables

3.2.2.1 Permafrost mapping

Two methods were used to map the distribution of permafrost and to determined the 'type' of solifluction environment: BTS and frost-table probing. The BTS method refers to the Basal Temperature of the late-winter Snowpack (BTS). This method is an indirect way for predicting the occurrence of permafrost. The method was developed by Haeberli (1973) and has been used to map the distribution of permafrost in the Alps

(e.g., Hoelzle, 1992; Keller and Gubler, 1993; Imhof, 1996; Imhof *et al.*, 2000), Scandinavia (e.g., King, 1984; Ødegård *et al.*, 1996) and recently in Japan (Ishikawa and Hirakawa, 2000). The method is based on the observed thermal equilibrium that develops at the base of the snowpack in late winter under a minimum snow cover of 80-100 cm. During this period, the BTS is mainly controlled by the ground heat flux and is not affected by diurnal temperature fluctuations due to the insulating properties of the snow cover. It has been shown in Europe that the BTS is generally $< -3^{\circ}\text{C}$ in areas underlain by permafrost, and is $> -2^{\circ}\text{C}$ in areas where permafrost is absent. This has led to the establishment of three diagnostic categories to predict the probability of permafrost occurrence: (1) permafrost probable (BTS $< -3^{\circ}\text{C}$); (2) permafrost possible (BTS of -2°C to -3°C); and permafrost not probable (BTS $> -2^{\circ}\text{C}$). It should be noted that BTS has not been explored as a permafrost prospecting method in North America prior to this study.

Seventy BTS measurements were made concurrent with the snow survey (see below) between April 28 and May 9, 2000. The temperature was measured at the base of snow pits with a YSI telethermometer attached to a Fluke multimeter. The precision of the measurements is better than $\pm 0.1^{\circ}\text{C}$. It is possible that the measurements were made too late in the winter so that the BTS values may have already increased from late-winter maxima (personal communication A.G. Lewkowicz, 2002).

The second permafrost mapping method used was frost-table probing. This method was also used to determine late-summer thaw depth on individual turf-banked lobes (see Section 3.2.2.3). Measurements were made during the period between July 28 and August 14, 2000, close to maximum thaw. Because measurements were made in

late summer, the reported depths to frozen soil are a reasonable estimate of the depth to permafrost. Soundings were made with a graduated pointed steel rod (13 mm diameter) to the point of refusal. The method has been reviewed by Mackay (1977) and used in several studies concerning the depth of thaw (e.g., Hegginbottom, 1971; Price, 1971; Linell, 1973; Harris, 1987; Leverington, 1995; Nolte *et al.*, 1998), and also as an approved technique in the Circumpolar Active Layer Monitoring (CALM) program (Brown *et al.*, 2000). On south-facing slopes where no frost table was encountered in the upper 1.2 m, two pits were excavated to depths of 2 m.

3.2.2.2 Snow cover

Snow cover was examined by systematically measuring the snow depth along the twenty-four transects and by excavating snow pits in April and May 2000. Snow depth was measured with a graduated 4 m collapsible steel probe (13 mm diameter). Two or three snow pits were dug along each transect and snow stratigraphy, temperature, density and BTS were measured. Temperature measurements were made with the telethermometer (see above). The density of the snow strata was derived from samples obtained with an aluminum tube (69.24 cm³). Each sample was placed in a bag and weighed in the field.

High-resolution measurements of snow cover variability and ground surface temperature were made on a west-facing slope where the risers and treads of individual lobes were exposed above the snow in late May 2000. Twenty lobes were measured which were distributed along the entire length of the slope. Snow depth was measured in front of each lobe and along the riser and tread. Temperature measurements were acquired at the same locations over a seven-day period from May 18-24 with a

telethermometer. The temperature measurements were made twice daily at 0800h and 1600h. Soil samples were also obtained from thawed areas along the tread and were measured for soil moisture and index properties (see below).

3.2.2.3 Late-summer thaw depth

The late-summer thaw depth was measured by making soundings of the frost table with a pointed steel rod. For each lobe encountered along the transects, ten measurements were taken along the tread surface. Four measurements were made along the downslope axis and six others were made orthogonal to the downslope axis. The measurement points were spaced evenly so as to cover the entire length and width of the lobe. Five parallel measurements were made 1-2 m downslope from the lobe (i.e., non-lobe site). The means of both groups of measurements were integrated into the statistical analyses.

3.2.2.4 Organic mat thickness

The organic mat thickness was interpreted as the thickness of organic material above mineral soil (*cf.* S.A. Harris, 1987), comprising both living vegetation and/or dead or decaying vegetation. The measurement points coincided with the same points used to delineate the late-summer thaw depth for both lobe and non-lobe sites. A hand trowel was used to make a small excavation to the base of the organic mat. Probing with the hand trowel assisted in delineating the organic mat/mineral soil interface because the mineral soil is denser and coarser. Measurements were made with a millimetric ruler.

3.2.2.5 Soil samples

Soil samples were collected for each lobe and non-lobe site. For lobe sites, soil samples were obtained from the central downslope axis a few meters upslope from the riser. For non-lobe sites, soil samples were obtained 1-2 meters downslope of the lobe. Sampling was done with a 3.5 cm diameter hand auger. Three samples were obtained from each borehole at 0-15 cm, 15-40 cm, and 40-80 cm. Samples were double bagged in the field and weighed within 48 hours.

3.3 LABORATORY METHODS

Laboratory analyses consisted of measuring the soil moisture content, index properties and particle size distribution. Soil moisture was measured gravimetrically for each sample following the procedures outlined in ASTM D2216-92 (ASTM, 1995). For the index properties, the 15-40 cm and 40-80 cm samples obtained from each borehole were combined because initial tests indicated that the amount of soil necessary to run the liquid limit test (i.e., passing 420 microns) was insufficient from just one of the samples. The combined sample was wet sieved and the index properties were determined by following the procedures outlined in ASTM D4328-93 (ASTM, 1995). Particle size analysis required two different methods, each involving pre-treatment with a dispersant (calgon) for 72 hours and removal of the organic content by Loss On Ignition (LOI). The distribution of the coarse fraction (> 420 microns) was determined by wet sieving. The finer fraction (< 420 microns) was determined using a Lecotrac laser particle size analyser.

3.4 STATISTICAL TREATMENT

The statistical treatment was carried out using the StatSoft Inc. STATISTICA (1995) statistical package. Successive steps were followed: (1) calculation of descriptive statistics, (2) data screening (I: outlier detection, II: testing for normal distribution), (3) correlation analysis, (4) nonparametric analyses, and (5) discriminant function analysis. The variables used, singly or in combination, are given in Section 1.5.

3.4.1 Descriptive statistics

Descriptive statistics used in this study include the mean, median, maximum, minimum, standard deviation, coefficient of variation, skewness and kurtosis. These statistics were used as a preliminary tool to compare variables for the pooled data and those subdivided by aspect, and to compare variables among groups.

3.4.2 Data screening I: detecting outliers

Outliers are extreme values that distort statistics and lead to both Type I and Type II errors: rejecting the null hypothesis when it is in fact true (I), and accepting the null hypothesis when it is in fact false (II). These can occur both in univariate and multivariate distributions. In this study, outliers were detected using two methods. This first was a Grubb's test for univariate distributions, also known as an extreme studentized deviate test (Spiegel, 1992), which calculates z-values and compares them with z-values in look-up tables. The equation used is:

$$z = \frac{|\text{mean} - \text{value}|}{\text{S.D.}} \quad (\text{eq. 2})$$

The test was performed in an iterative manner in order to account for changes in the dataset associated with the removal of outliers such that the number of iterations depended on the number of outliers detected in the sample. For example, once an outlier was detected, it was deleted and the test was run again until no other outliers were detected. Unless otherwise specified, outliers were removed before further statistical analysis.

The second method used was the Mahalanobis distance for multivariate distributions. The Mahalanobis distance is the distance of a case from the centroid of the remaining cases where the centroid is the point created at the intersection of the means of all the variables. Mahalanobis distance was evaluated for each case using the chi-square distribution at the 0.001 confidence level. When multivariate outliers were detected, they were deleted.

3.4.3 Data screening II: testing for normal distribution

Parametric statistical tests require that variables be normally distributed. Following the removal of outliers, univariate normality was tested by calculating the skewness of each variable and comparing these values to an acceptable range outlined by Jones (1969). The range of acceptability was within the 0.05 confidence level. The same method has been used in a number of studies concerning clast displacement (e.g., Pérez, 1993; Francou and Bertran, 1997). When the distribution of the sample was not symmetrical, the distribution was transformed to obtain a normal distribution. For the

present study, a number of different types of transformations were required to normalize the data (Chapter 4). In the case of multivariate data, normality was determined graphically with plots of the residuals.

3.4.4 Correlation analysis

Following the data screening, bivariate and multivariate correlation analyses were used to test for relationships among variables. Correlation analysis is a component of regression analysis which enables testing of the relationship between a dependent variable and one or more independent variables (Johnston, 1980). In this study, bivariate correlation was assessed with Pearson's correlation coefficient (r), which measures the association between two variables with no distinction between the independent variable (IV) and the dependent variable (DV). Pearson's r was calculated for combinations of morphometric and biophysical variables at various confidence levels (0.001, 0.01 and 0.05) for the pooled data and those subdivided by aspect. The resulting coefficients were also used to test for multicollinearity and singularity, which are measures of redundancy (i.e., $r \leq 0.9$). For combinations of variables with coefficients exceeding 0.9 at $p \leq 0.001$, only one of the variables was entered into the multivariate correlation analyses.

Multivariate correlation was assessed with the Pearson product-moment correlation coefficient (R). Unlike the bivariate correlations, only the pooled data were examined. The analysis involved a forward stepwise model. In this procedure, the analysis begins with no independent variables in the regression model. For each variable, the F -statistic is calculated, which is the ratio of between groups variance over the pooled within-group variance. The variable with the highest value of the F -statistic is considered for entry into the model; if the F -statistic is significant, that is, its p -value is

below the significance level for entry, then that variable is added to the model; if the F -statistic is not significant, then no variables are added to the equation. Residual analysis was performed after each regression in order to verify the assumptions of linearity, normality and multicollinearity or singularity.

3.4.5 Nonparametric tests

In order to examine preliminary differences in the morphometric and biophysical characteristics for groups of lobes subdivided by aspect and between the biophysical characteristics of lobe and non-lobe groups for the pooled data, comparisons of the data were made using nonparametric tests. These tests were also used to select variables for the discriminant analysis (Chapter 4). Differences in sample size among aspects and variance among groups prevented the use of two-group parametric tests such as ANOVA and the t -test. The nonparametric tests were used specifically to determine which morphometric parameters and biophysical variables were sufficiently different to have originated from different populations. These were then considered for inclusion (exclusion) in the discriminant function analyses.

Two forms of nonparametric tests were performed: a two-tailed Wilcoxon ranked sum test and a Wilcoxon matched pairs test. The former was used to evaluate the hypothesis that there were no differences in the morphometric and biophysical characteristics between different slope orientations. The latter was used to evaluate differences in the pooled data between lobes and non-lobe groups for equal numbers of independent samples.

The first test detects whether the distribution of one group is shifted to the right of the distribution of a second group, or vice versa. The second test is essentially the nonparametric equivalent of the *t*-test for dependent samples and tests the hypothesis that the scores of two variables are drawn from the same distribution (Spiegel, 1992). Both procedures assume that the variables under consideration were measured on a scale that allows rank ordering of observations based on each variable and that allows ordering of the differences between variables (Coombs, 1950). The two tests differ in that the former is used when unequal sample sizes are to be compared and the latter is used when the groups have equal and 'matched' sample sizes. In this study the tests were run on non-transformed data with outliers removed and tested at three confidence levels (0.001, 0.01 and 0.05).

3.4.6 Discriminant function analysis

Discriminant function analysis, a.k.a. discriminant analysis, has been used by numerous geoscientists to determine the linear combination of variables which discriminate between two or more naturally occurring groups (e.g., Reger, 1979; Carrara, 1983; Carrara *et al.*, 1991, De Scally *et al.*, 2001; Baeza and Corominas, 2001). The procedure is computationally similar to multivariate analysis of variance (MANOVA) in that it enables one to test whether two or more groups are significantly different from each other based on *F*-statistics. If the means are significantly different between the groups for a particular variable, then this variable discriminates between the groups.

There are several purposes for discriminant analysis (Lachenbruch, 1975):

- 1) To investigate differences between groups;

- 2) To determine the best way to distinguish between groups;
- 3) To discard variables which are little related to group distinctions;
- 4) To classify cases into groups; and
- 5) To test theory by observing whether cases are classified as predicted.

Some key terms and concepts in discriminant analysis relevant to this study are as follows:

Discriminant function: also called a canonical root, is a latent variable, similar to Multivariate R , which is created as a linear combination of discriminating (independent) variables, such that $L = b_1x_1 + b_2x_2 + \dots + b_nx_n + c$, where the b 's are discriminant coefficients, the x 's discriminating variables, and c is a constant (Klecka, 1980).

Wilks' lambda: is used in an ANOVA (F) test of mean differences in discriminant analysis, such that the smaller the lambda for an independent variable, the more that variable contributes to the discriminant function. Lambda varies between 0 and 1.

Partial Wilks' lambda: is a measure of the unique contribution of a variable to the discrimination between groups. In a sense, the partial Wilks' lambda is similar to the partial correlation coefficients in Multivariate R (STATISTICA, 1995).

Canonical correlation (R_c): is the percent of variation in the dependent discriminated by the set of independents in the discriminant analysis (Lachenbruch, 1975).

Eigenvalues: are the proportions of variance accounted for by the correlation between the respective canonical variates. For two-group discriminant analysis there is only one

eigenvalue. For three or more groups there are multiple eigenvalues which are ordered according to the magnitude of the correlation of the two sum scores (STATISTICA, 1995).

Square Mahalanobis distance: is a measure, similar to the standard squared Euclidean distance measure, of distance between two points in space defined by two or more correlated variables (STATISTICA, 1995).

F-distance: is similar to Mahalanobis distance but based on *F*-statistics.

Classification table: also called a confusion, assignment, or prediction matrix, is used to assess the performance of the discriminant analysis. This is simply a table in which the rows are the observed categories of the dependents and the columns are the predicted categories of the dependents (Lachenbruch, 1975).

Discriminant analysis shares all the usual assumptions of correlation, requiring linear and homoscedastic relationships, and untruncated interval or near interval data (Lachenbruch, 1975). Like multiple regression/correlation, it also assumes proper model specification (inclusion of all important independents and exclusion of extraneous variables). As such, variables used in the model should not be correlated, particularly if unequal sample sizes are used. Violations of normality are not critical if violations are caused by skewness rather than outliers. It also is assumed that the predictors are not multicollinear or singular although this is prevented by most computer programs which exclude predictors with insufficient tolerance (e.g., STATISTICA, 1995).

In this study, discriminant analysis was used as an exploratory tool to investigate differences (similarity/dissimilarity) of the morphometric and biophysical characteristics using aspect as the classification factor, and to examine biophysical differences in the pooled data using lobe/non-lobe as the classification factor. Two methods were used in the selection of variables for the discriminant analysis. The first involved an assessment of the bivariate correlations and Wilcoxon results. The second method was the stepwise procedure (Klecka, 1980), whereby variables are entered into the model one at a time from the discriminant function until the most significant model is generated. The stepwise method selects variables by minimizing the sum of unexplained variation (residual variance) between groups previously identified by the grouping variable. Further detail on the selection of variables is provided in Chapter 4.

CHAPTER 4

RESULTS

4.1 INTRODUCTION

Three important gaps occur in the literature on solifluction landforms. First, because most previous studies on solifluction features have largely focused on a small number of landform elements, there is a relatively poor understanding of the distribution and morphometry of solifluction features. Solifluction process studies by necessity often employ a scale-up strategy which results in a reductionist view of solifluction landforms. The spatial approach has been largely untested in solifluction research, yet it is particularly effective in exploratory work and as a tool for developing and testing basic hypotheses. Secondly, the role of spatial scale has been largely unobserved and there has been no detailed examination of solifluction features across a range of spatial scales. Lack of attention to spatial scale has resulted in very general accounts of landscape organization and possibly slowed progress in periglacial landscape modeling. Lastly, field programs have been carried out only during summer which results in potential gaps in our understanding of form and process. Observations made in winter provide insights into mechanisms responsible for periglacial landscape organization, particularly in areas where the bulk of soil moisture in the thaw period is dependent on the properties and distribution of the preceding winters' snowfall. The present study was designed to address the above issues by collecting measurements in both summer and late winter on a large sample of solifluction lobes, and analyzing their relationship at different spatial scales.

This chapter provides a broad discussion of a variety of aspects regarding the turf-banked solifluction lobes and terraces on Outpost Mountain plateau. Observations, measurements and intensive statistical analysis are used to address the research questions posed in Chapter 1. Unless otherwise specified, the terms 'lobe' and 'terrace' refer to turf-banked solifluction forms.

4.2 OBSERVATIONS ON DISTRIBUTION AND MORPHOLOGY

On the broad alpine plateau west of Outpost Mountain numerous turf-banked solifluction lobes and terraces occur on medium-angled, well-vegetated slopes above treeline at elevations ranging from 1440 to 1920 m a.s.l.. They are present on slopes which vary in form, but in many cases comprise an upslope convexity leading down to a near-rectilinear main slope which terminates in a basal concavity. On the east side of the study area, subdued turf-banked solifluction terraces are encountered as low as 1400 m a.s.l. beneath a cover of shrub willow (e.g., *Salix glauca*) and thick Hypnum moss; turf-banked solifluction lobes are encountered 100 m higher and have slightly thinner organic mats. On the west side of the study area, terraces occur rarely, and almost exclusively in basal concavities where the snowpack is more uniform and less wind-scoured in winter. The lobes on the west side of the plateau have a patchy distribution, and occur in high numbers only on wide uniform slopes (Figure 10) or on topographically conditioned snow accumulation slopes.

Table 1 shows summary data of the distribution of lobes along the twenty-four transects. Eighty-five simple lobes were measured during re-acquisition of the transects in July and August 2000. The highest density occurred on the northwest aspect followed by southwest, west, north and northeast aspects (Table 1). Although lobes occur on



FIGURE 10: Aerial photograph showing the pattern of turf-banked solifluction lobes on a west-facing slope along the west side of the plateau (location of transects 1 and 21 in Figure 8). Other elements include: (a) debris/slush flow chute (currently inactive); (b) outlined location of CALM grid; (c) base of slope (lowermost lobe); (d) top of slope (location of non-sorted stripes shown in Figure 17; (e) location of a late-lying snowpatch with a large lobe below (Source: National Air Photo Library A15434-08).

Aspect	Number of transects	Transect identifiers (see Figure 8)	Number of lobes	Transect length range (m)	Total length of transects on aspect (m)	Transect lobe density (lobes/1000m)
North	7	6, 7, 9, 10, 11, 20, 23	29	170-990	1880	7.4/1000
Northeast	5	2, 3, 12, 13, 22	7	230-940	2253	0.3/1000
Northwest	4	8, 14, 17, 19	18	180-266	1016	17.7/1000
West	5	1, 15, 16, 18, 21	25	160-500	3906	13.3/1000
South	2	5, 24	0	139-260	400	0/1000
Southwest	1	4	6	405	403	14.9/1000

TABLE 1: Distribution of lobes along transects.

almost all aspects, some slopes are devoid of solifluction landforms. For example, five transects (21%) have no lobes and show no other prominent signs of differential solifluction.

As stated above, the turf-banked solifluction terraces occur almost exclusively on the east side of the plateau. They exhibit mainly complex plan forms with lobes commonly emerging from the main riser at irregular intervals. This produces a shape closely resembling that of fingering forms in fluid mechanics experiments (*cf.* Hocking, 1982). Figure 11 shows the locations of some of the larger terraces as seen on an air photo. Their widths typically exceed several hundred meters. Their risers are typically 1-2 m high and occasionally up to 5 m in height. They occur on slopes with gradients similar to those where lobes are found but their upper and lower altitudinal limits are lower than the lobes (1780 m and 1440 m a.s.l., respectively). At lower elevations, the terraces are covered by willow. Some of the larger terraces have turf-banked solifluction lobes superimposed on their treads. Another particularly interesting characteristic of the solifluction terraces is that they rarely occur in isolation. The proximity of the terraces to each other, in conjunction with their preferred orientation roughly parallel to the local contour, creates a patterned landscape reflecting a degree of spatial self-organization



FIGURE 11: Aerial photograph showing the pattern and morphology of the turf-banked solifluction lobes and terraces on the east side of the plateau (source: National Air Photo Library A24763-143): (a) example of a turf-banked terrace; (b) example of a turf-banked lobe; (c) example of hillslope water tracks; (d) example of late-lying/perennial snow.

(Figure 11). Late-lying snowpatches occur in front of some of the terraces on north- and northeast-facing slopes. These snowpatches give rise to a pronounced brown coloured region in front of some of the terraces (Figure 12a). Closer examination typically reveals that the ground surface along this region is saturated in late summer with a high number of rocks exposed. The vegetation in this zone is composed primarily of a late-lying snowmelt community similar to the one described by Price (1970) (Figure 12b).

Four categories of risers were observed in the study area, presumably reflecting different stages or developmental processes. They are: (i) oblique, (ii) overhanging, (iii) terracette-covered, and (iv) ruptured. All four types were observed on the lobes, but only the oblique and ruptured types were observed on the terraces. The most commonly encountered riser is the oblique type, which does not show signs of folding under of the organic mat at the base of the riser (Figures 13a and 13b). The second type of riser displays an overhanging and folded under organic mat along the base of the riser (bulging), hinting at the build-up of gravity-induced stress and a stage of quasi-stability maintained by the restraining effect of the organic mat (Figure 13c). It is probable that this bulge is due the competition of gravity pulling the soliflual material down and the reluctance of the riser to move due to vegetation cover, leading to a build-up of sediment behind the riser. The third type of riser consists of those with miniature terracettes super imposed on the riser surface (Figure 13d). This phenomenon was documented by Price (1970, p.251) and suggests the presence of multiple shear planes within the feature. The final type comprises risers in which soil has (recently) spilled over or burst through the organic mat along the front, or which have experienced (recent) failure along the riser (Figures 13e and 13f).



FIGURE 12: Photographs of turf-banked terraces on east side of plateau with late-lying snow below the riser: (a) distant view of a series of angled terraces (arrow denotes a semi-circular feature); (b) close-up view of effects on vegetation caused by late-lying snow below the riser (90 cm tall backpack for scale).

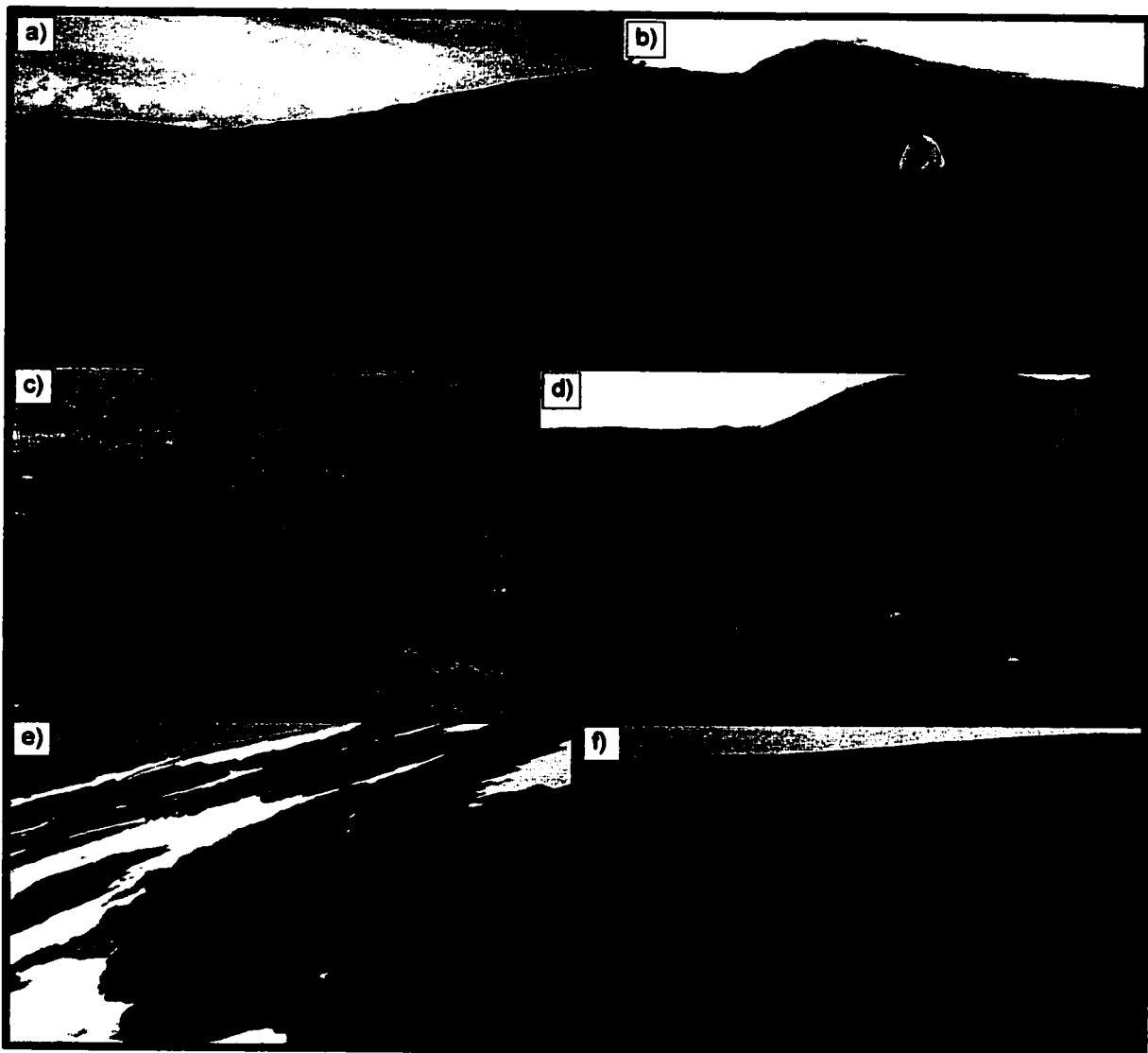


FIGURE 13: Photographic examples of four categories of riser types encountered: (a) oblique riser of a turf-banked lobes (50 cm digital level for scale); (b) oblique riser of a turf-banked terrace (notice large lobe in background which corresponds to b) in Figure 11); (c) overhanging riser of a turf-banked lobe (arrow denotes 80 cm tall probe for scale); (d) terracette-covered riser of a turf banked lobe; (e) ruptured riser of a turf-banked lobe (stake ~ 50 cm tall); (f) ruptured riser along turf-banked terrace (arrow denotes 1 m tall probe for scale).

In addition to the lobes and terraces, active-layer detachment slides are also a common occurrence at the study site (*cf.* Hugenholtz, 2000), but are much less numerous than at some high arctic sites (e.g., Lewkowicz, 1990). The toes of the slides often exhibit features resembling turf-banked lobes (Figure 14a) and may contribute to the formation of lobes in some cases. Some active-layer slides evolve into retrogressive thaw slumps, resulting in the downslope transfer of large amounts of material (Figure 14b). Active-layer failures resulting from liquefaction were also observed along the risers of some terraces (see Figure 13f). It is possible that previous failures along the riser are responsible for the irregularities in the frontal geometry of the terraces.

4.3 TURF-BANKED SOLIFLUCTION LOBE MORPHOMETRY

Results from the lobe measurements are summarized in Table 2 and their histograms are shown in Figure 15. Riser height ranges from 0.25-3.0 m with 91% of values between 0.25 and 1.5 m, and the remaining 10% > 1.5 m. Tread length ranges from 1.75-48 m with 41% < 6.4 m and 10% > 25 m. Tread width ranges from 3.6-13.9 m and has a strong reverse J-shaped distribution with 65% of lobes widths < 20 m and 8% > 100 m. A typical lobe is 0.7 m high, 7.5 m in length and 11.7 m in width (median values). Riser angle ranges from 18-90°, averaging 65°, and tread angle ranges from 4-20°, averaging 12°. Lobes occur on slopes ranging from 5-23°, averaging 13°. The length and width measurements yield an average length-to-width ratio of 0.7 indicating that lobe width is generally greater than lobe length. The average ratios of the height-to-length and height-to-width are 0.11 and 0.07, respectively.

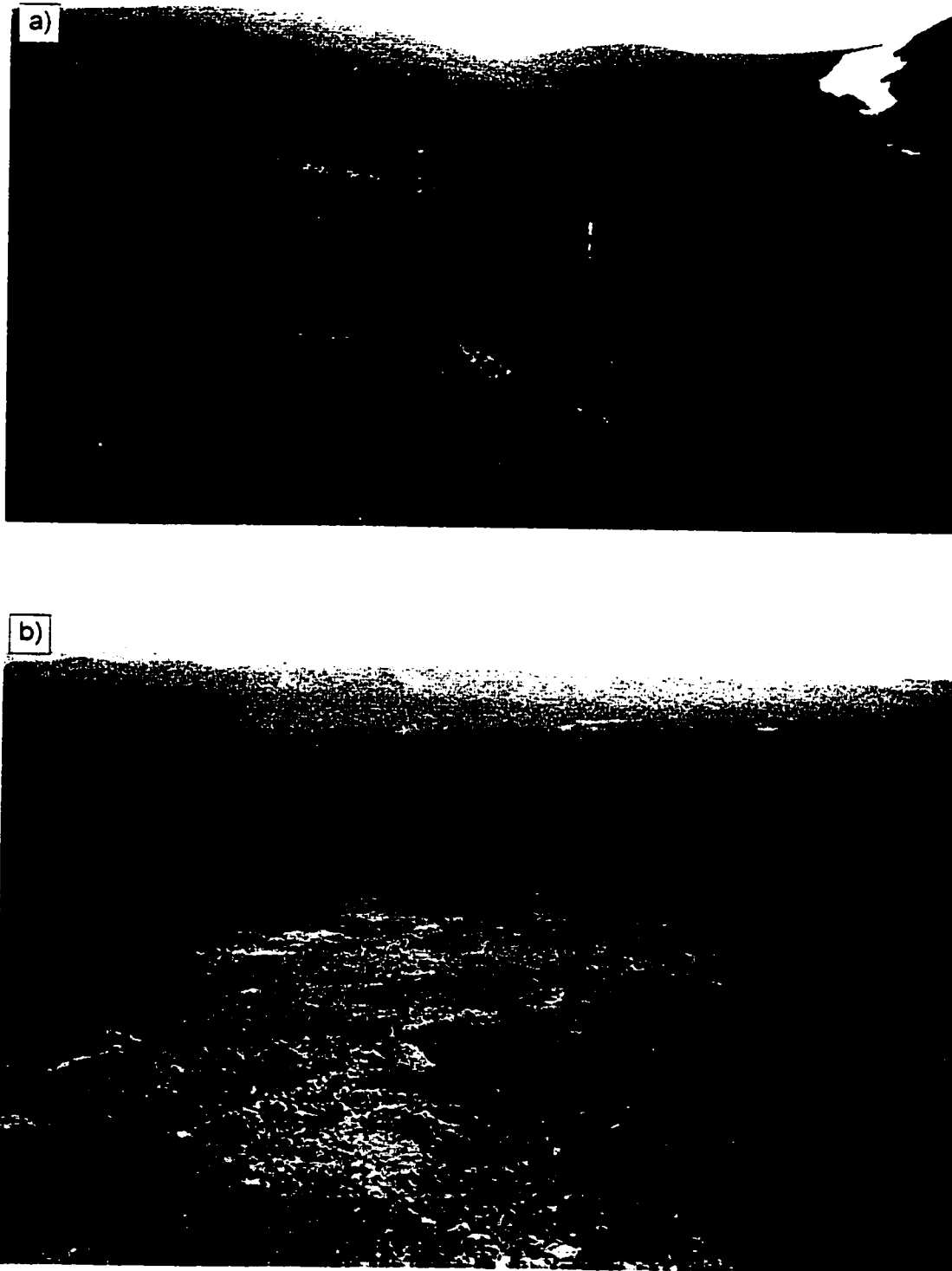


FIGURE 14: Photographs of active-layer detachment landslides: (a) slide toe resembling a turf-banked solifluction lobe; (b) view downslope of thawslide debris emanating from the scar of a recent active-layer detachment slide extending for 60 m downslope.

Parameter	Mean	Median	STD	Coefficient of variability	Min.	Max.	Skewness
Riser height (m)	0.81	0.68	0.37	0.5	0.25	3.00	0.89
Riser angle (°)	65.3	69	19.5	0.3	20	90	-0.88
Tread length (m)	11.17	7.50	8.58	0.8	1.75	48.00	1.28
Tread width (m)	20.87	11.70	23.15	1.1	3.64	138.60	1.93
Tread angle (°)	12.1	13	3.2	0.3	4	20	-0.03
Parent slope (°)	12.8	13	3.8	0.3	5	23	-0.37
Length-to-width	0.72	0.67	0.31	0.4	0.02	1.48	0.38
Height-to-length	0.11	0.08	0.09	0.8	0.02	0.62	3.28
Height-to-width	0.07	0.06	0.04	0.6	0.01	0.18	0.71

TABLE 2: Summary statistics for the pooled turf-banked solifluction lobe data (n = 85).

Tread width is the most variable parameter followed by the height-to-length ratio and tread length (coefficient of variability values are 1.1, 0.8 and 0.8, respectively). Riser angle, tread angle and parent slope are the least variable measures with coefficient of variability values well below unity. The height-to-length ratio, tread length, width and riser height have log-normal distributions. Tread angle is the closest parameter to a normal distribution with skewness near zero (Figure 15).

Summary statistics of lobe dimensions for the data subdivided by aspect are shown in Table 3 and their histograms are shown in Figure 16. Rankings for the mean values in Table 3, regardless of whether the differences between the means are statistically significant or not, are shown in Table 4. The statistically significant differences in the values are described in Section 4.3.3. Table 4 shows that lobes on northerly oriented slopes, particularly on northeast slopes, have the largest average dimensions. Average length-to-width values indicate that lobes on northwest-facing slopes (average coefficient = 0.84) were more elongate than on the other slope orientations.

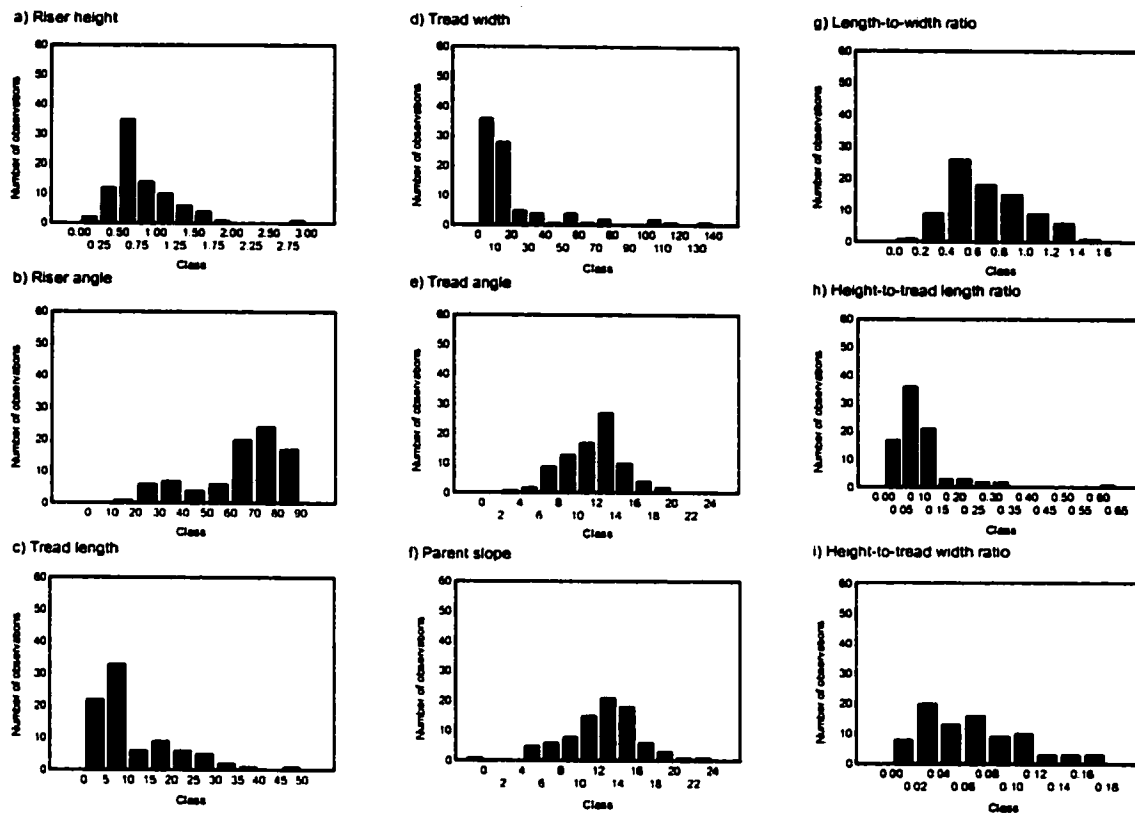


FIGURE 15: Histograms of morphometric parameters for the pooled data ($n = 85$).

