Université d'Ottawa · University of Ottawa

LONG-TERM DEVELOPMENT OF PALSAS AND OTHER PERMAFROST-CORED MOUNDS IN MOUNTAINOUS TERRAIN, WOLF CREEK, SOUTHERN YUKON

Presented by
TARA L. COULTISH

Master of Science Thesis submitted to the Faculty of Graduate and Post Graduate Studies

Department of Geography
University of Ottawa
Ottawa, Ontario
Canada

0-612-76571-7

ABSTRACT

Fifty-one frost mounds were examined in Wolf Creek, Yukon Territory (60°30'N, 135°13'W) at an elevation of 1235 m a.s.l. Cryostratigraphic analyses and aerial photographic interpretation were undertaken to investigate the origin and longevity of the mounds, and to assess their utility as climatic indicators. It was determined that 37 mounds were palsas, as evidenced by their dimensions, cryostructure of segregated ice and location within a fen; one mound was a frost blister, as evidenced by its core of intrusive ice; one mound may have been a compound form, with segregation and possibly intrusive ice; and 12 mounds were termed aggradational permafrost mounds as their cores were of segregated ice but they did not fit the locational requirements to be palsas.

Aerial photographs, spanning the period from 1946 to 2001, showed that palsas at the study site have been aggrading and degrading continually over the past 55 years, and are continuing to do so. The oldest palsa was initiated at least 150 years ago as determined by annual growth rings from shrubs on its summit. It was evident from the aerial photographs that palsas could aggrade and degrade over as short a period as 6 years, with maximum aggradation and degradation rates of 4 and 6 mounds per decade respectively.

The development of palsas in Wolf Creek appears to be influenced by non-climatic factors, which mask potential climatic effects. The construction and destruction of beaver dams along the stream, in particular can significantly alter water levels. It was inferred that high water has caused the degradation of palsas through thermal erosion, while palsas have grown in areas where ponds have drained. Dall sheep also may contribute to degradation by trampling of palsa sides and consumption of sediment.

The climate at the palsa site is sufficiently cold (MAT of –4°C from 2001-02) that permafrost is present in some of the surrounding terrain as well as within the palsas. Relatively deep snow observed on both aggrading and stable mounds, was insufficient to stop growth or cause degradation. This suggests that the palsas are not highly sensitive to climate at present. As a result of the additional influence of non-climatic factors, it is concluded that the palsas in Wolf Creek could be used as indicators only of very considerable future climate warming.

RÉSUMÉ

Cinquante et une buttes cryogéniques ont été examinées à Wolf Creek, dans le territoire du Yukon (60°30'N, 135°13'O) à une élévation de 1235 mètres. Des analyses cryostratigraphiques et de photos aériennes ont été réalisées afin de mieux comprendre l'origine et la longévité des buttes et pour déterminer si ces buttes peuvent êtres utilisées comme indicateurs des changements climatiques. En tout, il a été découvert que 37 buttes étaient des palses, rendu évident par leurs dimensions, leur cryostructure de glace de ségrégation et par leur proximité à un fen; une butte était un hydrolaccolite saisonnier, rendu évident par son cœur de glace intrusive; une de ces buttes est probablement une forme mixte, avec glace de ségrégation et possiblement de la glace intrusive; enfin, 12 buttes ont été classées comme buttes de pergélisol d'agradation car leurs coeurs sont composés de glace de ségrégation mais sans avoir les critères locaux pour être des palses.

Des photos aériennes de la période 1946 à 2001 ont démontré que les palses sur le terrain d'étude ont grossi et dégradé continuellement pendant les 55 dernières années et ce cycle se perpétue à ce jour. Les cernes de croissance annuelle des arbustes sur le sommet des palses révèlent que le palse le plus ancien a commencé à croître il y a 150 ans. Il est évident à partir des photos aériennes que les palses peuvent grossir puis dégrader sur une période aussi courte que 6 ans, avec des taux d'agradation et de dégradation maximals de 4 et 6 buttes par décennie respectivement.

Le développement des palses à Wolf Creek semble être influencé par des facteurs non-climatiques, ce qui masque les effets potentiels du climat sur ces formes. En particulier, la construction et la destruction de barrages de castor le long du ruisseau peuvent modifier les niveaux d'eau de façon significative. Il a été supposé que le niveau élevé de l'eau a causé la dégradation des palses par érosion thermique. Toutefois, des palses ont aussi grandit dans des endroits où des étangs ont été drainés. Des moutons de Dall peuvent également contribuer à la dégradation en écrasant les flancs des palses et en consommant les sédiments sur le pourtour.

Le climat au site des palses est suffisamment froid (température moyenne de l'air de –4°C de 2001-02) pour que l'on retrouve du pergélisol à quelques endroits sur le terrain et aussi dans les palses. Le couvert de neige relativement profond, observé à la fois sur des buttes qui grandissent et sur des buttes stables, est insuffisant pour en stopper la croissance ou causer leur dégradation. Ceci suggère que les palses ne sont pas particulièrement sensibles au climat actuel. Il est conclu qu'avec l'influence additionnelle des facteurs non-climatiques, les palses à Wolf Creek pourraient être utilisés comme indicateurs climatiques seulement à la suite d'un épisode de réchauffement global extrême.

ACKNOWLEDGEMENTS

This Master's thesis project has been both exhilarating and terrifying, but overall an amazing experience. This would not have been as rewarding or as enjoyable an experience if it were not for my supervisor, Dr. Antoni Lewkowicz. His support, guidance and optimism throughout this Master's degree have been invaluable. I am extremely grateful to have had Toni as a mentor, a friend, and a part-time psychologist on those particularly frustrating days. Toni and his family have always been there for me, and I cannot thank them enough.

Financial support was provided by the Northern Scientific Training Program and NSERC funds (Dr. A. Lewkowicz). Thanks must be given to Rick Janowicz, Water Resources Division, DIAND for logistical support in Wolf Creek; Isabelle Girard, for kindly allowing me access to the sedimentology laboratory at the Geological Survey of Canada; Peter Johnson, for gladly lending me his CRREL auger; and to the Department of Geography at the University of Ottawa for its excellent services to its graduate students.

Many warm thanks are extended to those who conducted the winter fieldwork for this thesis: Antoni Lewkowicz (2001, 2002), Marcia Phillips (2001), and Andje Lewkowicz-Lalonde (2002). Huge thanks are extended to my two summer field assistants, Christophe Kinnard and Mark Ednie. Their enthusiasm, friendship and superior dirt-digging abilities are very much appreciated. I wish them the best in completing their own theses. I would also like to thank Rebecca Zalatan, who graciously verified the shrub annual growth ring counts, and to Lisa Huisman and Nicole Ayotte for their help with the shrub work.

On a more personal note, I am grateful to my family and friends for their continued support, even though they couldn't understand why I wanted to study, "frozen dirt in the middle of nowhere." An especially warm final thanks is given to Éric Joly, who patiently and lovingly gave me tremendous encouragement throughout this degree. Together we've shared the ups and downs of a Master's degree: the pain of seemingly endless days of writing and the sheer joy and excitement of completion. Thank you for always being there.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 BACKGROUND

Large-scale climatic warming has been observed throughout the 20th century, with an increase of global mean surface temperature of 0.6 ± 0.2°C (IPCC 2001). The temperature increases in the northern hemisphere during the latter part of the 20th century have been the greatest in the past 1000 years. Future warming is expected for high latitude regions of North America, particularly over land areas in winter (IPCC 2001). In addition, it is projected that precipitation will increase in both summer and winter in these regions, whereas snow cover, permafrost, and sea-ice extent will decrease. It is predicted that the current distribution of permafrost could be reduced by 12-22% by the end of the 21st century, and that areas of warm, discontinuous permafrost will be the most sensitive to climatic warming (IPCC 2001). This creates the possibility of using areas of marginal permafrost as indicators of climate change (Kwong and Gan 1994).

Palsas often constitute the most southerly occurrence of permafrost (Harris 1982). Several perennial frost mounds, initially interpreted as palsas, were identified by A. Lewkowicz in the Wolf Creek Research Basin, southern Yukon Territory in 2000. These mounds, if palsas, would be expected to be particularly sensitive to climatic variations given their southerly location, and might be climatic indicators if an overall trend of permafrost (mound) degradation or aggradation were present (e.g. Laberge and Payette 1995, Matthews *et al.* 1997, Sollid and Sørbel 1998, Zuidhoff and Kolstrup 2000).

This thesis examines the origin and longevity of the mounds, and assesses their utility as climatic indicators. Its contribution lies in the identification of certain mounds that do not fit easily into current terminology, and in the recognition of non-climatic factors influencing mound inception, growth and degradation.

1.2 OBJECTIVES

This study had three main objectives. The first was to determine the origin of the frost mounds observed in the Wolf Creek Research Basin and to establish the reason for their presence at a particular location within the catchment. The cryostructures in cores taken from several mounds in various stages of development were examined in order to infer the freezing process responsible for their growth. Granulometric analyses were performed to determine the origin of the sediments in terms of depositional environment and their frost susceptibility.

The second was to develop a chronology of mound initiation, preservation and degradation in the Wolf Creek Research Basin because the longevity of mounds can be indicative of their origin. Aerial photographs spanning 55 years were used to investigate whether there was a detectable trend in aggradation or degradation of frost mounds (e.g. Horvath 1998, Sollid and Sørbel 1998, Sone and Takahashi 1993, Zuidhoff and Kolstrup 2000). This chronology was extended beyond the date of the earliest aerial photographs by counts of annual rings from shrub willows and shrub birch growing on the summits of the mounds.

The third was to determine the roles of climatic and non-climatic influences on the initiation and preservation of these frost mounds. It has been suggested that a regional trend in aggradation or degradation of palsas within an area can relate to a change in climate (e.g. Laberge and Payette 1995, Matthews *et al.* 1997, Sollid and

Sørbel 1998, Zuidhoff and Kolstrup 2000). This relation underpins the potential of palsas as indicators of climate change within areas of marginal permafrost. However, non-climatic influences on palsas could mask climatic influences and render the palsas unreliable as indicators of climate change.

2. LITERATURE ON FROST MOUNDS

2.1 PERENNIAL FROST MOUNDS

Perennial frost mounds exist throughout the circumpolar world, and comprise two main types: palsas and pingos. Palsas have frozen cores consisting of ice lenses formed solely by segregation ice processes. In contrast, pingos characteristically have cores of massive ice formed by the freezing of groundwater injected under pressure into frozen ground (Pissart 1988). It is not uncommon, however, for pingos to have large quantities of segregated ice (Mackay 1973, 1978). Although both mounds have segregated ice, pingos and palsas can be distinguished in the field by size, morphology, internal structure, growth patterns and location (Mackay 1978).

2.1.1 Palsas

The first scientific description of a palsa was made in 1792 by an Icelandic glaciologist, Sveinn Pálsson, who described hummocky forms as 'flas' or 'rusts'. In 1910, the Swedish scientists, T. Fries and E. Bergström, made similar observations, and named the form 'palse' (singular) or 'palsar' (plural) (*in* Nelson *et al.* 1992). The Fennoscandian usage of the term 'palsa' was solely morphological and referred to a very specific phenomenon (Lundqvist 1969). The classic Fennoscandian palsa is defined as:

> "A peat hummock with a core of frozen peat and/or mineral soil rising to a height of 0.5-10 m above a mire surface within the discontinuous permafrost zone (Seppälä 1988)."

The origin and formation processes were first associated with the term "palsa" in the mid-twentieth century. G. Lundqvist (1951) (*in* Nelson *et al.* 1992) suggested that ice segregation processes might be responsible for palsa growth. S.W. Muller (1947) (*in*

Nelson *et al.* 1992) suggested that palsa-like features might be the result of ice segregation in localized swamp terrain.

Because the Fennoscandian definition of a palsa was restricted to forms mainly comprised of peat, some scientists believed that there was a need to create new terms for features that were comprised partly or wholly of mineral soil. Terms used in the literature instead of 'palsa' include: minerogenic palsa (Åhman 1976), silt-cored palsa (Seppälä 1980), mineral cryogenic mound (Lagarec 1982), and lithalsa (Harris 1993). The abundance of terms describing similar features causes much confusion within the literature. In the article "What is a palsa?", Washburn (1983) set forth a broader definition to end the controversy:

> "Palsas are peaty permafrost mounds ranging from c. 0.5 to c. 10 m in height and exceeding c. 2 m in average diameter, comprising of (1) aggradation forms due to permafrost aggradation at an active layer/ permafrost contact zone and, (2) similar-appearing degradation forms due to the disintegration of an extensive peaty deposit (Washburn 1983)."

This broader definition only added to the debate. The proposed "aggradation forms" could be formed by either ice segregation or injection ice processes. Consequently, a number of authors have used the term 'palsa' to describe mounds that contain intrusive ice (e.g. Nelson *et al.* 1992, Outcalt and Nelson 1984a, Thórhallsdóttir 1994). These mounds are best-termed 'frost blisters' (e.g. Seppälä 1988, French 1996 p. 77), or 'seasonal frost mounds' (e.g. van Everdingen 1978, Pollard and French 1983). The literature on these features is reviewed in the following section.

Furthermore, the proposed "degradation forms" were believed to be created by the disintegration of peat plateaux (Lagarec 1982). However, it has since been demonstrated using ground penetrating radar in Macmillan Pass N.W.T., that no stratigraphic discontinuities exist within palsas that would suggest that they are produced by the degradation of peat plateaux (Horvath 1998, Matthews *et al.* 1997). For several reasons therefore, many authors explicitly or implicitly reject Washburn's definition of a palsa as being too broad. The IPA Multi-language Glossary of Permafrost and Related Ground-Ice Terms defines the term "palsa" as:

> "A peaty permafrost mound possessing a core of alternating layers of segregated ice and peat or mineral soil material (van Everdingen 1998)."

In supplementary comments, the IPA Glossary recommends that the use of the term "palsa" be restricted to:

> "Those features where the internal structure shows the presence of segregated ice and where the environment lacks high hydraulic potentials, provided that other parameters (size, shape, location in wetlands) are also satisfied (van Everdingen 1998)."

In this thesis, the definition of a 'palsa' from the IPA will be used. It is recommended that all other terms, (e.g. lithalsa) should not appear within the literature, as they are confusing and redundant.

Palsas naturally have a cyclical development. The growth cycle of a palsa can be several hundred years long, but dating methods for palsas have always been problematic (Seppälä 1988). Previous dating methods include tritium (Forsgren 1966), pollen and ^{14}C (e.g. Allard and Rousseau 1999, Savoie and Gangloff 1980, Seppälä 1980), vegetation seres (Harris 1993), and volcanic ash (Kershaw and Gill 1979). These methods have provided dates of formation from 100 to 3000 years B.P., but palsas of different ages or different stages of growth can be present within the same area (Allard *et al.* 1996, Zoltai 1993).

The growth stages of palsas are commonly determined by mound size and the type of vegetation present (e.g. Seppälä 1982, Cummings and Pollard 1990, Harris 1993). Small palsas in the earliest stages of growth typically have covers of bare peat. As permafrost aggrades, and the mound rises further above the water level, grasses and shrubs begin to colonize the bare peat surface. Older palsas typically have well-established shrub and/or tree covers. Some classifications, therefore, employ terms such as embryonic, incipient, young, mature, old and overmature (e.g. Seppälä 1982, Zoltai 1972). Cummings and Pollard (1990) suggest, however, that the terms aggrading, stable and degrading be used instead, as they best describe the growth and decay of palsas from a cryogenic perspective. These terms, which can easily be employed in the field, are used in this thesis. The five main factors responsible for cyclical growth and decay of palsas are snow, vegetation cover, peat cover, availability of water, and regional climate.

The depth of snow covering a palsa is argued to be a critical factor influencing its growth. Snow acts as an insulator due to its low thermal conductivity, and therefore impedes the advance of the freezing front into the ground (Williams and Smith 1989). The tops of palsas are frequently found to be wind-swept in winter, allowing permafrost to aggrade (Cummings and Pollard 1990, Kershaw and Gill 1979, Seppälä 1990). The snow cover is also largely dependent on the vegetation cover on the palsa (Allard *et al.* 1986, Kershaw and Gill 1979).

Vegetation alters the way in which snow is distributed on palsas. Shrub communities can enhance insulation of the mounds by trapping relatively low density snow covers (Kershaw and Gill 1979), but large trees on the palsa can intercept snow allowing greater heat loss and permafrost aggradation (Zoltai and Tarnocai 1971).

Vegetation can help stabilize the surface mechanically, preventing palsas from collapsing (Cummings and Pollard 1990). It has also been speculated that changes in albedo during vegetation succession (Kuhry 1998, Railton and Sparling 1973) and the shading effects of vegetation during the thaw season (Kershaw and Skaret 1993) could cause a negative heat budget allowing permafrost to aggrade.

The presence of peat is important to the existence of palsas, due to its variable thermal conductivity when frozen and unfrozen (Williams and Smith 1989). Dry peat has a very low thermal conductivity (0.12 W/m°C) (Outcalt and Nelson 1984b), and therefore acts as an insulator in the summer (Cummings and Pollard 1990, Seppälä 1982, Williams and Smith 1989). Frozen peat has a much higher thermal conductivity (5.20 W/m°C) (Outcalt and Nelson 1984b), which allows high rates of heat loss from the ground in the freezing season (Outcalt and Nelson 1984a, Williams and Smith 1989). The loss of peat due to wind abrasion or fire can sometimes result in palsa degradation (Zoltai 1972). However, stable palsas with thin peat covers, <15 cm, have also been reported in the literature (e.g. Allard and Rousseau 1999, Harris 1993, Matthews *et al.* 1997, Seppälä 1980, White *et al.* 1969).

Palsas are found in peat bogs or fens (e.g. Allard *et al.* 1986, Gurney 2001, Seppälä 1988, Zoltai 1972), where water is available for ice segregation. Ice lenses are formed through cryosuction of water from the surrounding fen (Brown 1968, Seppälä 1986), groundwater (An and Allard 1995), and possibly from meteoric water (Harris *et al.* 1992). Although ice lenses are typically thin, ranging from 1- 5 mm, ice lenses from 5-35 cm thick have been reported within palsas (e.g. Forsgren 1968, Seppälä 1980, 1988, Zoltai and Tarnocai 1971, Zuidhoff and Kolstrup 2000). Water is needed for the formation of ice lenses, but too much standing water can cause thermal erosion of palsa sides leading to block collapse (Friedman *et al.* 1971, Gurney 2001), and flooding normally prevents palsa formation (Brown 1980).

Finally, palsas are frequently found in the zone of discontinuous permafrost where mean annual air temperatures are close to 0°C (Harris 1982). The widespread degradation of palsas that exist in this marginal zone of permafrost has been linked in some studies to regional climate amelioration. Some authors have begun to detect an overall degradation in palsa fields in northern Québec (Laberge and Payette 1995), southern Norway (Matthews *et al.* 1997, Sollid and Sørbel 1998), and southern Sweden (Zuidhoff and Kolstrup 2000).

2.1.2 Pingos

Pingos are conical, ice-cored perennial mounds that range from a few metres to over 60 metres in height (French 1996 p. 102-103). In terms of genesis, there are two main types of pingos: closed-system and open-system pingos. It was suggested by Mackay (1979) that these terms be changed to hydrostatic and hydraulic system pingos as they are more representative of the pressure gradient supplying the water to a growing pingo, being either hydrostatically (closed-system) or hydraulically (open-system) induced (Mackay 1979). Along with intrusive ice, segregated ice and dilation crack ice are also responsible for some of the growth of pingos (Mackay 1979, 1998).

Hydrostatic system pingos are found within the continuous permafrost zone in poorly drained areas of low relief (van Everdingen 1998), and commonly found in the bottom of catastrophically drained lakes such as in the Tuktoyaktuk Peninsula, N.W.T.

(Mackay 1979). Permafrost rapidly aggrades in the newly exposed ground surface and inward from all sides of the talik beneath the recently drained lake. Hydrostatic pressures increase in the saturated unfrozen sediments of the talik and eventually water is injected into the overlying permafrost, and is frozen. This action causes the progressive growth of the pingo and the formation of its core of massive ice.

Hydraulic system pingos are mainly found within the discontinuous permafrost zone in areas of high relief (van Everdingen 1998). Intrusive ice forms in the hydraulic system pingo as a result of intra-permafrost or sub-permafrost groundwater flowing downslope under a hydraulic gradient (Mackay 1998). It is suggested that the continued development of a seasonal frost mound in the same location may be the origin of some hydraulic system pingos (French 1996 p. 77).

Although two degraded pingos have been reported within Wolf Creek (Seguin *et al.* 1999), no conclusive evidence to support this origin was found on-site. Therefore, pingos will not be further discussed in this thesis.

2.2 Seasonal Frost Mounds

There are fewer studies of seasonal frost mounds than perennial frost mounds. Earlier work was undertaken by A.E. Porsild (1938) and S.W. Muller (1943). The most detailed investigations have been carried out in the central Yukon Territory (e.g. Pollard and French 1983), and the Northwest Territories (e.g. Campeau and Héquette 1995, van Everdingen 1978). However, seasonal frost mounds are present throughout the circumpolar world, and have been found in such diverse locations as the Canadian high Arctic (Pollard 1991), Greenland (Dijkmans 1988), northern Sweden (Malmström 1987), and Mongolia (Froehlich and Slupik 1978). In addition, several studies have reported on palsas which might more properly be identified as seasonal frost mounds (e.g. Brown *et al.* 1983, Nelson *et al.* 1985, Thórhallsdóttir 1994).

Seasonal frost mounds differ from palsas in formation and duration. Seasonal frost mounds contain intrusive ice developed by hydraulic or hydrostatic pressures acting on groundwater trapped in the remaining unfrozen sediments of the active layer during freeze-back (Pollard and French 1983, van Everdingen 1978). As the term suggests, seasonal frost mounds typically grow in one freezing season and normally degrade the following summer. Some may persist for several years or regenerate in the same location from year to year. High groundwater pressures cause seasonal frost mounds to grow rapidly, up to 0.5 m/day (van Everdingen and Banner 1979).

There are three main types of seasonal frost mounds: frost blisters, icing mounds and icing blisters. Most frequently, seasonal frost mounds are found in: 1) areas of high relief where perennial groundwater springs provide suitable hydrological conditions; and 2) areas with permafrost close to the ground surface that can constrict the flow of groundwater as the freezing front penetrates the active layer (Pollard and van Everdingen 1992).

2.2.1 Icing Mounds and Icing Blisters

Icing mounds and icing blisters are comprised entirely of ice and have similar external morphology. These two types of seasonal frost mounds can only be differentiated by examining their internal structure. Icing mounds consist of ice produced from freezing of successive flows of water that has been forced by hydraulic or hydrostatic pressures to the surface through tension cracks or other areas of weakness (Pollard and van Everdingen 1992, van Everdingen 1978). The resultant stratigraphy consists of thin, horizontal or gently dipping layers of pale-white or clear ice. Icing mounds are reportedly circular in shape, ranging from 1 to over 3 m in height and up to 40 m in diameter (Pollard and French 1983, French 1996 p. 76).

Icing blisters are formed from the upheaval of ice layers by water under hydraulic or hydrostatic pressures. The surface layers of ice, 40-130 cm thick, are arched over an ice core, water-filled or empty cavity if the ice blister is ruptured (Pollard and van Everdingen 1992). Ice blisters are oval in shape, ranging from 1 to over 2 m in height, 2 to 23 m in length, and with widths generally one-third or one-half the lengths (Pollard and French 1983).

Since icing mounds and blisters have no insulating sediment or peat coverings, their decay can be rapid, and is often completed by early summer. These features only survive for one freezing season.

2.2.2 Frost Blisters

Frost blisters are similar in form to icing blisters but differ because sediment layers overlie the ice. A frost blister has an ice core formed from groundwater injected between the permafrost and the freezing active layer. The water remaining in the residual unfrozen zone of the active layer is constricted, resulting in increased hydraulic potentials (Pollard 1988). The mound develops when the hydraulic pressures exceed the resistance of the overlying materials. Frost blisters typically range from 0.5 to 5 m in height, but have been reported to be up to 8 m high (Pollard and van Everdingen 1992). Their diameters range from a few metres to over 100 m.

Their internal structure consists of seasonally frozen sediments covering a body of massive ice arched over a water-filled cavity. The water-filled cavity may freeze completely depending on the volume of cavity, the temperature regime and the thermal diffusivity of the overlying sediments (Pollard and van Everdingen 1992). It is also not uncommon for groundwater pressures to exceed the strength of the overlying sediments and cause the frost blister to rupture (van Everdingen 1982). In this case, the cavity will remain empty, unless the frost blister is able to reseal itself and continue to grow.

The decay of frost blisters is slower than that of icing mounds and icing blisters. Dilation cracks that expose the ice body and drainage of the water-filled cavity, along with warmer summer temperatures, ultimately cause degradation. However, the thermal conductivity of the overlying sediments and organics can insulate the massive ice body in the core of the frost blister from warm summer temperatures (Pollard 1988). If the overlying materials are sufficiently thick, the frost blister can remain intact for more than one freezing season.

2.3 Summary

It is evident that palsas and frost blisters can be morphologically similar, while pingos are generally much larger and can usually be identified by external characteristics. If their internal structure is not examined thoroughly, errors in identification can be made. Palsas form by processes of ice segregation whereas frost blisters form by processes of ice injection. It is therefore essential to examine the cryostratigraphy of frost mounds in order to identify them accurately. The use of sequential aerial photographs can also facilitate the identification and interpretation of mounds which are not cored, as it is known that palsas last much longer than frost blisters. Consequently, mounds present on sets of aerial photographs taken several years apart should be palsas.

3. STUDY AREA

The Wolf Creek Research Basin is situated 20 km south of Whitehorse, Yukon Territory in the sporadic permafrost zone (Heginbottom *et al.* 1995). The watershed occupies an area of ~190 km^2 with elevations ranging from 750 to 2250 m a.s.l. (Figure 3.1), and is part of the southern Yukon headwater system for the Yukon River. The specific study site can be found on NTS map 105D/6, at a scale of 1:50 000.

Frost mounds in Wolf Creek have not been studied in any detail previously. The advantages of the location include: (1) its proximity to Whitehorse, allowing easy access to the site as well as a long climate record; (2) the availability of numerous sets of aerial photographs of the region; and (3) the potential for permafrost features to be responsive to climate due to the region's southern location within the sporadic permafrost zone.

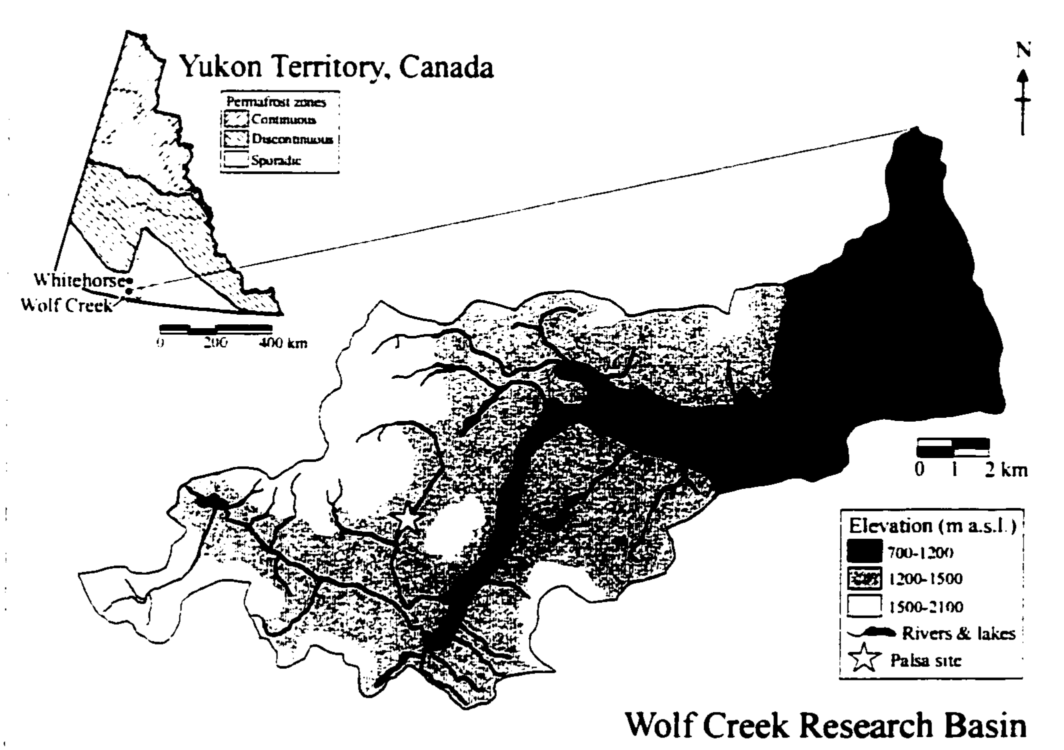

Figure 3.1: Permafrost zones of Yukon Territory (modified from Heginbottom *et al.* 1995) and elevations of the Wolf Creek Research Basin (modified from Seguin *et al.* 1999).

3.1 Quaternary History and Geology

The Wolf Creek Research Basin lies within the transitional zone between the Coast Mountains and the Yukon Plateau (Bostock 1948). The area is characterized by a relatively smooth, gently rolling upland surface with intermittent conical peaks or groups of peaks and U-shaped valleys (Wheeler 1961). During the last advance of the Cordilleran ice sheet, glacier movements in the southwest portion of the map area were mainly northward, flowing from an ice-divide in the Coast Mountains, called the Coast Mountain lobe.

Glacial action deepened the larger lakes in the map area, whereas smaller lakes, such as Coal Lake, are in valleys once dammed by glacial and fluvial material (Wheeler 1961). Large valleys in this part of the map area are commonly narrow, deeply incised and extensively scoured due to glacial movements (Janowicz 1999). Deglaciation of the Coast Mountain lobe is believed to have been southward, and led to the development of deglaciation features such as abandoned melt water channels, shorelines of proglacial lakes, kame terraces, lateral and frontal moraines, eskers, and elongate drift ridges (Seguin *et al.* 1999, Wheeler 1961). A subsequent alpine glaciation during the "Little Ice Age," resulted in the formation of many cirques, including the Coal Ridge cirque (Wheeler 1961).

Bedrock geology of the area consists mainly of Upper Triassic to Lower Cretaceous sedimentary rocks, including greywacke, argilite, limestone, sandstone, siltstone, and conglomerate. Also present in the area is andesite, basalt, quartz and intrusions of granite. The bedrock is overlain by a stony glacial till ranging from thin veneers to areas with depths of 1 to 2 m thick (Janowicz 1999). Fine-grained alluvium covers valley floors adjacent to areas of drainage and thin deposits of colluvial material and bedrock outcrops are present at higher elevations. Other surficial deposits are glaciofluvial and glaciolacustrine in origin (Francis *et al.* 1999, Janowicz 1999).

3.2 CLIMATE

The basin has a subarctic continental climate characterized by large seasonal temperature amplitudes, low relative humidity and low precipitation. The mean air temperature (MAT) from April 2001 to April 2002 for the site, measured on the summit of Mound 9C at an elevation of 1235 m, was approximately -4°C, with maximum and minimum hourly temperatures of +25°C and –36°C respectively (Figure 3.2). The MAT of –4°C is roughly in accord with Whitehorse, Yukon Territory (mean annual air temperature of approximately –1°C at ~700 m a.s.l.) given a lapse rate of 5-6°C/1000 m (Figure. 3.3). However, it is speculated that the MAT of Wolf Creek is most likely lower than -4°C due to particularly warm temperatures recorded in January 2002. Like other parts of the basin, the valley probably experiences air temperature inversions in winter (Janowicz 1999).

Several years of climate data have also been collected from 6 stations located 5-10 km north of the study site. The mean annual precipitation recorded from these stations is 300 to 400 mm, with 40% falling as snow (Janowicz 1999). Climatological investigations from 1996-1997 determined that rainfall typically occurs as low magnitude events lasting up to several days, and that snow depths are greater on north-facing slopes below the treeline than south-facing slopes due to higher sublimation rates on the south-facing slopes (Woo and Carey 1999).

