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THE UNIVERSITY OF ALBERTA

# HIGH LATITUDE GELIFLUCTION LOBES AS PALEOCLIMATIC INDICATORS

BY

PHILIP J. FRIEND

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SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

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## ABSTRACT

Gelifluction is a common process in periglacial climates. Its sensitivity to moisture supply has led to the speculation that the advance rate of gelifluction landforms might be tied to climatic change. Commonly, overrun organics from beneath gelifluction landforms are radiocarbon dated to provide the advance rates. The difference in advance rate between pairs of dates are attributed to periods of climatic severity if they are faster than average, and to periods of climatic amelioration if slower.

This first study of long-term rates of gelifluction in the Canadian High Arctic was conducted at Phillips Inlet ($82^{o}$N) on northwest Ellesmere Island, N.W.T. A gelifluction sheet sampled at the Pasley River ($70^{o}$N), Boothia Peninsula, N.W.T., was also analyzed for comparison. At both sites overridden organics were exposed in trenches excavated into the gelifluction lobes. These samples were $^{14}C$ dated by accelerator mass spectrometry (AMS).

Three overridden organic samples from a gelifluction lobe at Phillips Inlet were collected at 1.0, 1.7, and 4.0m from its terminus. These samples were dated by AMS at 845$\pm$50, 590$\pm$50, and 695$\pm$45 yrs B.P. respectively. It is apparent that the expected chronological sequence, increasing in age upslope, was not obtained.

At Pasley River, a conventional $^{14}C$ date of 1460$\pm$60 B.P. was obtained on buried organics 11.0m from the lobe front. Organics collected at 0.4, 3.0, 5.0, 7.0 and 9.0m from the same lobe were dated by AMS at 570$\pm$60, 270$\pm$50, 2900$\pm$50, 540$\pm$50, and 1520$\pm$80 yrs B.P. respectively. Together, these dates do not represent the consecutive

burial of organics by an advancing gelifluction lobe. These results, and associated observations on the periglacial modification of gelifluction lobes lead to two conclusions:

1. The organic layers are allocthonous rather than *in situ*. This is the result of rapid mass movement, infiltration, cryoturbation, and plug-like flow along the top of the lobes' basal organics.
2. Mass spectrometry is unable to reliably date blended samples. This brings into question the meaningfulness of conventional $^{14}C$ dates on bulk samples.

The problems encountered suggest that there are strong limitations in using $^{14}C$ dating (of either conventional or AMS techniques) to date gelifluction advance rates. This makes the suggested use of gelifluction landform advance rates as paleoclimatic indicators a speculative exercise.

It is therefore recommended that rigorous sample selection is required for future studies in this field, with particular attention being paid to the question of multiple organic layers and periglacial modification of basal organic layers.

# ACKNOWLEDGEMENTS

My principal supervisor, John England, gave encouragement and advice all through my master's degree, and applied the necessary indepth editing required during this thesis' earlier drafts. Art Dyke of the Geological Survey of Canada greatly expanded the scope of this paper when he made available his field results and samples from Pasley River. Logistical support was provided by the Polar Continental Shelf Project, Canada Department of Energy, Mines and Resources. Ian Campbell and Robert Gerard further improved this work by their suggestions and comments in the final preparation.

I would like to thank David Evans and Tim Fisher for their help with my fieldwork, and often humorous introduction to northern field life. Thanks are given to Anita Moore, who typed the text and subsequent edits. Many thanks also to Karan Smith whose aid in the graphic part of the thesis was invaluable. Finally, I'd like to express my gratitude to Tom Morris, Don Lemmen, Tom Stewart, and Catherine LaFarge-England, for their comradely advice.

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# CHAPTER I

# INTRODUCTION

## 1.1 Nomenclature

Solifluction is the slow flow of saturated regolith. Gelifluction is a kind of solifluction restricted to zones of frozen, or seasonally frozen ground. According to Washburn (1979):

> "This terminological distinction is necessary to avoid ambiguity because solifluction, by definition and observation, is not restricted to cold climates, yet its prominence there has led many writers to imply such an association. As a result the sense in which the term solifluction is being used, whether broad or restricted, is not clear whereas gelifluction is unequivocally periglacial."

The term gelifluction will be employed throughout this paper. This is because the field research was carried out in areas of pervasive frozen ground (England et al., 1983; Dyke, 1984). Another reason is the increasing use of the term gelifluction in recent literature (Gardner et al., 1977; MacKay, 1981; Hansen-Bristow and Price, 1985; Strömquist, 1983, 1985; Matthews et al., 1986).

## 1.2 Gelifluction and Radiocarbon Chronology

Gelifluction often gives rise to lobate, or tongue-like landforms on a slope. The rate at which a gelifluction lobe has advanced has often been determined by reference to the radiocarbon dating of organic layers (Benedict, 1966, 1970, 1976; Costin, 1972; Worsley and Harris, 1974; Mottershead, 1977; Ellis, 1979; Alexander and Price, 1980; Dyke, 1981; Gampier, 1983; Reanier and Ugolini, 1983; Hetu and Gray, 1985; Ballantyne, 1986; Matthews et al., 1986; Evans and Rogerson, 1987; Smith, 1987). The method, as first employed by Benedict (1966) is as follows. The lobe is trenched along its long axis and the surface soil horizons buried by its advance are sampled for $^{14}C$ dating. From the dates and distances from the riser three values can be estimated:

1. The average rate of advantage over the whole period dated.
2. A minimum date for the initiation of gelifluction. This is the earliest date determined at the highest upslope position in the lobe.
3. The change in the advance rate between pairs of dates in the whole series.

Benedict (1976) and others (Worsley and Harris, 1974; Gampier, 1981; Smith, 1985) have connected changes in advance rate with local climatic change. The theory maintains that during climatic minimums late-lying snowbanks would enlarge thus providing more runoff during spring thaw, which would feed the gelifluction landforms, saturating them more often and completely thus inducing more advance (Benedict, 1966; Smith, 1985). One might ask if the spring thaw runoff would be really larger during a climatic minimum, because it is possible that the snowbanks would be enlarging due not only to greater winter snowfall, but also to lessened ablation. This would not induce higher advance rates. Nevertheless, the common explanation given for changes in the apparent rate of gelifluction correlates greater runoff with worse climatic conditions.

The above three values are dependent on accurate radiocarbon dates. A very precise means of radiocarbon dating, accelerator mass spectrometry (AMS), can give dates on small samples. Previously, conventional beta-ray counting has been employed to date bulk gelifluction lobe organics. The author used AMS dating because of the small amount of organics present in the samples collected.

## 1.3 Objectives

The main objective of the 1985 fieldwork was to obtain samples of buried organics within selected gelifluction landforms for subsequent $^{14}C$ dating by AMS. From this data it was hoped that the rate of advance could be determined. Ancillary to this main focus was a series of observations on the characteristics of gelifluction landforms in the high arctic, and to ascertain if there are relationships between morphology, site condition (gradient, moisture supply), and sediment characteristics (size, shape). These are intrinsically valuable observations, owing to the paucity of observations from the two high latitude sites of this study. Where gelifluction landforms were not found debris flows were examined and subsequently compared to gelifluction lobes.

Discussion in this paper will therefore concentrate on:

1. The meaningfulness of $^{14}C$ dating given the range of periglacial processes capable of mixing allocthonous and autocthonous organics.
2. The difficulty of correlating climatic change with rates of gelifluction, when derived from either AMS or conventional $^{14}C$ dates.
3. How $^{14}C$ dates of gelifluction lobe organics might be made more meaningful by rigourous sample selection.

General observations on gelifluction lobes and debris flows are included because they aid discussion on periglacial processes capable of mixing allocthonous and autocthonous material (objective 1). Also, these observations have an intrinsic value to periglacial slope studies as they come from a largely unexamined environmental extreme.

1.4 Field Sites Locations

The majority of the observations were made at Phillips Inlet (82°01'N, 84°20'W) on the northwest coast of Ellesmere Island, N.W.T., from June 17 to August 7, 1985 (Figure 1.1). The greater majority of AMS-dated organic samples (5 of 8) were from a gelifluction sheet on the banks of the Pasley River, Boothia Peninsula, N.W.T. (70°25'N, 95°30'W, Figure 1.1) trenched by Dr. A.S. Dyke of the Geological Survey of Canada in the summer of 1982. These are two very different sites in terms of their style of gelifluction and degree of separation (ca. 1270km), and give the discussion on gelifluction advance rates a broader geographical base. In addition to the eight AMS dates produced during this study there were seven others dated by the beta-ray counting device at the Geological Survey of Canada. Although the conventional dates are spread over many lobes, preliminary rates were calculated by Dyke and provide a local contrast with the AMS-dated lobe organics.

The following chapter (Chapter Two) will discuss the two field sites, as per location, geology, climate and other factors commonly discussed in gelifluction studies.

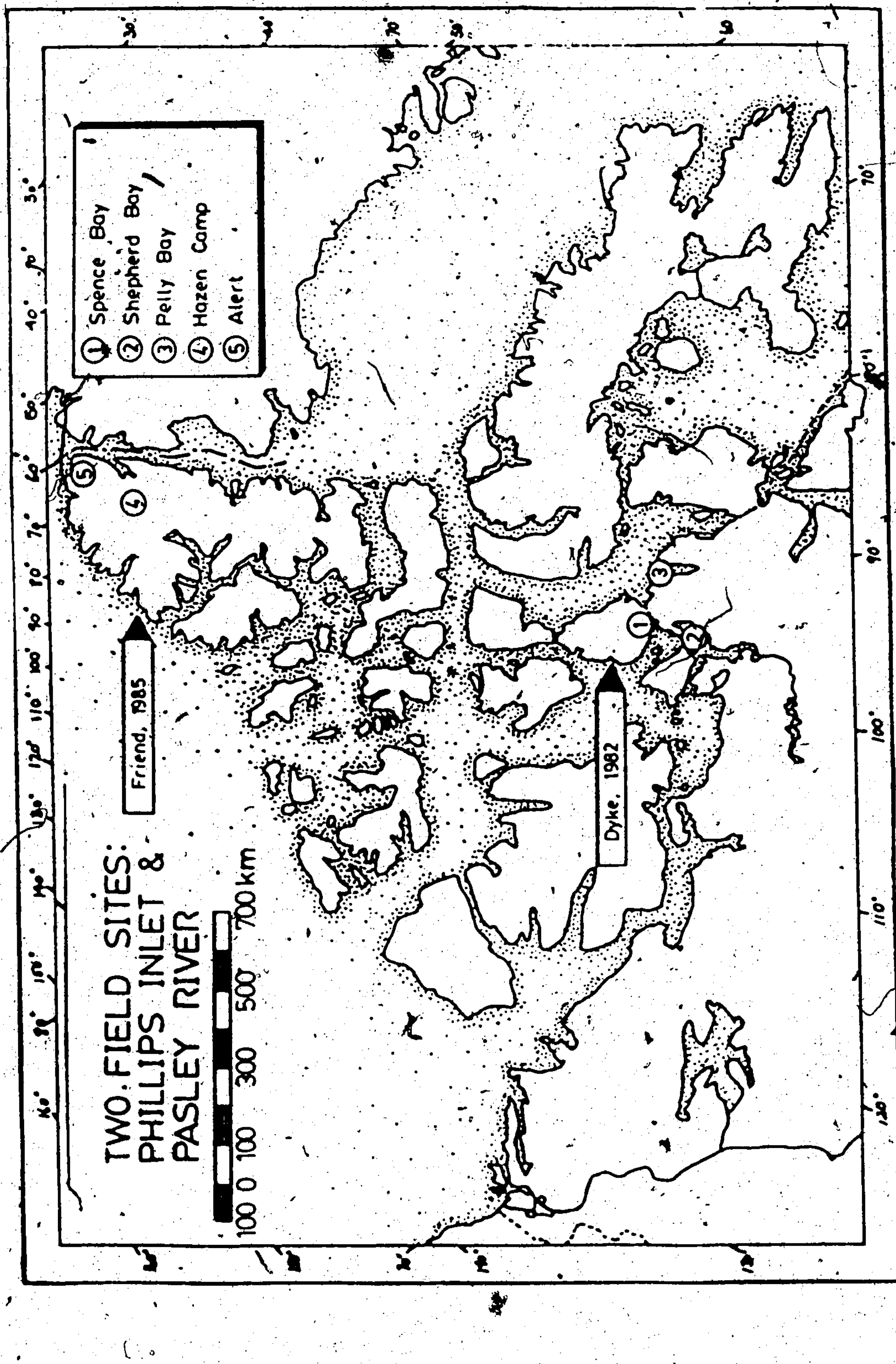


Figure 1.1 Field site location.

CHAPTER II

SITE DESCRIPTION

## 2.1 Phillips Inlet

### 2.1.1 Physiography

Ellesmere Island is the northernmost island of the Arctic archipelago, extending from 76° to 83°N and 83° to 100°W (Figure 1.1). The field area for this study, Phillips Inlet (Figure 2.1), is located on the northwest coast and was visited during the summer of 1985. Phillips Inlet is a large northwest to southeast orientated fiord with three parallel tribuatry fiords orientated north-northwest to south-southeast. The main fiord joins the Arctic Ocean.

The elevation of Phillips Inlet reaches ca. 1800m a.s.l. and at least seven glaciers reach the fiord from extensive upland icefields. Meltwater from glaciers and the seasonal snow cover contributes to numerous braided rivers and smaller, deeply incised, tributary streams. Many of the sites visited were covered by raised marine deltas, fine-grained marine sediments, and diamictons originating from past glacial and sea level fluctuations. Additionally, most of the slopes around the inlet above the limit of postglacial submergence are draped with colluvium whereas bedrock outcrops at higher elevations.

### 2.1.2 Bedrock geology

Northern Ellesmere Island exhibits a wide variety of lithologies (limestone, sandstone, shale, monzonite, basalt, schist) ranging from late-Precambrian to mid-Tertiary age. These rocks have

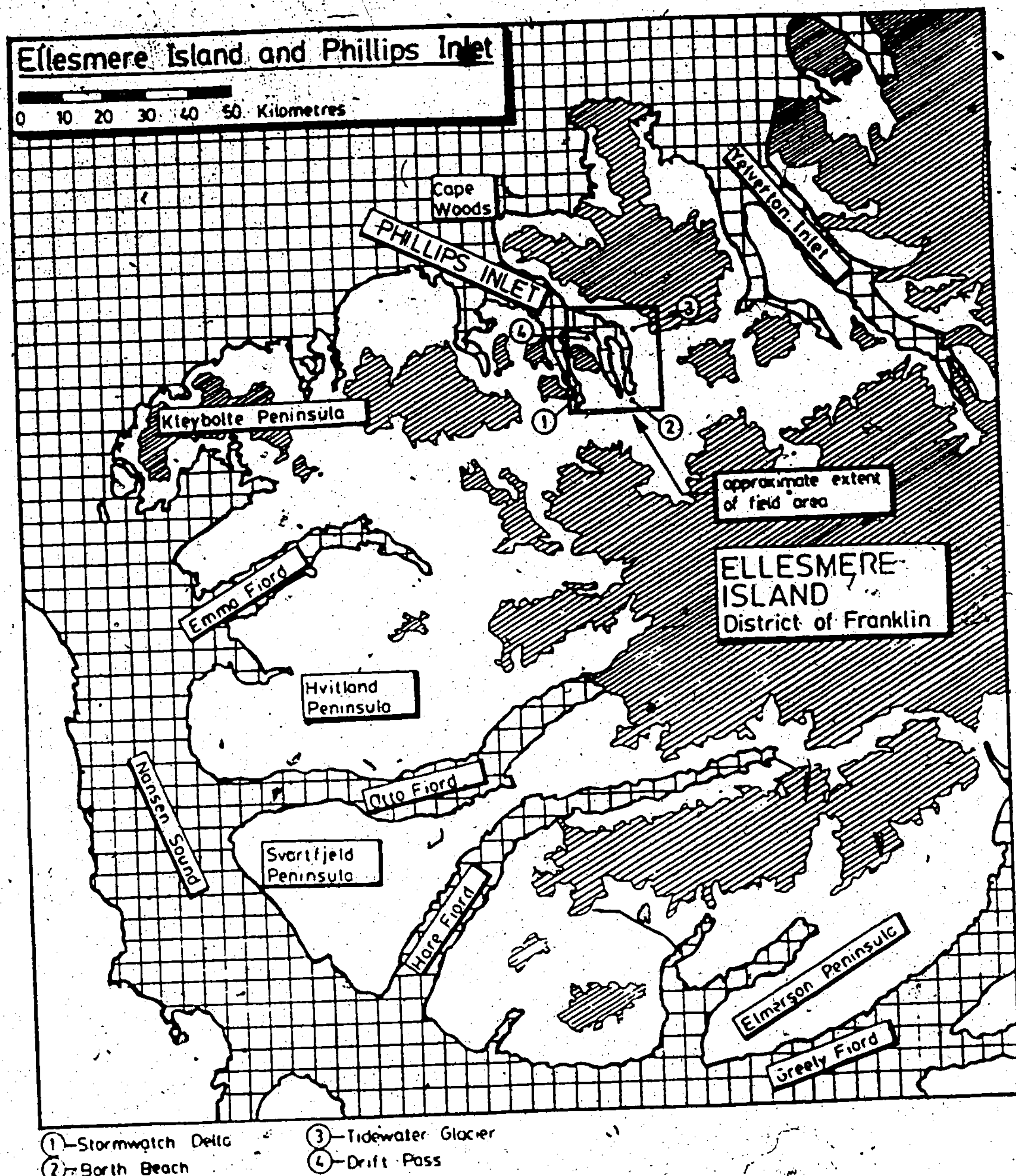


Figure 2.1 Location of four field camps within Phillips Inlet.

been folded, faulted and metamorphosed during several orogenies (Trettin, 1972). Phillips Inlet includes two principal bedrock terrains:

1) Sedimentary and metamorphosed rocks of the Franklin eugeosyncline in the southeast half; and,
2) Undifferentiated crystalline rocks along the northwest side of the inlet (Trettin, 1972).

The sedimentary rocks are largely represented by the Imina and Lands Lokk formations, and the crystalline rocks by various granitic intrusions. Because geliflucțion is a small-scale phenomena, it is essential to determine the lithologies which contribute to the local slope conditions. This will be discussed further in the detailed site descriptions.

2.1.3 Climate

England et al. (1981) state that:

> "The outstanding characteristics of the climate of northern Ellesmere Island is its great variability; spatially, seasonally and interannually. Particularly in terms of temperature, meaningful generalizations regarding this area simply cannot be made."

Nevertheless, some description of the coastal areas of Ellesmere Island can be made. Coastal areas experience moderated winter and summer temperatures because of the periodic break-up of the sea ice. The moderating effect of the ocean is most pronounced during the summer when:

> "...onshore winds tend to cross ocean water which is generally below 0$^{o}$C and hence they quickly offset any warming by radiation on the adjacent land. Hence, on average winter and summer temperature extremes are lower along the coast; and cloud cover, relative humidity, and fog increase. However, precipitation values are

> nevertheless low in terms of absolute amounts and these areas still constitute polar desert landscapes."