4.3.1 Downslope trends in turf-banked solifluction lobe morphometry

Results from lobe measurements along the transects do not reveal consistent trends in the downslope direction when the transect data are examined individually, partly because sample sizes are relatively small (Appendix A). However, when transects with similar altitudinal ranges are grouped into their respective parent slope orientations (Figure 17), several trends are apparent. Given the limited number of lobes from northeast- and southwest-facing slopes, these are not considered in this section but can be reviewed in Appendix A along with all other transects that contained lobes.

Parameter	Mean	Median	STD	Coeff. of variability	Min.	Max.	Skewness
NORTH (n = 29)							
Riser height (m)	0.88	0.67	0.43	0.5	0.38	1.80	0.77
Riser angle (°)	72.1	72	10.5	0.1	44	90	-0.31
Tread length (m)	11.33	7.40	87.36	0.8	2.60	30.30	0.97
Tread width (m)	31.28	11.00	38.51	1.2	3.80	138.60	1.61
Tread angle (°)	11.1	11	3.8	0.3	4	20	0.38
Parent slope (°)	11.9	12	3.7	0.3	5	23	0.64
Length-to-width	0.68	0.61	0.35	0.5	0.02	1.48	0.46
Height-to-length	0.12	0.08	0.11	0.9	0.02	0.62	3.44
Height-to-width	0.07	0.06	0.04	0.6	0.01	0.15	0.26
NORTHEAST (n = 7)							
Riser height	0.95	1.00	0.37	0.4	0.69	1.60	0.71
Riser angle	64.4	69	19.3	0.3	22	82	-2.27
Tread length	19.90	21.20	10.48	0.5	7.50	36.50	0.36
Tread width	35.74	35.00	25.11	0.7	10.30	71.00	0.23
Tread angle	13	13	3.7	0.3	9	20	1.16
Parent slope	17.1	17	3.1	0.2	12	21	-0.27
Length-to-width	0.68	0.73	0.23	0.3	0.30	0.97	-0.65
Height-to-length	0.06	0.06	0.04	0.7	0.02	0.13	1.01
Height-to-width	0.05	0.03	0.04	0.8	0.01	0.10	0.76
NORTHWEST (n = 18)							
Riser height	0.86	0.75	0.58	0.7	0.44	3.00	0.71
Riser angle	80.6	79	6.9	0.1	68	90	0.22
Tread length	10.21	5.80	11.00	1.1	1.75	48.00	1.42
Tread width	12.64	8.10	13.36	1.1	3.80	60.00	0.70
Tread angle	13.1	13.5	2.7	0.2	8	18	-0.44
Parent slope	13.4	14	3.1	0.2	7	20	-0.21
Length-to-width	0.84	0.81	0.26	0.3	0.45	1.29	0.24
Height-to-length	0.12	0.10	0.08	0.7	0.05	0.34	1.94
Height-to-width	0.09	0.08	0.04	0.4	0.04	0.18	0.92
WEST (n = 25)							
Riser height	0.82	0.74	0.28	0.3	0.34	1.56	1.02
Riser angle	53.2	56.7	22.3	0.4	20	90	-0.03
Tread length	11.18	8.50	83.24	0.7	3.03	35.00	1.48
Tread width	16.12	12.50	12.27	0.8	3.64	55.30	1.80
Tread angle	12.1	12	2.5	0.2	7	18	-0.06
Parent slope	12	13	1	0.1	5	18	0.94
Length-to-width	0.76	0.66	0.31	0.4	0.35	1.38	0.79
Height-to-length	0.10	0.09	0.06	0.6	0.03	0.29	1.43
Height-to-width	0.07	0.06	0.04	0.6	0.02	0.17	1.22
SOUTHWEST (n = 6)							
Riser height	0.32	0.33	0.61	0.2	0.25	0.39	-0.15
Riser angle	38.3	37.5	6.6	0.2	28	46	-0.39
Tread length	6.18	6.40	1.564	0.3	4.20	8.60	0.31
Tread width	11.03	12.70	5.42	0.5	4.50	16.20	-0.45
Tread angle	13.8	14.5	1.5	0.1	12	15	-0.71
Parent slope	14.2	14.5	1.9	0.1	11	16	-0.94
Length-to-width	0.66	0.58	0.26	0.4	0.41	1.07	0.86
Height-to-length	0.05	0.05	0.01	0.2	0.04	0.07	0.54
Height-to-width	0.04	0.02	0.02	0.5	0.02	0.08	1.36

TABLE 3: Descriptive statistics from the morphometric data subdivided by aspect.

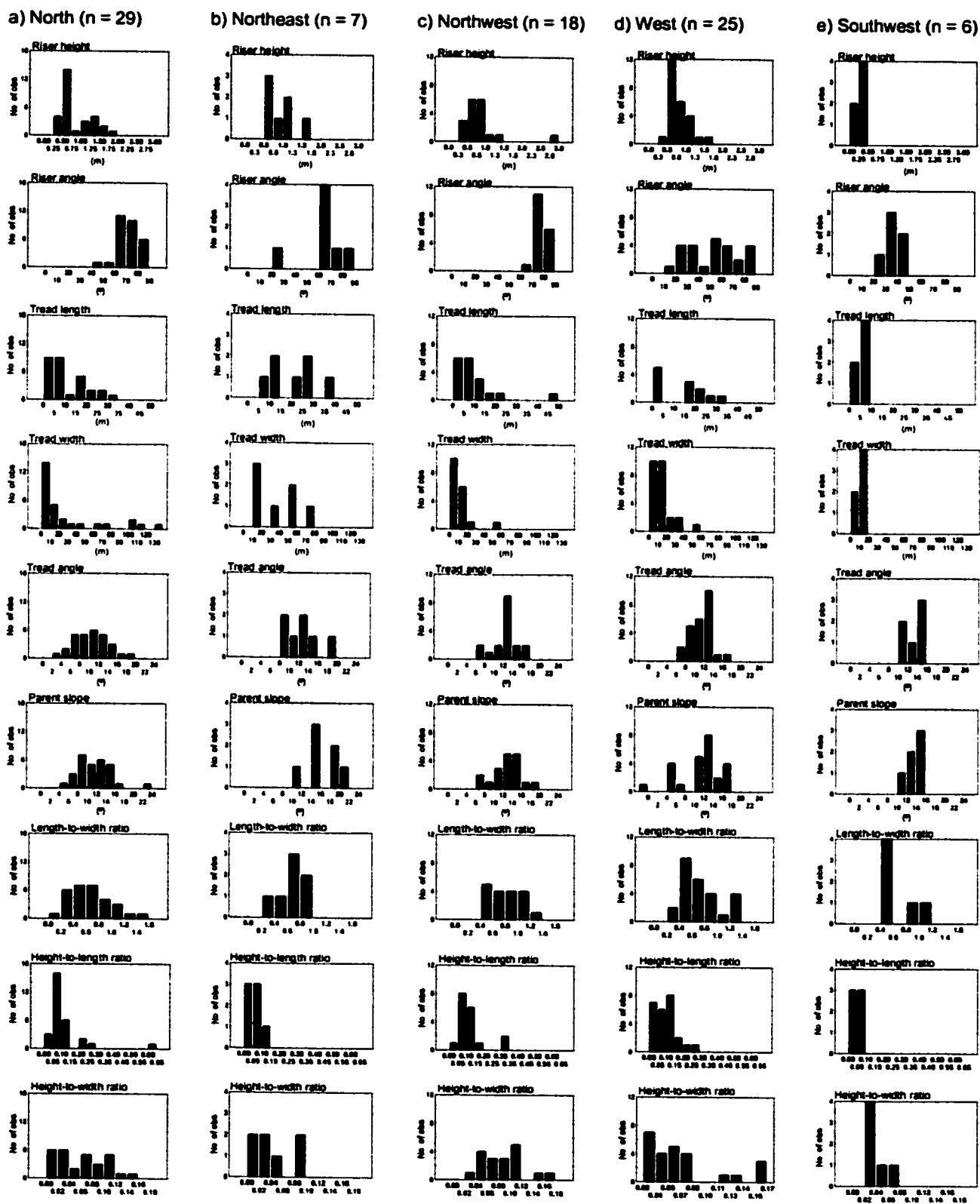


FIGURE 16: Histograms of morphometric parameters for the data subdivided by aspect.

Parameter	Ranking
Riser height	Northeast > North > Northwest > West > Southwest
Riser angle	Northwest > North > Northeast > West > Southwest
Tread length	Northeast > North > West > Northwest > Southwest
Tread width	Northeast > North > West > Northwest > Southwest
Tread angle	Southwest > Northwest > Northeast > West > North
Parent slope	Northeast > Southwest > Northwest > West > North
Length-to-width	West > Northwest > Northeast > Southwest > North
Height-to-length	North ≥ Northwest > West > Northeast > Southwest
Height-to-width	Northwest > North ≥ West > Northeast > Southwest

TABLE 4: Mean value rankings for the morphometric data by aspect.

Tread length, width and angle show consistent trends for all groups of aspects. Tread length and width show decreasing dimensions in the upslope direction, while tread angle shows an increase. Riser height shows a weak decrease on north- and northwest-facing slopes, and no change on west-facing slopes. Riser angle does not show a consistent trend, decreasing upslope on west-facing slopes, but increasing weakly on north- and northwest-facing slopes. Variance around the trend lines is particularly large for north-facing slopes for all the morphometric parameters except riser angle.

On most slopes where the transects were located, there were no obvious signs of a catena of solifluction landforms similar to that reported by Bennedict (1970) or Ballantyne and Harris (1994). This may reflect the fact that most of the transects did not extend for the entire length of any given slope, and/or that the slope profiles had too many breaks to enable the development of a solifluction catena. However, on two west-facing transects (1 and 21) located on the same slope, there is a noticeable evolution in the morphometry of turf-banked solifluction lobes and allied solifluction landforms (see Figure 10), hinting at the possibility of a solifluction catena. Along the wind-scoured crest of this slope there are crudely developed non-sorted stripes (Figure 18). The occurrence

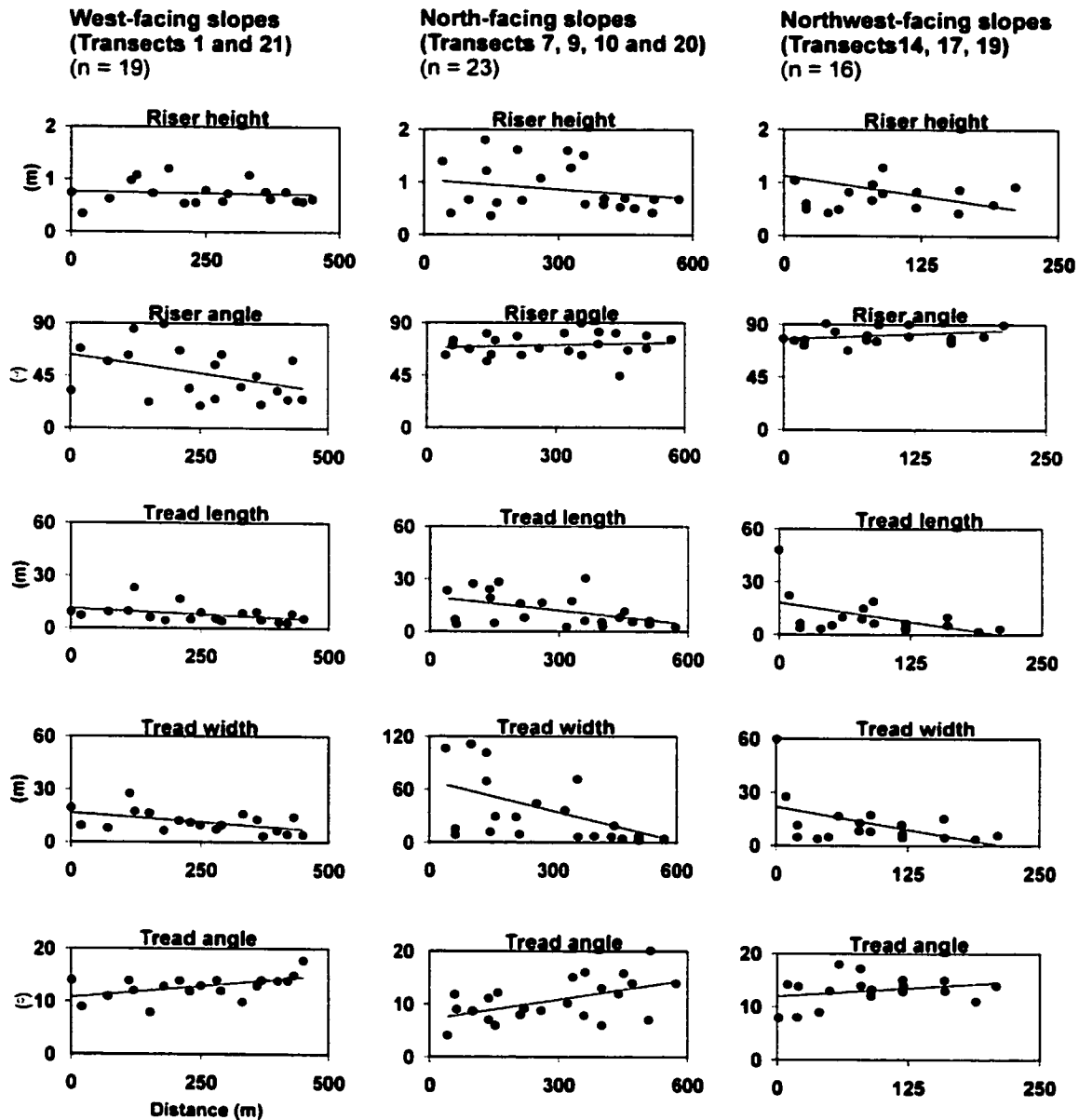


FIGURE 17: Charts showing trends in morphometric parameters according to aspect. Only those transects with similar altitudinal ranges were used. Distances are measured **upslope** from the base of the transect. *Note scale change for tread width on north-facing slopes.

of very minor vegetation cover has probably prevented further development of the stripes. At the same location several ephemeral drainage channels, possibly hillslope water tracks (*cf.* Hastings *et al.*, 1989; Walker *et al.*, 1989), are present, discernible only due to the presence of vegetation in the trough (Figure 18). Below the crest, the slope profile is slightly convex and incorporates non-sorted steps followed by numerous lobes which are much smaller than those on the segments below (Figure 19). The bulk of the turf-banked lobes occurs on the next slope segment, which has two poorly developed benches possibly associated with bedrock structure, where snow accumulates preferentially (Figure 20). The lower-most segment of the slope (near the location of the CALM grid) is gently sloping and convex in the across-slope direction with gradients $< 4\text{--}5^\circ$. This section is wet throughout the thaw season and devoid of lobes but contains numerous non-sorted circles.



FIGURE 18: Photograph of the west-facing slope looking downslope. Non-sorted stripes are present along the slope crest and ephemeral drainage channels along the right side of the photograph.



FIGURE 19: Photograph of smaller lobes near the top of the west-facing slope. Arrow denotes a 50 cm tall digital level for scale.

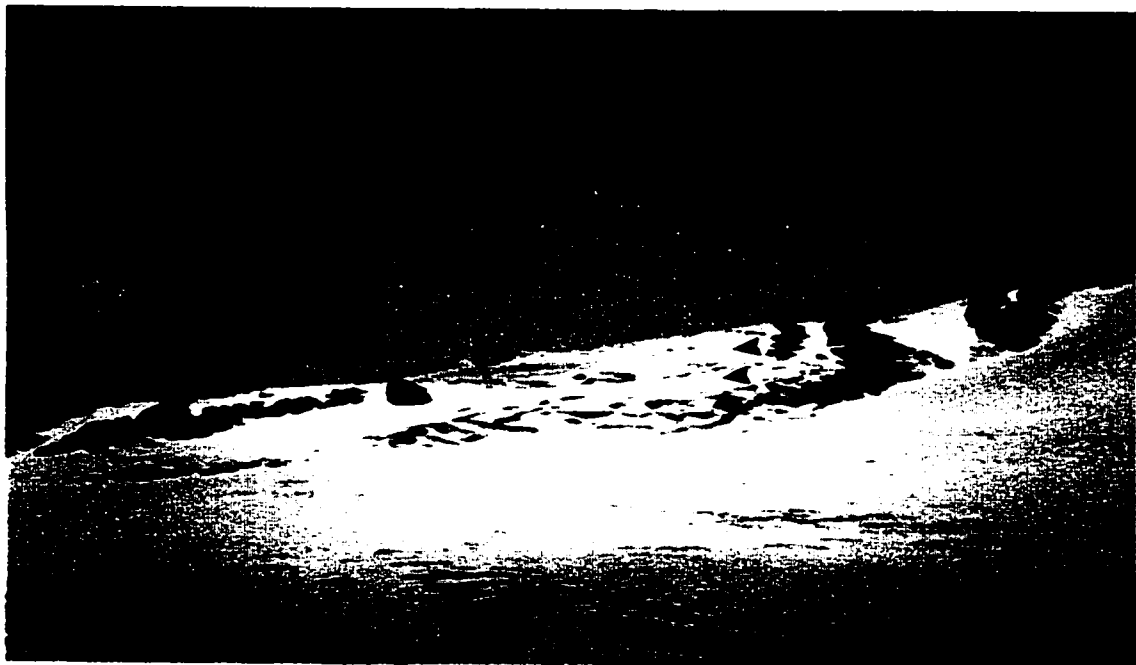


FIGURE 20: Photograph showing the distribution of snow on the west-facing slope shown in Figure 10. Arrows denote benches described in the text.

4.3.2 Relationships among morphometric parameters

Correlation analysis was used to test for significant relationships among the morphometric parameters (Section 3.4.4). Parametric correlation is predicated on the assumption of normality, so most of the parameters first had to be transformed to normalize the data. Transformed variables for the pooled data are presented in Table 5. In addition, eleven outliers were removed; one for riser height, one for tread length, four for tread width and five for the riser height-to-tread length ratio. Table 6 is the resultant correlation matrix for the pooled data. Fifteen of the comparisons are significant at 95% confidence level or better, and ten have $r \geq 0.50$ ($r^2 \geq 0.25$). The overall best correlation occurs between tread length and width ($r = 0.80$) followed by the correlation between the height-to-length and height-to-width ratios ($r = 0.78$).

Parameter	Initial skewness	Tolerance (Jones, 1969)	Type of Transform	Post-transform skewness
Riser height	0.97	± 0.499	Logarithm	-0.01
Riser angle	-0.88	± 0.499	Square	-0.35
Tread length	1.22	± 0.499	Logarithm	0.28
Tread width	1.93	± 0.499	Logarithm	0.50
Height-to-length	3.28	± 0.499	Square root	0.43
Height-to-width	0.71	± 0.499	Square root	0.08

TABLE 5: Transformed morphometric parameters for the pooled data ($n = 85$). Tolerance for normality after Jones (1969).

Correlations of the morphometric parameters from lobes subdivided by aspect required transformations for some of the parameters (Table 7). Thirteen outliers were removed; four from north-facing slopes, six from northwest-facing slopes and three from west-facing slopes. Table 8 shows the resultant correlation matrices. Significant ($p \leq 0.05$) correlations are present for all aspects. High numbers of significant correlations

Parameter	Riser height	Riser angle	Tread length	Tread width	Tread angle	Parent slope	Length-to-width	Height-to-length	Height-to-width
Riser height	1.00								
Riser angle	0.31**	1.00							
Tread length	0.50***	0.06	1.00						
Tread width	0.51***	-0.03	0.80***	1.00					
Tread angle	-0.09	-0.07	-0.13	-0.20	1.00				
Parent slope	-0.03	-0.04	-0.19	-0.13	0.54***	1.00			
Length-to-width	-0.06	0.14	0.06	-0.32**	0.24*	0.06	1.00		
Height-to-length	0.06	-0.00	-0.66***	-0.52***	0.12	0.20	-0.13	1.00	
Height-to-width	0.01	0.09	-0.52***	-0.64***	0.27*	0.24*	0.54***	0.75***	1.00

TABLE 6: Pearson product-moment correlations (*r*) between the morphometric parameters for pooled data (*n* = 85). Confidence levels: * < 0.05, ** < 0.01, *** < 0.001.

occur for north, northwest and west aspects with similar relationships between riser height and tread length, riser height and tread width, and tread length and tread width. Riser angle is significantly correlated to tread length and tread width only for lobes on west-facing slopes.

Aspect	Parameter	Initial skewness	Tolerance (Jones, 1969)	Type of Transform	Post-transform skewness
North (<i>n</i> = 29)	Tread length	0.97	±0.827	Logarithm	0.28
	Tread width	1.61	±0.827	Logarithm	0.61
Northwest (<i>n</i> = 18)	Tread length	2.69	±0.982	Logarithm	0.63
West (<i>n</i> = 25)	Riser height	1.02	±0.877	Logarithm	0.03
	Tread length	1.48	±0.877	Logarithm	0.42
	Tread width	1.8	±0.877	Logarithm	0.15
	Parent slope	-0.94	±0.877	Square	-0.04
	Height-to-length	1.01	±0.877	Square root	-0.63
	Height-to-width	1.22	±0.877	Square root	0.81

TABLE 7: Transformed morphometric parameters for the data subdivided by aspect. Tolerance for normality after Jones (1969).

In summary, the bivariate correlations indicate that riser height, tread length and tread width are the most correlated variables for both the pooled data and those subdivided by aspect. In other words, larger lobes are larger in all dimensions.

The results from forward stepwise multivariate correlation analyses among the transformed morphometric parameters are shown in Table 9. The three ratio parameters were omitted. Plots of predicted versus the residual scores are shown in Appendix B. All coefficients (R) are significant at 99.95% confidence level. The best correlation occurs for tread width ($R = 0.89$), followed by tread length ($R = 0.88$), riser height ($R = 0.64$), tread angle ($R = 0.52$) and riser angle ($R = 0.40$), respectively. The partial correlation coefficients and Beta coefficients shown in Table 9 reveal the relative contribution of each significant independent variable in the prediction of the dependent variable. It is not surprising that variables which are strongly correlated in the bivariate analyses, are also strongly correlated in the stepwise analysis. For example, tread length and tread width are significantly correlated at $p \leq 0.001$ in the bivariate correlation matrix (Table 7), and both contribute the most to each other's prediction in the stepwise analysis (Table 9).

4.3.3 Inter-aspect morphometric differences

In order to determine if significant differences occur in the morphometric parameters of lobes between different aspects, two types of tests were performed (see Sections 3.4.5. and 3.4.6). The first test, a nonparametric Wilcoxon ranked-sum test, was performed on each variable for all possible paired combinations of aspects with outliers removed. This test was chosen as a nonparametric alternative to the t-test and ANOVA because some of the parameters did not have normal distributions.

NORTH (n = 29)									
Parameter	Riser height	Riser angle	Tread length	Tread width	Tread angle	Parent slope	Length-to-width	Height-to-length	Height-to-width
Riser height	1.00								
Riser angle	0.14	1.00							
Tread length	0.49*	-0.04	1.00						
Tread width	0.73***	-0.02	0.67***	1.00					
Tread angle	-0.11	0.03	-0.08	-0.30	1.00				
Parent slope	-0.06	-0.07	-0.35	-0.36	0.67***	1.00			
Length-to-width	-0.47*	0.11	-0.40	-0.76***	0.40	0.24	1.00		
Height-to-length	-0.18	0.12	-0.75***	-0.63**	0.07	0.45*	0.17	1.00	
Height-to-width	-0.43*	0.10	-0.71***	-0.89***	0.30	0.44*	0.80***	0.69***	1.00
NORTHEAST (n = 7)									
Riser height	1.00								
Riser angle	0.30	1.00							
Tread length	0.26	-0.26	1.00						
Tread width	0.14	-0.07	0.75	1.00					
Tread angle	0.17	0.48	-0.45	-0.40	1.00				
Parent slope	0.11	0.77*	-0.73	-0.68	0.67	1.00			
Length-to-width	-0.09	0.02	-0.43	-0.89*	0.09	0.51	1.00		
Height-to-length	0.32	0.33	-0.75	-0.69	0.67	0.72	0.40	1.00	
Height-to-width	0.18	0.30	-0.79*	-0.85*	0.51	0.76*	0.65	0.94**	1.00
NORTHWEST (n = 18)									
Riser height	1.00								
Riser angle	-0.11	1.00							
Tread length	0.95***	-0.20	1.00						
Tread width	0.95***	-0.26	0.97***	1.00					
Tread angle	-0.34	-0.24	-0.28	-0.33	1.00				
Parent slope	-0.13	-0.15	0.26	0.15	0.66**	1.00			
Length-to-width	0.04	0.10	0.44	-0.20	0.17	0.30	1.00		
Height-to-length	0.28	0.32	-0.78**	-0.38	-0.19	-0.49	-0.70**	1.00	
Height-to-width	0.50	0.43	-0.49	-0.83***	-0.08	-0.24	0.41	0.33	1.00
WEST (n = 25)									
Riser height	1.00								
Riser angle	0.39	1.00							
Tread length	0.47*	0.54**	1.00						
Tread width	0.55**	0.48*	0.83***	1.00					
Tread angle	-0.17	-0.29	-0.37	-0.50*	1.00				
Parent slope	0.05	-0.23	-0.39	-0.26	0.31	1.00			
Length-to-width	-0.20	-0.01	0.20	-0.41*	0.30	-0.18	1.00		
Height-to-length	-0.21	-0.64***	-0.48**	-0.33	0.19	0.32	-0.16	1.00	
Height-to-width	-0.02	-0.30	-0.67***	-0.85***	0.50*	0.28	0.36	0.22	1.00
SOUTHWEST (n = 6)									
Riser height	1.00								
Riser angle	-0.82	1.00							
Tread length	0.61	-0.78	1.00						
Tread width	0.57	-0.57	0.87	1.00					
Tread angle	0.16	-0.59	0.39	0.11	1.00				
Parent slope	-0.60	0.65	-0.07	0.06	-0.57	1.00			
Length-to-width	-0.31	0.29	-0.74	-0.95**	0.06	-0.52	1.00		
Height-to-length	0.18	0.14	-0.66	-0.61	-0.25	-0.67	0.71	1.00	
Height-to-width	-0.14	0.22	-0.74	-0.88	0.02	-0.64	0.97***	0.86	1.00

TABLE 8: Pearson product-moment correlations (r) between the morphometric parameters for the data subdivided by aspect. Confidence levels: * < 0.05, ** < 0.01, *** < 0.001.

a) Riser height as the dependent variable

$R = 0.64$		$R^2 = 0.42$	$p\text{-level} = 0.00$
Significant variables in the model			
Parameters	Beta coefficient	Partial coefficient	$p\text{-level}$
Tread width	0.56	0.58	0.00
Riser angle	0.32	0.39	0.00

b) Riser angle as the dependent variable

$R = 0.40$		$R^2 = 0.16$	$p\text{-level} = 0.00$
Significant variables in the model			
Parameters	Beta coefficient	Partial coefficient	$p\text{-level}$
Riser height	0.47	0.39	0.00

c) Tread length as the dependent variable

$R = 0.88$		$R^2 = 0.77$	$p\text{-level} = 0.00$
Significant variables in the model			
Parameters	Beta coefficient	Partial coefficient	$p\text{-level}$
Tread width	0.83	0.81	0.00
Tread angle	0.17	0.29	0.01
Parent slope	-0.14	-0.23	0.04

d) Tread width as the dependent variable

$R = 0.89$		$R^2 = 0.79$	$p\text{-level} = 0.00$
Significant variables in the model			
Parameters	Beta coefficient	Partial coefficient	$p\text{-level}$
Tread length	0.78	0.81	0.00
Tread angle	-0.21	-0.35	0.00
Riser height	0.15	0.25	0.03

e) Tread angle as the dependent variable

$R = 0.52$		$R^2 = 0.27$	$p\text{-level} = 0.00$
Significant variables in the model			
Parameters	Beta coefficient	Partial coefficient	$p\text{-level}$
Parent slope	0.52	0.52	0.00

TABLE 9: Results of the forward stepwise correlations (R) between the morphometric parameters from the pooled data ($n = 85$).

The results of the Wilcoxon tests at confidence levels of 0.001, 0.01 and 0.05 are presented in Table 10. They show significant differences in all morphometric parameters with the exception of the length-to-width ratio. Three aspect combinations (N/NE, NE/W and NW/W) have only one significant difference. Four or more parameters are significantly different between north- and northwest-facing slopes and between

northeast- and southwest-facing slopes. The highest number of differences between pairs occurs for riser angle, as well as the strongest differences ($p \leq 0.01$), while tread angle has the least.

Following the initial examination of the data in the Wilcoxon tests, a multivariate analysis, namely discriminant analysis, was performed in order to explore morphometric differences between different aspects, in this case: north-, northwest- and west-facing slopes (due to low numbers, northeast and southwest aspects were not included). Using the criteria outlined by Lachenbruch (1975) for a three-sample population, only three parameters were entered in the discriminant analysis because otherwise it becomes extremely difficult to find the physical meaning of discrimination (*cf.* Sorriso-Valvo *et al.*,

Parameter	Paired slope orientation classes									
	N / NE	N / NW	N / W	N / SW	NE / NW	NE / W	NE / SW	NW / W	NW / SW	W / SW
Riser height				*			*		*	*
Riser angle		**	**	*	*		*	***	*	
Tread length		*	*			*	*			
Tread width		*	*				*			
Tread angle		*								
Parent slope	*	*			*		*			
Tread length / Tread width										
Riser height / Tread length				*					*	*
Riser height / Tread width		*							*	*

TABLE 10: Wilcoxon ranked sums tests among morphometric parameters. Class numbers: North ($n = 29$), Northeast ($n = 7$), Northwest ($n = 18$), West ($n = 25$), Southwest ($n = 6$). Probability of rejection of null hypothesis of no difference: * < 0.05 ; ** < 0.01 , *** < 0.001 .

1998). Two criteria were used to determine which variables were entered in the discriminant analysis. The first was that the parameters were uncorrelated or weakly correlated (see Table 8), because, if entered, correlated variables add bias to the analysis. The second was that the parameters were significantly different in the Wilcoxon tests for at least one of the three aspect combinations (see Table 10). The data were not normalized but outliers were removed. As a part of the analysis, canonical variables were computed and plotted. Canonical variables are discussed further by Lachenbruch (1975), Tatsoka (1971) and Kshirsagar (1972). The plots graphically illustrate the degree of association among samples within the three groups (aspects). A total of three analyses were performed using different combinations of parameters and aspect as the classification factor.

Results from the initial discriminant analysis are shown in Figure 21, employing aspect as the classification factor and riser angle, tread width and tread angle as the discriminant functions. Wilks' lambda, which ranges between 0 and 1 (values closer to 0 indicate strong discrimination and values closer to 1 indicate poor discrimination), is relatively high (0.52), indicating that the selected parameters had moderate discriminatory power. This is reflected in the plot of canonical roots, which shows a wide scatter in the data from north- and west-facing slopes (Figure 21b). The distance between group centroids (Squared Mahalanobis and F -distance) show greater separation between lobes on northwest- and west-facing slopes than the other combinations. The overall number of lobes correctly classified by the discriminant function on north-facing slopes is 19 out of 29 (65.5%), 10 out of 16 (62.5%) on northwest-facing slopes, and 15 out of 24 (62.5%) on west-facing slopes. The partial Wilks' lambda scores indicate that riser angle contributes most to the discrimination, and that tread width and angle are not significant (i.e., $p > 0.05$).

a)

Discriminant analysis results: RA, TW, TA

Wilks' lambda = 0.52 Eigenvalue = 0.64 Canonical correlation = 0.63 Significance level = 0.00

Variables in the model	Partial Wilks' lambda		P-level	Squared Mahalanobis Distance			
					N	NW	W
RA	0.61	0.00			0.00	1.55	2.18
TW	0.92	0.06			1.55	0.00	4.31
TA	0.96	0.23			2.18	4.31	0.00

Classification Matrix				Correct (%)	F-distance			
	N	NW	W			N	NW	W
N	19	6	4	65.50		--	4.90	8.91
NW	6	10	0	62.50		4.90	--	12.65
W	8	1	15	62.50		8.91	12.65	--
Total	33	17	19					

b)

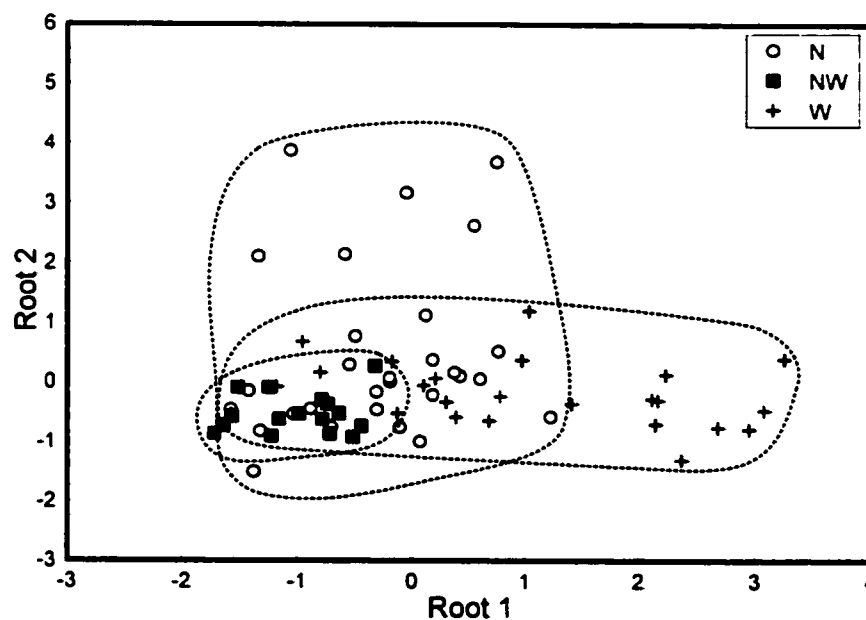


FIGURE 21: Results from the initial discriminant analysis of the morphometric parameters using riser angle, tread width and tread angle as the discriminant functions: (a) tabular results; (b) plot of canonical variables illustrating the scatter in the groups (i.e., North-facing, Northwest-facing and west-facing slopes).

Two additional analyses were performed using different combinations of discriminating variables (Figure 22), however the values for Wilks' lambda indicate that both were weaker than the first analysis (i.e., Wilks' lambda > 0.52). Using riser angle, tread length and tread angle, the percentage of correctly classified cases improved from the first analysis for lobes on north-facing slopes, decreased for those on northwest-, and was unchanged for those on west-facing slopes (Figure 22a). As in the first analysis, the greatest separation (Squared Mahalanobis and *F*-distance) occurred between northwest- and west-facing slopes. Using riser height, riser angle and tread angle, the percentage of correctly classified cases improved only slightly for lobes on north- and west-facing slopes, but decreased for those on northwest-facing slopes (Figure 22b). Again, the greatest separation was between lobes on northwest- and west-facing slopes.

In summary, the nonparametric Wilcoxon tests show that several parameters are significantly different between aspects, particularly riser angle. However, the discriminant analyses show that there is moderate differentiation between north-, northwest- and west-facing slopes, indicating that with the exception of riser angle the morphometry of lobes on these slopes is more similar than dissimilar.

