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LA THÈSE A ÉTÉ  
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A STUDY OF SEASONAL FROST MOUNDS,  
NORTH FORK PASS, NORTHERN INTERIOR  
YUKON TERRITORY

by  
Wayne H. Pollard

Thesis presented to the School of Graduate Studies and  
Research in partial fulfillment of the requirements for  
the degree of Doctor of Philosophy in Geography:

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## TABLE OF CONTENTS

LIST OF FIGURES .....	v
LIST OF TABLES .....	xii
ACKNOWLEDGMENTS .....	xiii
CHAPTER ONE - INTRODUCTION	
1.1 Aims and objectives .....	1
1.2 Frost mound terminology .....	3
1.3 Frost blisters .....	6
1.4 Geomorphic characteristics .....	9
1.4.1 Distribution and morphology .....	9
1.4.2 Structure, hydrology and ice characteristics .....	14
1.5 Growth mechanisms .....	18
1.6 Active layer hydrology .....	22
CHAPTER TWO - STUDY AREA	
2.1 Introduction .....	29
2.2 Regional setting .....	32
2.2.1 Quaternary history .....	33
2.2.2 Relief and geology .....	35
2.2.3 Regional climate .....	41
2.2.4 Permafrost .....	45
2.2.5 Vegetation .....	50
CHAPTER THREE - METHODS OF APPROACH	
3.1 Introduction .....	55
3.2 Field observations .....	56
3.2.1 Physical character .....	56
3.2.2 Measurement of thermal regimes ..	59
3.2.3 Background hydrology .....	61
3.2.4 Hydraulic potentials .....	62
3.3 Laboratory procedures .....	66
3.3.1 Ice petrofabric determinations ..	66
3.3.2 Water chemistry and isotope analyses .....	72

## CHAPTER FOUR - DISTRIBUTION, SETTING AND MORPHOLOGY

4.1	Introduction .....	77
4.2	Distribution and setting .....	79
4.3	Morphology .....	95
4.3.1	Introduction .....	95
4.3.2	Size, shape and orientation .....	96
4.3.3	Cross-profile characteristics .....	106

## CHAPTER FIVE - INTERNAL STRUCTURE AND ICE CHARACTERISTICS.

5.1	Introduction .....	110
5.2	Internal structure .....	110
5.2.1	Frost blisters .....	111
5.2.2	Icing mounds and blisters .....	120
5.3	Ice characteristics .....	125
5.3.1	Crystallography and optical properties .....	125
5.3.2	Crystal growth and bubble characteristics .....	129
5.4	Frost blister ice character .....	131
5.4.1	Frost mound 1-10 .....	131
5.4.2	Frost mound 1-17 .....	140
5.4.3	Frost mound 1-4 .....	144
5.5	Icing blister ice .....	150

## CHAPTER SIX - GROUNDWATER HYDROLOGY

6.1	Introduction .....	157
6.2	Background conditions .....	159
6.2.1	Discharge and runoff .....	159
6.2.2	Ground thermal and physical conditions .....	162
6.3	Hydrochemical and isotope analyses .....	168
6.3.1	Introduction .....	168
6.3.2	Springs and suprapermafrost groundwater .....	170
6.3.3	Isotope fractionation .....	177
6.4	Hydraulic potential .....	182
6.4.1	Introduction .....	182
6.4.2	Hydraulic potential measurement .....	183
6.4.3	Theoretical calculations of hydraulic potential .....	191

## CHAPTER SEVEN - CONCLUSIONS

7.1	Seasonal frost mound occurrence .....	198
7.2	Recommendations for future research .....	201

APPENDIX I - FROST MOUND MORPHOLOGY .....

204

REFERENCES .....

214

## LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1.1	Location map of the Northern Yukon and Mackenzie Delta, showing the Dempster Highway, the location of the North Fork Pass and the distribution of permafrost.	2
1.2	Diagram illustrating the formation of a frost blister .....	8
1.3	Diagrammatic representation of the sequential development of frost and icing blisters .....	20
1.4	A simplified flow diagram of the terrain-based portion of the hydrologic cycle ...	24
2.1	Air photo of the North Fork Pass area. The location of frost mound sites and the Dempster Highway are marked .....	30
2.2	Map showing the glacial limits of the northern interior, Yukon Territory .....	34
2.3	The North Klondike River, near Mount Tombstone (centre) is flanked on the left by The Three Sisters and Mount Campbell. Photo: September 1981 .....	36
2.4	General view of the East Blackstone River valley near the North Fork Pass. Note the lateral moraine on the far side of the valley (indicated by arrow). Photo: September 1980 .....	38
2.5	Map of landforms and surficial geology of the North Fork Pass area .....	40
2.6	Summary of selected climate data for Dawson City, 64°04'N, 139°24'W. The mean monthly temperature and precipitation for 1981 are highlighted .....	43
2.7	Ice-wedge polygons in lowlying valley tundra, North Fork Pass. Photo: July 1979	48

<u>Figure</u>		<u>Page</u>
2.8	Aerial view of a closed system pingo (see Hughes, 1969) located in the main Blackstone valley. Photo: July 1979 ...	48
2.9	Ground thermal regimes in the Eagle Plain area. (A) Fine grained sediments, Eagle River floodplain, (B) limestone surface, and (C) sandstone surface. Graphs (B) and (C) are predicted, and taken from Pollard (1980, p. 27) .....	49
2.10	Vegetation assemblages within the northern interior Yukon range from (a) boreal forest in the North Klondike Valley to, (b) alpine tundra in the North Fork Pass area .....	51
3.1	A gas driven coring unit was used for stratigraphic investigations of seasonal frost mounds and frozen ground. Photo: September 1980 .....	58
3.2	Piezometer pressure gauge assemblage ....	64
3.3	The lower end of the piezometer stand-pipe possessed a flexible rubber condom as a sensory membrane, separating the silicone oil from the groundwater .....	65
3.4	A brass check valve (left) with a 2.3 kPa cracking pressure was tested and perforated PVC extension tubes (left and right) provided protection of the lower end of the piezometer .....	65
3.5	(a) Thin section photographs were taken using a Leitz camera with polaroid film mounted on a polariscope. (b) Ice fabric determinations were performed using a universal stage (4 axes) .....	69
4.1	Location map of study sites, main drainage channels and spring outlets. The approximate limits of Figures 4.2, 4.6 and 4.8 are indicated .....	80
4.2	Physiographic map of sites 1 and 2, North Fork Pass, near KM 86 of the Dempster Highway. Based on field survey and air photo analysis .....	85

<u>Figure</u>		<u>Page</u>
4.3	Two frost blisters protrude through the icing at site 1 (mounds 1-10 and 1-11) ..	87
4.4	A small tundra pond, located at the south-east corner of site 1, is fed by perennial spring discharge. Two seepage/stream outlets from the pond are marked by arrows. Photo: August 1981, .....	87
4.5	Site 2, as seen from the highway looking west. Only the collapsed remnants of 4 frost blisters are visible (indicated by arrows). Photo: September 28, 1980 ....	88
4.6	Physiographic map of sites 3 and 4, North Fork Pass, based on field survey and air photo analysis .....	90
4.7	Frost mounds 3-1 and 3-2 were located at the north end of a small pond and formed in organic-rich silts. Photo: September 20, 1980 .....	91
4.8	Physiographic map of sites 5 and 6, North Fork Pass, based on field survey and air photo analysis .....	93
4.9	Alluvial fans provide the main aquifer materials for groundwater systems feeding perennial springs at site 5. (a) In summer (September 1981) a number of collapsed mounds are visible near the distal edge of the fan, and (b) each winter new mounds form (March 1982) in slightly different locations .....	94
4.10	(a) Frost blister 5-5 formed along the distal edge of an alluvial fan at site 5, and (b) frost blister 6-1 formed in a similar setting at site 6. Photos: March 19-20, 1982 .....	99
4.11	General view of icing and icing mound 3-6 located at site 3. Note the flow of water from the top of the mound, snowshoe prints in the lower left corner provide a rough scale. A dashed line identifies the top of the mound. Photo: March 20, 1982 .....	100