An important difference between the coastal sites referred to by England et al. (1981) on northeast Ellesmere Island, and those in Phillips Inlet, is that landfast sea ice prevailed on the north coast during the summer of 1985. Although the recent sea ice history of the north coast is poorly documented it is likely that landfast conditions are typical throughout the year, causing greater continentality. More maritime conditions occur only on the northernmost coast where equilibrium line altitudes (ELA's) descend to 300m a.s.l. compared to 1100m.a.s.l. in the interior fiords of northern Ellesmere Island (Miller et al., 1975).

Northern Ellesmere Island can be classified as a polar desert with an annual water balance close to zero (Barry and Jackson, 1969). Most coastal locations receive ca. 15 cm of precipitation whereas in the more arid interior, precipitation may decrease to ca. 2.5 cm $yr^{-1}$ (Jackson, 1959; England et al., 1981). Nevertheless, many of the sites around Phillips Inlet had wet active layers due, most certainly, to the presence of the permafrost table within 1m of the surface. Therefore, despite its aridity, Phillips Inlet is capable of supporting gelifluction.

## 2.1.4 Vegetation

The vegetation cover of coastal areas in the high arctic is highly variable. According to England et al. (1981):

> "Total plant cover was generally less than 10% with lichens often dominating. Areas of late snowmelt occasionally had 100% plant cover, but most sites had limited moisture available, and cover values were much lower."

The plant communities observed in the lowlands of Ellesmere Island are often described as being polar semidesert and polar desert (England et al., 1981). These communities are dominated by bryophytes.

Field observations by the author showed how vegetation cover could vary over even the smallest area. For example, the vegetation on a slope at Drift Pass (Plate 2.1) is very sparse on the upper part of the slope, whereas it thickens markedly as the gelifluction sheet approaches the stream (Plate 2.2).

A number of small streams were encountered, especially at the third and fourth camps. These valleys had greater vegetation cover than their unsheltered, neighbouring slopes. The valleys could have acted as snow traps and thus contributed a supply of meltwater. Frequently, these valleys contained gelifluction landforms such as sheets and lobes.

2.1.5 Individual site descriptions - Phillips Inlet

2.1.5.1 Introduction

Four sites were visted around Phillips Inlet, and each was investigated for their gelifluction landforms (Figure 2.1). The time spent at each site is listed in Table 2.1.

Table 2.1 Time spent at each site.

| Site name | Period of stay | Length of stay |
|---|---|---|
| Stormwatch Mountain | June 17-July 3, 1985 | 17 days |
| Borth Beach | July 3-July 12, 1985 | 9 days |
| Tidewater Glacier | July 12-July 25, 1985 | 13 days |
| Drift Pass | July 25-August 7, 1985 | 14 days |

Plate 2.1 View of a gelifluction lobe at the stream level of a valley at Drift Pass. Upslope of the well-vegetated lobe the vegetation is sparser. There is a very marked difference between the lobe and the adjacent surface to the immediate left. This illustrates the disparity in vegetation cover that can occur in high arctic sites within a short distance in an area of great relief.

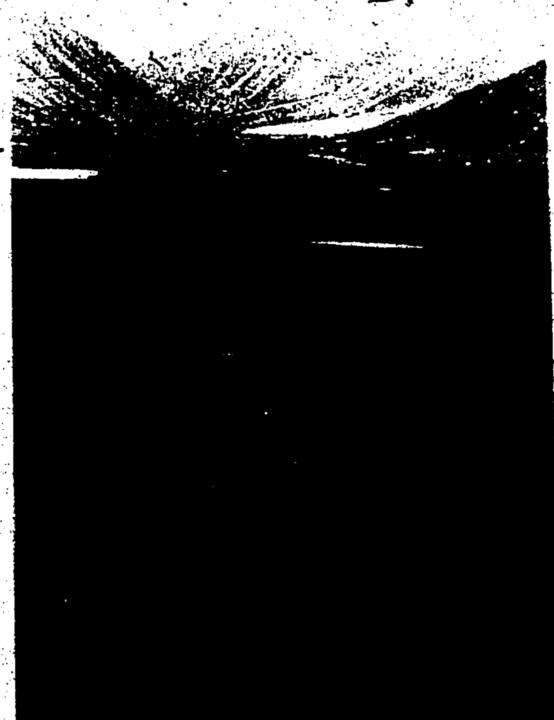

Plate 2.2 This is a down-valley view of one of two valleys opening out onto Drift Pass (in background). On the sides of the valley gelifluction streams can be observed terminating in lobes and sheets at the bottom of the valley.

These unofficial names for the sites (Table 2.1) will be referred to throughout the text. The following is a description of the location, physiography, bedrock geology, and surficial deposits of the four sites. The same will be done for the second collection site along the Pasley River, Boothia Peninsula ca. 1270 km to the south.

2.1.5.2 Stormwatch Delta

Stormwatch Delta (Figure 2.2) is located at the confluence of two braided rivers. This confluence occurs at the head of one of the four, unnamed tributary fiords in the inlet (Figure 2.1). A series of raised marine deltas occur on the higher slopes. Local relief in this area is 800m, consequently slopes are steep, except for the surface of abandoned marine deltas and shorelines.

Stormwatch Delta is dominated by Ordovician-Silurian greenschist facies (Trettin, 1972). This greenschist weathers readily into long platy fragments (Plate 2.3). Field observations at Stormwatch Delta showed that the upper slopes are well covered by this weathered debris (residium) whereas the lower slopes are draped with marine and glaciomarine deltaic sediments (Plate 2.4). Very few geliflection lobes were observed.

2.1.5.3 Borth Beach

Borth Beach (Figure 2.3) is located in another unnamed arm of the fiord (Figure 2.1). The site is dominated by steep slopes except for the area of Borth Isthmus, a lowland of raised marine sediments separating the two eastern fiords. The geology of this area is similar to that of Stormwatch Delta.

Stormwatch Delta Site

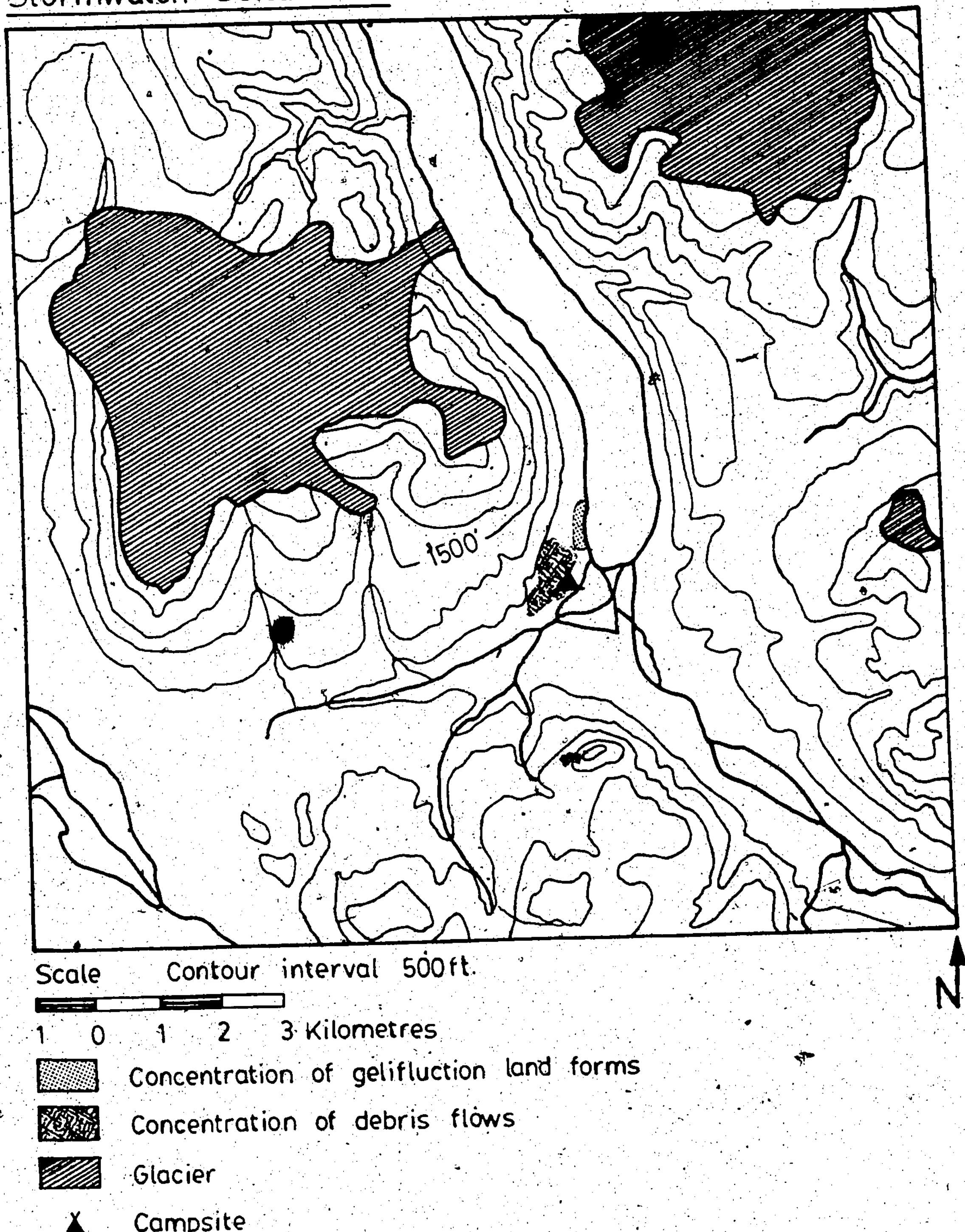


Figure 2.2 The Stormwatch Delta Map shows the camp location and the areas where concentrations of lobes and debris flows were observed. Trenching revealed no organics. One lobe was selected for morphological study.

Plate 2.3 Vertically-dipping schistose planes frequently outcropped at Stormwatch Delta. The schistosity of this rock causes the weathered products to be flat and angular. The fragments are moving downslope in the foreground, undergoing frost creep.

Plate 2.4 A raised delta of marine and fluvial deposits on the lower slopes of Stormwatch Delta, Phillips Inlet. This is the typical composition of most of the lower slopes of Phillips Inlet, unless the slopes are dominated by talus.

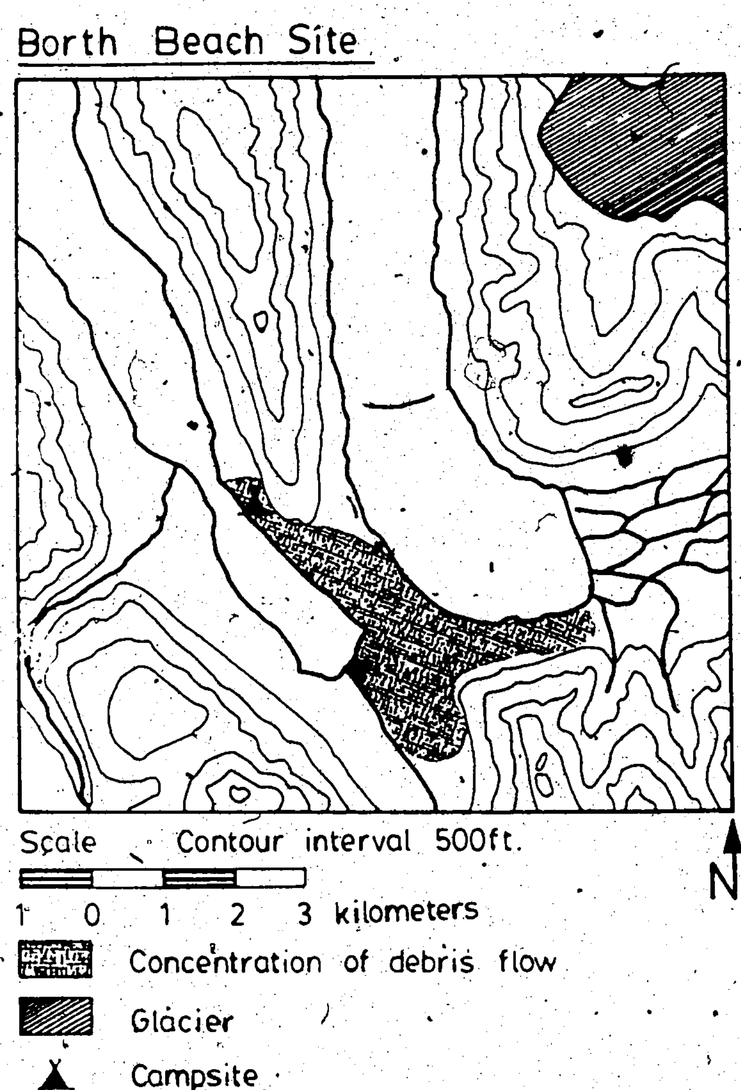


Figure 2.3 The Borth Beach map shows the broad area in which debris flows were found. No gelifluction landforms were located and studies concentrated on the morphology of debris flows.

The surficial deposits of Borth Beach are predominately fine grained marine sediments extending up to an elevation of ca. 50m a.s.l. (Evans, personal communication, 1986). The higher and steeper slopes are covered with talus, which descend to sea level at many points. Slope landforms include: talus sheets, retrogressive thaw flow slides, and debris flows (Plates 2.5, 2.6, and 2.7). Gelifluction lobes were not observed.

#### 2.1.5.4 Tidewater Glacier

Tidewater Glacier is situated at the southeastern end of Phillips Inlet (Figure 2.4). It is bounded by Tidewater Glacier to the north and a meltwater stream to the south. Although relief in this area is considerable (762m), there are areas of gentle slope near the shoreline. These gentle slopes are part of the deltaic deposits present at the mouth of Dogleg River. This lower area is crossed by a number of small streams whose banks occasionally provide gentle slopes across which gelifluction sheets and lobes are advancing.

Tidewater Glacier is the most geologically complex site of those visited. The part of the site most frequently visited by the author was composed of Silurian volcanics and metamorphosed rocks (Trettin, 1972).

The surficial deposits are largely of a single type. Deltaic sediments predominate at all the sites of trenched lobes. Closer to the margins of this site talus slopes are in evidence (Plate 2.8).

#### 2.1.5.5 Drift Pass

Drift Pass occurs along the northwestern coast of Phillips

Plate 2.5 This is an oblique aerial view of the profile of a talus slope on the north side of the Borth Beach fiord. In the background is the calving glacier which marks the limits of the Tidewater Glacier site.

Plate 2.6 This is the upslope scarp of a retrogressive thaw flow slide at Borth Beach. It is at the head of a valley, produced by thermokarst activity. These thermokarst features dominate the lower part of the Borth Beach site.

Plate 2.7 This debris flow appeared with nine others within a 100m stretch of shoreline of Borth Beach. Debris flows were often associated with thermokarst activity and the marine sediments found draping the lower slopes.

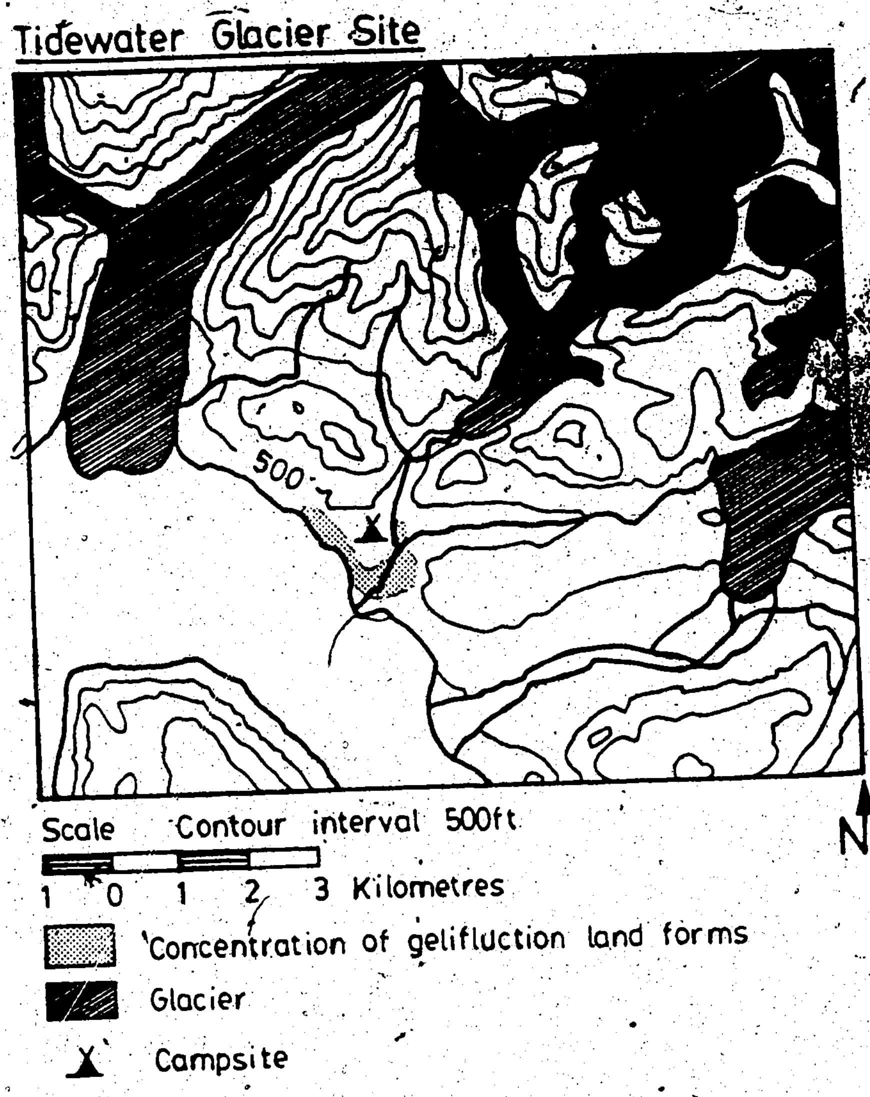


Figure 2.4 The Tidewater Glacier was the best site for gelifluction lobes the author explored. This opinion is based on the number of lobes found, the number of lobes with organics and the variety of slope micro-environments encountered.

Plate 2.8 A talus slope is visible behind a raised deltaic deposit. Both of these are typical of Tidewater Glacier surficial deposits. The fluvial-glacial sediments are found in the centre of the site, and the talus slope dominates the adjacent fiord slopes.

Inlet. It is a wide, flat-bottomed valley open to the ocean on its eastern and northwestern sides (Figure 2.5). The other sides of the valley are mountains reaching 762m a.s.l. Streams in the surrounding mountains often have gelifluction sheets flowing into them. These mountains are predominately composed of Devonian quartz monzonite, whereas the mountains to the south, and the valley itself, are composed of Ordovician or Silurian greenschists. Like most sites in Phillips Inlet, marine sediments are widespread below ca. 100m. On higher slopes a diamicton is quite widespread and owing to the proximity of glaciers and icecaps, a glacial origin is likely. Above the diamicton, talus occurs. The gelifluction lobes were in the lower parts of small sheltered valleys, and were situated mostly on talus and other colluvial sediments.

2.1.5.6 Conclusion

Phillips Inlet has a variety of slopes of different gradients and lithologies. Therefore, there is a wide variety of environments in which to investigate gelifluction landforms.

Three lobes were trenched at Stormwatch Delta, none at Borth Beach, eight at Tidewater Glacier, and four at Drift Pass, a total of fifteen. The observation of gelifluction landforms was severely limited by the presence of snow. In June, Stormwatch Delta was so well covered by snow that some large debris flows were completely hidden from view (Plate 2.9), so it is also likely that some less pronounced gelifluction lobes remained obscured.