4.4 BIOPHYSICAL VARIABLES

4.4.1 Permafrost

As discussed in Section 3.2.2.1, two methods were used to examine the distribution of permafrost in order to identify the type of solifluction environment: BTS

a)

Discriminant analysis results: RA, TL, TA									
Wilks' lambda = 0.53		Eigenvalue = 0.71	Canonical correlation = 0.64		Significance level = 0.00				
Variables in the model		Partial Wilks' lambda		P-level		Squared Mahalanobis Distance			
						N		NW	
RA		0.59		0.00		0.00		1.30	
TA		0.93		0.08		1.30		0.00	
TL		0.96		0.23		1.95		4.78	
						W		0.00	
Classification Matrix		N		NW		W		Correct (%)	
N		21		6		2		72.40	
NW		8		9		0		52.90	
W		8		1		15		62.50	
Total		37		16		17			
		N		NW		W		F-distance	
N		--		4.30		7.95		--	
NW		4.30		--		14.59		--	
W		7.95		14.59		--			

b)

Discriminant analysis results: RH, RA, TA									
Wilks' lambda = 0.56		Eigenvalue = 0.64	Canonical correlation = 0.63		Significance level = 0.00				
Variables in the model		Partial Wilks' lambda		P-level		Squared Mahalanobis Distance			
						N		NW	
RH		0.95		0.19		0.00		0.34	
RA		0.62		0.00		0.34		0.00	
TA		0.92		0.06		0.65		4.37	
						W		0.00	
Classification Matrix		N		NW		W		Correct (%)	
N		20		6		3		69.00	
NW		7		10		0		58.82	
W		9		0		16		64.00	
Total		36		16		19			
		N		NW		W		F-distance	
N		--		4.41		6.90		--	
NW		4.41		--		13.56		--	
W		6.90		13.56		--			

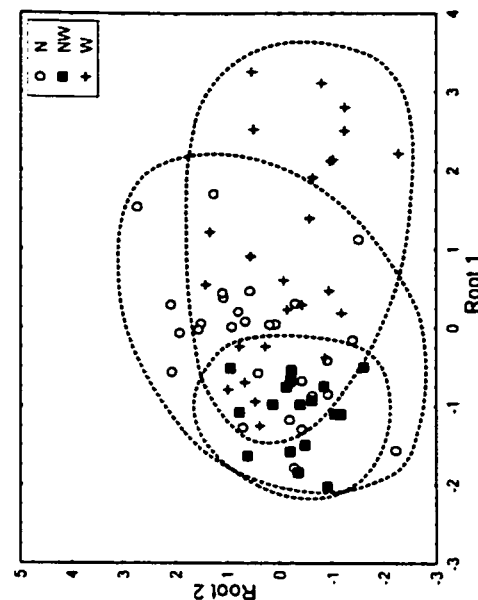
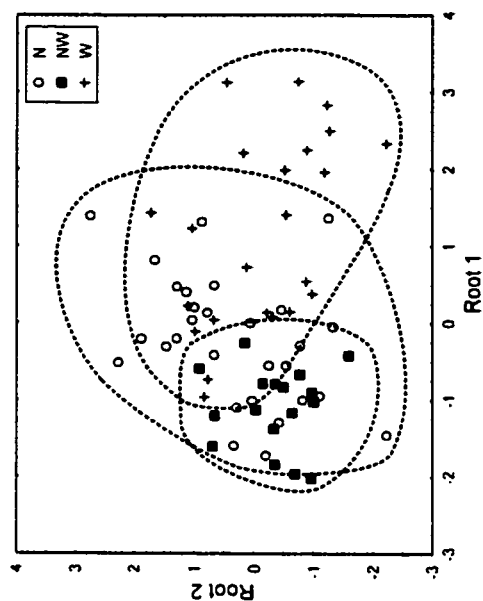


FIGURE 22: Results of discriminant analyses using: (a) riser angle, tread length and tread angle; (b) riser height, riser angle and tread angle.

and frost-table probing. Seventy BTS values were recorded in the field, however eleven of these values were excluded from the analysis due to insufficient snow depth (i.e., < 0.8 m). In support of the BTS measurements a total of 722 frost-table probing measurements were made along the transects in late summer.

BTS measurements could be made only at a small percentage of the transect measurement points due to highly variable snow cover on west-facing slopes. Several south-facing slopes were blown clear of snow during the field period and could not be included. Figure 23 shows the distribution of BTS values according to the different aspects. High values were obtained on wind-sheltered north- and northeast-facing slopes (n = 27) where the BTS ranged from -1 to -2.1°C. Lower values were obtained on west- and northwest-facing slopes (n = 32) where the BTS ranged from -2.1 to -5.8°C.

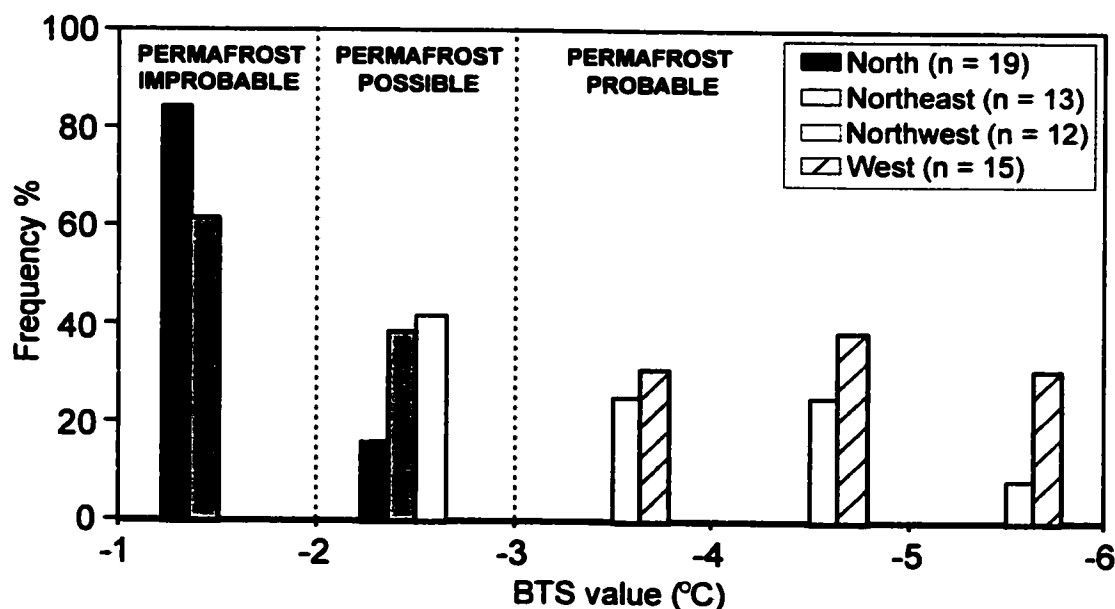


FIGURE 23: Distribution of BTS values from different aspects (April 28 to May 9, 2000). Permafrost categories after Haeberli (1973).

According to the established diagnostic values for predicting the occurrence of permafrost in Europe, these data suggest that permafrost is probable-to-possible beneath west- and northwest-facing slopes and possible-to-improbable beneath north- and northeast-facing slopes. A number of BTS values were close to the -2°C boundary between permafrost improbable and permafrost possible. If the measurements were uniformly in error by an over-reading of 0.1°C , the distribution shown in Figure 22 would change; the permafrost improbable category would decrease by 10% to 74% for north-facing slopes and by 15% to 47% for northeast-facing slopes. However, values do not agree with frost-table probing results (see below).

Late-summer probing of the frost table during the period between July 28 and August 14, 2000 suggests that permafrost is ubiquitous beneath all slopes on which BTS measurements were possible. The two pits on the south-facing slope did not encounter frost within 2 m of the ground surface and it is possible that permafrost is absent on this slope. The MAGT for the south-facing (see Figure 6) slope for 2000-2001 was -2°C with a range in temperature of 46°C (min. = -18°C and max. = 28°C), which also suggests the possibility of permafrost. Large temperature waves occur throughout the year, highlighting the importance of insolation on the surface temperatures and suggesting little, if any, snow cover during winter.

In summary, the results of the BTS and frost probing are not in agreement. The BTS method provides only a minimum indication of permafrost extent. All BTS values on slopes with westerly orientations fall into the probable category, as do 60% of the northwest values (40% are 'possible'). On the north- and northeast-facing slopes, BTS predictions were much less successful. More than 80% of the north BTS values and

60% of the northeast values were classified as "improbable", but probing showed that permafrost is present.

Three main possible reasons exist for the lack of complete accordance between BTS and probing. The first is the timing of measurement. Because measurements were made between April 28 and May 9, it is possible that the BTS values may have risen as a result of spring warming reaching the base of the snowpack. BTS temperatures at Wolf Creek Basin 170 km to the east warmed by 1°C or more from early April to early May even without surface melt in 2001 (personal communication A.G. Lewkowicz, 2002). Secondly, early and particularly deep snow, the case in the fall 1999 at Kluane (personal communication, M. Flummerfelt, Parks Canada, 2000), insulates the ground from low air temperatures and reduces heat loss from the active layer (*cf.* Keller, 1994). As a consequence of these conditions, BTS values for some sections of the plateau may have been higher than normal, thereby underestimating permafrost extent. Thirdly, established diagnostic categories for predicting permafrost based on European studies may not be accurate for this study site. The BTS method has mainly been applied to bedrock or coarse materials such as rock glacier and talus slopes in the European Alps (e.g., Haeberli 1973; Keller and Gubler, 1993; Hoelzle *et al.*, 1999). Relatively little latent heat will be present in these materials during freeze-up, allowing a stable temperature to develop beneath the snowpack by late winter. In contrast, the active layer of the study site is in relatively moist surficial deposits with an organic mat up to 34 cm in thickness. It is possible that the BTS diagnostic categories need to be amended to take into account the thermal characteristics of these materials. Clearly, rigorous testing of the BTS rules-of-thumb is needed before definitive conclusions can be reached.

4.4.2 Snow cover

Snow surveys were conducted at the same time as the BTS measurements between April 28 and May 9, 2000. The purpose of the surveys was to determine the relationship between snow cover and the distribution and morphometry of turf-banked solifluction lobes and terraces. Snow cover was generally more uniformly distributed on slopes with northerly orientations on the east side of the plateau (Figure 24a), while slopes on the west side had more variable snow cover and some were completely devoid of snow (Figure 24b). On the west side, for example, many turf-banked solifluction lobe treads were exposed above the snow (Figure 25). It is important to note that although the snow measurements represent only a single year's conditions, the difference in snow cover between the slope orientations is believed to be typical (personal communication, M. Flummerfelt, Parks Canada, 2000). Further support for this is the dominance of Hypnum moss on the east side of the plateau and its more localized occurrence on the west side, suggesting that the latter typically retains more snow over the winter.

Table 11 outlines the main characteristics of snow depth measured along the twenty-four transects. Figure 26 shows the snow depth histograms. Snow depth ranged between 0 and 355 cm, averaging 100 cm with a standard deviation of 73.8 cm (coeff. of var. = 0.74), skewness was 0.69 (normality tolerance range = $\forall 0.499$ at $p \leq 0.05$; Jones, 1969), and kurtosis was -0.02. Snow depth was greatest on north-facing slopes followed by northwest-, northeast-, southwest- and west-facing slopes respectively. There were no significant upslope (downslope) trends. The variability of snow depth was highest on windward west- and southwest-facing slopes, followed by northeast-, northwest and leeward north-facing slopes (Figure 26).

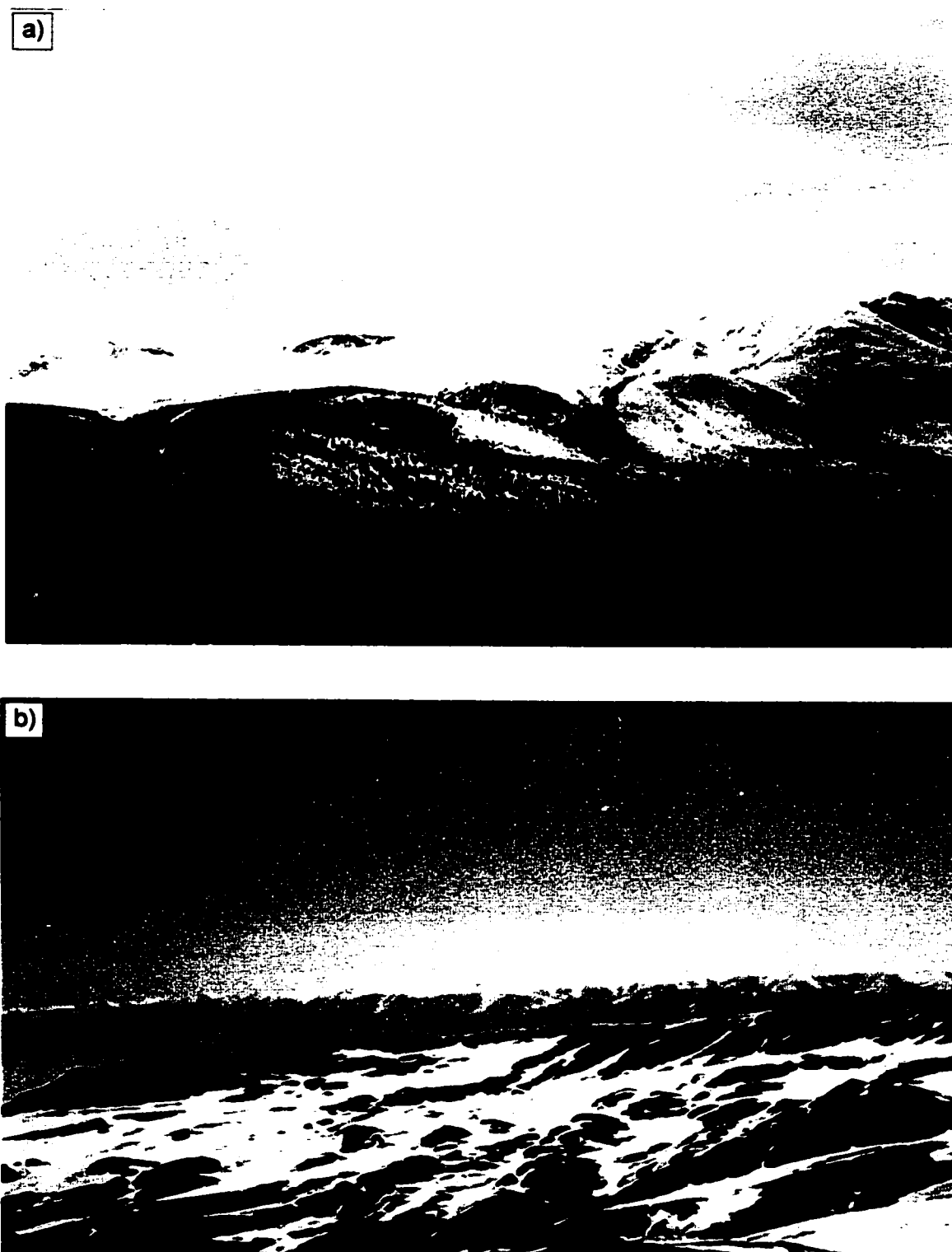


FIGURE 24: Photographs of the distribution of snow on: (a) the east side of the plateau (April 26, 2000) and (b) the west side (May 4, 2000).



FIGURE 25: Photograph showing the distribution of snow around lobes on a west-facing slope shown in Figures 10 and 17 on May 9, 2000. The small stake with flagging tape is 70 cm tall. *Note the occurrence of a large number of non-sorted circles on the treads of the lobes creating a stepped appearance.

Sample	Mean	Median	STD	Coeff. of variability	Min.	Max.
Entire field site (n = 720)	100.1	92	73.8	0.7	0	355
North (n = 212)	132.6	125	63.6	0.5	0	321
Northeast (n = 144)	100.5	97	72.2	0.7	0	355
Northwest (n = 111)	103.4	98.5	59.5	0.6	0	240
West (n = 205)	74.1	47	79.1	1.1	0	320
Southwest (n = 48)	41	35.5	36.6	0.9	0	124

TABLE 11: Descriptive statistics for the snow depth measurements (April 28 to May 9, 2000).

Snow pits were excavated along the transects (see Figure 8) in order to examine the snow stratigraphy and to determine the Snow Water Equivalent (SWE). Figure 27 shows snow stratigraphy profiles for twenty-two transects and their corresponding SWE

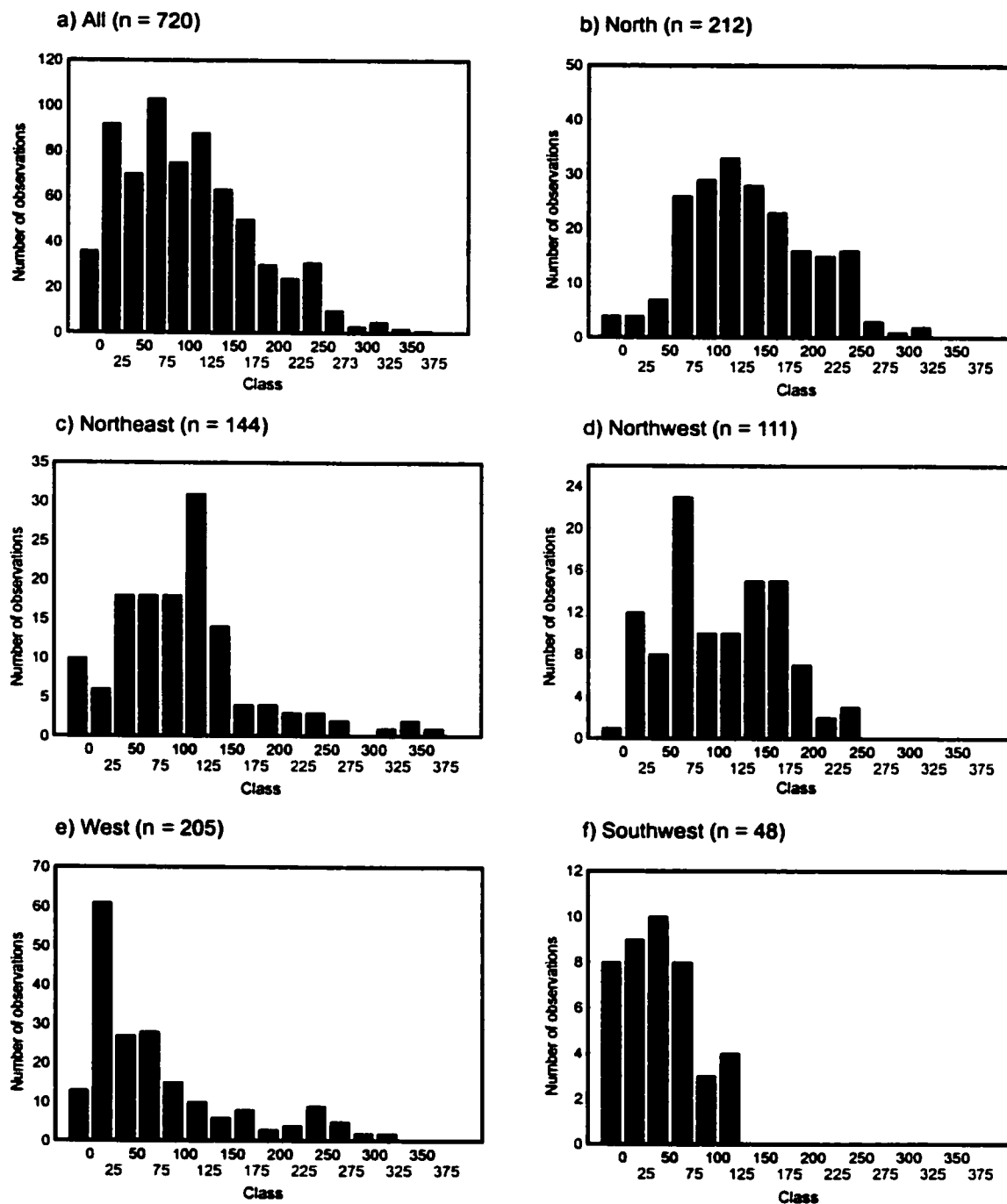
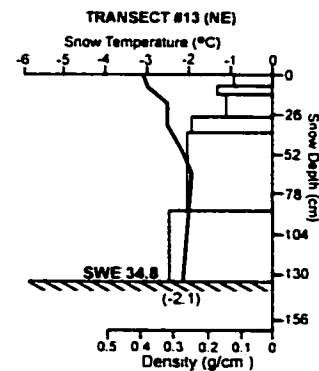
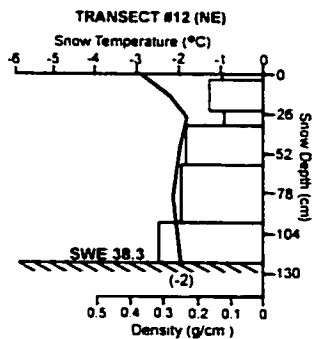
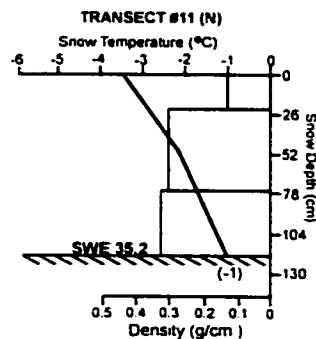
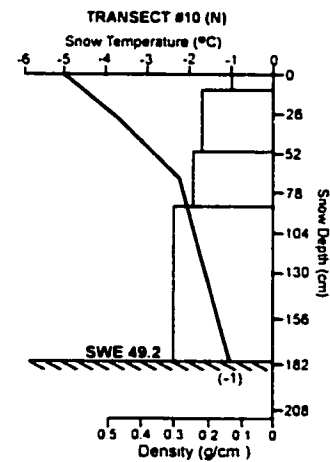
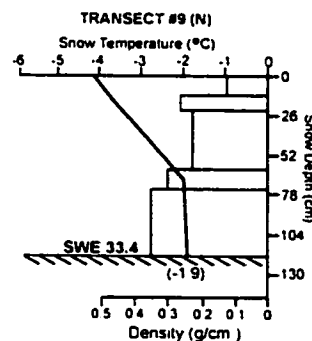
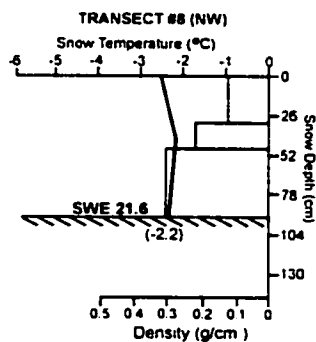
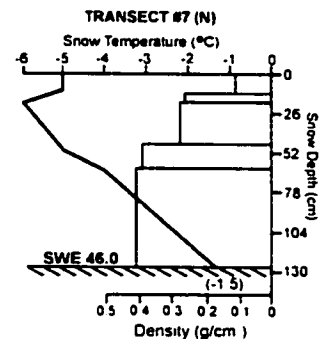
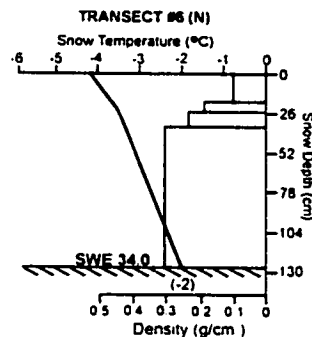
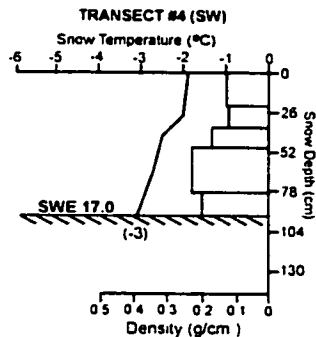
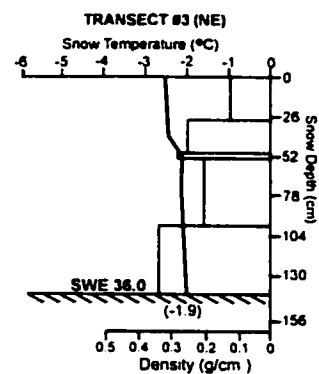
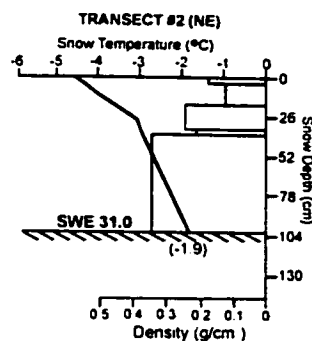
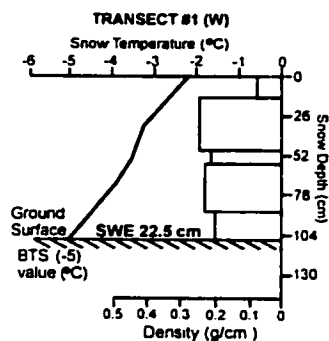


FIGURE 26: Frequency distributions of snow depth on different aspects between April 28 to May 9, 2000.



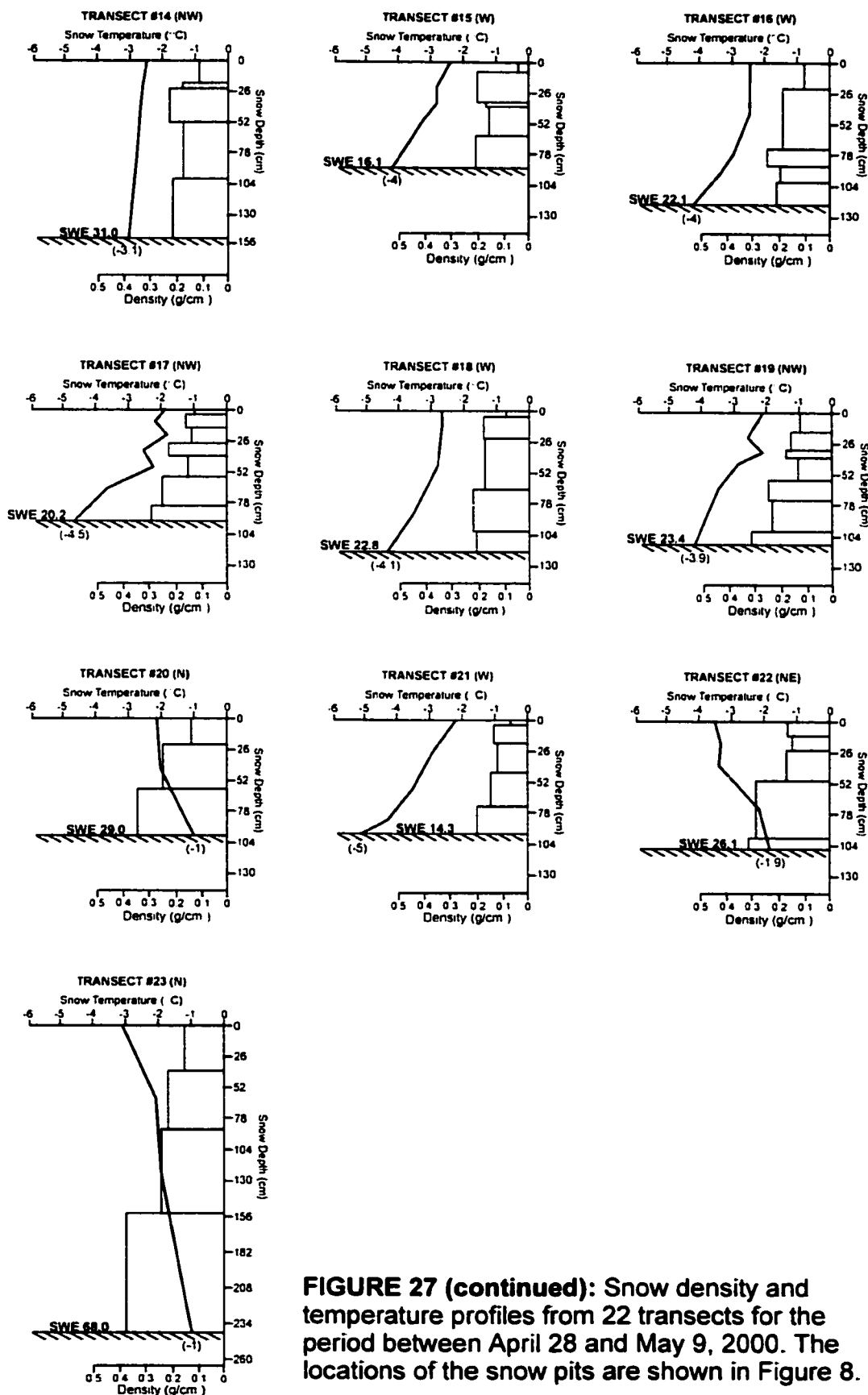


FIGURE 27 (continued): Snow density and temperature profiles from 22 transects for the period between April 28 and May 9, 2000. The locations of the snow pits are shown in Figure 8.

values. The thick uniform basal layer encountered on transects located on the sheltered east side of the plateau suggests that the initial snowpack formed from a relatively large snowfall. Snow density generally increased with depth on all transects. Snow water equivalent ranged from 28.6 cm up to 136.1 cm, and was generally higher on the sheltered east side of the plateau. There were no ice layers in the profiles to suggest significant midwinter thaw or pluvial events, and unlike some high arctic sites (e.g., Lewkowicz, 1998), there were no significant aeolian sediment deposits. Some of the probings at snowpatch sites encountered what was assumed to be basal ice, which suggests that perennial snow is present at these locations (see also Figure 11). Snow temperature data indicate that snowmelt had not commenced prior to fieldwork (Figure 27). On west- and northwest-facing slopes the snowpack temperatures generally decreased with depth, while on shaded north- and northeast-facing slopes the snowpack temperatures increased with depth. This suggests that snow surface temperatures had been affected more by insolation on the former than on the latter, but the cold basal values indicate limited, but possibly not negligible, influence at depth.

4.4.2.1 High-resolution measurements around turf-banked solifluction lobes

The risers and treads of numerous lobes were exposed as the result of variable snow cover on one of the west-facing slopes. The same pattern was also observed on Sheep Mountain (see Figure 3 for location) during the same period. An assessment of the thermal effects of this variable snow cover was made for one week from May 18 to 24, 2000 for twenty lobes. Snow was present in front of the lobes for the duration of the monitoring period. Snow depth values in front of the lobes ranged between 12 and 67 cm, averaging 32 cm. The standard deviation was 13 cm (coeff. of var. = 0.41), skewness was 1.06 (normality tolerance range = ± 0.949 at $p \leq 0.05$; Jones, 1969), and

kurtosis was 1.7. There was no upslope (downslope) trend in snow depths in front of the lobes.

Table 12 shows the diurnal temperature series obtained from ground surface measurements at various locations on the lobes. Over the seven-day monitoring period the exposed riser and tread experienced the greatest temperature range and freeze-thaw cycles. On the lobe tread, exposed non-sorted circles underwent thaw and re-freezing to depths between 5 and 15 cm. During overcast conditions (May 21 and 22) ground surface temperatures on the riser and tread did not rise above 0°C. Temperatures fluctuated very little under the snow cover in front of the lobes (-0.2° to -0.6°C), although small temperature waves are apparent.

Date	Temperature (°C)		
	Below riser (snow covered)	Riser	Tread
18/05/00 am	-0.29	-2.10	-2.27
18/05/00 pm	-0.15	5.95	6.21
19/05/00 am	-0.43	-1.99	-2.08
19/05/00 pm	-0.22	6.98	6.86
20/05/00 am	-0.48	-1.92	-1.89
20/05/00 pm	-0.30	5.25	5.17
21/05/00 am	-0.30	-1.59	-1.73
21/05/00 pm	-0.29	-1.40	-1.35
22/05/00 am	-0.51	-1.46	-1.15
22/05/00 pm	-0.51	-1.04	-0.88
23/05/00 am	-0.62	-1.72	-1.98
23/05/00 pm	-0.24	7.67	7.52
24/05/00 am	-0.50	-1.15	-1.02
24/05/00 pm	-0.33	8.94	8.87
Max.	-0.15	8.94	8.87
Min.	-0.62	-2.10	-2.27

TABLE 12: Values of the diurnal temperature series from different locations across twenty lobes during the period of May 18-24, 2000 (measurements taken at 0800 and 1600h).

The moisture content and index properties of soil samples from thawed non-sorted circles super imposed on the lobe tread are shown in Table 13. Soil moisture ranged between 37 and 71%, averaging 54.6 (S.D. = 11.1). The liquid limit ranged between 22 and 28%, averaging 24.3 (S.D. = 1.6). The plastic limit could not be obtained for the samples because there was insufficient cohesive material, indicating that the soils are non-plastic. On average, the soil moisture was twice the liquid limit, suggesting that the upper few centimeters of non-sorted circles on the tread were capable of viscous movement by gelifluction and were subject to frost creep during the monitoring period. The bulk of the moisture supply to the non-sorted circles was from snow melting along the upper portion of the tread, which effectively saturated the lower parts of the tread during periods of sunshine.

Lobe	Soil moisture (%)	Liquid limit (%)
1	42	23
2	54	22.4
3	39	22.7
4	66	25.1
5	61	24.6
6	59	22
7	43	22.8
8	37	23.2
9	68	24.1
10	65	24.6
11	70	23.8
12	41	27.1
13	53	26
14	71	28
15	69	25.9
16	45	24.7
17	48	23.5
18	52	23.3
19	61	24.4
20	47	25.7

TABLE 13: Soil properties from thawed sections on lobe treads (May 24, 2000).

4.4.3 Summary statistics for late-summer thaw depth, organic mat thickness and soil properties

The following section reviews the descriptive statistics for measurements on the late-summer thaw depth, organic mat thickness and soil properties from eighty-five lobes and non-lobe sites. Summary statistics are given in Tables 14 and 15, respectively. Rankings of the mean values from different aspects, regardless of whether the differences between the means are statistically significant or not, are shown in Tables 16 and 17. Raw data for both groups are presented in Appendices C and D.

4.4.3.1 Late-summer thaw depth

The late-summer thaw layer thickness (July 28 and August 14, 2000) along the tread surface of lobes ranged between 37 and 120 cm, averaging 84 cm with a standard deviation of 19 cm (coeff. of var. = 0.22). Skewness was within the normality tolerance range $\forall 0.499$ at $p \leq 0.05$, and kurtosis was -0.69. The deepest average thaw was measured on west-facing slopes ($n = 25$) followed by southwest ($n = 6$), northwest- ($n = 18$), northeast- ($n = 7$) and north-facing slopes ($n = 29$), respectively (Table 16). The coefficient of variability for the different aspects (Table 14) was consistently low, ranging between 0.1 and 0.3, indicating little variation in thaw depth for lobes on the same aspect.

The late-summer thaw layer thickness for non-lobe sites ranged between 64 and 106 cm, averaging 95 cm with a standard deviation of 15 cm (coeff. of var. = 0.2), skewness was -3.14, indicating a strong j-shaped distribution, and kurtosis was high at 9.81 (leptokurtic). Within group variability was similar to that of the lobes.