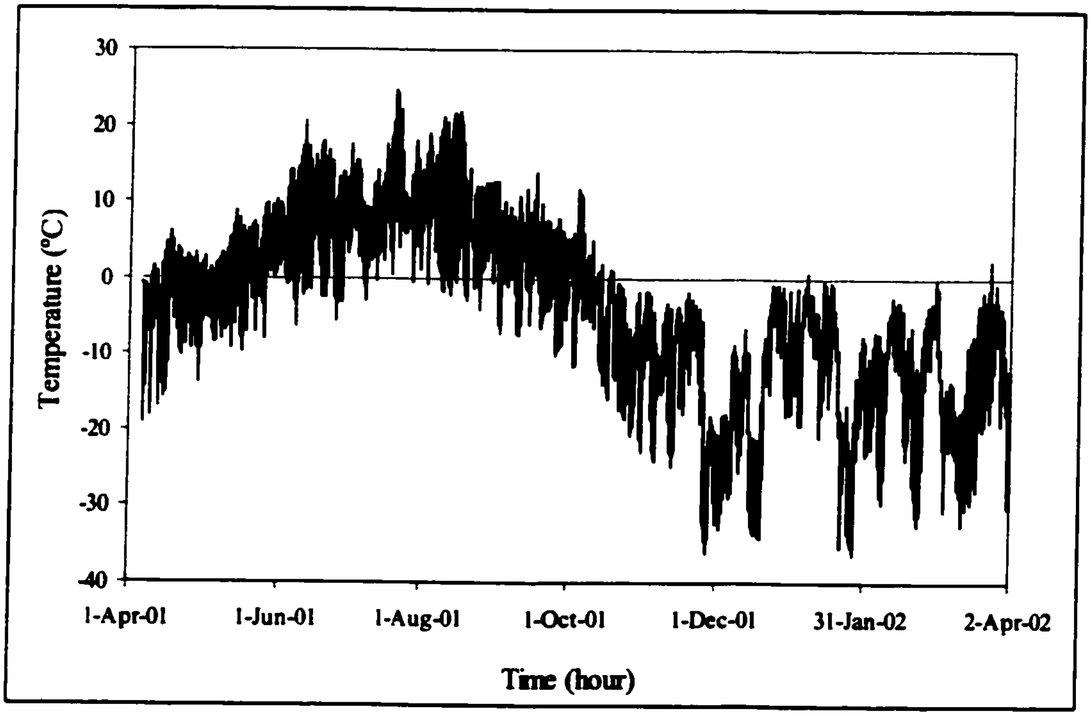

Figure 3.2: Hourly temperatures recorded on the summit of Mound 9C from April 2001 to April 2002. Note the particularly warm temperatures in January 2002.

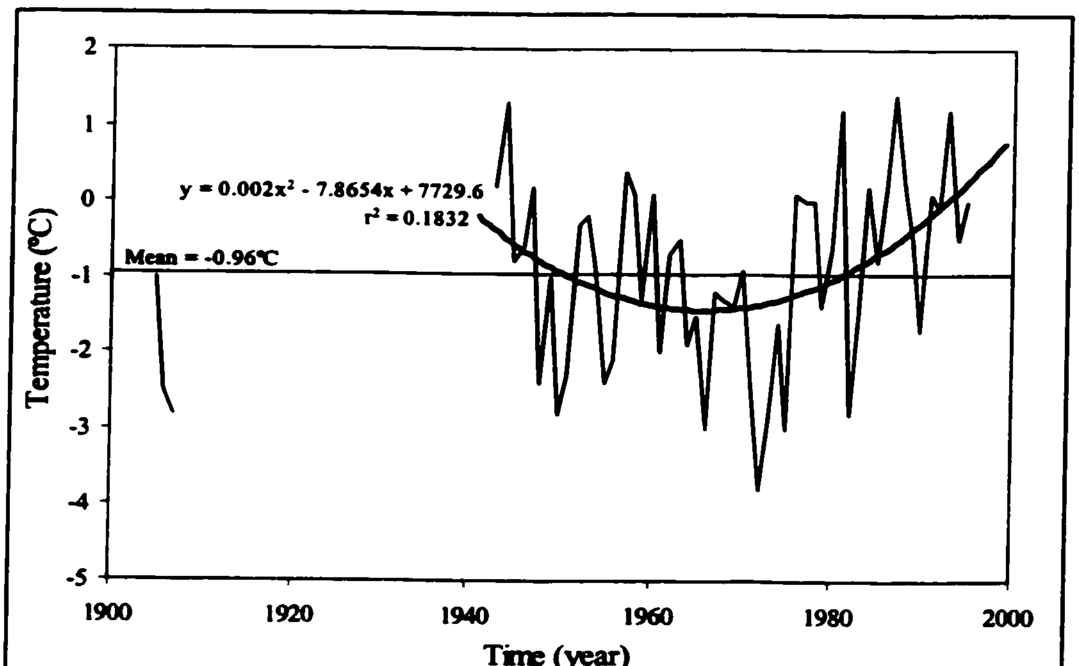

Figure 3.3: Mean annual air temperatures for Whitehorse, Yukon Territory (60°42'N, 135°04'W) at elevation of 706 m a.s.l. from 1905-1907 (Canadian Climate Normals) and 1941-1999 (Vincent and Gullett 1999). Note: trend line is only based on the 1941-1999 data.

Woo and Carey (1999) noted that south-facing slopes received higher incoming short-wave radiation than the north-facing slopes. Vegetation studies also demonstrate the impact of reduced levels of insolation on north and east-facing slopes (Francis *et al.* 1999). Differences in insolation levels also occur between mountain summits and valley bottoms. The valley bottom where the mounds are found is affected by shading from Coal Ridge to the east and an unnamed mountain with a peak at 1900 m a.s.l. to the west. This reduces the hours of direct sunlight in summer. Analysis using a 30 m DEM and Solar Analyst software (Fu and Rich 1999) showed that modelled incoming radiation over the thaw season (May 15 – September 30 2001) was 5% lower than on a fully exposed horizontal surface (M. Ednie, *Department of Geography, University of Ottawa, personal communication 2002*). This may be a factor in permafrost development at the site.

3.3 Groundwater and Hydrology

Previous studies have determined that Wolf Creek has a mountainous subarctic streamflow regime, characterized by peak flows of 10-20 m^3/s in late May or early June from snowmelt, and lowest flows during March. On average, winter flows in the area are higher than expected, 0.4 m^3/s, due to lake storage and groundwater contributions (Janowicz 1999).

Observations during April 2001 and 2002 found icings up to 1 m thick covering the valley floor at the study site. During the summer of 2001, there was evidence of groundwater flow within the area. Large areas of the valley sides had substantially different vegetation patterns probably due to the influence of icing development in the winter. It was in these areas that a number of small mound forms were found. Springs were also found in a number of places at the study site, and measurements indicated high conductivities, suggesting intra-permafrost or sub-permafrost groundwater flow.

3.4 VEGETATION

The Wolf Creek Research Basin consists of three main ecological zones that roughly correspond to elevation. A boreal forest zone exists at elevations <1200 m a.s.l, and represents 22% of the total basin area. This zone is dominated by white spruce and lodgepole pine, but also supports such deciduous species as aspen, bearberry, willow and birch. There is no evidence that the basin has experienced a fire within the last 150 years (Francis *et al.* 1999).

A sub-alpine zone exists roughly between 1100 and 1500 m a.s.l., and accounts for 58% of the total area. Shrub willow and shrub birch species are most common at the elevations with occasional white spruce stands and grass-sedge meadows. Above 1500 m a.s.l. is the alpine zone. Representing approximately 20% of the total area, the alpine zone consists of various tundra vegetation communities and unvegetated areas (Francis *et al.* 1999). The transition between these three broad ecological zones is often gradual and difficult to delineate spatially due to the topographic characteristics of the watershed (Francis *et al.* 1999).

The mounds are found within the sub-alpine zone at approximately 1235 m a.s.l. The area supports both shrub willow and shrub birch species and grass-sedge meadows. The areas of grass-sedge meadows are related to zones that are frequently covered by icings in the winter. Areas of peat are present along the course of Wolf Creek and have not previously been reported.

3.5 Soils

Previous studies have determined that soils in valley bottoms are orthic regosols with a range of textures from gravels to clays (Janowicz 1999). These soils commonly result from intermittent flooding and deposition of material (Agriculture Canada 1987). The parent material is a combination of alluvium, lacustrine deposits, and till that ranges from poorly to well-drained.

Soils at higher elevations are orthic eutric brunisols with a range of textures from sandy loam to gravely sandy loam. These soils commonly form on parent material on upland forests and shrublands (Agriculture Canada 1987). The parent material is mainly comprised of a moderately stony till and is well-drained.

During the summer field season, the stony nature of the sediments was evident on numerous occasions at the study site, causing frost probing and manual excavations to be very difficult. Only in the larger frost mounds were sediments mainly fine-grained, but even here large boulders and gravel were present.

3.6 Permafrost

Although the Wolf Creek Research Basin has been the focus of a number of hydrological, geophysical, ecological, and biological studies, little work has been conducted on permafrost within the catchment. A preliminary study suggests that permafrost occupies approximately 25 to 32% of the Wolf Creek basin, and is predominately found on the north-facing slopes and at high elevations (Seguin *et al.* 1999).

The current study shows that permafrost exists within the basin in a number of mounds at 1235 m a.s.l. Permafrost is also present around thermokarst lakes in glaciolacustrine silts and sands south of the inlet of Coal Lake, at an elevation of approximately 1150 m a.s.l. An exposure on the side of one of the thermokarst lakes on August 17th 2001, showed regular and irregular reticulate ice lenses ranging from 0.5 to 20 cm in thickness.

3.7 Study site

The main groups of frost mounds are located in a NE-SW trending valley centred at 60°30'N, 135°13'W. Forty-nine frost mounds were found within a fen that ran along an approximately 1 km long stretch of the main stream channel (Figure 3.4A and B). The larger mounds are divided into the north group and south group, and other smaller mounds are present on the valley slopes between the two groups of larger frost mounds, approximately 30 m from the bank of the creek. Two other mounds, located 1.3 km south and 2.2 km southeast from the south group were also studied.

Figure 3.4: A) Study area illustrating the main study site which consists of Mounds 1-51 (Air photo A27127-120, Aug 25th 1987 National Resources Canada); B) Oblique view of main study site (within box).

4. METHODS

4.1 AERIAL PHOTOGRAPHIC INTERPRETATION

Changes in the size and distribution of the frost mounds in Wolf Creek were examined using aerial photographs dating from 1946 to 2001 at various scales (Table 4.1). This method has been used in a number of studies to calculate percentage changes in the distribution of mounds (e.g. Horvath 1998, Sollid and Sørbel 1998, Sone and Takahashi 1993, Zuidhoff and Kolstrup 2000).

Table 4.1: Aerial photographs available for the Wolf Creek study site.

Aerial Photograph Series	**Frame Numbers**	**Date**	**Scale** (at elevation 1250 m)
A10553	121-122	Aug 25th 1946	1 : 20800
A10558	29-30	Aug 25th 1946	1 : 20800
A10569	11-13	Aug 26th 1946	1 : 20800
A19425	64-66	July 11th 1966	1 : 51800
A27018 – Infra-red	229-230	August 1986	~1 : 40000
A27217	120-121	Aug 25th 1987	1 : 39800
A27327	1-2	September 1988	1 : 43800
A28238	6-10	September 1995	1 : 21800
A28474	206-207	Aug 10th 2001	~1 : 10000

Source: National Air Photo Library, Natural Resources Canada.

The aerial photographs were examined with a binocular stereoscope to identify the locations of the frost mounds prior to going into the field. This proved difficult due to their small scale and the poor tonal contrast of some of the photographs. After the field season, however, it was possible to identify the larger frost mounds found in the basin, as well as other frost mounds that were no longer present, but were visible on earlier aerial photographs.

The series selected to map the distribution of frost mounds were A10569 (1946), A19425 (1966), A27217 (1987), A28238 (1995) and A28474 (2001). The 2001 aerial photographs were actually taken during the field season, which allowed a direct comparison between the map made from a topographic survey and the photographs. The aerial photographs were scanned into CorelDraw 8 and area maps were made directly from the photographs. This method proved to be a quick and effective method of mapping the distribution of mounds and water bodies for the selected years.

4.2 FIELD METHODS

4.2.1 Topographic survey

A Nikon NE-10LA digital theodolite and 5 m stadia rod were used to conduct a detailed topographic survey of the study site to map the area and facilitate the interpretation of aerial photographs. Where appropriate, an e-Trek Summit hand-held GPS unit was also used to facilitate mapping the area. The highest points on each frost mound were surveyed, as were perimeter locations every 3-5 m around the base. Less detailed grid-based maps were also made of two areas of smaller mounds discovered later in the field season when surveying equipment was no longer available. Beaver dams were also surveyed, none of which were actively ponding water within the study site in 2001 or 2002 (A. Lewkowicz, *Department of Geography, University of Ottawa, personal communication 2002*). However, an intact dam with a large associated pond was present 400 m upstream from the site and beaver were observed in the stream.

4.2.2 Description of frost mounds

Each mound was classified into one of three stages of growth: aggrading, stable, or degrading (Cummings and Pollard 1990). This classification was done qualitatively according to height, vegetation and evidence of degradation (Table 4.2). The following table was designed only to be used in reference to the characteristics of the features currently found within Wolf Creek. Conditions in other locations would likely change the characteristics of each growth stage in the table. During the survey, the depth to the frost table was measured in a minimum of four places on the summit of each large frost mound with a standard frost probe.

Table 4.2: Growth stage classification system used at Wolf Creek, Yukon Territory.

Growth Stage	Height	Vegetation Coverage	Evidence of Aggradation or Degradation
Aggrading	0.5 to 1.5 m	Peat or grass covered	Dilation cracks
Stable	1 to 4 m	Shrubs and grasses	None
Degrading	2 to 4 m	Shrubs and grasses	Stress cracks and visible areas of block collapse

4.2.3 Vegetation

The percent cover of shrubs and grasses was estimated visually on each frost mound and the dominant shrub, either willow or birch was noted. Up to four shrubs were cut for annual growth ring analysis from the summit area of each frost mound. The largest shrubs were selected for sampling as it was expected that the largest shrubs would be the oldest. Shrub species have prostrate branches that radiate from a central burl, where the greatest number of annual growth rings is found (Beschel and Webb 1962). To ensure that the maximum age of the shrubs was recorded, the "burl" or "root-crown" of the shrubs was excavated from just below the ground surface. Due to the high mortality rate of shrub willows (Bryant 1987), it was difficult to find trees that did not have rotten piths on several mounds.

4.2.4 Internal mound structure

Seven of the large frost mounds were cored with a hand-driven 75 mm diameter CRREL auger in order to examine their cryostratigraphy. A hole was first excavated manually to the frost table on each of the selected frost mounds, and then the auger was used on frozen sediment. From 5 to 20 cm of core was extracted at a time. The depth of the borehole was measured using a tape measure suspended from a bar placed horizontally across the top of the borehole. This method proved more accurate than measuring the extruded core sections which were often broken along lenses.

Typically, each section of the core was described in the field immediately, and then placed into labelled ziplock bags for later laboratory analysis in Ottawa. The field description included general grain-size, Munsell colour, and tentative cryostructure identification following the method outlined by Murton and French (1994). However, when ice lenses were >1 cm thick and continuous throughout the width of the core barrel, it sometimes proved difficult, or impossible, to determine if the cryostructures were segregation ice or intrusive ice forms.

It was the intent to core to the bottom of permafrost on each mound, but this proved impossible. The sediment was often stony, and hitting rocks deep in the core prevented the auger from penetrating further. Large ice lenses also proved to be quite difficult to penetrate, as the blades of the auger skidded over them. Persistence and three people on the auger were needed to get through some of these lenses. Lastly, it was suspected that the bottom of permafrost could be in excess of 5 m deep on the largest mounds (e.g. Allard *et al.* 1986), and it was not necessary to reach it in order to establish mound origin.

4.2.5 Air and ground temperatures

Air temperature was recorded on the summit of Mound 9C by a shielded Onset Hobo Pro logger at hourly intervals at a height of 1.5 m from April 6th 2001 onwards. Temperature data from April 6th 2001 to April 1st 2001 were retrieved from the data logger and a mean annual air temperature was calculated from this.

4.2.6 Water conductivity

Various areas of surface water, groundwater and ice were tested for conductivity with a YSI conductivity probe. Field measurements were made by inserting the probe directly into the water body or sample bottle within 24 hrs of their collection. Specific conductance of the melted ice from the cores was measured in the laboratory with a TDS Tester 3^{TM} w/ATC to 25°C. The conductivity of the samples from the field was converted into specific conductances by increasing the original value by 2% for every degree Celsius below 25°C (Wetzel 2001). These results proved useful in determining the possible maximum depth of thaw of the cored mounds (Brouchkov 2002).

4.2.7 Snow profiles

M. Phillips and A. Lewkowicz completed snow surveys on one small mound (Mound 20) and on one large mound (Mound 12) in April 2001. In April 2002, A. Lewkowicz and A. Lewkowicz-Lalonde completed snow surveys on the same two mounds, as well as on all other frost mounds that had been cored in the summer of 2001. Snow depths were measured at 1 m intervals using a graduated steel probe on approximately north - south transects that passed over the highest points of the mounds.

4.3 Laboratory Methods

4.3.1 Gravimetric moisture content and excess ice

Gravimetric moisture content was established following ASTM guidelines. Each sample was placed in a beaker, the wet weight (Ww) of the sediment was measured, and it was covered with plastic wrap to prevent evaporation or contamination while allowing the sediment to settle out of the supernatant water. The approximate volume of the supernatant water (Vw) and sediment (Vs) were recorded to calculate excess ice content:

$$\text{Excess ice content} = [(Vw)/(Vw+Vs)]*100 \quad (1)$$

The water was then decanted into a glass vial to store for possible tritium analysis. The sediment remaining in the beaker was oven-dried for 24 hrs at 105°C, and the dry weight (Wd) was recorded (ASTM 2001b). The gravimetric moisture content was calculated from:

$$\text{Gravimetric moisture content} = [(Ww-Wd)/(Wd)]*100 \quad (2)$$

The drying process solidified the wet samples, and it was necessary to break them up with mortar and pestle. The samples were then sub-sampled with a soil splitter for grain-size analysis.

4.3.2 Grain-size analyses

The coarse fractions (sand and gravel) were determined using ASTM guidelines for wet sieving. From 50-70 g of each sample were taken and soaked in Sodium Hexametaphosphate ($Na_6O_{18}P_6$) for 48 hrs. The mixture was then put in a milkshake mixer for approximately 1 min. and poured into sieves with openings of 4 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm, 125 μm, and 63 μm. The portions left on each sieve were collected, oven dried, and weighed (ASTM 2001a).

The granulometry of the fine fraction (silts and clays) was determined using a Laser Particle-Size Analyzer (PSA). Prior to this, organics were removed with 30% H_2O_2 (Kunze 1965). 10-20 g of each sample was placed in 1000 mL beakers, and 50 mL of 30% Hydrogen peroxide was added. After 24 hrs, another 50 mL of 30% H_2O_2 was added, and the mixture was warmed. It was determined that for samples that had an LOI of less than 6%, 200 mL was a sufficient amount of 30% H_2O_2 to remove the organics. For those samples that had an LOI greater than 6%, 300 mL was used.

After the organics had been burned off, the samples were air-dried and transferred to jars to soak in approximately 50 mL of 50 g/L $Na_6O_{18}P_6$. The samples soaked for 2-3 days before taking them to the Geological Survey of Canada (GSC) sedimentology laboratory for laser particle size analysis (PSA) with the LECOTRAC™LT-100 version 7.01 and LECOTRAC™ASVR systems.

At the GSC laboratory, samples were mixed with a milk shaker mixer for 1 min. with deionized water. The samples were wet sieved through a 90 μm sieve into a 1 L plastic beaker ensuring no sediment was splashed or spilled. The sediment retained on the 90 μm sieve was discarded. The portion that passed through the sieve was placed on a bench stirrer to keep the particles in suspension. To run the particle size analysis, the LECOTRAC™ASVR was set to flow and allowed to de-aerate for one minute. After identifying the sample number, the load setting was activated. Approximately 4 mL of the suspended sediment sample was taken with a plastic syringe and placed into the reservoir. The sample was exposed to 30 seconds of ultrasonic waves to break up any aggregates before the "run" function was activated. The LECOTRAC™ASVR provided the percent cumulative grain-sizes below 63 μm, and this was added to the results from the wet sieving to calculate grain-size statistics.

The graphical median, mean, standard deviation (sorting), skewness, and kurtosis of each sample were calculated using the cumulative grain-size curve and phi scale. The following equations were implemented by interpolating the percentile values from the cumulative curves (Folk 1974):

$$\text{Median} = \Phi 50 \quad (3)$$

$$\text{Mean} = (\Phi 16 + \Phi 50 + \Phi 84) / 3 \quad (4)$$

$$\text{Standard Deviation} = [(\Phi 84 - \Phi 16)\ 4] + [(\Phi 95 - \Phi 5) / 6.6] \quad (5)$$

$$\text{Skewness} = [(\Phi 84 + \Phi 16 - 2(\Phi 50)) / 2(\Phi 84 - \Phi 16)] + [(\Phi 95 + \Phi 5 - 2(\Phi 50)) / 2(\Phi 95 + \Phi 5)] \quad (6)$$

$$\text{Kurtosis} = (\Phi 95 - \Phi 5) / [2.44 * (\Phi 75 - \Phi 25)] \quad (7)$$

4.3.3 Loss on Ignition

Weight-loss-on-ignition (LOI) is a simple way to approximate the percent organic content (Bengtsson and Enell 1986). Approximately 5 g of sediment was placed in clean weighed crucibles and placed overnight in an oven at 95°C. The sample was cooled to room temperature in a dessicator and the dry weight (Dw) was measured. The crucible was then put in a muffle furnace set at 500°C for 3 hours, after which it was again cooled in a dessicator until at room temperature. The ignited sample was then weighed (Iw), and the loss on ignition was calculated:

$$\text{Loss on Ignition} = ((Dw-Iw)/(Dw))*100 \quad (8)$$

4.3.4 Analysis of shrub annual growth rings

Shrubs were cut from the summit area of Mounds 1-27.* The cut sections of shrubs were sanded with progressively finer sanding paper so that annual growth rings could be distinguished. The polished tree sections were examined under a 400x microscope. The age of each sample was recorded by counting the number of annual growth rings. In a few cases, the piths of the shrub sections were rotten, in which case an approximate age was inferred based on the number of countable rings plus an estimated number of years depending on the amount of rotten pith. In all but one shrub, the estimated age was not more than 5 years older than the countable annual growth rings. The counts of annual growth rings from shrubs sampled from the summits of the mounds extend the minimum ages of the mound beyond the earliest date of aerial photographs.

* Not all the mounds from 1-27 had shrubs. In these cases, the recorded shrub age was 0 years.

4.3.5 Tritium analyses

In the mid-1950's to early 1960's, hydrogen bomb testing elevated concentrations of tritium within the atmosphere. Ice that formed from precipitation that fell in the years soon after the bomb testing is higher in tritium than precipitation in pre-bomb or post-bomb years. As a result, the tritium content of an ice lens can provide an approximate date (Chizhov *et al.* 1985). The mean tritium concentration in precipitation in Whitehorse was ~4500 tritium units (T.U.) in 1963. In 2001, it would have decayed to ~550 T.U., as tritium has a half-life of 12.32 years (IAEA/WMO 2001). There was not a complete record of tritium in precipitation from Whitehorse, so a proxy record was derived from the more complete Ottawa, Ontario records (see Lewkowicz and Harry 1991). These estimated values were decayed to produce values that would represent the present-day tritium concentrations in the area (Figure 4.1). Precipitation from before the atmospheric bomb tests would have only a trace concentration of tritium, whereas, according to Figure 4.1, precipitation from after 1972 to 1999 would have a mean concentration of ~30 T.U.

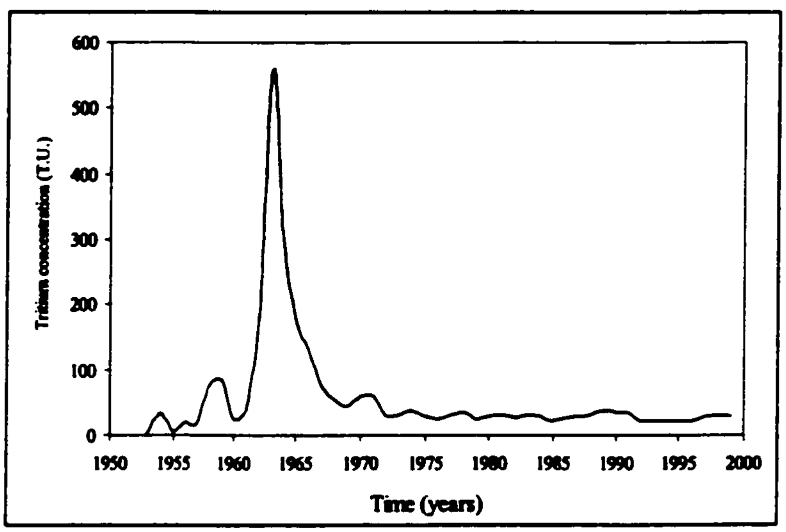

Figure 4.1: Estimated yearly mean tritium concentrations in precipitation for Whitehorse, Yukon Territory 1953-1999 derived from Ottawa, Ontario values. Concentrations shown have been decayed using a half-life of 12 years.

Supernatant water from each core sample was collected and refrigerated until being sent to the Environmental Isotope Laboratory at the University of Waterloo for testing. Since the core sections were generally 5 to 20 cm in length, they represented a number of years of freezing, and cannot be dated precisely. The bottom-most sample of the core is expected to be the youngest, and therefore would be most likely to show the elevated tritium levels of the 1960's.

The bottom-most ice sample of a degrading form (Mound 7A), and a stable form (Mound 9A), were sent for testing as well as three samples (at regular intervals) of aggrading Mounds 10 and 17. The bottom-most sample of Mound 39, found on the valley slope, was also tested. Unfortunately, all tritium concentrations were too low to draw any conclusions about when the ice formed (Table 4.3). These results could be interpreted as ice forming either from precipitation that fell pre-bomb testing, suggesting possibly groundwater with a long residency time was supplying the mounds, or as recent winter precipitation, which has low to negligible tritium concentrations (Burn 1990, Chizhov *et al.* 1985). For this reason, the results of the tritium analyses will not be discussed further.

Table 4.3 Tritium concentrations in the cores of the mounds.

Mound #	Depth in core (cm)	Tritium Concentration (T.U.)
7A	325-351	<6 ± 8
9A	207-214	<6 ± 8
10	36-51	9 ± 8
10	81-86	<6 ± 8
10	124-135	<6 ± 8
17	33-50	7 ± 8
17	72-80	<6 ± 8
17	105-110	14 ± 8
39	50-75	<6 ± 8

5. RESULTS

5.1 Aerial Photographic Interpretation

Aerial photographs from 1946, 1966, 1987, 1995, and 2001 were compared to examine changes in the distribution of frost mounds over the 55-year period. Only the larger mounds could be identified on the aerial photographs and it was not possible to infer the heights of individual mounds in the photographs. Therefore, although a mound appeared similar in size in all photographs, it may have increased or decreased in height. Consequently, it is possible only to examine the changes in areal extent of the larger frost mounds, and to determine if any large mounds completely degraded or aggraded over the time period. Changes in water levels around the mounds could also be examined. The sets of aerial photographs were taken at approximately the same time of year (see Table 4.1) so that the water levels should have been comparable.

Five maps were produced from the aerial photographs (Figure 5.1). The most obvious differences are the dramatic changes in the extent of surface water. Particularly high water levels occur around the north group of mounds in 1966 and 1995 due to the effects of beaver damming of mounds. High water levels around the south group are present in 1966 and 1987. The years 1946 and 2001 generally show lower water levels. The possibility of heavy or little antecedent precipitation events just prior to the aerial photography causing the differences in water levels between photos can be eliminated because the differences occur in relative surface water extent between the north and south groups of mounds in three of the five stereo-pairs (1946, 1987, and 1995). Moreover, the high water in 1966 can be attributed to beaver damming as the downstream edge of the

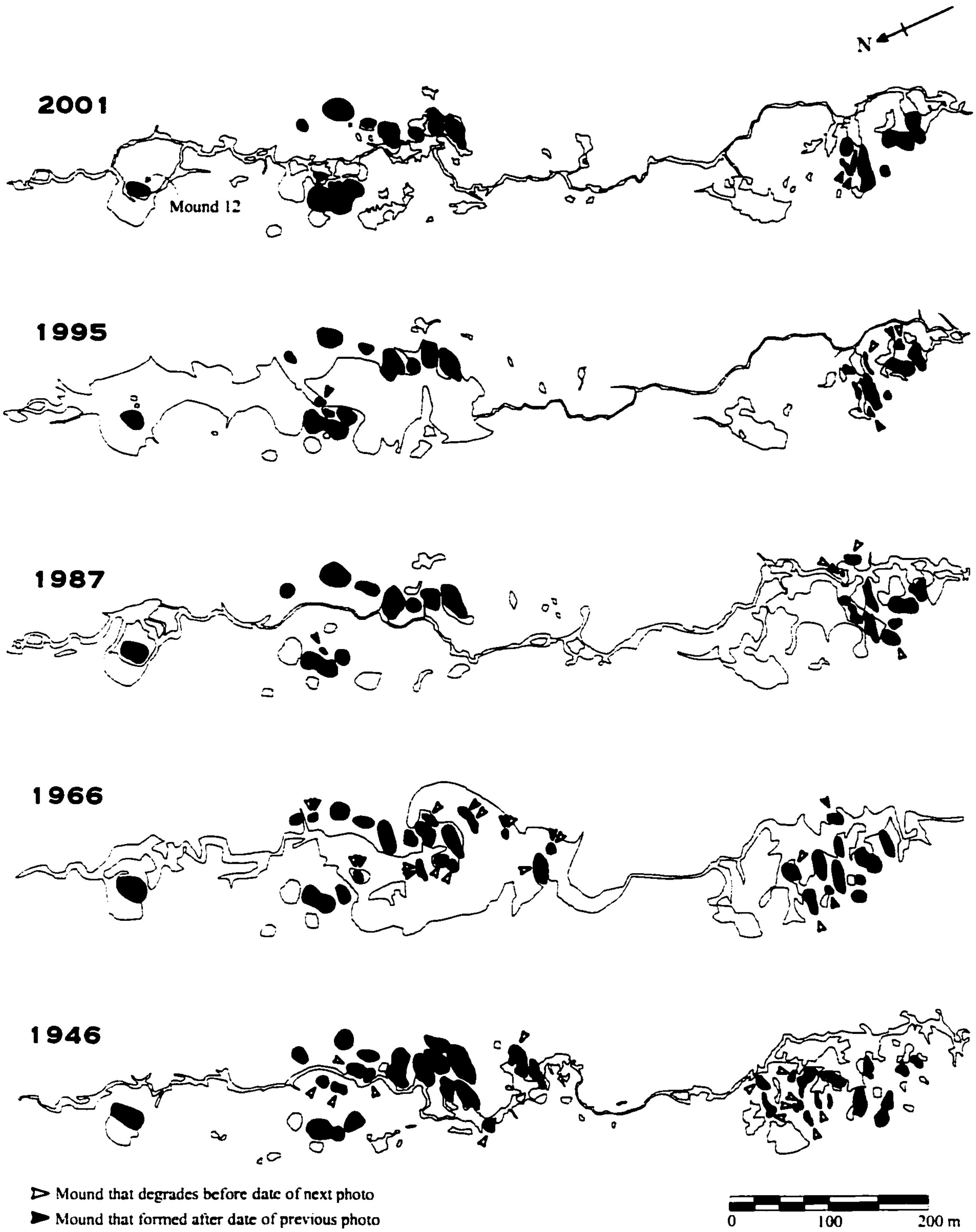

Figure 5.1: Maps of frost mounds and surface drainage at the main study site produced from the aerial photographs A10569 (1946), A16425 (1966), A27217 (1987), A28238 (1995) and A28474 (2001). Frost mounds are shown in black. Grey areas are surface water. Note: smaller mounds were not detectable using the aerial photographs.

pond surrounding the north group is the result of one of the ten breached dams identified during the summer field season (Figure 5.2A).

Photographs from sequential years (1986: A27018-229; 1987: A27217-120 (see Figure 5.1); and 1988: A27327-1) provide an indication of the rapidity of change in surface water extent. The northern group of palsas had relatively low water levels and the southern group had extensive ponding in 1986, a pattern that persisted in 1987 (see Figure 5.1). However, the 1988 photographs show much less water in the southern group, presumably due to a dam breach. Another example of change occurred between 1995 and 2001, when a dam was built ~400 m upstream of the study site and a pond with a surface area of 3500 m^2 developed. A second dam was constructed at the upstream end of this body of water between August 2001 and July 2002 (A. Lewkowicz, *Department of Geography, University of Ottawa, personal communication 2002*), creating an additional pond 1000 m^2 in area. These examples demonstrate that water levels in the study site and surrounding area can change rapidly, and certainly from one year to the next.

Although these beaver dams were not distinguishable on the aerial photographs, it can be concluded that the construction and breach of beaver dams are responsible for the major changes in surface water extent. There is also much evidence that shows that these changes have had an effect on the mounds.

Beaver damming has two potential effects on the distribution of frost mounds. First, high water levels can cause mound degradation. Thirteen mounds visible within the north group on the 1946 aerial photographs degraded during subsequent years of aerial photographs (see Figure 5.1). The 1966 photographs show most of these mounds to be entirely surrounded by water ponded by beaver dams. The 1987 photographs show much lower water levels similar to those in 1946, but by then, the mounds had completely degraded. Also, some of the mounds visible in 1946 had degraded prior to the 1966 photographs, indicating that high water levels were possibly present before 1966.