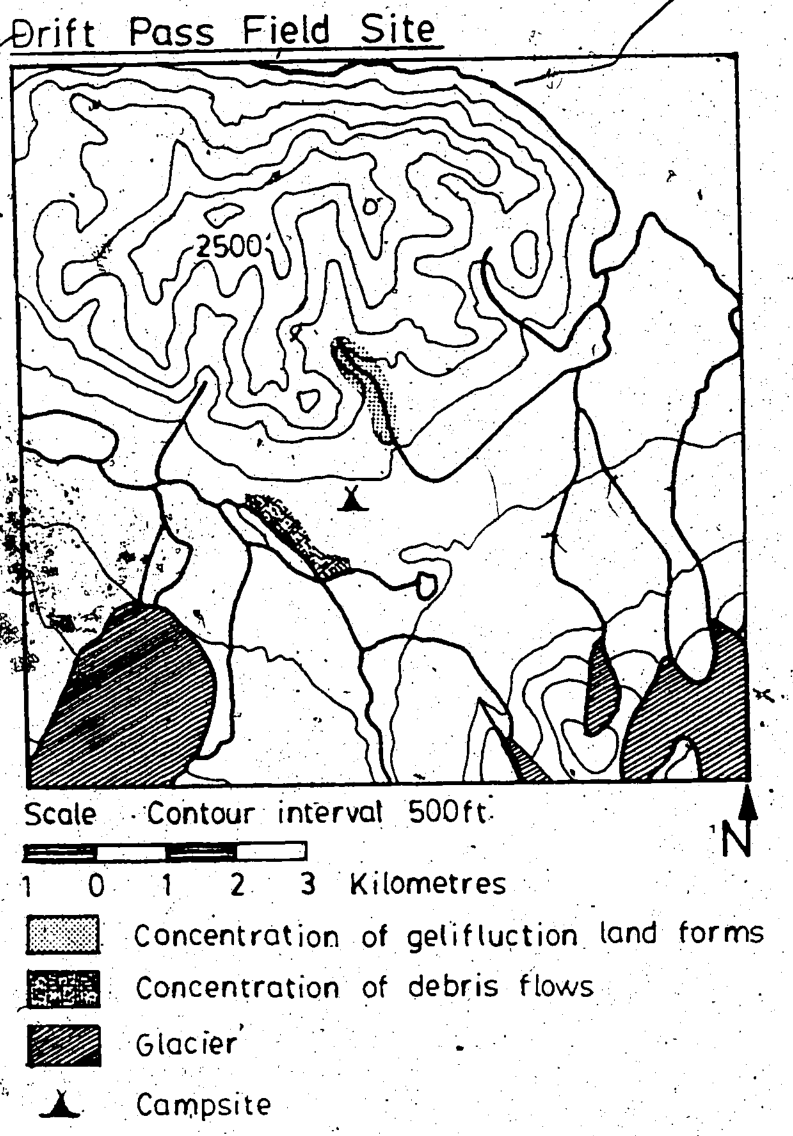


Figure 2.5 Drift Pass gelifluction lobes were found mostly in a small tributary valley, and the debris flows on a river valley slope. Organics were sparse at this site. Measurements of lobe morphology were difficult, due to the merging of individual lobes with the two large gelifluction sheets on either side of the sheltered valley.

Plate 2.9 Four debris flow lobes are seen here emerging from a late June snowbank. In many other areas of Phillips Inlet the June snowcover obscured mass movement landforms.

## 2.2 Boothia Peninsula

### 2.2.1 Location and physiography

Boothia Peninsula forms the northeastern extremity of the District of Keewatin, mainland Canada, extending from 72°n to 68°N, and from 101°W to 90°W. Boothia Peninsula is separated from Somerset Island to the north by Bellot Strait. To the northwest is Franklin and James Ross Straits and to the east is the Boothia Strait (Figure 2.6).

Boothia Peninsula consists of two central plateaus: the Boothia and Wagner plateaus, which are flanked by five lowlands: the Simpson, Rasmunssen, Wrottersley and Abernathy lowlands, and the Pasley Plain. The large gelifluction sheet investigated by A.S. Dyke (Geological Survey of Canada) occurs on the Pasley Plain, therefore, this site will be described in detail. Dyke (1984) describes the Pasley Plain as:

> "an extensively drift-mantled surface of low relief whose elevation is between those of lowlands and plateaus mostly between 100 meters and 177 meters above sea level."

The low relief of the Pasley Plain generally results in shorter and lower slopes compared to those found at Phillips Inlet.

### 2.2.2 Bedrock geology

Pasley Plain is considered by Dyke (1984) to be part of a single faulted erosion surface, dropped down from a position level to the connected Boothia and Wagner plateaus during the late Tertiary block faulting of the arctic islands. Like Ellesmere Island, Boothia Peninsula is characterized by a broad range of lithologies that range in age from Precambrian to Tertiary. The plateaus are underlain by

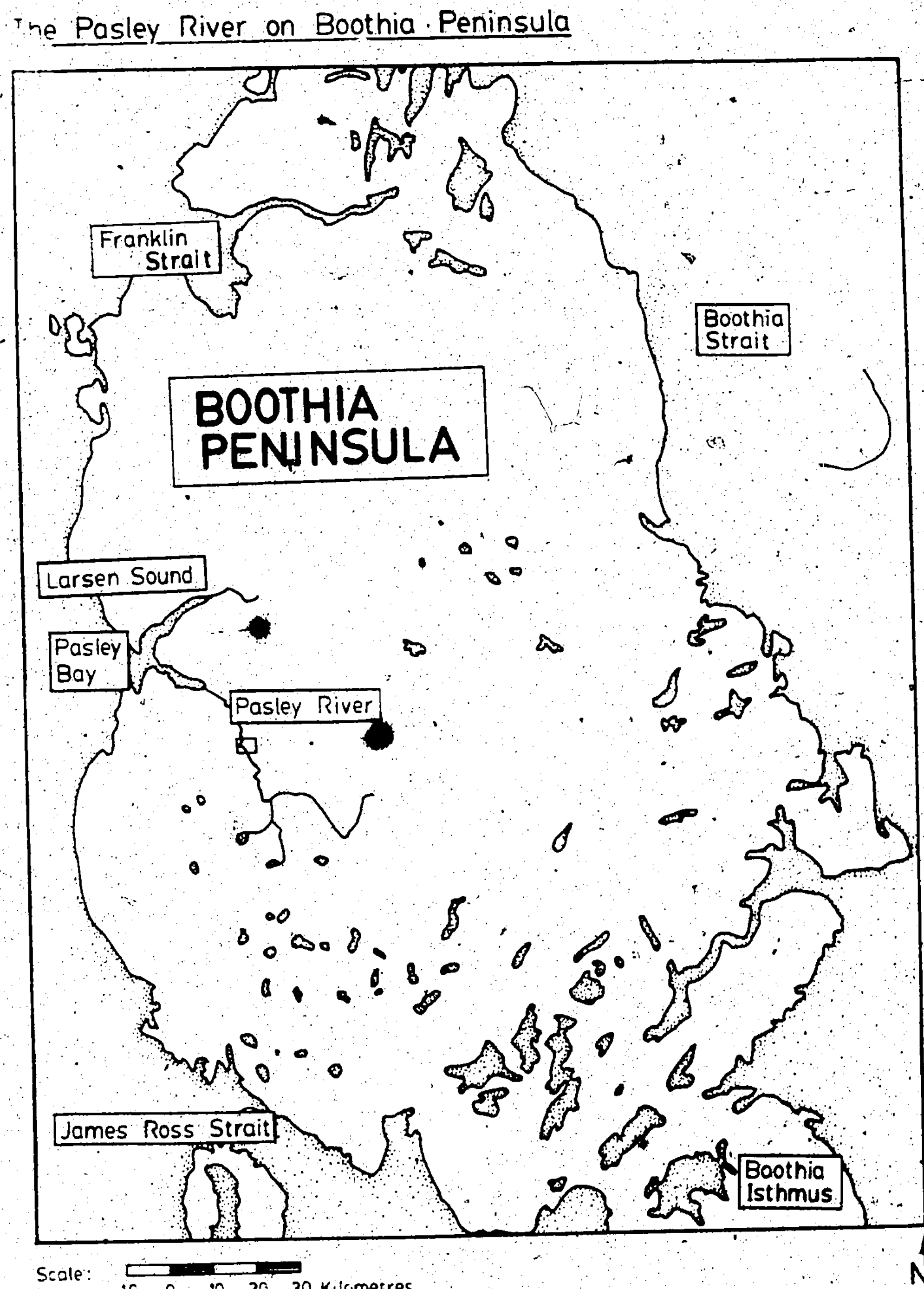


Figure 2.6 The small squared-off part of the Pasley River is the area covered by the air photograph (Plate 2.10).

the oldest rocks, namely folded and faulted gneiss and granite of the Boothia Horst (Precambrian Shield). On either side of the horst, and dipping away from its north-south axis, are the Paleozoic sedimentary rocks of the lowlands. These sedimentary rocks generally grade from clastic lithologies in the more proximal locations to carbonates in the more distal ones.

### 2.2.3 Climate

The statement below summarizes the available temperature and precipitation records from Pelly Bay and Shepherd Bay on southern Boothia Peninsula and from Spence Bay on Simpson Peninsula.

Dyke (p.2) states that:

> "The three stations have closely similar weather patterns with long, cold, dry winters and brief cool, damp summers. The climate at Pelly Bay (southern Boothia) seems slightly more marine than that at Spence Bay (Simpson Peninsula) or Shepherd Bay (southern Boothia) in that it receives appreciably more precipitation in both winter and summer and has slightly cooler and slightly shorter summers."

Pasley River is further inland, so one would expect a climate less marine than those of these coastal sites. There is little difference between Ellesmere Island and Boothia Peninsula in terms of the seasonal temperature regime, however, it should be noted that all of the Boothia Peninsula stations can receive more than ten times as much precipitation as the arid, continental interior of the Hazen Plateau (Ellesmere Island) (England, 1981; Dyke, 1984).

### 2.2.4 Vegetation

There are two ecological zones on Boothia Peninsula as determined by Tarnocai and Boydell (1975). The Pasley Plain occurs in their mid-Arctic ecosystem which is described as continuously vegetated. This contrasts sharply with Ellesmere Island which is discontinuously vegetated and where even lowlands often have less than 10% surface cover (England et al., 1981). According to the authors' observations, long stretches of coastline were unvegetated in Phillips Inlet, which heightens its contrast to the Pasley Plain.

## 2.2.5 Individual site description - Boothia Peninsula

### 2.2.5.1 Introduction

In the summer of 1982 A.S. Dyke of the Geological Survey of Canada examined the Quaternary geomorphology of the Pasley Plain. In the process of these studies a large gelifluction sheet was discovered and six trenches were excavated that extended ca. 10m from its terminus and from which 46 organic samples were taken for $^{14}C$ dating. In 1985 these samples were sent to the author for analysis, as well as the site descriptions. This transfer of data was necessary because of Dyke's commitments to other projects and because the Pasley Plain field studies complimented the investigation of similar gelifluction landforms from Phillips Inlet.

### 2.2.5.2 Pasley River

Gelifluction lobes were excavated along the northern banks of the Pasley River at 62m a.s.l. (70°25'N, 95°37'W, Figure 2.6). The gelifluction sheet occurs at a bend of the Pasley River which incises the extensively drift-mantled surface of the Pasley Plain. The Pasley River empties into Pasley Bay on the western shore of Boothia Peninsula.

The gelifluction sheet is approximately 100 metres long by 1000 metres wide. It originates from the base of a small bluff which borders the river valley, and extends over a beach of fluvial sands and gravels (Plate 2.10). Unlike the Phillips Inlet sites, where lobes are often discrete features, the gelifluction sheet at Pasley River takes up a large part of the entire site.

#### 2.2.5.3 Conclusion

The Pasley River site is very different from the Phillips Inlet sites. The Pasley River site is less steep, continuously vegetating and drift-mantled. This is a consequence of its greater precipitation and lithology. Finally, given the numerous differences between Pasley River and Phillips Inlet it would be wrong to account for any differences in their gelifluction lobe shapes and velocities, by simply invoking the great latitudinal differences between sites ($12^{0}$). The following will detail processes and morphology of gelifluction landforms reported from other sites.

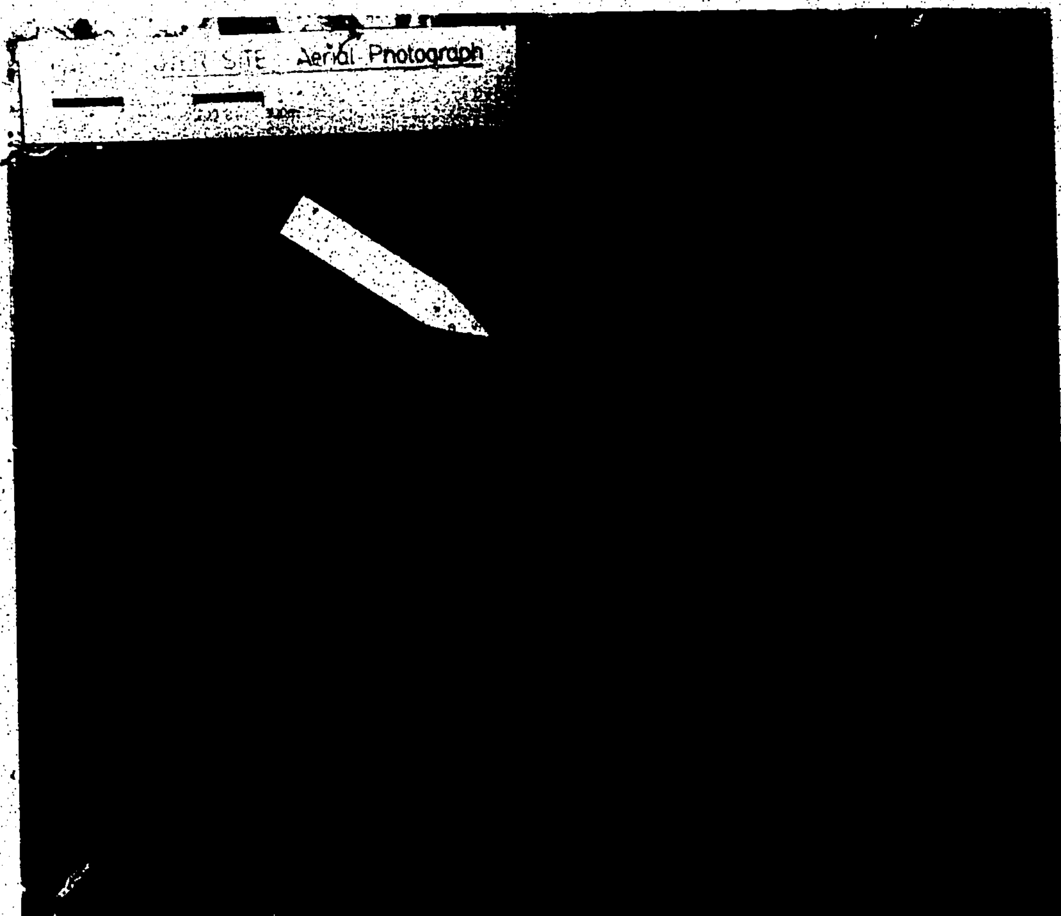


Plate 2.10 The large gelifluction sheet at Pasley River is the dark mat of material inside the river bend. It is constrained to the east by the white late-lying snowbanks which are its moisture source. The approximate location of the trenches is indicated by the white arrow. North is at the top of the photograph.

# CHAPTER III

# GELIFLUCTION LANDFORMS: FORM AND PROCESS

## 3.1 Introduction

This chapter reviews gelifluction form and process. However, it should be recognized that the following is not intended to be all-encompassing or detailed, rather it will provide only the basic background on gelifluction landforms found in the periglacial literature. For a comprehensive review of gelifluction the reader should see Washburn (1979), or Harris (1981).

## 3.2 Components of Gelifluction

### 3.2.1 Introduction

Gelifluction describes the slow movement of debris downslope in periglacial environments. Gelifluction landforms are the results of three discernable slope processes: gelifluction, frost creep, and retrograde motion. Each will be described in the following sections.

### 3.2.2 Gelifluction

Gelifluction is the slow deformation of the active layer. The deformation is entirely seasonal. In the high arctic the period of greatest movement usually coincides with the spring thaw or nival melt (Cook, 1959; Carson and Kirkby, 1972; French, 1976; Smith, 1985). Most authors who have measured rates of flow have concluded that it is the most rapid in the uppermost 50 cm of the active layer (Carson and Kirkby, 1972; French, 1976; Harris, 1981).

### 3.2.3 Frost creep

Frost creep is best understood by the following sequence (Figure 3.1). Soil moisture freezes during the fall and winter causing frost heave normal to the surface of the slope. During the subsequent spring and summer the soil thaws and settles vertically parallel to the vector of gravity. As a consequence, soil particles will have made a net advance downslope (French, 1976; Harris, 1981). This rachet-like movement (Washburn, 1979) will be repeated annually causing incremental displacement downslope. The effectiveness of frost creep will naturally depend on the amount of vertical displacement and the slope angle. The greater these are, the greater the downslope displacement.