LOBES	Parameter	Mean	Median	STD	Coeff. Of variability	Min.	Max.	Skewness
ALL (n = 85)	OM	13.8 cm	12.8	8.8	0.6	0	34	0.58
	THL	83.8 cm	85	18.7	0.2	37	116	-0.38
	S40	30.2 %	28.2	10.5	0.3	10.5	61.4	0.98
	S80	32.9 %	30	11.6	0.4	11.4	64.4	0.87
	LL	24 %	23.9	1.9	0.1	20	29	0.50
	%GR	20.1	20.6	6.4	0.3	4	46.8	-0.05
	%SD	31.7	32.3	5.5	0.2	11.7	49	-0.98
	%ST	45.5	44.9	7.6	0.2	24.1	66.9	0.65
	%CL	2.5	2.5	0.4	0.2	1.3	3.7	0.34
	%GRSD	51.8	52.6	7.9	0.2	29.5	74.5	-0.98
	%STCL	48.0	47.3	8.1	0.2	25.5	70.5	0.65
NORTH (n = 29)	OM	15.5	15.2	8.8	0.6	1	31	0.05
	THL	79.5	78.2	15.9	0.2	52	105	0.14
	S40	27.2	27.2	6.2	0.2	11.3	44.1	1.05
	S80	30	30	7.3	0.2	11.4	44.9	1.05
	LL	23	22.4	1.6	0.1	20	27.3	0.63
	%GR	21.5	21	6.8	0.3	10.5	46.8	1.99
	%SD	32	32.9	2.4	0.1	27.3	36.6	-2.65
	%ST	43.6	44.7	6	0.1	24.1	52.5	0.08
	%CL	2.5	2.5	0.2	0.1	2.1	2.9	0.05
	%GRSD	52.3	52.6	7.3	0.1	29.8	74.5	-0.04
	%STCL	47.2	47.4	7.6	0.1	25.5	70.2	0.11
NORTHEAST (n = 7)	OM	24.3	31.6	10.6	0.4	11.4	34	-0.38
	THL	67.1	59.8	18.7	0.3	47	89	0.19
	S40	25.5	24.3	7.4	0.3	16.4	35.1	0.30
	S80	28.3	28.7	9.8	0.3	18.1	44.2	0.61
	LL	24.5	24.7	1.2	0.0	22.2	25.8	0.06
	%GR	16.3	15	3.5	0.2	12.3	22.9	0.50
	%SD	33.4	33.6	2.7	0.1	29.5	38	-1.65
	%ST	47.4	47	3.3	0.1	43.5	53.2	1.81
	%CL	2.6	2.6	0.2	0.1	2.4	2.9	1.81
	%GRSD	47.1	50.4	8.5	0.2	29.5	54.1	-0.81
	%STCL	52.9	49.6	8.5	0.2	45.9	70.5	1.81
NORTHWEST (n = 18)	OM	10.2	10.6	5.5	0.5	0	23	0.59
	THL	79.8	81	18	0.2	49	111	-0.21
	S40	29.5	26.1	10.4	0.4	18.6	55	1.48
	S80	28.1	26.1	7.5	0.3	20.3	51.6	2.00
	LL	24.1	24.1	0.6	0.0	23.1	25.9	1.23
	%GR	23.4	23.2	6.6	0.3	6.1	39.3	-0.21
	%SD	30.8	31.4	6.2	0.2	15	45	0.47
	%ST	43.5	43.7	7.6	0.2	27.9	63.3	0.59
	%CL	2.5	2.5	0.4	0.2	1.5	3.5	-0.03
	%GRSD	54.1	53.9	8.0	0.1	33.3	70.5	-0.57
	%STCL	45.9	46.1	8.0	0.2	29.5	66.7	0.57
WEST (n = 25)	OM	9.9	8.8	6.5	0.7	0	27	1.04
	THL	96.6	99.2	13.5	0.1	63	115	-1.13
	S40	33.1	30.4	12.5	0.4	10.5	55.8	0.22
	S80	38.4	40.1	14.5	0.4	12.2	61.3	-0.04
	LL	25.4	25.4	2.2	0.1	22.3	30.2	0.37
	%GR	18.4	19.4	6.3	0.3	4	31.8	-0.47
	%SD	32.9	32.5	3.9	0.1	26.7	39.6	1.12
	%ST	46.2	43.8	7.8	0.2	36.5	65.7	1.02
	%CL	2.5	2.4	0.5	0.2	1.5	3.6	0.45
	%GRSD	51.5	53.8	8.5	0.2	30.7	64.0	-0.99
	%STCL	48.5	46.2	8.5	0.2	36.0	69.3	0.99
SOUTHWEST (n = 6)	OM	18.8	17.9	5.9	0.3	13	28	0.60
	THL	92.4	85.3	13.8	0.1	82	116	1.37
	S40	37.1	29.8	13.3	0.4	27.8	61.4	1.61
	S80	35.3	34.9	4.2	0.1	28.9	42	0.21
	LL	21.9	21.7	1.1	0.1	21	23.9	1.93
	%GR	19.5	20.1	3.2	0.2	14.9	23.2	-0.46
	%SD	29.7	32.3	9	0.3	11.8	36.3	-2.21
	%ST	48.1	45.9	6.8	0.1	43.8	61.7	2.21
	%CL	2.6	2.5	0.4	0.2	2.4	3.4	2.21
	%GRSD	49.3	51.5	7.2	0.1	35.0	53.9	-2.21
	%STCL	50.7	48.5	7.2	0.1	46.1	65.1	2.21

TABLE 14: Summary statistics of biophysical variables from lobes.

NON-LOBES	Parameter	Mean	Median	STD	Coeff. Of variability	Min.	Max.	Skewness
ALL (n = 85)	OM	11.4	11.0	5.6	0.5	0.0	32.0	0.36
	THL	95.4	97	14.8	0.2	64	106	-0.01
	S40	21.2	20.9	7.7	0.4	1.8	48.8	-0.10
	S80	20.4	20.8	7.7	0.4	2.9	51.4	-0.03
	LL	24.2	23.8	2.4	0.1	19	30.7	0.44
	%GR	21.7	20.9	8.2	0.4	1.2	45	0.46
	%SD	33.2	33.3	6.3	0.2	7.7	58.8	-1.8
	%ST	43.8	43.6	8.5	0.2	17.3	67.3	0.04
	%CL	1.3	1.3	0.3	0.2	0.5	1.9	-0.07
	%GRSD	54.7	55.0	8.3	0.2	30.7	82.0	-0.07
	%STCL	45.3	45.0	8.3	0.2	18.0	69.3	0.07
NORTH (n = 29)	OM	11.7	13.0	3.6	0.3	3.0	32.0	0.30
	THL	92	92	9.9	0.1	68	112	-0.15
	S40	22	20.6	8.7	0.4	11.4	48.8	0.18
	S80	20.2	19.2	6.5	0.3	9.3	33.9	0.46
	LL	23.4	23.4	2.1	0.1	19	28.3	0.02
	%GR	20.3	20.2	6.1	0.3	10.5	34.3	0.34
	%SD	33.7	32.9	4.9	0.1	23.3	46.6	0.23
	%ST	44.7	44	5.8	0.1	29.1	56.1	-0.21
	%CL	1.4	1.3	0.2	0.1	1.1	1.9	0.35
	%GRSD	54.0	54.8	5.9	0.1	42.3	69.0	-0.31
	%STCL	46.0	45.2	5.9	0.1	30.7	57.7	0.31
NORTHEAST (n = 7)	OM	13.6	13.0	5.9	0.4	7.0	22.0	0.32
	THL	96	98	9.5	0.1	77	107	-1.19
	S40	18.9	17.8	4.8	0.3	13.5	26.7	0.50
	S80	17.7	16	5.7	0.3	11	29.7	1.51
	LL	24.3	23.6	1.9	0.1	21.9	27.2	0.53
	%GR	22	22.3	6.7	0.3	11.5	31.5	-0.22
	%SD	28	32.7	11.4	0.4	7.7	37.5	-1.33
	%ST	48.5	48.1	8.4	0.2	37.6	61.7	0.25
	%CL	1.5	1.5	0.3	0.2	1.1	1.8	0.01
	%GRSD	48.9	49.0	8.7	0.2	36.5	61.3	-0.10
	%STCL	51.1	51.0	8.7	0.2	38.7	63.5	0.10
NORTHWEST (n = 18)	OM	8.4	8.0	2.9	0.3	4.0	14.0	0.53
	THL	91.7	92.5	10.3	0.1	73	123	0.65
	S40	20.1	19.9	8.3	0.4	1.8	33.5	-0.26
	S80	19.9	21.8	9	0.5	2.9	34.8	-0.26
	LL	24.6	24.3	2.2	0.1	21	13.2	0.46
	%GR	24.1	23	4.4	0.2	18	28.8	0.74
	%SD	36	34	8	0.2	26.5	58.8	1.97
	%ST	38.7	40	6.7	0.2	18.7	46.9	-1.01
	%CL	1.2	1.2	0.2	0.2	0.5	1.7	0.96
	%GRSD	58.5	57.7	4.6	0.1	51.7	70.3	-1.00
	%STCL	41.5	42.3	4.6	0.1	29.7	48.3	1.00
WEST (n = 25)	OM	10.4	9.0	6.0	0.6	0.0	20.0	0.26
	THL	101.1	102	8.5	0.1	86	126	-0.18
	S40	22.9	24	6.9	0.3	5.7	33.9	-0.47
	S80	23.5	23	7.9	0.3	9.1	51.4	1.62
	LL	25.3	25.1	2.6	0.1	21.8	30.7	0.59
	%GR	21.9	20.1	12.5	0.6	1.2	45	0.46
	%SD	32	31.8	3.3	0.1	26	37.9	-0.16
	%ST	44.8	45.1	11.7	0.3	17.3	67.3	-0.22
	%CL	1.4	1.4	0.3	0.2	0.8	2	-0.24
	%GRSD	53.8	53.6	12.0	0.2	30.7	82.0	-0.23
	%STCL	46.2	46.4	12.0	0.3	18.0	69.3	0.23
SOUTHWEST (n = 6)	OM	19.5	18.0	6.4	0.3	14.0	32.0	2.01
	THL	104	106	8.8	0.1	92	114	-0.48
	S40	16.1	14.5	6	0.4	9.6	23.9	0.51
	S80	14.3	12.5	5.9	0.4	9.9	26.1	2.23
	LL	22.5	22.3	1.8	0.1	20.5	24.6	0.18
	%GR	19.5	19.6	2.4	0.1	16.7	23.1	0.25
	%SD	34.3	34.4	1.3	0.0	32.5	36.3	0.07
	%ST	44.9	44.6	2	0.0	43	48.5	1.38
	%CL	1.3	1.3	0.1	0.1	1.2	1.5	0.70
	%GRSD	53.8	54.1	2.1	0.0	50.1	55.8	-0.81
	%STCL	46.2	45.9	2.1	0.0	44.2	49.9	0.81

TABLE 15: Summary statistics of biophysical variables from non-lobe sites.

Parameter	Ranking
Organic mat	Northeast > Southwest > North > Northwest > West
Thaw depth	West > Southwest > Northwest > North > Northeast
Soil moisture 40 cm	Southwest > West > Northwest > North > Northeast
Soil moisture 80 cm	West > Southwest > North > Northeast > Northwest
Liquid limit	West > Northeast > Northwest > North > Southwest
Percent gravel	Northwest > North > Southwest > West > Northeast
Percent sand	Northeast > North > West > Northwest > Southwest
Percent silt	Southwest > Northeast > West > North > Northwest
Percent clay	Southwest > Northeast > West > Northwest > North
Percent gravel and sand	Northwest > North > West > Southwest > Northeast
Percent silt and clay	Northeast > Southwest > West > Northwest > North

TABLE 16: Mean value rankings of biophysical variables from lobe sites by aspect.

Parameter	Ranking
Organic mat	Southwest > Northeast > North > West > Northwest
Thaw depth	Southwest > West > Northeast > North > Northwest
Soil moisture 40 cm	West > North > Northwest > Northeast > Southwest
Soil moisture 80 cm	West > North > Northwest > Northeast > Southwest
Liquid limit	West > Northwest > Northeast > North > Southwest
Percent gravel	Northwest > Northeast > West > North > Southwest
Percent sand	Northwest > Southwest > North > West > Northeast
Percent silt	Northeast > Southwest > West < North > Northwest
Percent clay	Northeast > North > West > Southwest > Northwest
Percent gravel and sand	Northwest > North > West > Southwest > Northeast
Percent silt and clay	Northeast > Southwest > West > North > Northwest

TABLE 17: Mean value rankings of biophysical variables from non-lobe sites by aspect.

4.4.3.2 Organic mat thickness

The organic mat thickness along the tread surface of lobes ranged between 0 and 34 cm, averaging 14 cm with a standard deviation of 9 cm (coeff. of var. = 0.6). Skewness was just outside the normality tolerance range at 0.60, and kurtosis was -0.58. On lobes, the thickest organic mat corresponded to the thinnest thaw depth, and the thickest organic mat to the greatest thaw depth (see Table 14), but this pattern was not present for non-lobe sites (see Table 15). The average organic mat for lobes was

thickest on northeast-facing slopes, followed by southwest-, north-, northwest- and west-facing slopes respectively. The coefficient of variability ranged between 0.3 and 0.7 and was highest for west-facing slopes followed by north-, northwest-, northeast- and southwest-facing slopes, respectively (see Table 14).

The organic mat thickness for non-lobe sites ranged between 0 and 32 cm, averaging 11 cm with a standard deviation of 5.6 cm (coeff. of var. = 0.51). Skewness was 0.81 and kurtosis was 1.12. The average values for non-lobe sites are very similar to those from lobes with the exception of the southwest-facing slope where the organic mat was thicker. The coefficients of variability for the data subdivided by aspect indicate that variability was greatest on west-facing slopes followed by northeast-, north-, northwest- and southwest-facing slopes, respectively (see Table 15).

4.4.3.3 Soil properties

The typical soil properties for lobes encountered along the transects include soil moisture approximately 9% greater than the soil liquid limit, and a particle size distribution consisting predominantly of silt (46%) followed by sand (32%), gravel (20%) and small amounts of clay (2.5%). The high amount of silt indicates that the bulk of soil in the thawed layer is frost susceptible. Figure 28 shows the particle size envelope for both lobes and non-lobe sites. The particle size classes are characterized by relatively small variability (see Table 14). Late-summer soil moisture at 40 and 80 cm below ground surface differed only slightly, with higher average moisture content at 80 cm. The liquid limit for lobes was relatively low, ranging between 20 and 29%. The plastic limit is not included in the results because after more than fifty trials (from a total of 170), only six samples yielded plastic limits, and these were very low. Therefore, the bulk of the soil

is non-plastic. This may reflect two factors. First, the organic content was not removed from the samples prior to testing, and this has very low frictional and cohesive strength. Secondly, the clay content, which provides the bulk of cohesive strength, was very low, and indicates that the soil relies primarily on the frictional shearing resistance of the > clay-sized particles for stability. The predominantly silty nature of the sediments, combined with their low liquid limit values, indicates a high probability of viscous flow during the thaw period when the soil moisture level from thawing ice lenses and snowmelt is high. It should be noted that sampling with a small diameter auger, such as the one used here, biases the results because large clasts are effectively neglected. However, it is clear from the augering process that the soil is matrix-supported, and therefore, the main geotechnical characteristics, in terms of mechanical strength, are determined by the matrix sediments (*cf.* Vallejo and Mawby, 2000).

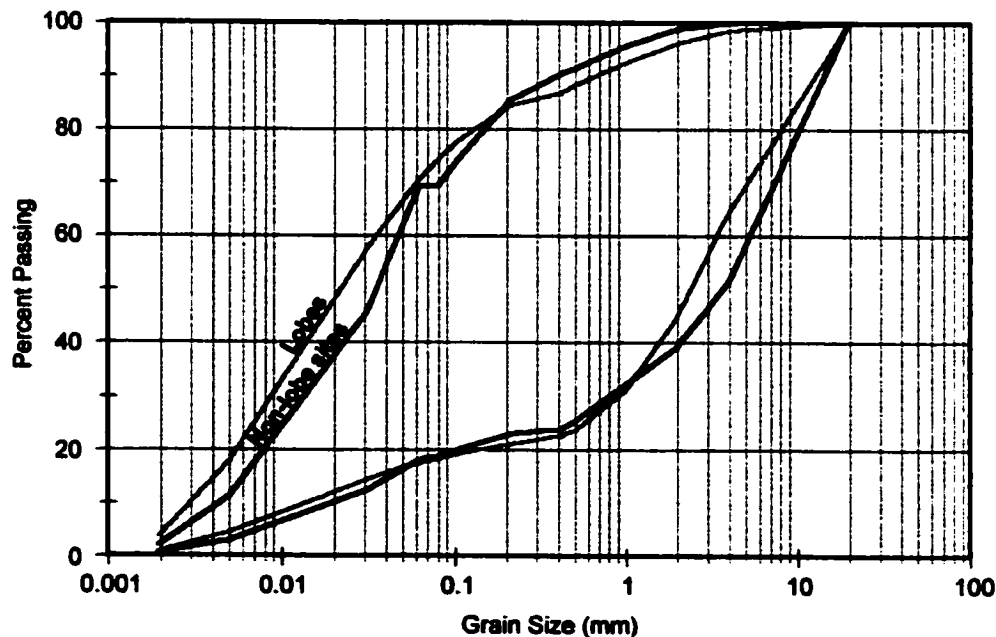


FIGURE 28: Particle size envelope from lobe and non-lobe sites.

Compared to summary data from Harris (1987, p.548), the liquid limit results presented here show that the soil texture from the Kluane lobes are within the range of those compiled for sites on Banks Island (French, 1974), Greenland (Everett, 1967; Washburn, 1967) and Norway (Harris, 1977). The non-plastic nature of the Kluane soils is not unique. A similar finding was arrived at by Elliot and Worsley (1999) for a series of samples from a lobe in northern Norway and they suggested that the low plasticity is a reflection of low clay content, as in the case for the Kluane lobes (Figure 29). Compared to summary data from Harris (1981, p.105) the clay contents from the Kluane lobes are similar to those reported from Taseriaq, Greenland (Everett, 1967) and Mt. Kosciusko, Australia (Costin *et al.*, 1967). Clay content as low as 2% has also been reported for lobes in the Front Range of the Canadian Rocky Mountains by Smith (1988).

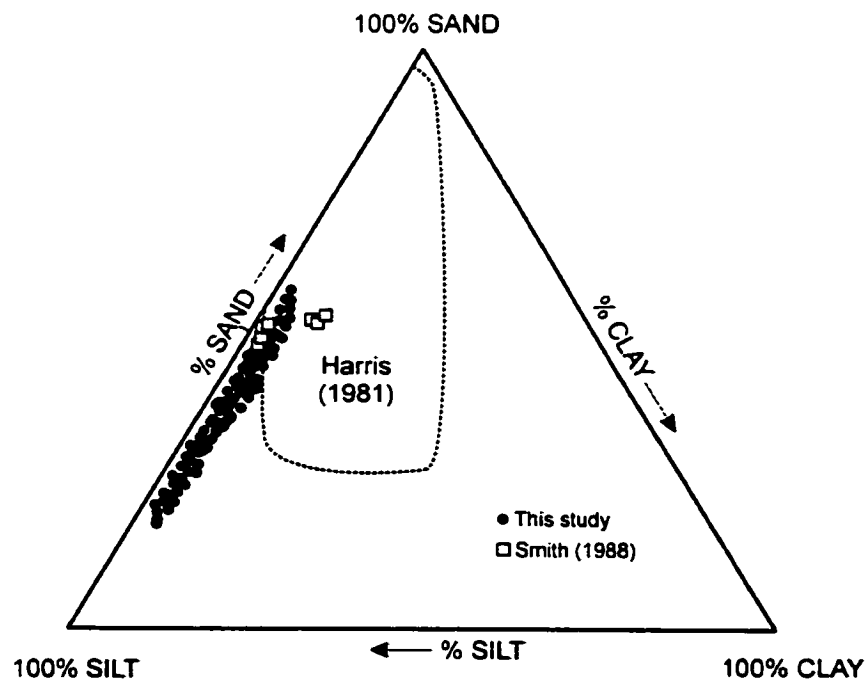


FIGURE 29: Ternary plot of sand:silt:clay for the matrix component (< 2 mm) of sediment from solifluction lobes compared to summary envelope from Harris (1981) and Smith (1988).

Variability in the soil properties for data subdivided by aspect was very low (see Table 14). The average liquid limit for lobe sites was similar on all aspects with the exception of the southwest, where the average liquid limit was lower. The average percent silt, sand and percent gravel did not change greatly when subdivided by aspect. The average percent clay was the most similar soil property for different aspects. Oddly, the average late-summer soil moisture was higher on west- and southwest-facing slopes, although these were the slopes where the SWE values were lowest. The lack of contrast between aspects may be a result of the persistent summer precipitation in 2000 (see Section 2.2).

The typical soil properties for non-lobe sites (see Table 15) include soil moisture slightly lower than the liquid limit, and a particle size distribution similar to but slightly coarser than the lobes. Soils consist predominantly of silt (44%) followed by sand (33%), gravel (22%) and small amounts of clay (1.3%). As with the lobes, the plastic limit could not be obtained for the majority of samples (see above), indicating that for the most part the soils are non-plastic.

4.4.4 Biophysical Relationships

Correlation analysis was used to test for significant relationships between the biophysical variables from lobe and non-lobe sites for the pooled data and those subdivided by aspect. For the latter, the analysis was performed only on the data from lobes. Before the correlations were calculated for the pooled data, several transformations were required to normalize the data (Table 18) and five outliers had to be removed (one for lobes and four for non-lobe sites). The resultant correlation matrix for the lobes is shown in Table 19. Thirty-three of the comparisons are significant at 95%

confidence level or better and sixteen have $r \geq 0.50$ ($r^2 \geq 0.25$). Some of the correlations between the grain size variables are dependent on each other's value (italicized in Table 19), and therefore some of the strong correlations are not surprising. Late-summer thaw depth and organic mat thickness are negatively correlated, which might be expected because of the insulating properties of the latter. The limited number of significant correlations for the late-summer thaw depth and liquid limit show that these variables are

	Initial skewness	Tolerance (Jones, 1969)	Transform	Post-transform skewness
LOBES				
Organic mat	0.58	± 0.499	Square root	0.00
Soil moisture 40cm	0.98	± 0.499	Logarithm	-0.06
Soil moisture 80cm	0.87	± 0.499	Logarithm	-0.04
Liquid limit	0.51	± 0.499	Logarithm	-0.06
%Gravel	0.71	± 0.499	Square root	-0.35
%Sand	-0.98	± 0.499	Square	0.47
%GRSD	-0.65	± 0.499	Square	0.16
%STCL	0.65	± 0.499	Logarithm	-0.28
NON-LOBE SITES				
%Sand	-1.8	± 0.499	Square	-0.50

TABLE 18: Transformed biophysical variables for the pooled data. Tolerance for normality after Jones (1969).

	OM	THL	S40	S80	LL	%GR	%SD	%ST	%CL	%GRSD	%STCL
OM	1.00										
THL	-0.53***	1.00									
S40	0.03	0.22	1.00								
S80	-0.01	0.26*	0.75***	1.00							
LL	-0.10	0.15	-0.12	-0.05	1.00						
GR	-0.29	0.07	-0.11	-0.28*	-0.30**	1.00					
SD	-0.16	0.11	-0.40***	-0.34**	0.07	-0.03	1.00				
ST	0.36**	-0.12	0.33**	0.41***	0.22	-0.68***	-0.65***	1.00			
CL	0.32**	-0.19	0.33**	0.41***	0.16	-0.64***	-0.68***	0.93***	1.00		
GRSD	-0.33**	0.10	-0.34**	-0.42***	-0.19	0.70***	0.67***	-0.97***	-0.96***	1.00	
STCL	0.36**	-0.12	0.33**	0.41***	0.22	-0.68***	-0.65***	1.00***	0.94***	-0.97***	1.00

TABLE 19: Pearson product-moment correlations (r) between biophysical variables from lobes for the pooled data ($n = 85$). Confidence levels: * < 0.05 , ** < 0.01 , *** < 0.001 . Italicized values are coefficients between variables which are not independent.

relatively independent of the others. The significant positive correlations between the soil moisture at 80 cm, and the percent silt and clay is probably an indication of the greater water retention capabilities of < sand-sized particles, while the significant negative correlations with the percents gravel and sand reflect the opposite. The significant negative correlation between the liquid limit and percent gravel reflects the low cohesive strength of > sand-sized particles.

The non-lobe biophysical correlation matrix is shown in Table 20. There are several significant correlations that are not significant for lobe sites and vice-versa. For example, the correlation between the organic mat and late-summer thaw depth is not significant for non-lobe sites, but is for lobes, while most of the correlations between the liquid limit and other soil properties, most of which are significant for the non-lobes but not for lobes.

	OM	THL	S40	S80	LL	%GR	%SD	%ST	%CL	%GRSD	%STCL
OM	1.00										
THL	-0.05	1.00									
S40	0.14	-0.02	1.00								
S80	0.00	-0.06	0.79***	1.00							
LL	-0.17	0.17	0.44***	0.52***	1.00						
GR	-0.31**	-0.09	-0.35**	-0.26*	-0.14	1.00					
SD	-0.10	0.11	-0.19	-0.07	-0.23*	-0.27*	1.00				
ST	0.36***	0.03	0.44***	0.29**	0.24*	-0.90***	-0.31**	1.0			
CL	0.21*	0.19	0.35**	0.31**	0.21*	-0.71***	-0.14	0.7***	1.00		
GRSD	-0.36***	-0.04	-0.44***	-0.30**	-0.25*	0.90***	0.31**	-1.0***	-0.69***	1.0	
STCL	0.36***	0.04	0.44***	0.30**	0.25*	-0.90***	-0.31**	1.0***	0.69***	-1.0***	1.0

TABLE 20: Pearson product-moment correlations (r) between biophysical variables from non-lobe sites for the pooled data ($n = 85$). Confidence levels: * < 0.05, ** < 0.01, *** < 0.001. . Italicized values are represent correlations between variables which are not independent.

Correlations of the biophysical variables from lobes subdivided by aspect required transformations for some of the parameters (Table 21). Nine outliers were removed; five from north-facing slopes, two from northwest-facing slopes and two from

west-facing slopes. Table 22 shows the resultant correlation matrices. Significant ($p \leq 0.05$) correlations are present for all aspects. The highest number of significant correlations occurs for lobes on west-facing slopes followed by north, southwest, northeast and northwest, respectively. There are no clear trends when the coefficients from different aspects are compared, suggesting that unlike the morphometric parameters (see Tables 6 and 8), the biophysical variables are more sensitive to differences in aspect.

Aspect	Parameter	Initial skewness	Tolerance (Jones, 1969)	Type of Transform	Post-transform skewness
Northwest (n= 18)	S40	1.48	± 0.982	Logarithm	0.89
	S80	1.01	± 0.982	Logarithm	0.60
West (n = 25)	OM	1.04	± 0.877	Logarithm	-0.76
	THL	-1.13	± 0.877	Square	-0.81
	%ST	1.02	± 0.877	Logarithm	0.69
	%GRSD	-0.99	± 0.877	Square	-0.80
	%STCL	0.99	± 0.877	Logarithm	0.66

TABLE 21: Transformed biophysical variables from lobes subdivided by aspect.

4.4.5 Downslope trends in biophysical variables from turf-banked solifluction lobes

Downslope trends in the biophysical variables are shown in Appendix E. Percent gravel, sand and the two composite soil variables (%GRSD and %STCL) are not included but their trends can be inferred from those included. The results indicate that, as with the morphometric parameters, there are no entirely consistent upslope (downslope) trends when the biophysical data from lobes are examined on a transect-by-transects basis. On many transects, however, there is a fining of grain size

NORTH (n = 29)										
	OM	THL	S40	S80	LL	%GR	%SD	%ST	%CL	%GRSD
THL	-0.87***	1.00								
S40	0.25	-0.13	1.00							
S80	0.31	-0.18	0.78***	1.00						
LL	-0.43*	0.46*	-0.39*	-0.44*	1.00					
GR	-0.34	0.23	-0.29	-0.49*	0.15	1.00				
SD	-0.19	0.12	-0.18	-0.11	0.39*	-0.31	1.00			
ST	0.59**	-0.47*	0.27	0.46*	-0.25	-0.64***	-0.17	1.00		
CL	0.47*	-0.32	0.39*	0.56**	-0.37	-0.84***	-0.26	0.77***	1.00	
GRSD	-0.45*	0.30	-0.40*	-0.56**	0.38	0.84***	0.26	-0.75***	-1.00***	1.00
STCL	0.59**	-0.47*	0.28	0.46*	-0.25	-0.66***	-0.17	1.00***	0.79***	-0.77***
NORTHEAST (n = 7)										
THL	-0.96***	1.00								
S40	-0.89**	0.94**	1.00							
S80	-0.77*	0.86*	0.95**	1.00						
LL	0.36	-0.35	-0.14	-0.02	1.00					
GR	-0.47	0.45	0.34	0.46	-0.30	1.00				
SD	-0.15	0.24	0.34	0.29	-0.55	0.07	1.00			
ST	0.33	-0.40	-0.44	-0.45	0.61	-0.48	-0.91**	1.0		
CL	0.33	-0.40	-0.44	-0.45	0.61	-0.48	-0.91**	1.0***	1.0	
GRSD	-0.33	0.40	0.44	0.45	-0.61	0.48	0.91**	-1.0***	-1.0***	1.0
STCL	0.33	-0.40	-0.44	-0.45	0.61	-0.48	-0.91**	1.0***	1.0***	-1.0***
NORTHWEST (n = 18)										
THL	-0.00	1.00								
S40	0.10	0.06	1.00							
S80	0.22	-0.29	0.47	1.00						
LL	-0.09	-0.21	-0.36	-0.54*	1.00					
GR	0.10	-0.13	-0.17	-0.29	0.37	1.00				
SD	0.18	0.23	-0.10	-0.42	-0.27	-0.07	1.00			
ST	-0.19	-0.00	0.20	0.48	-0.17	-0.83***	-0.50	1.00		
CL	-0.07	-0.40	0.15	0.55*	-0.01	-0.59	-0.59	0.83***	1.00	
GRSD	0.19	0.02	-0.20	-0.49	0.16	0.82***	0.51	-1.00***	-0.85***	1.0
STCL	-0.19	-0.02	0.20	0.49	-0.16	-0.82***	-0.51	1.00***	0.85***	-1.0***
WEST (n = 25)										
THL	-0.54**	1.00								
S40	0.02	-0.29	1.00							
S80	0.06	-0.17	0.78***	1.00						
LL	0.43*	0.00	-0.05	-0.08	1.00					
GR	-0.53**	0.36	-0.31	-0.42*	-0.67***	1.00				
SD	-0.21	0.53**	-0.33	-0.29	0.01	0.27	1.00			
ST	0.48*	-0.52*	0.39	0.48*	0.48*	-0.89***	-0.68***	1.0		
CL	0.46*	-0.55**	0.40	0.47*	0.44*	-0.87***	-0.67***	1.0***	1.00	
GRSD	-0.48*	0.52*	-0.39	-0.48*	-0.48*	0.89***	0.68***	-1.0***	-0.98***	1.0
STCL	0.48*	-0.53**	0.39	0.48*	0.48*	-0.89***	-0.68***	1.0***	0.99***	-1.0***
SOUTHWEST (n = 6)										
THL	0.87*	1.00								
S40	0.87*	0.73	1.00							
S80	0.57	0.63	0.18	1.00						
LL	0.67	0.88*	0.75	0.22	1.00					
GR	0.59	0.36	0.77	0.21	0.31	1.00				
SD	-0.81	-0.84*	-0.93**	-0.28	-0.88*	-0.89	1.00			
ST	0.75	0.90**	0.82*	0.26	0.97**	0.43	-0.95**	1.0		
CL	0.75	0.90**	0.82*	0.26	0.97**	0.43	-0.95**	1.0***	1.0	
GRSD	-0.75	-0.90**	-0.82*	-0.26	-0.97**	-0.43	0.95**	-1.0***	-1.0***	1.0
STCL	0.75	0.90**	0.82*	0.26	0.97**	0.43	-0.95**	1.0***	1.0***	-1.0***

TABLE 22: Pearson product-moment correlations (*r*) between the biophysical variables for the data subdivided by aspect. Confidence levels: * < 0.05, ** < 0.01, *** < 0.001.

downslope, an increase in moisture content at 80 cm depth, an increase in organic mat thickness and a decrease in thaw depth. These trends also emerge when the biophysical variables are grouped for north-, northwest- and west-facing slopes (Figure 30).

4.4.6 Inter-aspect differences in biophysical characteristics of turf-banked solifluction lobes

In order to determine if significant differences occur in the biophysical characteristics of lobes between different aspects, two types of tests were performed: a Wilcoxon ranked sum tests and a discriminant analysis (see Sections 3.4.5. and 3.4.6).

The results from a two-tailed Wilcoxon ranked sum test at significance levels of 0.001, 0.01 and 0.05 are presented in Table 23 for the biophysical variables subdivided by aspect. They show some significant differences by aspect for all biophysical variables except percent clay. Thirty-one percent of combinations are significantly different ($p \leq 0.05$), and one third of these are significantly different at $p \leq 0.01$. Percent gravel, liquid limit, organic mat thickness, thaw depth and soil moisture (80 cm) are different between four or more aspect combinations. Overall, particularly strong differences ($p \leq 0.01$) occur between north- and both northwest- and west-facing slopes, and between northwest- and west-facing slopes.

Following the initial examination of the data in the Wilcoxon tests, discriminant analysis was performed to explore differences (similarity/dissimilarity) of the biophysical variables using aspect (north, northwest and west aspects) as the classification factor. However, because there was some difference in the significant correlations

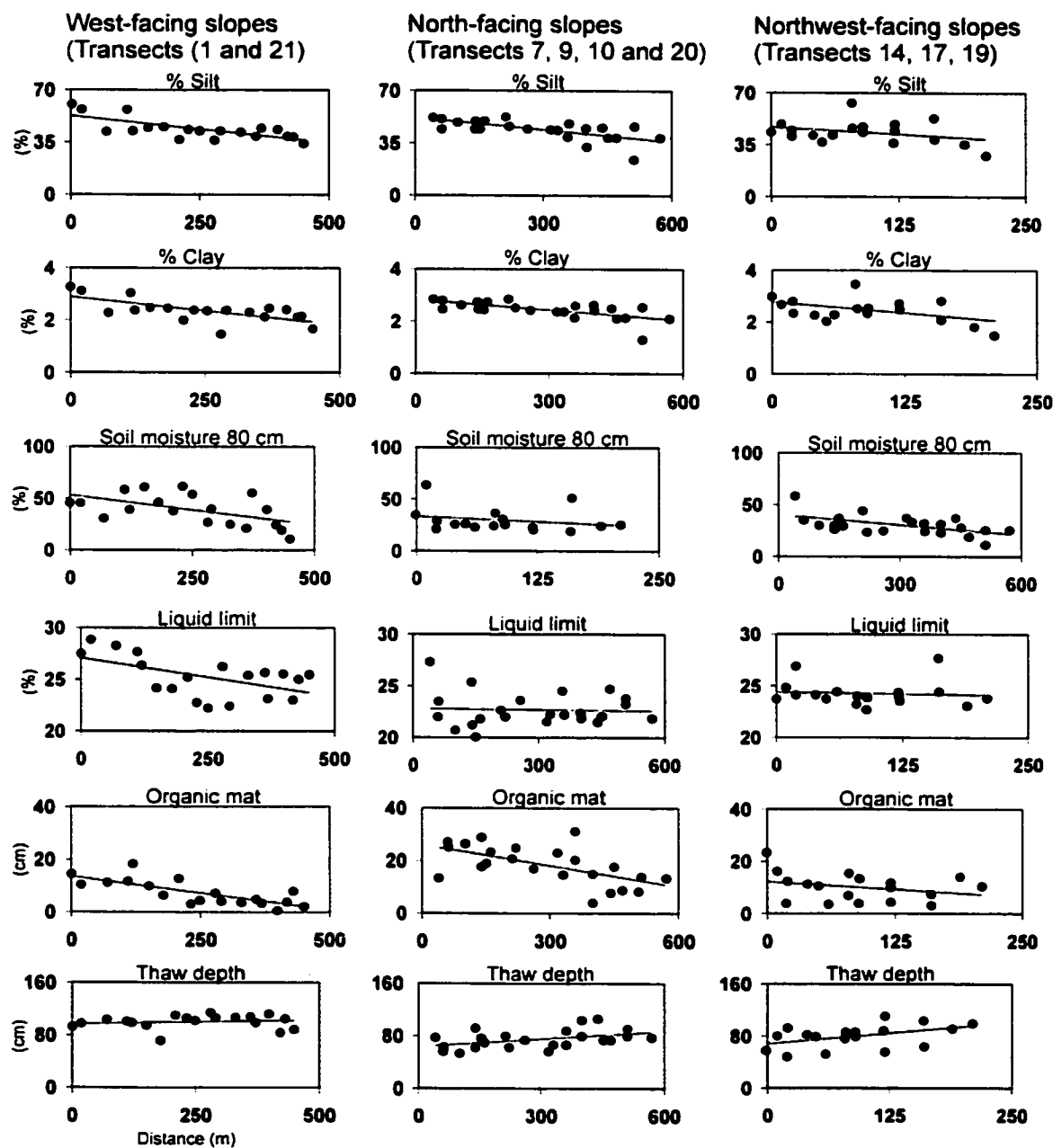


FIGURE 30: Charts showing trends in biophysical variables according to aspect. Only those transects with similar altitudinal ranges were used. Distances are measured upslope from the base of the transect.

between north, northwest and west slope orientations, the procedure used in Section 4.3.3 (for the morphometric parameters) of selecting the same uncorrelated or weakly correlated variables could not be achieved for all three sample populations. Instead, a stepwise discriminant analysis procedure (*cf.* Reger, 1979; Dillon and Goldstein, 1986) was used, in which variables were entered or deleted from the discriminant model until the most significant model was generated. As in Section 4.3.3, canonical variables were computed and plotted in order to give a graphic representation of the similarity or dissimilarity between the sample populations on the basis of the included variables.