<u>Figure</u>		<u>Page</u>
4.12	Frequency distribution histograms of seasonal frost mounds (a) by height and (b) by length .....	102
4.13	A morphologic classification of seasonal frost mounds based on plan shape and long-axis profile .....	103
4.14	(a) Correlation of slope angle and L/W ratio. (b) Correlation of slope direction and seasonal frost mound long-axis orientation .....	105
4.15	Typical mound cross-profiles, based on survey data obtained during 1980, 1981 and 1982 .....	107
5.1	A cross-section through frost blister 1-2, observed in September 1980 .....	112
5.2	A cross-section through frost blister 1-16, based on drill data obtained in September 1981 .....	112
5.3	Vertical cross-sections through frost blister 1-4, (a) based on coring performed in September 1980, and (b) based on an excavated section observed in September 1981 .....	113
5.4	A vertical cross-section through frost blister 3-1, sectioned in September 1980 .....	119
5.5	A dilation crack runs the entire length of icing blister 1-19. Photo: May 1981 .....	121
5.6	Patches of powdery yellow precipitate are often observed on the icing surface. Photo: May 1981 .....	123
5.7	An icing mound formed part of frost mound complex 1-23. Photo: March 1982 .....	123
5.8	In March 1982, a large icing mound was observed at site 3. Note the recent overflow from the top of the mound .....	124
5.9	Frost blister 1-10, (a) protruding through the icing, May 1981, and (b) excavated in September 1981 .....	132

<u>Figure</u>	<u>Page</u>
5.10	Ice from frost blister 1-10, (a) a 40 cm high block from the top of the ice sequence, including the upper segment contact, (b) a close-up of the lower portion of the block, and (c) elongated to bulbous gas bubbles .. 134
5.11	Vertical thin sections of frost blister ice from mound 1-10 at depths of (a) 7 cm, and (b) 40 cm below the upper sediment contact. (Crossed polarizers) ..... 136
5.12	Horizontal thin sections of frost blister ice from mound 1-10 at depths of (a) 7 cm, and (b) 40 cm. Note the greater grain size with depth. (Crossed polarizers) ..... 137
5.13	Petrofabric diagrams for frost blister ice (mound 1-10) based on crystal orientations of vertical thin sections from depths of (a) 7 cm, and (b) 20 to 40 cm. Horizontal line represents the plane of compositional layering ..... 139
5.14	Oriented block samples obtained from frost mound 1-17. (a) The upper sediment contact, and (b) clear massive ice from deep in the mound core ..... 142
5.15	Petrofabric diagrams based on vertical thin sections of frost blister ice from mound 1-17 at depths of (a) 2 cm, and (b) 20 to 35 cm. Horizontal line corresponds to the plane of compositional layering .... 145
5.16	The solid ice core of frost blister 1-4 is characterized by an irregular contact with overlying sediments, unconformities between ice layers and candling of exposed ice. Photo: August 1981 ..... 147
5.17	An ice sample from frost blister 1-4 showing the contact between first and second year ice. Note the variation in the direction and pattern of gas bubbles .. 149
5.18	Sections cut from the ice sample shown in Figure 5.17: (a) thick section, and (b) thin section. Both show the relationship between the gas bubble pattern and ice texture along the contact between first and second year ice. (Crossed polarizers) ... 149

Figure

Page

5.19 Ice samples obtained from icing blister 1-24. (a) The upper part of the mound was characterized by opaque, layered ice while, (b) at greater depth the ice was clear with a low bubble content .... 152

5.20 Photographs (cross polarizers) of thin sections of icing ice and corresponding fabric diagrams: (a) vertical thin section showing the layered nature of icing ice, (b) fabric diagram based on this thin section, (c) horizontal thin section showing a slight flow pattern, and (d) fabric diagram based on the horizontal thin section. The ice sample was from a depth of 20 cm ..... 154

6.1 Detailed physiographic map of study site 1, North Fork Pass, showing location of instrumentation, seasonal frost mounds, spring outlets, seepage lines and icing distributions. Based on field survey data for 1980, 1981 and 1982 ..... 160

6.2 A breathing hole through the snow marks the location of perennial spring discharge and a zone of near-surface groundwater transmission in winter. Photo: December 1981 ..... 163

6.3 Measured active layer temperature profiles at site 1, North Fork Pass. (a) Floodplain, (b) seepage zone, (c) lower valley side slope, and (c) spring outlet and pond area. Measurements made in September 1982 ... 166

6.4 Summary of thermistor cable observations at (a) vegetated side valley location, (b) gravelly unvegetated side valley location, (c) frost blister 1-15, and (d) saturated floodplain location during 1981-1982 ..... 167

6.5 Grain-size distribution curves for surficial sediments in the floodplain and lower valley side slope locations, North Fork Pass ..... 169

6.6 Isotope data for water and snowpack samples plotted against global meteoric water line ..... 174

<u>Figure</u>		<u>Page</u>
6.7	Mineral precipitate deposited on the icing surface during freezing. Photo: May 1981 .....	176
6.8	Plot of isotopic variation against depth .....	179
6.9	Plot of weighted mean isotope values for frost blister ice samples compared with isotope data for springs .....	179
6.10	Evidence of explosive frost blister rupture occurs in the form of (a) a water-filled depression (September 1980), and (b) displaced and overturned blocks of peat (May 1981) .....	181
6.11	Antifreeze-filled piezometers were installed in 5 seasonal frost mounds during March 1982: (a) icing blister 1-24, and (b) frost blister 1-26 .....	187
6.12	Plot of hydraulic potential values measured in the North Fork Pass area .....	188

## LIST OF TABLES

<u>Table</u>		<u>Page</u>
1.1	A classification of frost mound phenomena, based on duration and morphogenetic characteristics, and including a summary of commonly used synonyms documented from the literature.....	7
2.1	Selected climatological data for the interior northern Yukon Territory. (A) Temperature and precipitation data for Old Crow, 1959-1980. (B) Sporadic temperature and precipitation data for the Dempster Highway maintenance camps .....	44
4.1	A chronology of site observations in the North Fork Pass .....	82
4.2	A summary of seasonal frost mound physical characteristics for the North Fork Pass area .....	97
6.1	Hydrochemical data for spring waters, icing and frost mound ice at site 1, North Fork Pass .....	171
6.2	Isotope data for spring waters and snow pack samples from the North Fork Pass area .....	173
6.3	Summary of hydrologic conditions for each seasonal frost mound type encountered during drilling in March 1982 .....	186
6.4	A comparison of calculated and measured pressure values for frost mounds in the North Fork Pass based on data obtained in March 1982 .....	195

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CHAPTER ONE

INTRODUCTION

## 1.1 Aims and objectives

Seasonal frost mounds constitute an interesting but little studied meso-scale landform in areas underlain by permafrost. This thesis attempts to understand the geomorphic and hydrologic controls which influence their occurrence. The North Fork Pass area in the Southern Ogilvie Mountains, Yukon Territory, in the vicinity of KM 82-86 of the Dempster Highway, was chosen as the study area (Figure 1.1). Attention focussed upon three problems associated with the activity of seasonal frost mounds in that area:

- (1) Do they possess typical geographic locations and site-specific characteristics?
- (2) What is their shape, size and duration, and is the term 'seasonal' an appropriate descriptive term?
- (3) What is their internal structure, and associated groundwater hydrology, and what is their mechanism(s) of growth?

Frost blisters, a specific type of seasonal frost mound, are examined in the greatest detail.