Second, beaver dams can aid the development of new palsas. Beaver dam collapse can quickly drain water from an area, as evidenced by field observations of peat draping on the branches of dead shrubs. Permafrost may aggrade in the newly exposed surface, and frost mounds may form. The 1995 photos show an area adjacent to Mound 9A experiencing flooding. By 2001, most of this area had drained, exposing fresh peat. Two small peat-covered mounds less than 1 m high (Mounds 17 and 18) were found growing in this area in 2001.

The maps produced from the aerial photographs show a decrease in the number of frost mounds, from 36 mounds in 1946 to 18 mounds in 2001. Most of the largest mounds appear in each set of photographs, except for those that were inundated by water in 1966. However, it must be stressed that smaller mounds are not discernible on the aerial photographs. Thirty frost mounds identified in the field in 2001 were not mapped from the 2001 aerial photographs. If it is assumed that the same number of indiscernible smaller mounds is present in each year, then it can be concluded that there has been an overall degradation of mounds within the area. However, the aerial photographic interpretation strongly suggests that aggradation or degradation of the frost mounds found at Wolf Creek is related partly or wholly to fluctuations in water levels due to the effects of beaver damming, so that no climate inferences can be drawn.

5.2 Description of the Frost Mounds

Forty-nine frost mounds were identified and mapped in the main study area (Figures 5.2 A, B, C) (Table 5.1). The largest mounds (Figure 5.2A) were clustered along the creek in two main groups: the north group (Mounds 1-18) and south group (Mounds 20-27). Two other groups of smaller mounds existed: i) the valley bottom east of the south group; and ii) between the north and south group on the west valley slope. All three stages of frost mound development (aggrading, stable, degrading) were evident. The stable and degrading mounds supported shrub willow and shrub birch colonies, as well as grasses and flowering plants, whereas the aggrading mounds generally had areas of exposed bare peat and some supported grasses*, flowering plants, and very young shrubs. Degrading mounds had signs of active block collapse, whereas aggrading mounds had dilation cracks.

Thirteen frost mounds, representing the three stages of development of frost mounds found in Wolf Creek, were cored and/or cross-sectioned. Two frost mounds, which were not cored, but provide important details on mound development, were also described in detail. For comparison purposes, a palsa located at Fox Lake, Yukon Territory, approximately 100 km north of Wolf Creek, was also cored.

* the use of the term "grasses" throughout the entire text implies both grasses and/or sedges.

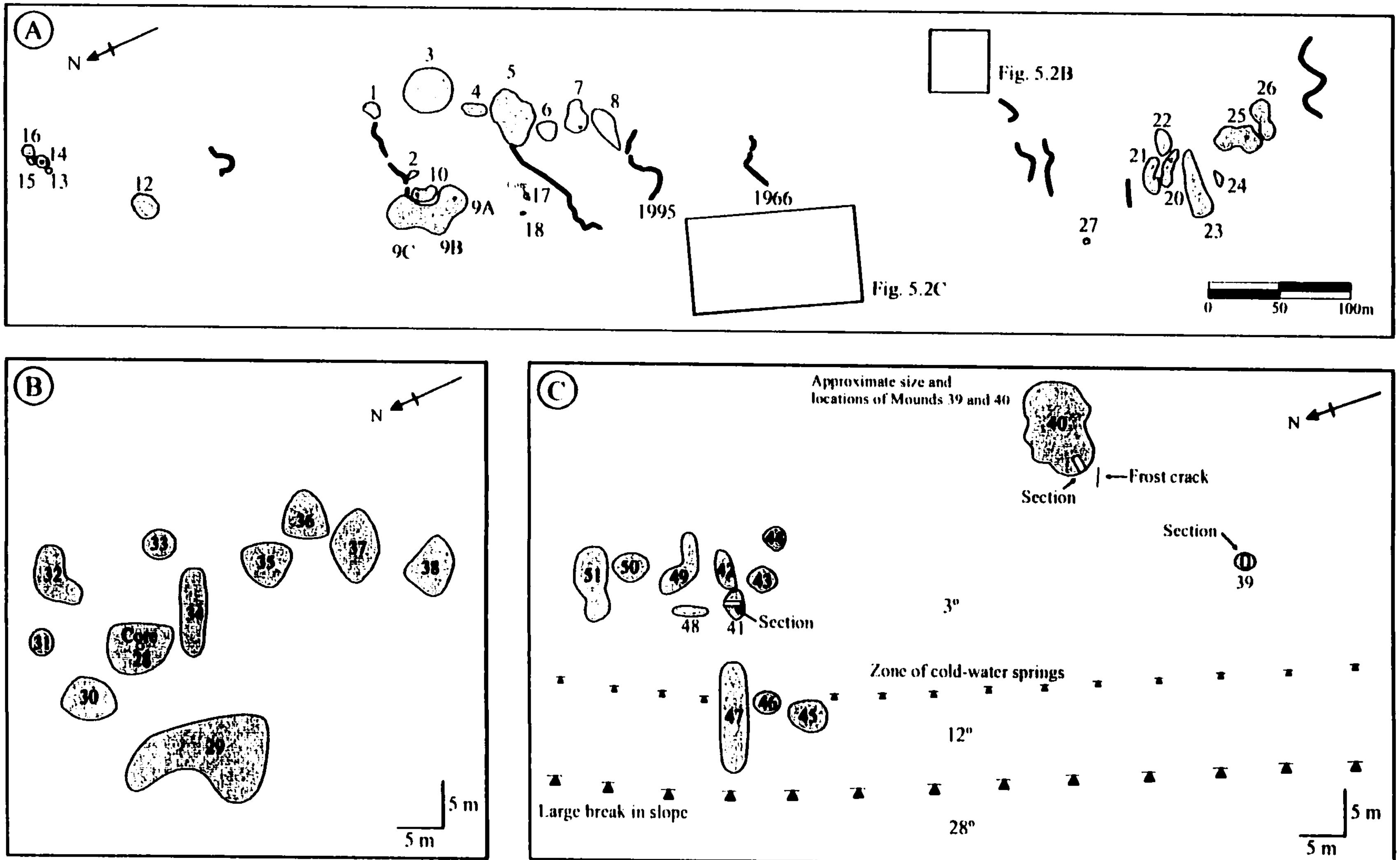

Fig. 5.2: A) Survey of the frost mounds (in grey) and beaver dams (thick black lines) in Wolf Creek (2001). Dams affecting drainage around the north group of mounds in 1966 and 1995 are labelled; B) Sketch map of frost mounds on east valley bottom; C) Sketch map of frost mounds on west valley slope. Note: no mound is designated "11" or "19".

Table 5.1: Frost mound inventory (note: there is no Mound 11 or 19*, estimated heights are indicated as ~, and sinuous mounds have maximum height and average width listed).

Mound	Height (m)	Length (m)	Width (m)	Mound	Height (m)	Length (m)	Width (m)
1	1.5	12	10	27	~0.4	5	4.5
2	~ 1.0	9	5	28	1.4	7	6
3	1.6	33	32	29	1.3	17	10
4	1.3	18	9	30	0.8	5	4
5	2.2	42	30	31	0.4	3.5	2.5
6	2.8	14	13	32	0.7	7	6
7 A	3.0	16	12	33	0.5	3	3
7 B	1.5	12	8	34	0.8	10	2
8	1.9	33	12	35	1.0	5	5
9 A	3.6	20	17	36	1.1	4.5	4
9 B	3.6	21	20	37	1.3	10	5.5
9 C	2.7	24	23	38	0.7	7	5
10	0.9	16	8	39	0.5	3	2
12	3.0	20	17	40	~0.8	16	12
13	0.3	6	5	41	0.7	3.4	2.3
14	1.1	11	9	42	0.7	2.8	1.5
15	1.0	10	8	43	0.3	3.4	3
16	0.8	6	4	44	0.4	3	2.6
17	0.7	10	8	45	0.3	3.4	3
18	~0.3	6	6	46	0.3	2.7	2.4
20	1.2 max	28	7 avg	47	0.7	12.3	3
21	1.2 max	27	9 avg	48	0.2	4	1
22	2.9	19	11	49	0.5	8.5	2
23	3.6 max	48	14 avg	50	0.7	4.3	3.5
24	0.7	11	6	51	0.6	10	6
25	2.7	34	18	52	~0.8	35	30
26	1.9	29	12	53	0.6	5	1

* These designations were applied to features which later analysis showed to be simple topographical highs.

5.2.1 Mound 7A

Mound 7A (see Figure 5.2A) is a degrading form, 16 m long, 12 m wide, and 3.0 m high (Figure 5.3A). It is conjoined to Mound 7B, which is 12 m long, 8 m wide, and 1.5 m high. The frost table depth on the summit averaged 90 cm on the north side and 125 cm on the south side (Aug 6th 2001). The vegetation on Mound 7A was patchy, consisting mainly of shrub willow, some shrub birch and grasses. There were more shrubs on the north side of the mound, while grasses dominated on the south side. Mound 7A could be seen on all the aerial photographs dating back to 1946, giving the form a minimum age of 56 years. The oldest shrub sampled was 80 years old. Allowing 5-10 years for initial colonization (Walkerton *et al.* 1986), the results from the annual growth ring analysis extend the age of the mound to a minimum age of about 90 years. A mean depth of 60 cm of snow on Mound 7A was measured April 1st 2002. The snow on the north side of the mound had a mean depth of 73 cm, and that on the south side averaged 82 cm. Snow on the summit of the mound averaged 43 cm.

The southwest side of Mound 7A showed signs of active block collapse, exposing a 10 m long section of mineral soil. The stratigraphy of Mound 7A was examined by clearing the section to a depth of 2 m. This showed curved bedding running parallel to the ground surface, indicating sediments were laid down horizontally prior to upheaving of the mound from aggrading permafrost. A large boulder (Figure 5.3B) estimated to be approximately 100 cm on its long axis was also found within the cleared section of unfrozen sediments. It is believed that this boulder was transported by mass movement from the surrounding slopes. Numerous ground squirrel burrows penetrated deep within the thawed layer of the mound, an observation repeated for several of the large mounds.

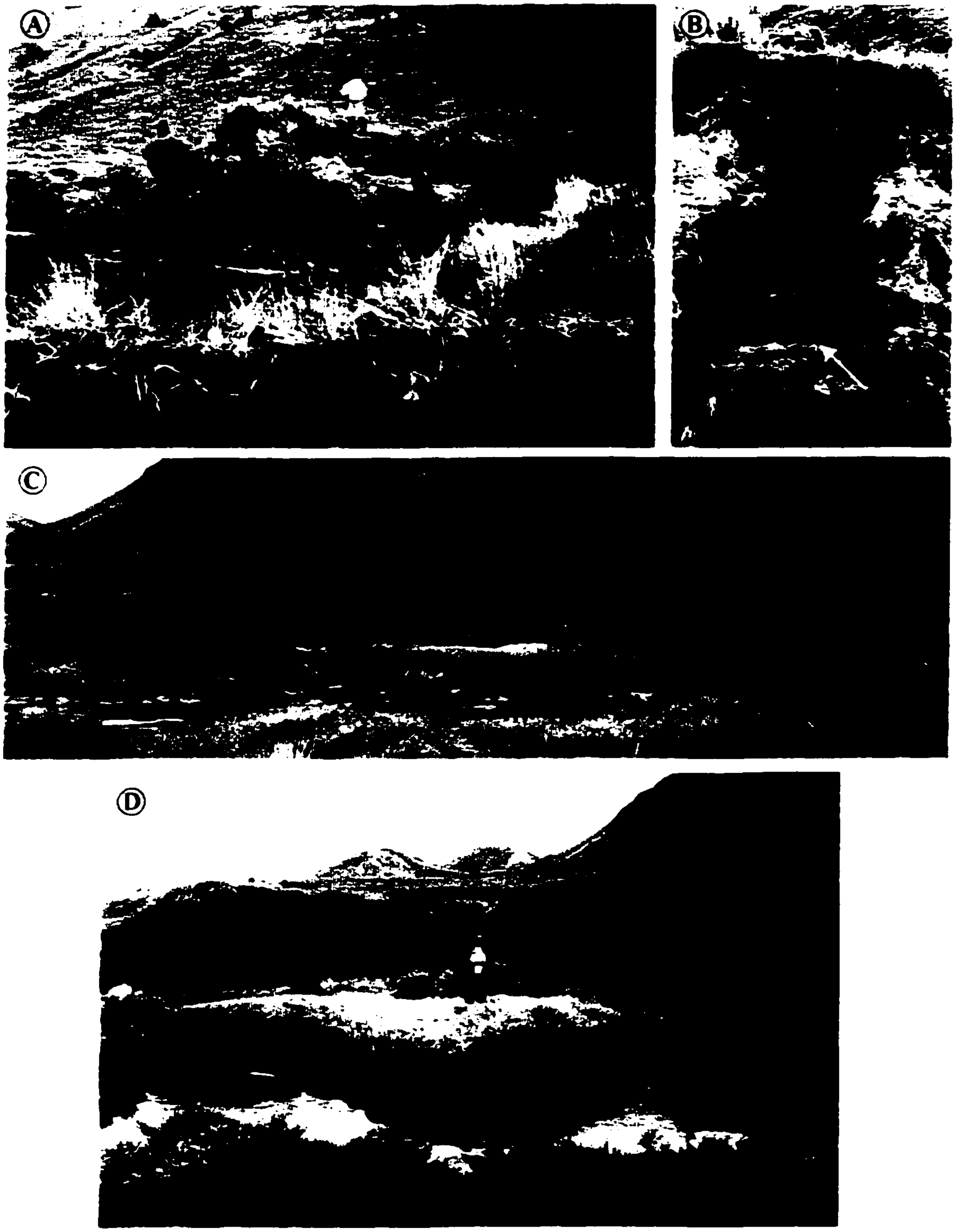

Figure 5.3: Photographs of Mounds 7A, 9A and 10: A) Mound 7A, note beaver dam in foreground; B) Depth of frost table marked with measuring tape and curved bedding of the sediment. Note the large boulder in centre of mound; C) Mound 9A (to left), 9B (in centre) and 9C (to right with air temperature sensor on mound summit) and Mound 10 in foreground with person for scale; D) close-up of Mound 10.

Mound 7A was cored beneath the section to a depth of 3.6 m, where auger refusal occurred within the frozen material. The borehole extended below the surrounding stream level. The peat layer on Mound 7A was 5-10 cm thick (Figure 5.4) and the frost table was at 135 cm (Aug 1st 2001). The sediments throughout the mound varied from organic-rich silty sands to sandy silts with traces of gravel and clay. Unfrozen sediments were dark yellowish brown (10YR 4/4) and frozen sediments were dark grey (10YR 4/1).

The cryostructures consisted of short, lenticular, parallel, wavy lenses that were 1-2 mm thick, 5-10 mm long, spaced 2-5 mm apart with lenticular, parallel 20 mm thick lenses interspersed throughout the core. The visible ice content and gravimetric moisture content increased with depth, as the ice lenses became larger and more frequent. From 254-280 cm and 310-325 cm, the core had a suspended cryostructure: the ice contained flattened bubbles up to 1.5 mm in diameter and thin sediment layers 2-5 mm thick. From 280-310 and 325-363 cm, alternating sediment and ice layers, 20-40 mm thick were found in association with a slight increase in gravel and sand content.

Temperatures were close to 0°C throughout the borehole and a value of –0.05°C was recorded at the base of the hole. The specific conductance was somewhat variable down core, with the lowest values coinciding with ice layers as a result of salt exclusion during the freezing process (Brouchkov 2002). The highest values, ranging from 670-810 μS/cm, were found in the upper 66 cm of frozen soil. Below this, the specific conductance values dropped, and steadily increased with depth. An increase in solute concentration with depth occurs due to the migration of water and salts with the downward advancement of the freezing front (Brouchkov 2002). The high values measured in the upper 66 cm of frozen sediments suggest that this section may thaw later

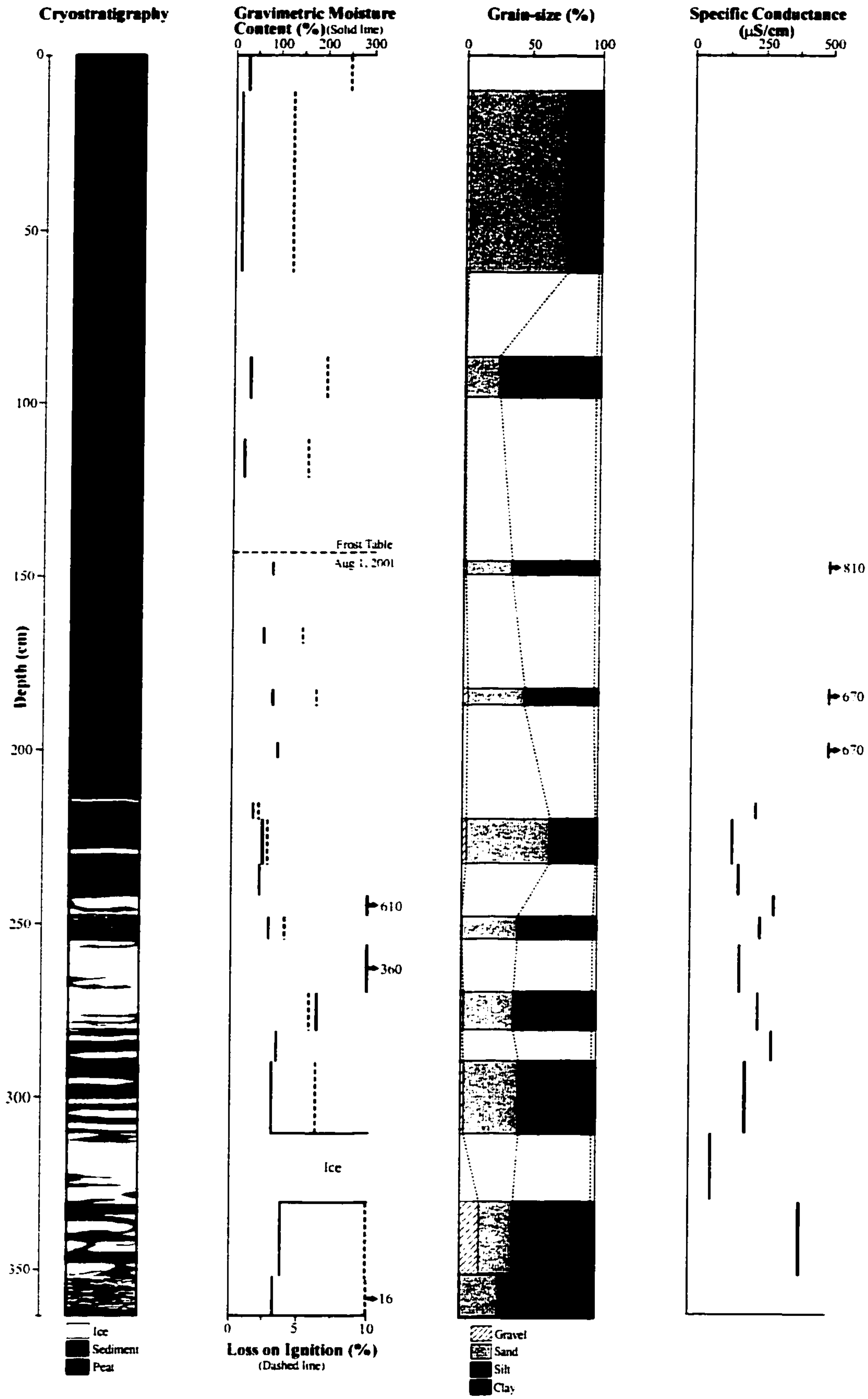

Figure 5.4: Core diagram of Mound 7A.

in the summer, or in certain warmer years. Similar trends in specific conductance were observed in most of the cores.

The curved bedding visible in the section demonstrated that the mound formed by upheaving. The cryostructure was consistent with ice segregation processes. However, the potential influence of groundwater pressures was revealed when the borehole filled up with water to the 220 cm depth the day after drilling, a level which was approximately 80 cm above the adjoining stream.

5.2.2 Mound 9A

Mound 9A is a stable form, 20 m long, 17 m wide, and 3.6 m high. It is part of a larger complex, consisting of three main peaks (9A, 9B, and 9C) (see Figures 5.2A and 5.3C). The whole mound complex is 57 m long and runs parallel to the valley bottom. Mound 9A is at the south end and has fewer shrubs than the other parts of the complex. It can be seen in all the aerial photographs, although it appears not to be conjoined to mounds 9B and 9C in the earliest sets. The oldest shrub sampled was 56 years old, so the minimum age of the mound is about 60 years. Shrub-covered areas had average frost table depths of 95 cm, whereas mainly grassy areas had average frost table depths of 115 cm (Aug 6th 2001). The average snow depth recorded on April 1st 2002 for Mound 9A was 52 cm. More specifically, average snow depths were 100 cm on the north side, 43 cm on the south side, and 33 cm on the top. The distribution of the snow suggests that prevailing winds are from the south and/or sublimation rates are higher on the south side of the mound.

A grassy section on the summit of Mound 9A was selected to core. The peat layer was 8-10 cm thick, and the frost table was at 125 cm (Aug 5th 2001) (Figure 5.5). The unfrozen sediments were organic-rich dark yellowish brown (10YR 4/4) sands and silts with traces of gravel and clay. The sediments became progressively finer down-core with a median grain-size from 2.6 to 5.4 Φ. The sediments below the frost table were very dark greyish brown (2.5Y 3/2).

The cryostructure within the top layers of frozen sediment consisted of short, lenticular, parallel, wavy lenses <1 mm thick, 5-10 mm long, spaced 5-10 mm apart. The ice lenses became larger and more frequent with depth. From 135-219 cm, ice lenses up to 30 mm thick were interspersed within the ice-rich sediment. At 219 cm, a rock caused auger refusal. The gravimetric moisture content showed an initial peak beneath the frost table and a general increase with depth. The mean specific conductance throughout the core was 97 μS/cm, with the greatest value (150 μS/cm) at the base of the core.

The cryostructure of Mound 9A was consistent with ice segregation processes. Temperatures recorded in the core were -0.05°C at 145 cm and –0.1°C at 230 cm (below the base of the core).

5.2.3 Mound 10

Mound 10 is an aggrading fonn located in the lee of the 4 m high Mound 9A to its south and west (see Figures 5.2A and 5.3D). It was 0.9 m high, 16 m long, and 8 m wide. Mound 10 was mainly covered by grasses, but a few shrub willow seedlings had started to colonize its south side. The oldest shrub sampled was 7 years old, giving this mound a possibly minimum age of 12-17 years. This mound could be detected in the 1987 set of

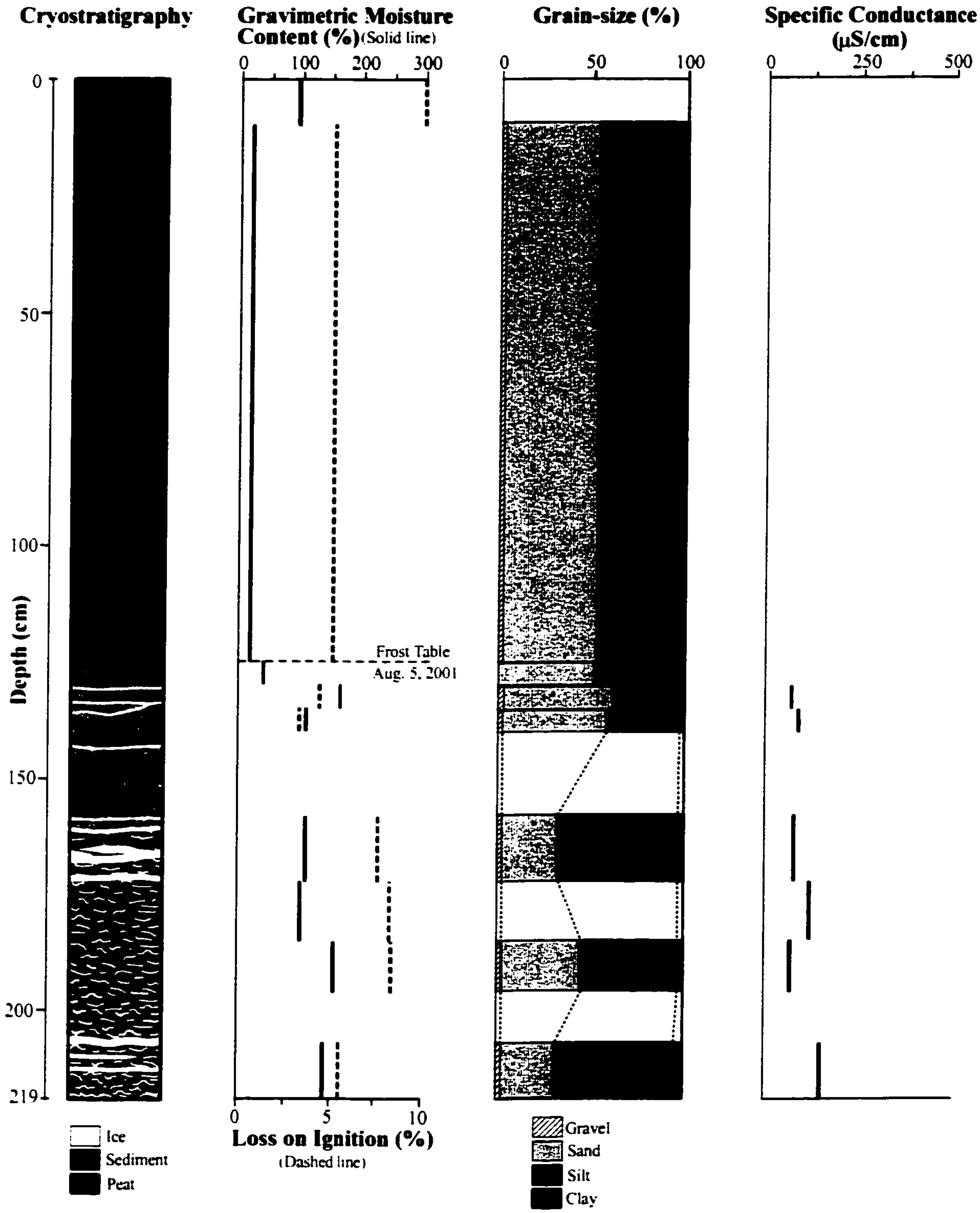

Figure 5.5: Core diagram of Mound 9A.

aerial photographs, but not in those from 1966, suggesting the mound has a maximum age of 36 years.

The average snow depths were strongly influenced by Mound 9A to the south and were 20 cm on its north side, 52 cm on its south side, and 28 cm on the top on April 1st 2002. This mound had the lowest total average snow depth (32 cm) recorded at any of the frost mounds. The lack of shrubs could explain the smaller amounts of snow on the mound.

Mound 10 had a 20 cm thick peat layer overlying very dark greyish brown (10YR 3/2) organic-rich sands and silts with traces of clay and gravel (Figure 5.6). The frost table was at 36 cm (August 5th 2001) and unfrozen sediments were encountered again beneath the base of the core at 146 cm. The frozen sediments were dark grey (10YR 4/1) silts and sands with traces of clay and gravel.

The cryostructure consisted of short, lenticular, parallel, wavy lenses <1 mm thick, 10-20 mm long and spaced 5-10 mm apart at the top of the core. Down-core, the ice lenses became 1-2 mm thicker and spaced 1-2 mm apart. At 62 cm, a 20 mm thick ice lens occurred. At the bottom of the core, from 124 to 146 cm, a 220 mm thick body of ice was encountered. This ice body was relatively clear and contained 20 mm long tubular bubbles and two 5 mm thick sediment layers immediately above the base of the core. Temperatures measured in the frozen part of the borehole were very close to 0°C. A slight positive gradient was present in the underlying unfrozen sediment, with a temperature of 0.6°C at 230 cm depth. The specific conductance of Mound 10 was highest just below the frost table (140 μS/cm) in soil that is likely part of the active layer, and lowest within the 220 mm thick ice lens (20 μS/cm).

The cryostratigraphy of the bulk of the core indicates that segregation processes were operational. The 220 mm thick ice lens which spanned the base of the core could be either segregation or intrusive ice, based on form alone. However, ice lenses up to 15 cm thick have been reported in the literature (e.g. Forsgren 1968, Seppälä 1980), and An and Allard (1995) predict that a thick segregated lens should be formed at bottom of a palsa. The thin sediment layers within the ice layer also suggest that the ice is of segregation origin.

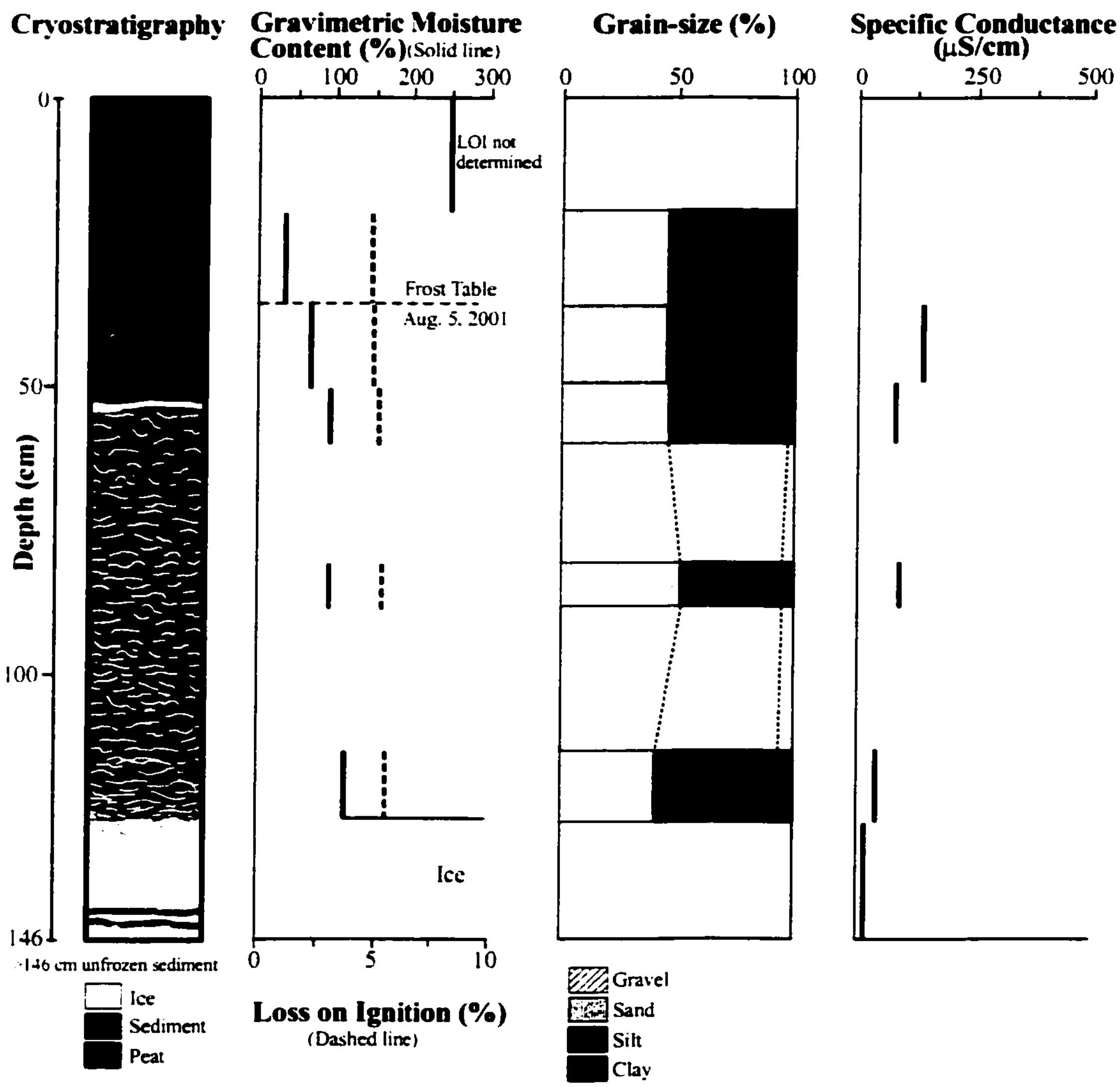

Figure 5.6: Core diagram of Mound 10.

5.2.4 Mound 12

Mound 12 (see Figure 5.2A) is a relatively stable form but it also exhibited evidence of growth and precursors of degradation (Figure 5.7A). Minor cracking that could lead to block collapse was present along the mound's east and south sides. Areas of aggradation were also present on the west side on the mound as several dilation cracks were observed on raised areas of peat. Mound 12 is situated beside a pond and is visible in all the aerial photographs.

Shrub willows and shrub birch almost fully cover the 20 m long, 17 m wide, and 3 m high mound. The frost table depth averaged 148 cm in areas with no shrubs, and 95 cm in shrub-covered areas (Aug 6th 2002). The oldest shrub sampled was 102 years old, signifying that Mound 12 had a minimum age of about 110 years. Although no core was extracted, given external similarities, it can be inferred that Mound 12 the same origin as the other mounds on the valley floor.