Variable	Paired slope orientation classes									
	N / NE	N / NW	N / W	N / SW	NE / NW	NE / W	NE / SW	NW / W	NW / SW	W / SW
% Gravel	*	*			*	*		**	*	
% Sand	*									
% Silt					*			**		
% Clay										
S40			*			*	*			
S80		*	*	*		*		**	*	*
Liquid limit	*	***	***		*		*		*	
Organic mat		**	**			*			*	*
Thaw depth			***	*		*	*			
%CLST					*			**		
%SDGR					*			**		

TABLE 23: Results of Wilcoxon ranked sums tests for biophysical variables. Class numbers: North ($n = 29$), Northeast ($n = 7$), Northwest ($n = 18$), West ($n = 25$), Southwest ($n = 6$). Probability of rejection of null hypothesis of no difference: * ≤ 0.05 ; ** ≤ 0.01 , *** ≤ 0.001 .

Results from the discriminant analysis are shown in Figure 31. Wilks' lambda is 0.46, indicating moderate discriminating power. The variables in the model included liquid limit, percent gravel, soil moisture at 80 cm, percent clay, organic mat and thaw depth, but the latter two variables were not significant at the 95% confidence level. The partial Wilks' lambda values indicate that liquid limit contributes the most to the discrimination, which is consistent with the results of the Wilcoxon tests for N/NW and

a)

Discriminant analysis results:

Wilks' lambda = 0.46 Eigenvalue = 0.63 Canonical correlation = 0.62 Significance level = 0.00

Variables in the model	Partial Wilks' lambda	P-level	Squared Mahalanobis Distance		N	NW	W
LL	0.77	0.00		N	0.00	2.23	3.33
%GR	0.87	0.01		NW	2.23	0.00	3.07
S80	0.90	0.03		W	3.33	3.07	0.00
CL	0.91	0.05					

Classification Matrix	N	NW	W	Correct (%)	F-distance	N	NW	W
N	20	4	4	71.4		—	3.61	6.53
NW	8	9	1	50		3.61	—	4.71
W	4	1	20	80		6.53	4.71	—
Total	32	14	25					

b)

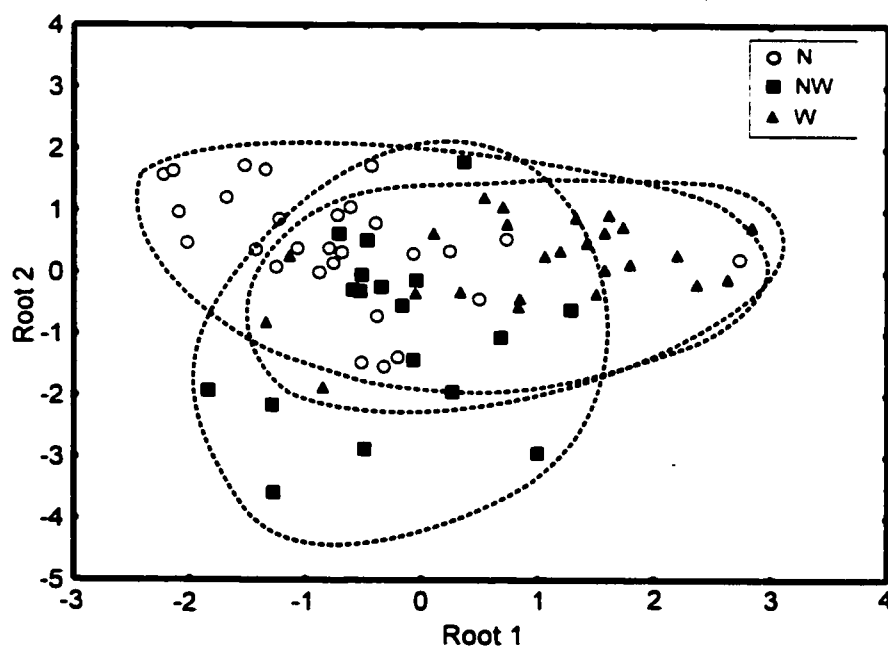


FIGURE 31: Results from the stepwise discriminant analysis of the biophysical variables: (a) tabular results; (b) plot of canonical variables illustrating the scatter in the groups (i.e., North-facing, Northwest-facing and west-facing slopes).

NW aspect combinations (see Table 23). Distances between groups (Squared Mahalanobis and *F*-distance) were relatively small, which is further illustrated in the plot of canonical variables (Figure 31b), but there is slightly greater separation between north and west aspects (Figure 31a). The classification matrix shows that 80% of lobes were successfully classified for west-facing slopes and that 71% and 50% were successfully classified for north- and northwest-facing slopes, respectively.

In summary, this analysis shows that only a few variables are successful at discriminating among slopes. The discriminant functions yield relatively good results for discriminating north- and west-facing slopes and suggest a basic biophysical difference between lobes on these aspects.

4.5 BIOPHYSICAL CONTROLS ON TURF-BANKED SOLIFLUCTION LOBE MORPHOMETRY

In order to explore the association between the biophysical variables and the morphometric parameters, correlations were computed for the pooled data and those subdivided by aspect. Transformations and outliers had been removed in the earlier analyses. Table 24 outlines the correlation coefficients calculated from the normalized pooled data.

Thirty-three of the values are significant correlations ($p \leq 0.05$), and twenty-four of those are significant at $p \leq 0.01$. The bulk of the significant values occur for the tread length, width, height-to-length ratio and height-to-width ratio. Only one correlation coefficient is significant for riser height, riser angle, tread angle, parent slope and the

length-to-width ratio, indicating that the selected biophysical variables have almost a negligible association with these parameters.

The correlations from the data subdivided by aspect (Table 25) reveal some similarities with those from the pooled data for riser height, riser angle and tread width, but are inconsistent for the other parameters. North-facing slopes have the greatest number of significant correlations (36) followed by west (21), northeast (16), northwest (14) and southwest (4), respectively.

	Riser height	Riser Angle	Tread length	Tread width	Tread angle	Parent slope	Length-to-width	Height-to-length	Height-to-width
OM	-0.05	0.04	0.43**	0.46***	-0.29**	-0.23*	-0.13	-0.55***	-0.54***
THL	-0.03	-0.17	-0.27*	-0.28*	0.19	0.08	0.16	0.27*	0.32**
S40	0.00	-0.08	-0.04	0.04	-0.05	0.08	-0.11	0.09	-0.02
S80	0.02	-0.10	0.05	0.12	-0.07	0.02	-0.09	0.03	-0.06
LL	0.28*	0.06	0.16	0.09	0.12	-0.07	0.09	-0.00	0.06
GR	-0.10	0.05	-0.36**	-0.30**	0.14	0.18	-0.03	0.30**	0.24*
SD	-0.11	-0.14	-0.17	-0.23*	0.11	-0.05	0.24*	0.07	0.21
ST	0.15	0.01	0.42***	0.40***	-0.15	-0.10	-0.11	-0.32**	-0.34**
CL	0.12	0.10	0.37***	0.37**	-0.17	-0.13	-0.17	-0.25*	-0.32**
GRSD	-0.14	-0.04	-0.41***	-0.39***	0.15	0.10	0.13	0.30**	0.33**
STCL	0.15	0.02	0.42***	0.40***	-0.16	-0.10	-0.12	-0.32**	-0.34**

TABLE 24: Pearson's product-moment correlations (r) between the morphometric parameters and biophysical variables for the pooled data ($n = 85$).

The results from forward stepwise multivariate correlation analyses among the transformed pooled variables are shown in Table 26 using the morphometric parameters as the dependents and the biophysical variables as the independents. The three ratio parameters were omitted. Plots of predicted versus the residual scores are shown in Appendix F. Pearson's correlation coefficient (R) is significant at 95% confidence level

NORTH (n = 29)									
	Riser height	Riser Angle	Tread length	Tread width	Tread angle	Parent slope	Length-to-width	Height-to-length	Height-to-width
OM	0.18	-0.15	0.36	0.51**	-0.25	-0.47*	-0.36	-0.61**	-0.60**
THL	-0.10	0.27	-0.22	-0.46*	0.17	0.32	0.34	0.59**	0.55**
S40	0.44**	-0.01	0.33	0.47*	-0.35	-0.13	-0.47*	-0.15	-0.44*
S80	0.35	0.06	0.26	0.44*	-0.35	-0.19	-0.33	-0.18	-0.39
LL	0.20	0.07	0.12	0.02	0.00	0.10	0.01	0.20	0.16
%GR	-0.35	-0.17	-0.57**	-0.47*	0.33	0.51	0.22	0.38	0.39
%SD	0.12	-0.02	0.23	0.12	0.37	0.03	0.16	-0.11	0.11
%ST	0.37	0.07	0.53**	0.49*	-0.55**	-0.58**	-0.25	-0.51*	-0.49*
%CL	0.32	0.23	0.48*	0.45*	-0.54**	-0.58**	-0.32	-0.35	-0.47*
%GRSD	-0.31	-0.23	-0.47*	-0.44*	0.53**	0.57**	0.32	0.33	0.46*
%STCL	0.37	0.08	0.53**	0.49*	-0.55**	-0.58**	-0.25	-0.51*	-0.49*
NORTHEAST (n = 7)									
OM	0.16	-0.38	0.90**	0.92**	-0.50	-0.87**	-0.73	-0.75	-0.87**
THL	-0.11	0.51	-0.94**	-0.79**	0.56	0.91**	0.54	0.81**	0.86**
S40	-0.15	0.30	-0.95**	-0.76*	0.39	0.73	0.49	0.83**	0.89**
S80	-0.16	0.30	-0.89**	-0.62	0.53	0.66	0.29	0.84**	0.84**
LL	0.51	-0.24	0.40	0.18	-0.12	-0.33	-0.06	0.17	0.13
%GR	-0.24	-0.00	-0.50	-0.48	0.82	0.39	0.13	0.49	0.36
%SD	-0.43	-0.17	-0.51	0.03	-0.21	-0.06	-0.29	-0.01	-0.05
%ST	0.48	0.15	0.65	0.17	-0.16	-0.11	0.20	-0.20	-0.11
%CL	0.48	0.15	0.65	0.17	-0.16	-0.11	0.20	-0.20	-0.11
%GRSD	-0.48	-0.15	-0.65	-0.17	0.16	0.11	-0.20	0.20	0.11
%STCL	0.48	0.15	0.65	0.17	-0.16	-0.11	0.20	-0.20	-0.11
NORTHWEST (n = 18)									
OM	0.38	0.14	-0.52	-0.74**	-0.17	-0.12	0.34	0.15	0.75**
THL	-0.24	0.29	-0.17	-0.20	-0.06	-0.04	0.19	0.07	0.32
S40	0.02	0.36	0.10	-0.08	-0.02	0.20	0.42	-0.20	0.21
S80	0.49	-0.32	-0.38	-0.36	0.22	0.03	-0.27	0.35	0.19
LL	0.56*	-0.50	-0.16	-0.27	0.21	0.07	-0.07	0.07	0.10
%GR	0.10	0.10	-0.41	-0.23	-0.14	-0.14	-0.42	0.28	-0.07
%SD	0.50	0.22	-0.67**	-0.74**	-0.27	-0.02	0.26	0.29	0.75**
%ST	-0.34	-0.20	0.69**	0.57*	0.27	0.14	0.23	-0.36	-0.26
%CL	-0.25	-0.11	0.57*	0.56*	0.17	-0.07	-0.13	0.02	-0.32
%GRSD	0.34	0.20	-0.69**	-0.57*	-0.26	-0.13	-0.21	0.35	0.27
%STCL	-0.34	-0.20	0.69*	0.57*	0.26	0.13	0.21	-0.35	-0.27
WEST (n = 25)									
OM	0.14	0.50*	0.62**	0.55**	-0.57**	-0.36	0.02	-0.41*	-0.55**
THL	-0.14	-0.15	-0.22	-0.25	0.45*	0.22	0.09	0.41*	0.12
S40	0.09	-0.01	-0.11	0.09	-0.25	0.26	-0.27	-0.02	-0.05
S80	-0.02	-0.01	-0.03	0.17	-0.24	0.09	-0.25	-0.09	-0.19
LL	-0.18	0.36	0.17	0.10	-0.12	-0.38	0.09	-0.14	-0.25
%GR	-0.00	-0.25	-0.31	-0.28	0.28	0.35	-0.03	0.27	0.30
%SD	-0.16	-0.16	-0.10	-0.38	0.47*	0.14	0.54**	0.01	0.35
%ST	-0.17	-0.29	-0.28	-0.47*	0.54**	0.35	0.36	0.20	0.43*
%CL	0.13	0.27	0.29	0.44*	-0.50*	-0.35	-0.30	-0.21	-0.42*
%GRSD	-0.10	-0.28	-0.28	-0.43*	0.48*	0.34	0.30	0.20	0.43*
%STCL	0.10	0.28	0.28	0.43*	-0.48*	-0.34	-0.30	-0.20	-0.43*
SOUTHWEST (n = 6)									
OM	0.46	-0.46	0.47	0.32	-0.28	-0.12	-0.20	-0.11	-0.22
THL	0.77	-0.75	0.77	0.58	0.01	-0.31	-0.38	-0.19	-0.35
S40	0.25	-0.52	0.46	0.14	0.11	-0.17	0.01	-0.24	-0.10
S80	0.80	-0.46	0.33	0.51	-0.38	-0.30	-0.37	0.30	-0.17
LL	0.59	-0.76	0.80	0.44	0.37	-0.34	-0.23	-0.36	-0.29
%GR	0.15	-0.47	0.13	-0.07	0.21	-0.31	0.23	0.09	0.20
%SD	-0.49	0.78	-0.73	-0.42	-0.34	0.25	0.22	0.35	0.28
%ST	0.55	-0.77	0.86*	0.56	0.33	-0.18	-0.38	-0.49	-0.44
%CL	0.55	-0.77	0.86*	0.56	0.33	-0.18	-0.38	-0.49	-0.44
%GRSD	-0.55	0.77	-0.86*	-0.56	-0.33	0.18	0.38	0.49	0.44
%STCL	0.55	-0.77	0.86*	0.56	0.33	-0.18	-0.38	-0.49	-0.44

TABLE 25: Significant correlations between biophysical variables and morphometric parameters.

a) Riser height as the dependent variable

$R = 0.24$		$R^2 = 0.06$	$p\text{-level} = 0.08$
Significant variables in the model			
Parameters	Beta coefficient	Partial coefficient	$p\text{-level}$
Liquid limit	0.23	0.23	0.04

b) Riser angle as the dependent variable

$R = 0.29$		$R^2 = 0.09$	$p\text{-level} = 0.12$
No significant variables in the model			

c) Tread length as the dependent variable

$R = 0.55$		$R^2 = 0.30$	$p\text{-level} = 0.00$
Significant variables in the model			
Parameters	Beta coefficient	Partial coefficient	$p\text{-level}$
Percent silt	0.34	0.32	0.00
Organic mat	0.33	0.34	0.00

d) Tread width as the dependent variable

$R = 0.54$		$R^2 = 0.29$	$p\text{-level} = 0.00$
Significant variables in the model			
Parameters	Beta coefficient	Partial coefficient	$p\text{-level}$
Organic mat	0.39	0.41	0.00
Percent clay	0.27	0.29	0.00

e) Tread angle as the dependent variable

$R = 0.36$		$R^2 = 0.13$	$p\text{-level} = N/A$
No significant variables in the model			

TABLE 26: Results of the forward stepwise correlations (R) between morphometric parameters as the Dependent Variables (DV's) and the biophysical variables as the Independent Variables (IV's) for the pooled data ($n = 85$).

only for tread length and width as the dependent variables. The best correlation occurs for tread length ($R = 0.55$), followed by tread width ($R = 0.54$), tread angle ($R = 0.36$), riser angle ($R = 0.29$) and riser height ($R = 0.24$), respectively. The partial correlation coefficients and Beta coefficients show that percent silt and organic mat contribute the most to the prediction of tread length, and organic mat and percent clay contribute the most to that of tread width.

4.6 COMPARISON OF LOBE AND NON-LOBE BIOPHYSICAL VARIABLES

In order to assess the biophysical differences between lobes and the ground 1-2 m down from the riser (non-lobe site), data were first examined statistically using Wilcoxon matched pairs tests followed by discriminant analysis. The Wilcoxon tests were used as a preliminary tool to determine which variables differed significantly between the two sample populations. The discriminant analysis was used for two purposes: first, to determine if there was a significant difference between lobes and non-lobes, and secondly, to determine which combination of variables produced the greatest separation.

The results of a Wilcoxon matched pairs test at significance levels of 0.001, 0.01 and 0.05 are shown in Table 27. The hypothesis of no difference is rejected at the 0.05 confidence level for all the variables except liquid limit, percent gravel and percent sand. Four variables are significantly different at the 99.9% confidence level.

Variable	p - value	H ₀
OM	0.003**	Reject
THL	0.000***	Reject
LL	0.148	Accept
S40	0.000***	Reject
S80	0.000***	Reject
%GR	0.232	Accept
%SD	0.175	Accept
%ST	0.046*	Reject
%CL	0.000***	Reject
%GRSD	0.013*	Reject
%STCL	0.018*	Reject

TABLE 27: Wilcoxon matched-pairs tests between lobe and non-lobe biophysical variables. Probability of rejection of null hypothesis of no difference: * < 0.05; ** < 0.01, *** < 0.001.

The methodology used in the discriminant analysis is similar to that used in Section 4.4.7, namely the stepwise selection process. Univariate outliers were removed prior to the analysis but the data were not transformed. Only variables that were significantly different in the Wilcoxon matched pairs tests at 95% confidence level were tested (see Table 27). Results of the two-group discriminant analysis are shown in Table 28. The discriminant function comprises two variables: percent clay and the combined percent of gravel and sand. The value for Wilks' lambda is low (0.12), indicating that the selected variables have strong discriminating power. The discriminant function is also characterized by a large eigenvalue at 7.72 (the ratio of the between-groups to within-groups sums of squares) and a high canonical correlation (0.94). The distance between groups is fairly large (see Table 28), further confirming the strong discrimination. The overall number of lobes correctly classified is 84 out of 85 (98.8%) and 81 out of 84 (96.4%) for non-lobe sites. The partial Wilks' lambda scores indicate that percent clay (0.97) contributes most to the separation between groups. Because only one canonical root is computed for a two-group discriminant analysis, the results could not be shown graphically.

Discriminant analysis results:

Wilks' lambda = 0.12 Eigenvalue = 7.72 Canonical correlation = 0.94 Significance level = 0.00

Variables in the model	Partial Wilks' lambda	p-level	Squared Mahalanobis Distance	LOBE	NLOBE
%CL	0.97	0.00	LOBE	0.00	30.87
%GRSD	0.26	0.00	NLOBE	30.87	0.00

Classification Matrix	LOBE	NLOBE	Correct (%)	F-distance	LOBE	NLOBE
LOBE	84	1	98.8	LOBE	--	640.62
NLOBE	3	81	96.4	NLOBE	640.62	--
Total	87					

TABLE 28: Results of the stepwise discriminant analysis between lobe and non-lobe biophysical variables.

4.7 SUMMARY

The results presented in this chapter can be summarized into seven main points:

(1) The distribution of turf-banked solifluction lobes and terraces on the plateau west of Outpost Mountain differs between the east and west sides of the plateau. The terraces occur almost exclusively on the east side of the plateau where slopes are more extensive (wider and longer). The lobes also occur in greatest number on the east side of the plateau and are clustered in smaller groups on the west side of the plateau where the topography is more complex.

(2) Snow cover measured between April 28 and May 9, 2000 was generally more uniformly distributed on slopes with northerly orientations on the east side of the plateau, while slopes on the west side had more variable snow cover and some were completely devoid of snow. The risers and treads of many lobes on the west side of the plateau were exposed above the snow early in the thaw period. An assessment of the thermal effects of this variable snow cover showed that the greatest temperature range occurs on the exposed riser and tread while the ground in front of the lobe, which was covered by snow during the measurements, remained $< 0^{\circ}\text{C}$.

(3) Measurements on the morphometry of the lobes show that the tread width is typically greater than tread length. Bivariate correlations among the morphometric parameters are strong for tread length and width, and tread angle and parent slope gradient, while riser angle has few significant correlations. There is strong similarity in the basic morphometric parameters (length, width and height) when the significant correlations from the pooled data matrix (see Table 6) are compared with the correlation matrices for

the data subdivided by aspect (see Table 8), indicating consistency in the form of lobes between aspects.

(4) Correlations between the biophysical variables and morphometric parameters from lobes show that tread length and width are correlated to several biophysical variables, while riser angle, height and tread angle have few significant correlations. There are few consistent morpho-biophysical correlations among different aspects, possibly reflecting the importance of site-specific factors on the modern biophysical characteristics of lobes.

(5) Although the form of lobes is similar at different sample sizes and between aspects (see above), non-parametric tests indicate that some of the dimensions of lobes differ significantly between pairs of aspects. However, when multivariate discriminant analysis is performed, only riser angle produces a statistically significant separation between north-, northwest- and west-facing aspects. For the biophysical variables from lobes, there are also numerous significant differences between pairs of aspects using non-parametric tests, but only liquid limit, percent gravel, soil moisture (80 cm) and percent clay produce a significant separation between aspects using discriminant analysis.

(6) Upslope (downslope) trends in lobe morphometry along transects on different slope orientations show that tread length and width increase downslope and tread angle decreases. Upslope (downslope) trends also occur in several biophysical variables from lobes on different aspects. On many transects there is a fining of grain-size downslope, an increase in soil moisture, an increase in organic mat thickness and a decrease in thaw depth. On a west-facing slope there is a catena of solifluction features, which consists of non-sorted stripes near the crest followed by non-sorted steps and then progressively larger solifluction lobes in the downslope direction.

(7) Statistical comparison of the biophysical characteristics of lobes and non-lobe sites using discriminant analysis shows that the percent clay, despite its low values, contributes to a highly successful discrimination between the two groups.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 DISTRIBUTION AND MORPHOMETRY

Turf-banked solifluction lobes and terraces on the plateau west of Outpost Mountain are distributed as follows. First, they occupy moderate to well-vegetated slopes which vary between 5-23°. Secondly, they are absent on slopes where winter snow cover is blown clear and absent on slopes where vegetation cover is thin. Thirdly, the terraces occur almost exclusively on the east side of the plateau on long and wide topographically positioned lee slopes with relatively consistent gradients, whereas the lobes occur on almost all slopes irrespective of slope extent and orientation. Lastly, slopes with deep and uniform snow cover are better suited to the development of the terraces and large lobes, while those with heterogeneous and thin snow cover favour the development of smaller lobes. A speculation on the reason for this last point is that the spatial distribution and quantity of soil moisture resulting from snowmelt is a limiting factor in the development and subsequent growth of the solifluction lobes and terraces. For example, slopes where winter snow cover is absent are unlikely to have lobes and those with patchy snow distribution are unlikely to have terraces. A more detailed discussion of the implications of snow cover is presented in Section 5.5.

The main parameters which describe the size of lobes (length, width and height) exhibit a log-normal distribution for both the pooled data ($n = 85$) and those subdivided by aspect where $n \geq 18$. The log-normal probability distribution has been previously reported for other periglacial landforms (*cf.* King, 1971; Vitek and Tarquin, 1984) and

process studies (Caine, 1968). In the present study, the log-normal distribution indicates that in the absence of a biased sampling scheme, the majority of lobes fall into the smaller class sizes with a progressive reduction in frequency towards the larger classes. Overall, the log-normal distribution of lobe size has important implications for future studies concerned with modeling solifluction landforms and slope evolution.

The ratio parameters (length-to-width, height-to-length and height-to-width) indicate the following relationships for the pooled data ($n = 85$): $\text{length} = \text{width}/1.4$; $\text{height} = \text{length}/10$; $\text{height} = \text{width}/14$. These relationships are the same for the data subdivided by aspect where $n \geq 18$ (see Table 3), and indicate that the form of lobes is consistent at different spatial scales. At this point it is difficult to make inferences on process from the above ratios. However, in the literature on landslide morphometry, Crozier (1973) in his benchmark study in the loess-covered hills of eastern Otago, New Zealand, suggests that the more fluid the mass movement, the more elongated a landslide is likely to become. Borrowing from this suggestion, it might be expected that solifluction lobes would take on an elongated form, particularly given the high soil moisture levels which often exceeded the liquid limit (see Section 4.4.3.3). But this is not the case at the study site. This may indicate that viscous flow en masses is not the dominant process in the Outpost Mountain lobes. These observations highlight the need for further process studies which take into account lobe form.

The correlation results among the morphometric parameters for the pooled data (see Table 6) and those subdivided by aspect (see Table 8, where $n \geq 18$) show that certain relationships are consistent for different sample sizes and spatial scales, primarily between tread length, width and riser height. This indicates that, similar to the morphometric ratios (see above), there is consistency in the form of lobes at different

scales. Furthermore, these results suggest some sort of morphogenetic underpinning controlling lobe form, but this is not apparent from the relationships with modern biophysical variables (see below).

The key points from the correlation analyses between the morphometric and biophysical variables indicate that large lobes are associated with a higher percentage of fines. This likely reflects the increased frost-susceptibility of the finer soils. The positive association between larger height-to-width and height-to-length ratios and coarser soils may be due to the additional shear strength provided by interlocking cobbles and rocks which are particularly common behind the riser of certain lobes.

The absence of a significant correlation between thaw depth and riser height might appear unexpected since the former denotes the maximum lower boundary of solifluction at any given time, and riser height reflects the maximum depth of differential movement. However, excavations of lobes along transects 1 and 21 in 2001 showed that on some lobes, riser height was greater than thaw depth, while more commonly, the reverse was true. Furthermore, buried organic horizons were often located well above the frost table (personal communication, A.G. Lewkowicz, 2001). A possible explanation for this comes from process studies which show that solifluction rates along the tread typically exceed the downslope advance of the riser (Benedict, 1970; Price, 1973; Gengnian *et al.*, 1995). Over time, this leads to a thickening of the soliflual material along the riser, thereby enhancing the step-like profile and also providing an explanation of why the tread angle is typically less than that of the parent slope.

5.2 COMPARISONS WITH PREVIOUS STUDIES

Summary details of selected turf-banked and stone-banked solifluction lobe morphometric characteristics drawn from this study and a handful of previous studies are shown in Table 31, allowing for inter-site and inter-morphological comparisons. Basic turf-banked lobe dimensions fall within or near the range of previous studies (see Table 29a), but a difference occurs in the riser angle (see Table 29a), which is much steeper than in the previous reports. In addition, the solifluction lobes at Outpost Mountain are much larger than their nearest studied neighbors in Alberta (Smith, 1987). The mean tread length-to-width ratio at Outpost Mountain of 0.72 is very similar to those obtained by Smith (1987) and Gengnian *et al.* (1995) of 0.86 and 0.74, respectively. When the average tread length and width values are examined from selected stone-banked lobe studies in South Africa (see Table 29b), all their length-to-width ratios lie above unity, indicating an elongated form.

A comparison of the morphometric correlations derived from this study with those obtained by Smith (1987) from a study of turf-banked lobes at three non-permafrost sites in the Alberta Rocky Mountains is shown in Table 30. Similar correlations between the two studies occur for relationships between tread length and width, and between tread angle and parent slope. However, half of the correlations that were significant in the present study were also significant in Smith's and only 40% of Smith's correlations were significant in the present study. This suggests that, with the exception of TL/TW ratios and the obvious relationship between TA and PS, factors unique to particular study areas must play an important role in turf-banked lobe form.

Location (sample size)	Source	Height (m)	Length (m)	Width (m)	Riser angle (°)	Tread angle (°)	Parent slope (°)
a) Turf-banked lobes							
Outpost Mtn., Yukon (n = 85)	This study	0.81	11.2	20.9	65.3	12.1	12.8
Canadian Rockies (n = 58)	Smith (1987)	0.41	2.6	3.9	N/A	21.2	18.8
Olympic Mtns., Washington (n = 16)	Hansen-Bristow and Price (1985)	0.57	2.7	N/A	N/A	N/A	12-24
Svalbard (N/A)	Åkerman (1996)	0.65	N/A	N/A	N/A	N/A	2-10
Jostedalbreen, Norway (n = 4)	Nesje <i>et al.</i> (1989)	N/A	3.0	5.6	N/A	N/A	N/A
Jotunheimen, Norway (n = 20)	Matthews <i>et al.</i> (1986)	1.00	7.3	8.8	42.3	17	N/A
Tianshan, China (n = 11)	Gengnian <i>et al.</i> (1995)	1.75	15.4	16.5	53.2	20	20
Niwot Ridge, Colorado (N/A)	Benedict (1970)	0.5-3.5	3-100	3-50	10-35	2-14	4-23
b) Stone-banked lobes							
Marion Is., South Africa (n = 375)	Hall (1981)	0.32	0.9	N/A	N/A	3.7	13.4
Drakensberg, South Africa (n = 11)	Grab (2000)	1.01	8.8	4.4	25.7	N/A	N/A
Drakensberg, South Africa (N/A)	Dardis and Granger (1986)	0.2-0.5	10-60	2-6	N/A	N/A	N/A
Drakensberg, South Africa (N/A)	Boelhouwers (1994)	8-30	2-7	0.3-3	N/A	N/A	14-18

TABLE 29: Characteristics of turf-banked and stone-banked lobes as reported by various authors.

A = this study B = Smith 1987	Riser height		Tread length		Tread width		Tread angle	
	A	B	A	B	A	B	A	B
Tread length	0.50***	0.21						
Tread width	0.51***	0.10	0.80***	0.35*				
Tread angle	-0.09	0.35*	-0.13	-0.44*	-0.20	-0.04		
Parent slope	-0.03	0.18	-0.19	-0.26	-0.13	-0.34*	0.54***	0.63*

TABLE 30: Comparison of correlations among morphometric parameters from the present study and from Smith (1987).

Compared to results presented by Hall (1981) in a survey of stone-banked lobes at six sites on Marion Island ($n = 41$ to 89 , totaling 375), there are similarities in the correlations between riser height and tread length (Hall reports $r = 0.32$ to 0.66), and tread angle and parent slope (Hall reports $r = 0.20$ to 0.55). Although Hall (1981) does not present measurements of lobe width, Grab (2000) reports a positive correlation from eleven samples between tread length and frontal bank width ($r = 0.88$). An important result from Hall's study, which is similar to results presented in this study, is that there is consistency in the correlations between riser height and tread length and between tread angle and parent slope angle when Hall's data is subdivided by site (*cf.* Hall, 1981, p.130).

Collectively, the above comparisons suggest the possibility of a fundamental morphogenetic difference in the elongation of turf-banked and stone-banked forms, with the former being wider than long and the latter being elongated downslope. However, there is similarity in the relationships between riser height and tread length and between tread angle and parent slope angle, indicating that there may be fundamental relationships for lobate solifluction forms regardless of type (*i.e.*, stone-banked or turf-

banked). A speculation for the difference in elongation is that the turf cover, which has a restraining effect on near-surface solifluction as a result of root cohesion, causes the riser to stagnate while the tread advances. This leads to a dispersion of the movement vectors along the tread (Figure 32). Some support for this argument is taken from previous studies by Benedict (1970), Price (1973) and Gengnian *et al.* (1995) which have shown that when the riser movement is monitored concurrently with tread movement, the magnitude of the former is less than that of the latter. It is also possible that a lesser relative reduction in frontal movement occurs for the stone-banked features resulting in more elongated forms.

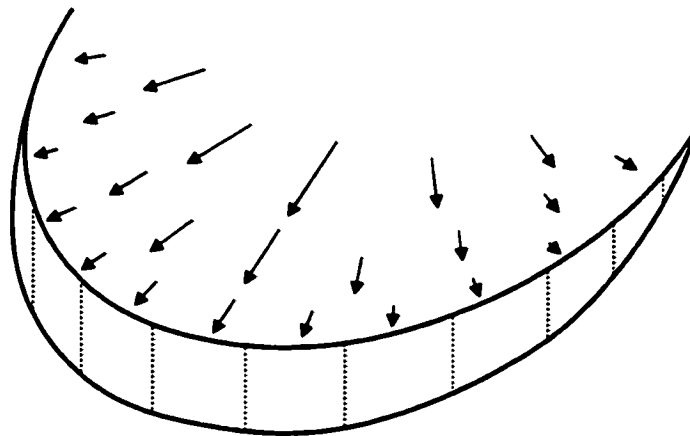
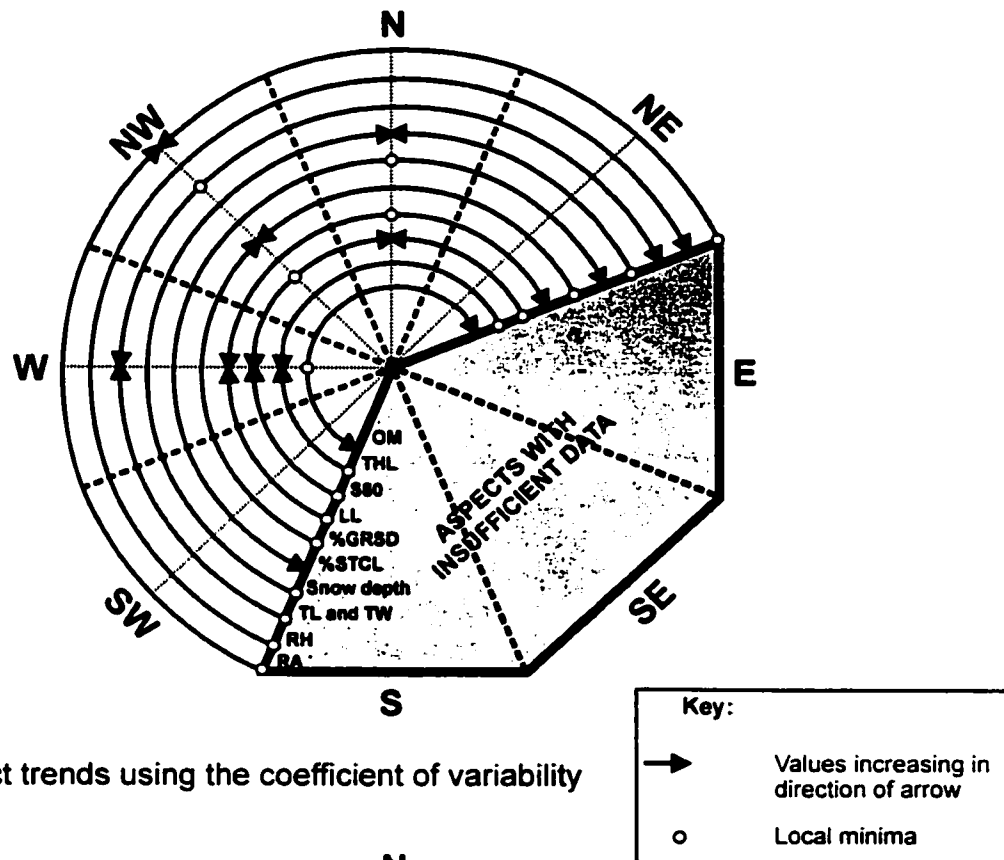


FIGURE 32: Speculated distribution of movement vectors around a turf-banked solifluction lobe. Length of arrow denotes magnitude of movement.