### 3.2.4 Retrograde motion

Unlike the previous two mechanisms, retrograde motion does not directly contribute to movement. Gelifluctng sediment is often held back from settling vertically during frost creep. One can envisage this movement as a shrinkage of the soil mass, that prevents the soil from advancing as far as it should, if it could settle vertically. Various causes of retrograde motion or shrinkage have been suggested. These include: capillary pressures, interparticle adhesion, desiccation, and the closing of cracks or fissures (Young, 1960; Smith, 1985). Washburn (1967) reports that retrograde motion can prevent 10% to 50% of total lobe advance. Retrograde motion has been seen as an actual motion of gelifluced regolith upslope (French, 1976) whereas in fact it may merely represent the difference between

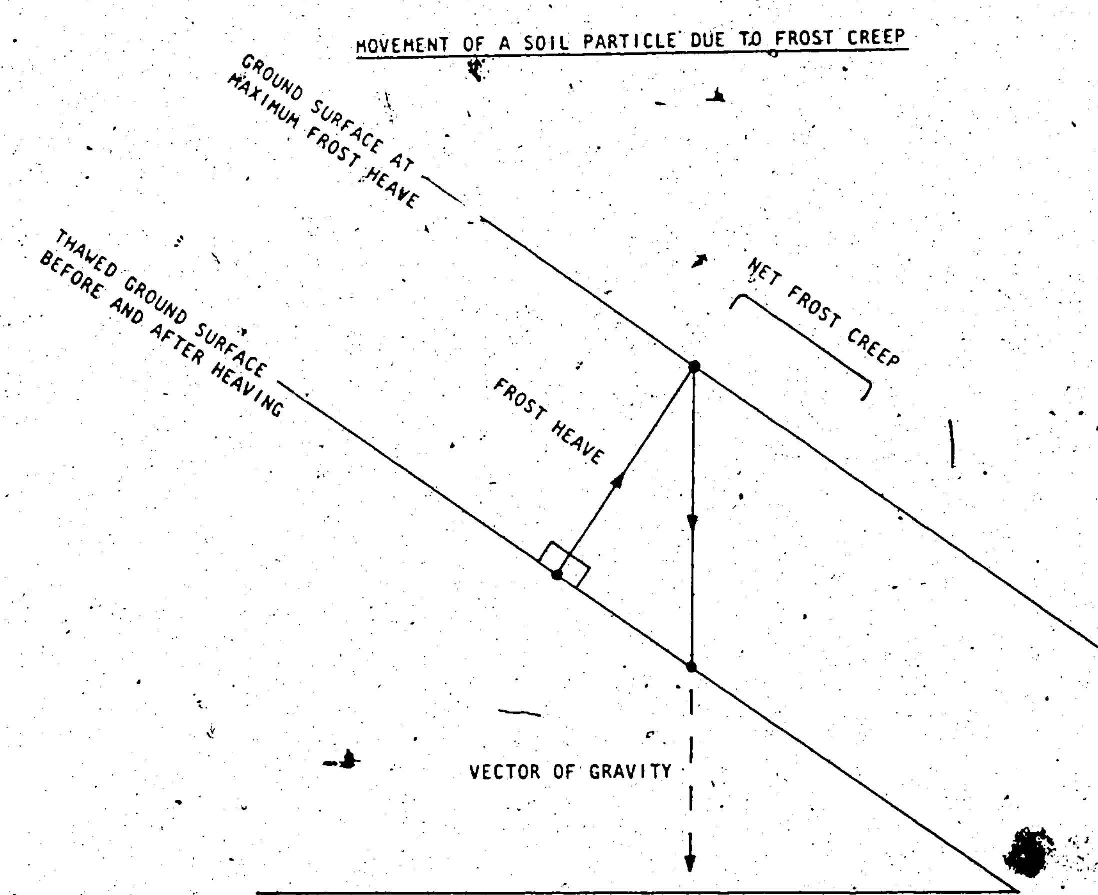


Figure 3.1 This diagram shows the path of a soil particle undergoing frost creep. The process starts with a particle being raised by frost heave perpendicular to the slope surface. When the ground thaws in spring the particle follows a line parallel to the vector of gravity and effects a net downslope movement. Repeated every year the particle will appear to creep downslope.

predicted advance by frost creep and the actual observed advance (Smith, 1985).

### 3.2.5 Summary

The effects of the first two mechanisms are reduced with depth. Flow decreases with depth because sediments at the surface have a longer period of thaw and the earliest exposure to snowmelt compared to those at greater depth. This provides the surface sediments with a longer period in which they are free to move downslope. Thus the surface sediments move further than material which is thawed later and they experience sustained saturation during nival melt when the active layer is shallow. Furthermore, cumulative frost heave is greatest at the surface. This raises sediments away from the slope, so that upon thawing they will settle parallel to gravity, effectively moving downslope. The particles heaved the most will thus be able to go the farthest upon thawing and settling. It is not known how retrograde movement changes with depth.

## 3.3 Controls on Gelifluction

### 3.3.1 Gradient

The force that drives gelifluction is derived from the mass of the involved regolith and the acceleration due to the earth's gravity. As gradient increases so too does the component of the force applied to bring the soil mass downslope. Therefore one would expect the fastest moving gelifluction landforms to be on the steepest slopes. However, this is not always the case in the field; for example Smith (1985) reports that although the surface velocity of gelifluction lobes in the Front Ranges of the Rocky Mountains increases with greater gradient, the overall rate of a gelifluction lobe will not necessarily be faster on a steep slope (Harris, 1981; Smith, 1985). Evidently, other factors such as moisture content and soil texture are hard to isolate from the effect of gradient. Gradient also seems to determine the kind of gelifluction landform. For example, sheets tend to be found on lower gradients than gelifluction lobes (French, 1976; Harris, 1981).

### 3.3.2 Soil moisture

Soil moisture is essential to gelifluction because neither frost creep nor flow can occur without it. The sources of moisture are seasonally thawed snow, ground ice, seasonal groundwater and rainfall. Saturation of the landform is aided by the presence of an impermeable permafrost table. Obviously, controls such as climate, aspect, vegetation cover, soil texture, and micro-slope morphology will affect the supply and retention of moisture at a site.

### 3.3.3 Soil characteristics

Soil texture and soil particle shape also constitute controls on gelifluction. Soil texture is important because the strength of a soil is often influenced by the soil's texture (Casagrande, 1947). Sandy and silty soils such as those found in gelifluction lobes, have less strength. This, allied with the frost heave susceptability of coarse sediments, promotes gelifluction and frost creep (Harris, 1981).

Particle shape also has been suggested as a control (Holdgate, et al., 1967; Soderman, 1980). For example, mica flakes in gelflucted soil reduce the coefficient of friction due to the ability of water to lubricate parallel fragments of mica. However, it would be difficult to isolate this effect in the field owing to the influence of other controls.

## 3.4 Morphology of Gelifluction Landforms

### 3.4.1 Introduction

A generalized gelifluction lobe (Figure 3.2) has three basic components: the riser, tread, and field slope. The relative dimensions of these components are used to classify gelifluction lobes and each is discussed in more detail.

The riser is the steep frontal bank of the gelifluction lobe. This term is also applied to the fronts of other mass movement landforms such as debris flows. The tread is the surface of the landform and represents its more mobile part. The tread is measured for: length, slope, and occasionally for width. The field slope is simply the slope of the surface land over which the gelifluction landform is advancing. The field slope is commonly measured for its angle and aspect. The next section will show how types of gelifluction landforms are differentiated by these three basic features.

### 3.4.2 Types of gelifluction landforms

Three types of gelifluction landform (sheets, terraces, and lobes) are commonly referred to in the literature (Benedict, 1970, 1976; French, 1976; Washburn, 1979; Harris, 1981; Williams, 1984;

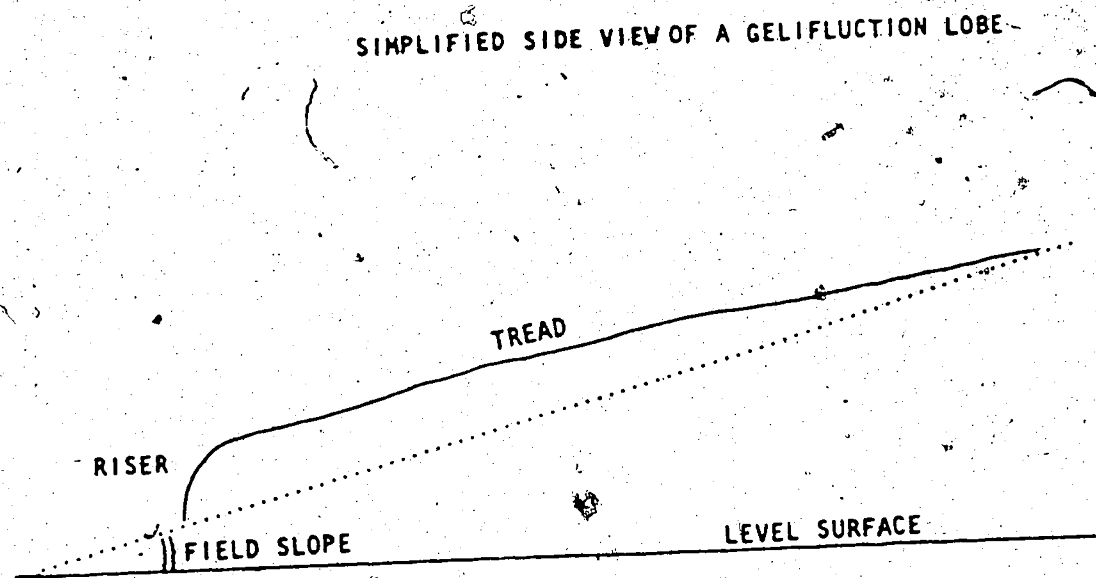


Figure 3.2 This diagram shows a much simplified side view of a gelifluction lobe and the features that are usually measured in morphological studies (Hall, 1980).

Chorley et al., 1984). Sheets are broad, shallow expanses of moving soil. They have low risers (<1m), great tread widths and length, and they can develop on slopes as low as $1^{o}$ to $5^{o}$. Terraces are comprised of an overlapping series of risers and treads in which the width of the tread is greater than the length. Risers can occasionally reach 1m in height. Terraces resemble contours or subdued agricultural terraces when viewed from above. Lobes are the most concentrated expressions of gelifluction and have received the most attention in the literature. The flow of gelifluction lobes is more channelled than other gelifluction landforms. Such lobes tend to be tongue-shaped and have a long tread (2 to 60m), and a steep, high riser, sometimes >1m (Price, 1974; Harris, 1981).

### 3.4.3 Turf vs. stone-banked gelifluction landforms

Terraces and lobes are further classified into turf and stone-banked landforms based on their surface cover. The "bank" refers to the riser; it is here that the turf and boulders are concentrated by the movement of the tread.

There are other differences between turf and stone-banked landforms. Stone-banked risers are composed of large tilted boulders whereas turf-banked risers have fewer large clasts (boulders) and these tend to be more horizontally orientated. The concentration of boulders in the risers of stone-banked landforms is due to the predominance of frost heave (Smith, 1985). Frost heave lifts boulders to the surface of the tread. The boulders are transported rapidly on the tread to the lobes margin and there accumulate (Harris, 1981). Turf-banked landforms are largely composed of fine material, thus, there are few boulders to sort (Smith, 1985).

The type of lobe is controlled largely by the nature of the original sediments. Also, the covering of a lobe is strongly tied to climate. For example, in Okstindan, Norway, stone-banked lobes are found at higher altitudes than turf-banked lobes, no doubt due to the climatic gradient which coincides with a change in altitude (Harris, 1981).

### 3.4.4 Dimensions

Gelifluction landforms are common on many arctic and alpine slopes. Their frequency permits many measurements of lobe dimension. In turn, this provides the statistical basis for determining the relationships between such variables as: length, riser height, tread slope and field slope.

Generally, Hall (1981) and Smith (1985) have shown that small lobes with high risers develop on steep slopes (> $15^{0}$) and large lobes with low risers develop on gentle slopes (< $25^{0}$). On steep slopes gelifluction is concentrated into narrow routes promoting rapid movement. The slower advance of gelifluction on more gentle slopes involves greater amounts of material (Smith, 1985). Although observations show a morphological control by gradient, gradient alone does not explain gelifluction because other variables, such as moisture supply, are equally important.

## 3.5 Composition

### 3.5.1 Introduction

Gelifluction sediments are divided into clasts, matrix and organics. Both clasts and matrix can be described in terms of: size, shape and orientation. Organics can be described in terms of their deposition, composition and age.

3.5.2 Non-organic sediments

The size, shape and orientation of clasts are important attributes of any gelifluction landform. Non-organic sediments found in gelifluction landforms range in size from clay to boulders. The size distribution of clasts, and their shape, resemble that of the parent material. Because gelifluction landforms are so slow moving, little mechanical breakup (comminution) of the source material should be expected. Therefore, the type of source material is very important for size and shape. Most non-organic sediments in a gelifluction landform are angular, as would be expected from freshly weathered bedrock.

Frost creep and flow are both favoured by a certain range of clay and silt content. For example, the highest amount of clay reported from a gelifluction landform sediment sample is 33% (Williams, 1966), however, the level of clay content is usually much lower. The textural envelope of gelifluction sediments include those grain sizes that are most susceptible to frost heave. For example, sandy sediments allow water to drain efficiently, reducing frost creep and flow. Conversely, clay prevents sufficient infiltration into the sediments, to support frost heaving. The textural range for gelifluction is the same as the textural range of sediments susceptible to frost heaving. Consequently, one can say that wet, frost susceptible sediments on low to moderate slopes are prone to gelifluction in periglacial environments.

The orientation of large non-organic sediments reflects the dynamics of the gelifluction process. There is enough movement in gelifluction landforms to modify the orientation of large sediments. Provided there is no impediment to movement, most large clasts show a strong downslope orientation of their long axis. There is also a slightly transverse orientation where restrictions to flow occur causing compression (Harris, 1981). The preferred orientation of large clasts in gelifluction landforms is sufficiently developed that this characteristic is used as evidence for past gelifluction in areas that are no longer periglacial environments such as Eastern Canada (Benedict, 1976; Hetu and Gray, 1985).

Particles of sand and gravel have dips parallel to the ground surface. This is simply a result of the alignment of these particles with the direction of gelifluction movement downslope. However, the orientation of finer material, such as silt cappings on small grains, is the result of freeze-thaw cycles. During the winter the grains are surrounded by a coating of accumulated ice. The coating creates a space in the soil larger than the particle. Upon thawing of the ice coating the particle falls to rest on the bottom of the space. Silt and finer material is then washed down into the top of the space, capping the particle (Harris, 1981).

### 3.5.3 Organics

Buried organic layers are commonly reported from gelifluction lobes. These organics represent former A-horizons and/or vegetation mats buried by the advancing gelifluction lobe. On heavily vegetated gelifluction lobes the tread rolls over, and beneath, the advancing riser and in the process becomes incorporated in the landform in an inverted position. Thus, two superimposed organic layers can be found in these landforms (Benedict, 1970).

Buried organic layers are a common subject of research in the literature because they provide a source for $^{14}C$ which, in turn, can be used to determine the velocity of the gelifluction lobes' advance. More than one distinct layer of buried organics are commonly reported from gelifluction lobes. For example, Alexander and Price (1980) have described a lobe from the Ruby Range of the Yukon Territories, which contains multiple organic layers. As would be expected multiple organic layers pose problems for interpretation. They could be a result of multiple episodes of advance across a series of vegetated surfaces, or they may represent the disruption by shearing of pre-existing buried organics (Everett, 1967; Price, 1970). The problem of properly interpreting multiple organics at Phillips Inlet will be examined in the fifth chapter.

## 3.6 Summary

Gelifluction has been shown to be a result of flow and frost creep on low-to-moderate slope. The process is especially active in sediments with moderate amounts of clay and silt because of high moisture retention. Because the above mechanisms and sediments characterize many arctic and alpine sites, gelifluction landforms are commonly observed features.

The fiords and valleys of Phillips Inlet have been weathered an[illegible]lated. This provides an abundant supply of coarse sediments on many slopes. Although summer precipitation is low, snow covers many slopes to a depth of approximately 1m each spring. When this melts, the sudden input of water, plus the contribution from the thawed active layer, saturates many sediments causing rapid mass movement. Although the lack of vegetation apparent on aerial photographs made the presence of buried organics doubtful, buried organics were nonetheless observed in excavated lobes. Similar excavations obtained thicker and longer organic layers from gelifluction sheets at Pasley River, Boothia Peninsula. The description of these organics, and the landforms where these were collected from, constitutes Chapter Four.

# CHAPTER IV

# FIELD RESULTS

## 4.1 Introduction

This chapter reports the field observations and radiocarbon dates from Phillips Inlet and Pasley River. For the most part discussion of these results will be witheld until the fifth chapter. This chapter is divided into four main parts:

1) Descriptions of slope and soil moisture characterists.
2) Gelifluction lobe morphology.
3) Gelifluction sediments.
4) Tables and diagrams of organic sediment stratigraphy and radiocarbon dates.

## 4.2 Slope Characteristics

Gelifluction landforms were found on slopes which varied in gradient and moisture conditions. Gradients varied between 5.0$^{o}$ and 22.6$^{o}$ for all gelifluction landforms. Differences in gradient were not observed between lobes and sheets as has been reported in the literature (Everett, 1967; Sigafoos and Hopkins, 1951) (Table 4.1). Gelifluction sheets in two adjacent valleys at Drift Pass were observed on slopes between 8.0$^{o}$ and 18.0$^{o}$, whereas the two extreme values (5.0$^{o}$ and 22.6$^{o}$) are from gelifluction lobes and were measured on a single 500m stretch of coastline near Tidewater Glacier. So there are no characteristic ranges of gradient for a given type of gelifluction landform. Gelifluction terraces were not observed at Phillips Inlet or Pasley River.

Table 4.1 Gradient of slopes with Gelifluction Landforms and Debris Flows

| Field Region | Local Site | Landform | Gradient Range | Gradient Mean |
|---|---|---|---|---|
| Phillips Inlet | Borth Beach | Debris flows | $8.0^{o}$-$15.0^{o}$ | $11.0^{o}$ |
| | Tidewater Glacier | Lobes | $5.0^{o}$-$22.6^{o}$ | $11.1^{o}$ |
| | | Sheets | $4.0^{o}$-$7.5^{o}$ | $5.5^{o}$ |
| | Drift Pass | Lobes | $8.8^{o}$-$19.4^{o}$ | $13.6^{o}$ |
| | | Sheets | $8.3^{o}$-$18.0^{o}$ | $11.9^{o}$ |
| | | Debris flows | | $6.7^{o}$* |
| Boothia Peninsula | Pasley River | Sheet | | |

*-only one observation

Absolute measurements of moisture content within gelifluction sediments were not made at either Phillips Inlet or Pasley River. However, relative moisture levels were observed. For example, all of the lobes found at the Tidewater Glacier site were dry (i.e, the sediments in the trench were not visibly saturated with water nor were they easily moulded by hand, rather they crumbled when manipulated). However, all the sediments at the other sites were very wet, commonly the surface of the landforms held ponded water, and upon trenching the sides of the excavation continually collapsed. This sediment was easily moulded, or it was too fluid for moulding. The lobes at

Stormwatch Delta filled with water to a depth of 1cm. This flow was maintained throughout one day of observation. This high water content was clearly related to numerous late-lying snowbanks upslope. However, at Drift Pass (Plate 4.1) the lobes were wet even in early August, when few snowbanks remained. Possibly this moisture was stored in the soil upslope, and became concentrated in the lobes by overland flow and throughflow. Precipitation directly onto the landform was minimal by comparison.

## 4.3 Lobe Morphology

The morphology of gelifluction landforms was measured allowing profile and plan view sketches of the landforms to be drawn (see Appendix). The longitudinal profiles of the lobes were obtained by placing an 88.5 cm long wooden stake on the lobe and taking a measurement of its inclination. The stake was moved up the lobe in 88.5 cm steps; the inclination was determined at each step. The base of the profile was assumed to be the same as the inclination of the immediately adjacent slope. Determining the exact profile of the underlying slope would have required the excavation of a trench to the overridden surface. However, this was considered impractical. Plan view sketches were made from a single length measurement along the long axis of the lobe together with three width measurements, taken at one-quarter, one-half, and three-quarters along the length of the lobe.

The same measurements were also made on debris flows (see Appendix) allowing a comparison to be made between debris and gelifluction lobes. These reveal some general differences in their

Plate 4.1 This view of gelifluction lobes at Drift Pass covered with flowing water illustrates the wet conditions found at many sites.

respective morphologies. Finally there were too few gelifluction lobes found in Phillips Inlet to attempt a statistical comparison between gelifluction landforms' morphological features (riser height, gradient, etc.) as was done by Hall (1981) and Smith (1985).

## 4.4 Gelifluction Sediments (Texture)

Most studies of gelifluction landforms characterize the texture of the sediment, and particularly the relative portions of sand, silt, and clay. Because the sediments in Phillips Inlet are comparable with studies from gelifluction sites worldwide, they shall be dealt with only briefly.

Six gelifluction lobes and sheets were examined at Phillips Inlet for their texture. In addition, the gelifluction sheet at Pasley River was sampled at six locations. All clasts were measured for their size and shape whereas the matrix was analyzed for its relative amounts of gravel, sand, silt and clay. This section is consequently divided into two sub-sections: clasts and matrix.