Permafrost is defined as 'the thermal condition in soil or rock of having temperatures below 0°C persist

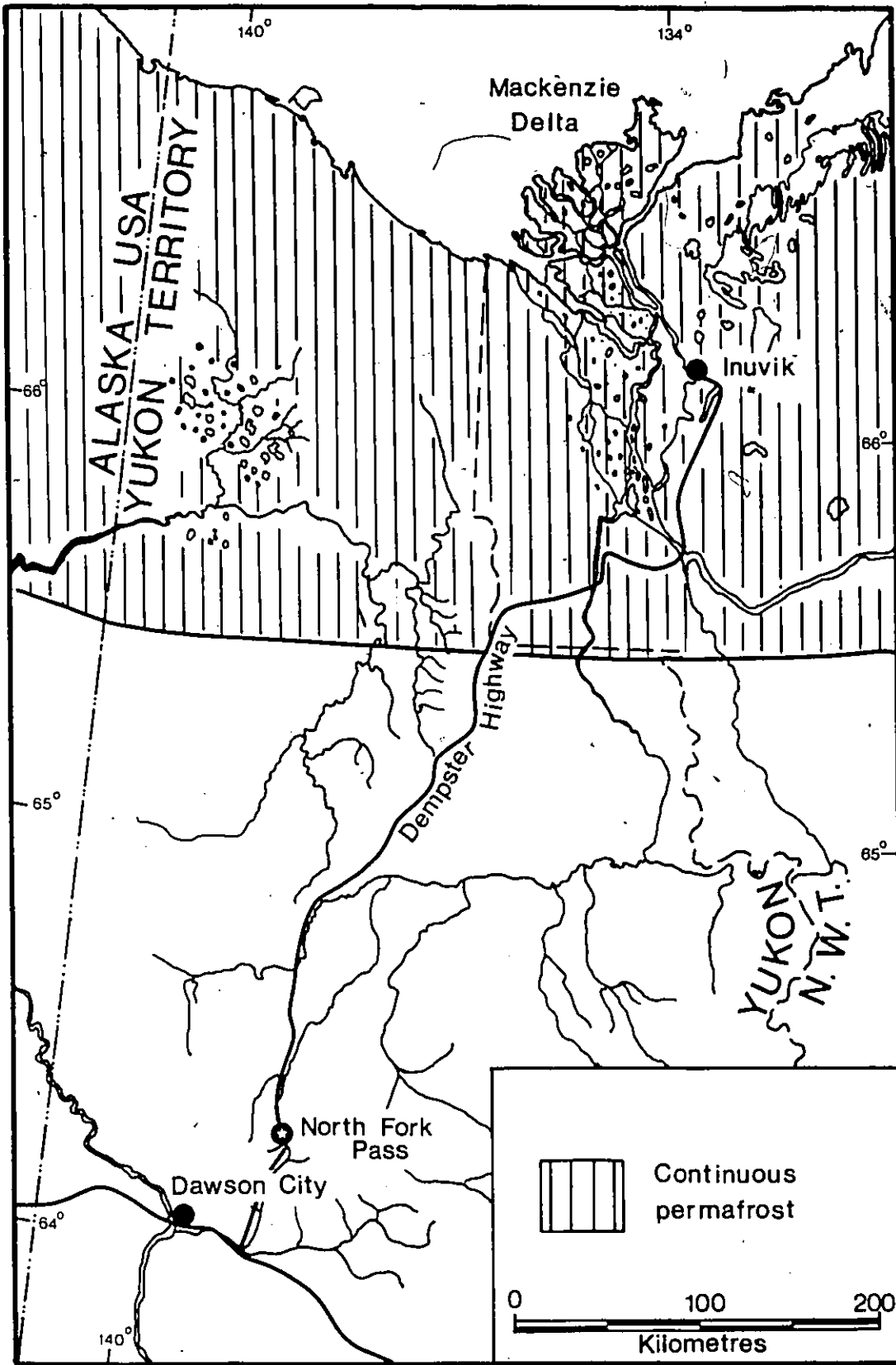


Figure 1.1 Location map of the Northern Yukon and Mackenzie Delta, showing the Dempster Highway, the location of the North Fork Pass and the distribution of permafrost. Source: Brown (1978) and Ferrians (1965).

over two consecutive winters and the intervening summer' (Brown and Kupsch, 1974, p. 25). Recently, the term 'perennially cryotic' has been proposed as a more suitable alternative because it emphasizes the thermal nature of the definition (van Everdingen, 1976, p. 863). Thus, the occurrence of permafrost does not imply the presence of ground ice. (Brown, 1970; 1974) and unfrozen water is a common constituent of permafrost materials.

Permafrost is not the only factor responsible for the formation of frost mounds; the active or dynamic components of frost mounds and related phenomena (e.g., icings) are a direct function of the presence, movement and subsequent freezing of groundwater. In permafrost areas, the groundwater system is complex since supra-, intra- and subpermafrost groundwater is recognized. In some groundwater systems, sub-, intra- and suprapermafrost groundwater may all eventually form part of the surface hydrologic system.

## 1.2 Frost mound terminology

The term 'frost mound' is the family name proposed for all mounds produced by the combined action of:

(a) the volumetric expansion of water during its phase change to ice, (b) the hydrostatic pressure of groundwater, and (c) the force of crystallization during freezing, unless their specific character, origin and structure are known (Muller, 1945, p. 59; Williams, 1965, p. 21). This

definition, either in whole or in part, has been adopted by subsequent researchers (e.g., Frederking, 1979; Hennion, 1955; Maarleveld, 1965; Toth, 1972; 1972; van Everdingen, 1978; 1982).

In one of the first North American classifications of frost mound phenomena, Muller (1945, p. 59) distinguished between pingos, frost blisters, icing mounds and peat mounds (palsas). A similar classification was adopted by Lundquist (1969); however, only earth hummocks, frozen peat mounds, pingos and palsas were included, while frost blisters and icing mounds were not discussed.

The literature proliferates with frost mound synonyms, many of which are summarized in Muller (1945, p. 216), Troll (1958, pp. 76-77) and Williams (1965, p. 21). Their existence and frequent incorrect usage generate significant problems. In addition, the random use of Soviet, German, Scandinavian and Inuktitut terms in the North American literature (e.g., bugor, bulgannyakh, pingo, kotchi, naled, aufeis, karnig, etc.) is also confusing, particularly since some have English-language equivalents (e.g., aufeis--icing) while others have taken on new meanings to fill terminological gaps (e.g., hydrolaccolith).

Frost mounds may be either perennial (i.e., long-term) or seasonal (i.e., short-term). Pingos and palsas are examples of perennial frost mounds. As such, perennial frost mound phenomena have received considerable attention in the permafrost and periglacial literature (e.g., French,

1976, pp. 93-101; Mackay, 1979; Washburn, 1979a, pp. 180-191). Conversely, seasonal frost mounds have received only limited attention. While a few observations on seasonal frost mounds are quite detailed in the North American literature (e.g., Frederking, 1979; Lewis, 1962; van Everdingen, 1982; van Everdingen and Banner, 1979), in general most are of a casual nature (e.g., Brown and Berg, 1980, pp. 29, 82; Leffingwell, 1919, pp. 150-158; Linell, 1973, p. 189; Mackay, 1979, pp. 26, 48; Porsild, 1938, p. 47). Probably, this is due in part to their relatively small expression and ephemeral nature together with their occurrence during the winter seasons when snow and ice obscure the landscape.

Seasonal frost mounds can be divided into three types: frost blisters, icing blisters and icing mounds. All are characterized by a relatively short period of rapid growth (van Everdingen and Banner, 1979), most often attaining their maximum expression during the course of a single winter and then lasting from a few months to two or three years. Since some features occasionally last less than a full year, the term annual frost mound is sometimes used (van Everdingen, 1978, p. 271). Frost blisters are sometimes erroneously identified as other types of frost mounds, especially palsas (e.g., Academia Sinica, 1981; Brown et al., 1983; Hughes et al., 1972; Lewis, 1962; Maarleveld, 1965; Sharp, 1942). In the Soviet Union, seasonal frost mounds appear to be better documented (e.g., Gokeov, 1939; Shumskii, 1964a; b; Soloviev, 1952; 1973;

Sumgin, 1940).

Table 1.1 presents a classification of frost mound phenomena as described in the literature. This classification is based on duration, structural and morphogenetic characteristics. Also included are the various terms and synonyms frequently used.

### 1.3 Frost blisters

Frost blisters are a specific type of seasonal frost mound. They are described by Muller (1945, p. 59) as mounds or upwarps of the ground "produced by localized hydrostatic pressure of groundwater" (see Figure 1.2). A similar definition applies to the term hydrolaccolith, used in Soviet literature (Tolstikhin and Tolstikhin, 1974, p. 20). In North America the latter has a broader meaning covering virtually all frost mounds resulting from the hydrostatic and hydraulic pressure of groundwater which subsequently freezes to form injection ice (French, 1976, pp. 101-104; Washburn, 1979a, p. 180; Williams, 1965, p. 24). Van Everdingen (1978, p. 271) recommends that Muller's frost blister definition (1945) be modified to include the term 'high hydraulic potential' in place of 'hydrostatic pressure' to provide a better hydrodynamic interpretation of frost blister genesis.