5.3 INTER-ASPECT VARIATIONS IN TURF-BANKED LOBE MORPHOMETRY AND BIOPHYSICAL CHARACTERISTICS

Trends between aspects of selected morphometric parameters and biophysical variables are shown in Figure 33 using the average values and the coefficient of

a) Inter-aspect trends for lobe sites using average values
(Source: Tables 3 and 14)



b) Inter-aspect trends using the coefficient of variability

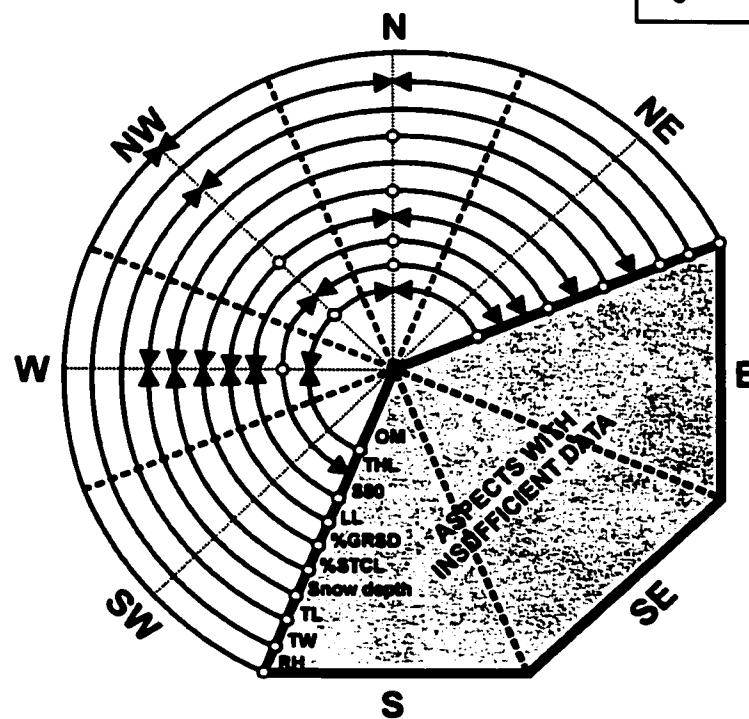


FIGURE 33: Inter-aspect trends of selected parameters and variables.

variation, which indicates intra-aspect variability. There is considerable inter-aspect variation and only a few trends that cover more than three aspects. Using average values, forty-three percent of neighboring tri-aspect combinations are either divergent (increase towards neighboring aspects) or convergent (decrease towards neighboring aspects). Using the coefficient of variability, sixty-three percent of neighboring tri-aspect combinations are either divergent or convergent. Collectively, these findings indicate that in many cases the morphometry and biophysical characteristics of lobes do not follow lateral gradients, and therefore the differences between aspects are more likely to be the result of site-specific factors related to the complexity of the terrain and microenvironments.

As far as the statistical analyses are concerned, the results presented in Sections 4.3.3 and 4.4.6 show that lobes have several characteristics that are significantly different between aspects. In the Wilcoxon results (see Tables 10 and 23), it is important to note that some of the significant differences occur between pairs of aspects in which one of the pair has a very small sample population (i.e., $n \leq 7$). In these cases the reliability of the differentiation is not strong and therefore robust conclusions about differences involving southwest- and northeast-facing slopes cannot be drawn with confidence. Nevertheless, some significant differences occur between the other aspects, particularly for the riser angle, liquid limit, organic mat thickness and late-summer thaw depth.

The application of discriminant analyses to the morphometric and biophysical characteristics from lobes enabled modest discrimination between north-, northwest- and west-facing slopes. Most of the biophysical variables do not bear a clear physical meaning with relation to turf-banked solifluction lobe morphometry, and as such, were

used mainly as an exploratory tool to derive qualitative associations with the morphometric parameters. In the discriminant analyses of the morphometric characteristics of lobes, between 52% and 72% of lobes were correctly classified using a subset of three parameters. Surprisingly, tread length, width and riser height did not contribute significantly to the discrimination as was initially expected from observations made in the field. Instead, riser angle produced the only significant contribution to the discrimination and produced greater separation between lobes on northwest- and west-facing slopes. It was anticipated that a discriminant analysis of the biophysical variables might provide a qualitative explanation for this difference if greater separation occurred between northwest- and west-facing slopes. However, using the stepwise selection process, there turned out to be greater separation between lobes on north- and west-facing slopes using four discriminating variables, thereby precluding a qualitative explanation for the stronger difference in riser angle between lobes on northwest- and west-facing slopes.

In summary, the Wilcoxon results indicate some strong inter-aspect differences which reflect, as do the morpho-biophysical correlations and the comparison of morphometric correlations with Smith (1987) (see above), the influence of more localized (highly site-specific) factors in controlling lobe morphometry. For the discriminant analyses, on the basis of the selected morphometric and biophysical characteristics, the results are interpreted as indicating a modest discrimination of lobes on north-, northwest- and west-facing slopes. The multivariate approach taken in this study was exploratory, however, and caution must be taken when attempting to extrapolate these results to other situations. In view of the complex topography which resulted in certain transects being located at great distance from others with the same orientation (see for example transects 8 and 19 on Figure 8), caution must also be taken against

overextending these results to other study areas. With some refinement to the sampling scheme used in this study, an ideal test would be to perform discriminant analyses on a large dataset from different study areas and at different scales in an effort to determine the broader geographical controls on lobe size and form.

5.4 SOLIFLUCTION CATENA

Observations on one of the slopes from the west side of the plateau demonstrate the ability of the solifluction lobes to organize into a crude form of a catena, in which lobe size progressively increases downslope. Although the organization of the lobes does not show a systematic pattern as a result of local irregularities, there is a measurable trend in their overall size in the upslope direction. Similar trends occur on other slopes in the study area, but the organization of lobes is not as obvious, indicating that specialized conditions must be required. These trends may be explained by parallel upslope (downslope) trends in biophysical variables such as soil moisture, organic mat thickness, late-summer thaw depth and particle size (see below). A summary of these trends is shown diagrammatically in Figure 34.

The downslope increase in soil moisture reflects the transfer of moisture from snowmelt, rainfall and thawing ice lenses toward the slope base above the aquiclude of the frost table by overland flow and throughflow within the active layer. This enables the establishment of more extensive vegetation cover at lower elevations and in turn leads to the progressive thickening of the organic mat. The latter effect increases the insulating properties of the surface and ultimately reduces the penetration depth of the summer temperature wave, leading to a thinner active layer.

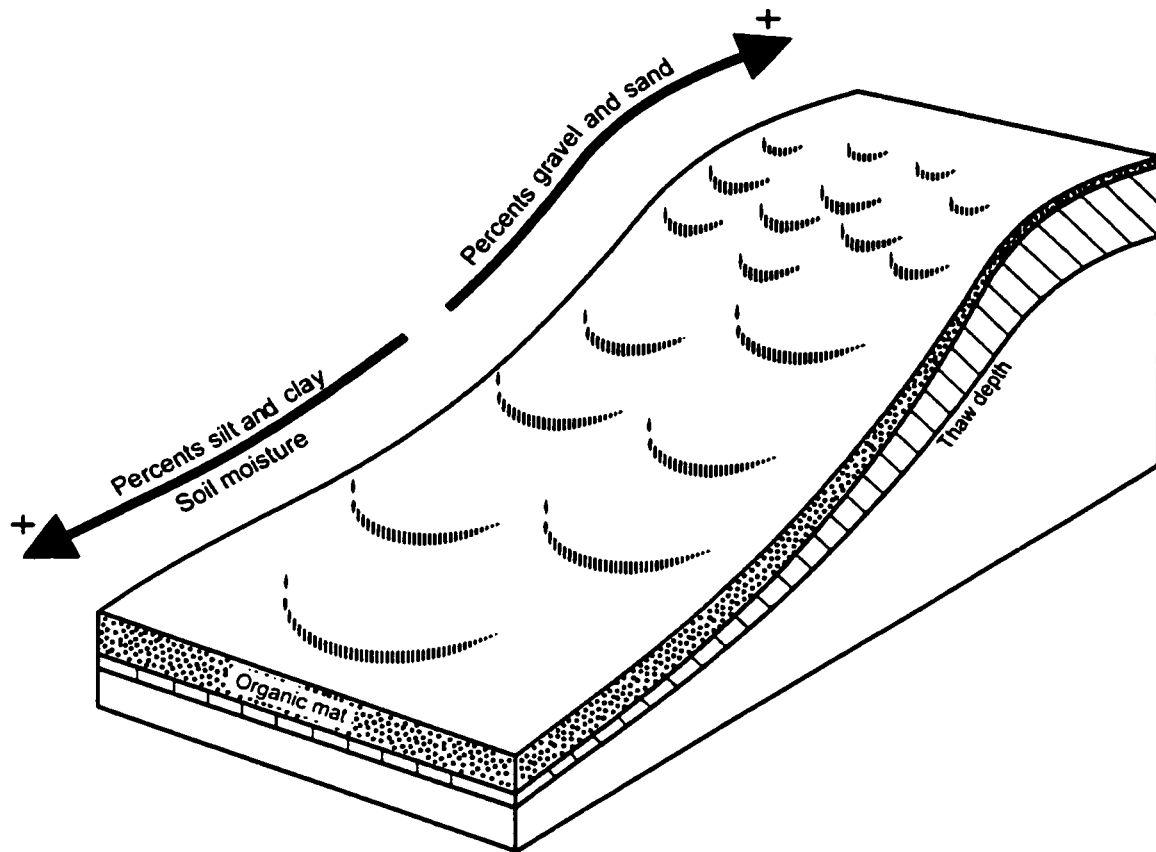


FIGURE 34: Diagram illustrating upslope (downslope) trends in lobe morphometry and biophysical variables.

The increase in the amount of silt and clay in the downslope direction likely reflects a combination of slopewash processes and mass movements such as flowsliding, solifluction and active-layer detachment slides. The effects of slopewash were evident as: (i) overland flow occurring as sheetflow on the east side of the plateau (see Figure 35); (ii) fresh sediment deposited in a small rivulet on the west side of the plateau (Figure 36); and (iii) the occurrence of hillslope water tracks (*cf.* Hastings *et al.*, 1989; Walker *et al.*, 1989). The latter are linear zones of enhanced soil moisture in poorly defined depressions which convey flow downslope (see Figure 11). On the east side of the plateau, thick vegetation prevents slopewash sediments from being

transported great distances downslope, but exposed sediments in detachment slides or secondary thaw slides are removed and deposited downslope via rapid flow (see Figure 14b). Exposed sediment was also observed along many lobe fronts on transects 1 and 21 where non-sorted circles were effectively spilling over the riser in early spring 2000 (see Figure 13e) and this potentially could be transported by slopewash processes.

Overall, slopewash processes are probably the main factors accounting for the biophysical gradients, which ultimately lead to conditions favoring enhanced solifluction at lower portions of the slope and a corresponding increase in the size of the lobes thereon.



FIGURE 35: Photograph of overland flow occurring on a north-facing slope on the east side of the plateau on August 8, 2000.

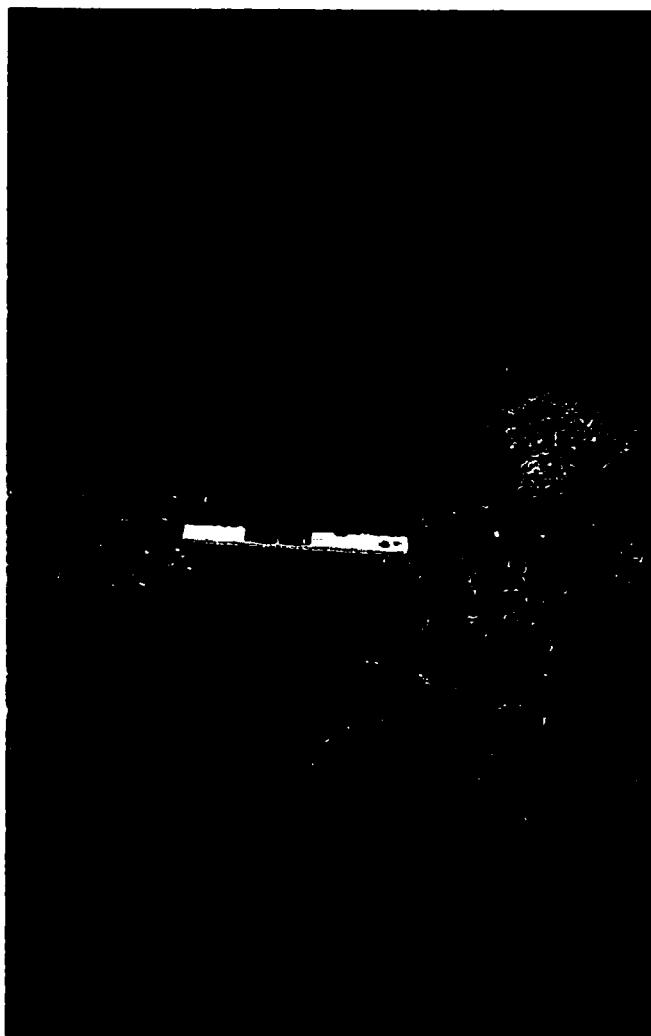


FIGURE 36: Photograph of a rivulet with a small deposit of silty sediment (digital level is 50 cm across).

5.5 IMPLICATIONS OF SNOW

As noted in Section 5.1, snow appears to have an important effect on the distribution and morphometry of turf-banked solifluction lobes and terraces. The importance becomes still clearer, however, when the spatial distribution of snow is examined at two different scales: landscape and landform.

From a landscape perspective, the more uniform snow cover and snowmelt on the east side of the plateau is likely to result in fairly homogenous soil moisture conditions during the thaw period. In contrast, the more irregular and localized occurrence of snow on the west side is likely to result in soil moisture conditions that are spatially heterogeneous. These conditions will affect the spatial characteristics of the rates of solifluction, particularly for frost creep and gelifluction, being higher in the wetter sections than in the drier sections (*cf.* Washburn, 1967). In terms of the morphology of solifluction landforms, several important qualitative associations are apparent. First, the average values for tread length, width and riser height from lobes on the east side of the plateau were generally greater than those on the west side (see Table 4). Secondly, large turf-banked terraces are almost completely absent from the west side of the plateau, but were almost as common as lobes on the east side. These observations are in line with those of Benedict (1970) and Price (1970) who both observed large terraces on snow accumulation slopes. Benedict (1970, p. 215) stated that "lobate forms develop in snow-free areas and on slopes where winter snow accumulation is patchy and irregular", and that terraces "develop in snow-accumulation areas where moisture is distributed more-or-less uniformly along the contour of the slope". Price (1970) noted that larger turf-banked lobes occurred on snow accumulation slopes. Although there may be differences in the definition of turf-banked lobes/terraces between these studies and the present one, the results presented here support these statements.

On the scale of individual landforms, the distribution of snow in spring has an important influence on local thermal and moisture variability. Observations presented in Section 4.4.2 (see Figure 25) reveal that many lobes on the west side of the plateau, and elsewhere in the alpine region around Kluane Lake, were exposed above the snow surface during early spring. During a brief monitoring period between May 18 and 24,

2000, the local variations of snow cover produced differential thaw across individual turf-banked solifluction lobes. Indirect evidence from measurements on soil moisture and liquid limit suggest that the differential thaw contributes to differential solifluction because the soil downslope from the riser remains frozen and immobilized while the soil on the riser and the lower portion of the tread surface is subject to frost creep and gelifluction. In contrast to the west side of the plateau, turf-banked solifluction lobes and terraces on northerly oriented slopes on the east side were completely snow covered during the same period and therefore effectively immobilized under frozen conditions. Later in the thaw season, however, the situation is reversed. As the snowpack thins on the north-facing slopes, snow clearance occurs first on the upper riser followed by the tread, and due to shading effects, not until much later in the thaw period does it clear from the ground downslope from the riser (Figure 37). This may represent a feedback as the presence of the riser contributes to snow accumulation in winter and retardation of melt in spring by shading, allowing soil on the tread to move and build up on the riser, which progressively overrides the immobile soil downslope. However, this feedback effect in total applies only to northerly oriented slopes because snow depths are greater.

Further evidence of the effects of differential snow cover around individual lobes during spring thaw is taken from the biophysical differences between lobes and non-lobes. Results presented in Section 4.6 show a strong difference in the percent clay and the combined percent of gravel and sand between lobes and non-lobes. Overall, despite its small range, percent clay provides the strongest contribution to the discrimination in the model. One process that may account for these differences is slopewash along the ground in front of the riser and along the upper portion of the tread. Figures 25 and 37 show that the riser and lower portion of the tread become exposed first during the thaw period, with snow remaining both along the upper portion of the tread and immediately

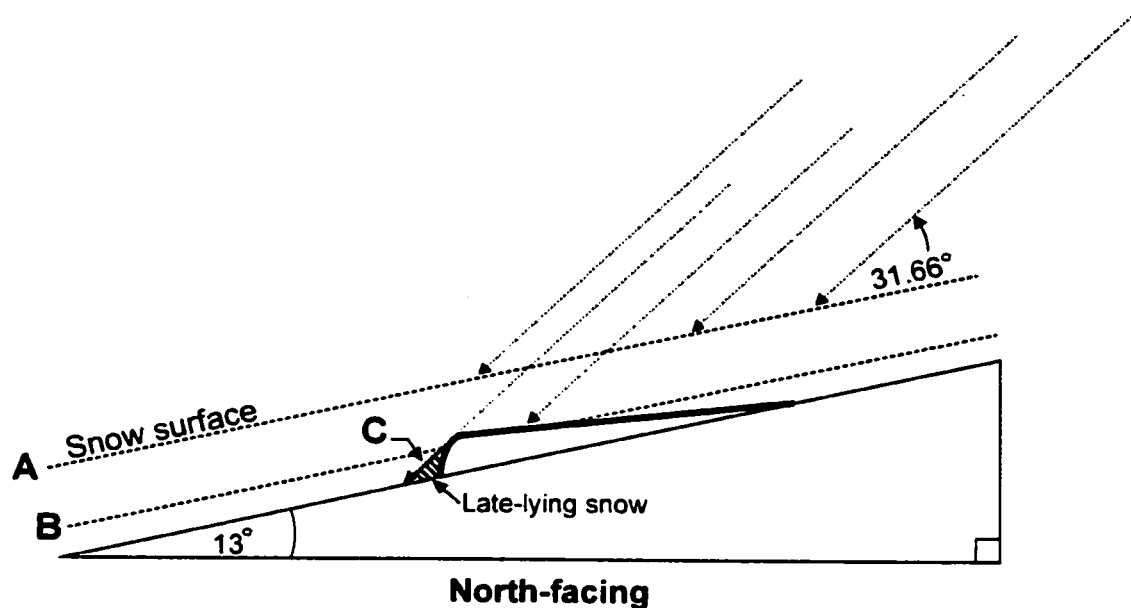


FIGURE 37: Diagram illustrating shading effect on north-facing slopes. A) is the initial deep, continuous snowpack, B) is after considerable melt when the lobe and terrace risers begin to appear, and C) is late-lying snow in a shaded location downslope of the riser. Incident solar radiation calculations were made for 61°N latitude at solar noon on May 21.

in front of the riser. According to Kling (1998), a plausible effect of snowpatches can be increased production of fine material and mobilization of silt and clay, ultimately to be transported and deposited to locations below, and possibly producing a frost-susceptibility gradient (Van Vliet-Lanoë, 1988). For the lobe, snow melting along the upper portion of the tread transports fines and produces an enrichment along the lower tread and riser, while fines are depleted along the ground 1-2 m in front of the riser by the melting snow in its lee. Thus, the topographic expression of the lobes and terraces creates a feedback condition favoring the accumulation of frost-susceptible material along the lower portion of the tread and preferential removal of this material downslope.

5.6 CONCLUSIONS

The principal conclusions from this study are summarized as follows:

- 1) The distribution of turf-banked solifluction lobes and terraces on Outpost Mountain plateau is controlled by two broad factors: the complexity of the local topography and the spatial distribution and characteristics of snow cover. The terraces occur only on long and wide topographically smooth slopes which have deep and uniform snow cover, whereas the lobes occur on almost all slopes regardless of extent so long as they retain snow cover during the winter. The importance of snow cover and topography is mainly in the resultant distribution of soil moisture during the thaw period, which is more uniformly distributed on the east side of the plateau where the terraces occur almost exclusively, and more heterogenous on the west side where lobes tend to cluster in small populations.
- 2) Trends in lobe dimensions and ratio parameters, and in biophysical variables, were not evident on all aspects. It was possible to modestly discriminate among lobes on three aspects using riser angle, tread width and tread angle. These results suggest that site-specific conditions have a role to play in lobe size.
- 3) Larger plan-form lobes are significantly associated with a thick organic mat, a thin active layer and high fines content. Riser heights that are large relative to the tread length/tread width ratio are associated with a thin organic mat, a thick active layer and high coarse particle content. As a result of these associations, combined with inter-aspect and downslope trends in biophysical variables, lobe

plan-form dimensions (tread length and tread width) are greatest on northeast slopes and generally increase downslope.

- 4) The tread length-to-width ratio had a mean value < 1 for this study and for other published studies in a variety of environments. The ratio was independent of aspect and had virtually no association with biophysical variables. This suggests a common evolutionary plan form for turf-banked solifluction lobes. Further studies which examine both process and form are required to fully explain these results.
- 5) Differential snow cover across individual turf-banked solifluction lobes on the Outpost Mountain plateau creates conditions favoring gelifluction and frost creep along the tread while the snow-covered ground downslope from the riser remains immobile. The differential snow cover also produces conditions favoring an enrichment of fines along the lower tread and riser, while fines are depleted along the ground 1-2 m in front of the riser by the melting snow in its lee. For northerly-oriented slopes this may represent a feedback as the presence of the riser contributes to snow accumulation in winter and retardation of melt in spring by shading, allowing soil on the tread to move and build up on the riser, which progressively overrides the immobile soil downslope. This may explain why some previous studies (Benedict, 1970, Price, 1973 and Gengnian *et al.*, 1995) have measured greater rates of movement along the tread than the riser.

5.7 SUGGESTIONS FOR FUTURE RESEARCH

Many opportunities exist for further work in this field, and a number of specific topics of future research may be identified. Four key topics identified in this study include: (i) further exploration of analogous forms and processes in scaled fluid mechanics experiments; (ii) further morphometric measurements of solifluction lobes, terraces and sheets from different environments; (iii) combined studies on nivation and solifluction; (iv) increased use of spatial and multivariate statistical methods in both landform and process studies.

The forms developed in scaled fluid mechanics experiments have many similarities to those in solifluction. Given the possibility of controlling a range of variables (temperature, rheology, cross-sectional area, gradient, slope form, etc.), scaled fluid mechanics experiments provide an ideal setting to develop and test hypotheses about landform development in periglacial environments. Attempts have already been made in the study of lava flows using scaled physical models with cooling wax (e.g., Fink and Griffiths, 1998), and it is believed that similar tests can provide new insight into solifluction landform development.

A second topic that requires additional investigation is that of landform morphology. Although an attempt is made in this study to derive measurements of form and compare these between slope orientations, more measurements are needed from different periglacial environments in order to make a more comprehensive review. A central issue in such studies is consistency of terminology and landform identification. Although a modest attempt is made in the present study, it is apparent that further

amendments are required to enable universal adoption of definitions for lobe, terrace and sheet forms.

An interesting observation in this study, but largely untested in previous studies, is that nivation processes may be significant in the development of solifluction landforms. Although modern use of the term nivation is not recommended (French, 1996) due to the difficulty in deriving its causal relationship with landform development, it is clear that the thermal and slopewash processes associated with late-lying snow exert a considerable effect on modern periglacial landform development (e.g., Christiansen, 1998). Further process-based investigation of nivation and solifluction is warranted in order to better characterize and model the evolution of the lobes, terraces and sheets.

A final area for future research is the use of statistical analysis in both process- and form-based studies concerning solifluction. Previous reports have highlighted the need for increased statistical analysis in the study of solifluction (Pissart, 1993; Matthews and Berrisford, 1993), but very little work has been accomplished to date. This study presents a modest attempt to use multivariate statistics as a preliminary tool to explore quantitative relationships, but more could be done. Of particular interest, in the context of the present study, would be to perform a mirror study in a different periglacial environment and compare the morpho-biophysical characteristics of turf-banked solifluction lobes from both sites using discriminant analysis.

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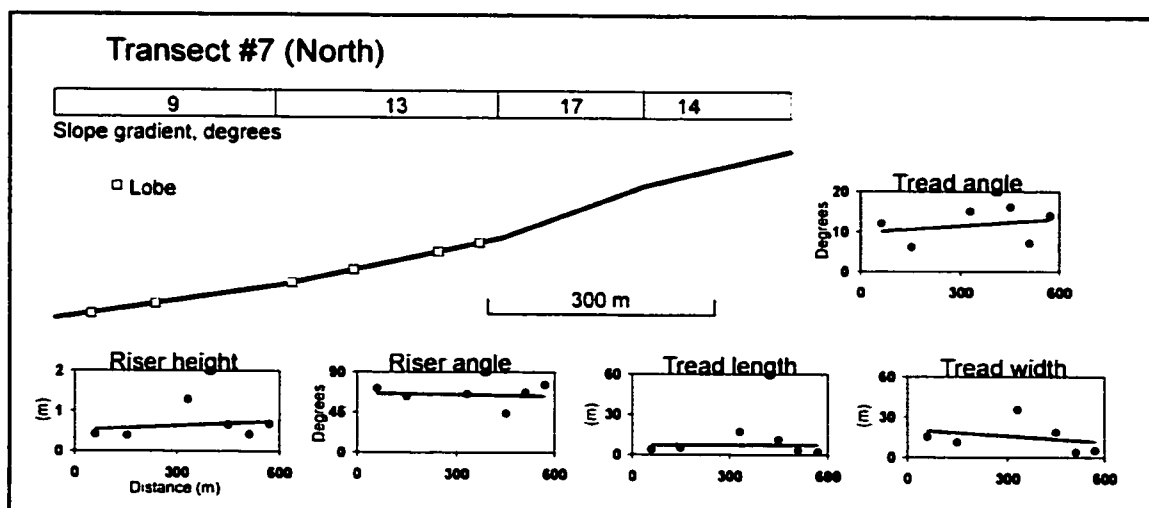
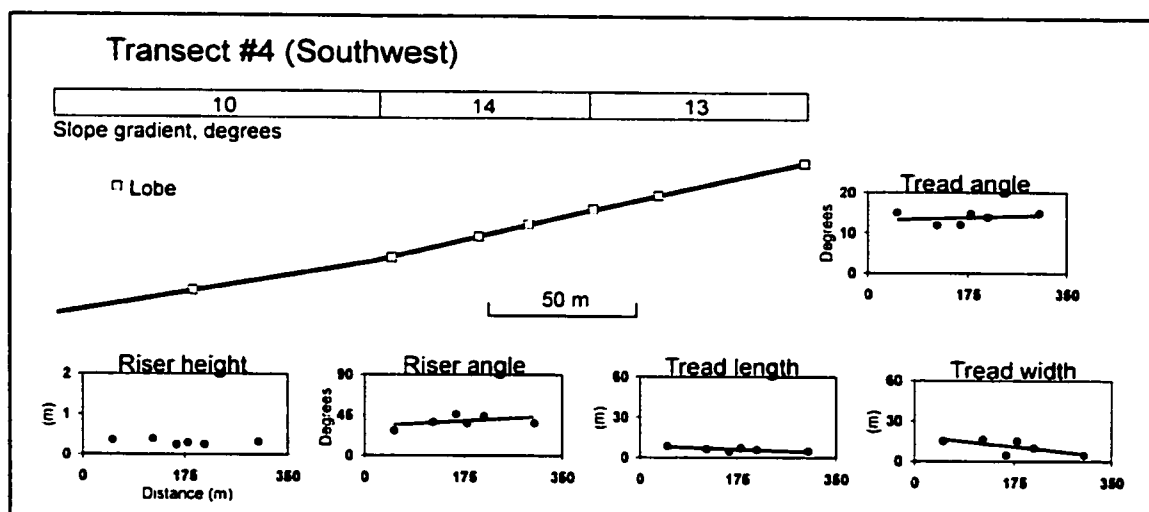
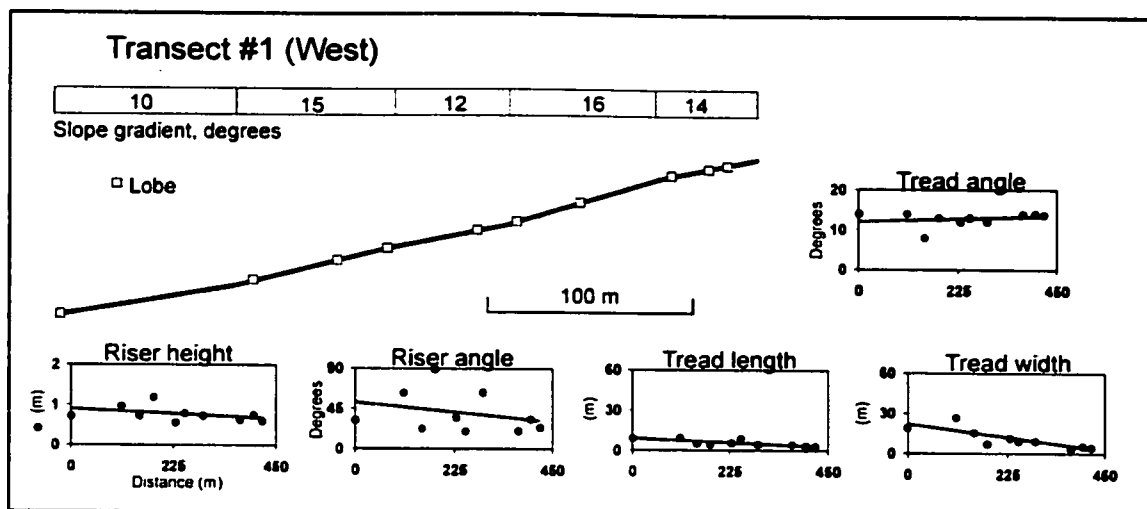
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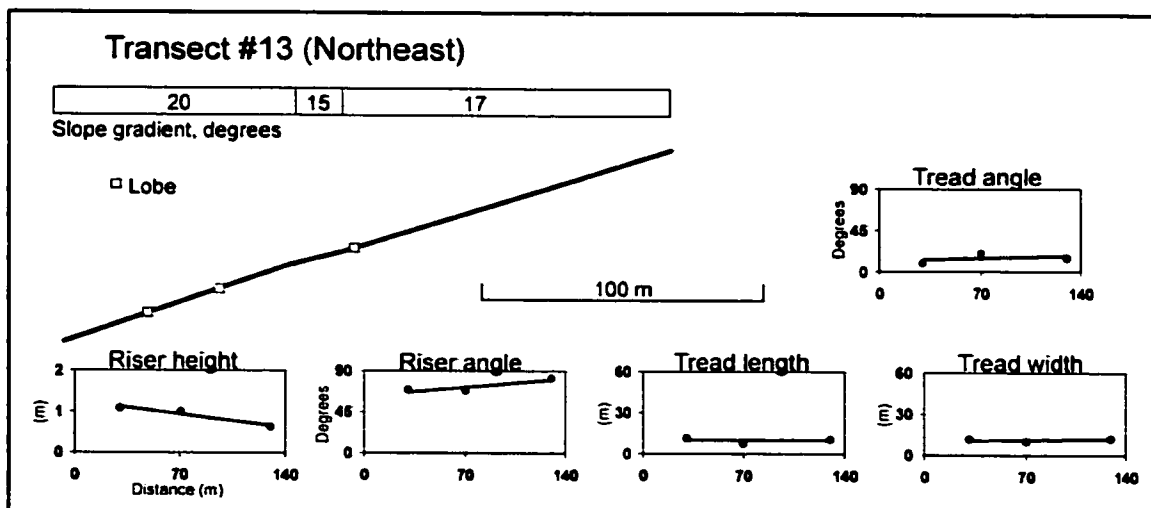
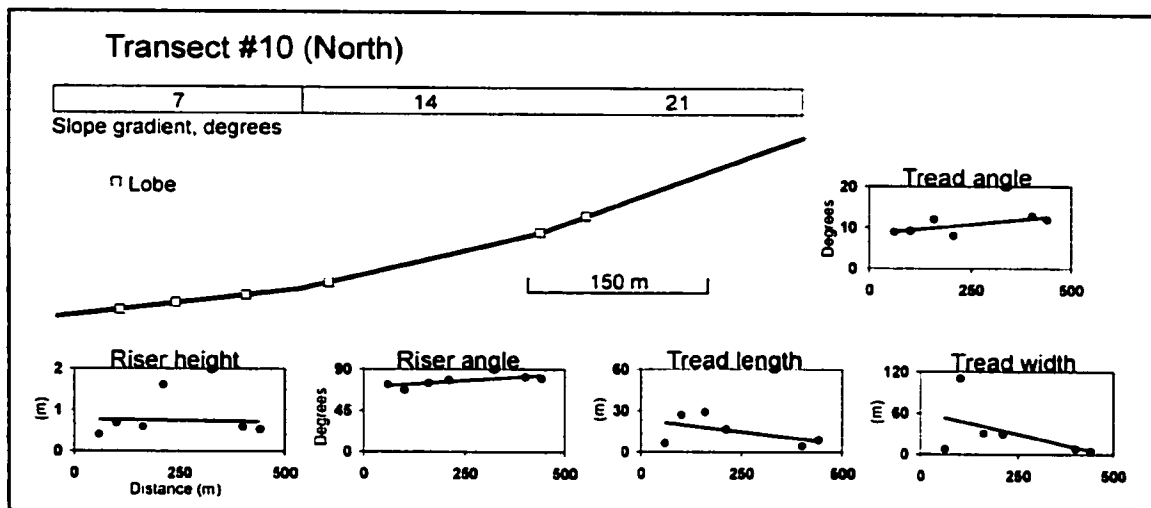
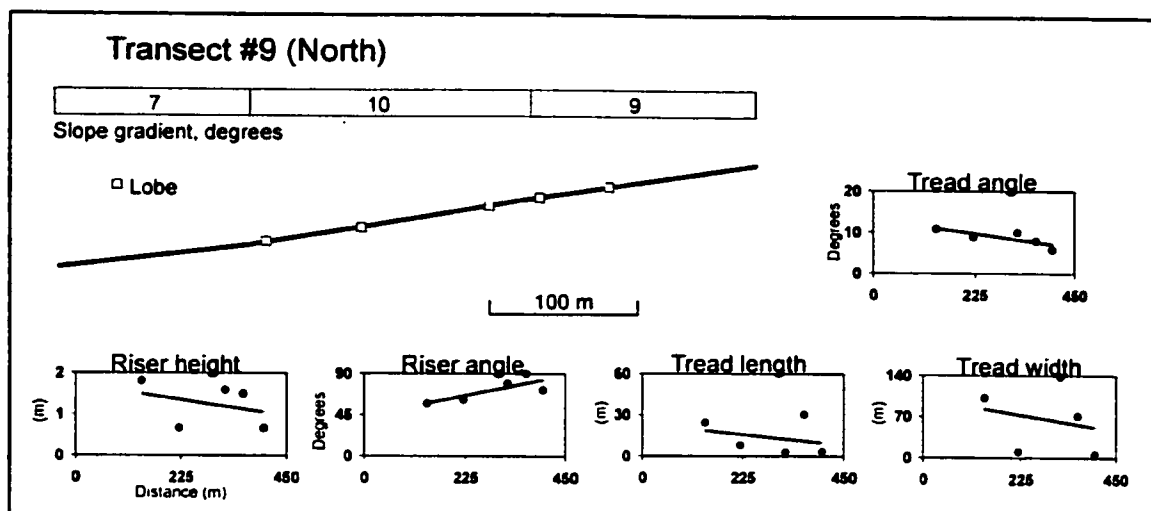
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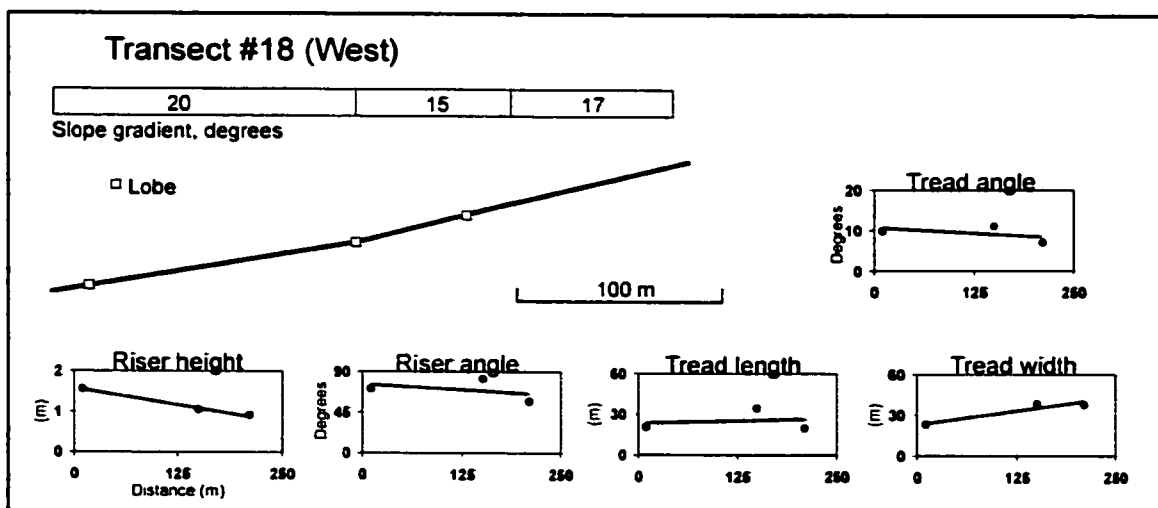
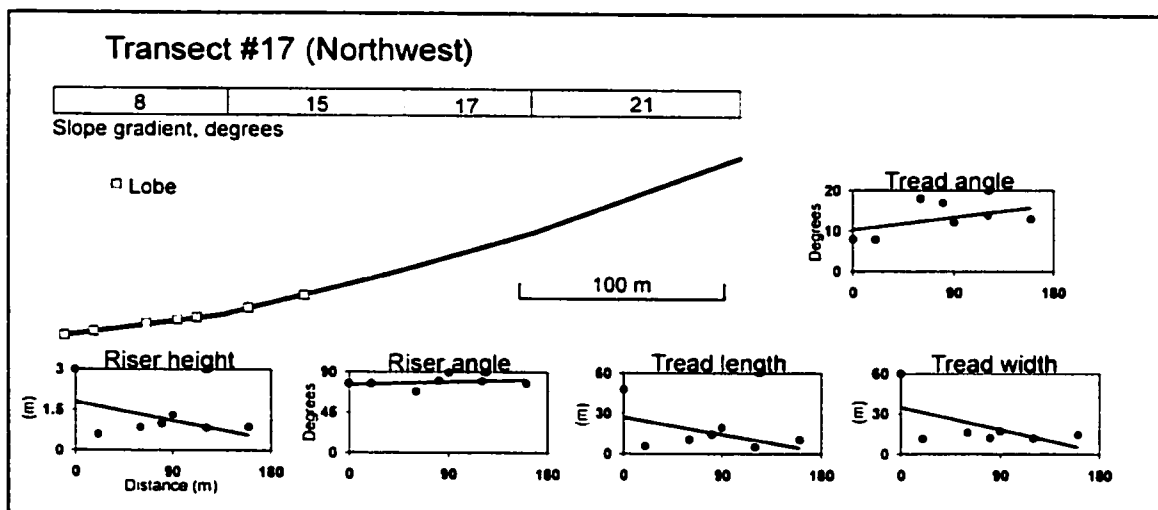
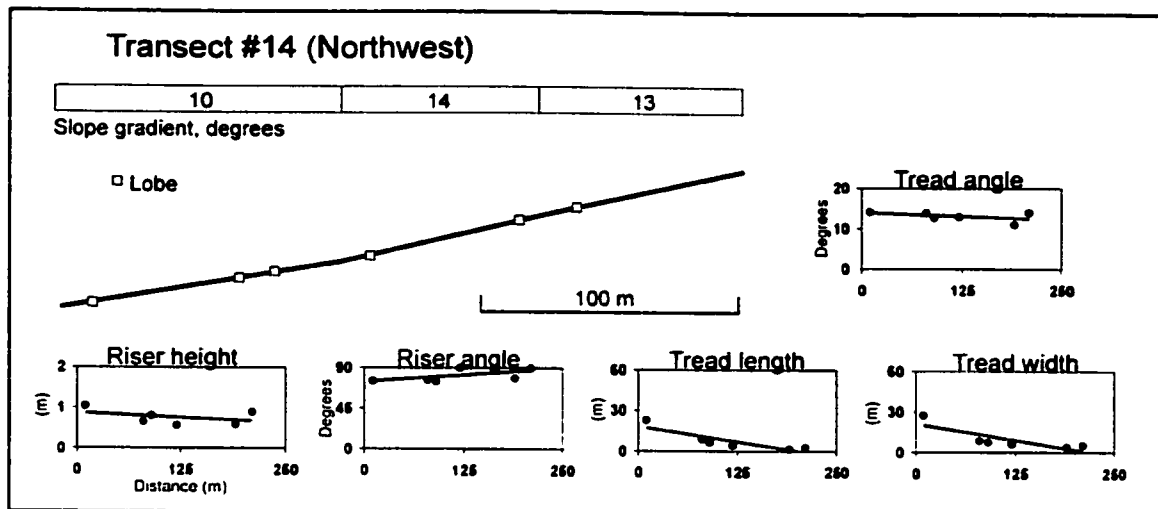
APPENDIX A