Mound 12 had a mean snow depth of 39 cm on April 6th 2001 and 57 cm on April 1st 2002. Although there was a greater amount of snow in 2002, the mean snow depth was thinnest on the south side of the mound in both 2001 (19 cm) and 2002 (57 cm). The mean snow depths on the north side and summit of Mound 12 were 33 cm and 56 cm in 2001 and 72 cm and 64 cm in 2002 respectively. On April 6th 2001, the greatest snow depth on the summit of Mound 12 was 85 cm. The bottom 35 cm of the snow pack was depth hoar with a basal temperature (0 cm) of –2.2°C, -3.7°C at 35 cm and –4.7°C at 75 cm (note: instantaneous temperatures were taken at an air temperature of 1°C).

Figure 5.7: Photographs of Mound 12 and surrounding area in winter: A) Mound 12 during summer, note area of aggradation in foreground; B) Mound 12 in winter 2001 with extensive icing across valley floor; C) icing blister in pond adjoining Mound 12 (photo taken winter 2002). Photos B and C: A. Lewkowicz.

In both winters, an extensive icing covered the valley floor (Figure 5.7B), and icing blisters were present in the pond surrounding Mound 12 and near the Mound 9 complex. The largest icing blister, observed in 2002, was 34 m long, 14 m wide and 0.5 m high (Figure 5.7C). A dilation crack system was partly covered with snow, and individual cracks were up to 20 m long and 5 cm wide. The specific conductance of the water melted from the icing blister was 20 µS/cm.

5.2.5 Mound 14

Mound 14 (see Figure 5.2A) is an aggrading form located on the edge of a gravel bar adjacent to the creek bed (Figure 5.8A). The mound was 11 m long, 9 m wide and approximately 1.1 high. Entirely covered in peat, the mound only had few grasses and very small shrubs colonizing its sides. A 2-10 cm peat layer covered clast-rich sediment containing sub-angular to sub-rounded clasts with long axes of 5-30 cm. A mean frost table depth of 70 cm was measured on the top of the mound (July 30th 2001). During the winter of 2002, Mound 14 and nearby Mounds 13, 15, and 16 were completely encased in an icing (Figure 5.8B). This mound is too small to be visible on any of the aerial photographs.

A section was made in the side of Mound 14 to examine the stratigraphy (Figure 5.9). The unfrozen matrix varied from brown (10YR 4/3) silty sands with some gravel and trace clay to very dark grey (5Y 3/1) sands with some silt and some gravel. The median grain-size for the section was approximately 2.0 Φ (not including unsampled large clasts). The gravimetric moisture content within the core was similar to the other mounds, but the peat layer was much drier at only 8.5%. At the 84 cm depth, water flowed into the section, halting further excavation. The frost table at the site of the section was deeper than elsewhere and was detected at 105 cm, well below the water surface.

It was necessary to core the mound to determine the cryostructure, but the clast-rich nature of the sediment made this difficult. Three attempts were made to core in the centre of the mound after removing the active layer, and the longest core retrieved was 9 cm in length (see Figure 5.9). The frozen sediments were dark grey (5Y 3/2) silty sand

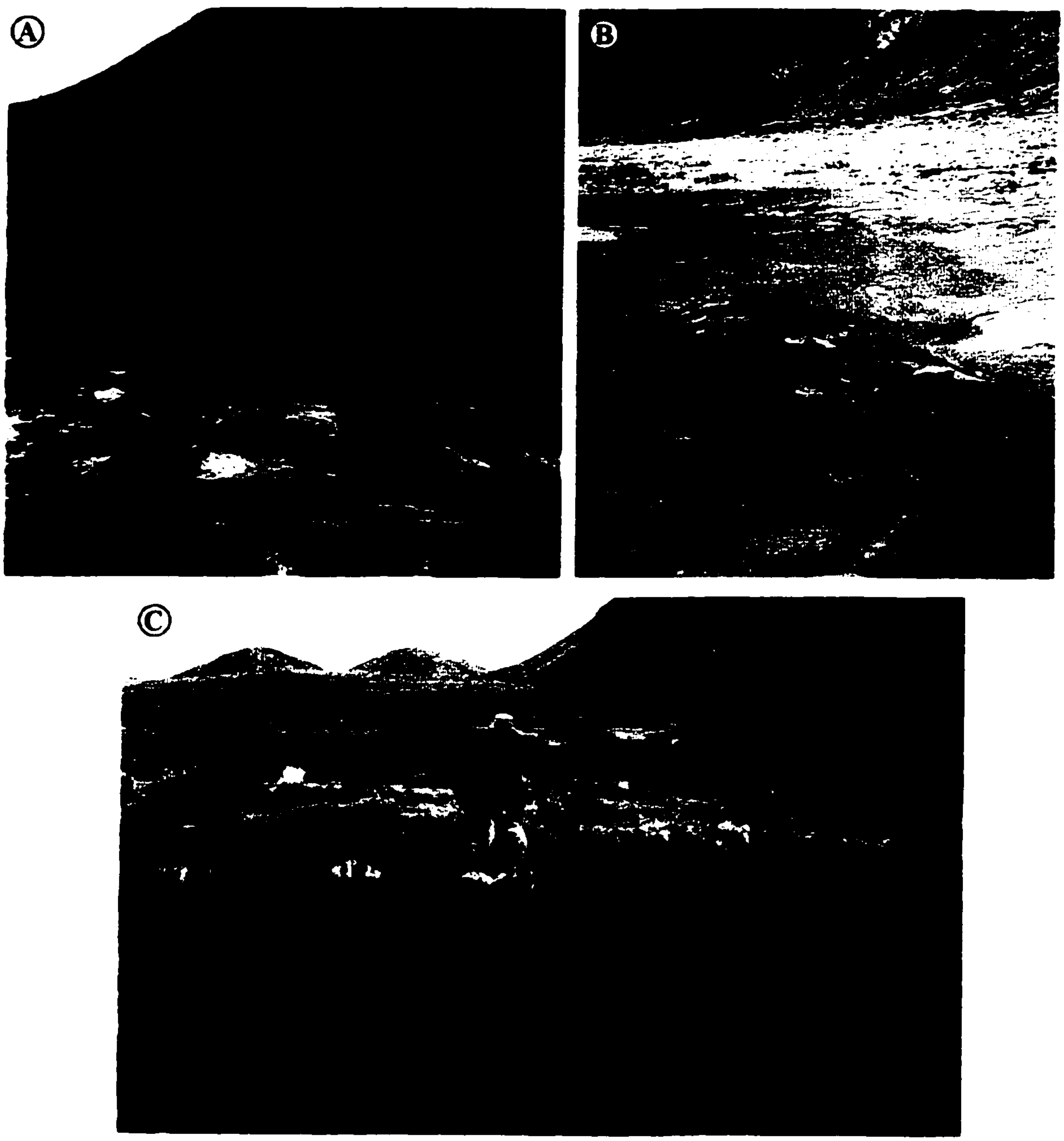

Figure 5.8: Photographs of Mounds 14 and 17: A) Mound 14 with creek in foreground; B) the top of Mound 14 showing through icing; note Mounds 13, 15, 16 are also encased in ice, but are not visible; C) Mound 17, note proximity of pond in background and dilation cracks in peat on surface of mound.

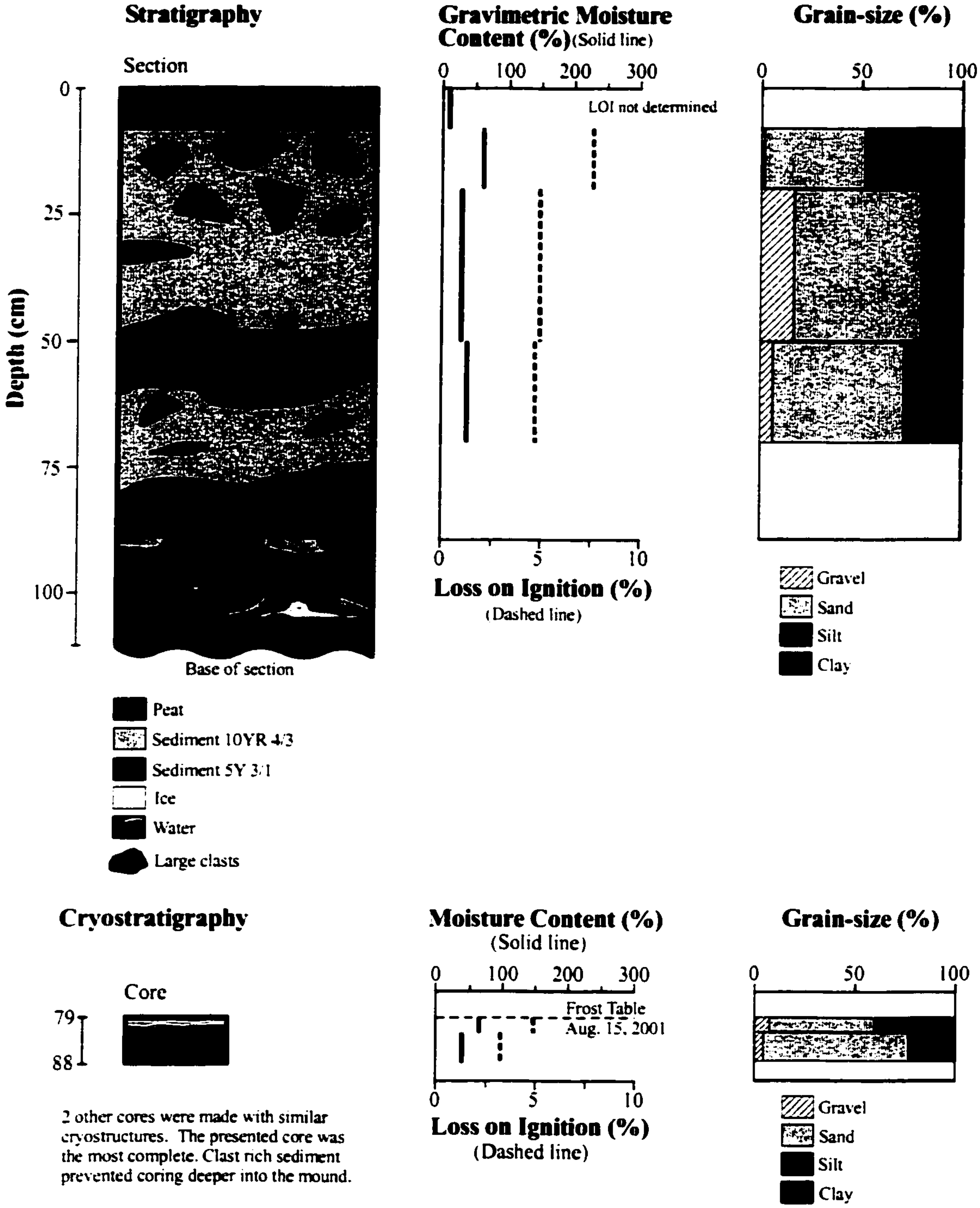

Figure 5.9: Core diagram of Mound 14.

with traces of gravel clay. The cryostructure consisted of short, lenticular, parallel, wavy lenses 1-2 mm thick, 10-20 mm long, spaced 5-10 mm apart. The cryostructure was similar to that of the other mounds, indicating that segregation processes were responsible for the upheaving of this form.

5.2.6 Mound 17

Mound 17 (see Figure 5.2A) is an aggrading form, as indicated by dilation cracks on the surface. The mound is approximately 10 m long, 8 m wide, and 0.7 m high at its highest point, which is situated approximately 2 m away from a body of water (Figure 5.8C). The mound is completely covered in peat, with no vegetation established. The mound is too small to be visible on any of the aerial photographs.

Mound 17 had a 10 cm peat layer and a frost table depth of 33 cm (Aug. 5th 2001) (Figure 5.10). The unfrozen sediments were very dark greyish brown (2.5Y 3/2) sands and silts with traces of gravel and clay. Frozen sediments were olive grey (5Y 4/2) silts and sands, and silty sands with traces of gravel and clay. The median grain-sizes for Mound 17 ranged from 2.8 to 4.4 Φ.

The cryostructure included short, lenticular, parallel, wavy lenses 1-3 mm thick, 5-10 mm long, spaced 2-5 mm apart. Interspersed throughout the ice-rich sediment were 10-20 mm thick ice lenses. At 93 cm, a 240 mm thick ice body extended across the core, similar to that in Mound 10. The ice had relatively few bubbles and some organic inclusions. The mean specific conductance from 33-93 cm was ~140 μS/cm, whereas the 240 mm thick ice lens was only 10 μS/cm. At 117 cm, the auger broke through the ice into water. Immediately, the water rose to 59 cm in the borehole, which surveying with a theodolite showed to be 5 cm above the level of the nearby pond. Saturated unfrozen sediment could be detected at 133 cm. A temperature probe was pushed through the soft sediment and recorded 0.1°C at 133 cm, 0.3°C at 171 cm and 0.4°C at 203 cm.

A trench was excavated between the edge of Mound 17 and the adjacent pond, (Figure 5.10), in order to determine if the water in the core was disconnected from the pond as suggested by the different levels. Below 10 cm of peat was a 6 cm layer of unfrozen silty sand above a 26 cm layer of relatively clear ice. No water was found beneath this large ice layer, only unfrozen sediment.

The conductivity of water from within the borehole, the nearby pond, and two areas of pooled surface water was also measured to determine if there was a relation between them. The core water had a conductivity of 315 μS/cm at 2°C, whereas the pond water had a lower conductivity of 79 μS/cm at 16°C (see Figure 5.10 for specific conductance). The following day, the water in the borehole still had a high conductivity of 310 μS/cm at 1.5°C. These differences indicate two separate water sources. The pooled areas of surface water had specific conductances similar to that of the pond: 117 μS/cm and 168 μS/cm. Water from melted ice sampled within the trench had a specific conductance averaging 12 μS/cm. Frost probing in the area surrounding the mound indicated that this ice layer was probably continuous, and was overlain entirely by peat.

Segregation processes are clearly responsible for the majority of the mound, and the 240 mm thick ice lens is not uncommonly thick compared to lenses in other mounds. However, the rise of the water in the core to above the level of the pond suggests the existence of groundwater pressures at the mound site. This origin of this mound is discussed further in section 6.1.4.

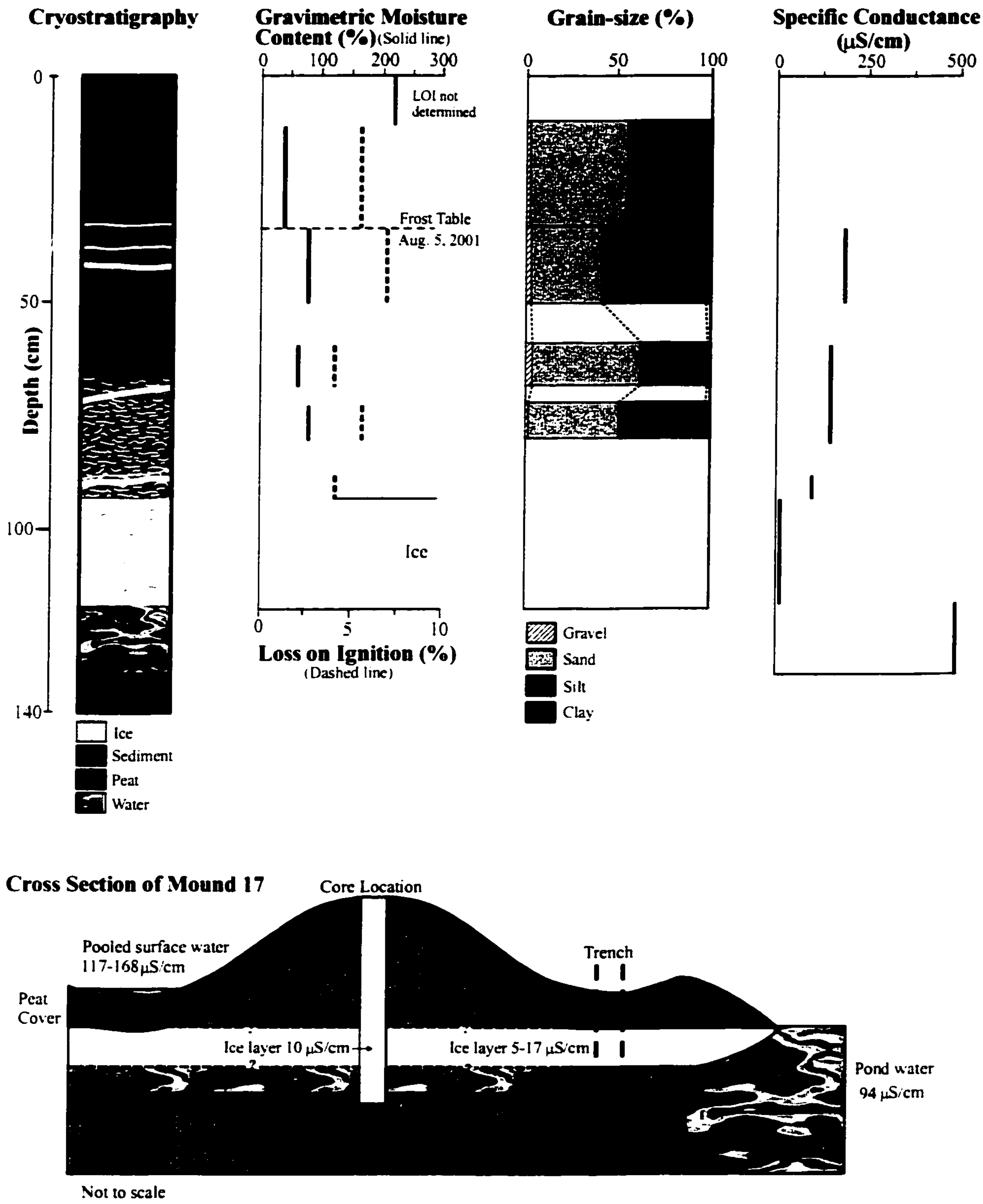

Figure 5.10: Core diagram of Mound 17.

5.2.7 Mound 20

Mound 20 is an aggrading form 28 m long, averaging 7 m wide with a maximum height of 1.2 m. It was found in the lee of a larger mound (Mound 23) to its south, which has a maximum height of 3.6 m (see Figure 5.2A; Figure 5.11A). Approximately 70% of Mound 20 was covered in grasses with 30% bare peat, and a few small shrubs had begun to colonize the sides of the mound. This mound appears very faintly in the 2001 and 1995 aerial photographs and the oldest shrub sampled was 9 years old, giving this mound a possibly minimum age of 14-19 years. Along the top of this sinuous mound frost table depths varied from 40 to 65 cm (Aug 2nd 2001).

Snow surveys were performed on a part of Mound 20 in April 2001 and 2002. The mean snow depth on the mound was 24 cm on April 6th 2001 and 42 cm on April 1st 2002. More specifically, the north side, south side, and top mean snow depths were 18 cm, 31 cm, and 21 cm respectively on April 6th 2001 (Figure 5.11B), and 35 cm, 47 cm, 42 cm respectively on April 1st 2002. The snow was therefore much deeper in 2002 than in 2001 at a similar time of year. In both years, the south side had greater snow depths, most likely due to the influence of Mound 23 upwind. A similar snow distribution was observed at Mound 10 which is in the lee of Mound 9A. Also, the summit of Mound 20 had more snow than its north side in both years.

Mound 20 had a 15 cm peat layer with a frost table at 40 cm (Figure 5.12). Unfrozen sediments were dark greyish brown (2.5Y 4/2) sandy silts with traces of clay. The grain-size distributions of the frozen sediments were fairly constant down-core consisting of dark olive grey (5Y 3/2) sandy silts with traces of clay. The median grain-sizes for Mound 20 ranged from 5.1-5.8 Φ. The specific conductance values down-core

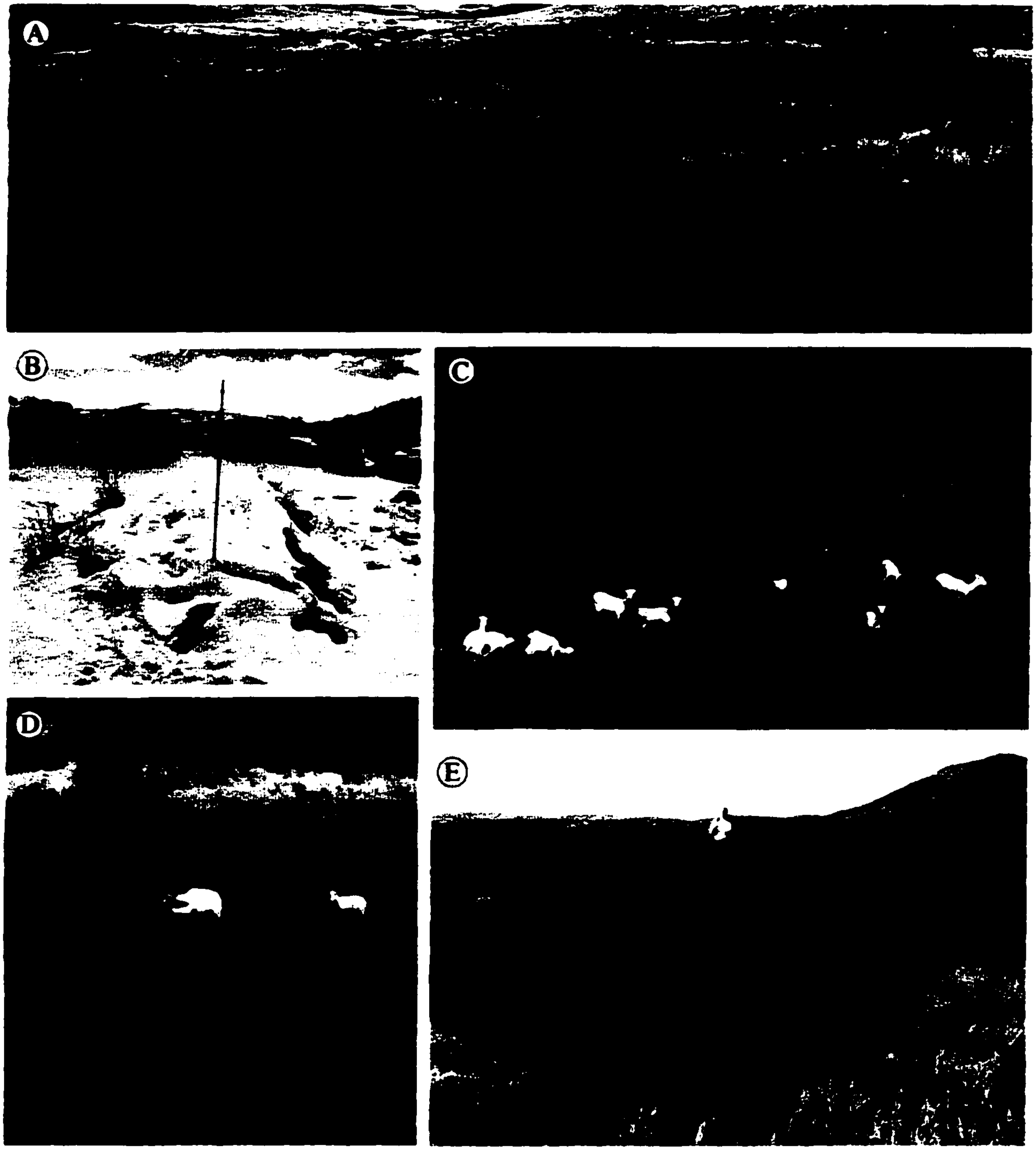

Figure 5.11: Photographs of Mounds 20, 23 and 25: A) Mound 20, the long sinuous mound in the foreground with Mound 22 in back right; B) snow distribution on part of Mound 20, April 2001; C) Dall Sheep on side of Mound 23; D) Dall Sheep eating exposed mineral soil on side of Mound 23; E) Mound 25.

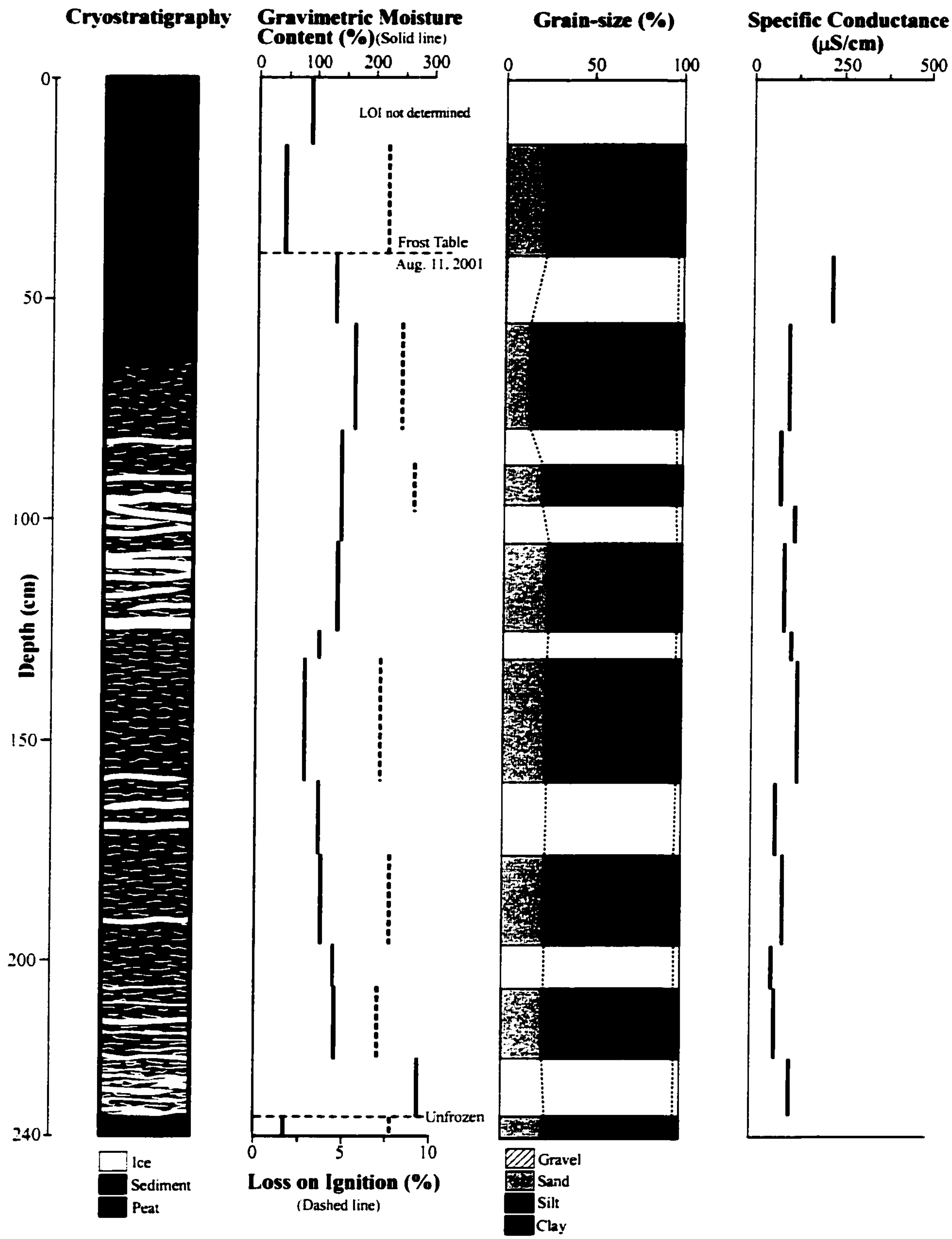

Figure 5.12: Core diagram of Mound 20.

were fairly consistent, with a mean value of ~90 μS/cm. The highest specific conductance (220 μS/cm) was found just below the frost table.

The cryostructure showed short, lenticular, parallel, wavy lenses 0.5-1 mm thick, 5-10 mm long, and 2-5 mm apart. Ice lenses increased in thickness and frequency down-core. A few 10-50 mm thick ice lenses were encountered throughout the core, with high concentrations from 86-126 cm and 190-235 cm. At 235 cm, the auger broke through into unfrozen sediment. It is evident that segregation processes are responsible for the formation of this mound.

5.2.8 Mound 23

Mound 23 (see Figure 5.2A) is a degrading mound with mineral soil exposed on its north and south sides by block collapse. It was 48 m long, averaged 14 m wide, and had a maximum height of 3.6 m. Only the top of the mound supported shrubs and grasses, as its sides were bare sediment. The average depth to the frost table was 89 cm (Aug 6th 2001). The mean snow depth measured April 1st 2002 over the whole mound was 61 cm. More specifically, the mean snow depth was 64 cm on the north side, 73 cm on the south side, and 60 cm on the summit. Mound 23 can be seen on all sets of aerial photographs. The oldest shrub sampled was 115 years old, giving the mound a minimum age of about 120 years. This mound was not cored, but its longevity and its similarity to the other mounds on the valley floor suggest a common origin.

An unexpected agent accelerating the degradation of this mound was observed on July 31st 2001. A group of approximately 20 Dall sheep traversed the valley bottom at the location of the southern group of frost mounds. The Dall sheep pawed at the exposed sediment on Mound 23, and consumed the mineral soil (Figures 5.11B and 5.11C). Disturbed by the observers' presence, the Dall sheep left the frost mounds after approximately 30 minutes. The sides of Mound 23 were trampled by the Dall sheep, and together with soil consumption, this could lead to accelerated degradation.

5.2.9 Mound 25

Mound 25 (see Figure 5.2A) is a stable form 34 m long, 18 m wide and 2.7 m high (Figure 5.11E). The mound was completely covered by shrub willows and shrub birches. The oldest shrub sampled was 73 years, giving the mound a minimum age of about 80 years. Mound 25 can be seen on all the aerial photographs, but it appears to be much smaller in the 1946 set. Probing on top of Mound 25 determined that the frost table varied from 69 to 93 cm deep (Aug 6th 2001).

The core on Mound 25 exhibited a 20 cm thick peat layer overlying unfrozen organic-rich silty sands with some gravel and traces of clay varying from dark yellowish brown (10YR 4/4) to greyish brown (10YR 5/2) (Figure 5.13). The frost table was at 69 cm and an 8 mm thick lenticular parallel ice lens was encountered at the frozen ground interface. The frozen sediments became progressively finer with depth, consisting of dark greyish brown (2.5Y 4/2) sandy silts with traces of clay. The specific conductance values were again fairly consistent down-core, with the highest value (550 μS/cm) found just below the frost table.

The cryostructure was very similar to that of the previous mounds cored: short, lenticular, parallel, wavy lenses 1-2 mm thick, 5-10 mm long, 2-5 mm apart with some 10-30 mm thick lenses interspersed throughout. At 160 cm, a nearly 45° dipping ice lens

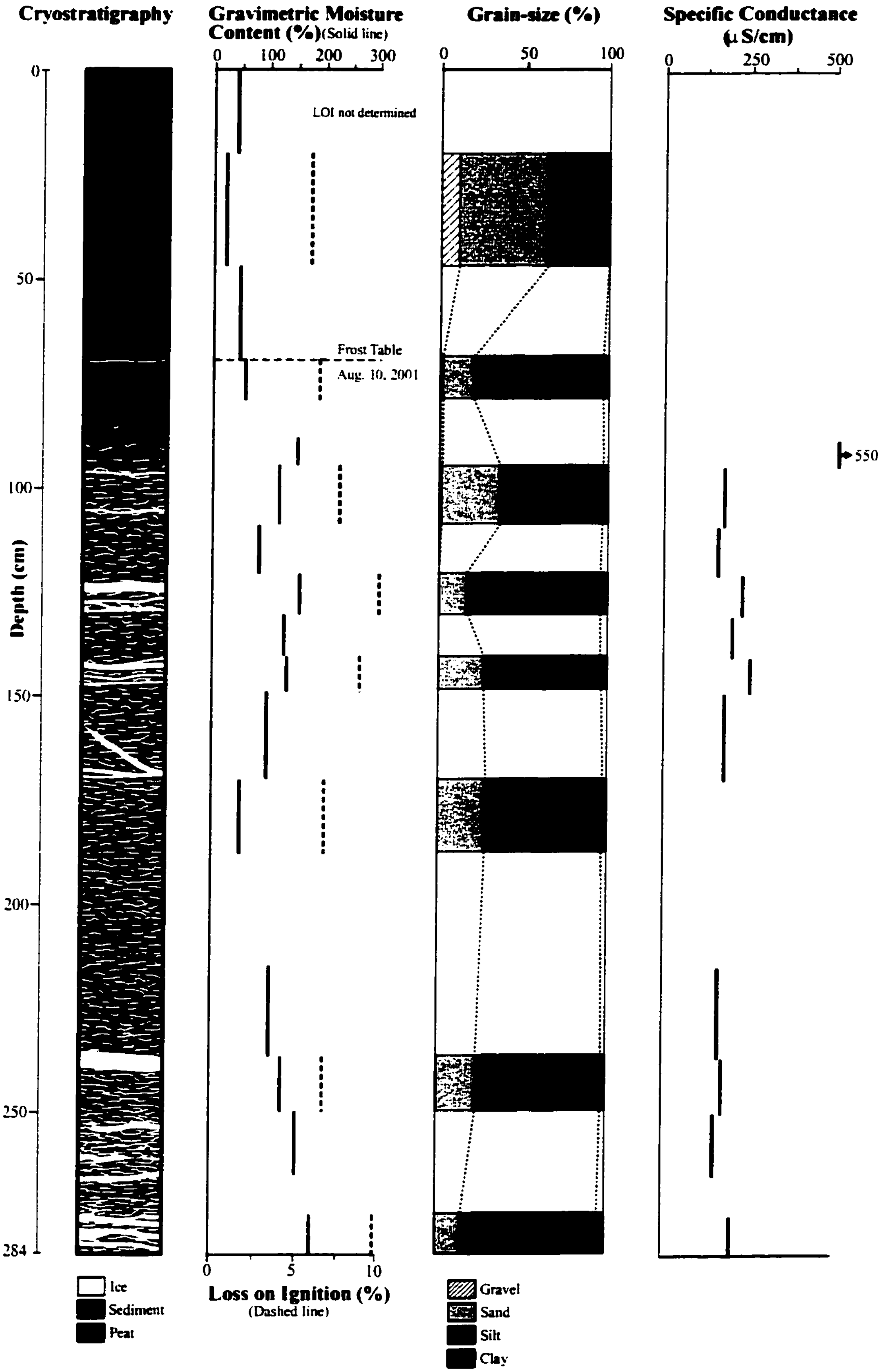

Figure 5.13: Core diagram of Mound 25.

was encountered. The tubular bubbles in this lens were orientated vertically, as were the bubbles in the horizontal ice lenses. This suggests that the ice lens was not angled after its formation.