CATEGORY	Terminology study	Origin of water and transfer processes	Ice type (Mackay, 1972)	Growth mechanisms	Morphology	Alternative terminology and source
SEASONAL FROST MOUNDS (Short-term <1 to 3yrs)	Frost blister <sup>1</sup>	Supraterratost groundwater	Intrusion (injection) ice Open cavity ice	Freeze-back of the active layer conducts supraterratost groundwater circulation resulting in high hydraulic potentials which subsequently freeze dome overlying sediments to form a frost blister, or inject the water into the overlying ring forming an ring blister.	Circular to elongated mounds; often compound or lobate. Height 1-7 m, averaging 3-5 m, diameter 3-50 m, averaging 10-15 m. Occur in groups or individually.	Small mound, ice hood, leads (Trick, 1958); annual frost mound (van Everdingen, 1978); seasonal ice mound (Dovick, 1958); seasonal ring, ice ridge, seasonal hydrocarbon ice cored earth mound, (Froehlich and Saps, 1978); soil blister, earth mound, (Miller, 1945); ground ice mound (Sharp, 1942)
	icing mound <sup>1</sup>	Pressure potential by gravity transfer (hydraulic) and hydrostatic pressure of closed system freezing	Ice (surface) ice Intrusion (injection) ice Ice (surface) ice	Forming in ring mound. Cold winters, a steep hydraulic gradient and a shallow, low permeability layer are present. Ring blisters and mounds often occur in river banks.	Circular to irregular shaped, mounds of ice, either a smooth or a rippled surface. Often forms part of an ring, similar to the above.	sublimation knob, convex and concave, (Williams, 1968); ice mound (Auerbach, 1962); ice hummock, hydrocarbon (Shumak, 1964); ice knob, ice heap (Miller, 1945); injection mound, cavity mound (Aksamen, 1980); spring ice dome (Dovick, 1938); ring (Lundquist) (Frederick, 1976); ice bazar (Froehlich and Saps, 1978); ice mound (Toshtanov and Toshtanov, 1974); ice mound, (Rus) (Trick, 1958);
	icing blister <sup>2</sup>		Intrusion (injection) ice Ice (surface) ice		Oval to elongated dome shape similar to the above. Shallow cracks occur along the top rim of the ring.	
PERENNIAL FROST MOUNDS <sup>1</sup> (Long-term 10s-1000s yrs)	Pingo <sup>3</sup>	Sub- and intrapermafrost groundwater	Intrusion (pingo) ice	Hydraulic (transient) pressure of sub- or intrapermafrost groundwater forces fluid into the surface permafrost gradually heaving the overlying materials and freezing to form an ice core. Usually occur in areas with high relief and discontinuous permafrost.	Conical shaped mounds, smooth profiles located in narrow valleys. Usually occur in areas of hydrostatic seepage, heights 8-25 m, diameters 50-300 m, frequently recognized in its collapsed form.	Open system (Holmes et al., 1966); East Greenland type (Miller, 1943); Type 1 (Trick, 1939); ring mound (Trick, 1959); hydrocarbon (Miller, 1945); budjarnak (Rus) (Shumak, 1964); Mackenzie Delta type - closed system (Miller, 1963); Type 2 (Porada, 1938); earth mound, Pogorostzjak & Agdassartog (Lundquist) (Williams, 1965);
	Hydraulic (open) system <sup>5</sup>	Pressure potential supplied by gravity transfer	Segregation ice (epigenetic)	Permafrost degradation into supraterratost taliks beneath drained lake basins and river channels results in pore water stagnation and high hydrostatic pressure		
	Pingo <sup>3</sup>	Minor soil water potential (both groundwater and supraterratost)	Pore ice	Groundwater under pressure domes the overlying materials and injects water which freezes to form an ice core. Occur in continuous permafrost and low relief.	Conical mound, smooth profile, also elongated and irregular forms. Also occur, heights 2-70 m, diameter 30-600 m average 250 m. Both occur singly or in groups. They may also have compound forms.	
	Hydrostatic (closed) system <sup>4</sup>	Hydrostatic pressure potential supplied by aggregating permafrost	Intrusion (pingo) ice Segregation ice (epigenetic) Pore ice	Permafrost degradation into supraterratost taliks beneath drained lake basins and river channels results in pore water stagnation and high hydrostatic pressure		
	Ice-cored mound <sup>6</sup>	Soil water in the active layer Soil water potential	Segregation ice (epigenetic) Minor expansion and pore ice	Form by ice segregation in the saturated active layer during freeze-back and hydrostatic pressures associated with closed system freezing. Observed in continuous permafrost.	Low circular to elliptical mound upto 2 m high and 5-20 m in diameter. Occur singly or in groups.	hydrocarbon, bogor (Rus) (Toshtanov and Toshtanov, 1974); ice-cored hummock (French, 1971); micro-pingo, winter pingo (Froehlich and Saps, 1978); soft mound, peat mound (Black, 1954); <b>PALISA and MICHELSON, 1958;</b>
PERENNIAL FROST MOUNDS <sup>1</sup> (Long-term 10s-1000s yrs)	Palisa <sup>7</sup>	Surface water augmented by groundwater	Segregation ice (epigenetic)	Palisa growth is the result of the formation of ice lenses by aggregation in a mineral soil core or a thick accumulation of peat	Round to elongated mound, large features flat-topped height 1-10 m, averaging 7 m, commonly 10-30 m wide and 15-150 m long, may coalesce to form palis complexes, sporadic or discontinuous permafrost. <b>AND ALSO CONTINUOUS PERMAFROST.</b>	palis bog, palis, palis, palien (pt Ger.), palis (Gt. Swedish), palarna (Sappat, 1972); peat mound (Trick, 1958); peat plateau (French, 1976); bogor, budjarnak (Rus) (Washington, 1976a); palis complex (Nelson and Orcutt, 1982);
	peat -minerogetic	Soil water potential, minor hydrostatic and hydrostatic potential	Pore ice	Palis may form in peat or mineral soils or a combination of both, they occur in bog areas with standing water mostly in areas of sporadic or discontinuous permafrost. <b>AND ALSO CONTINUOUS PERMAFROST.</b>		
	Hummock <sup>8</sup>	Soil water (active layer) cryoturbation and frost heaving	Segregation ice (active layer) Pore ice	Form by thawing of pore and soil water, in mineral soil by cryoturbation and cryostatic pressure. Permafrost not a prerequisite	Small spherical to dome- or knob-shaped mounds, vegetation covered or bare height 10-100 cm, diameter 25-150 cm	thall (Lcelandic), tundra hummock or tussock (Washington, 1979a) turf hummock (Rupp, 1966) peat mound, nigger-head, lorthuegal (Ger.) (Miller, 1945) mud hummock

Alter 1: Miller (1945) 2: van Everdingen (1978) 3: Porada (1938) 4: Miller (1945) 5: Mackay (1979) 6: French (1971, 1976) 7: Lundquist (1969) Sappat (1972) 8: Brown and Kutsch (1974) and Washington (1979a)

Table 1.1: A Classification of Frost Mound Phenomena, Based on Duration and Morphogenetic Characteristics, and Including a Summary of Commonly Used Synonyms Documented from the Literature.