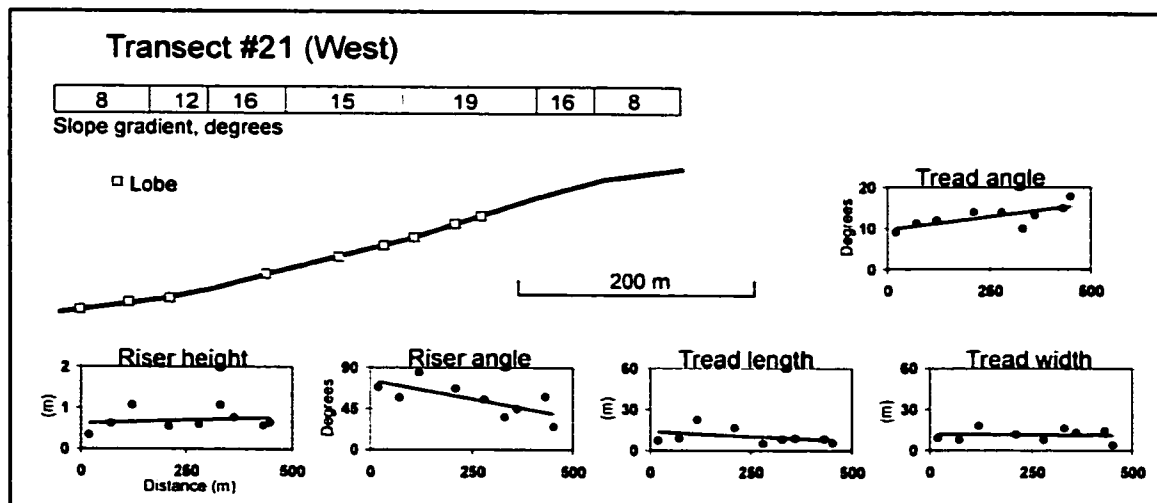
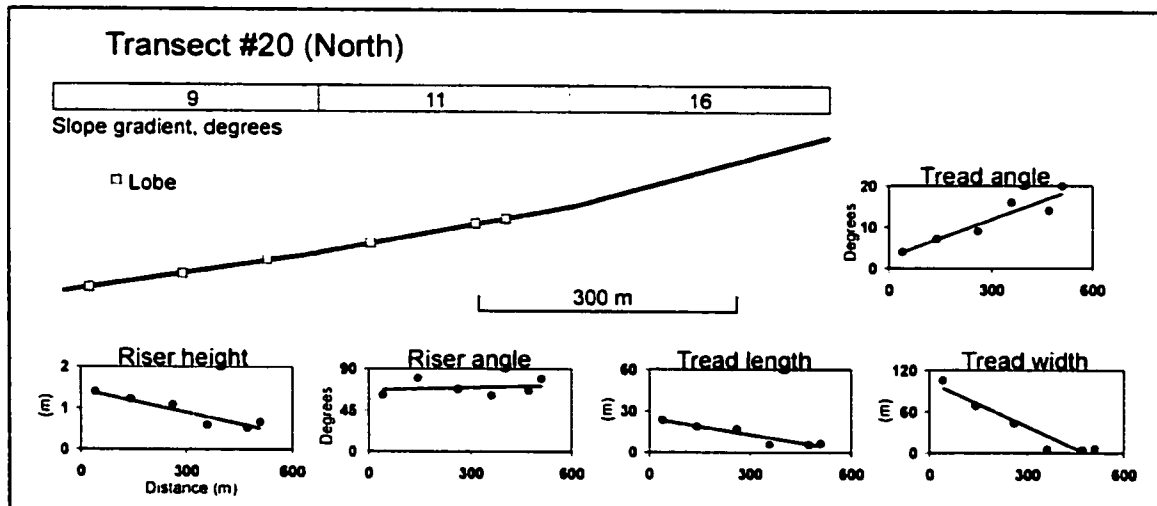
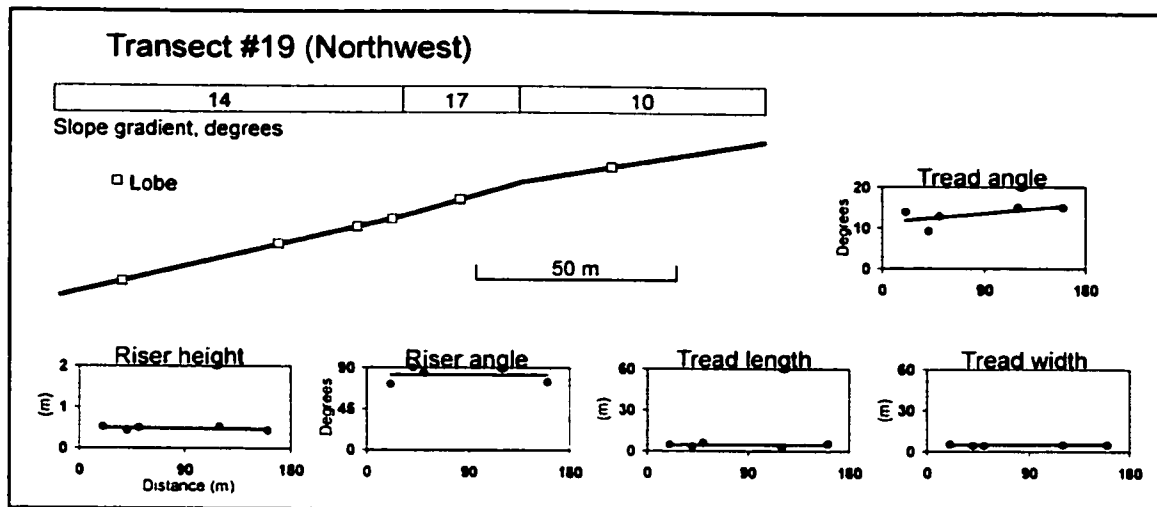
Morphometric characteristics of the lobes on the transects.

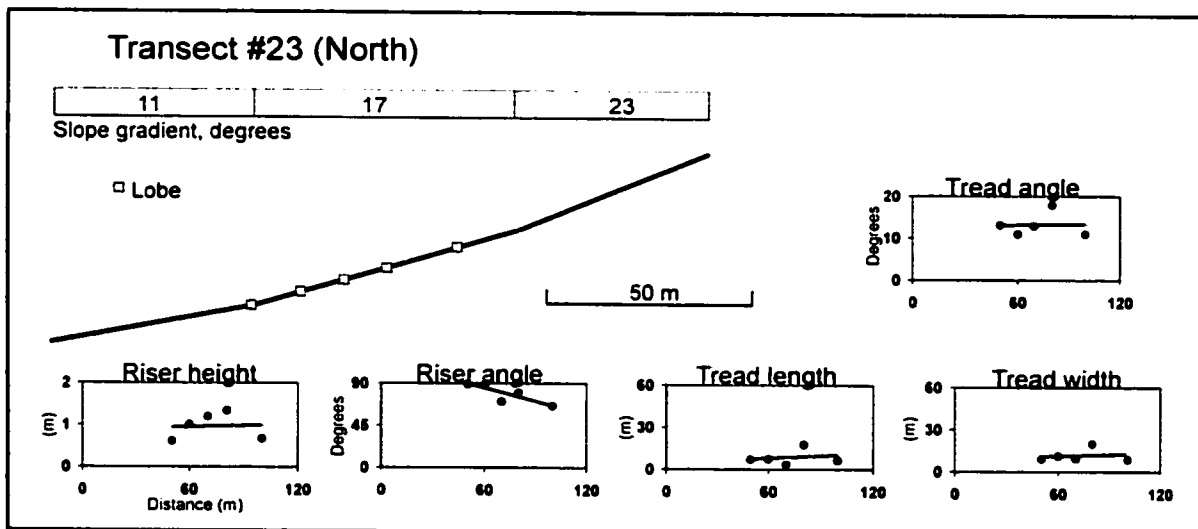
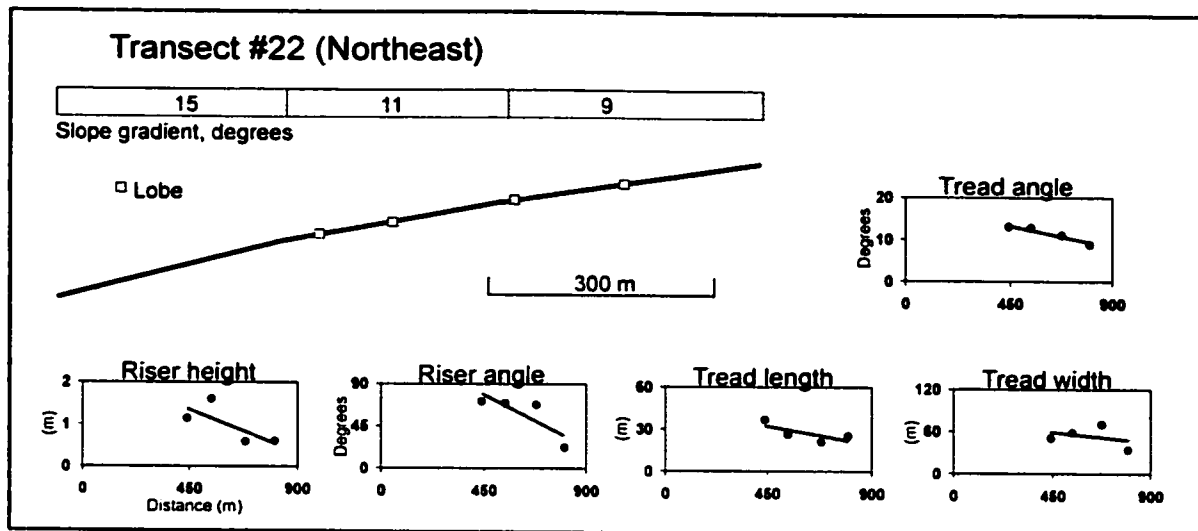
***Note: all distances are measured from the bottom of the slope.**





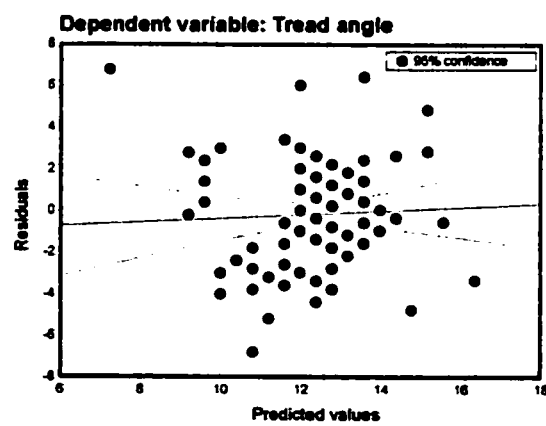
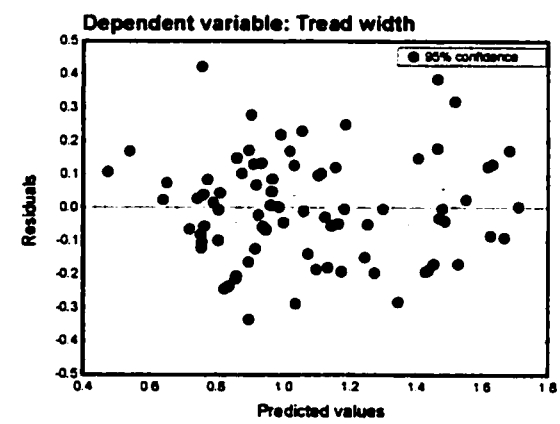
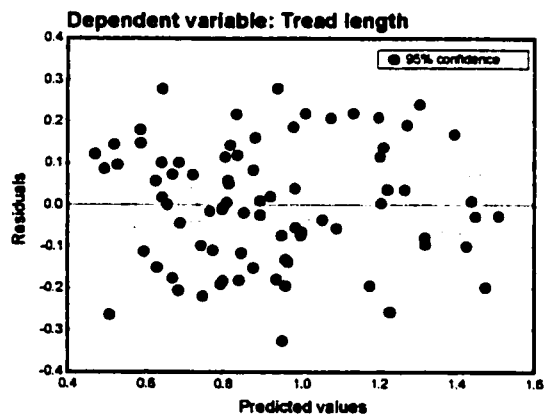
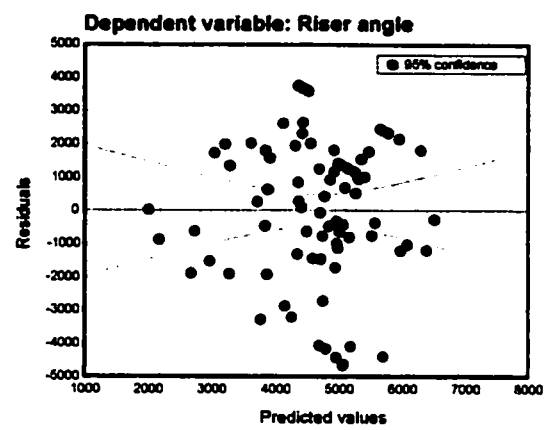
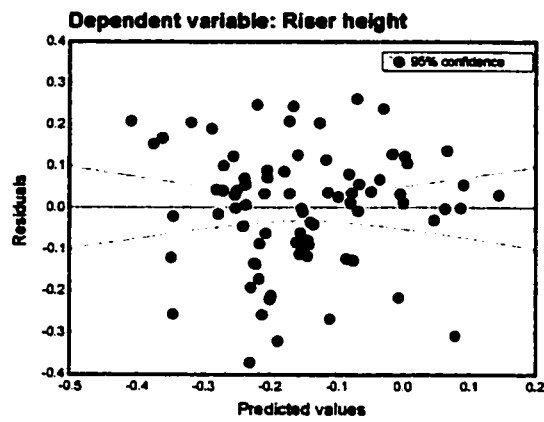






APPENDIX B

Residual plots of the stepwise multiple correlations between the morphometric parameters.



APPENDIX C

Raw morphometric and biophysical data from lobes.

LOBE	ASPECT	RH	RA	TL	TW	TA	PS	OM	THL	S40	S80	LL	%GR	%SD	%ST	%CL	%GRSD	%STCL
1.01	W	0.73	32.20	9.35	19.26	14.00	0.00	14.20	93.40	35.57	46.00	27.50	9.48	26.81	60.41	3.30	36.29	63.71
1.20	W	0.98	63.00	9.57	27.30	14.00	18.00	11.60	101.00	50.10	58.30	27.60	8.34	32.51	56.08	3.06	40.85	59.15
1.30	W	0.74	23.00	5.70	15.90	8.00	13.00	10.20	94.60	48.00	61.30	24.20	18.94	33.13	45.44	2.48	52.07	47.93
1.40	W	1.20	90.00	4.12	7.17	13.00	13.00	6.40	70.00	44.30	46.00	24.15	18.95	33.35	45.23	2.47	52.30	47.70
1.50	W	0.56	35.60	5.36	11.27	12.00	16.00	3.00	105.00	55.77	61.00	22.80	24.02	29.82	43.77	2.39	53.84	46.16
1.60	W	0.80	20.00	9.10	9.65	13.00	12.00	4.40	101.80	36.37	54.10	22.30	22.04	32.45	43.16	2.36	54.48	45.52
1.70	W	0.74	63.00	4.55	9.50	12.00	13.00	4.20	106.00	30.00	40.08	22.50	21.84	32.31	43.48	2.38	54.15	45.85
1.80	W	0.63	21.00	4.60	3.64	14.00	17.00	3.40	97.00	44.56	54.20	23.25	17.20	35.72	44.64	2.44	52.92	47.08
1.90	W	0.77	33.00	3.36	6.31	14.00	13.00	0.60	113.40	40.00	38.60	25.50	20.82	33.09	43.70	2.39	53.91	46.09
1.10	W	0.60	25.00	3.03	4.52	14.00	16.00	3.60	85.40	28.36	24.19	23.20	31.76	26.97	39.13	2.14	58.73	41.27
4.10	SW	0.38	28.00	8.60	15.40	15.00	13.00	27.80	116.20	61.35	36.86	23.90	23.20	11.75	61.68	3.37	34.95	65.05
4.20	SW	0.39	38.00	6.70	16.20	12.00	14.00	21.40	102.20	29.60	42.00	21.80	16.76	33.15	47.50	2.60	49.90	50.10
4.30	SW	0.25	46.00	4.20	4.70	12.00	15.00	22.00	85.60	44.13	34.58	21.00	22.21	31.54	43.85	2.40	53.75	46.25
4.40	SW	0.31	36.00	6.70	15.20	15.00	15.00	14.40	83.40	30.05	35.13	21.10	20.67	31.20	45.64	2.49	51.86	48.14
4.50	SW	0.25	45.00	6.10	10.20	14.00	16.00	13.20	82.20	27.83	28.94	21.70	14.93	36.29	46.25	2.53	51.22	48.78
4.60	SW	0.34	37.00	4.80	4.50	15.00	11.00	13.80	85.00	29.60	34.09	21.60	19.46	34.41	43.75	2.39	53.86	46.14
7.10	N	0.42	72.00	4.20	15.10	12.00	13.00	25.60	62.40	26.50	36.06	23.40	22.99	29.68	44.88	2.45	52.67	47.33
7.20	N	0.38	63.00	4.60	11.00	6.00	10.00	19.20	76.40	36.79	36.08	20.00	25.29	27.29	44.97	2.45	52.58	47.42
7.30	N	1.30	66.00	17.30	35.90	15.00	16.00	14.60	67.60	34.80	33.10	22.30	19.98	33.79	43.84	2.40	53.77	46.23
7.40	N	0.67	44.00	10.80	19.00	16.00	16.00	18.00	72.00	29.00	28.03	22.10	24.75	34.33	38.80	2.12	59.08	40.92
7.50	N	0.43	68.00	3.90	3.80	7.00	9.00	13.40	80.00	25.63	25.10	23.35	20.14	30.80	46.52	2.54	50.94	49.06
7.60	N	0.68	76.00	3.00	4.60	14.00	14.00	13.80	78.20	28.90	26.02	21.80	26.52	32.86	38.52	2.10	59.38	40.62
9.10	N	1.80	57.00	24.30	102.00	11.00	12.00	29.00	62.80	27.87	30.30	21.20	17.55	29.98	49.75	2.72	47.53	52.47
9.20	N	0.66	62.00	8.30	9.00	9.00	9.00	24.80	61.60	22.26	23.91	22.00	21.70	29.36	46.41	2.54	51.06	48.94
9.30	N	1.60	81.00	2.60	138.60	10.00	11.00	23.20	56.80	30.08	37.17	21.60	20.82	32.90	43.88	2.40	53.72	46.28
9.40	N	1.50	90.00	30.30	71.80	8.00	8.00	31.40	65.40	30.13	31.20	22.27	20.61	29.19	47.60	2.60	49.80	50.20
9.50	N	0.68	72.00	3.10	6.40	6.00	7.00	15.20	80.00	20.48	23.03	22.40	21.00	31.00	45.50	2.50	52.00	48.00
10.10	N	0.41	74.00	6.20	7.60	9.00	9.00	27.00	55.40	26.30	36.66	21.95	13.12	32.64	51.43	2.81	45.76	54.24
10.20	N	0.68	68.00	27.50	111.10	9.00	9.00	26.60	52.40	27.15	29.07	20.70	16.42	32.90	48.06	2.63	49.32	50.68
10.30	N	0.60	75.00	29.00	30.00	12.00	5.00	23.20	69.20	24.37	30.00	21.78	14.15	33.01	50.11	2.74	47.15	52.85
10.40	N	1.62	79.00	16.20	28.10	8.00	9.00	21.00	78.00	44.10	44.73	22.60	13.34	31.33	52.46	2.87	44.67	55.33
10.50	N	0.57	82.00	4.40	7.20	13.00	14.00	3.80	103.80	30.18	31.15	21.90	18.00	31.00	33.00	2.60	49.00	35.60
10.60	N	0.54	81.00	8.30	5.60	12.00	14.00	7.60	103.60	29.15	36.80	21.68	21.15	31.19	45.19	2.47	52.34	47.66
11.10	N	0.58	66.00	4.55	6.20	8.00	11.00	4.80	104.40	22.37	30.45	22.21	21.07	34.28	42.33	2.31	55.35	44.65
13.10	NE	1.09	69.00	11.20	11.60	10.00	19.00	14.20	84.60	35.14	37.16	25.30	12.25	31.66	53.18	2.91	43.92	56.08
13.20	NE	1.00	68.00	7.50	10.30	20.00	20.00	13.60	88.60	34.38	44.20	25.05	22.87	29.49	45.17	2.47	52.36	47.64
13.30	NE	0.63	82.00	11.00	12.30	15.00	21.00	11.40	86.40	28.52	28.73	22.20	18.80	33.57	45.16	2.47	52.38	47.62
14.10	NW	1.03	76.00	22.30	27.50	14.00	15.00	16.60	80.40	33.05	64.37	24.85	24.92	24.09	48.35	2.64	49.01	50.99
14.20	NW	0.69	77.00	9.10	8.60	14.00	15.00	15.40	85.80	18.61	24.90	23.95	17.76	33.31	46.40	2.54	51.07	48.93
14.30	NW	0.81	76.00	6.80	7.60	13.00	7.00	13.40	80.20	19.03	26.19	23.80	22.36	31.63	43.62	2.38	53.99	46.01
14.40	NW	0.56	90.00	4.40	5.90	13.00	13.00	11.80	89.20	32.86	24.23	23.85	20.96	31.63	44.96	2.46	52.59	47.41
14.50	NW	0.59	80.00	1.75	3.80	11.00	14.00	14.80	92.40	27.93	26.08	23.10	19.00	44.00	35.20	1.80	63.00	37.00
14.60	NW	0.93	90.00	3.00	5.30	14.00	15.00	10.60	100.80	24.01	25.83	23.80	39.26	31.27	27.94	1.53	70.53	29.47
15.10	W	0.84	83.00	8.00	12.50	9.00	12.00	27.00	83.40	50.99	45.05	29.00	9.61	26.90	60.20	3.29	36.51	63.49
15.20	W	0.70	56.00	16.90	19.30	9.00	13.00	29.40	63.60	52.69	49.81	26.24	4.00	26.68	65.72	3.59	30.68	69.32

LOBE	ASPECT	RH	RA	TL	TW	TA	PS	OM	THL	S40	S80	LL	%GR	%SD	%ST	%CL	%GRSD	%STCL
16.10	W	1.40	79.00	28.00	55.30	12.00	13.00	12.80	99.20	28.16	50.74	23.70	17.50	30.36	49.44	2.70	47.86	52.14
17.10	NW	3.00	77.00	48.00	60.00	8.00	10.00	23.40	57.00	36.15	34.50	23.80	28.00	25.00	44.00	3.00	53.00	47.00
17.20	NW	0.61	77.00	5.30	11.70	8.00	8.00	4.00	49.00	23.54	29.16	24.10	28.00	28.00	41.20	2.80	56.00	44.00
17.30	NW	0.84	68.00	10.40	16.50	18.00	20.00	3.20	53.00	22.12	23.34	24.42	27.19	29.22	41.33	2.26	56.41	43.59
17.40	NW	0.98	80.00	14.60	12.50	17.00	18.00	6.80	76.60	37.30	36.54	23.28	6.14	27.14	63.26	3.46	33.28	66.72
17.50	NW	1.30	90.00	19.20	17.30	12.00	12.00	3.80	84.40	29.38	29.63	22.80	19.82	31.12	46.52	2.54	50.94	49.06
17.60	NW	0.85	80.00	5.80	11.70	14.00	12.00	4.40	111.40	27.16	22.58	24.36	20.19	28.05	49.08	2.68	48.24	51.76
17.70	NW	0.86	78.00	10.50	15.10	13.00	16.00	3.80	103.80	55.02	51.61	24.45	29.79	15.00	52.35	2.86	44.79	55.21
18.10	W	1.56	72.00	20.80	22.90	10.00	6.00	8.80	104.40	20.14	21.85	25.35	19.39	29.16	48.79	2.67	48.55	51.45
18.20	W	1.04	82.00	35.00	38.00	11.00	11.00	23.00	68.40	21.16	22.49	23.52	20.95	32.28	44.35	2.42	53.23	46.77
18.30	W	0.91	56.70	20.00	37.70	7.00	7.00	22.00	36.80	30.42	24.74	23.40	20.75	31.60	45.19	2.47	52.35	47.65
19.10	NW	0.52	72.00	4.50	5.10	14.00	13.00	12.00	91.80	23.50	20.32	26.90	21.36	32.51	43.74	2.39	53.86	46.14
19.20	NW	0.44	90.00	3.80	4.30	9.00	14.00	11.60	81.60	25.02	26.06	24.15	21.10	35.41	41.24	2.25	56.51	43.49
19.30	NW	0.50	84.00	5.80	4.50	13.00	14.00	10.60	79.80	52.52	26.84	23.70	25.35	34.80	37.78	2.06	60.15	39.85
19.40	NW	0.54	90.00	3.00	5.10	15.00	12.00	10.00	56.40	22.46	23.38	24.00	24.00	37.00	36.30	2.70	61.00	39.00
19.50	NW	0.44	75.00	5.50	5.10	15.00	15.00	7.60	62.40	21.20	20.29	27.57	25.48	33.51	38.89	2.12	58.99	41.01
20.10	N	1.38	62.00	23.30	106.00	4.00	9.00	13.60	79.20	51.77	59.32	27.30	10.47	34.41	52.27	2.86	44.87	55.13
20.20	N	1.22	80.00	18.90	68.70	7.00	7.00	17.80	91.40	27.64	26.72	25.30	19.06	33.77	44.72	2.44	52.83	47.17
20.30	N	1.07	68.00	16.70	44.00	9.00	11.00	16.80	73.80	27.86	25.77	23.50	18.85	33.76	44.94	2.46	52.60	47.40
20.40	N	0.60	62.00	6.10	5.40	16.00	16.00	20.00	87.80	24.40	25.13	24.50	23.70	35.13	39.04	2.13	58.83	41.17
20.50	N	0.51	67.00	5.40	4.40	14.00	15.00	8.60	73.20	16.80	19.39	24.83	25.10	34.25	38.54	2.11	59.35	40.65
20.60	N	0.67	79.00	6.50	6.30	20.00	16.00	8.80	90.40	11.32	11.41	23.74	46.80	27.74	24.15	1.32	74.53	25.47
21.10	W	0.34	68.00	7.30	9.30	9.00	5.00	10.40	96.20	15.81	46.03	28.80	7.63	31.83	57.40	3.14	39.46	60.54
21.20	W	0.62	57.00	9.00	8.20	11.00	6.00	10.60	102.80	28.85	30.69	28.20	16.42	39.26	42.02	2.30	55.68	44.32
21.30	W	1.08	85.00	22.50	17.80	12.00	6.00	18.40	98.00	32.33	40.22	26.30	18.42	35.94	43.28	2.36	54.35	45.65
21.40	W	0.55	67.00	16.50	12.00	14.00	12.00	12.80	109.60	34.54	38.28	25.30	21.28	39.58	37.12	2.03	60.85	39.15
21.50	W	0.59	55.00	5.60	8.00	14.00	17.00	7.20	115.40	23.82	26.94	26.25	25.00	37.00	36.50	1.50	62.00	38.00
21.60	W	1.07	36.00	8.50	16.00	10.00	14.00	3.60	106.40	24.48	25.19	25.42	16.83	39.00	41.88	2.29	55.83	44.17
21.70	W	0.77	45.00	8.70	13.10	13.00	17.00	4.60	109.00	20.84	21.48	25.68	22.24	36.26	39.34	2.15	58.51	41.49
21.80	W	0.59	58.00	8.40	14.40	15.00	14.00	7.60	104.00	19.94	20.02	25.10	23.19	35.31	39.35	2.15	58.50	41.50
21.90	W	0.64	25.00	5.50	4.00	18.00	12.00	2.20	89.60	10.50	12.16	25.50	15.00	49.00	34.34	1.66	64.00	36.00
22.10	NE	1.15	72.00	36.50	52.00	13.00	16.00	34.00	47.80	16.38	18.08	25.75	14.22	15.25	66.88	3.65	29.47	70.53
22.20	NE	1.60	69.00	26.30	58.00	13.00	16.00	32.60	55.40	19.66	19.70	24.68	14.94	32.06	50.26	2.75	47.00	53.00
22.30	NE	0.59	69.00	21.20	71.00	11.00	15.00	33.20	59.80	24.33	30.01	24.10	14.57	39.55	43.51	2.38	54.12	45.88
22.40	NE	0.60	22.00	25.60	35.00	9.00	12.00	31.60	47.20	20.06	20.17	24.65	16.78	33.64	47.01	2.57	50.43	49.57
23.10	N	0.62	90.00	7.40	9.70	13.00	17.00	4.40	82.00	34.77	44.86	24.83	15.04	14.76	66.56	3.64	29.80	70.20
23.20	N	1.00	90.00	7.40	11.20	11.00	13.00	1.00	105.20	26.24	26.47	24.72	20.54	33.50	43.58	2.38	54.04	45.96
23.30	N	1.20	71.00	4.00	9.70	13.00	23.00	5.20	95.20	25.54	27.59	23.57	24.81	29.30	43.51	2.38	54.11	45.89
23.40	N	1.34	80.00	18.10	19.80	18.00	12.00	6.00	100.00	24.55	31.38	24.62	15.76	36.59	45.18	2.47	52.35	47.65
23.50	N	0.67	66.00	6.20	9.00	11.00	13.00	3.80	98.40	21.49	21.77	23.89	29.89	28.05	39.88	2.18	57.94	42.06

APPENDIX D

Raw biophysical data from non-lobes.