The core showed that segregation processes were the cause of the upheaving of the mound. Coring was stopped at 284 cm as it was clear that the ice present was of segregation origin. In addition, the bottom of permafrost on such a large mound could be at least another 6 m below the base of the core since in palsas, height is typically only one-third the thickness of permafrost (Allard *et al.* 1986).

5.2.10 Mound 28

Mound 28 (see Figure 5.2B) is an aggrading form 7 m long, 6 m wide, and 1.4 m high (Figure 5.14A). The mound was situated among many similar mounds in an area inundated by water on the eastern side of the valley bottom. All the mounds in this area were completely covered in grass with very few small shrubs.

The mound had an 8 cm thick peat layer and the frost table was at 51 cm (Aug 12th 2001) (Figure 5.15). The unfrozen sediments ranged from dark greyish brown (10YR 4/2) silts and sands with traces of clay and gravel to dark yellowish brown (10YR 4/4) silty sands with traces of clay and gravel. The frozen sediments were predominately dark olive grey (5Y 3/2) with variable median grain-sizes ranging from 5.3 Φ mid-core to 1.8 Φ at the base. The specific conductance was slightly higher below the frost table, but was fairly consistent down-core with a median value of ~130 μS/cm, and lower values (20 μS/cm) in ice layers.

Figure 5.14: Photographs of Mounds 28, 39 and 40: A) Mound 28; B) Mound 39; C) Mound 40, note large break of slope in background; D) icy core of Mound 40.

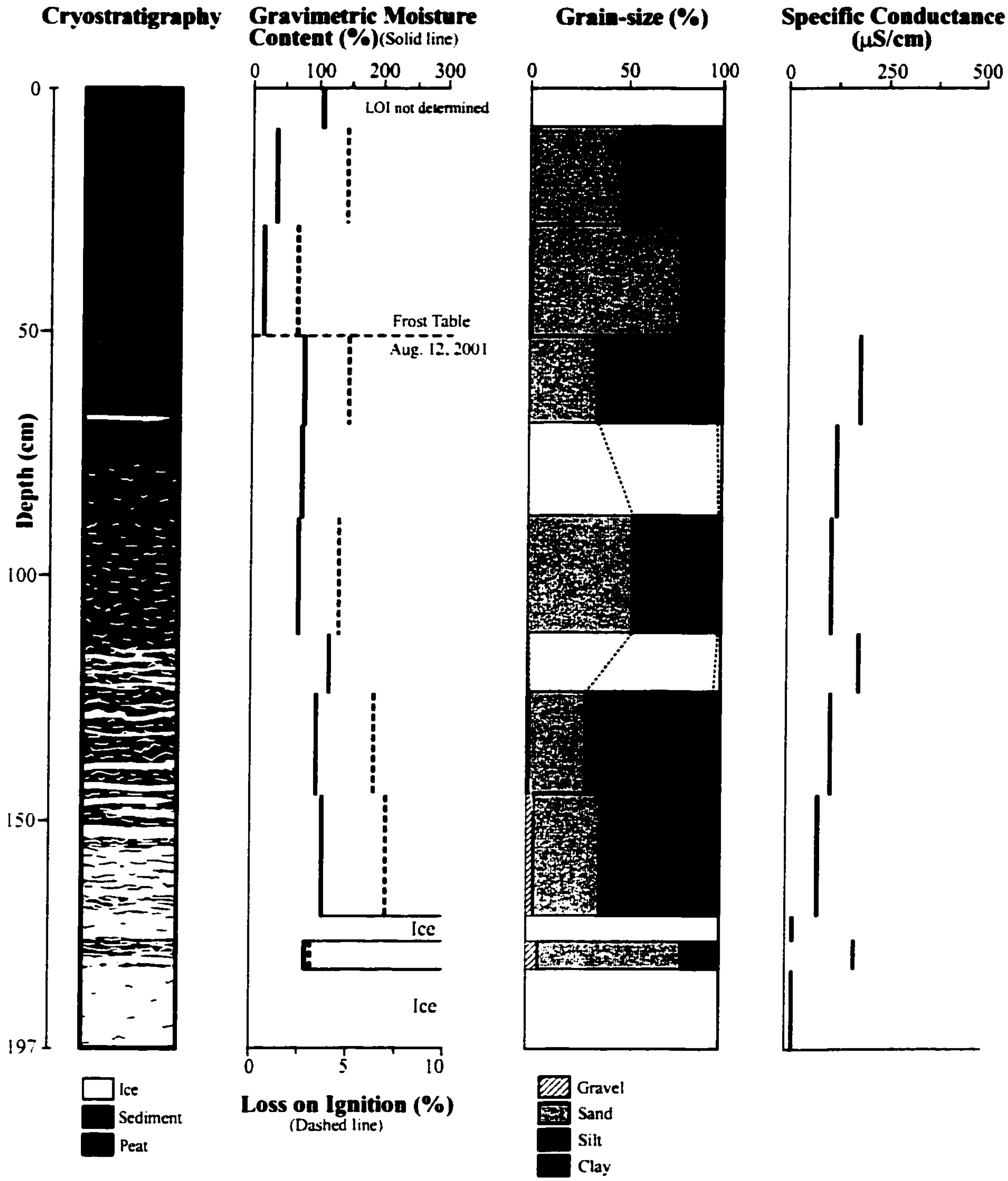

Figure 5.15: Core diagram of Mound 28.

The cryostructure was again short, lenticular, parallel, wavy lenses 1-2 mm thick, 5-10 mm long, 5-10 mm apart with occasional 10-50 mm thick lenticular parallel lenses. From 150 to 197 cm, the core had a suspended cryostructure consisting of ice with sediment inclusions up to 10 mm thick. The auger met refusal at 197 cm on a rock. It is believed that this was close to the base of permafrost due to the similarities in size and stratigraphy between Mound 28 and Mound 20. The cryostructure indicates that Mound 28 was formed due to ice segregation processes.

5.2.11 Mound 39

Mound 39 is found on the valley slope, approximately 30 m west of the creek (see Figure 5.2C). It was an estimated 3 m long, 2 m wide, and 0.5 m high (Figure 5.14B). The mound supported grasses, flowering plants and a few young shrub willows and birch. There were dilation cracks across the surface of the mound 1-3 m long, and 1 cm wide.

A cross-section was excavated as the sediment was too clast-rich to core. Mound 39 had a 20 cm peat layer and a frost table at 50 cm (Aug 4th 2001) that followed the general shape of the mound (Figure 5.16). In the field, the cross-section appeared to have two distinct sediment units. Unit 1, which comprised all the unfrozen sediment and some of the frozen sediment, was found to have slightly different grain-size characteristics. The unfrozen sediments were organic-rich black (10YR 2/1) sandy silts with some gravel and some clay. The sub-angular clasts, up to 30 cm on their long axes, were not included in the granulometry. There was poorly defined layering within the sediments, dipping sub-parallel to the surface. Rootlets extended through the unfrozen layer into the frozen ground beneath. The frozen sediments were mottled very dark brown (10YR 2/2) organic rich silts and sands with some gravel and traces of clay, and light olive grey (2.5Y 5/4) sands and silts with some gravel and traces of clay. The median grain-size of the matrix in the mound ranged from 3.2 to 4.25 Φ. The cryostratigraphy was more complicated and irregular in this mound than in those described above. The sediments were ice-poor immediately beneath the frost table while visible ice increased below a depth of 70 cm. Here, lenticular, parallel and non- parallel, wavy ice lenses 1-3 mm thick, 10-100 mm long, spaced 5-50 mm apart were present, as well as some vertical veins. A crustal cryostructure was also apparent, evidenced by thin ice coatings on some of the clasts.

Although segregation ice was present, this mound does not easily fit within the definition of a palsa due its location on a slope. Mound 39 also differs from a frost blister as it lacks any evidence of intrusive ice or an empty or water-filled cavity. In addition, the presence of shrubs on the mound surface, compared to lack of shrubs on the surrounding terrain, suggests that it may be a perennial form. It is possible that Mound 39 is a turf-covered/tussock hummock (Porsild 1955), or a tussock-birch-heath polygon (Sigafoos 1951). These forms would be less than 1 m high, possess a frozen core and have a much richer vegetation community than the surrounding area due to the action of nesting animals (H.M. French, *Departments of Geography and Geology, University of Ottawa, personal communication 2002*). However, such forms are reportedly found within areas of ice-wedge polygons in the high Arctic, and it seems unlikely that Mound 39 is such a form. For the purposes of this thesis, the term aggradational permafrost mound with a core of segregated ice is a generic term that appears to be best suited to describe Mound 39.

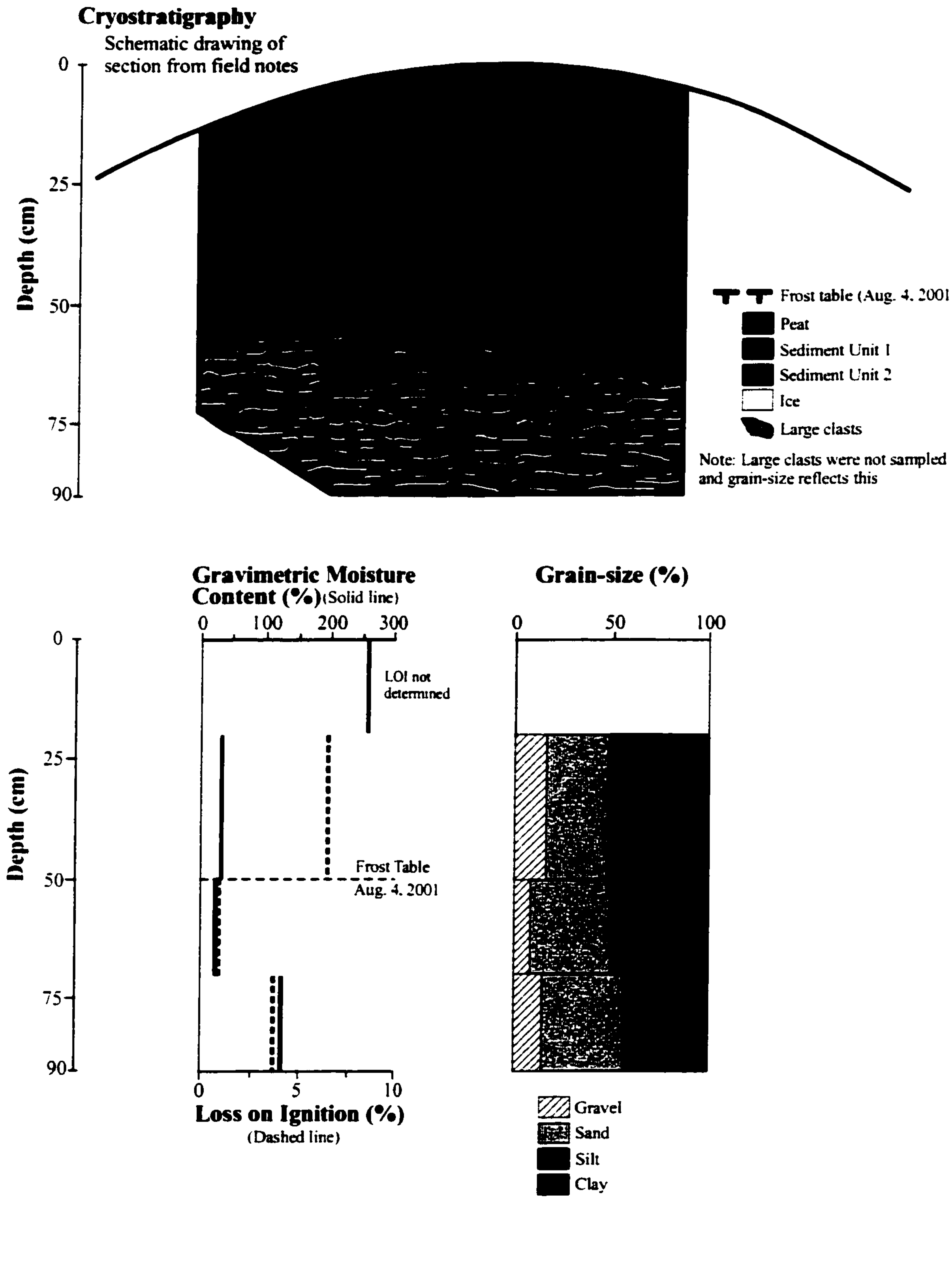

Figure 5.16: Section diagram of Mound 39.

5.2.12 Mound 40

Mound 40 is a complex frost mound located on the valley slope approximately 15 m northwest of Mound 39 (see Figure 5.2C). It was estimated to be 16 m long and 12 m wide, with an undulating surface ranging 0.6-1.0 m high (Figure 5.14C). Mound 40 had several dilation cracks on its surface that ranged from 1-5 m long, and 1-2 cm wide. In some cases, these cracks bisected small shrub willows. Some parts of the mound had voids beneath the surface layer of peat, grasses, and shrubs. Areas that were not hollow had a frost table depth of 20-30 cm (Aug 11th 2001). There was also pooled water in areas nearby the mound. A domed section of Mound 40, estimated to be 2.5 m long, 2 m wide, and 0.8 m high, was examined. It had a 5-10 cm thick peat layer overlying 10-20 cm of unfrozen gravely silty sand with traces of clay containing clasts up to 30 cm on their long axes (Figure 5.17). The frost table in the cross-section was found at 20-30 cm,

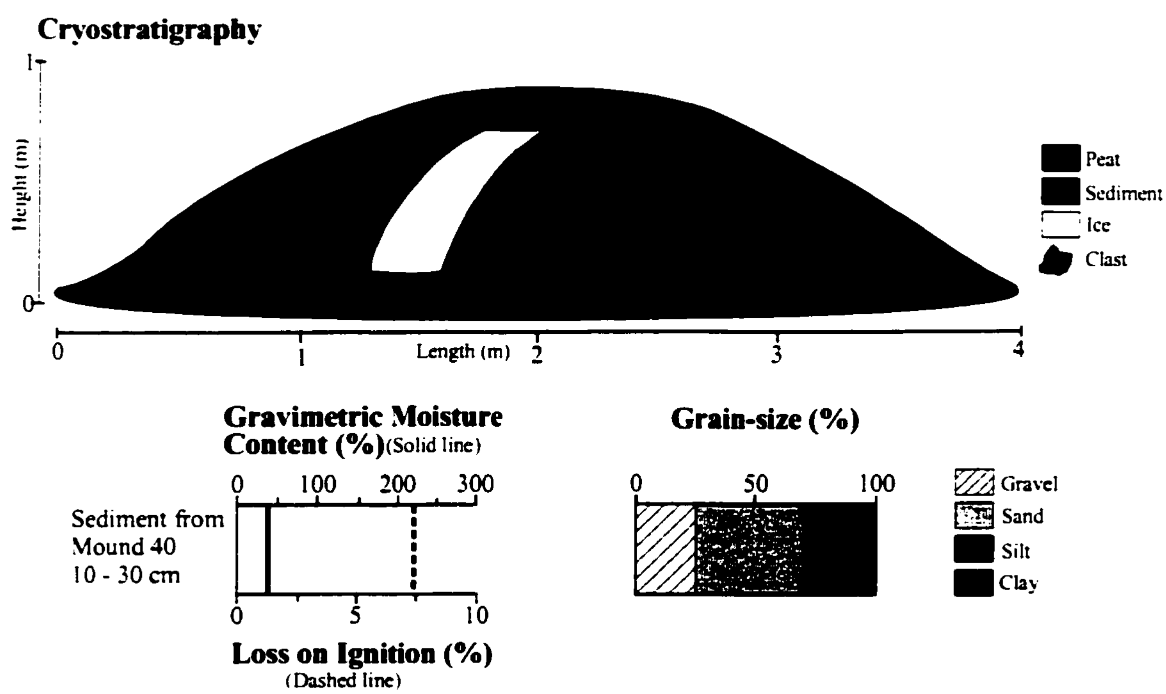

Figure 5.17: Section diagram of Mound 40.

which coincided with a body of massive ice (Figure 5.18D). The ice appeared somewhat milky and followed the surface of the mound. At the lower end of the mound cross-section, the massive icy body pinched out and unfrozen sediment and water could be detected beneath the ice. Probing across the entire domed-section determined that the massive ice body was present throughout. Also, the underside of the ice body could be felt to 30 cm back from the edge, indicating that the body of ice was lens-shaped, and was estimated to be 40-50 cm thick. The specific conductance of the ice from within the mound was less than 10 μS/cm.

A number of cracks were present in the ground beside Mound 40. These cracks were not on associated with any obvious upheaval of the surface. One of the cracks, located approximately 5 m from Mound 40, was excavated (Figure 5.18A and D). It was an estimated 3 m long and 1 cm wide. A 5 cm thick layer of peat overlaid unfrozen, organic-rich, very dark brown (10YR 2/2) silts and sands with some clay and some gravel. The unfrozen sediment, varying between 10-30 cm thick, overlaid a lens-shaped body of massive ice 2.5 m long, 0.5 m wide and 22 cm thick at its thickest point (Figure 5.18B). This ice was much clearer than that of Mound 40 and showed large vertical tubular bubbles trains 1-2 mm wide and as long as the icy body (Figure 5.18C). The specific conductance from the ice was 30 μS/cm. Water present beneath the ice supports the hypothesis that groundwater flow caused the formation of the ice within the crack and therefore the ice is intrusive ice.

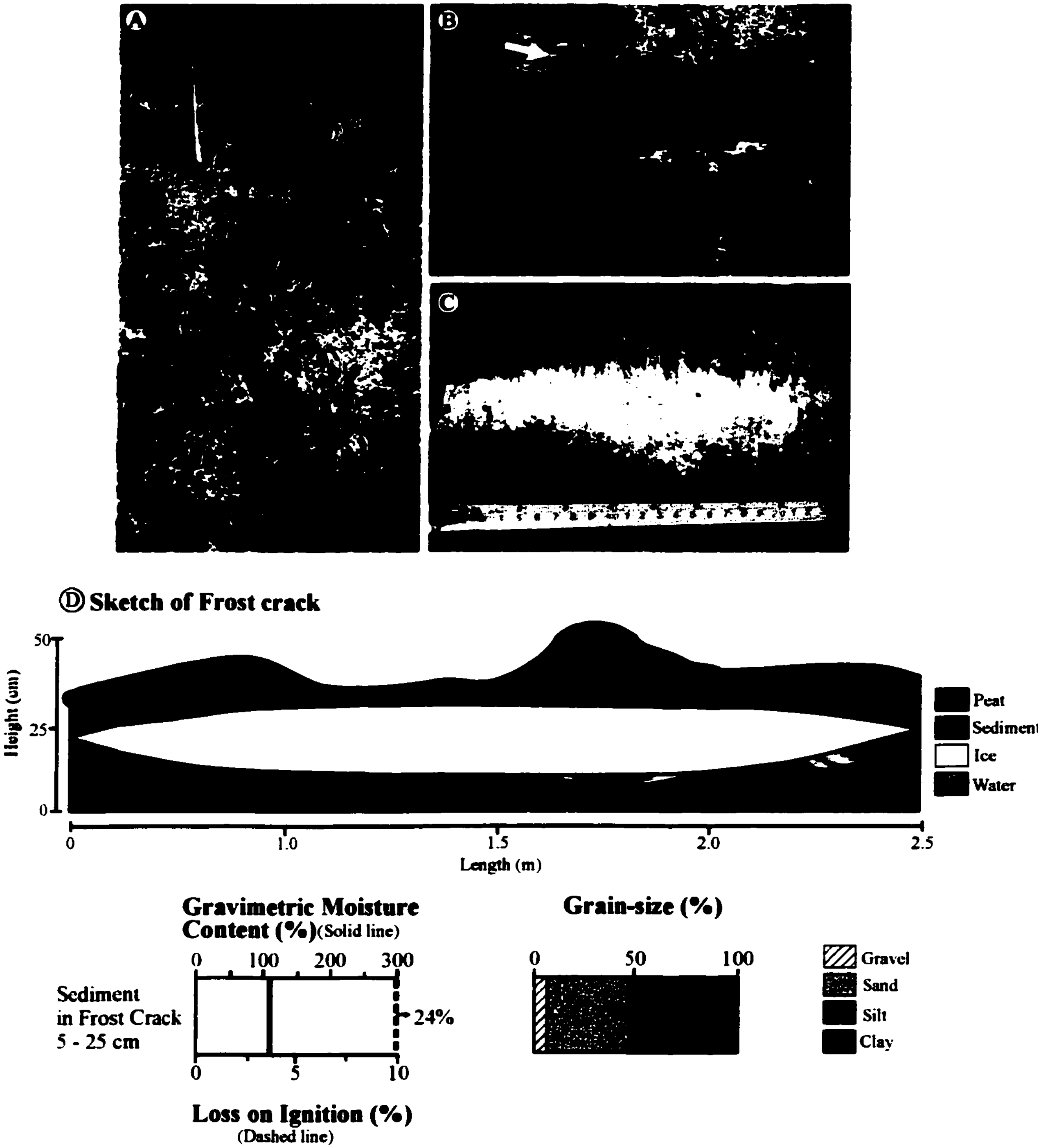

Figure 5.18: Crack adjacent to Mound 40: A) Photograph of crack in ground surface, note pick-axe for scale; B) photograph of ice in the crack, note trowel for scale; C) photograph of ice in crack, note the long vertical tubular bubbles; D) long-section of the crack.

The stratigraphy of Mound 40 is consistent with the definition of a frost blister as it has a massive ice body interpreted as intrusive, hollow cavities where other icy bodies have thawed, and evidence of groundwater. The presence of shrubs on the mound suggests that it is a perennial form, however, as the slope surrounding the mound does not exhibit shrubs. It is possible that the mound forms seasonally, but tends to recur in the same location year after year, allowing the development of shrubs. However, the ice core had thawed out in late August 2002, and no frost table was detected in nearby parts of the mound (M. Ednie, *personal communication*). The adjacent cracks appear to be dilation cracks, formed as a result of ice injection processes along linear water paths.

5.2.13 Mound 41

Mound 41 is located within a cluster of similar mounds (Mounds 41-51) close to a large break in slope (see Figure 5.2C). All the mounds supported prostrate shrub willows and grasses and many small pools of water are nearby, indicating groundwater spring sources. The springs at the base of the large break in slope had a mean temperature of 1.8°C and a mean specific conductance of 325 μS/cm.

Mound 41 was 3.4 m long, 2.3 m wide and 0.6 m high (Figure 5.19A). A 4 m long cross-section was excavated along the length of the mound to the frost table, found at a depth of 48 cm (Aug 12th 2001)(Figure 5.20). The mound had a 17 cm peat layer underlain by unfrozen, very dark grey (10YR 3/1) sands and gravels with some silt and traces of clay. The unfrozen sediment had a median grain-size of –0.25 Φ. The frozen sediments varied between black (5YR 2.5/2) gravels and sands with some silt and traces of clay, and olive (5Y 4/3) gravely silty sand with traces of clay. The average median grain-size of the frozen sediments was 0.2 Φ.

At 48 cm, a 20-40 mm thick ice layer with a suspended cryostructure was found along the length of the excavation. The specific conductance below the frost table was 130 μS/cm. The cryostructures from 54 to 71 cm were variable, including structureless pore ice, crustal ice coatings on clasts, as well as some lenticular, parallel and non-parallel, wavy lenses 1-2 mm thick, 10-50 cm long, spaced 5-25 cm apart. From 71 to 79 cm, the cryostructure consisted of irregular reticulate ice lenses up to 5 mm thick. At 79 cm, a 20 mm thick continuous ice lens was found, at which point the cross-section filled up with water and further excavation was prevented.

The presence of groundwater near the Mounds 41-51 could suggest hydraulic potential for the formation of intrusive ice, however the cryostructure of the first 41 cm of permafrost is indicative of ice segregation processes. The lack of evidence for intrusive ice causing the upheaving of this mound demonstrates that this form is not a frost blister. The cryostructure, size and shape of this mound suggest it could be a palsa, however, it is not located within a fen, and therefore should not be classified as one according to the definition from the IPA Glossary. The mounds are morphologically similar to earth hummocks (Tarnocai and Zoltai 1978), which are circular to elongated downslope in shape, range 0.2 – 0.7 m high, possess a layer of organic matter on the surface, and possess an ice content. However, the dimensions of Mounds 41-51 are generally larger (up to 3x larger), possess much coarser sediments, and have no evidenced of intrusive ice. It is therefore suggested that Mound 41, as well as mounds 42–51, are best termed, "aggradational permafrost mounds with cores of segregated ice."

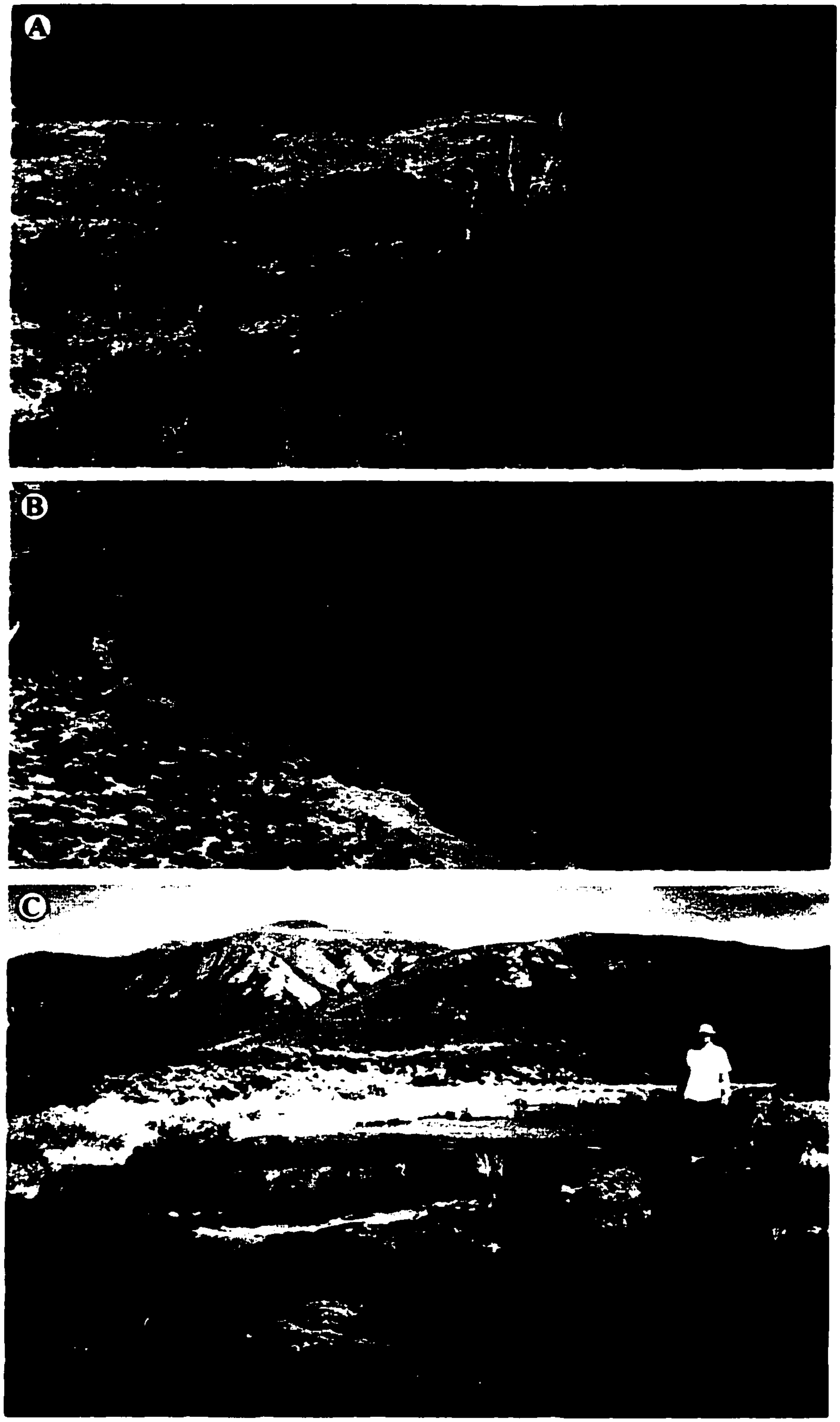

Figure 5.19: Photographs of Mounds 41, 52 and 53: A) Mound 41 (shovel for scale); B) oblique aerial photograph of Mound 52; C) Mound 53.

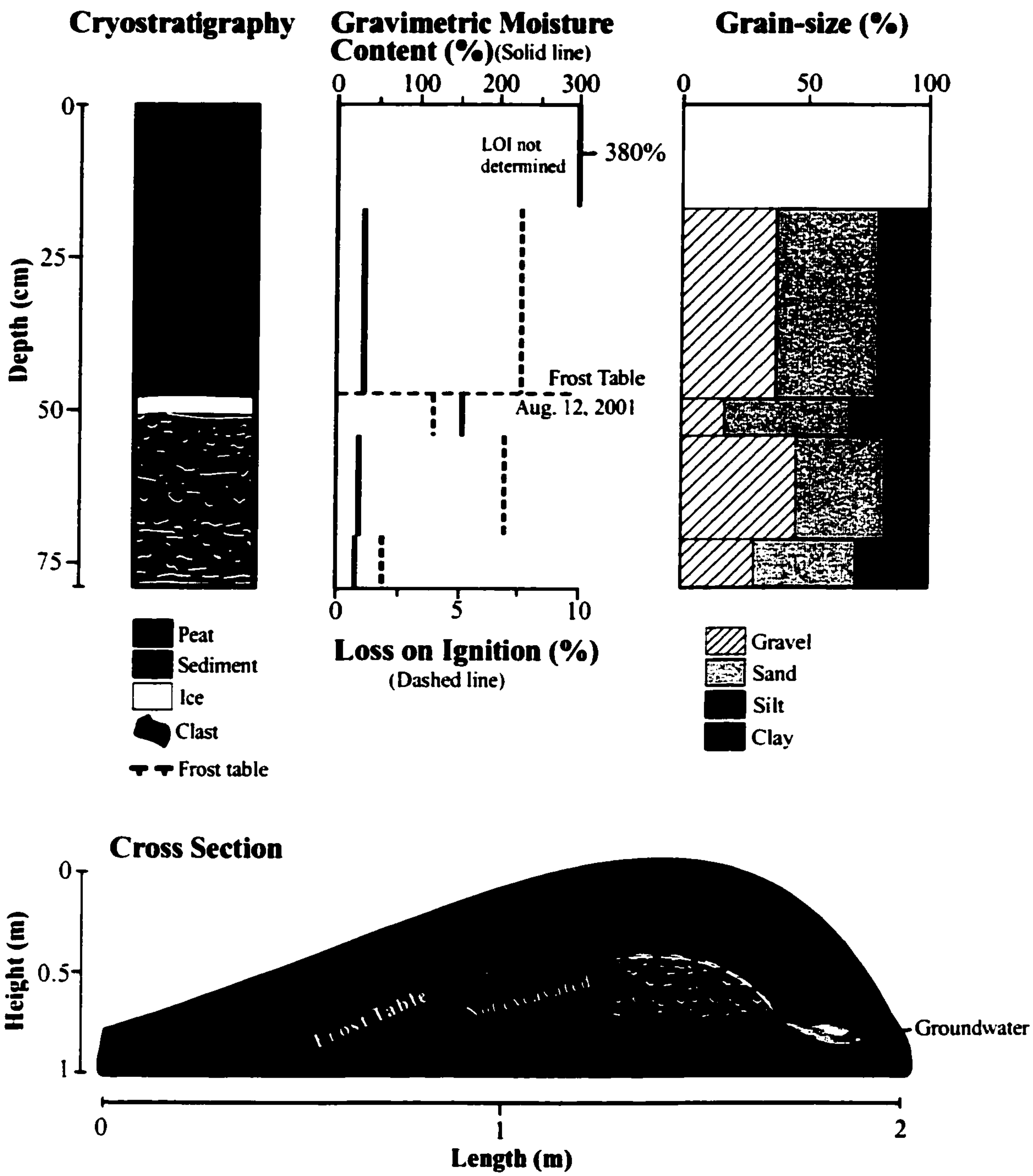

Figure 5.20: Core diagram of Mound 41.