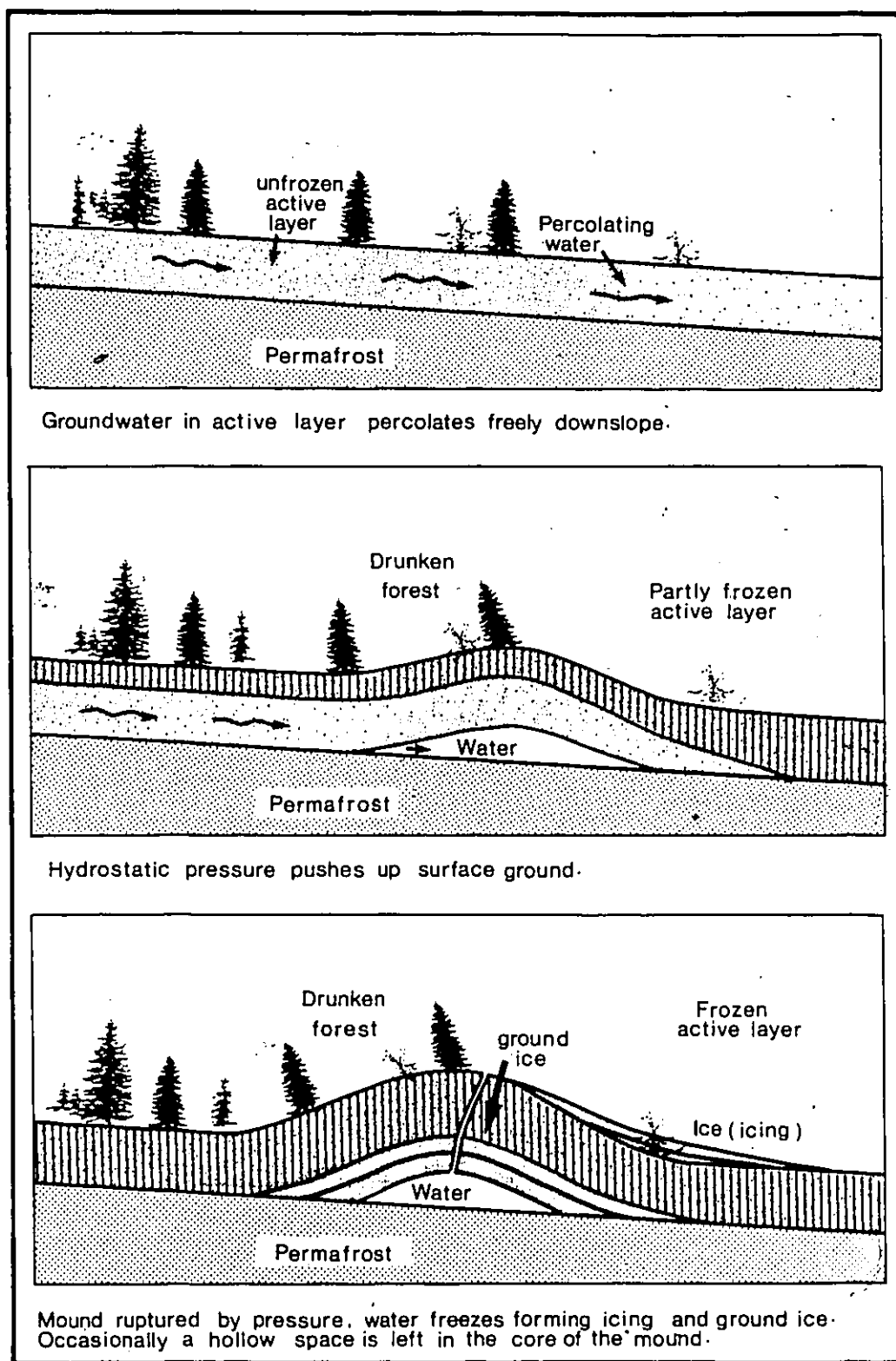


Figure 1.2 Diagram illustrating the formation of a frost blister.  
Source: Muller, 1945, p. 61.

## 1.4 Geomorphic characteristics

### 1.4.1 Distribution and morphology

Seasonal frost mounds have been reported from many areas of arctic North America. Leffingwell (1919) describes their occurrence in the Canning River region of northern Alaska, as does Porsild (1938) from Greenland and the Mackenzie Delta, N.W.T. The frost mounds described by Porsild (1938) in the Tuktoyaktuk Peninsula are further mentioned by Muller (1945) and Mackay (1979). In the Wolf Creek area of the northeastern St. Elias Mountains, Yukon Territory, Sharp (1942) identified 'tundra ground ice mounds'. From his description, it seems possible that these features may have been frost blisters. Further references identify seasonal mounds occurring in the Fairbanks area, Alaska (Linell, 1973), the Bear Rock-Fort Norman area of the Mackenzie Valley (van Everdingen, 1978), the Dempster Highway in the northern Yukon (Hughes and van Everdingen, 1978), Cape Dorset, Baffin Island (Frederking, 1979), the Khangay Mountains region, Mongolia (Froehlich and Slupik, 1978), Yakutia and other permafrost regions of the U.S.S.R. (Shumskii, 1964b; Sumgin, 1940; 1941) and the Tanglha and Fenghuoshan areas, China (Academia Sinica, 1981, pp. 6-12).

Apparently, the major controlling factor is the availability of groundwater under hydraulic pressure. At Bear Rock in the Mackenzie Valley for example, frost blisters occur in an area characterized by cold, perennial spring discharge from a near-surface aquifer in a groundwater

system underlain by a low permeability layer. (van Everdingen, 1978; 1982). A further requirement includes long, cold winters with mean daily temperatures well below freezing. It follows that the required combination of physical and hydrologic conditions conducive to seasonal frost mound activity occurs most readily in areas underlain by discontinuous permafrost. However, they may also develop in areas of thin continuous permafrost or possibly in areas of deep seasonal frost where a shallow aquifer is confined by a low permeability bedrock or clay layer.

Seasonal frost mounds form an integral part of the suprapermafrost groundwater system. In some instances, they indicate zones of groundwater transmission (Froehlich and Slupik, 1978) and, in other cases, locations of groundwater discharge.

Frost blisters indicate hydrologic activity in the active layer, while icing blisters and icing mounds are the result of surface effusion of groundwater; the two commonly occur together (e.g., Linell, 1973; Muller, 1945; Tolstikhin and Tolstikhin, 1974; van Everdingen, 1978). Where both frost blisters and icings occur, the differentiation between frost blisters and either icing blisters or icing mounds becomes difficult without stratigraphic information. Occasionally, vegetation from the top of the frost blister will protrude through the ice, or a tension crack may penetrate the organic or mineral soil layers, thus providing the basis for field identification

(van Everdingen, 1978).

Frost blisters usually result from the interruption of suprapermafrost groundwater circulation during active layer freezeback in the fall and winter. As such, frost blisters are a fast-growing, dynamic and potentially destructive landform which should not be confused with other types of frost mounds (e.g., pingos or palsas).

A consequence of the seasonal nature of frost blisters is their tendency to shift location and vary in size and shape from one year to the next. Generally they are small, seldom exceeding 7 to 8 m in height (Muller, 1945) and most often measuring between 1 and 4 m (Froehlich and Slupik, 1978; Linell, 1973; Muller, 1945; van Everdingen, 1978; Zoltai and Johnson, 1978).

Icing mounds and icing blisters associated with both river and groundwater (seepage) icings have been described in both continuous and discontinuous permafrost zones (Carey, 1973) and generally have a wider distribution than frost blisters. Shape characteristics seem highly variable in contrast to height which, regardless of shape, is relatively consistent. Mound diameters ranging from 6 to 30 m have been reported (Hughes et al., 1972) with long axis dimensions of 45 m (Linell, 1973). Tension (dilation) cracks have been observed radiating from the crown of the mound or running along the long axis of both frost blister and icing blister phenomena. Icing mounds and icing blisters associated with river icings are

generally similar in shape to their groundwater icing equivalents. However, the latter are consistently smaller.

In contrast to seasonal frost mounds, perennial frost mound phenomena such as pingos and palsas are generally larger. As stable intrapermafrost features, seasonal thaw does not cause degradation of the ice or frozen mineral soil core, thus giving both pingos and palsas significantly longer, or perennial, duration. However, disruption of the insulating cover by tension cracking, desiccation cracking or man-induced modification can result in degradation of the feature. Unlike pingos, which tend to occur as solitary features, seasonal frost mounds often occur in groups and/or as compound features. A further difference is that the growth rate of pingos is slow, commonly only a few centimetres per year, although occasionally up to 1 or 2 m per year (Mackay, 1963; 1967; 1979; Soloviev, 1973; Washburn, 1979a). As shown in Table 1.1, pingos are divided into two types, each characterized by a different distribution and setting. Hydraulic system pingos occur predominantly in areas of widespread discontinuous permafrost characterized by high relief (e.g., interior Yukon Territory, Hughes [1969] and Alaska, Holmes et al. [1968]). Hydrostatic system pingos are found in areas of continuous permafrost and low or gentle relief (e.g., Mackenzie Delta, Mackay [1973; 1977]).