### 4.4.1 Clasts

Tests of the clasts sphericity conform the expectation (Briggs, 1977) that since there is little movement, hence abrasion in a gelifluction landform, then the clasts should retain the low degree of sphericity they had when initially weathered. Three hundred clasts from six lobes were measured for their sphericity at Phillips Inlet. Sphericity was 0.584, which is in the low-medium range (Chorley et al., 1984). This value is typical of a regolith produced by weathered bedrock or glacial sediments deposited close to their source (Briggs, 1977). Therefore, the sediments of Phillips Inlet lobes are likely the products of recent weathering, and glacial deposition. Both processes are much in evidence at Phillips Inlet. The sphericity is not as low as it could be (low as opposed to low-medium), possibly because some glacio-fluvial sediments could have been incorporated into the lobe, or because of further mechanical break-up *in situ* (i.e., by frost shattering).

#### 4.4.2 Matrix

Five samples of matrix underwent sieve and hydrometer analysis; three from Pasley River and two from Phillips Inlet. The samples were taken from the middle of lobe trenches near the organic layer. The ternary diagram (Figure 4.1) shows the coarseness of the < 2.00mm fraction of the samples at both sites, as evidenced by the near total lack of clay and the predominance of sand and silt. The gravel content of the samples ranged from 53.5% to 25.6% for Phillips Inlet, and from 3.3% to 0.03% for Pasley River. It is evident that Phillips Inlet sediments are coarser than Pasley River's. The Pasley River sediments are finer due to the gelifluction sheets incorporation of fluvial sediment from the nearby Pasley River. The coarser texture of the Phillips Inlet sediments is due to the lobes incorporation of weathered debris and glacial deposits. The matrix texture conforms with Beskows frost heave susceptability limits (1935), and are thus no different from other gelifluction sediments in the literature (Harris, 1981).

TEXTURAL PROPERTIES OF GELIFLUCTION LOBE SEDIMENTS AT PHILLIPS INLET AND PASLEY RIVER

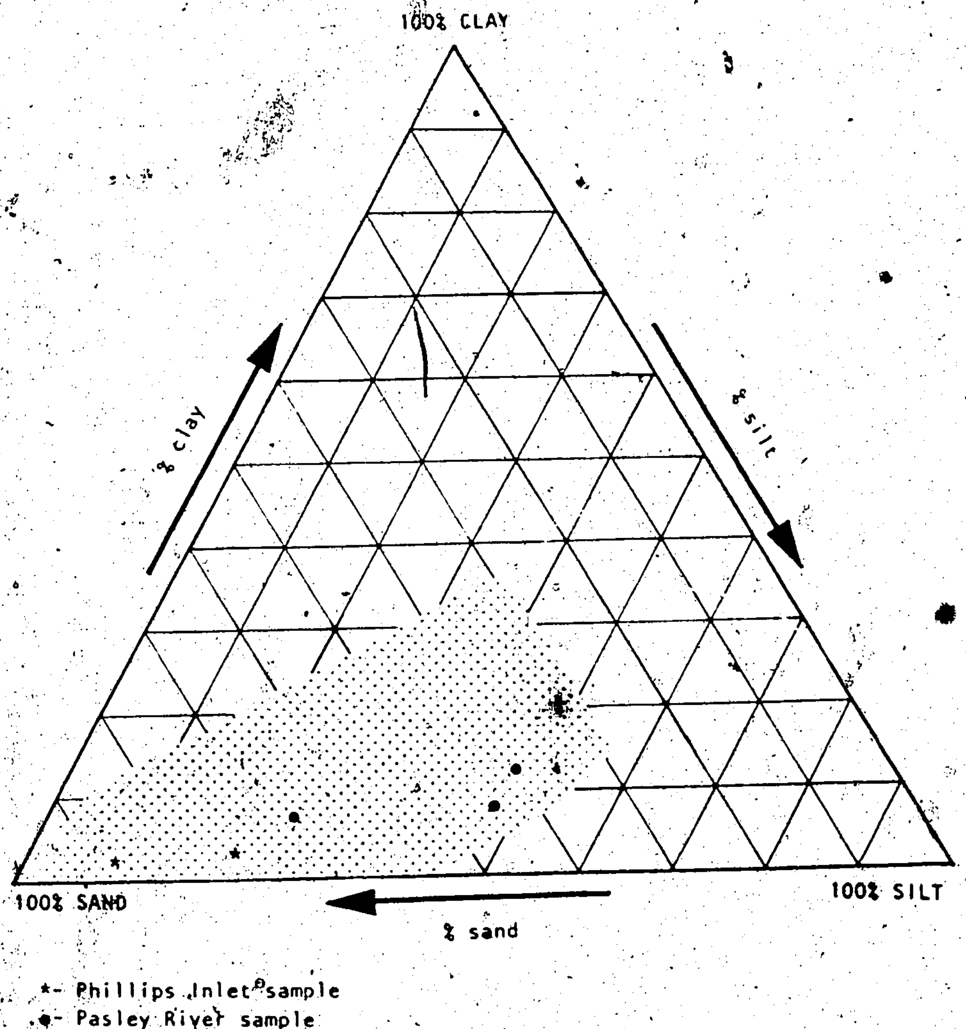


Figure 4.1 The shaded area in this textural diagram shows the range of sediment composition found in gelifluction landforms from arctic and alpine sites worldwide (Harris, 1981). As can be seen all the samples from both sites fit into the textural envelope. The sediments are generally low in clay. There is a tendency, ~~albeit~~ based on only a few points, for Phillips Inlet sediments to be coarser than Pasley River sediments.

## 4.5 Organic Sediments

Two lobes were selected for an analysis of their buried organics lobes, B-4 and No. 4 at Phillips Inlet and Pasley River respectively (Figures 4.2 and 4.3). There were also four other lobes from Pasley River previously dated by A.S. Dyke. B-4 is located on a $14^{0}$ slope along the southern bank of the Musk Ox River, near the Tidewater Glacier. Directly upslope, and slightly overlapping it was a smaller lobe (B-5, Plate 4.2). The steep riser ($67^{0}$) of B-4 had a pronounced frontal bulge which is diagnostic of the slow restrained flow of most gelifluction lobes. In the case of lobe B-4, it was possible to insert one's fingers underneath the riser and trace the overturned organics back beneath the advancing lobe. This suggested that a continuous layer of organics might be present and therefore excavation was warranted.

A trench 4.0 m long and between 0.5 to 0.25 m deep was dug into lobe B-4 and two thin (< 1 cm) organic layers were uncovered. The upper organic layer (Plate 4.3) pinched out 1 m from the riser whereas the basal organic layer extended the whole length of the trench although it thinned considerably at some points. From the basal layer five samples were collected, because of its greater length. The organics were composed of well-decomposed twigs and leaves of cushion plants (La Farge-England, personal communication, 1986) interspersed with reddish-brown and humified debris.

Care was taken to remove the shortest possible length of the basal layer in order to limit the age range within the sample. Upon removal, it was also noted that the samples were often mixed with non-organic sediments. This explains the weight of the three samples

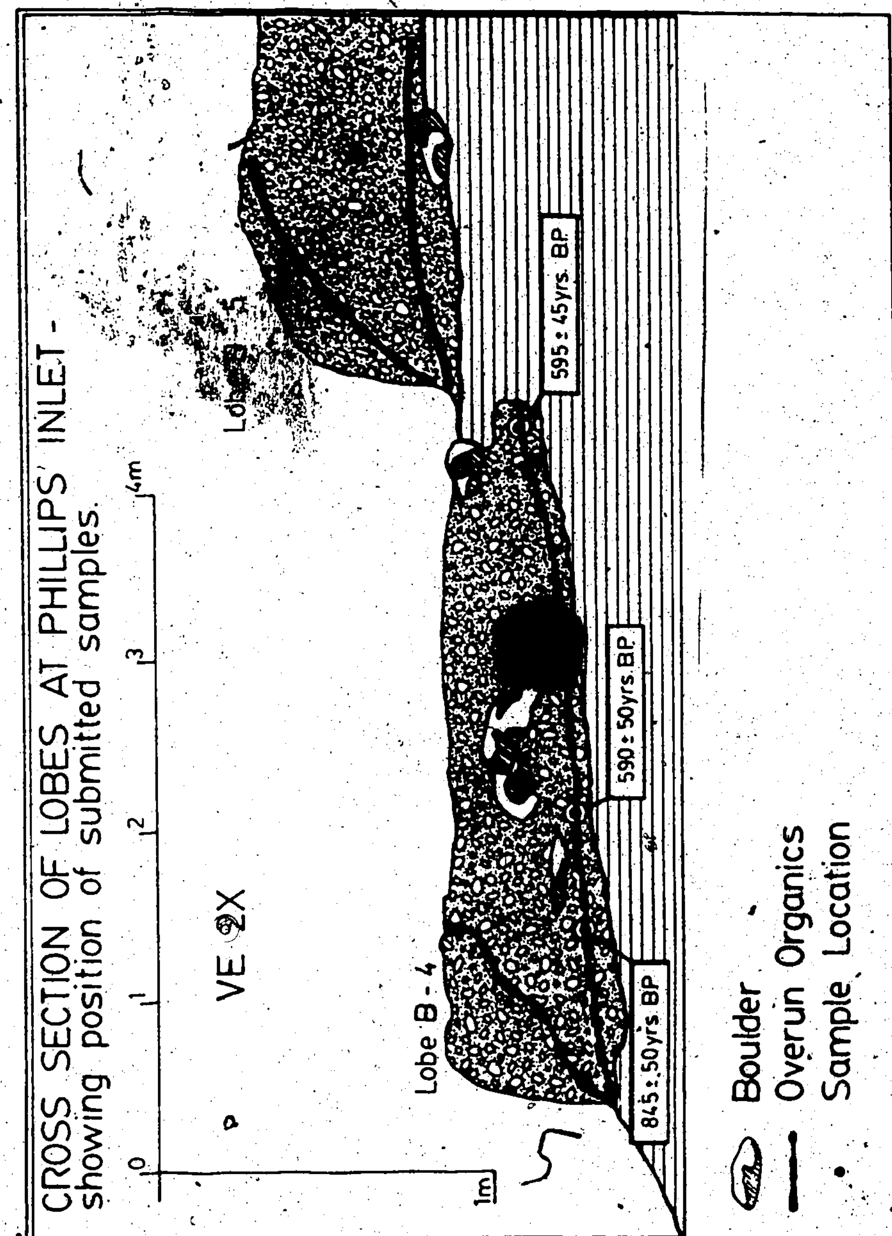


Figure 4.2 Lobe B-4 was the most heavily sampled lobe at Phillips Inlet. Three of the five samples were submitted and dated. The line showing the organic layers should not be taken to imply that a continuous layer of uniform thickness was uncovered. Rather the organics thickened and thinned throughout the lobe. The double layer of organics is a common feature in gelifluction lobes. The dates decrease in age upslope, the opposite of the expected results.

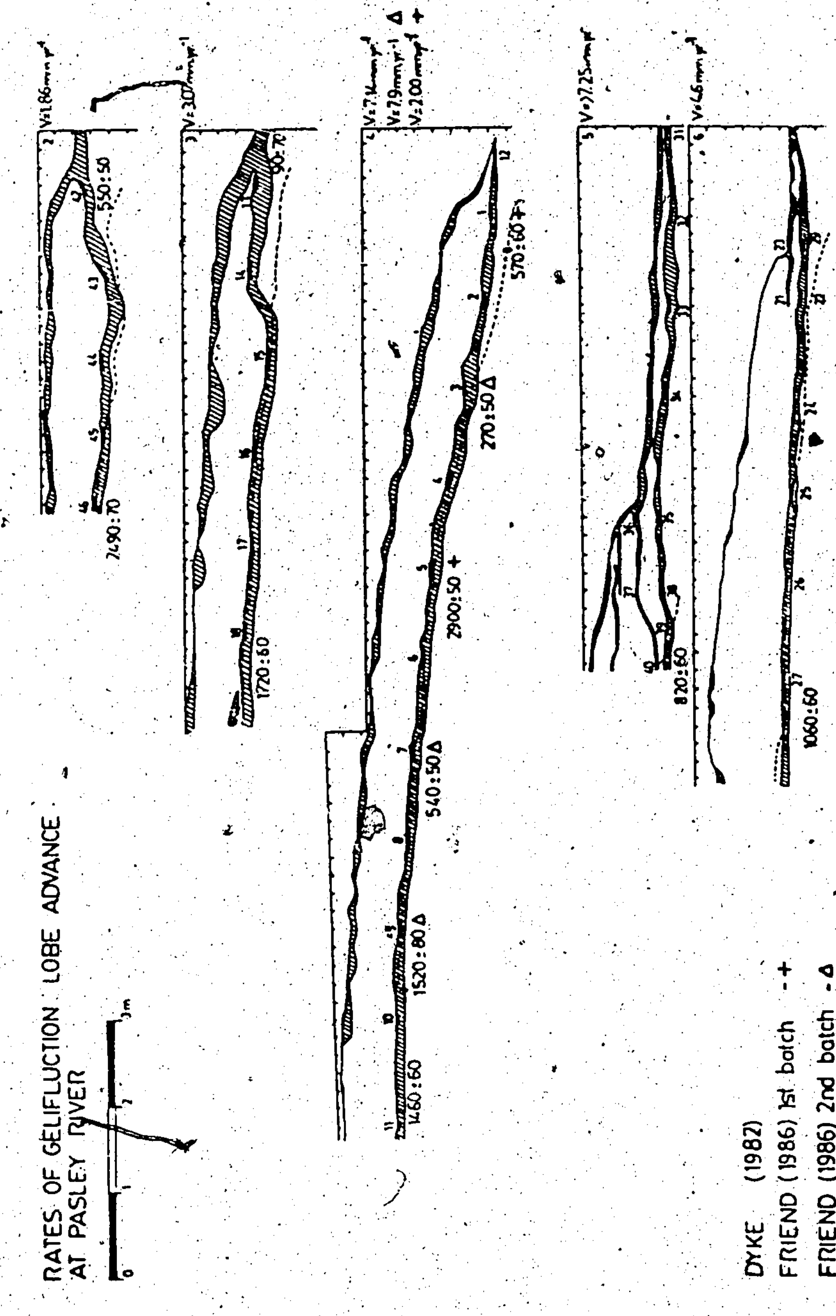


Figure 4.3 This diagram shows cross-sections of five gelifluction lobes which issue from the large gelifluction sheet of the Pasley River site. Lobe No. 4 was focussed on in this study, but the four other lobes are represented here for comparison. GSC dates and the author's AMS dates are shown, with the derived rates. There are three rates for Lobe No. 4. The other lobes are capable of being ascribed a velocity, but with little authority because of the sparseness of data. Lobe No. 1 is missing from this diagram because it was not dated owing to the difficulty encountered in discerning any pattern at all in its buried organics.

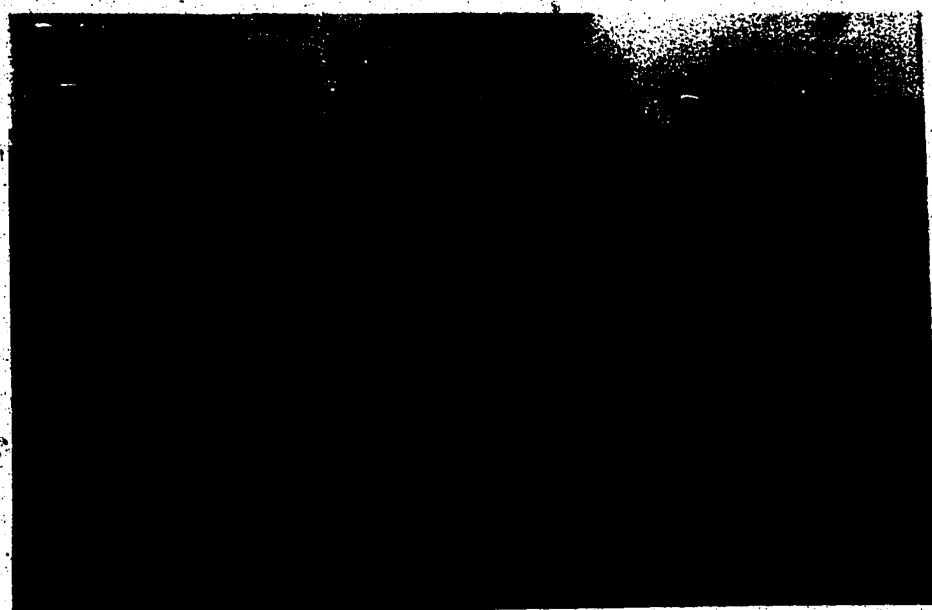

Plate 4.2 Lobe B-5 is shown overlapping Lobe B-4, after they were trenched for organics. The riser of B-4 bulged under a restraining mat of vegetation. The spoil was used as material for shape analysis and particle size analysis. Over the crest of the hill in the background was a late lying snowpatch; the source of moisture for this landform.

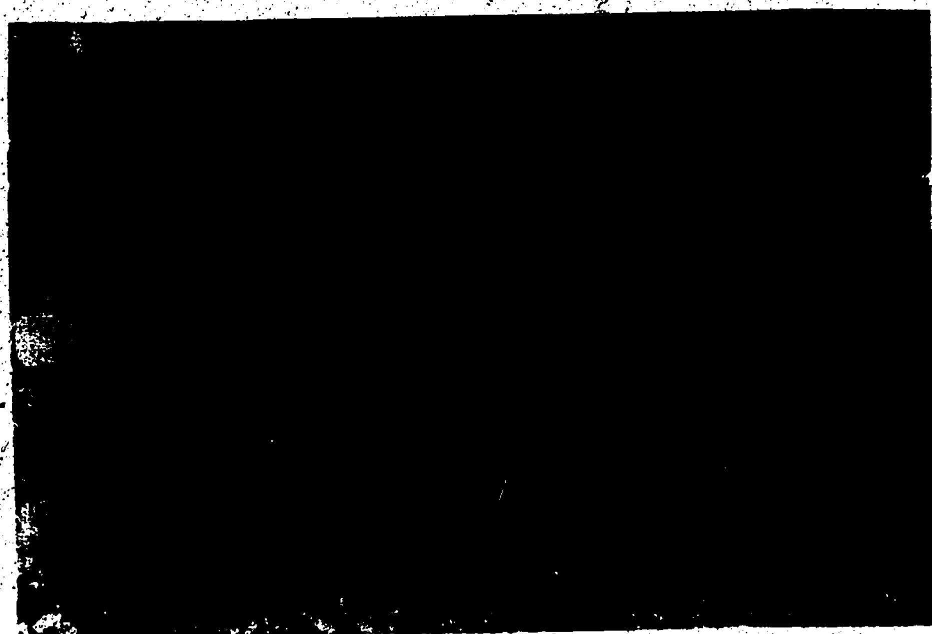

Plate 4.3 The risers frontal bulge is more apparent in [illegible] side view of the trench. Also visible is the upper la[illegible]organics illustrated in Figure 4.2. This layer was n[illegible]led because it was felt it would have little bear[illegible]n the rate of basal advance. Note the amount of rootlets. Smaller ones had to be separated from the submitted part of the sample after microscopic examination.

submitted for $^{14}C$ analysis.

The weight of the organics was not more than 15% of the entire sample weight (Table 4.2).