5.2.14 Mound 52

Mound 52 is a large, flat-topped mound that appeared to be in an advanced stage of degradation. The mound is estimated to be 35 m long, 30 m wide and <1 m high. Located approximately 1.3 km southwest of the south group of mounds (see Figure 3.4A), it is a singular mound almost completely surrounded by water (Figure 5.19B). Blocks of material submerged in the adjacent pond indicate the collapse of its sides. The surface of this mound was mainly peat, but included a variety of grasses, lichens, mosses, flowering plants and a few small shrubs.

Mound 52 had a frost table depth of 62 cm (Aug 16th 2001) and was composed entirely of peat (Figure 5.21). The very dark brown (10YR 2/2) unfrozen peat located directly above the frost table had a gravimetric moisture content of 420%. Immediately

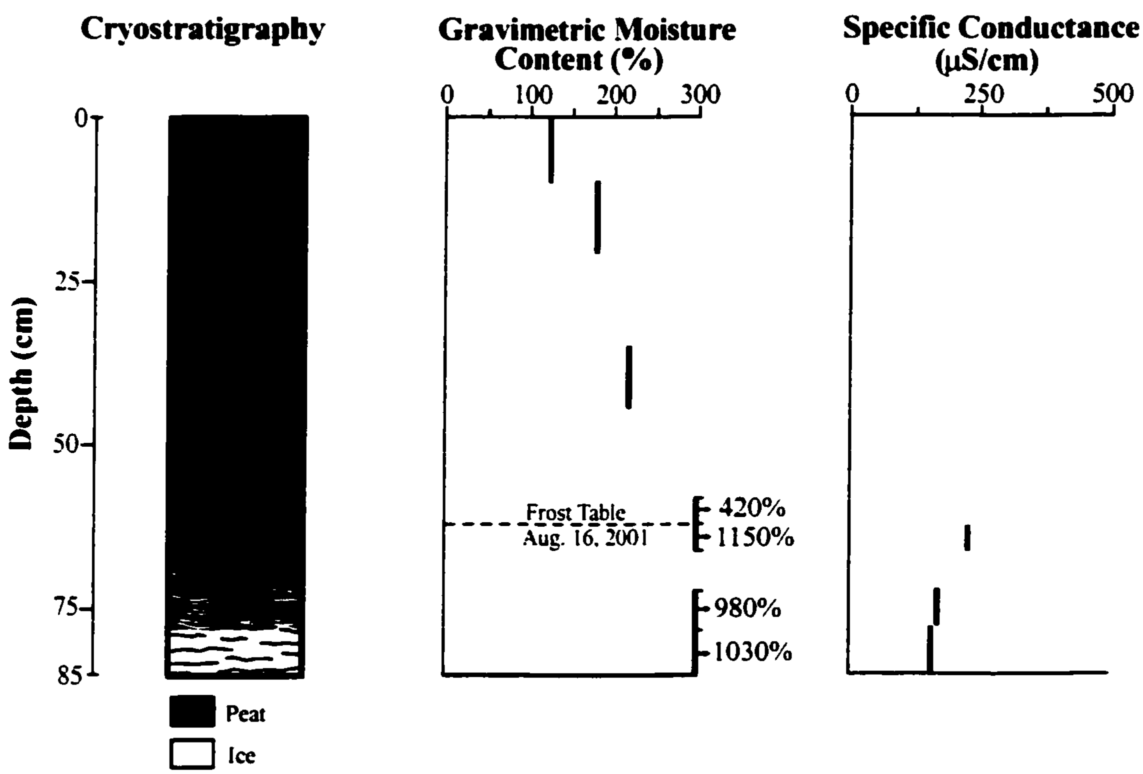

Figure 5.21: Core diagram of Mound 52.

below the frost table, the visible ice content was 50%, the gravimetric water content was very high at 1150%, and the specific conductance was 230 μS/cm. The cryostructure from 62-72 cm was long, lenticular, parallel, planar and wavy lenses 1-3 mm thick, 10-30 cm long, spaced 5 to 10 mm apart. The ice lenses became progressively thicker and more frequent down-core, and were associated with lower specific conductance values. The cryostratigraphy shows ice segregation processes at work.

5.2.15 Mound 53

Mound 53 is an aggrading mound in an early stage of development. It is located approximately 2.2 km southeast from the south group (see Figure 3.4A). The mound consisted solely of peat, and was estimated to be 5 m long, 1 m wide, with a maximum height of 0.6 m (Figure 5.19C). The whole mound was 70 cm thick, and the frost table was at 20 cm (Aug 16th 2001)(Figure 5.22). An excavated section showed that the mound was frozen from 20 to 70 cm, with the last 10 cm extending into the pond water. Beneath 78 cm, loose, unfrozen peat was floating in the water. The gravimetric moisture content in the mound was very high, over 340% in the unfrozen peat and nearly 5000% in the frozen peat.

From 20-33 cm, a thick ice lens with some peat layers was encountered. This ice layer had a specific conductance of 110 μS/cm. The cryostructure from 33-70 cm consisted of long, lenticular, parallel, planar ice lenses 1-3 mm thick, 10-30 cm long, spaced 5 to 10 mm apart. The specific conductance from 25-50 cm was 440 μS/cm. The cryostructure indicates that Mound 53 was formed due to ice segregation processes.

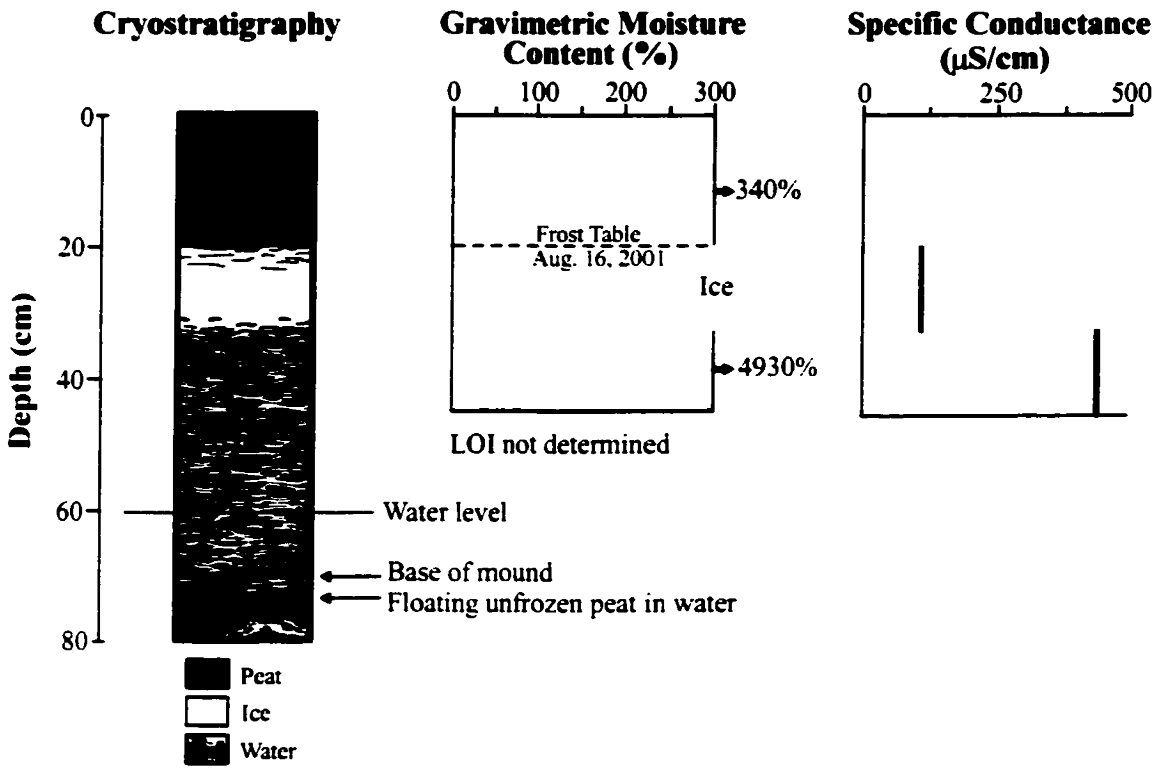

Figure 5.22: Core diagram of Mound 53.

5.2.16 Valley bottom

Permafrost is not restricted to the frost mounds at Wolf Creek. Permafrost was present throughout the valley bottom, particularly in areas that are covered with icings in the winter. In order to better understand why the mounds are formed where they are, a comparison between the cryostratigraphy of the mounds and the surrounding permafrost was performed.

The depth to the frost table was probed on two transects across the valley bottom on Aug 14th 2001. Frost table depths ranged from 37 cm to >1.5 m, with an average depth of 70 cm (n = 102). The sediments encountered during probing were very stony, and many attempts were needed to reach the frost table at a particular spot. Occasionally, the sediments were too stony to penetrate down to the frost table.

A core was taken from a random location on the valley bottom where permafrost was present. The chosen area supported grasses and prostrate shrub willows. The core had an 11 cm peat layer and the frost table was at 49 cm (Aug 9th 2001) (Figure 5.23). The unfrozen sediments were organic-rich, black (10YR 2/1) sands and silts with some gravel and traces of clay. Frozen sediments immediately below the frost table were very dark grey (10YR 3/1) silty sands with some gravel and traces of clay with almost no visible ice content. At 59 cm, two 1 cm thick lenticular, parallel, planar ice lenses were found. Below this, the visible ice content increased to nearly 50% with short, lenticular, parallel, wavy lenses 1-3 mm thick, 3-10 mm long, spaced 2-5 mm apart. At 81 cm, the cryostructure was crustal due to an increase in gravel content, which caused auger refusal. As in most mounds, the specific conductance values within the core were highest just below the frost table, and lower in the remaining core.

Permafrost formation within the valley bottom was accompanied by ice segregation processes. The sediments are similar to those in the mounds on the valley slope (mounds 39- 51), which are coarser those in the valley floor. Although palsas are typically the only areas of permafrost within the sporadic permafrost zone, at this site permafrost can exist within the valley bottom as: 1) the recorded air temperatures are cold enough to preserve permafrost; 2) the valley bottom has an insulative peaty-organic layer at the surface; and 3) the area is potentially covered by regular icing events in the winter, which could help to cool the ground.

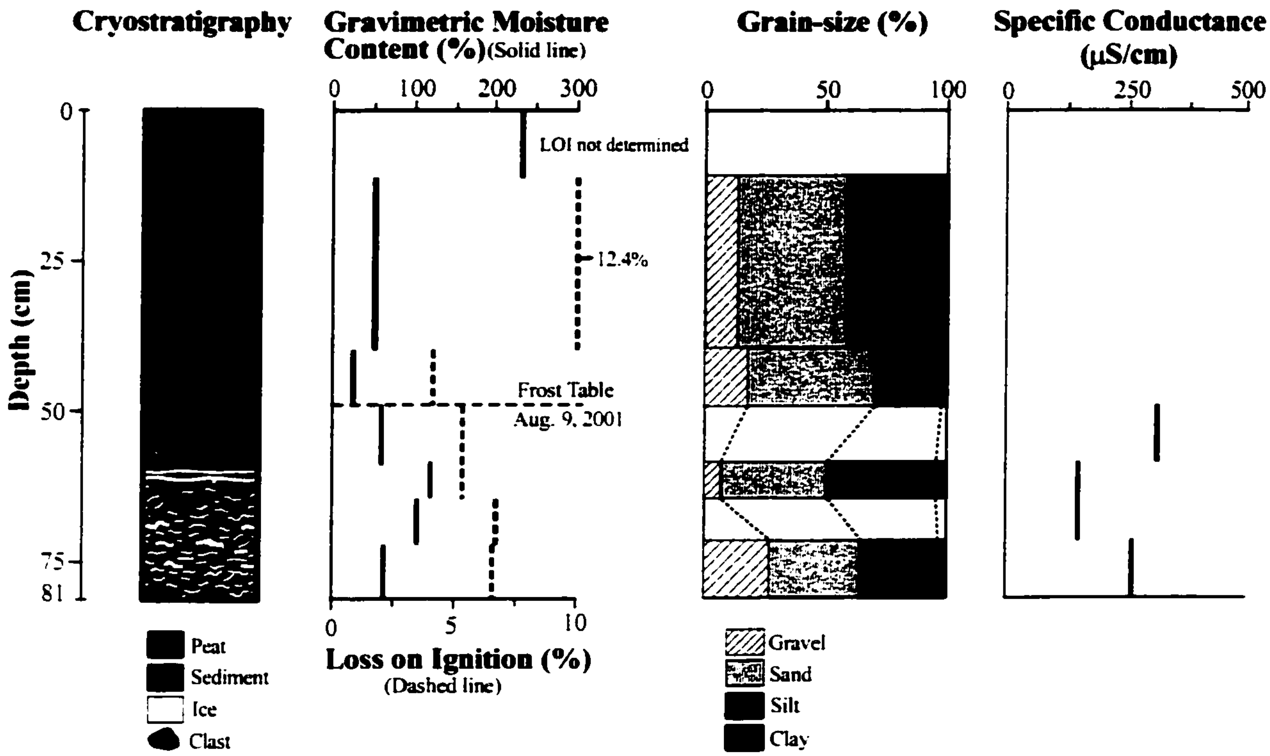

Figure 5.23: Core diagram of valley bottom.

5.2.17 Fox Lake palsa

A number of palsas can be found at Fox Lake, approximately 80 km north of Whitehorse adjacent to the Klondike Highway (Harris 1993). One of these palsas was selected for a borehole for comparison purposes. The Wolf Creek mounds are at an elevation of approximately 1235 m a.s.l., whereas Fox Lake palsas are only at 800 m a.s.l. The mean annual air temperature was estimated at –2°C in 1993 (Harris 1993). The vegetation at Fox Lake is also different. Large white spruce grow within the fen and on stable palsas.

The palsa selected for coring was approximately 1.5 m high, 10 m long and 10 m wide (Figure 5.24). Vegetation on the palsa included grasses, lichens, shrub willows and white spruce trees up to 3 m high. At the core site, the palsa had a 9 cm thick peat layer and the frost table varied from 43 to 53 cm (Aug 22nd 2001)(Figure 5.25). An excavated section revealed that the top of the frozen core roughly paralleled the ground surface. The unfrozen sediments were heavily mottled silts and sands with some clay and traces of gravel in a variety of colours: pale brown (10YR 6/3), brown (7.5YR 4/5) and black (5YR 2.5/1). The upper frozen sediments were greyish brown (10YR 5/1) silts and sand with some clay. At 108 cm, there was a noticeable transition in the frozen sediment to pale yellow (5Y 7/3) sandy silts with some clay. The average median grain-size for the frozen sediments was 5.4 Φ.

Figure 5.24: Photograph of Fox Lake palsa.

The cryostructure was similar to those observed in most of the mounds in Wolf Creek. Ice lenses were short, lenticular, parallel, and wavy 0.5-1 mm thick, 5-10 mm long, spaced 3-5 mm apart. The ice lenses became more frequent, thicker, and spaced closer together with depth. From 123 to 155 cm, 10-20 mm thick ice lenses were encountered with 1 mm thick tubular bubbles. The sediment was plastic due to a high unfrozen moisture content. The core was mainly ice with thin sediment layers from 155-160 cm. From 160-165 cm, the sediment was partially frozen, with three <0.5 mm thick ice lenses. Sediments below 165 cm were unfrozen and temperatures in the underlying sediment reached 0.25°C at 170 cm and 0.3°C at 180 cm.

The sediments in the Fox Lake palsa were finer than in most of the valley-floor mounds and other frost mounds found at Wolf Creek. Also, the sediment in the Fox Lake palsa was rich in macrofossils of fresh water bivalves and gastropods. No macrofossils were found in any of the samples taken from Wolf Creek. The specific conductance values were generally much higher than the values from Wolf Creek. The highest values (1120-1200 μS/cm) were found in upper parts of the permafrost, and decreased to 550 μS/cm near the base.

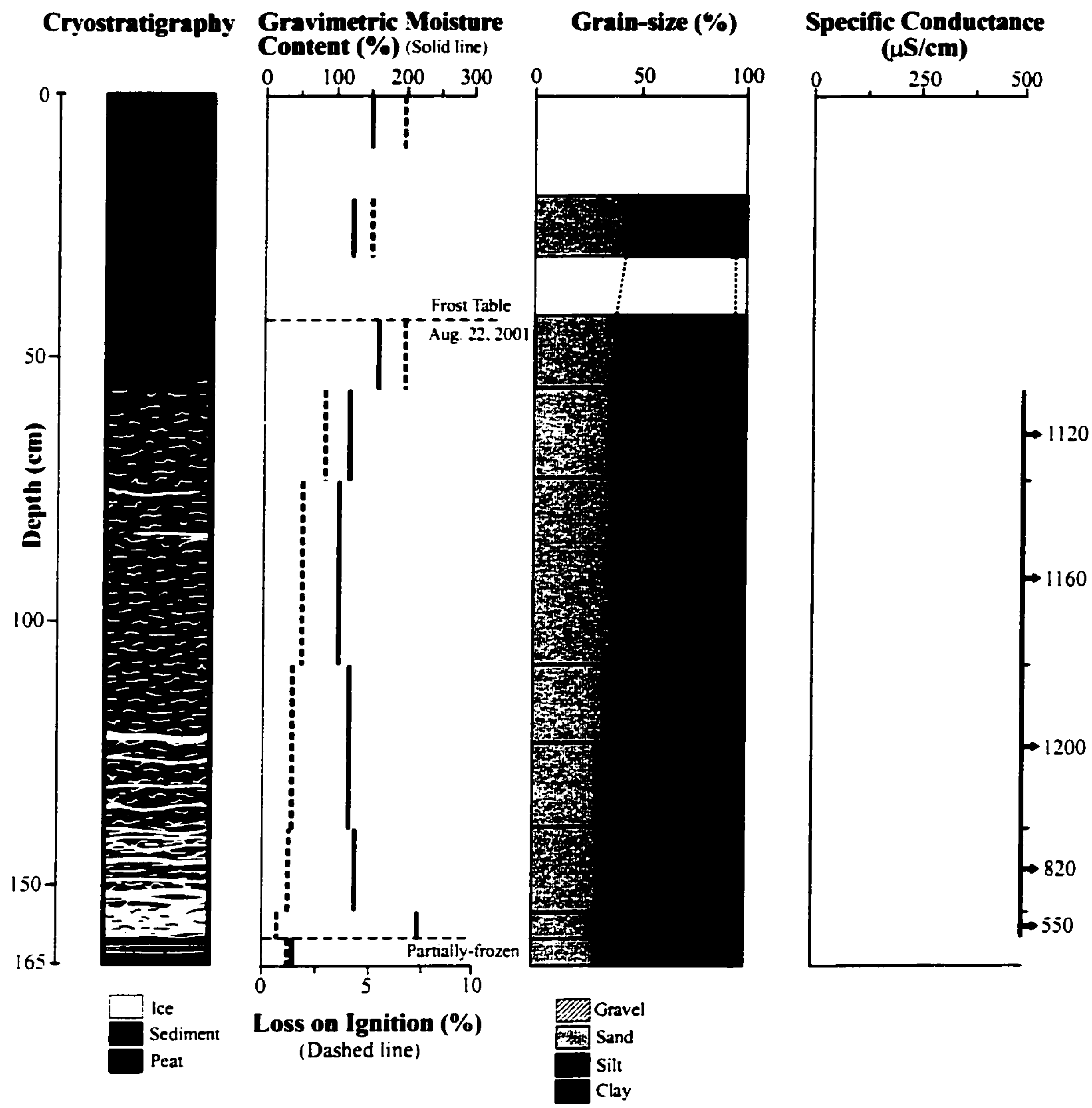

Figure 5.25: Core diagram of Fox Lake palsa.

5.3 SYNTHESIS

Most of the cores from the Wolf Creek mounds exhibited similar trends in gravimetric moisture content, organic content, and specific conductance. The unfrozen sediments generally had the lowest moisture contents, which were mainly less than 50%. Gravimetric moisture content typically peaked immediately below the frost table, in association with an ice-rich zone. In Mounds 7A, 10, 20, and 25, the maxima occurred a short distance below the frost table, suggesting that the lower part of the active layer was still frozen at the time of sampling. An ice-rich zone was also observed near the base of permafrost, which was only reached in the smaller mounds (Mounds 10, 17, 20, 28, and the Fox Lake palsa). Amounts of excess ice for most of the mounds averaged 35-45%. These values roughly account for the amount of heave of the forms.

The specific conductance of the water within the mounds was inversely correlated with the trends in gravimetric moisture content. Thick ice lenses had the lowest specific conductance values due to salt exclusion during the freezing process (Brouchkov 2002). Within the frozen sediments, solute concentrations gradually increased with depth, probably as a result of the migration of water and salts during the downward advancement of the freezing front (Brouchkov 2002). High specific conductance values just below the frost table in some of the mounds (Mounds 7A, 10, 20, 25 52, and in the valley bottom), again suggest that these layers may have become unfrozen later in the summer, or in years that are particularly warm.

The majority of the mounds were made up of sands and silts with varying amounts of gravel and/or clay. There were no consistent trends, either fining up or fining downwards in the cores. Trends in organic content (loss on ignition) of the sediments were also variable. Not counting the surface peat, the organic content of the cores averaged 6%, with peak values generally occurring in the ice-rich zone below the frost table. The origin of the sediment is discussed further in section 6.1.2.

Within some of the mound cores, certain ice lenses were quite thick and traversed the whole core. The origin of these ice layers could not be demonstrated conclusively because only one core was extracted from each mound and it could not be determined if the layer was lens-shaped, i.e. segregated ice, or if it was a continuous layer throughout the mound, i.e. intrusive ice. According to the IPA definition, a palsa is a mound formed strictly from segregated ice. Although certain ice layers were equivocal in nature, their presence with numerous other small lenticular, parallel and wavy lenses, ranging from <1-10 mm thick, 1-10 mm long, and spaced 1-10 mm throughout the entire length of the cores strongly suggest that the cored mounds 7A, 9A, 10, 14, 17, 20, 25 and 28 are formed by ice segregation and therefore are interpreted as palsas. The presence of segregated ice but absence of mineral soil from Mounds 52 and 53 suggests these mounds may be examples of "classic" Fennoscandian palsas. Much smaller in size with no vegetation growth, Mound 53 is interpreted as a palsa in its earliest stage of development. The pond water surrounding and beneath this palsa suggests that the form is a floating palsa (e.g. Harris and Nyrose 1992). Other mounds in the valley floor (1-6, 8, 12, 13, 15, 16, 18, 19, 21-24, 26, 27, 29-38) that were not cored but display similar external characteristics and have equal longevity are also interpreted as palsas.

The IPA definition of a palsa restricts the form to areas that lack high hydraulic potentials. However, there are many indicators of groundwater under pressure at the site in Wolf Creek. In winter, an extensive icing, with associated icing blisters, covers the valley floor. Water filled up the borehole in Mound 7A one day after coring, and immediately rose in the hole in Mound 17. Thick ice layers at the base of the core of Mounds 10 and 17 could represent intrusive ice. Mound 40 possessed a core of massive ice, and is interpreted to be a frost blister. It is possible that some of the mounds may have initially started by high hydraulic pressures, and subsequent upheaving of the forms occurred by ice segregation. This possibility is discussed further below (see section 6.1.4). Regardless of these deviations from the IPA Glossary definition, the weight of evidence from all the mounds (i.e. size, shape, longevity, location within a wetland, and presence of segregated ice) strongly suggests that Mounds 1-38, as well as 52-53, are palsas.

The remaining 13 mounds are more complicated to categorize. As mentioned above, Mound 40 is interpreted to be a frost blister as evidenced by its core of massive ice, but its shrub cover suggests it may be perennial or frequently recur in the same location. Mounds 39 and 41 have similar cryostructures indicating a segregation origin: lenticular, wavy, parallel and non-parallel ice lenses and clasts with ice coatings. The cryostructures correspond with the definition of palsas, but the location of the mounds away from the fen and on a slope with evidence of groundwater springs is problematic. Mounds 42 – 51, found within the same area as Mound 41, also appear to be similar in origin. It is therefore suggested the best-suited term for these mounds is generic: aggradational permafrost mound with a core of segregated ice.

6. DISCUSSION

6.1 Origin of the Mounds

6.1.1 Characteristics of mound sediment

Observations of the exposed sides of degrading palsas showed well-defined bedding. The grain-size analyses, however, revealed that sediments from all the frost mounds are poorly sorted and very poorly sorted, with some extremely poorly sorted sediment from the valley bottom and Mounds 39 and 41. Poorly sorted sediments are indicative of short transport distances or high-energy levels during time of sediment deposition, allowing a wide range of particles to settle (Greenwood 1969).

The sediments from the mounds at Wolf Creek have variable skewness values, that can range from negatively-skewed to positively-skewed within a single mound. The skewness of a sediment gives an indication of the frequency of occurrence of energy fluctuations during transport (Greenwood 1969). By examining trends in skewness and standard deviation, it is evident that sediments from the north and south group of palsas are quite similar (Figure 6.1). Figure 6.1 also shows that the sediment from Mounds 39-51 ("other mounds") is likely of a different origin than the sediment the palsas. The origin of these sediments is most likely colluvial, resulting from mass wasting of the slopes on both sides of the valley.

Sediments found within a thaw slump on the edge of a thermokarst lake south of Coal Lake were finer (median grain-size 7.0 Φ) than the palsa sediments, yet poorly sorted. These sediments differ from all the mounds (see Figure 6.1), indicating a different origin, possibly due to a deeper water depositional regime.

Sediments from the palsa at Fox Lake have a much smaller variability, but lie within the general range of the north and south groups on the graph. This suggests that although the sediments in the Fox Lake palsa were finer than those in the Wolf Creek mounds, the depositional regime was most likely similar. Also, the sediments from Wolf Creek did not contain any macrofossils, unlike those from Fox Lake. This suggests that the environment of Wolf Creek is an unsuitable habitat for the growth of these organisms or that the depositional environment was unsuitable for the preservation of macrofossils.

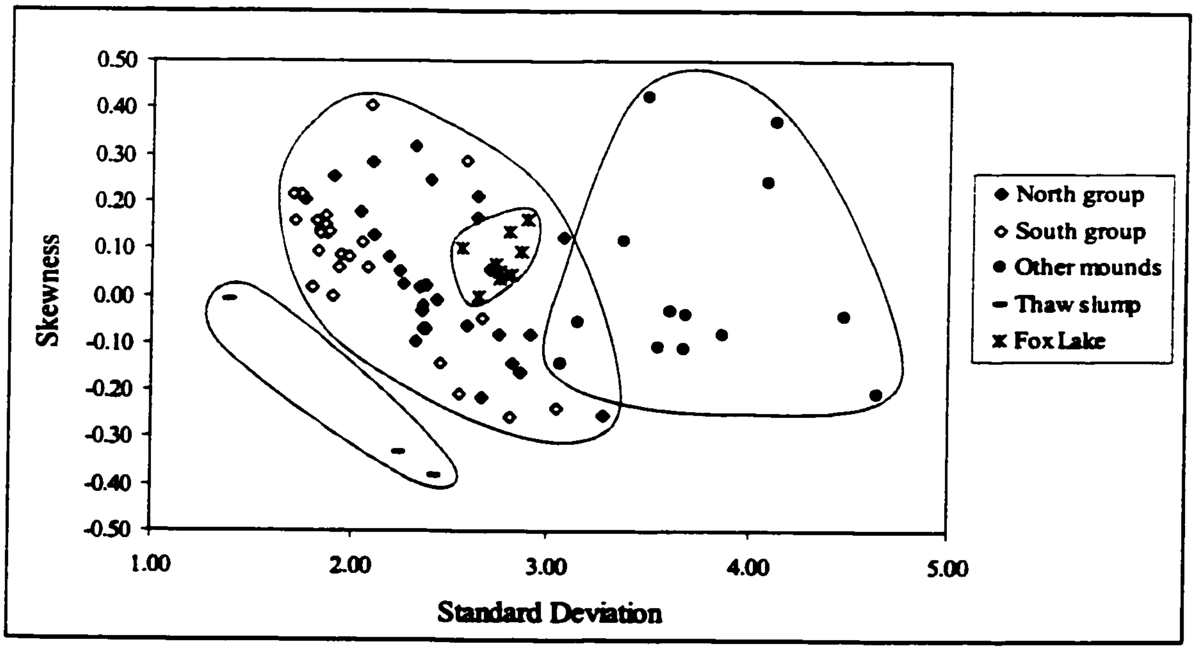

Figure 6.1: Bivariate scattergram of skewness vs. standard deviation (sortedness) of the sediments from the mounds and thaw slump (n=3) at Wolf Creek and the Fox Lake palsa (n=9). Note: north group represents Mounds 1-18 (n=33), south group represents Mounds 20-27 plus mounds 28-38 on the east valley bottom (n=23), and other mounds represents Mounds 39-51 and valley bottom sample (n=13).

6.1.2 Origin of the mound sediments

During the freezing process, the unfrozen water content of a sediment gets progressively confined, lowering its free energy (Williams and Smith 1989). Through cryosuction, water migrates to the freezing front and forms segregated ice lenses. This process is responsible for the upheaving of palsas. The amount of heave by ice segregation is dependent on temperatures at time of freezing, water availability, overburden pressures, and sediment grain-size. Fine-grained sediments, termed "frost-susceptible," favour the growth of segregated ice (French 1996 p. 34). The Wolf Creek palsa sediments have median grain-sizes ranging from 1.6–5.85 Φ (see Appendix A). According to Beskow's textural limit of frost-susceptibility (see Matthews *et al.* 1997), these sediments are predominantly frost-susceptible (Figure 6.2).

These palsa sediments greatly differ from the clast-rich tills and colluvial deposits found within the majority of the Wolf Creek basin. This is significant as the distribution of the palsas in Wolf Creek coincides with that of the frost-susceptible sediments, which

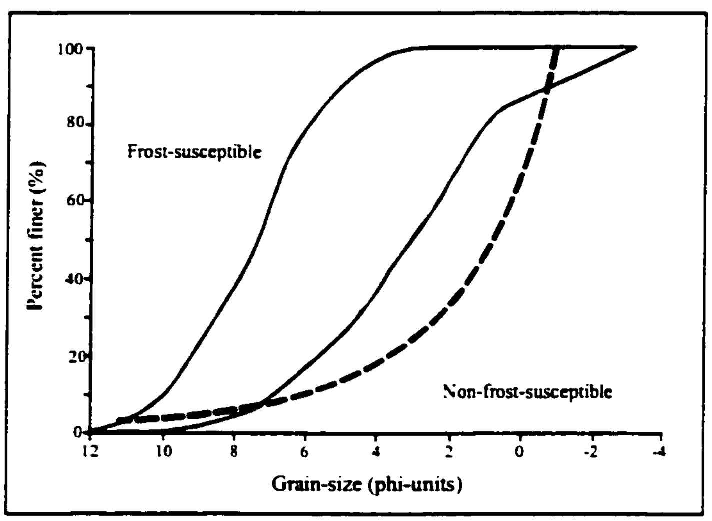

Figure 6.2: Grain-size envelope of palsa sediments at Wolf Creek and Beskow's textural frost-susceptibility limits (as found in Matthews *et al.* 1997).

are found only within the valley bottom. It is therefore pertinent to discuss the possible origin of these sediments.