Palsas differ morphologically and structurally from seasonal frost mounds, although there are some who suggest

that a continuum may exist between palsas and pingos (e.g., Lundquist, 1969; Svenson, 1976; Washburn, 1979a; 1983). Palsas are a form of perennial frost mound. They are slow growing and occur predominantly in areas of discontinuous or sporadic permafrost. In some locations, palsas are intrapermafrost features extending into the underlying permafrost, while elsewhere they occur as 'islands' of permafrost in areas dominated by seasonal frost or sporadic permafrost. Their occurrence is associated with bogs where thick accumulations of peat insulate underlying mineral strata in which ice lenses usually develop. Palsas range from small hump-like features to large irregular mounds, and from moderately straight to winding ridges (Washburn, 1979a, pp. 176-177). Typically palsas may reach to over 7 m in height (Lundquist, 1969; Seppälä, 1972; 1977; 1982; Washburn, 1979b). Palsa widths usually range from 10 to 30 m and lengths range from 15 to 150 m. It is not unusual for groups of palsas to coalesce to form palsa complexes or peat plateaus several hundred metres in extent (Brown, 1968; 1969; Kershaw and Gill, 1979; Lundquist, 1969).

Seasonal frost mounds are the smallest of the frost mound features discussed in the literature. However, the small hydrolaccoliths occurring within low centre polygons on Banks Island described by French (1971) and gas-domed mounds on Kendall Island described by Mackay (1965) are approximately the same size as small frost blisters. Thus identifying frost blisters, and distinguishing them from

small pingos, palsas or various transitional forms on strictly morphologic characteristics appears difficult without detailed study.

#### 1.4.2 Structure, hydrology and ice characteristics

A typical frost blister structure consists of a mound or upwarp of soil, peat and ice overlying a layer of clear ice vaulted over a water-filled cavity. During late winter, the water-filled cavity may freeze completely, forming a core of solid ice (Hughes et al., 1972; Muller, 1945; van Everdingen, 1978). Excessive internal hydraulic or hydrostatic pressures may result in mound rupture and subsequent draining of the water cavity. If the supply of water is cut off or if the mound fails to reseal itself then the cavity inside the frost blister will remain empty (e.g., Mackay, 1979; van Everdingen, 1978). Most descriptions of frost blister structure are based on observations of partially collapsed or ruptured features (e.g., van Everdingen, 1978). There are no descriptions concerning the characteristics of the water lens or central reservoir. Muller (1945, p. 59) suggests that the presence of the water inside a growing frost blister can be detected as a "springy feel beneath one's feet". Icing blister rupture and subsequent groundwater discharge have been described by van Everdingen (1978, p. 267) and Frederking (1979, p. 606) and for frost blisters by Academia Sinica (1981, p. 6). It has been suggested that frost blisters which

have solid ice cores (lacking an air- or water-filled cavity) would be structurally and thermally more stable (Hughes and van Everdingen, 1978), particularly if the overlying soil and organic cover remained intact. Hughes (personal communication, March 1981) suggests that this type of frost blister could become semipermanent if incorporated into the permafrost as an intrapermafrost feature.

The ice occurring within seasonal frost mounds is classified as injection or intrusion ice (Mackay, 1972a). Generally, injection ice tends to be pure and transparent. It displays an absence of solid impurities except along contacts between the ice and enclosing sediments where stringers or tongues of material are found in the ice. Thus, streaks of small mineral particles, plant roots and stems, or clumps of soil are sometimes incorporated into injection ice (Shumskii, 1964a; b). Gas inclusions of various dimensions and shapes occur in the ice mass. These gas inclusions produce an indistinct stratification parallel to the confining structure. Individual bubble trains rise vertically through the ice, sometimes in straight lines or frequently forming wavy patterns. Large spherical bubbles indicate slow freezing conditions, a cylindrical shape parallel to growth direction indicates an intermediate rate of growth, and small spherical bubbles or no bubbles at all suggest rapid freezing conditions (Gell, 1976). Bubble pattern can also be used to determine freezing direction.

There have been few studies of frost mound ice fabrics. Gell (1975; 1976; 1978) discusses crystal characteristics of ice wedges, pingos and icing mounds. Other ice fabric studies have been concerned predominantly with pingo and wedge ice (Black, 1953; Mackay and Stager, 1966b; Müller, 1963; Shumskii, 1964a; b). Ice fabric analysis by Gell (1976; 1978) of an icing mound adjacent to a pingo in the Tuktoyaktuk Peninsula identified a wide range of ice crystal characteristics. A chill zone was identified by a layer of small ice crystals indicating rapid freezing. Small crystals were also identified in zones of small bubbles. With increasing depth, ice crystals became larger and elongated.

Water and ice chemistry have been used to determine the source of water which forms frost mounds. At Bear Rock, Northwest Territories, van Everdingen (1978) reports high  $\text{SO}_4^{2-}$  content in the spring water derived from dissolution of gypsum beds from the local geology. Sulphur-isotope analyses confirm the source of dissolved sulphates. Hydrochemical analyses of water discharging from the frost mounds indicate that nearby perennial springs are the source of the water. Icing mounds and icing blisters form essentially by the same process, only they are composed entirely of ice. Icing mounds form by the freezing of successive layers of water or overflow that discharge from cracks in the icing.

Structurally, icing mounds consist of arched sequences of ice layers which are thickest near the source of water and thin toward the edge of the mound (Muller, 1945, p. 62). Icing blisters form by the intrusion of water between layers within the icing, subsequently doming the overlying layers of ice into a mound. Identification of seasonal frost mounds, when occurring in association with an icing, can be difficult. Occasionally, even when the structure is known, frost mounds have been misidentified. For example, the palsa (pals) described by Maarleveld (1965, p. 11, after Chemekov, 1959) more closely resembles the structure of a frost blister.

In contrast to seasonal frost mounds, pingo structure generally consists of a conical mound characterized by a massive plano-convex ice core (Mackay, 1962; 1963). However, recent studies have shown this to be an oversimplification and that pingo structure can be very complex ranging from a massive ice core to compound ice cores or a combination of massive ice, ice lenses, mineral soil and layers of intrusion ice (French and Dutkiewicz, 1976; Mackay, 1979). Drilling records and exposures indicate that, like seasonal frost mounds, the pingo ice core generally resembles the gross outer shape of the feature.

A frost blister may occasionally have a similar appearance as a small palsa resulting in frequent misidentification; however, their structures vary significantly. In contrast to the massive ice core and water-filled cavity

of a frost blister, the main constituents of a palsa include a thick insulating layer of peat overlying an ice-rich mineral soil core characterized by segregation ice lenses (Ahman, 1976). These ice lenses rarely exceed 2 to 3 cm in thickness (Lundquist, 1969) although thicker lenses have been reported (e.g., Forsgen, 1968).

#### 1.5 Growth mechanisms

The main process forming seasonal frost mounds is ice injection by a perennial, spring-fed suprapermafrost groundwater system. As the active layer refreezes in the fall, suprapermafrost groundwater circulation gradually becomes constricted. The gradual penetration of the freezing front into the water-bearing active layer reduces hydraulic transmissivity, resulting in a build-up of water in the hydrologic system. As hydraulic potential increases, the artesian pressure may exceed the confining pressure, deforming the overlying materials into a mound enclosing a reservoir of water. The mound will increase in size as the reservoir increases or if the reservoir freezes completely. The uplift process is assumed to be slow, allowing the overlying material to deform plastically. If the internal stresses exceed the strength of the confining materials, the mound will subsequently rupture.

The frost mound definitions presented by both Muller (1945, pp. 58-59, 216) and Williams (1965, p. 21) identify the combined influences of (a) hydrostatic

pressure of groundwater, (b) the force of crystallization, and (c) expansion due to freezing of water, as essential processes in all types of frost mound development. The role of hydraulic pressure as a major process contributing to frost mound formation was suggested by Leffingwell (1919, pp. 150-158) for both perennial and seasonal frost mound phenomena. This hypothesis was further discussed by Porsild (1938, pp. 46-47) as the dynamic process responsible for pingos in Alaska and Greenland, and more recently by Mackay (1979) for pingos in the Tuktoyaktuk Peninsula.

Figure 1.3 is a diagrammatic representation of the sequential development of both frost and icing blisters. It is clear that the same mechanisms are responsible for both features. However, they differ in the nature of the material uplifted. For example, frost blisters always include a layer of peat or soil whereas icing blisters are composed exclusively of ice. Frost blisters and icing blisters may occur together or independently. The requirements for both frost blister and icing blister formation are generally the same.