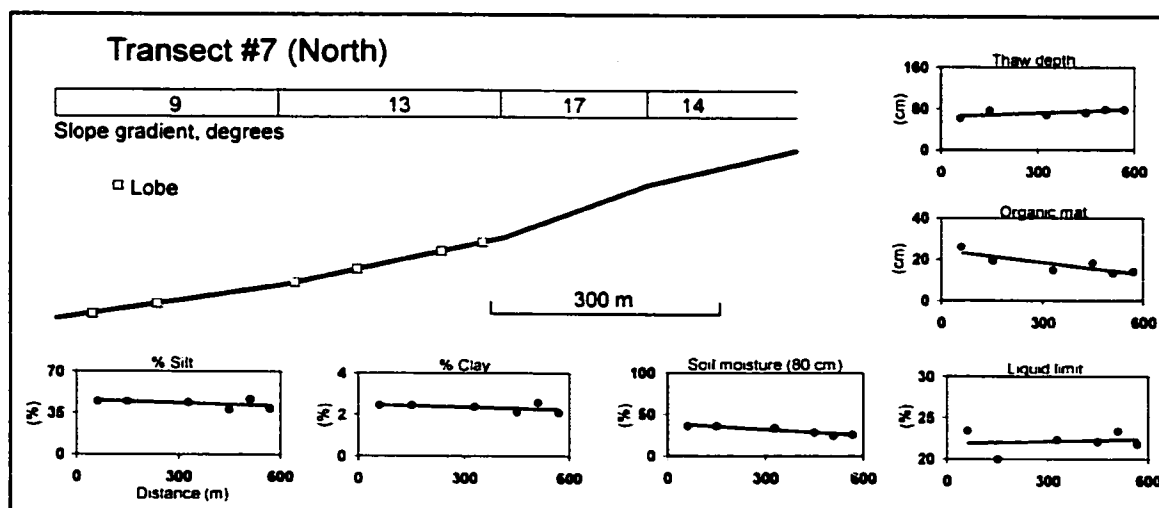
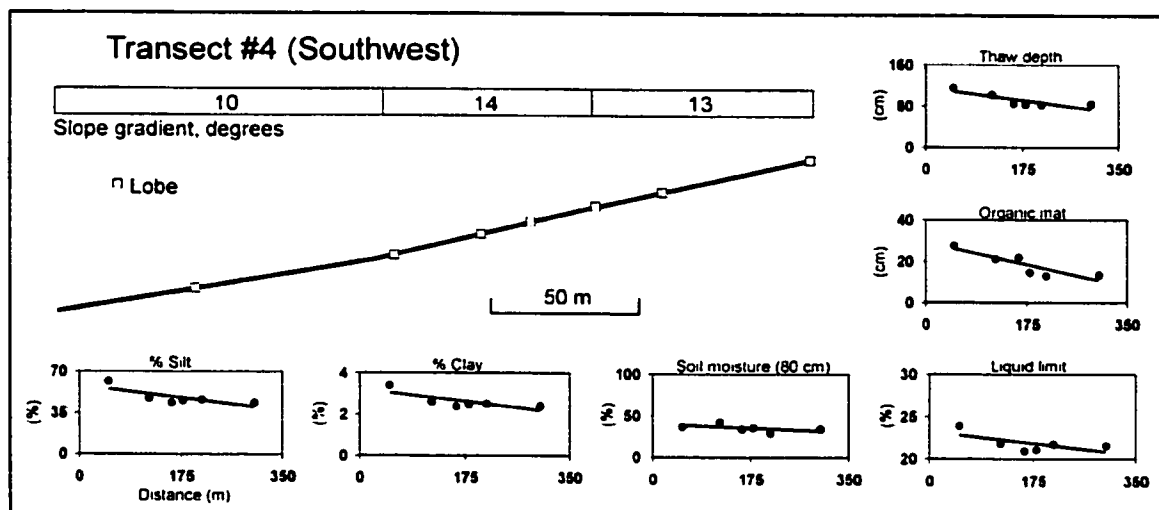
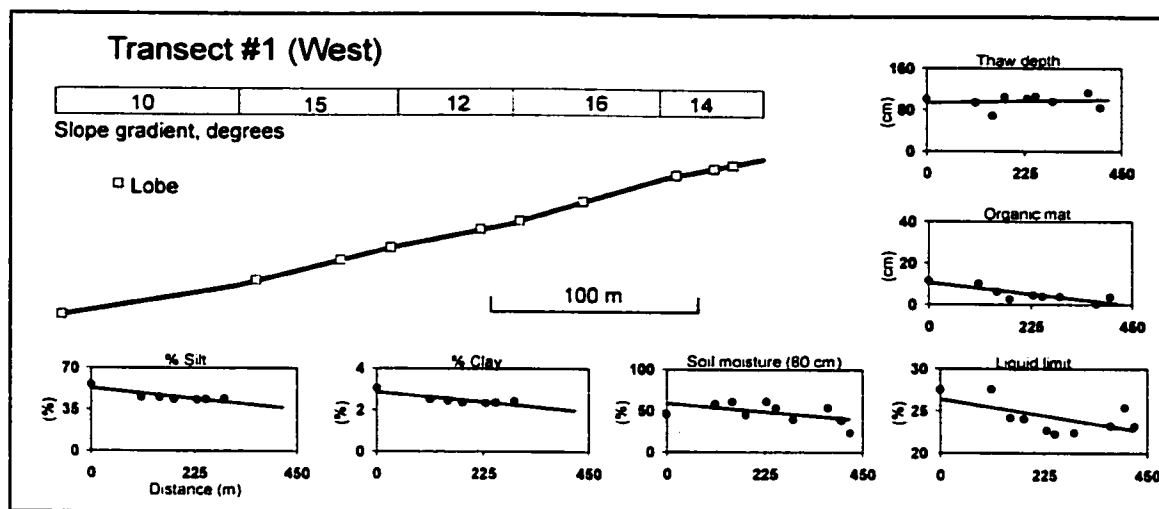
NLOBE	ASPECT	OM	THL	S40	S80	LL	%GR	%SD	%ST	%CL	%GRSD	%STCL
1.0	W	10.0	92.0	19.6	20.5	22.6	20.4	34.7	43.7	1.3	55.1	44.9
1.2	W	10.0	106.0	16.4	15.8	22.7	21.0	34.0	43.5	1.5	55.0	45.0
1.3	W	8.0	105.0	18.9	18.1	23.1	21.0	32.0	45.4	1.7	53.0	47.0
1.4	W	20.0	108.0	19.7	16.8	22.9	37.6	26.6	34.8	1.0	64.2	35.8
1.5	W	9.0	101.0	24.4	26.1	24.6	32.0	34.0	32.5	1.6	66.0	34.0
1.6	W	7.0	105.0	26.0	25.6	25.4	20.1	31.7	46.8	1.4	51.9	48.1
1.7	W	9.0	97.0	28.7	26.3	25.4	17.7	36.5	44.6	1.3	54.1	45.9
1.8	W	6.0	91.0	21.2	23.0	23.7	15.2	34.0	49.4	1.4	49.2	50.8
1.9	W	9.0	86.0	15.1	30.4	25.1	13.0	35.4	50.1	1.5	48.4	51.6
1.1	W	8.0	87.0	17.1	18.0	22.7	22.1	31.5	45.1	1.3	53.6	46.4
4.1	SW	16.0	114.0	10.9	9.9	21.0	20.9	34.9	43.0	1.2	55.8	44.2
4.2	SW	18.0	107.0	15.5	12.3	23.2	19.3	34.9	44.6	1.3	54.1	45.9
4.3	SW	22.0	95.0	23.9	26.1	24.6	16.7	33.4	48.5	1.4	50.1	49.9
4.4	SW	18.0	111.0	9.6	13.1	24.5	23.1	32.4	43.2	1.3	55.5	44.5
4.5	SW	14.0	92.0	22.8	11.5	20.5	17.0	36.3	45.4	1.3	53.2	46.8
4.6	SW	19.0	105.0	13.6	12.8	21.3	20.0	34.0	44.6	1.5	54.0	46.0
7.1	N	13.0	89.0	19.2	21.6	22.0	18.7	37.3	42.8	1.2	56.0	44.0
7.2	N	14.0	104.0	13.7	12.3	20.5	25.2	37.1	36.7	1.1	62.3	37.7
7.3	N	7.0	93.0	16.5	11.1	19.8	19.5	35.8	43.4	1.3	55.3	44.7
7.4	N	9.0	89.0	11.8	15.7	22.5	23.1	32.9	42.8	1.2	56.0	44.0
7.5	N	13.0	78.0	15.1	15.9	19.0	19.8	35.0	43.9	1.3	54.8	45.2
7.6	N	11.0	79.0	11.4	16.5	22.3	27.9	30.8	40.1	1.2	58.8	41.2
9.1	N	14.0	89.0	27.4	29.2	22.3	21.0	38.0	39.6	1.5	59.0	41.0
9.2	N	17.0	90.0	22.7	19.2	24.7	21.2	31.5	46.0	1.3	52.7	47.3
9.3	N	16.0	86.0	32.1	27.6	21.4	20.3	32.0	46.4	1.3	52.3	47.7
9.4	N	23.0	68.0	31.5	24.8	23.1	23.0	32.0	43.8	1.3	54.9	45.1
9.5	N	11.0	99.0	22.4	19.8	23.1	22.0	33.0	43.7	1.3	55.0	45.0
10.1	N	13.0	82.0	31.0	33.5	24.3	16.7	32.6	49.2	1.4	49.3	50.7
10.2	N	23.0	78.0	32.5	33.9	23.4	12.2	30.1	56.1	1.6	42.3	57.7
10.3	N	18.0	98.0	15.3	11.6	21.8	15.2	37.8	45.7	1.3	53.0	47.0
10.4	N	17.0	92.0	28.8	27.4	24.8	15.8	30.1	52.6	1.5	45.9	54.1
10.5	N	15.0	104.0	27.7	22.5	20.9	11.0	32.6	54.7	1.6	43.7	56.3
10.6	N	13.0	112.0	27.3	24.0	22.6	10.5	35.4	52.5	1.5	46.0	54.0
11.1	N	5.0	102.0	16.5	17.7	21.8	20.2	25.1	53.2	1.5	45.3	54.7
13.1	NE	9.0	102.0	23.5	21.6	23.7	20.6	31.0	47.0	1.4	51.7	48.3
13.2	NE	7.0	89.0	13.5	16.3	23.4	19.9	37.5	41.5	1.2	57.3	42.7
13.3	NE	13.0	98.0	15.7	15.6	23.0	24.9	36.4	37.6	1.1	61.3	38.7
14.1	NW	8.0	81.0	30.7	34.8	27.8	27.0	29.9	41.9	1.2	56.9	43.1
14.2	NW	9.0	91.0	16.9	17.2	24.6	20.9	30.8	46.9	1.4	51.7	48.3
14.3	NW	12.0	100.0	32.1	30.8	23.6	23.1	33.1	42.5	1.2	56.3	43.7
14.4	NW	11.0	83.0	9.8	9.3	22.4	33.8	26.5	38.6	1.1	60.3	39.7
14.5	NW	14.0	82.0	13.3	10.7	22.1	19.1	34.2	45.3	1.3	53.4	46.6
14.6	NW	12.0	94.0	20.2	14.8	21.0	26.9	30.7	41.2	1.2	57.7	42.3
15.1	W	19.0	98.0	25.6	24.4	29.7	3.9	29.8	64.4	1.9	33.7	66.3
15.2	W	13.0	107.0	25.3	26.8	27.7	15.9	30.6	51.9	1.5	46.6	53.4

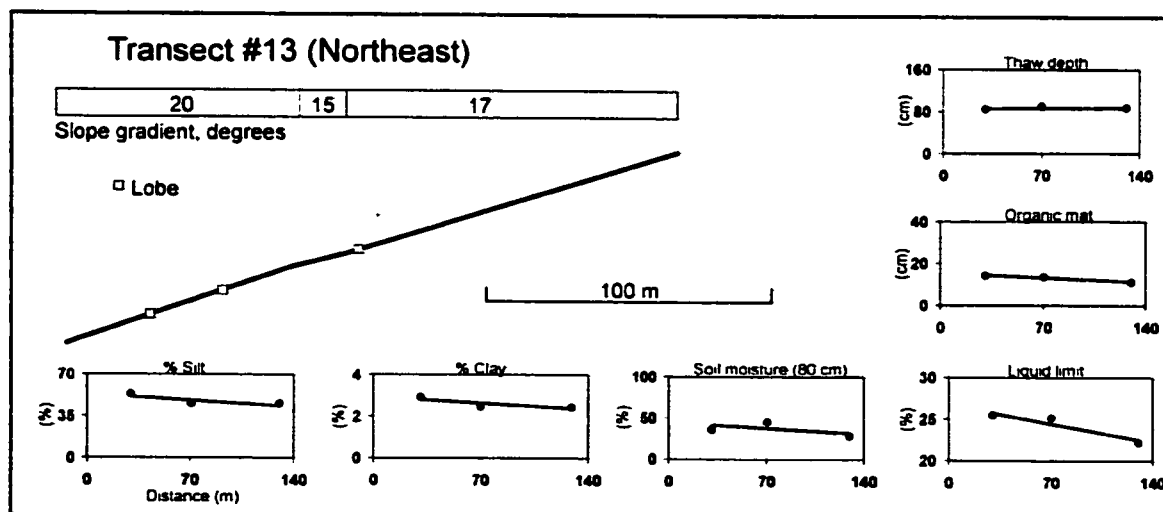
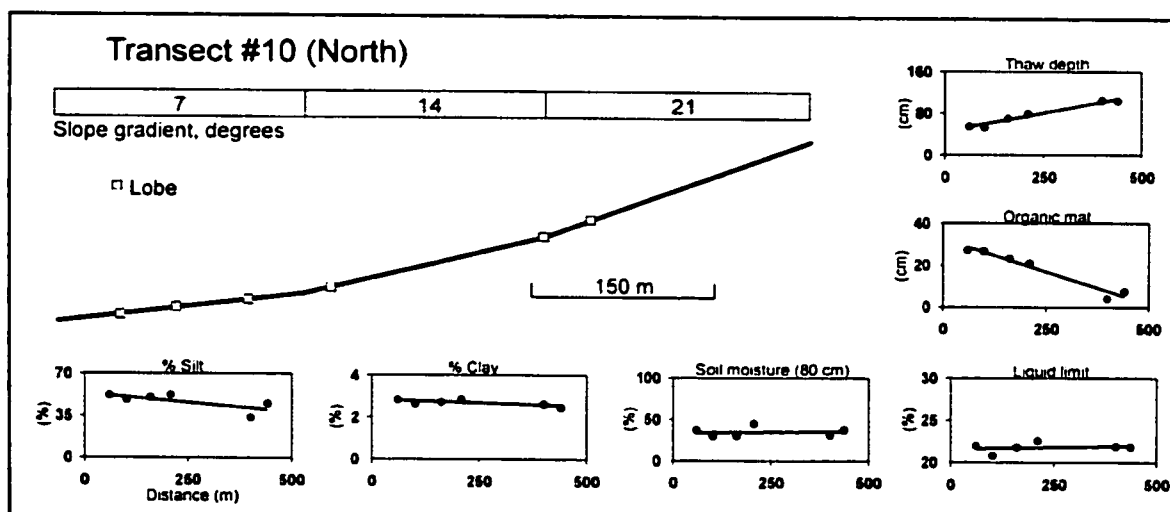
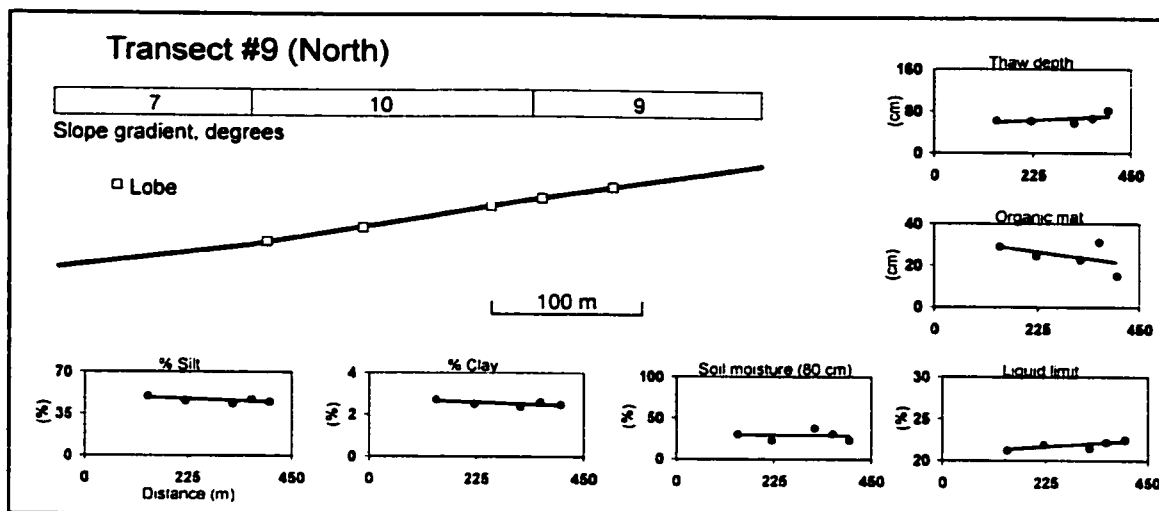
NLOBE	ASPECT	OM	THL	S40	S80	LL	%GR	%SD	%ST	%CL	%GRSD	%STCL
16.1	W	7.0	103.0	25.9	26.0	28.7	23.8	34.0	41.0	1.2	57.8	42.2
17.1	NW	6.0	77.0	26.4	27.1	28.2	26.1	33.9	38.8	1.1	60.0	40.0
17.2	NW	7.0	87.0	25.8	28.1	27.5	25.8	34.1	38.9	1.1	59.9	40.1
17.3	NW	5.0	88.0	15.4	24.7	24.1	20.6	35.0	43.1	1.2	55.6	44.4
17.4	NW	6.0	99.0	33.5	27.4	28.2	32.0	33.6	33.5	1.0	65.6	34.4
17.5	NW	4.0	123.0	22.6	23.7	24.8	26.0	35.0	37.7	1.3	61.0	39.0
17.6	NW	8.0	108.0	19.5	25.4	23.6	21.0	40.0	37.6	1.5	61.0	39.0
17.7	NW	6.0	98.0	25.6	26.3	22.5	30.0	40.3	28.1	1.7	70.3	29.7
18.1	W	14.0	102.0	24.6	25.5	27.3	11.1	31.8	55.5	1.6	42.9	57.1
18.2	W	19.0	96.0	33.0	21.2	23.0	18.4	28.8	51.3	1.5	47.3	52.7
18.3	W	12.0	93.0	32.9	21.5	24.4	17.1	31.1	50.4	1.5	48.2	51.8
19.1	NW	9.0	104.0	14.7	8.2	23.5	19.7	36.3	42.8	1.2	56.0	44.0
19.2	NW	8.0	89.0	13.0	10.8	24.5	27.5	30.3	41.0	1.2	57.8	42.2
19.3	NW	13.0	105.0	23.8	15.8	25.2	22.9	32.6	43.2	1.3	55.5	44.5
19.4	NW	7.0	99.0	1.8	2.9	25.5	22.0	38.8	38.7	0.5	60.8	39.2
19.5	NW	7.0	107.0	16.6	19.8	22.9	21.0	40.6	37.3	1.1	61.6	38.4
20.1	N	3.0	92.0	15.6	17.1	23.8	11.0	46.6	41.2	1.2	57.6	42.4
20.2	N	8.0	99.0	12.3	14.2	26.1	17.5	35.8	45.3	1.3	53.3	46.7
20.3	N	7.0	85.0	14.0	9.3	24.8	25.0	30.2	43.5	1.3	55.2	44.8
20.4	N	11.0	91.0	26.8	22.0	25.4	22.7	28.5	47.4	1.4	51.2	48.8
20.5	N	16.0	96.0	16.2	14.3	24.4	13.4	40.3	45.0	1.3	53.7	46.3
20.6	N	13.0	86.0	32.0	29.5	28.3	15.4	35.1	48.1	1.4	50.5	49.5
21.1	W	13.0	112.0	22.6	23.9	23.5	20.1	35.5	43.2	1.3	55.6	44.4
21.2	W	0.0	106.0	23.6	22.6	25.9	7.6	37.9	53.0	1.5	45.5	54.5
21.3	W	17.0	126.0	33.9	33.4	30.7	5.7	31.0	61.5	1.8	36.7	63.3
21.4	W	6.0	106.0	33.2	21.4	27.9	1.2	29.5	67.3	1.9	30.7	69.3
21.5	W	13.0	99.0	24.0	21.6	29.5	28.7	32.2	38.0	1.1	60.9	39.1
21.6	W	7.0	106.0	25.2	24.8	26.5	43.5	26.3	29.4	0.9	69.8	30.2
21.7	W	4.0	102.0	19.2	22.4	25.5	42.0	26.0	31.1	0.9	68.0	32.0
21.8	W	15.0	97.0	10.2	11.9	22.6	42.0	28.0	29.2	0.8	70.0	30.0
21.9	W	4.0	96.0	5.7	9.1	21.8	45.0	37.0	17.3	0.8	82.0	18.0
22.1	NE	17.0	103.0	14.9	11.0	22.8	31.5	12.2	54.8	1.6	43.6	56.4
22.2	NE	21.0	77.0	22.0	15.3	27.2	28.8	7.7	61.7	1.8	36.5	63.5
22.3	NE	13.0	107.0	26.7	29.7	26.3	11.5	31.4	55.5	1.6	42.9	57.1
22.4	NE	22.0	98.0	19.8	17.3	25.7	15.0	34.0	49.2	1.8	49.0	51.0
23.1	N	3.0	88.0	21.7	21.3	25.8	34.2	23.3	41.3	1.2	57.5	42.5
23.2	N	7.0	92.0	25.2	22.0	25.9	16.5	39.9	40.4	1.2	58.4	41.6
23.3	N	8.0	102.0	20.6	18.0	24.8	26.7	26.8	45.2	1.3	53.5	46.5
23.4	N	5.0	95.0	19.8	15.4	23.7	30.0	32.0	36.5	1.5	62.0	38.0
23.5	N	7.0	109.0	11.5	18.7	26.3	31.0	38.0	29.1	1.9	69.0	31.0

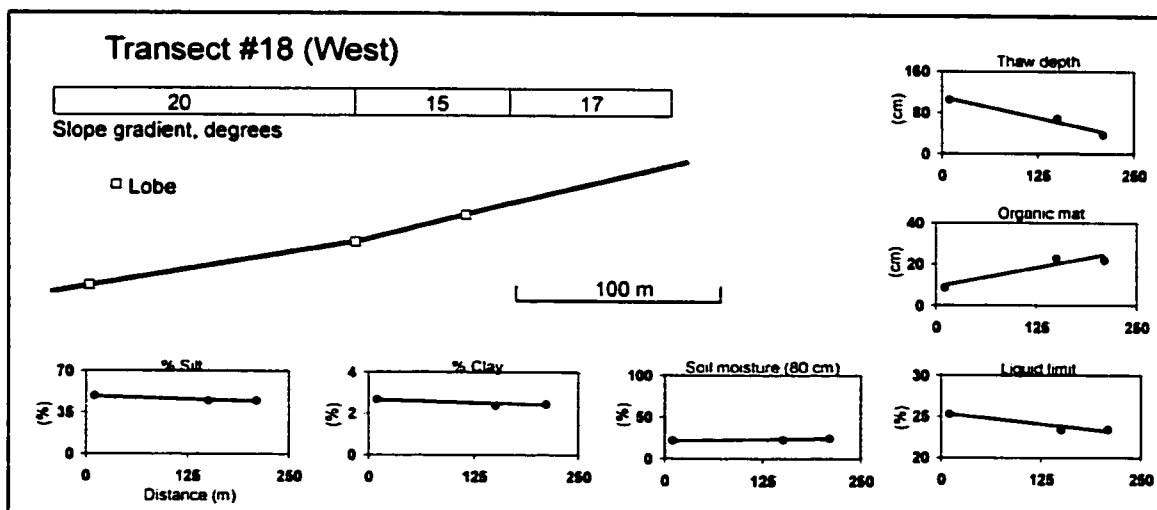
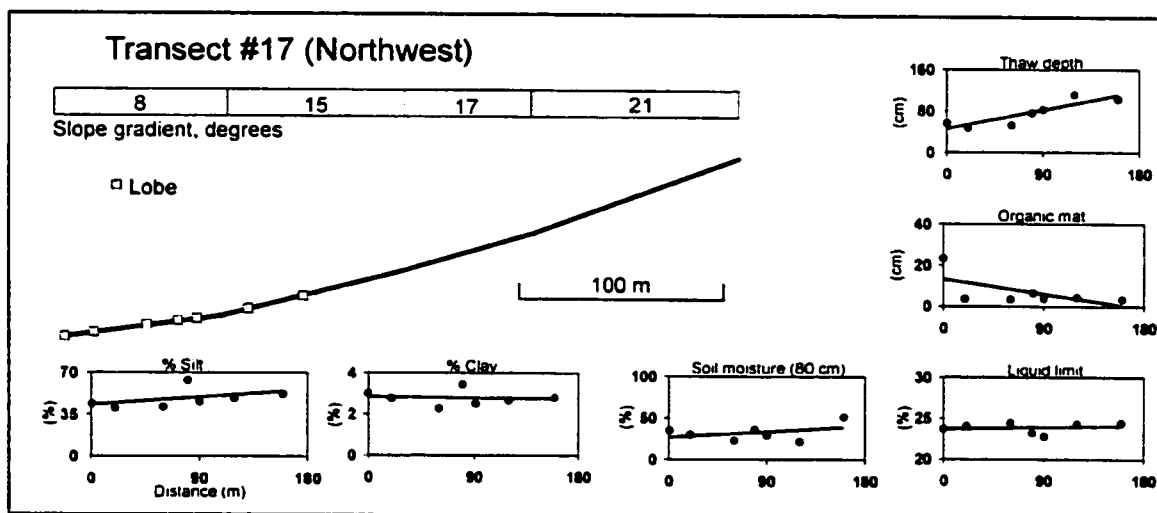
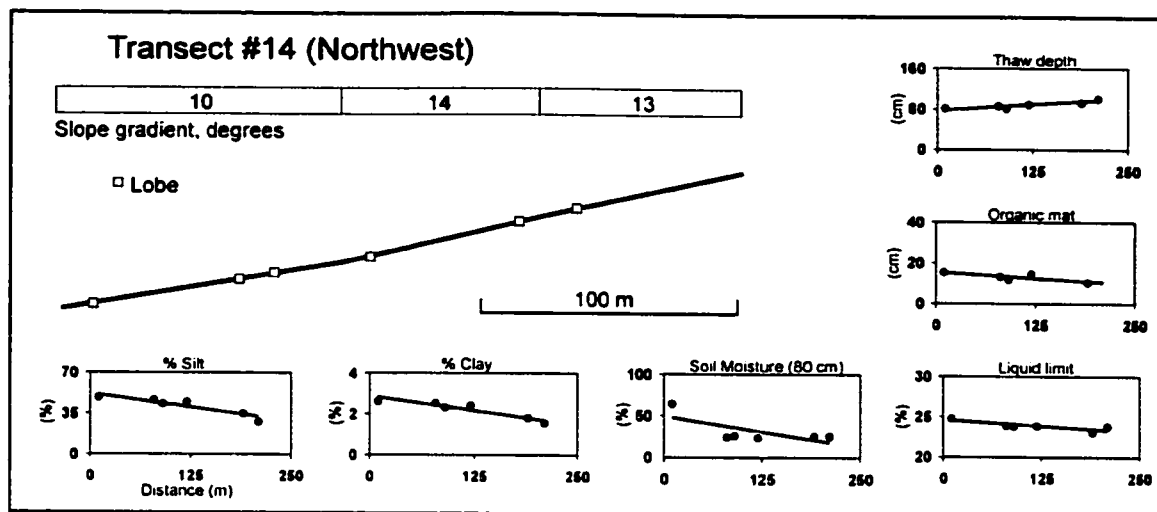
APPENDIX E

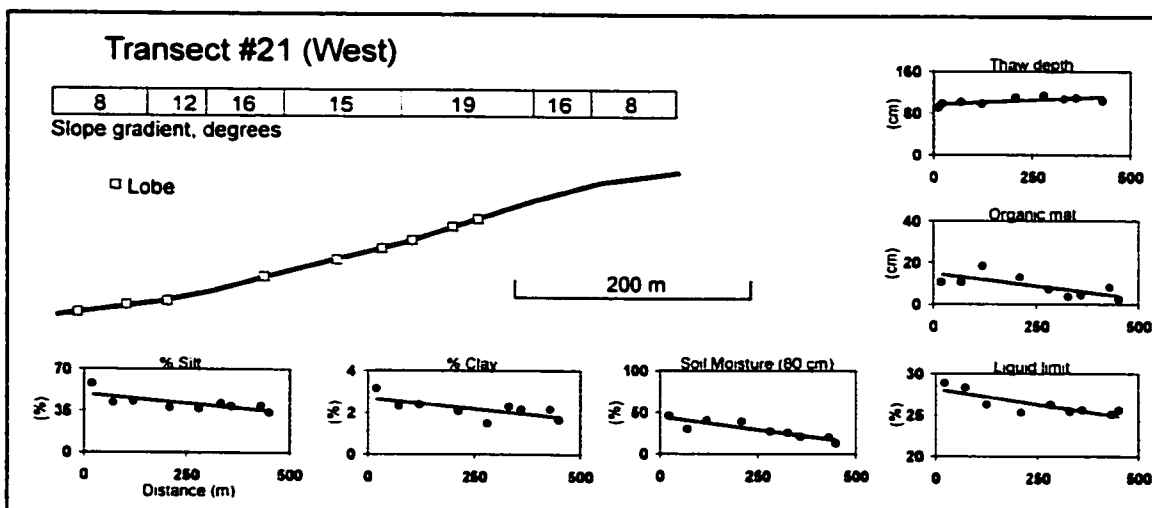
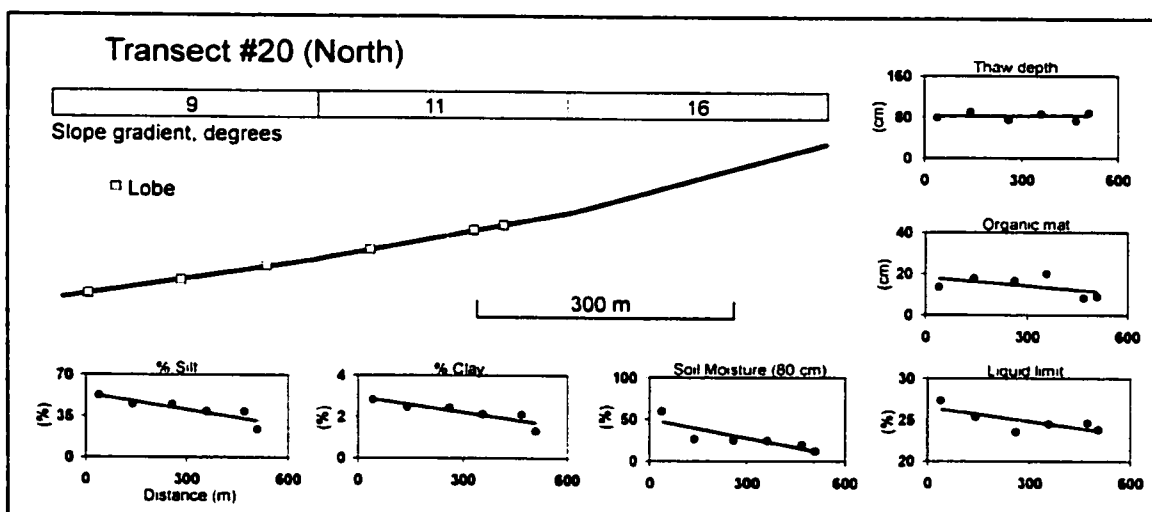
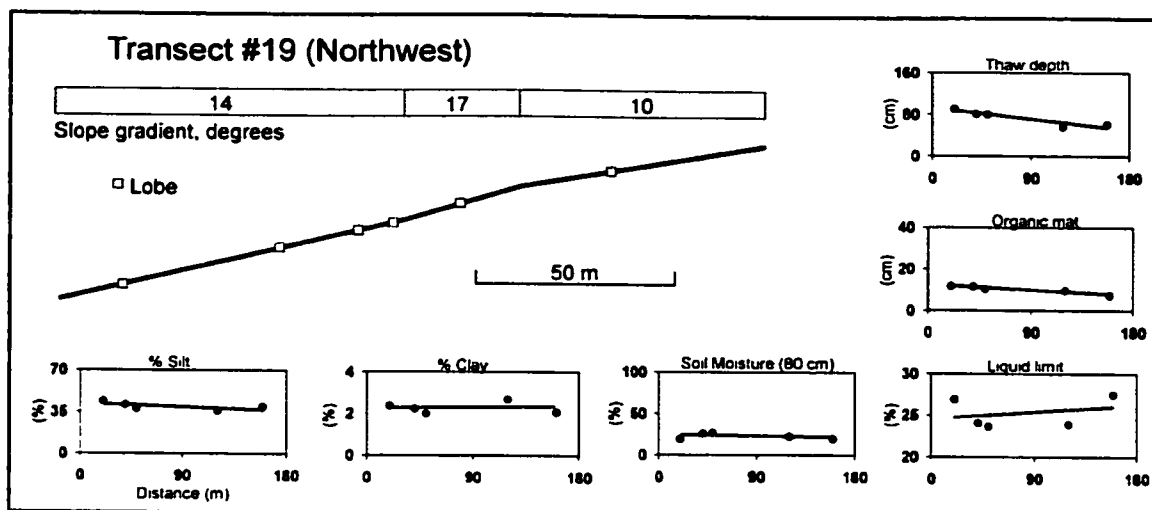
Biophysical characteristics of lobes along the transects.

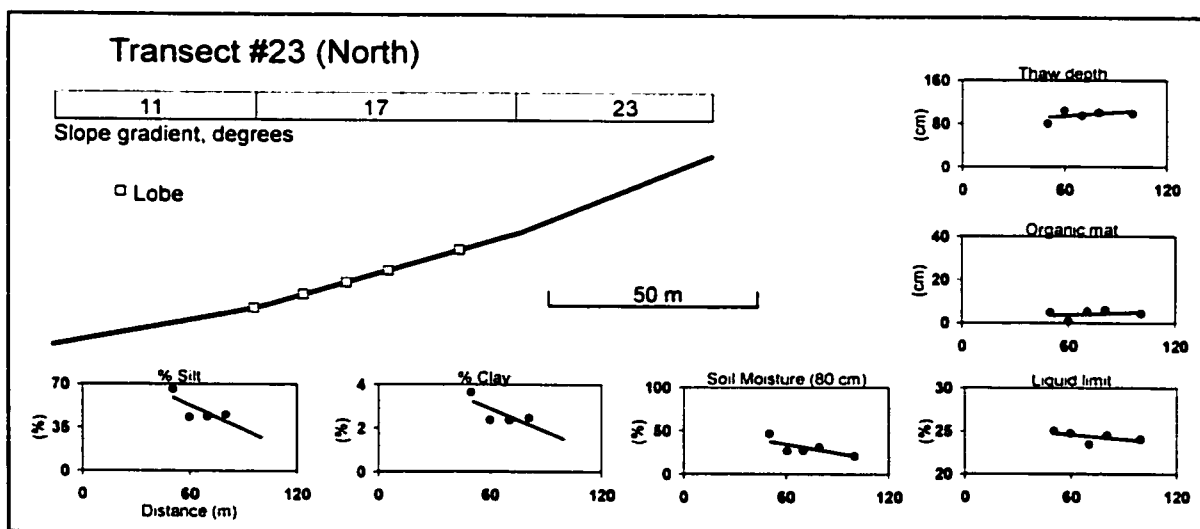
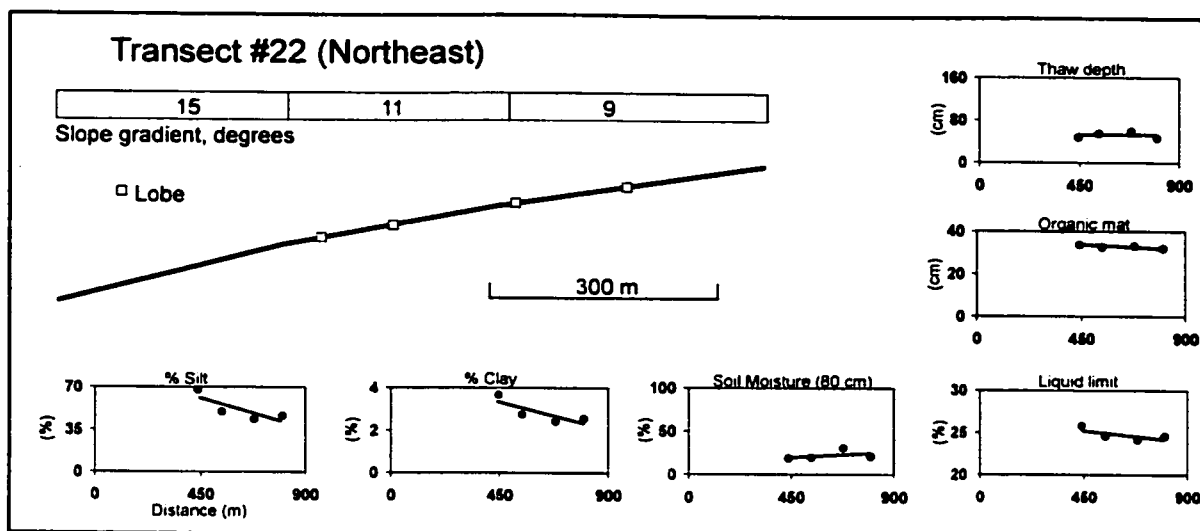
***Note: all distances are measured from the bottom of the slope.**











APPENDIX F

Residual plots of the stepwise multiple correlations using the morphometric parameters as the Dependent variable and the biophysical variables as the Independent variables.