No consistent grain-size trends were found in any of the palsas, both down-core or spatially. Some cores display weak fining-down trends or coarsening-down trends, but most are variable, flip-flopping back and forth between finer and coarser sediments (Figure 6.3). Organic contents ranged from 2 to 16% with an average value of 6% (not

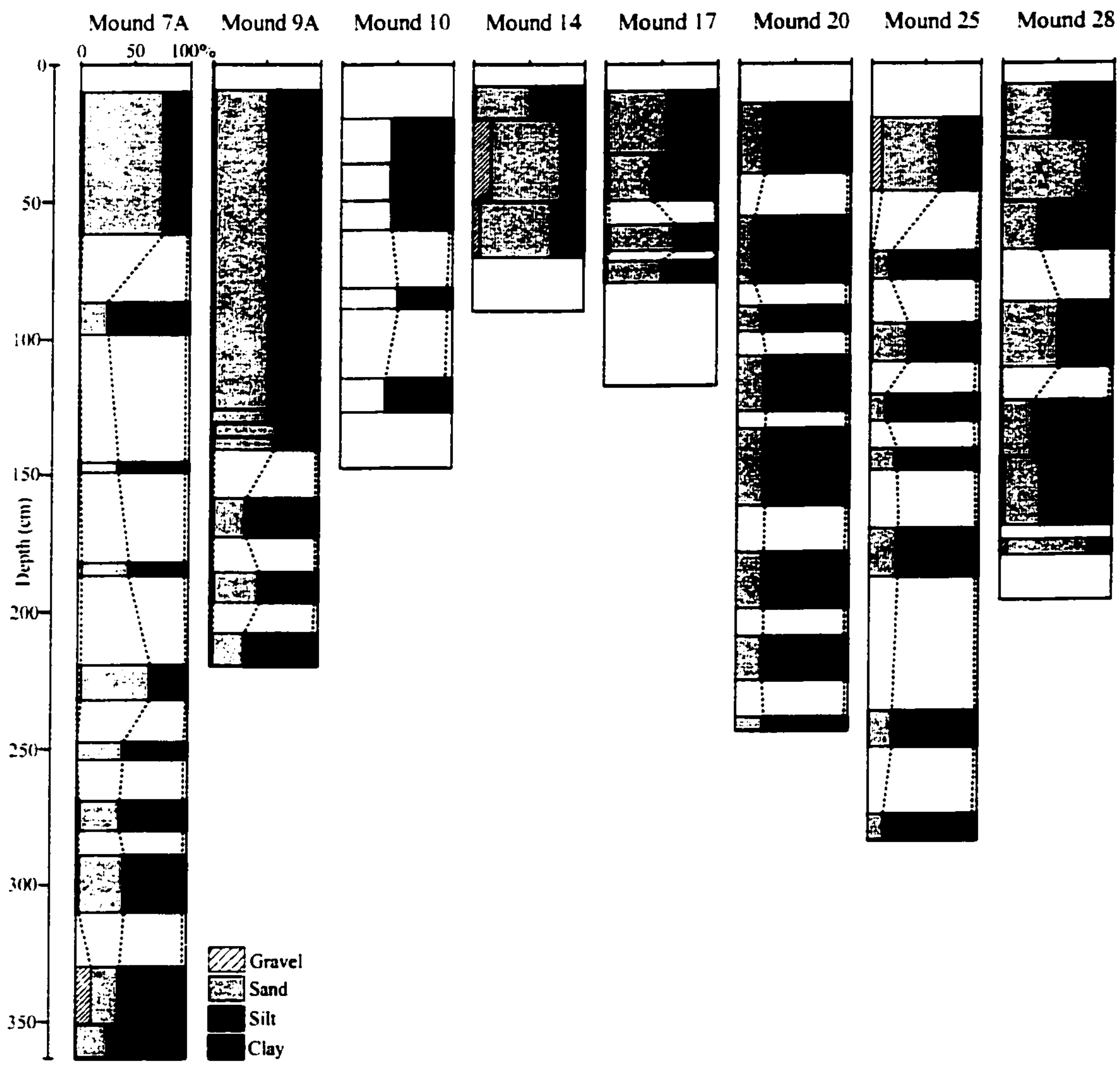

Figure 6.3: The grain-size distributions of the eight palsa cores.

including surface peat) and twigs and rootlets were sometimes present more than 2 m below the frost table.

These sediments are interpreted as having being deposited in beaver ponds. This is inferred from the irregular nature of the grain-size trends, the organic content of the sediments and the localized distribution of sediments within this section of the valley bottom. Similar poorly-sorted deposits with irregular trends in grain-size were found in mountain beaver ponds in Colorado (Bulter and Malanson 1995). Organic contents in that study averaged 10% in younger ponds and 35% in older ones. The Wolf Creek values are somewhat lower than the aforementioned, possibly because this site is further north and at treeline. Butler and Malanson (1995) also found a general fining of sediments down-pond, and coarser sediments close to the dam. Deposits laid down during multiple periods of ponding with varying dam locations would be expected to exhibit the variety of grain-size trends shown in Figure 6.3.

The presence of beaver dams in the valley bottom also promotes the poor drainage that allows peat formation. Peat deposits are rare in the basin, but their thermal characteristics are important to palsa development and preservation (Cummings and Pollard 1990, Outcalt and Nelson 1984a, Seppälä 1982, Williams and Smith 1989). Beaver activity, therefore appears to be intimately associated with palsa formation, helping to create both the pre-conditions of frost-susceptible sediments and an overlying layer of peat.

6.1.3 Importance of snow

The snow depth data are of interest as it is stated many times within the literature that low snow depths on the summits of palsas, as compared to surrounding areas, are primarily responsible for the initiation and preservation of the mounds. Mean snow depths on palsa summits described in the literature tend to be less than 20 cm with palsa sides having more snow (Table 6.1). One model demonstrated that palsa growth could not be initiated if a critical thickness of 30 cm of snow was exceeded (Outcalt and Nelson 1984b). The model also showed that snow depths of 40 cm or more could be sufficient to trigger the degradation of an existing palsa.

Table 6.1: Snow depths reported in the literature.

Author	Location	Snow Depths
Cummings and Pollard 1990	Northern Québec	- Palsas 0-45 cm, average 10 cm - Surrounding fen 48-175 cm with an average of 69 cm
Kershaw and Gill 1979	Macmillan Pass NWT	- Mature palsas averaging 40 cm - Young palsas averaging 7.5 cm
Seppälä 1990	Northern Finland	- Palsa sides 20-50 cm (Nov/Dec) up to 140 cm (Apr) - Palsa tops 3-20 cm (Nov/Dec) decreased to 0-5 cm (Jan)
Zoltai and Tarnocai 1971	Northern Manitoba	- No trees on palsa 53 cm - Some trees on palsa 38 cm - Dense trees on palsa 14.5 cm

The snow depths recorded at Wolf Creek (Table 6.2), with mean values of 21 to 66 cm, are unusually high when compared to those within the literature and of the same order as those which caused degradation in Outcalt's and Nelson's (1984b) simulations. Shrub willow and shrub birch on the palsas were effective at trapping snow. Also, contrary to Seppälä's (1994) observations, the sides of the palsas in Wolf Creek did not always have greater snow depths. Based on observations in the valley, winds that redistribute the snow are mainly from the southwest. Consequently, snow depths were generally greater on the north (lee) sides than on the south (windward) sides of the palsas, with the exception of the younger forms Mounds 10 and 20. These younger palsas were found in the lee of much larger palsas, which caused their south sides to be more heavily covered in snow. The lack of shrubs also resulted in younger palsas having lower mean snow depths, ranging 23 to 41 cm. However, these values were still greater than most reported within the literature.

Table 6.2. Mean snow depths (cm) on the north sides (N), south sides (S), tops and overall average (Avg) snow depths of selected palsas in Wolf Creek.

Palsa ID#	Growth Stage	April 6, 2001				April 1, 2002			
		N	Top	S	Avg	N	Top	S	Avg
10	A	-	-	-	-	20	28	52	33
20	A	18	21	31	23	35	42	47	41
9A	S	-	-	-	-	100	33	43	59
9C	S	-	-	-	-	50	49	69	56
12	S	33	56	19	36	72	64	57	64
7A	D	-	-	-	-	73	43	82	66
8	D	-	-	-	-	93	66	68	76
23	D	-	-	-	-	64	60	73	66

Note: Growth stage: A = aggrading; S = stable; D = degrading.

The overall significance of the thick snow cover is difficult to assess as the insulative properties of snow also depend on density and structure, and these were not studied in any detail. The snowpack on the shrub-covered palsas at Wolf Creek was soft with a pronounced depth hoar layer. Depth hoar has low density and low thermal conductivity, and therefore high insulative capabilities (Zhang *et al.* 1996). Zhang *et al.*'s (1996) model, which neglected convective heat flow, predicted that a depth hoar layer representing 60% of the total snow pack could delay freeze-up of the active layer by up to four months.

These results suggest that although low snow depths may contribute to the initial formation of palsas, unlike other studies (e.g. Cummings and Pollard 1990, Outcalt and Nelson 1984b, Seppälä 1982, 1990), they are not critical for the preservation of the forms at the Wolf Creek site. This appears to be possible because climatic conditions are sufficiently cold to produce permafrost in the surrounding area and on valley slopes, even at typical snow depths.

6.1.4 Importance of groundwater pressures

Several observations demonstrate that groundwater under pressure is present at the main study site: (1) springs with water temperatures close to 0°C in summer are present at a break of slope 50 m from the stream; (2) the valley floor was covered by an icing in winters 2000-01 and 2001-02; (3) icing mounds with dilation cracks were present in both winters; (4) a frost blister (Mound 40) was present on the valley slope.

The influence of groundwater on palsa dynamics is much more difficult to assess. Indications of groundwater pressure within palsas were noted on two occasions: 1) water rose up the borehole in Mound 7A within one day of drilling to a level above the surrounding stream; and 2) water immediately rose up borehole in Mound 17 after breaking through an ice layer. At the very least, the presence of groundwater means that the palsas have a ready water supply for segregation processes.

The influence on groundwater pressures on the aggradational permafrost mounds (Mounds 39, 41-51) is also undetermined. These mounds are located on the valley slopes near groundwater springs. Four aggrading palsas were encased in an icing ~1 m thick icing during the winter (see Figure 5.8B). It seems likely that the effect of icing growth and decay is to cool the ground, thereby favouring mound growth. However, this is a two-dimensional or three-dimensional thermal modelling problem, which is beyond the scope of the present thesis.

It is possible that groundwater pressures could be responsible for the initial upheaval of the mounds, with subsequent growth by ice segregation. If this were true, however, one would expect to see a thick ice body of intrusive ice at the top of permafrost. On the other hand, thicker ice bodies could conceivably have melted since their formation as the result of a deeper active layer thaw. There was no evidence extant in any of the mounds examined to confirm or deny this possibility.

Mound 17 (see Figure 5.10) could have formed partly under the influence of groundwater pressures. A 24 cm thick ice lens was located at the base of its core. This layer of ice was observed to be present throughout most of an estimated 25 m by 15 m peaty area. Immediately after coring through a 24 cm thick ice lens, water from below rose up the core to a level 5 cm above the nearby pond. The water from within the core had a higher specific conductance than the water from the pond, indicating a separate water source beneath the mound; e.g. sub-permafrost groundwater.

There are two possible explanations for this. Firstly, the 24 cm thick ice lens could be segregated ice. If the water below was in a closed-system, the rise of water in the borehole could be attributed to a release of hydrostatic pressures. The higher conductivity of the water would be caused by salt exclusion as the ice lens above grew (Kay and Groenevelt 1983). However, Mounds 7A, 10, and 28 also had thick lenses of ice, ranging from 15 to 24 cm, near or at the base of their cores. The model of An and Allard (1995) predicted that a thick ice lens would be present at the base of permafrost in palsas, and thick lenses of segregated ice in palsas have been reported within the literature (e.g. Forsgren 1968, Seppälä 1980).

The second possibility is that the 24 cm thick ice lens was intrusive ice formed under hydraulic pressures. Although it is improbable that intrusive ice would form a planar layer beneath a relatively thin cover of peat alone, the 1 m thick icing that covers the valley floor in the winter could supply sufficient overburden pressure to cause sub-permafrost water to be injected as an extensive layer. In this case, the water would have risen in the borehole due to the overburden pressure of the mound over the area of water in a semi-closed system. The sub-permafrost water would have a high conductivity due to expulsion of salts from the ice layer above, or would simply be groundwater with a conductance comparable to those in nearby springs. If this possibility is correct, it suggests that Mound 17 is a compound form, comprised of both segregation and intrusive ice.

6.2 Longevity of the Mounds

6.2.1 Rates of change

Palsas in all stages of development were found within the study area: 22 aggrading palsas, 8 stable palsas, and 6 degrading palsas. There is little in the literature regarding the rate of growth of palsas. One experiment by Seppälä (1982) produced a small palsa that grew ~10 cm/year. The model of An and Allard (1995) predicts that under a stable climate the initial growth of a palsa averages 5 cm/year so that a 3 m high palsa could grow in 60 years. Growth would then slow and it would take a further 140 years to double in height (An and Allard 1995). Palsa degradation has been discussed in the literature at the scale of palsa fields rather than individual forms (Table 6.3). It must be stressed that rates of degradation are site specific, since they can be controlled by several climatic and non-climatic factors.

Table 6.3: Rates of degradation of palsas reported in the literature.

Source	Location	Rates of Degradation of Palsas
Kershaw and Gill 1979; Horvath 1998	Macmillan Pass NWT	Two palsa fields completely degraded from 1944 to 1978 from thermal erosion; two other fields declined in area by 20% and 36% from 1949-1988.
Laprise and Payette 1987; Laberge and Payette 1995	Northern Québec	49% decrease in total cover of palsas and collapsed scars from 1957 to 1983; 33% decrease in permafrost within the peatland from 1983 to 1993 but no significant change in shape and contour of the palsas.
Sollid and Sørbel 1998	Southern Norway	Several small palsas found in 1972 had completely degraded by 1997.
Sone and Takahashi 1993	Daisetsu Mountains Japan	A palsa field reduced by 36% in 27 years, however at the same time some palsas were not affected and some grew.
Zuidhoff and Kolstrup 2000	Northern Sweden	50% decrease in area of palsas and no new palsas developed from 1960 to 1997.

The aerial photographic record of Wolf Creek, dating from 1946, gives an indication of the longevity of the mounds. Palsas that were visible on the first photographs and that are still currently present within the basin, have a minimum age of 55 years. Overall, there are fewer palsas present in the study site in 2001 than in 1946 (see Figure 5.1). Between each set of aerial photographs, palsas both aggraded and degraded.

The calculated maximum rate of degradation is 6 mounds/decade and the maximum rate of aggradation is 4 mounds/decade (Figure 6.4). Local temperatures at the Wolf Creek site over the past five decades have likely followed the patterns in Whitehorse, only 20 km to the north and 500 m lower in elevation. During the 1940-1970's cooling phase (IPCC 2001, Overpeck *et al.* 1997) the largest imbalance occurred between 1966 and 1987, when degradation of palsas far outweighed aggradation. During the warmest period of the past 50 years (1990 onwards), aggradation and degradation of those palsas visible on the aerial photographs have been balanced. However, field mapping in 2001 (see Figures 5.2 A & B), shows aggrading palsas to be in the great majority. The palsa development does not appear to be following climatic trends in this region.

Evidence from the aerial photographs suggests that non-climatic factors, such as beaver damming, have a more significant role in palsa dynamics than climate. At the very least, non-climatic factors mask any effect that climatic factors have on the palsas.

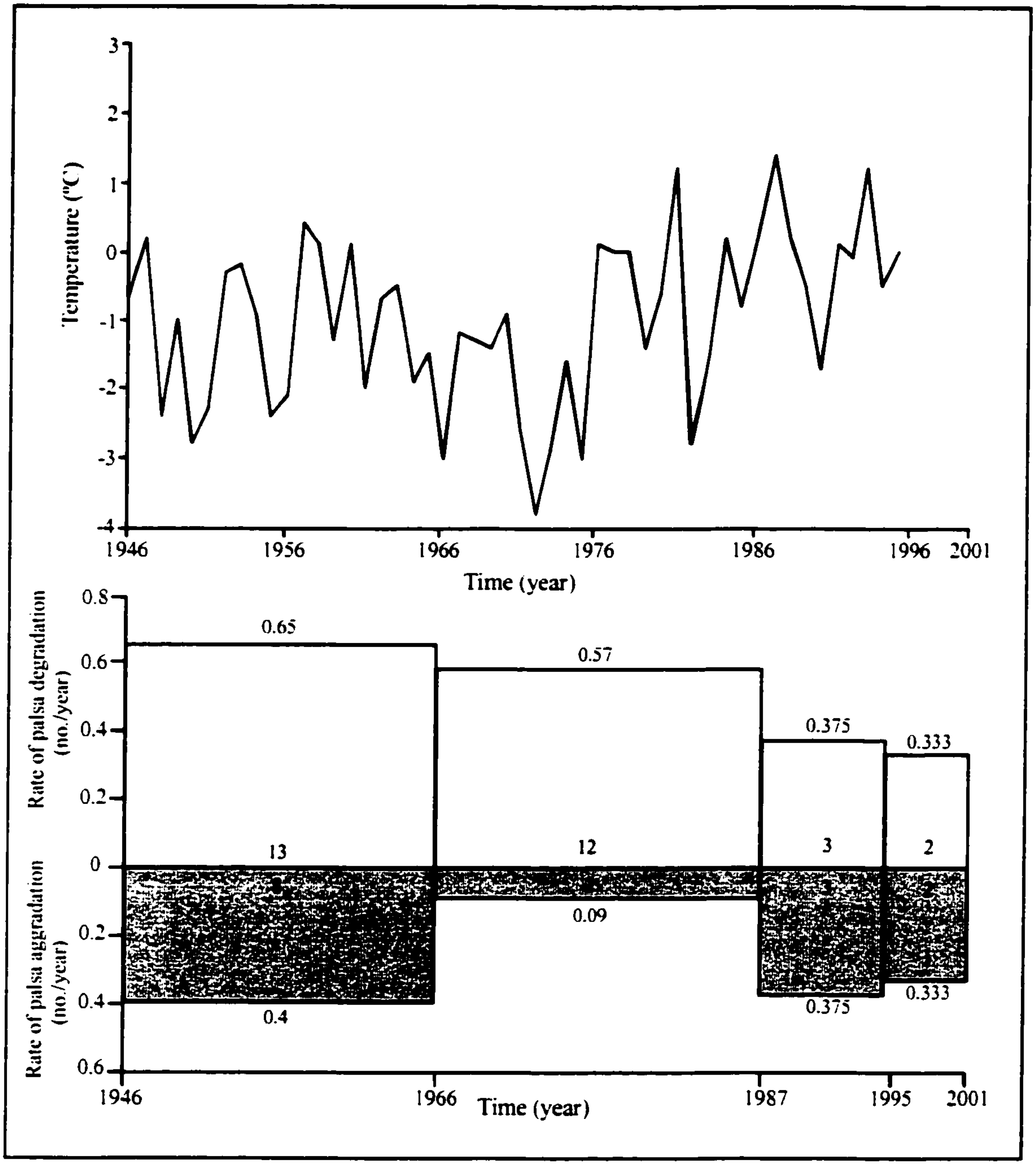

Figure 6.4: Rates of aggradation and degradation of mounds at Wolf Creek based on analysis of aerial photographs (see Figure 5.1) as compared to the mean annual air temperatures in Whitehorse, Yukon Territory (Vincent and Gullett 1999). Values inside bars on the graph are actual number of mounds that aggraded or degraded within a given time period. Values outside the bars are the calculated rates of aggradation and degradation for a given time period. Note: small mounds, not visible on the aerial photographs, are not included.

6.2.2 Influencing factors

Palsa aggradation and degradation can be attributed to several agents of change. Circumstantial evidence of the importance of variations in surface water extent on mound degradation is provided by the 1946, 1966 and 1987 photos (see Figure 5.1). Fourteen palsas visible on the 1946 photographs had completely degraded by 1966, and they were located in areas that were nearly or completely inundated by water.

One of the causes for the change in water levels is the construction and destruction of beaver dams. During fieldwork, ten breached beaver dams were found traversing the valley bottom of the study site. The beaver dams responsible for damming water within the north group of palsas can be identified on the 1966 and 1995 photographs (see Figure 5.2A). It is reasonable to infer that high water levels due to beaver damming can cause thermal erosion and resultant degradation of a mound (e.g. Brown 1980, Friedman *et al.* 1971, Gurney 2001). The photos indicate that complete degradation of a palsa can occur in less than a decade. It remains unknown, however, how long the beaver dams were actively damming the water, and the duration necessary to cause complete palsa degradation.

It can be inferred that a drop in water level, either from beaver dam construction re-directing the stream channel, or a dam breach that drains a previously flooded area, may allow permafrost to aggrade in newly exposed peat and sediment. For example, permafrost grew at rates of 1.5-3 m/yr in the bed of an experimentally drained thaw lake in the Mackenzie Delta (Mackay 1986). In the 1995 aerial photographs, an area beside the Mound 9 complex appears flooded. This area drained after 1995, and two small aggrading mounds (Mounds 17 and 18) have now formed. Similarly, new mound growth occurred in a relict palsa bog in Iceland after extensive flooding to the area had receded (Thórhallsdóttir 1994). The last 40 cm of core from one these palsas was "pure" ice. It is unclear whether or not the mound was a palsa, a frost blister, or a compound form similar to Mound 17.

Debris flow chutes could be partially responsible for changes in water levels. In the 1995 aerial photograph, the tongue of a debris flow chute extends into the path of the stream (Figure 6.5). This event could have blocked the channel used in previous years, which was flooded due to beaver damming by the time of this photograph.

It is also possible that Dall sheep have a negative effect on palsas. On July 31st 2001, several Dall sheep traversed the valley bottom at the location of the southern group of palsas. The sheep were witnessed consuming the exposed mineral sediments of Mound 23. Together with heavy trampling of the palsa sides and removal of stabilizing vegetation, the actions of the Dall sheep could contribute to palsa degradation.

Figure 6.5: The north group of palsas with a debris flow tongue extending into the path of the stream (Photo: A28238-7, September 1995, National Resources Canada).

6.2.3 Shrub growth rings and mound longevity

Thirteen of the mounds present in 2001 appear on the earliest set of photos and must be at least 55 years old. The counts of annual growth rings from shrubs sampled from the summits of the mounds extend their minimum ages beyond 1946. Of these 13 mounds, 12 have the oldest maximum shrub ages (Figure 6.6), supporting the interpretation of the aerial photographs. The annual growth ring analyses of the shrub willow and shrub birch show that the oldest palsa (Mound 8) is at least 158 years old, and allowing 5-10 years for the initial colonization of *Salix* species (e.g. Walkerton *et al.* 1986), it could have a minimum age of nearly 170 years. Mound 22, a mound that should be at least 55 years old, had a shrub age of only 19 years, which was much lower than expected. However, annual growth ring counts indicate only minimum ages because the shrubs sampled were the largest, but not necessarily the oldest, and some had rotten piths. Consequently, these dates cannot be taken as a precise time of formation.

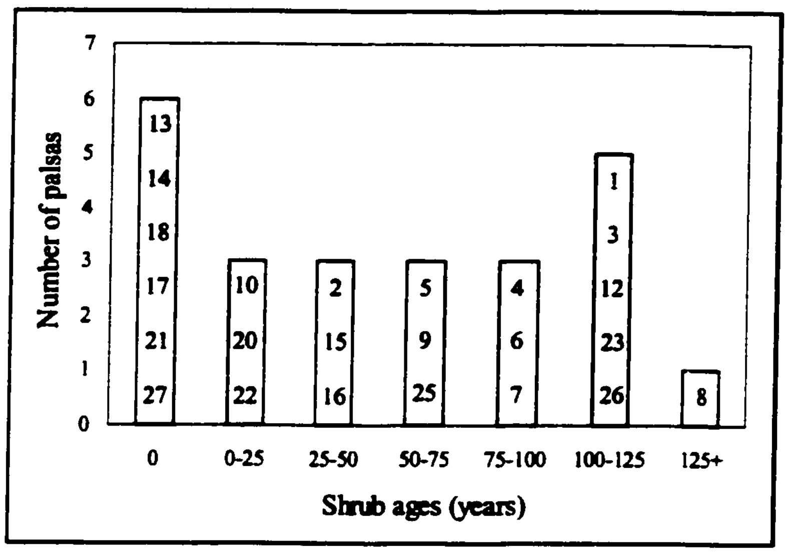

Figure 6.6: Histogram of maximum shrub ages based on annual growth ring counts for palsas within the north and south groups (Mounds 1-27). The number of the mound that the shrub came from is indicated in each bar of the histogram (n=24, note there are no mounds 11 or 19, and the sample was lost for mound 24).

Equally unexpected, Mounds 15 and 16 had maximum shrub ages of 41 and 34 years respectively. These two mounds were small aggrading forms that were not visible on any of sets of aerial photographs, and were expected to be younger forms. These mounds are most likely smaller than expected based on their ages, as they are located in a clast-rich, less frost-susceptible, sediment which would not be conducive to much ice segregation.

Despite the uncertainties in the methods, Figure 6.4 shows that palsas have been forming and degrading continually over the past 55 years, and Figure 6.6 extends the period of continual mound formation through more than 125 years. The histogram of maximum shrub ages (Figure 6.6) shows a slightly higher frequency of palsas with annual growth ring counts of 100-125 years, which could indicate a period of increased palsa formation 100-125 years ago. This time period coincides with the end of the Little Ice Age (Jacoby and D'Arrigo 1989), and it is possible that there was a higher rate of palsa aggradation at this time. However, the weight of evidence suggests that the palsas in Wolf Creek are more strongly influenced by non-climatic factors, which mask any potential effects of climate. The palsas are meta-stable within their environment, as their cyclical aggradation and degradation has been balanced. It can therefore be concluded that the palsas in Wolf Creek cannot be used as reliable indicators of climate change.

7. CONCLUSIONS

The following conclusions can be drawn from this study:

1. Fifty-one frost mounds were examined in the Wolf Creek Research Basin.
    a. Thirty-seven mounds were identified as palsas, as evidenced by their dimensions, location within a fen, and cryostructure of segregated ice. The palsas are located in the valley bottom where fine-grained, frost-susceptible sediments can be found. These sediments are interpreted as having been deposited within beaver dam ponds.
    b. One mound was identified as a frost blister, as evidenced by its core of intrusive ice. It appears to recur seasonally, in the same location as evidenced by its shrub cover.
    c. Twelve mounds were best described as aggradational permafrost mounds with cores of segregated ice, as all other genetic terms within the literature proved unsatisfactory. They are present on the lower valley slopes, and are formed of coarser colluvial sediments.
    d. One mound (#17) appeared to be a compound form, as evidenced by the presence of segregated ice and possibly ice within the core. The latter formed from a sub-permafrost water lens under pressure as suggested by the immediate rise of water within the borehole upon coring through the mound.

2. Palsas at the study site have been continually degrading and aggrading over the last 55 years, as evidenced by the aerial photographs, and are continuing to do so.

Maximum rates of change of mounds large enough to be visible on the photos were 6 per decade (degradation) and 4 per decade (aggradation). Annual growth ring analyses of the shrubs from the palsas, showed that the oldest palsa is at least 150 years old and suggest that palsas formed in each of the six 25-year periods since 1850. From the aerial photographs, it is evident that palsas can aggrade and degrade over as short a period as 6 years.

3. The aggradation and degradation of palsas in Wolf Creek appear to be triggered in part by non-climatic agents of rapid change. The construction and destruction of beaver dams and debris flow chutes alter the course of the stream occupying the valley bottom. An increase in water level can result in thermal erosion of palsa sides and leads to block collapse. The latter may be exacerbated by soil consumption and erosion of palsa sides by trampling by Dall sheep. A reduction in water level caused by dam breaching can lead to mound formation during permafrost aggradation in newly exposed peat and sediments.

4. A MAT of –4°C recorded at the palsa site allows permafrost to be present in some of the surrounding terrain as well as within the palsas themselves. This suggests that the palsas are not likely to be highly sensitive to climatic warming, since they probably could persist even if air temperatures increased. This is also suggested by the presence of relatively deep snow on both aggrading and stable mounds, which seems insufficient to stop growth or cause degradation. When combined with the impact of changes in water level and other non-climatic factors, it can be

concluded that the palsas in Wolf Creek cannot be used as past indicators of climate change and could not be used to track future change unless warming was sufficiently extreme to dominate the non-climatic factors.

Several questions remain unanswered and warrant further research.

1. What is the origin of the "aggradational permafrost mounds with cores of segregated ice"? Similar mounds have been found on colluvial fans in the Kluane region, Yukon Territory and at the base of a long slope in the Sawtooth Range, Ellesmere Island, Nunavut (A. Lewkowicz, *Department of Geography, University of Ottawa, personal communication 2002*).

2. What is the source and age of the water stored as ice in the palsas and aggradational permafrost mounds? Geochemical analyses could be used to better understand the influence of groundwater on compound mound development. Intensive sampling for tritium at small intervals throughout an entire core in an aggrading mound could be used to quantify the residence time of water prior to incorporation in the mound.

3. What are the thermal characteristics of the snow on the palsas compared to the surrounding area? This question includes establishing the relation between snow depths and densities with varying vegetation covers. It would also be important to determine the thermal characteristics and possible ground cooling influence of icings on the valley bottom and around the mounds.

4. What are the annual and seasonal growth rates of the palsas over time? This question could be answered by regular precision topographic surveying. Surveying would also reveal more about sub-palsa heat flow and ice segregation processes, and would help confirm the identification of the mounds as palsas: hydrostatic pressures should be revealed by slow change in elevations, while more rapid change would suggest hydraulic pressures.

5. Are the mounds observed at an elevation of ~1700 m a.s.l in Wolf Creek in the summer of 2002 in fact palsas? What is the difference, if any, in their cryostratigraphy compared to the palsas described in this thesis.

6. Could mound aggradation and degradation be triggered by the placement of artificial dams along the valley bottom? The time it takes for a palsa to completely degrade if surrounded by water could be monitored, as well as the time needed for new palsas to aggrade in newly exposed peat.

Hopefully, some of these questions will be the subject of future research.

REFERENCES

Åhman, R., 1976: The structure and morphology of minerogenic palsas in northern Norway. *Biuletyn Periglacjalny*, 26: 25-31.

Allard, M. and Rousseau, L. 1999: The internal structure of a palsa and peat plateau in the Riviere Boniface region, Québec: inferences on the formation of ice segregation mounds. *Géographie physique et quaternaire.* 53(3): 373-387.

Allard, M., Caron, S. and Bégin, Y., 1996: Climatic and ecological controls on ice segregation and thermokarst: the case history of a permafrost plateau in northern Québec. *Permafrost and Periglacial Processes*, 7: 207-227.

Allard, M., Seguin, M.K. and Lévesque, R., 1986: Palsas and mineral permafrost mounds in northern Québec. In: V. Gardiner (ed.), *International Geomorphology, Part II.* Chichester: John Wiley and Sons Ltd., 285-309.

An, W. and Allard, M., 1995: A mathematical approach to modelling palsa formation: insights on processes and growth conditions. *Cold Regions Science and Technology*, 23(3): 231-244.

Agriculture Canada Expert Committee on Soil Survey, 1987: The Canadian system of soil classification - 2nd edition. Agriculture Canada. Publication 1646, 164 p.

American Society for Testing and Materials, 2001a: *American Standard Test Method D422-63, 1998: Standard Test Method for Particle-Size Analysis of Soils*. West Conshohocken, PA.

American Society for Testing and Materials, 2001b: *American Standard Test Method D2216-98: Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass*. West Conshohocken, PA.

Bengtsson, L. and Enell, M., 1986: Chemical analysis. In: B.E. Berglund (ed.), *Handbook of Holocene Palaeoecology and Palaeohydrology*. Chichester: John Wiley and Sons Ltd., 423-451.

Beschel, R. E. and Webb, D., 1962: Growth ring studies on arctic willows. In: F. Müller, (ed.) *Axel Heiberg Island: Preliminary Report 1961-1962.* Montréal: McGill University, 189-198.

Bostock, H.S. 1948: Physiography of the Canadian cordillera, with special reference to the area north of the fifty-fifth parallel. *Geological Survey of Canada, Memoirs v.247.* Ottawa: E. Cloutier, King's Printer, 106 p.

Brouchkov, A., 2002: Nature and distribution of frozen saline sediments on the Russian Arctic coast. *Permafrost and Periglacial Processes*, 13: 83-90.

Brown, G., 1980: Palsas and other permafrost features in lower Rock Creek Valley, west-central Alberta. *Arctic and Alpine Research.* 12(1): 31-40

Brown, J., Nelson, F., Brockett, B., Outcalt, S.I. and Everett, K.R., 1983: Observations on ice-cored mounds at Sukakpak Mountian, south central Brooks Range, Alaska. In: *Proceedings, Fourth International Conference on Permafrost.* Washington, D.C.: National Academy Press, 91-96.

Brown, R.J.E., 1968: Occurrence of permafrost in Canadian peatlands. *Proceedings of Third International Peat Congress*, 174-181.

Bryant. J.P., 1987: Feltleaf willow-snowshoe hare interactions: plant carbon/ nutrient balance and floodplain succession. *Ecology*, 68(5): 1319-1327.

Butler, D.R. and Malanson, G.P., 1995: Sedimentation rates and patterns in beaver ponds in a mountainous environment. *Geomorphology.* 13: 255-269.

Burn, C.R., 1990: Implications for palaeoevironmental reconstruction of recent ice-wedge development at Mayo, Yukon Territory. *Permafrost and Periglacial Processes*, 1: 3-14.