Icing mounds, the remaining type of seasonal frost mound, differ in that the hydraulic potential does not result in uplift of either soil materials or ice, but simply forces water to the surface of the ground or icing through a tension crack or along some plane of weakness to eventually freeze. As in the case of icing blisters, icing mounds are composed entirely of ice. In the past, the

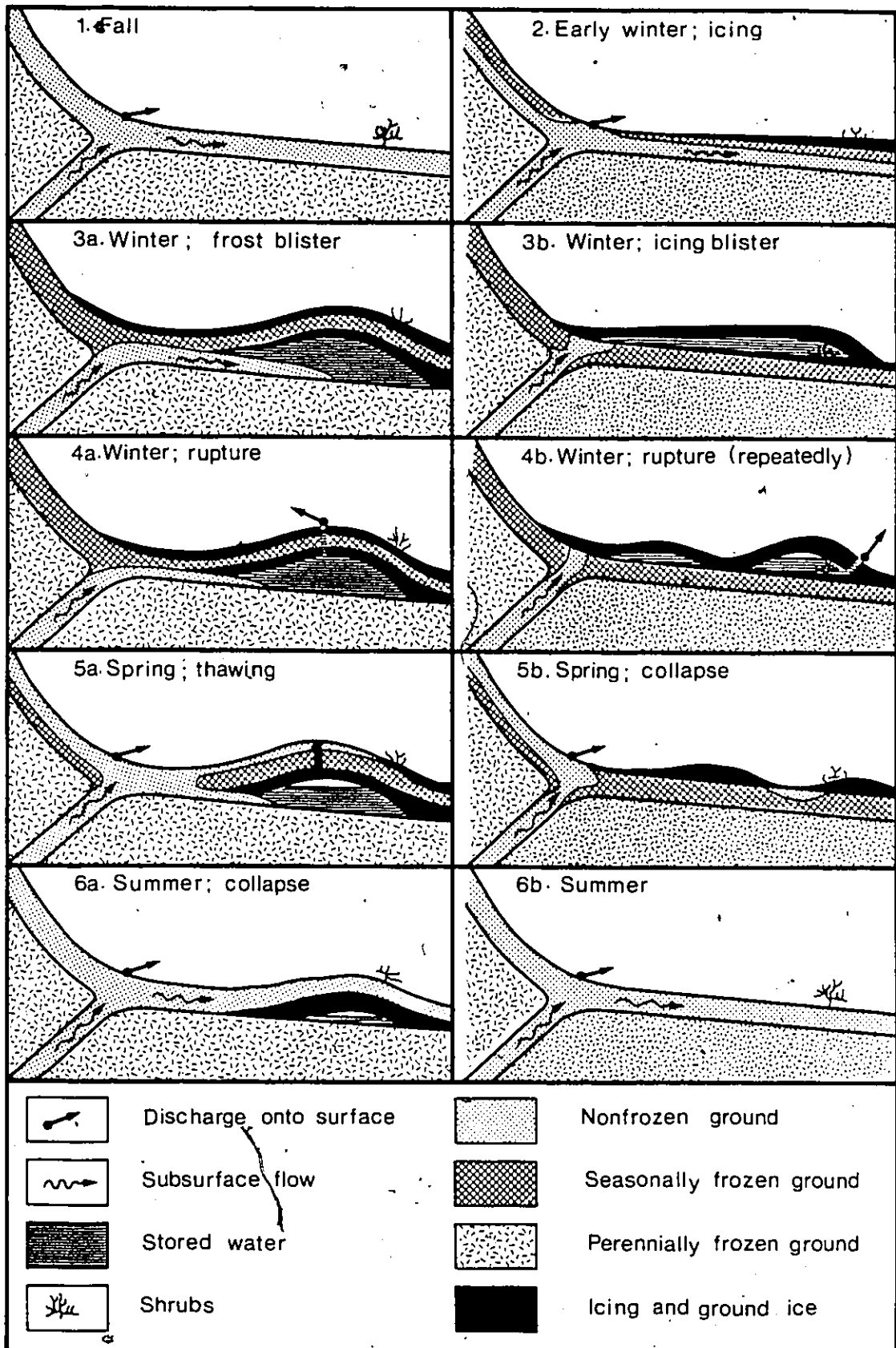


Figure 1.3 Diagrammatic representation of the sequential development of frost and icing blisters. Source: van Everdingen, 1978, p. 273.

term icing mound has been used quite loosely in the literature, often in reference to features defined here as icing blisters and frost blisters.

Although the role of groundwater under pressure has been suggested by several researchers as the dynamic component of seasonal frost mound growth (e.g., Maarleveld, 1965; Muller, 1945; van Everdingen, 1978), there have been no direct measurements of hydraulic potential. A minimum approximation of hydraulic potential was estimated by R. O. van Everdingen (1978) using the height and density of various materials displaced. It was calculated that frost blisters 2 to 5 m high require a minimum hydraulic potential of 2.6 to 4.9 m (25 to 50 kPa). A Soviet study (Petrov, 1934; abstracted from Williams, 1965, pp. 160-161) determined the groundwater pressure of an icing mound (frost blister) by measuring the depression of the freezing point due to pressure. In an area where frost mounds ranged from 1 to 2.5 m high and 10 to 30 m in diameter, the freezing point was depressed by 0.4°C. Since lowering of the freezing point of water by 0.01°C corresponds to a pressure of 1.3 atmospheres, it was concluded that the pressure inside the mound was 52 atmospheres or  $5.2676 \times 10^3$  kPa. A number of studies have investigated active layer pressures associated with earth hummocks or pore pressures during freeze-back (Mackay, 1980; Mackay and Mackay, 1976; Pissart, 1970; Slusarchuk et al., 1973) but have failed to record significantly high values.

The processes and mechanisms of palsa formation are considerably different from those associated with seasonal frost mounds. Ice segregation and the formation of ice lenses in the mineral soil core are identified as the primary growth mechanisms (Lundquist, 1969, p. 209). Capillary flow and moisture migration during ice segregation are believed to be the main hydrologic processes; however, hydrostatic or hydraulic pressure may contribute by supplying water to the system feeding the palsa but is not responsible for uplift or displacement (Lundquist, 1969).

In contrast to all of the above, pingo formation relies on the processes of both ice injection and ice segregation combined with hydrostatic and/or hydraulic pressure. Two different hydrologic systems dominate in pingo growth. Although the genetic terms 'open' and 'closed' (Muller, 1963; Porsild, 1938) are widely used (e.g., French, 1976, pp. 95-100; Washburn, 1979a, pp. 181-185), the terms 'hydraulic' and 'hydrostatic' (Mackay, 1978a; b; 1979) better reflect the hydrodynamics involved.

#### 1.6 Active layer hydrology

Seasonal frost mounds are generally recognized as evidence of groundwater discharge and/or movement through the active layer (Fröhlich and Slupik, 1978; van Everdingen, 1978; 1982). Therefore, an understanding of the factors influencing the behaviour of groundwater in the active layer is fundamental to the analysis of seasonal frost mound

occurrence. The annual cycle of freezing and thawing of the active layer, and its impact on groundwater circulation, forms the basis for the seasonal occurrence of these mounds.

The hydrodynamic characteristics of suprapermafrost groundwater in a flow system controlled by gravity transfer, combined with a seasonal freezing of the active layer, are the main processes influencing the occurrence of seasonal frost mounds and groundwater icings (Carey, 1973; Tolstikhin and Tolstikhin, 1974; van Everdingen, 1978; 1982). The presence of permafrost as a low permeability layer retarding downward percolation of groundwater is also considered important (van Everdingen, 1982).

The effect of permafrost on various aspects of the hydrologic cycle has been described in several Canadian studies (Anderson, 1974; Brandon, 1962; 1965; 1966; Church, 1972; Lewkowitz, 1981; Lewkowitz and French, 1982a; b; Lissey, 1974; McCann and Cogley, 1972; van Everdingen, 1978; 1981). Figure 1.4 is a simplified hydrologic flow model identifying the primary terrain-based components of the hydrologic cycle. At each stage, the flow of the system is modified in some way by either the presence of permafrost or the cold climatic conditions responsible for permafrost occurrence.