Table 4.2 Total weight of samples submitted for dating

| No. of submitted sample | Weight | Organics extracted (wt and %) |
|---|---|---|
| C-36 | 530 g | 19 g (3.6%) |
| C-34 | 337 g | 10 g (3.0%) |
| C-32 | 191 g | 25 g (13.1%) |

This would be a rather small sample to send to a conventional beta-ray counter for radiocarbon dating. Consequently, it was decided to use the accelerator mass spectrometer (AMS) operated by Isotrace Laboratories of Toronto because it is capable of analyzing samples containing as little as 700 $\mu$g to 5 mg of carbon. Shell or foraminifera samples of 2 mg and wood, charcoal or macrofossils of 5 mg are commonly dated.

After removal of the samples they were placed in airtight Whirl-Pack bags and stored for a few weeks prior to freezing at the University of Alberta. Sample preparation consisted of picking out the organics from the mineral fractions of the samples and removing modern rootlets by hand. Under a microscope modern rootlets were discernable by their intactness and light colouration. Otherwise the organics sent for dating were woody fragments sometimes found in association with decomposing leaves, which suggests that they had once been on the surface. The same procedure was was adopted for the Pasley River organics.

Lobe No. 4 was chosen from the site at Pasley River. An extensive organic layer 4 to 18 cm thick was excavated at six points along the Pasley River gelifluction sheet. Although there was one large gelifluction sheet at Pasley River, its otherwise straight riser was punctuated by numerous lobate extensions. Lobe No. 4 was chosen for analysis because it had the longest layer of buried organics. Other lobes at Pasley River were not only shorter but they had multiple organic layers, which would be difficult to interprete if both the upper and basal layers were dated. Although this would be instructive in itself, the real test was to determine the long-term rates of gelifluction. Nevertheless, seven samples from these lobes had been dated by Dyke in 1983 using the beta-ray counting device of the Geological Survey of Canada. This total includes sample L-11 from Lobe No. 4. They will be included in this paper as well, directly following the results from the AMS-dated lobes. Lobe No. 4 occupies a $4^{o}$ slope, and the trench exposed a continuous basal layer 12 m in length. Dyke removed twelve samples along this trench (Figure 4.3) and dated the one furthest from the lobe front using the conventional beta-ray counter at the G.S.C. laboratory. Subsequently, for this study, five samples from Lobe No. 4 were dated by Isotrace laboratories including a second part of the sample originally dated by the G.S.C.

All the data were plotted according to their location from their respective risers (Table 4.3, Figures 4.2 and 4.3).

Table 4.3 Sample dates from Phillips Inlet and Pasley River

| Location | Sample No. | Distance from riser (m) | Age (yrs B.P.) | Batch |
|---|---|---|---|---|
| Phillips Inlet | C-36 | 1.0 | 845 ± 50 | 1st |
| Phillips Inlet | C-34 | 1.7 | 590 ± 50 | 1st |
| Phillips Inlet | C-32 | 4.0 | 595 ± 45 | 1st |
| Pasley River | L-2 | 0.4 | 570 ± 50 | 1st |
| Pasley River | L-3 | 3.0 | 270 ± 50 | 2nd |
| Pasley River | L-5 | 5.0 | 2900 ± 50 | 1st |
| Pasley River | L-7 | 7.0 | 540 ± 50 | 2nd |
| Pasley River | L-9 | 9.0 | 1520 ± 80 | 2nd |
| Pasley River | L-11 | 11.0 | 1460 ± 60* | GSC dated |

* - conventional beta-ray counting date

One would normally expect an increase in age upslope, i.e., with increase of distance away from the riser. This is because the organics near the riser should have been buried most recently, as opposed to the furthest upslope, which would have been the earliest buried. However, this was not the case for either of the two lobes. B-4 has the sequence practically reversed with the oldest date (845 ± 50 yrs B.P.) nearest the riser and the second youngest (595 ± 45 yrs B.P.) furthest from it (Figure 4.2). The Pasley River Lobe No. 4 is not in any apparent order at all (Figure 4.3). For instance, the oldest date (2900 ± 50 yrs B.P.) is in the middle position from the riser, just following the youngest date (270 ± 50 yrs B.P.).

It is therefore not possible to ascribe the data purely to the advance of a gelifluction lobe over proximal vegetation and soil. Other modes of organic debris entrainment, and sources of dating error will be discussed in the fifth chapter in order to explain these results.

The data from the GSC-dated lobes at Pasley River do indicate an increase in age upslope (Table 4.4)

Table 4.4 GSC dates (beta-ray counting) of Pasley River samples (dates from Dyke, 1983)

| Lobe No. | Sample No. | Age (yrs B.P.) | Distance from front (m) | Rate (mmyr$^{-1}$) |
|---|---|---|---|---|
| 2 | L-42 | 550 ± 50 | 0.0 | --- |
| | L-46 | 2490 ± 70 | 3.6 | 1.86 |
| 3 | L-13 | 90 ± 70 | 0.0 | --- |
| | L-18 | 1720 ± 60 | 5.0 | 3.07 |
| 5 | L-39 | 820 ± 60 | >5.6 | >7.25 |
| 6 | L-27 | 1060 ± 60 | 4.8 | 4.60 |

Although it is possible to calculate the mean rate of advance, the scarcity of control points (< two per lobe) limits their representativeness. In two cases (5 and 6) only one date was available, so the assumption was made that the front of the lobe is contemporary. For this reason, they will not be discussed in much detail in chapter five, rather the discussion will focus largely on lobes B-4 and No. 4, dated by the author.

## 4.6 Summary

A number of preliminary conclusions can be made on the observations made at Phillips Inlet and Pasley River. There is no correlation between slope gradient and the kind of gelifluction landform on them. Lobe morphology was found to be different from debris flow morphology. The texture of gelifluction lobes matrix is notably coarser in Phillips Inlet than at Pasley River. Clast shape was found to be of low to moderate sphericity.

This is a reflection of the different origins of the local regolith; colluvial and glacial in Phillips Inlet and fluvial at Pasley River. Despite the different origin and textural properties, both sets of sediments differ little from the gelifluction sediments found in the literature. The same can be said for the shape analysis of the clasts; nothing different from what was expected was found.

The organic sediments were found not to increase in age upslope. The organics in lobe B-4 actually decreased in age upslope. The organics from Pasley River lobe No. 4 showed no order at all. This indicates that something other than the straightforward overriding of vegetation is occurring, or that other processes are introducing contaminants to the organics. Broader conclusions concerning the observations will be discussed in chapter five.

# CHAPTER V

## SUMMARY AND CONCLUSIONS

### 5.1 Introduction

The purpose of this chapter is to analyse and discuss the field observations presented in chapter 4. It will be shown how gelifluction landforms in Phillips Inlet and Pasley River are different from each other, and from those found further south. Specific reference is made to the problem of dating allocthonous material by means of both conventional and AMS dating. Finally, the directions that gelifluction landform studies might take in the future, are suggested.

### 5.2 Slope Characteristics

This section discusses why the gradients on which gelifluction landforms are found in Phillips Inlet are so variable. It is not possible to ascribe a certain range of gradients to a certain type of gelifluction landform. One cannot say, for example, that slopes of $1^{o}$ to $5^{o}$ are occupied mostly by gelifluction sheets. Even within small parts of the field area, containing slopes of diverse gradient, the landforms may be of one type. There are two possible reasons for this:

1. The sample population may have been too small, 23 gelifluction landforms were observed at Phillips Inlet whereas over a hundred were observed in Halls' (1981) study.

2. Characteristics of a site, other than gradient, may be the factors determining the type of gelifluction landform in Phillips Inlet.

The fact that gradient is superceded by other factors is demonstrated at two sites; Tidewater Glacier and Drift Pass. At Tidewater Glacier all the landforms were lobes whereas at Drift Pass all the landforms were sheets. The principal difference between the two sites is due to the way that moisture was supplied to their respective landforms. At Tidewater Glacier, the moisture originated from individual, late-lying snowbanks which fed isolated gelifluction lobes. At Drift Pass, the moisture originated from beneath the regolith upslope and emerged on a broad front to encompass a gelifluction sheet. The gradients of these landforms varied from 5$^{o}$ to 22.6$^{o}$. Therefore, gradient is not the controlling factor at these sites and it is clearly secondary to the way in which moisture is delivered to the slopes. Consequently, at Tidewater Glacier concentrated moisture delivery produces concentrated gelifluction lobes whereas a diffuse source of moisture produces gelifluction sheets at Drift Pass. At Tidewater Glacier there is an exception which strengthens this relationship. In a small valley adjacent to the raised marine delta there is a gelifluction sheet which is supplied by moisture along a broad front which takes up that entire slope. All that differentiates it from the setting of the lobate gelifluction landforms at Tidewater Glacier is the diffuse nature of the moisture input.

In conclusion, unless the number of observations is inadequate, the morphology and the occurrence of gelifluction landforms is controlled by the concentration of moisture supply. The effect of gradient on gelifluction landform morphology cannot be discerned.

## 5.3 Lobe Morphology

In the field, morphological differences between gelifluction landforms and debris flows were readily apparent. Subsequent comparisons between gelifluction lobes and debris flows reveals discernible differences in both their longitudinal and plan views. Gelifluction landforms are shorter, lack an upslope scar, and are usually vegetated. In contrast, debris flows are longer and thinner than gelifluction lobes. A comparison between the average length width ratio shows that whereas gelifluction lobes have a ratio of 1:0.72; debris flows have a ratio of 1:0.45. Although there is some overlap, such cases usually involve readily apparent reasons, such as a concentrated moisture source upslope. On the other hand, the few debris flows with length/width ratios resembling those of gelifluction lobes were found to be constrained from flowing further by either a mat of vegetation, or by a break in slope. This measureable difference between gelifluction lobes and debris flows might be of use when interpreting large scale air photographs.

Lobe profiles can also be compared to those of debris flows. In profile sketches, gelifluction lobes can be distinguised further by the common appearance of a bulging riser. Most lobes had these features, whilst debris flows had fewer and more subdued bulging risers. The bulges were not readily apparent in the profiles (see Appendix) but field observations show that seven lobes had distinctly bulging risers, while only two debris flows had this feature in a subdued form.

According to Price (1974) gelifluction lobe profiles can also be compared in order to determine their degree of development. Price (1974) identifies a developmental sequence through which a gelifluction landform will pass.

Snow accumulation in the lee of small lobes encourages the development of vegetation. This increased growth binds the lobe riser together enabling the lobe to grow longer. At a certain threshold riser height the amount of snow becomes a hinderance by staying long enough to prevent the plants' maturity. The decay of the binding vegetation allows the riser to become eroded. At Prices' (1974) site in the Ruby Range (Yukon Territory) the threshold riser height is 2.5m. The smallest lobes are heavily vegetated and have very steep risers, often bulging with the geliflucted sediment they are contraining. The largest lobes have gentler, eroded risers with little vegetation cover (Price, 1974).

The above is noteworthy for two reasons; 1) it ascribes a biogenetic origin to lobe form, and 2) it implies a short-lived equilibrium for mature gelifluction landforms. Although many gelifluction lobes at Phillips Inlet had bulging risers, none even approached 2.5m in height. Price also makes mention of lobes with risers 4m to 6m high.

Phillips Inlet has a climate at least as severe as southern alpine heights occupied by stone-banked lobes. Price's developmental sequence requires a less severe climate for the development of a binding mat of vegetation. Even at the most heavily vegetated site at Pasley River risers do not even approach 1m in height (Plate 5.1). In

Plate 5.1 This lobe at Pasley River is well vegetated compared to Phillips Inlet lobes, which could explain the thicker organics found at Pasley River. This would be simply because there is more organic matter in the area to be incorporated. The riser bulge is also less readily apparent here as opposed to Phillips Inlet Lobe B-4.

contrast some Phillips Inlet risers do reach 1m.

Given the lack of similarly-sized landforms, and questions in the literature (Harris, 1981; Hall, 1982; Smith, 1985), about what factors, besides climate and vegetation, affect lobe growth and morphology, it is difficult to apply Price's developmental sequence to the two sites. The apparent contradiction between riser heights at the sparsely vegetated Phillips Inlet and the vegetated Pasley River lobes implies some other factor affecting lobe riser profile. In any case, it can be seen that care must be taken in applying biogenetic models to sites in very different climates, especially when abiotic factors are not included.

## 5.4 Long-term Rates of Gelifluction

### 5.4.1 The allocthonous nature of gelifluction lobe organics

There are numerous processes by which buried organics can be incorporated by a gelifluction lobe and most of these imply that the organics will be allocthonous. Stuckenrath et al. (1979) dated various fractions of one organic layer from eastern Baffin Island demonstrating that a significant range of ages can be obtained from sediments with low organic content as well as peaty sediments. For example, AMS and conventional $^{14}C$ dating of a single sample from eastern Baffin ranged from 720 to 1245 B.P.. In this thesis wide ranging ages were found on what is clearly allochthonous organics. Four ways by which organics can be redeposited are discussed below.

1. A variety of periglacial processes can affect the organic content of gelifluction landforms. For example, Evans (personal communication, 1986) returned to Phillips Inlet in 1986 and

investigated a gelifluction sheet at Cape Alfred Ernest. A trench 7.0m long was excavated and six samples of buried organics were collected (Plate 5.2). The samples are undated because it was noted that there was a series of injection structures penetrating what appeared to be a single organic layer. These structures demonstrate disturbance by cryoturbation which has introduced allocthonous organics to the sediments. Dyke and Zoltai (1980) also demonstrated similar subduction of organics by cryoturbation on Somerset Island. Most of the lobes at Phillips Inlet and Pasley River were observed to have hummocks on their tread surface. The presence of hummocks, along with stratigraphic evidence of the process of cryoturbation, supports the view that organic layers in Phillips Inlet have a mixed assemblage of organics and therefore are not in situ.

2. Another way in which organics can be redeposited occurs by the plug-like flow observed by MacKay (1981) at Garry Island ($69^{O}$N, $136^{O}$W) in the western arctic. Plug-like flow is movement across an ice-rich mud at the bottom of the active layer. The plug-like flow has the capability to entrain interhummock peat during the formation of hummocks and smear it along the organic-mud zone. Consequently $^{14}C$ dates from such organic layers will bear little relationship to the advance of the gelifluction landform. Dates from a gelifluction lobe at Garry island reflect the smearing of such interhummock organics along the upslope part of the lobe resulting in decreasing ages upslope. There is no evidence of plug-like flow at Phillips Inlet, such as a concave downslope velocity profile, or ice lensing from both the top and bottom of the active layer (Mackay, 1981). Nevertheless, because the age of the samples from lobe B-4 decreases upslope it

Plate 5.2 Mr. David Evans excavated this gelifluction sheet in 1986 and removed organics from the intensively cryoturbated organic layer. Hummocks are visible on the surface of the sheet. This shows that the gelifluction sheet is undergoing further modification by other periglacial processes.

might suggest that this lobe has been affected by plug-like flow.

3. In Phillips Inlet the sediments were often observed to be so full of water that trench walls were continually slumping. This suggests that contamination by groundwater is also likely. Plate 5.3 shows a small stream flowing out of a 2m long trench. This flow was maintained for at least two days before the trench was filled. Consequently, organic layers in such lobes could become contaminated by the infiltration of fine organics older or younger than the layer in question, nor is it known how much dissolved $^{14}C$ there is in such runoff. Many of the lobes in Phillips Inlet are covered by a sheet of water for the entire summer. Root penetration which was much in evidence at Phillips Inlet (Plate 4.3), and the concentration of percolating organic acids in buried soils is also capable of contaminating buried organics (Matthews, 1985).

4. Rapid mass movement is another possible mechanism for the entrainment of organic material. Plate 5.4 shows two lobes side by side in different stages of a riser burst. The lobe in the background is supplying a fan of fine material from its lowered riser. The lobe in the foreground has had the same event occur previously, because its fan has become vegetated. A reactivation of this riser burst could bury this vegetated fan, preserving it as a downward dipping layer of organics over a basal layer. Ellis (1977) infers just such a sequence of events from the dip of clasts in a gelifluction lobe at Oskindan, Norway. The main body of the lobe could also advance and smear the vegetation under the riser.

A further example of the effects of riser failure on dated layers can be found in the front of a lobe excavated at Nachuak Fiord,

Plate 5.3 A lobe at Stormwatch Delta has just been trenched in this photograph. A small stream is issuing from the sides of the trench. The trench flowed with water for a day until it was filled in. It is difficult to see how an organic layer would not be affected by water-borne contaminants under these conditions.

Plate 5.4 Two lobes with burst risers are shown here. The riser burst in the background has occurred recently, as it is still running with fine sediment-laden water. The fan of the riser burst in the foreground is older, as evidenced by the vegetation on it. An overrunning of this vegetated fan by the lobe, or a subsequent riser burst could introduce another organic layer to the lobe.

Labrador (Evans, 1987 in press). Here a very young (70±90 $^{14}C$ years B.P.) riser date is explained as being the result of the riser slumping and mixing both surface and basal organics. It is apparent that eroding lobes might undergo the mixing of organics, especially in their risers. The low vegetation cover, and low cohesiveness of Phillips Inlet sediments would encourage riser failure and subsequent colonization by vegetation.

In summary, gelifluction lobe organics are redeposited by several processes. These include: infiltration; modern rootlet penetration; cryoturbation; plug-like flow of interhummock organics; and rapid mass movement. All of these add allocthonous material to the basal layer of a lobe or they can result in the deposition of multiple layers of organics. Such material clearly plays havoc with the assumption that such deposits date the time of burial. This problem is exacerbated when AMS dating is employed (next section).

### 5.4.2 Problems of $^{14}C$ dating of buried organics

Chapter 1 introduced the concept of using radiocarbon dates of organic layers to model past climate. The assumption is that if the rate of gelifluction changes between dates, then this is evidence of climatic change. An even more basic assumption is that the dates obtained are true representations of the advance rate of the lobe, and not records of other processes. Chapter 4 showed that the sequence of dates on buried organics within gelifluction landforms at both Phillips Inlet and Pasley River contradict the expected order of increasing age upslope. It is evident that the dates obtained cannot be explained by a progressive overrunning of an autocthonous layer of organics. There are two important considerations which address this contradiction.

1) Radiocarbon ($^{14}C$) dating by accelerator mass spectrometer (AMS) only requires very small samples typically <5mg (Beukens, 1987). This provides greater precision, but it also has the encumbent requirement of rigorous sample selection and preparation. Only the age of the particular fragment selected from the larger sample would be determined.

2) Because most buried organics are allocthonous, it is not possible to select any one fragment for AMS dating that represents the true age of burial unless one dates many fragments and selects the youngest and oldest to set a maximum and minimum age. The expense of this would be prohibitive because a single $^{14}C$ date costs $400 (1987). Conversely, conventional dating (beta-ray counting) of buried organics gives a mean age for a bulk sample that may be equally misleading. It is intriguing to note that many studies of gelifluction lobes around the world have reported similar rates of movement using conventional dating of bulk samples (Dyke, 1981). This similarity of rates in very different environments may be the fortuitous by-product of such conventional $^{14}C$ dating. Collectively the problem experienced in this study is due to the use of a very precise technique (AMS dating) on a heterogeneous bulk sample many orders of magnitude larger than that required to produce a conventional $^{14}C$ date (10-20g). If the sample is made up of diachronous sediments, then the results of AMS dating will simply reflect a random selection within the true range of ages found in that sample. It is likely that such a fraction would not be an accurate reflection of burial by a gelifluction landform.