Campeau, S. and Hequette, A., 1995: Butted cryogenes saisonnieres de plages arctiques, Peninsule de Tuktoyaktuk, Territoires du Nord-Ouest. *Géographie physique et quaternaire*, 49: 265-274.

Canadian Climate Normals 1994: Canadian monthly climate data and 1961-1990 normals: Ottawa: Environment Canada. CD-rom.

Chizhov, A.B., Chizhova, N.I., Romanov, V.V., Morkovkina, I.K. and Boyarskiy, O.G., 1985: Tritium analysis in geocryological research. *International Geology Review*, 27: 1370-1377.

Cummings, C.E. and Pollard, W.H., 1990: Cryogenetic categorization of peat and mineral cored palsas in the Schefferville area, Québec. In: *Proceedings, Fifth Canadian Permafrost Conference,* Québec City, Nordicana No. 54, 95-102.

Dijkmans, J.W.A., 1988: Seasonal frost mounds in an eolian sand sheet near Søndre Strømfjord, W. Greenland. In: *Proceedings, Fifth International Conference on Permafrost.* Trondheim: Tapir Publishers, 728-733.

Folk, R.L., 1974: *Petrology of Sedimentary Rocks.* Austin: Hemphill's Publishing Co., 182 p.

Forsgren, B., 1966: Tritium determinations in the study of palsa formations. *Geografiska Annaler*, 48A: 102-110.

Forsgren, B., 1968: Studies of palsas in Finland, Norway and Sweden. *Biuletyn Peryglacjalny*, 17: 117-123.

Francis, S., Smith, S. and Janowicz, J.R. 1999: Data integration and ecological zonation of Wolf Creek watershed. In: J.M. Pomeroy and R.J. Granger (eds.), *Wolf Creek Research Basin: Hydrology, Ecology, Environment.* Environment Canada, 125-134.

French, H.M., 1996: *The Periglacial Environment, 2^{nd} ed.* Essex: Addison Wesley Longman Limited, 341 p.

Friedman, J.D., Johansson, C.E., Oskarsson, N., Svensson, H., Thorarinsson, S. and Williams Jr., R.S., 1971: Observations on Icelandic polygon surfaces and palsa areas. Photo interpretation and field studies. *Geografiska Annaler*. 53A: 115-144.

Froehlich, W. and Slupik, J., 1978: Frost mounds as indicators of water transmission zones in the active layer of permafrost during the winter season (Khangai, Mts., Mongolia). In: *Proceedings, Third International Conference on Permafrost.* Ottawa: National Research Council, 188-193.

Fu, P. and Rich, P.M., 1999: Design and implementation of the Solar Analyst: an Arcview extension for modeling solar radiation at landscape scales. Accessible at: http://www.esri.com/library/userconf/proc99/proceed/papers/pap867/p867.htm

Greenwood, B., 1969: Sediment parameters and environment discrimination: an application of multivariate statistics. *Canadian Journal of Earth Sciences*, 6: 1347-1357.

Gurney, S.D., 2001: Aspects of the genesis, geomorphology and terminology of palsas: perennial cryogenic mounds. *Progress in Physical Geography*. 25(2): 249-260.

Harris, S.A., 1982: Identification of permafrost zones using selected permafrost landforms. In: *Proceedings of the Fourth Canadian Permafrost Conference.* Ottawa: National Research Council of Canada, 49-57.

Harris, S.A., 1993: Palsa-like mounds developed in a mineral substrate, Fox Lake, Yukon Territory. In: *Proceedings, Sixth International Conference on Permafrost.* Beijing: Science Press, 238-243.

Harris, S.A. and Nyrose, D., 1992: Palsa formation in floating peat and related vegetation as illustrated by a fen bog in the Macmillan Pass, Yukon Territory, Canada. *Geografiska Annaler*, 74A:349-362.

Harris, S.A., Schmidt, I.A. and Krouse, H.R., 1992: Hydrogen and oxygen isotopes and the origin of ice in peat plateaus. *Permafrost and Periglacial Processes*. 3: 19-27.

Heginbottom, J.A., Dubreuil, M.A. and Harker, P.A. 1995: Canada- Permafrost. In: *National Atlas of Canada, 5th ed.*, National Atlas Information Service, Natural Resource Canada, Ottawa, MCR 4177.

Horvath, C.L., 1998: An evaluation of ground penetrating radar for investigation of palsa evolution, MacMillan Pass, NWT, Canada. In: *Proceedings, Seventh International Conference on Permafrost*. Québec City: Université Laval, 473-478.

IPCC 2001: *Climate Change 2001: Synthesis Report - A Contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, Watson, R.T. and the Core Writing Team (eds.) Cambridge: Cambridge University Press, 398 p.

IAEA/WMO 2001: *Global Network of Isotopes in Precipitation* (Whitehorse, Yukon Station #7196400). Environmental Isotope Laboratory, University of Waterloo, Waterloo, Canada. The GNIP Database. Accessible at: http://isohis.iaea.org

Jacoby, G.C. and D'Arrigo, R., 1998: Reconstructed northern hemisphere annual temperature since 1671 based on high-latitude tree-ring data from North America. *Climatic Change*, 14: 39-59.

Janowicz, J.R. 1999: Wolf Creek Research Basin – overview. In: J.M. Pomeroy and R.J. Granger (eds.), *Wolf Creek Research Basin: Hydrology, Ecology, Environment*. Environment Canada, 125-134.

Kay, B.D. and Groenevelt, P.H., 1983: The redistribution of solutes in freezing soil: exclusion of solutes. In: *Proceedings, Fourth International Conference on Permafrost*. Washington, D.C.: National Academy Press, 584-588.

Kershaw, G.P. and Gill, D., 1979: Growth and decay of palsas and peat meadows in MacMillan Pass- Tsichu River area, Northwest Territories, Canada. *Canadian Journal of Earth Sciences*, 16(7): 1362-1374.

Kershaw, P.G. and Skaret, K.D., 1993: Microclimatic characteristics of palsas along an altitudinal gradient, Mackenzie Mountains, NWT, Canada. In: *Proceedings, Sixth International Conference on Permafrost*. Beijing: Science Press, 338-343.

Kuhry, P., 1998: Late Holocene permafrost dynamics in two subarctic peatlands of the Hudson Bay Lowlands, Manitoba, Canada. *Eurasian Soil Science*, 31(5): 529-534.

Kunze, G.W., 1965: Pretreatment for mineralogical analysis. In: C.A. Black, D.D. Evans, L.E. Ensminger, J.L. White and F.E. Clark (eds.), *Methods of Soil Analysis Part 1, Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling, Agronomy no. 9*. American Society of Agronomy, Wisconsin, 568-577.

Kwong, J.Y.T. and Gan, T.Y., 1994: Northward migration of permafrost along the Mackenzie highway and climatic warming. *Climatic Change*, 26: 399-419.

Laberge, M.-J. and Payette, S. 1995: Long term monitoring of permafrost change in a palsa peatland in northern Québec, Canada: 1983-1993. *Arctic and Alpine Research*, 27: 167-171.

Lagarec, D., 1982: Cryogenetic mounds as indicators of permafrost conditions, northern Québec. In: *Proceedings, Fourth Canadian Permafrost Conference*. Ottawa: National Research Council of Canada, 43-48.

Laprise, D. and Payette, S., 1987: Évolution récente d'une tourbière à palses (Québec subarctique) : analyse cartographique et dendrochronologique. *Canadian Journal of Botany*, 66: 2217-2227.

Lewkowicz, A.G. and Harry, D.G., 1991: Internal structure and environmental significance of a perennial snowbank, Melville Island, N.W.T. *Arctic*, 44(1): 74-82.

Lundqvist, J., 1969: Earth and ice mounds: a terminological discussion. In: Péwé, T. L. (ed.), *The Periglacial Environment Past and Present*. Montréal: McGill's-Queen's University Press, 203-215.

Mackay, J.R., 1973: The growth of pingos, western arctic coast, Canada. *Canadian Journal of Earth Sciences*, 8: 397-422.

Mackay, J.R., 1978: Sub-pingo water lenses, Tuktoyaktuk Peninsula, Northwest Territories. *Canadian Journal of Earth Sciences*, 15(8): 1219-1227.

Mackay, J.R., 1979: Pingos of the Tuktoyaktuk Peninsula area, Northwest Territories. *Géographie physique et quaternaire*, 33: 3-61.

Mackay, J.R., 1986 : The first seven years (1978-1985) of ice wedge growth, Illisarvik experimental drained lake site, western Arctic coast. *Canadian Journal of Earth Sciences*, 23(11): 1782-1795.

Mackay, J.R., 1998: Pingo growth and collapse, Tuktoyaktuk Peninsula area, western arctic coast, Canada: a long-term field study. *Géographie physique et quaternaire*, 52: 271-323.

Malmström, B., 1987: Frost mounds in the marginal zone of permafrost, northern Sweden. In: M. Pésci and H.M. French (eds.), *Loess and Periglacial Phenomena*, 191-201.

Matthews, J.A, Dahl, S.-O., Berrisford, M.S. and Nesje, A., 1997: Cyclic development and thermokarstic degradation of palsas in the mid-alpine zone at Leirpullan, Dovrefjell, southern Norway. *Permafrost and Periglacial Processes*, 8: 107-122.

Muller, S.D., 1943: Permafrost or permanently frozen ground and related engineering problems. *U.S. Engineers Office, Strategic Engineering Study, Special Report No. 62*, 136 p.

Murton, J.B. and French, H.M. 1994: Cryostructures in permafrost, Tuktoyaktuk coastlands, western Arctic Canada. *Canadian Journal of Earth Sciences*, 31: 737-747.

Nelson, F.E., Hinkel, K.M. and Outcalt, S.I., 1992: Palsa-scale frost mounds. In: *Periglacial Geomorphology: Proceedings of the 22nd Annual Binghamton Symposium in Geomorphology*, Chichester: John Wiley and Sons Ltd., 305-325.

Nelson, F.E., Outcalt, S.I., Goodwin, C.W. and Hinkel, K.M., 1985: Diurnal thermal regime in a peat-covered pasla, Toolik Lake, Alaska. *Arctic*, 38(4): 310-315.

Outcalt, S.I. and Nelson, F.E., 1984a: Growth mechanisms in aggradation palsas. *Zeitschrift für Gletscherkunde und Glazialgeologie*, 20: 65-78.

Outcalt, S.I. and Nelson, F.E., 1984b: Computer simulation of buoyancy and snow-cover effects in palsa dynamics. *Arctic and Alpine Research*, 16(2): 259-263.

Overpeck, J., Hughen, K., Hardy, D., Bradley, R., Case, R., Douglas, M., Finney, B., Gajewski, K., Jacoby, G., Jennings, A., Lamoureux, S., Lasca, A., MacDonald, G., Moore, J., Retelle, M., Smith, S., Wolfe, A. and Zielinski, G., 1997: Arctic environmental change of the last four centuries. *Science*, 278: 1251-1256.

Pissart, A., 1988: Pingos: An overview of the present state of knowledge. In: M.J. Clark (ed.), *Advances in Periglacial Geomorphology*. Chichester: John Wiley and Sons Ltd., 279-297.

Pollard, W.H., 1988: Seasonal frost mounds. In: M.J. Clark (ed.), *Advances in Periglacial Geomorphology*. Chichester: John Wiley and Sons Ltd., 201-229.

Pollard, W.H., 1991: A high arctic occurrence of seasonal frost mounds. In: T.D. Prowse and C.S.L. Ommanney (eds.), *Northern Hydrology: Selected Perspectives. Proceedings of Northern Hydrology Symposium 10-12 July 1990, Saskatoon, Saskatchewan*. National Hydrology Research Institute, Inland Waters Directorate, 63-275.

Pollard, W.H. and French, H.M., 1983: Seasonal frost mound occurrence, North Fork Pass, Ogilvie Mountains, northern Yukon, Canada. In: *Proceedings, Fourth International Conference on Permafrost*. Washington, DC: National Academy Press, 1000-1004.

Pollard, W.H. and van Everdingen, R.O., 1992: Formation of seasonal ice bodies. In: J.C. Dixon and A.D. Abrahams (eds.), *Periglacial Geomorphology, Proceedings of the 22nd Annual Binghamton Symposium on Geomorphology*, Chichester: John Wiley and Sons Ltd., 281-304.

Porsild, A.E., 1938: Earth mounds in unglaciated Arctic northwestern America. *Geographical Review*. 28: 46-58.

Porsild, A.E., 1955: The vascular plants of the western Canadian Arctic archipelago. *National Museum of Canada, Bulletin no. 135*, Ottawa: Edmond Cloutier, Queen's Printer, 226 p.

Railton, J.B. and Sparling, J.H, 1970: Preliminary studies on the ecology of palsa mounds in northern Ontario. *Canadian Journal of Botany*, 51: 1037-1044.

Savoie, L. and Gangloff, P., 1980: Analyse pollinique d'une palsa au site archéologique de Vieux-Port-Burwell (Killiniq), Territoires du Nord-Ouest. *Géographie physique et quaternaire*. 34: 301-320.

Seguin, M.K., Stein, J., Nilo, O., Jalbert, C. and Ding, Y. 1999: Hydrogeophysical investigation of the Wolf Creek watershed, Yukon Territory, Canada. In: J.M. Pomeroy and R.J. Granger (eds.), *Wolf Creek Research Basin: Hydrology, Ecology, Environment.* Environment Canada, 55-78.

Seppälä, M., 1980: Stratigraphy of a silt-cored palsa, Atlin Region, British Columbia, Canada. *Arctic*, 33(2): 357-365.

Seppälä, M., 1982: An experimental study of the formation of palsas. In: *Proceedings, Fourth Canadian Permafrost Conference.* Ottawa: National Research Council of Canada, 36-42.

Seppälä, M., 1986: The origin of palsas. *Geografiska Annaler*, 68A: 141-147.

Seppälä, M., 1988: Palsas and related forms. In: M.J. Clark (ed.), *Advances in Periglacial Geomorphology*, Chichester: John Wiley and Sons Ltd., 247-278.

Seppälä, M., 1990: Depth of snow and frost on a palsa mire, Finnish Lapland. *Geografiska Annaler*, 72A: 191-201.

Seppälä, M., 1994: Snow depths controls on palsa growth. *Permafrost and Periglacial Processes*, 5: 283-288.

Sigafoos, R.S., 1951: Soil instability in tundra vegetation. *The Ohio Journal of Science*, 51(6): 281-298.

Sollid, J.L. and Sørbel, L., 1998: Palsa bogs as a climate indicator- examples from Dovrefjell, southern Norway. *Ambio*, 27(4): 287-291.

Sone, T. and Takahashi, N., 1993: Palsa formation in the Daisetsu Mountains. In: *Proceedings, Sixth International Conference on Permafrost.* Beijing: Science Press, 2: 1231-1234.

Tarnocai, C., and Zoltai, S.C., 1978: Earth hummocks of the Canadian arctic and subarctic. *Arctic and Alpine* Research, 10(3): 581-594.

Thórhallsdóttir, T.E., 1994: Effects of changes in groundwater levels on palsas in central Iceland. *Geografiska Annaler*, 76A(3): 161-167.

van Everdingen, R.O., 1978: Frost mounds at Bear Rock, near Fort Norman, Northwest Territories, 1975-1976. *Canadian Journal of Earth Sciences*, 15: 263-276.

van Everdingen, R.O., 1982: Frost blisters of the Bear Rock spring area near Fort Norman, N.W.T. *Arctic*, 35: 243-265.

van Everdingen, R.O., 1998: *Multi-language glossary of permafrost and related ground-ice terms*. International Permafrost Association. The Arctic Institute of North America, University of Calgary, Calgary, 268 p.

van Everdingen, R.O. and Banner, J.A., 1979: Use of long-term automatic time-lapse photography to measure the growth of frost blisters. *Canadian Journal of Earth Sciences*. 16: 1632-1635.

Vincent, L.A. and Gullett, D.W., 1999: Canadian historical and homogenous temperature datasets for climate change analyses. *International Journal of Climatology*, 19: 1375-1388.

Walkerton, L.R., Zasada, J.C. and Chapin III, F.S., 1986: The role of life history processes in primary succession on an Alaskan floodplain. *Ecology*, 67: 1243-1253.

Washburn, A.L., 1983: What is a palsa? *Abhandlungen der Akademie der Wissenschaten in Göttigen, Mathematischen-Physikalische Klasse Dritte Folge*, 35: 34-47.

Wetzel, R.G., 2001: *Limnology: Lake and River Ecosystems* (3rd ed.). New York: Academic Press, 1006 p.

Wheeler, J.O., 1961: Whitehorse map-area, Yukon Territory, 105D, *Geological Survey of Canada Memoirs v. 312*. Ottawa: Department of Mines and Technical Surveys, Canada, 156p.

White, S.E., Clark, G.M. and Rapp, A., 1969: Palsa localities in Padjelanta National Park, Swedish Lappland. *Geografiska Annaler*, 51A(3): 97-103.

Williams, P.J. and Smith M.W. 1989 *The Frozen Earth: Fundamentals of Geogcryology*, Cambridge: Cambridge University Press, 306 p.

Woo, M. and Carey, S.K., 1999: Permafrost, seasonal frost and slope hydrology, central Wolf Creek Basin, Yukon. In: J.M. Pomeroy and R.J. Granger (eds.), *Wolf Creek Research Basin: Hydrology, Ecology, Environment*. Environment Canada, 45-54.

Zhang, T., Osterkamp, T.E. and Stamnes, K., 1996: Influences of the depth hoar layer of the seasonal snow cover on the ground thermal regime. *Water Resources Research*, 32(7): 2075-2086.

Zoltai, S.C., 1972: Palsas and peat plateaus in central Manitoba and Saskatchewan. *Canadian Journal of Forest Research*, 2: 291-302.

Zoltai, S.C., 1993: Cyclic development of permafrost in the peatlands of northwestern Alberta, Canada. *Arctic and Alpine Research*, 25(3): 240-246.

Zoltai, S.C. and Tarnocai, C., 1971: Properties of a wooded palsa in Northern Manitoba. *Arctic and Alpine Research*, 3(2): 115-129.

Zuidhoff, F.S. and Korstrup, E., 2000: Changes in palsa distribution in relation to climate change in Laivadalen, northern Sweden, especially 1960-1997. *Permafrost and Periglacial Processes*, 11: 55-69.

APPENDIX A

Grain-size statistics

SD	Qualitative	Skewness	Qualitative	Kurtosis	
0.0 - 0.35	Very well sorted	1.0 - 0.3	Strongly fine-skewed	< 0.67	Very platykurtic
0.35 - 0.5	Well sorted	0.3 - 0.1	Fine skewed	0.67 - 0.9	Platykurtic
0.5 - 0.71	Moderately well sorted	0.1 to -0.1	Near symmetrical	0.9 - 1.11	Mesokurtic
0.71 - 1.0	Moderately sorted	-0.1 to -0.3	Coarse skewed	1.11 - 1.5	Leptokurtic
1.0 - 2.0	Poorly sorted			1.5 - 3	Very leptokurtic
2.0 - 4.0	Very poorly sorted			> 3	Extremely leptokurtic
> 4	Extremely poorly sorted				

	5%	16%	25%	50%	75%	84%	95%	Mean	Median	Standard deviation	Skewness	Kurtosis
Mound 7A												
1,14	-0.4	0.45	0.9	2	3.85	4.65	6.5	2.37	2	2.10	0.28	0.96
1,15	2.2	3.3	3.95	4.85	6.1	6.9	8.35	5.02	4.85	1.83	0.14	1.17
1,17	0.4	2.2	3.1	4.7	6.1	6.95	8.3	4.62	4.7	2.38	-0.07	1.08
1,19	-0.7	0.7	2	4.2	5.7	6.6	8.2	3.83	4.2	2.82	-0.14	0.99
1,02	-0.8	0	0.45	2.3	4.7	5.55	7.5	2.62	2.3	2.65	0.21	0.80
1,05	0	2.1	2.9	4.35	5.7	6.6	8.15	4.35	4.35	2.36	-0.03	1.19
1,07	0.6	2.25	2.95	4.5	6	6.9	8.4	4.55	4.5	2.34	0.02	1.05
1,09	-0.6	0.6	1.7	4.3	5.75	6.7	8.25	3.87	4.3	2.87	-0.16	0.90
1,11	-3.4	1.1	3	4.55	6.15	7	8.5	4.22	4.55	3.28	-0.25	1.55
1,12	1.1	2.8	3.65	5.2	6.8	7.6	8.8	5.20	5.2	2.37	-0.03	1.00
Mound 9A												
5,13	-0.35	1.05	1.8	3.6	5.2	5.95	7.7	3.53	3.6	2.44	-0.01	0.97
5,14	-0.7	0.35	0.85	2.85	4.5	5.25	6.9	2.82	2.85	2.38	0.02	0.85
5,15	-0.3	0.8	1.3	2.65	5	5.7	7.5	3.05	2.65	2.41	0.24	0.86
5,16	0.7	1.75	2.25	3.45	5.1	5.8	7.5	3.67	3.45	2.04	0.18	0.98
5,17	1.2	2.5	3.4	4.75	6.1	7.1	8.5	4.78	4.75	2.26	0.02	1.11
5,19	0.6	1.95	2.65	4.35	5.9	6.8	8.35	4.37	4.35	2.39	0.02	0.98
5,20	1.35	2.8	3.5	5.4	7.1	7.75	8.8	5.32	5.4	2.37	-0.07	0.85
Mound 10												
05,11	1	2.05	2.7	4.3	5.75	6.6	8.25	4.32	4.3	2.24	0.05	0.97
05,04	0.8	2.4	3.05	4.3	5.7	6.6	8.3	4.43	4.3	2.19	0.08	1.16
05,05	1.25	2.4	3	4.25	5.7	6.6	8.2	4.42	4.25	2.10	0.13	1.05
05,06	0.45	1.3	1.8	4	5.45	6.2	8	3.83	4	2.37	-0.02	0.85
05,07	-0.1	2.1	3.1	4.45	5.65	6.4	8.15	4.32	4.45	2.33	-0.10	1.33
05,09	2.3	3.3	3.85	4.95	6.3	7.1	8.4	5.12	4.95	1.87	0.13	1.02
Mound 14												
15,01	-1.2	-0.01	0.65	2.9	5.4	6.5	8.35	3.13	2.9	3.07	0.12	0.82
15,03	-0.85	0.8	1.25	2.15	3.7	4.9	7.65	2.62	2.15	2.31	0.32	1.42
13,01	-3.7	-1	-0.3	1.9	3.6	4.35	6.7	1.75	1.9	2.91	-0.08	1.09
13,02	-1.15	0.15	1	2.4	4.25	5.35	7.7	2.63	2.4	2.64	0.17	1.12
13,04	1.4	2.5	3	3.85	5.3	6.1	8	4.15	3.85	1.90	0.25	1.18

	5%	16%	25%	50%	75%	84%	95%	Mean	Median	Standard deviation	Skewness	Kurtosis
Mound 17												
5,22	-0.4	0.5	1.3	3.6	5.1	5.9	7.8	3.33	3.6	2.59	-0.06	0.88
5,23	-0.7	1	2.8	4.4	5.6	6.35	8.1	3.92	4.4	2.67	-0.22	1.29
5,24	-0.9	-0.1	0.45	2.8	4.8	5.6	7.6	2.77	2.8	2.71	0.06	0.80
5,25	-0.5	0.4	1	3.8	5.5	6.3	8	3.50	3.8	2.76	-0.08	0.77
06,03	2.1	3	3.4	4.4	5.7	6.4	8.1	4.60	4.4	1.76	0.20	1.07
Mound 20												
11,02	3	3.7	4.1	5.1	6.35	7.1	8.6	5.30	5.1	1.70	0.21	1.02
11,04	2.7	4.15	4.7	5.8	7.05	7.7	8.7	5.88	5.8	1.80	0.02	1.05
11,06	2.5	3.65	4.2	5.25	6.6	7.35	8.85	5.42	5.25	1.89	0.13	1.08
11,08	2.45	3.45	4	5.05	6.4	7.2	8.6	5.23	5.05	1.87	0.15	1.05
11,10	2.6	3.55	4.05	5.1	6.45	7.2	8.6	5.28	5.1	1.82	0.16	1.02
11,12	2.4	3.5	4.1	5.3	6.75	7.45	8.7	5.42	5.3	1.94	0.08	0.97
11,14	2.3	3.4	4.1	5.25	6.75	7.4	8.75	5.35	5.25	1.98	0.08	1.00
11,16	2.85	3.6	4.05	5.25	6.75	7.45	8.8	5.43	5.25	1.86	0.17	0.90
Mound 25												
10,02	-2.2	0.7	2	3.45	4.6	5.25	7.2	3.13	3.45	2.56	-0.21	1.48
10,04	2.3	3.8	4.3	5.5	6.9	7.6	8.8	5.63	5.5	1.93	0.06	1.02
10,06	1.8	2.9	3.5	4.75	6.2	7	8.55	4.88	4.75	2.05	0.11	1.02
10,08	2.6	4	4.55	5.85	7.2	7.8	8.9	5.88	5.85	1.90	0.00	0.97
10,10	2	3.3	3.95	5.25	6.75	7.5	8.8	5.35	5.25	2.08	0.06	1.00
10,12	2.1	3.4	3.9	4.9	6.15	6.95	8.35	5.08	4.9	1.83	0.13	1.14
10,14	2.8	3.6	4.1	5	6.3	7.1	8.5	5.23	5	1.74	0.21	1.06
10,16	3.2	4	4.5	5.5	6.8	7.5	8.75	5.67	5.5	1.72	0.16	0.99
Mound 28												
12,07	-0.1	1.1	2.1	4.15	5.4	6.1	7.9	3.78	4.15	2.46	-0.14	0.99
12,08	-0.35	0.3	0.6	1.6	3.6	4.5	6.5	2.13	1.6	2.09	0.41	0.94
12,09	1.55	3.05	3.6	4.55	5.65	6.4	8.1	4.67	4.55	1.83	0.09	1.31
12,11	-0.15	0.55	1.1	3.8	5.55	6.35	7.95	3.57	3.8	2.68	-0.05	0.75
12,13	0.05	1.3	3	5.25	6.65	7.4	8.6	4.65	5.25	2.82	-0.26	0.96
12,14	-0.5	1.1	2.3	5.2	6.95	7.65	8.8	4.65	5.2	3.05	-0.24	0.82
12,16	-1.1	-0.2	0.35	1.75	3.45	4.8	7.7	2.12	1.75	2.58	0.29	1.16
Mound 39												
04,01	-2.6	-1.65	0.6	3.2	6.25	7.4	8	2.98	3.2	3.87	-0.08	0.77
04,02	-1.5	-0.45	0.9	4.25	6.85	7.8	9.1	3.87	4.25	3.67	-0.11	0.73
04,03	-1.6	0.4	1.5	4	5.6	6.3	8.9	3.57	4	3.07	-0.14	1.05
Mound 40												
11,19	-1.5	0.35	1.3	4.4	7.75	8.45	9.45	4.40	4.4	3.68	-0.04	0.70
11,20	-3.4	-2.05	-1.1	1.3	4.8	6.8	8.95	2.02	1.3	4.08	0.24	0.86
Mound 41												
12,02	-3.5	-2.3	-1.65	-0.25	3.1	4.8	7.8	0.75	-0.25	3.49	0.42	0.97
12,03	-2.8	-1.05	-0.2	2	4.7	5.8	8.15	2.25	2	3.37	0.12	0.92
12,04	-5.5	-4.45	-3.4	-1.6	2.5	4.2	7.45	-0.62	-1.6	4.12	0.37	0.90
12,05	-5.3	-3.6	-1.4	1.6	4.6	6	8.4	1.33	1.6	4.48	-0.05	0.94

	5%	16%	25%	50%	75%	84%	95%	Mean	Median	Standard deviation	Skewness	Kurtosis
Valley bottom												
09,02	-2.8	-0.7	0.45	3.15	5.5	6.8	8.65	3.08	3.15	3.61	-0.03	0.93
09,03	-3.35	-1.9	0.3	2.45	4.3	5.4	8	1.98	2.45	3.54	-0.11	1.16
09,05	-1.5	0.5	1.65	3.9	5.75	6.95	8.7	3.78	3.9	3.16	-0.06	1.02
09,07	-5.4	-4.1	-1.7	2.45	4.9	6.1	8.45	1.48	2.45	4.65	-0.21	0.86
Fox Lake Palsa												
22,01	0.9	2.25	2.95	5.05	7.15	7.9	9.1	5.07	5.05	2.65	0.00	0.80
22,02	1.35	2.6	3.3	5.35	8.15	8.85	9.95	5.60	5.35	2.87	0.09	0.73
22,03	1.6	2.5	3.05	5.18	8.2	9	10	5.56	5.18	2.90	0.16	0.67
22,05	1.6	2.7	3.4	5.3	8.2	8.9	9.9	5.63	5.3	2.81	0.13	0.71
22,06	1.6	2.8	3.62	5.6	8.3	8.87	9.8	5.76	5.6	2.76	0.05	0.72
22,08	1.65	2.8	3.6	5.55	8.25	8.83	9.8	5.73	5.55	2.74	0.07	0.72
22,09	1.85	3.2	3.9	5.55	8.1	8.7	9.7	5.82	5.55	2.56	0.10	0.77
22,10	1.7	3	3.7	5.8	8.48	9.05	9.9	5.95	5.8	2.75	0.04	0.70
22,12	0.3	2	2.9	4.7	7.1	7.9	9.13	4.87	4.7	2.81	0.04	0.86

APPENDIX B

Snow depths measurements

April 6th 2001

Palsa 12 Location	Distance (m)	Snow depth (cm)
North side	0	0
	1	32
	2	38
	3	42
	4	54
	5	58
	6	60
	7	59
	8	48
	9	57
	10	45
	11	20
	12	20
	13	0
South side	14	10

April 1st 2002

Palsa 12 Location	Distance (m)	Snow depth (cm)
Onto ice	0	2
side	1	38
side	2	70
side	3	80
top of side	4	98
	5	67
	6	78
crest	7	80
	8	70
	9	60
	10	45
	11	75
	12	53
	13	45
side	14	64
	15	85
	16	52
	17	25
onto ice	18	1

April 6th 2001

Palsa 20 Location	Distance (m)	Snow depth (cm)
North side	0	10
	1	10
	2	20
	3	30
	4	15
	5	20
	6	40
	7	10
	8	36
	9	35
	10	35
	11	30
South side	12	20

April 1st 2002

Palsa 20 Location	Distance (m)	Snow Depth (cm)
North side	0	25
	1	34
	2	45
	3	45
	4	40
	5	38
	6	43
	7	48
	8	60
	9	48
South side	10	30

All other snow measurements were taken on April 1st 2002

Palsa 9C Location	Distance (m)	Snow depth (cm)
	0	ice
	1	ice
	2	2
	3	48
	4	68
	5	62
	6	50
	7	42
	8	43
	9	38
	10	45
	11	55
	12	65
	13	50
	14	55
	15	35
crest + west side	16	42
	17	35
	18	45
	19	45
	20	56
	21	55
	22	45
	23	56
side	24	55
	25	50
	26	61
	27	100
	28	100
	29	60
	30	55
	[redacted]	

Palsa 10 onto 9A Location	Distance (m)	Snow depth (cm)
North side	1	20
	2	25
	3	18
	4	17
	5	16
	6	22
	7	30
	8	42
	9	49
	10	52
	11	55
	[redacted]	
in btw	12	75
in btw	13	85
onto 9A	14	108
	15	98
	16	95
	17	112
	18	97
top	19	87
	20	78
	21	70
	22	50
	23	34
	24	20
	25	13
	26	13
	27	22
	28	21
	29	17
	30	26
	31	30
	32	30
	33	40
	34	40
	35	45
	36	40
	37	60
	[redacted]	

Palsa 7 to 8 Location	Distance (m)	Snow depth (cm)
	0	10
	1	50
	2	85
	3	85
	4	80
	5	80
	6	60
	7	50
	8	55
crest of P7	9	45
	10	27
	11	35
	12	46
	13	51
	14	90
	15	78
	16	95
	[redacted]	
trough	17	95
	18	90
	19	108
	20	100
	21	91
top of P8 side	22	75
	23	70
crest of 8	24	72
	25	78
	26	82
	27	83
	28	50
	29	48
	30	48
	31	44
	32	48
	33	86
	34	60
	35	62
	36	105
	[redacted]	
off	37	84

Palsa 23 Location	Distance (m)	Snow depth (cm)
not on palsa	0	60
	1	68
	2	90
	3	55
	4	58
steep slope	5	55
top of side	6	60
	7	52
	8	61
	9	65
	10	80
	11	75
	12	64
ridge point	13	82
3m to east	14	78
	15	73
	16	58
	17	60
	18	53
crest	19	50
	20	45
	21	55
	22	55
	23	66
grnd squirrel hole	24	65
	25	35
	26	60
	27	53
	28	42
	29	45
top of south slope	30	58
	31	78
	32	70
	[redacted]	
trough	33	86

APPENDIX C

CD-rom of photos from the field

T. Coultish took the majority of the summer photographs.
A. Lewkowicz took the winter photographs.