5.4.3 Discussion and recommendations

One might argue that taking into account the assumed mean residence time (AMRT) of the presumably overridden organics would remove most of the source of error in the $^{14}C$ dates. However, this assumes that such layers are in situ soil horizons rather than allocthonous layers such as those at Phillips Inlet and Pasley River. The problem with both of these sites is the evident mixing of ages that occur in their buried organics. Subtracting a hypothetical AMRT from such organic layer dates could actually result in negative ages upslope! One could cite gelifluction lobe stratigraphies which also do not easily lend themselves to the simple interpretation of a lobe overrunning in situ organics (Mottershead, 1977; Alexander and Price, 1980; Matthews et al., 1986; Evans, 1987 in press). In these cases it is necessary to acknowledge similar problems of organic mixing reflected in the formation of multiple organic layers, due to a variety of processes.

From the above it can be seen that more research is required in four areas:

1) More detailed analyses must be made of the buried organic horizons and their mechanism of formation. For example, what is the organic and non-organic composition? Can allocthonous be separated from autochthonous vegetation? Particularly, a systematic study of the plant communities bordering gelifluction lobes could aid the problem of dating the best material. Matthews (1986) also recognizes this problem. In the literature, samples have been reported to contain buried wood (Costin, 1972); woody plant fragments (Matthews, 1986);

peat (Mottershead, 1978); and soil humus (Benedict, 1976; Alexander and Price, 1980; Smith, 1985; Hetu and Gray, 1985). The material which best indicates the time of overriding will vary from site to site. At each site the soil in front of the lobe should be investigated not only for its AMRT, but also its botanical composition. Also, the nature of soils over a wider area should be examined, preferably in different microenvironments, so that some idea of the possible range of soil development could be ascertained. This will allow some understanding of how the soil could change as it is being overrun.

2) How do gelifluction lobes advance, and in what ways does the particular periglacial climate and environment alter this? More detailed studies of the processes are still required. The assumption of uniform advance rates varied only by climatic change needs challenging in view of commonly observed riser bursts and multiple organic layers. Biogenetic models (Price, 1974) and gradient-control models (Hall, 1980; Smith, 1985) of gelifluction landform need further examination in a variety of environments.

3) How does the advance of gelifluction lobes account for multiple organic layers? The cause of multiple organic layers may be climatic (i.e., they may be indicators of climatic change (Matthews et al., 1986)). Alternatively, many of these may be due to other factors unrelated to climate change such as cryoturbation or overrunning of revegetated riser bursts. In any case, the understanding of the origin of all organic layers in lobes is essential if we are to understand the overall process and to effectively assess what layers warrant dating and for what reasons.

4) What processes occur within a gelifluction lobe other than those associated with advance? What do these processes contribute to organic layer stratigraphy? Instrumentation to monitor the movement of gelifluction soil in plan and depth is necessary to determine the causes and effects of cryoturbation, plug-like flow and frost heave. This problem would be best resolved by the long-term monitoring of selected lobes.

What these problems and questions have in common is the need for better dating control of periglacial sediments. At present the techniques for accurate dating of small organic samples are clearly ahead of our understanding of lobe stratigraphy. Many of the questions concerning lobe chronology and its supposed synchronicity with paleoclimatic events could be resolved via stratigraphically meaningful $^{14}C$ dates. The challenge presented by this study of the gelifluction lobes at Phillips Inlet and Pasley River, is whether such meaningful dates can be obtained and whether the comparable rates of movement previously reported from many different environments, both arctic and alpine, are more coincidental than real?. This thesis has served to expose the problem of using AMS versus conventional $^{14}C$ dating of buried organics. Existing models of process, stratigraphy and chronology of gelifluction landforms cannot be accepted if we so poorly understand the chronology and how to resolve its apparent impasse.

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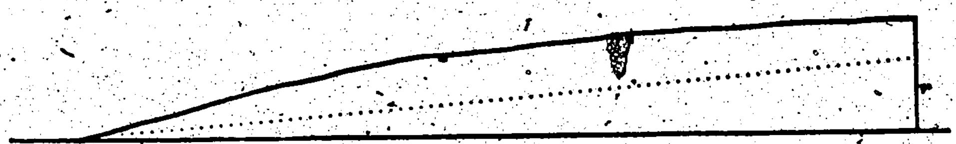
# APPENDIX

# LOBE PROFILES

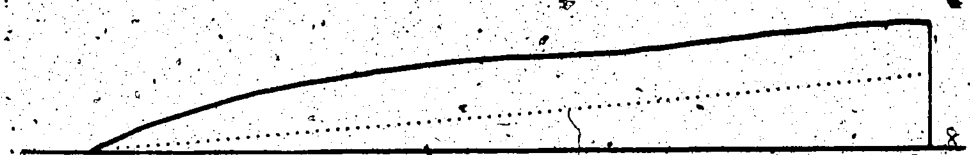
PROFILE 1 OF LOBE A-1

FIELD SLOPE 5.0°
RISER SLOPE 15.0°
LENGTH 10.5 m
SCALE 1:92



PROFILE 2 OF LOBE A-2

FIELD SLOPE 5.0°
RISER SLOPE 23.0°
LENGTH 10.5 m
SCALE 1:92

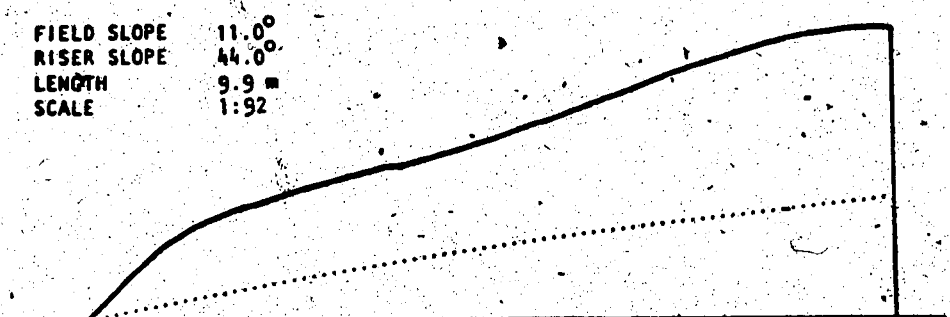


PROFILE 3 OF LOBE A-3

FIELD SLOPE 11.0°
RISER SLOPE 49.0°
LENGTH 9.8 m
SCALE 1:92

PROFILE 4 OF LOBE A-4

FIELD SLOPE 11.0°
RISER SLOPE 44.0°
LENGTH 9.9 m
SCALE 1:92



PROFILE 5 OF LOBE A-5

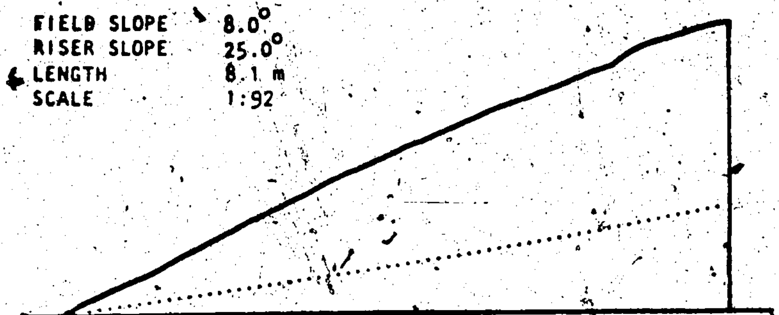
FIELD SLOPE 20.5°
RISER SLOPE 50.0°
LENGTH 9.3 m
SCALE 1:92

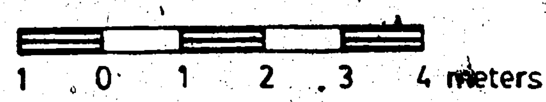
PROFILE 6 OF LOBE A-6

FIELD SLOPE 22.6°
RISER SLOPE 35.0°
LENGTH 9.6 m
SCALE 1:92

PROFILE 7 OF LOBE C-3

FIELD SLOPE 8.0°
RISER SLOPE 25.0°
LENGTH 8.1 m
SCALE 1:92

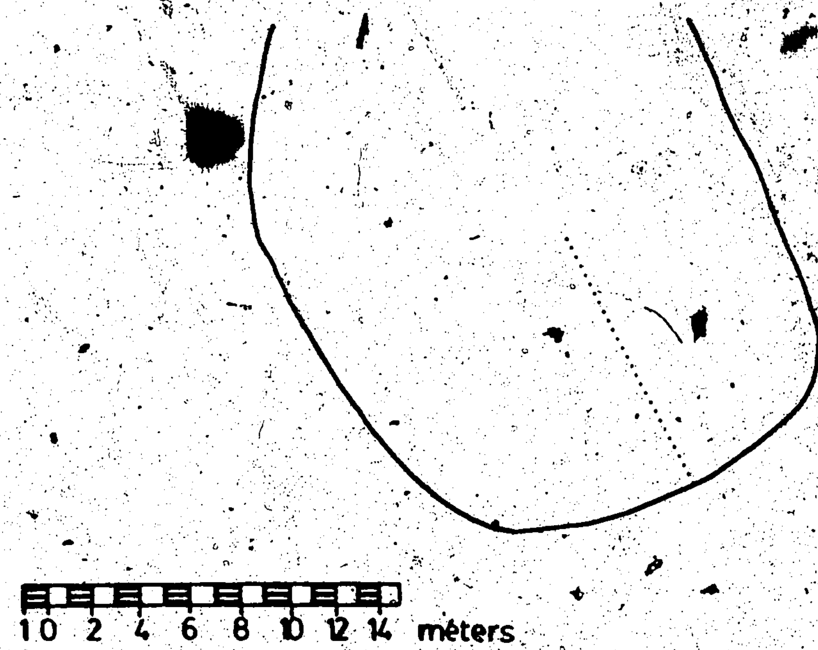




# LOBE PLAN VIEWS

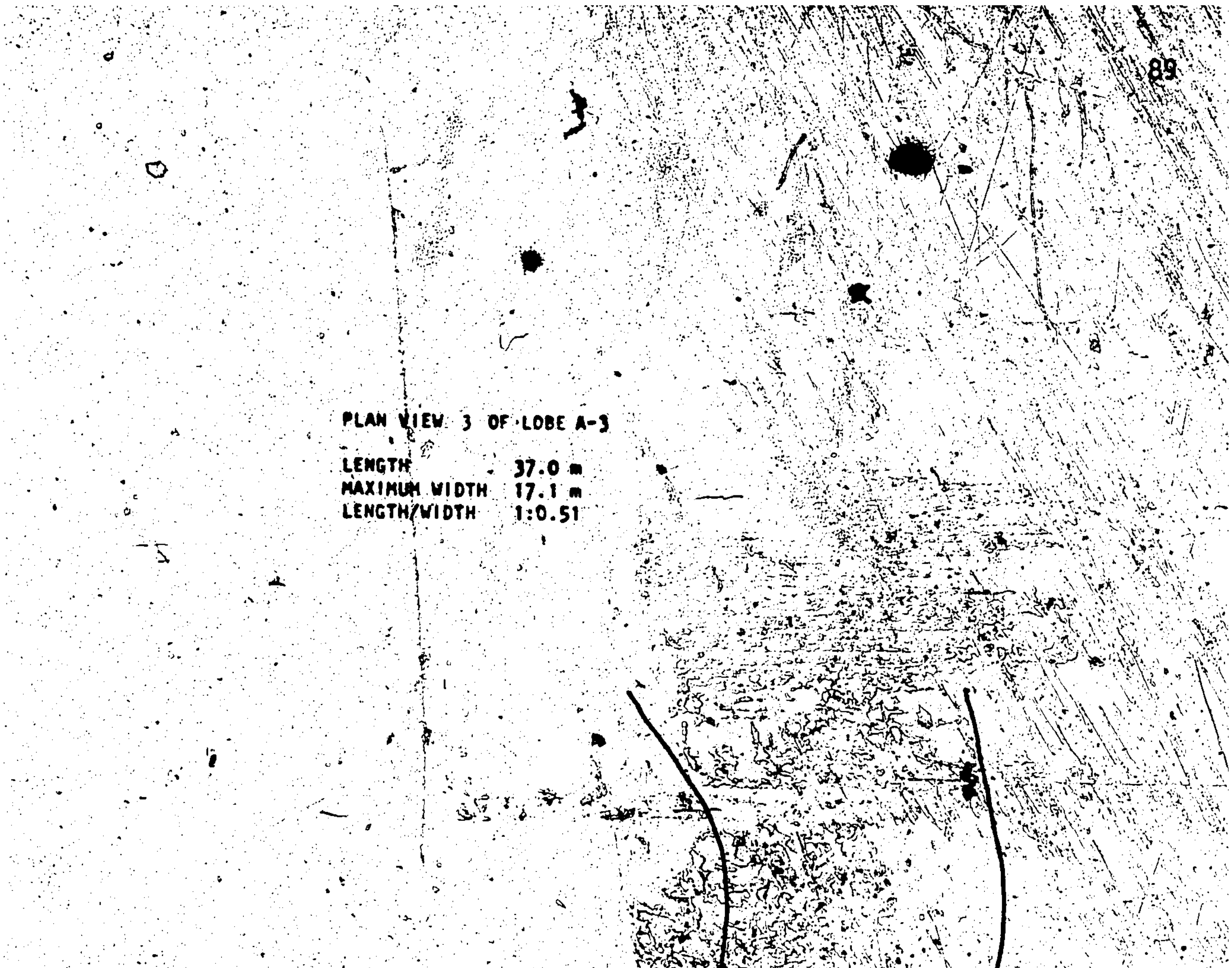
PLAN VIEW 1 OF LOBE A-1

LENGTH 27.7 m
MAXIMUM WIDTH 17.5 m
LENGTH/WIDTH 1:0.76



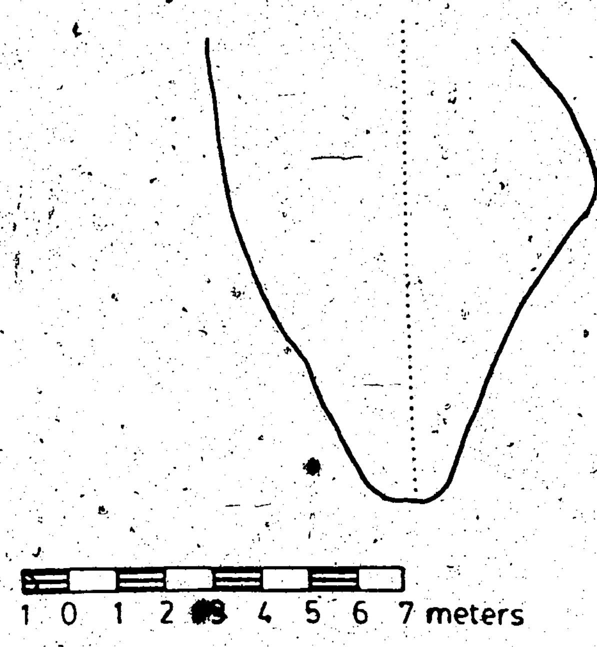

PLAN VIEW 2 OF LOBE A-2

LENGTH 26.7 m
MAXIMUM WIDTH 17.6 m
LENGTH/WIDTH 1:0.66


PLAN VIEW 3 OF LOBE A-3
LENGTH 37.0 m
MAXIMUM WIDTH 17.1 m
LENGTH/WIDTH 1:0.51
1 0 1 2 3 4 5 6 7 meters

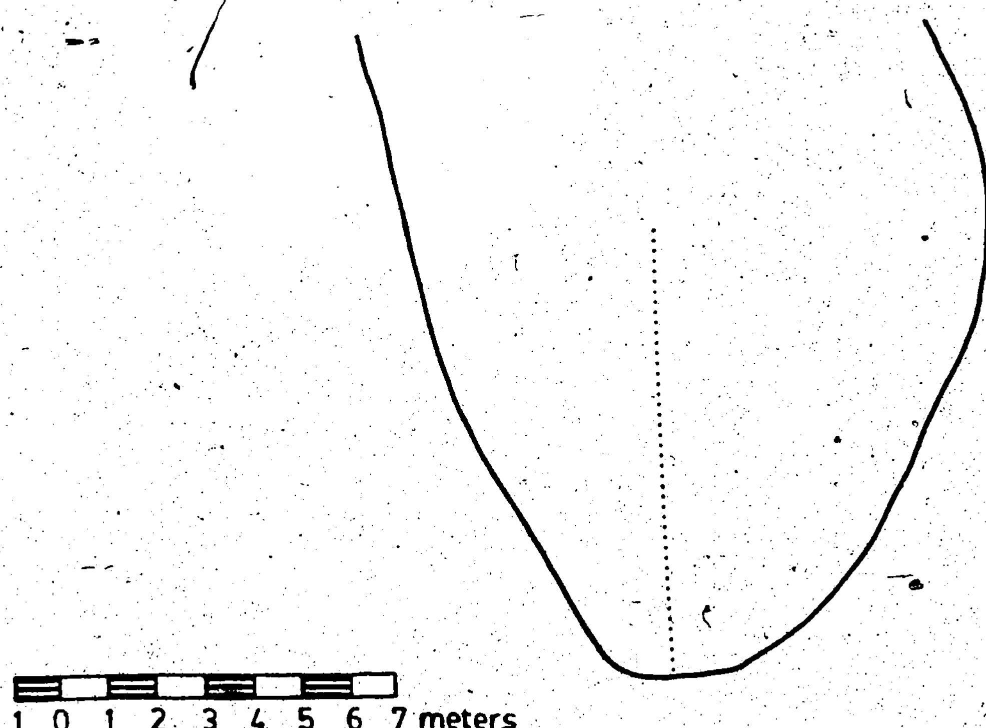
PLAN VIEW 4 OF LOBE A-4

LENGTH 12.6 m
MAXIMUM WIDTH 7.7 m
LENGTH/WIDTH 1:0.61



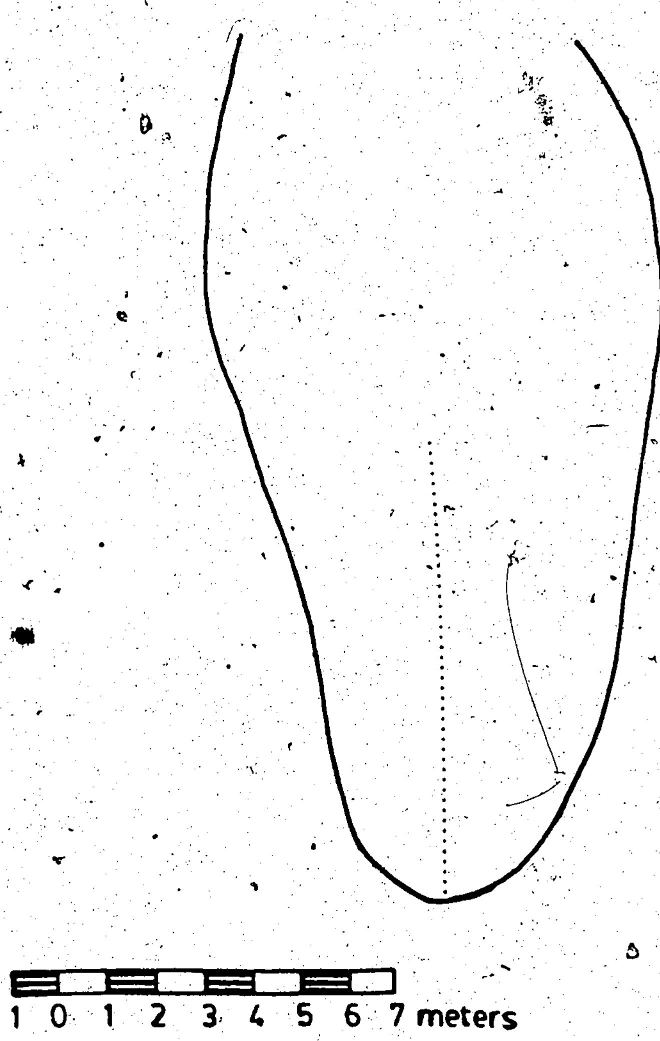
PLAN VIEW 5 OF LOBE A-5

LENGTH 17.4 m
MAXIMUM WIDTH 12.0 m
LENGTH/WIDTH 1:0:69



PLAN VIEW 6 OF LOBE A-6

LENGTH 23.5 m
MAXIMUM WIDTH 11.7 m
LENGTH/WIDTH 1:0.61

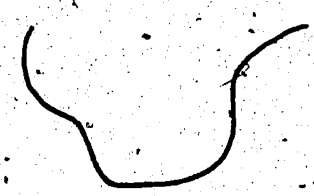


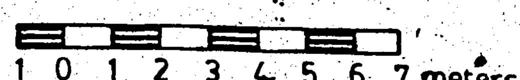
PLAN VIEW 7 OF LOBE-B-3

| | |
|---|---|
| LENGTH | 3.3 m |
| MAXIMUM WIDTH | 2.2 m |
| LENGTH/WIDTH | 1:0.67 |

PLAN VIEW 8 OF LOBE B-4

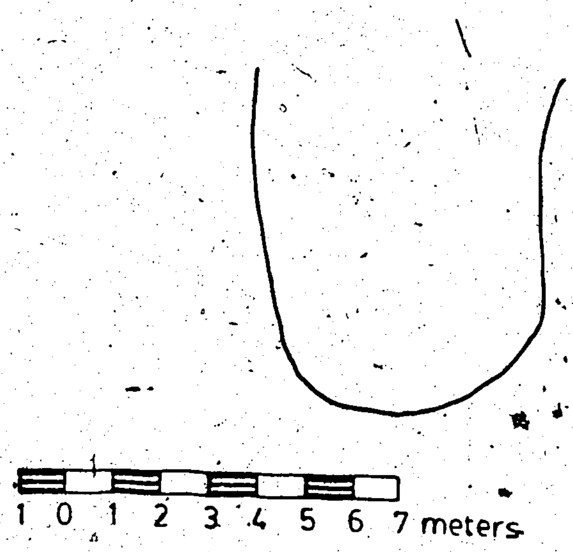
| | |
|---|---|
| LENGTH | 4.3 m |
| MAXIMUM WIDTH | 5.8 m |
| LENGTH/WIDTH | 1:1.35 |





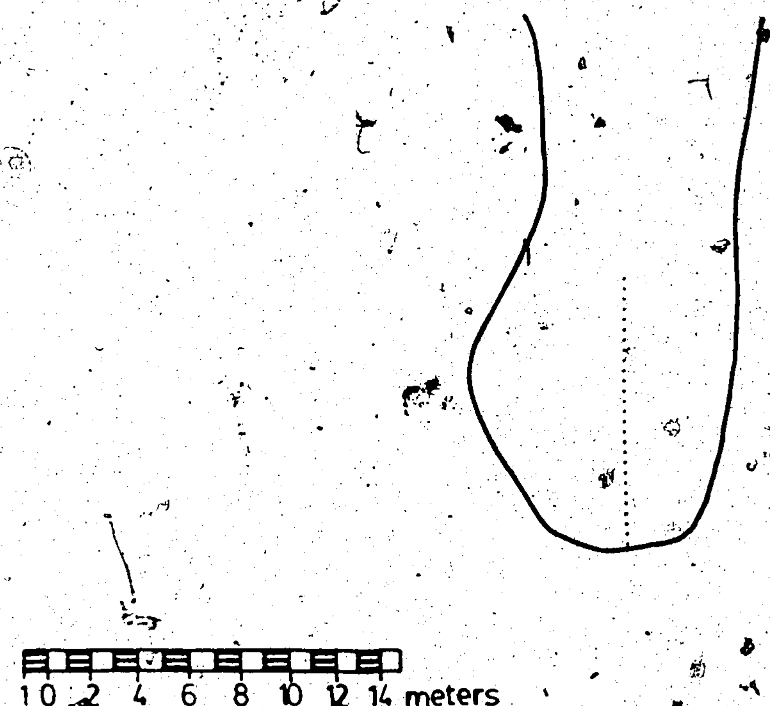
PLAN VIEW 9 OF LOBE C-2

LENGTH 9.4 m
MAXIMUM WIDTH 6.4 m
LENGTH/WIDTH 1:0.68



PLAN VIEW 10 CF LOBE C-3

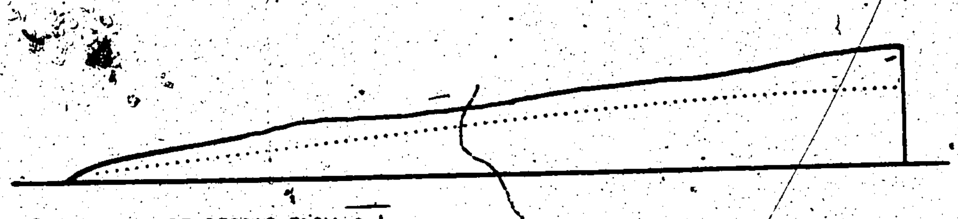
LENGTH 19.4 m
MAXIMUM WIDTH 10.0 m
LENGTH/WIDTH 1:0.38



# DEBRIS FLOW PROFILES

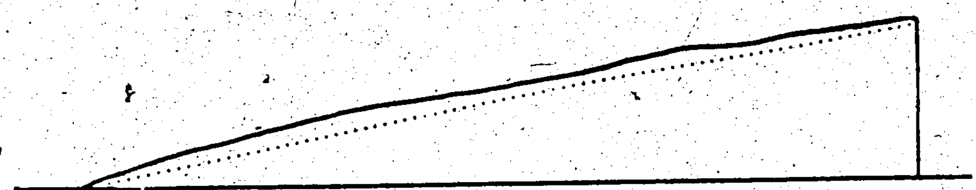
## PROFILE 1 OF DEBRIS FLOW C-3

FIELD SLOPE 8.0°
RISER SLOPE 18.0°
LENGTH 10.5 m
SCALE 1:92



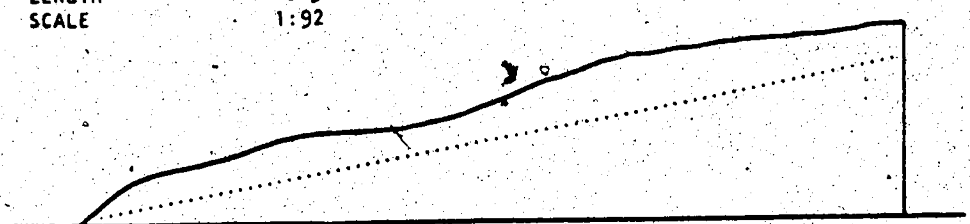
## PROFILE 2 OF DEBRIS FLOW C-4

FIELD SLOPE 11.3°
RISER SLOPE 17.0°
LENGTH 10.4 m
SCALE 1:92



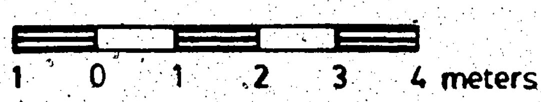
## PROFILE 3 OF DEBRIS FLOW C-5

FIELD SLOPE 11.5°
RISER SLOPE 37.0°
LENGTH 10.3 m
SCALE 1:92



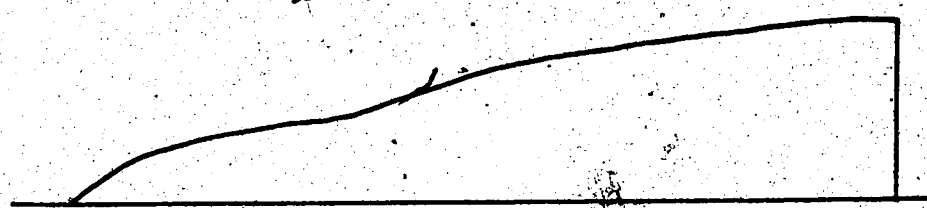
## PROFILE 4 OF DEBRIS FLOW C-6

FIELD SLOPE 11.5°
RISER SLOPE 42.0°
LENGTH 10.2 m
SCALE 1:92



PROFILE 5 OF DEBRIS FLOW C-7

FIELD SLOPE NA
RISER SLOPE 31.0°
LENGTH 10.3 m
SCALE 1:92

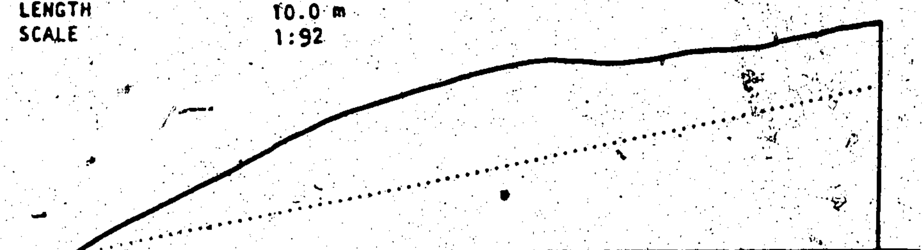


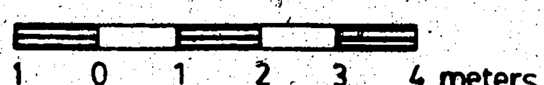
PROFILE 6 OF DEBRIS FLOW C-8

FIELD SLOPE 15.0°
RISER SLOPE 36.0°
LENGTH 10.1 m
SCALE 1:92

PROFILE 7 OF DEBRIS FLOW C-9

FIELD SLOPE 11.5°
RISER SLOPE 29.0°
LENGTH 10.0 m
SCALE 1:92





# DEBRIS FLOW PLAN VIEWS

PLAN VIEW 1 OF DEBRIS FLOW A-3

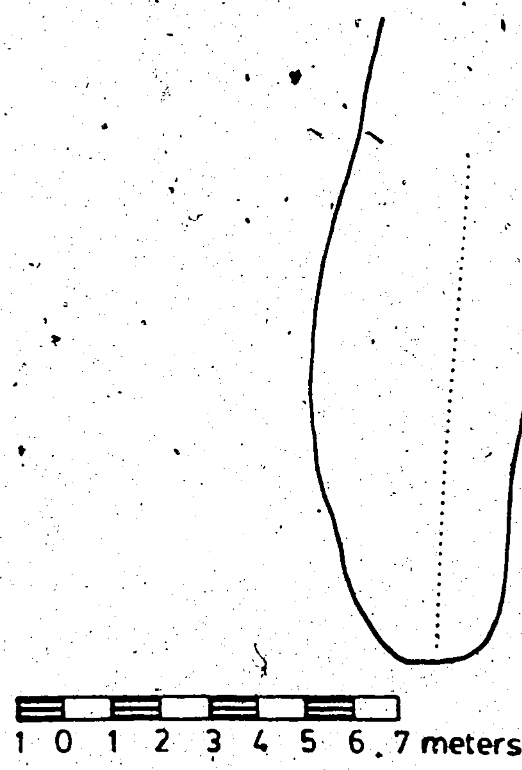
| | |
|---|---|
| LENGTH | 35.4 m |
| MAXIMUM WIDTH | 15.2 m |
| LENGTH/WIDTH | 1:0.43 |

PLAN VIEW 2 OF DEBRIS FLOW C-4

| | |
|---|---|
| LENGTH | 25.3 m |
| MAXIMUM WIDTH | 15.0 m |
| LENGTH/WIDTH | 1:0.60 |

PLAN VIEW 3 OF DEBRIS FLOW C-5

| | |
|---|---|
| LENGTH | 17.6 m |
| MAXIMUM WIDTH | 5.2 m |
| LENGTH/WIDTH | 1:0.30 |

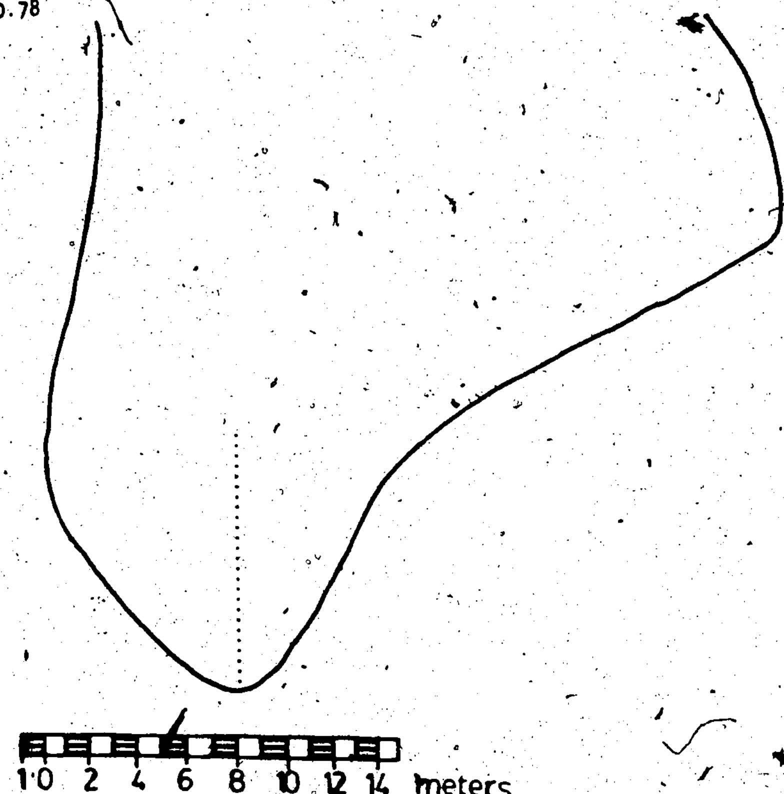


PLAN VIEW [illegible] DEBRIS FLOW C-6

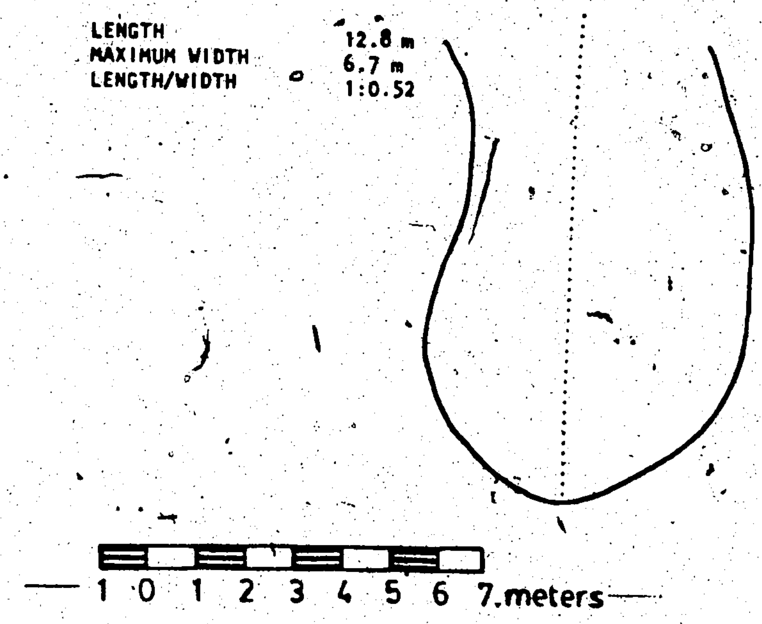
| | |
|---|---|
| LENGTH | 22.0 |
| MAXIMUM WIDTH | 6.2 |
| LENGTH/WIDTH | 1:0.28 |

PLAN VIEW 5 OF DEBRIS FLOW C-7

LENGTH 37.1 m
MAXIMUM WIDTH 29.0 m
LENGTH/WIDTH 1:0.78

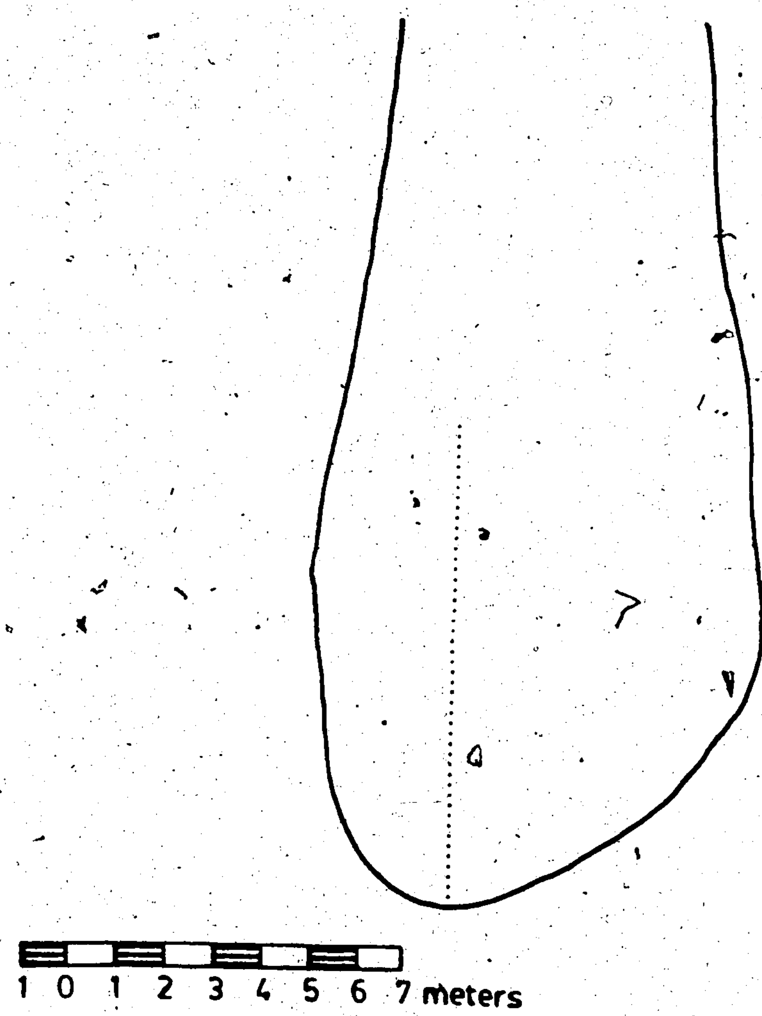


PLAN VIEW 6 OF DEBRIS FLOW C-8



PLAN VIEW OF DEBRIS FLOW C-9

| | |
|---|---|
| LENGTH | 24.9 m |
| MAXIMUM WIDTH | 9.2 m |
| LENGTH/WIDTH | 1:0.37 |



PLAN VIEW 7 OF DEBRIS FLOW C-9

LENGTH 24.9 m
MAXIMUM WIDTH 9.2 m
LENGTH/WIDTH 1:0.37