Three types of groundwater have been described in areas of permafrost (Tolstikhin and Tolstikhin, 1974): (a) water occurring above the permafrost table is referred to as suprapermafrost groundwater, (b) water found within

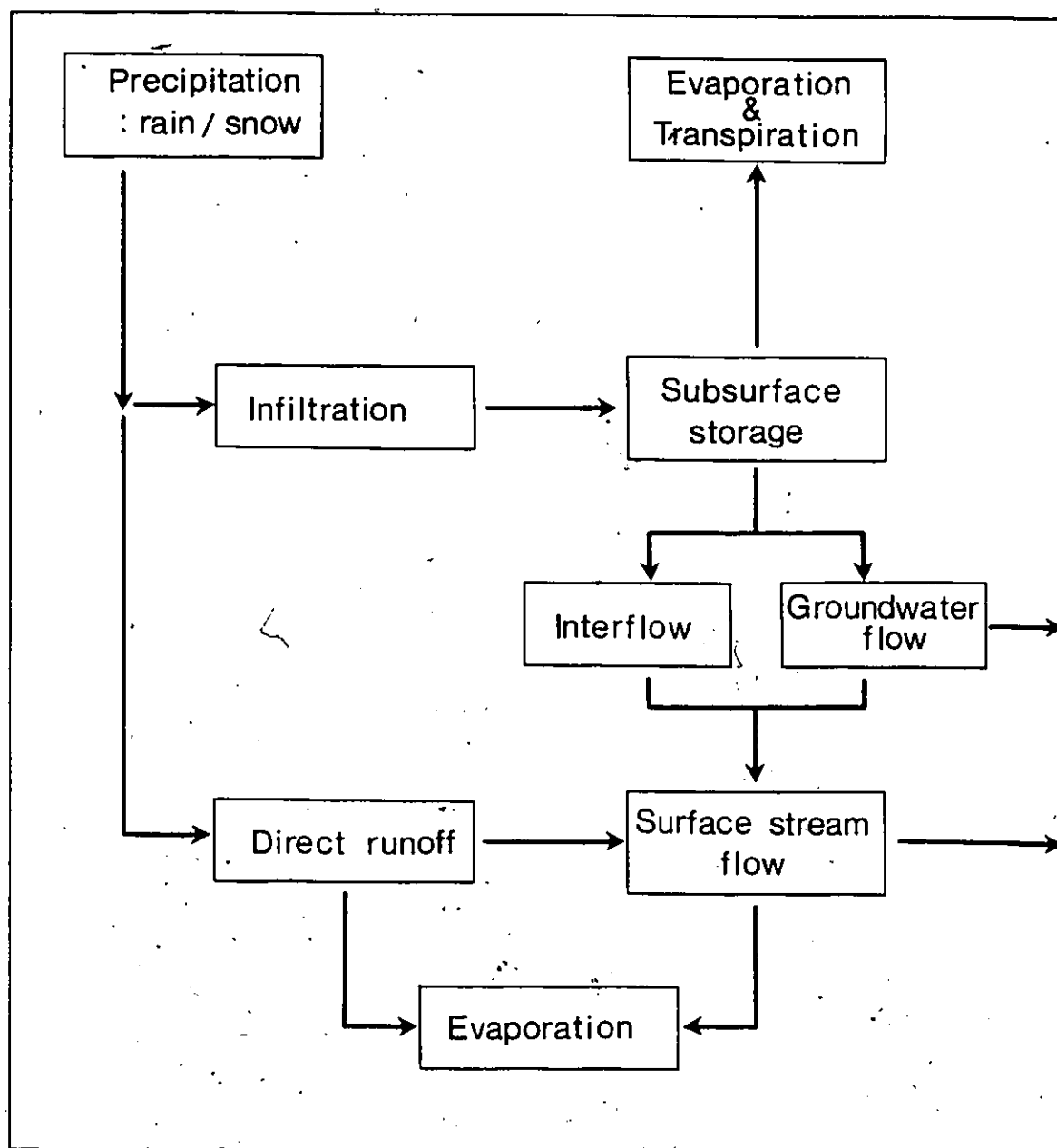


Figure 1.4 A simplified flow diagram of the terrain-based portion of the hydrologic cycle.

or between layers of permafrost is called intrapermafrost groundwater, and (c) water occurring below the base of permafrost is called subpermafrost groundwater. More detailed classifications of groundwater in permafrost regions have been developed, incorporating subdivisions based on stratigraphic position, aquifer characteristics, source, pressure and temperature conditions (e.g., Tolstikhin and Tolstikhin, 1974, pp. 2-3). These classifications clearly illustrate how the presence of permafrost is a complicating factor in groundwater circulation. In previous hydrologic studies, permafrost has been assumed a priori to constitute an impermeable barrier to groundwater movement (Brandon, 1962). While this assumption may be reasonably valid under most conditions, it has been shown that in certain situations both liquid and vapor transfer within permafrost can be highly significant (e.g., Harlan, 1974; Mackay, 1983). In this regard, permafrost should not be classified indiscriminately as impermeable but more appropriately as an aquitard in a traditional hydrologic sense. Significant amounts of liquid water have been shown to exist in soil-water and clay-water systems in equilibrium with ice at temperatures considerably below 0°C, as films adsorbed on the surfaces of soil particles and in clay platelets (Nersesova and Tsytoovich, 1966; Schofield, 1935; Tsytoovich, 1975; Williams, 1968). Temperatures significantly below 0°C are often required to initiate the change of pore-water to ice (Anderson and Morgenstern, 1973; Banin and Anderson, 1974).

The magnitude of depression of the initial freezing temperature depends on several factors, including fluid pressure, salt content of the pore-water, grain size distribution, soil mineralogy and soil structure (van Everdingen, 1976).

The hydrologic importance of frozen ground lies in the large differences in hydraulic conductivity that exist for most geologic materials between their frozen and unfrozen state.

The rate of groundwater flow,  $v$ , by intergranular permeation is defined by Darcy's law, where;

$$v = -K \frac{dh}{dl} \quad [1]$$

where  $h$  is hydraulic head expressed in terms of the change in height or elevation  $dh$ ,  $l$  is length and  $dl$  is change in length or distance, and  $K$ , hydraulic conductivity, is a constant of proportionality.

Equation [1] shows that the rate of groundwater flow is directly proportional to the hydraulic conductivity which is influenced by the fluid properties of mass density and dynamic viscosity as well as media permeability. The formation of pore ice dramatically reduces soil permeability. It is not unusual for a decrease in temperature of a few tenths of a degree below  $0^{\circ}\text{C}$  to decrease the hydraulic conductivity by several orders of magnitude (Burt and Williams, 1976). Also, temperatures of near surface groundwater in northern latitudes frequently range between  $3^{\circ}\text{C}$  and  $0^{\circ}\text{C}$

(Hubbert, 1940; 1956). These waters have a range in viscosity from 1.55 to 1.79 cp (centipoise). In more temperate regions, groundwater temperatures are often between 10°C and 15°C with viscosities from 1.30 to 1.05 cp.

CHAPTER TWO

STUDY AREA

## 2.1 Introduction

The northern Yukon is a roughly triangular region of approximately 130,000 square kilometres, lying north of latitude  $63^{\circ}30'N$ . It approximates the drainage divide between the main Yukon and Mackenzie Rivers (Bostock, 1961; 1970). This portion of the Yukon Territory forms the northernmost extension of the Western Cordillera region of Canada, and is characterized by a number of topographically rugged and geologically distinct mountain ranges interspersed with lowlands, plains and plateaus (Bird, 1972; Templeman-Kluit, 1966).

Reconnaissance fieldwork was undertaken at locations adjacent to the Dempster Highway (Figure 1.1) during the summer of 1979. In addition, helicopter visits to a number of abandoned wellsites in the Eagle Plain and Peel Plateau (French, 1981) provided an opportunity to undertake comparative observations elsewhere. In September 1980, following extensive air photo analysis, the North Fork Pass area (lat.  $64^{\circ}35'N$ ; long.  $138^{\circ}18'W$ ) in the Southern Ogilvie Mountains was identified as the main study location (Figure 2.1). Frost mounds, first interpreted as palsas, have been identified previously in the North Fork Pass area by O. L. Hughes (Hughes et al., 1972) and more recently by R. O. van Everdingen (Hughes and van Everdingen, 1978; van Everdingen,

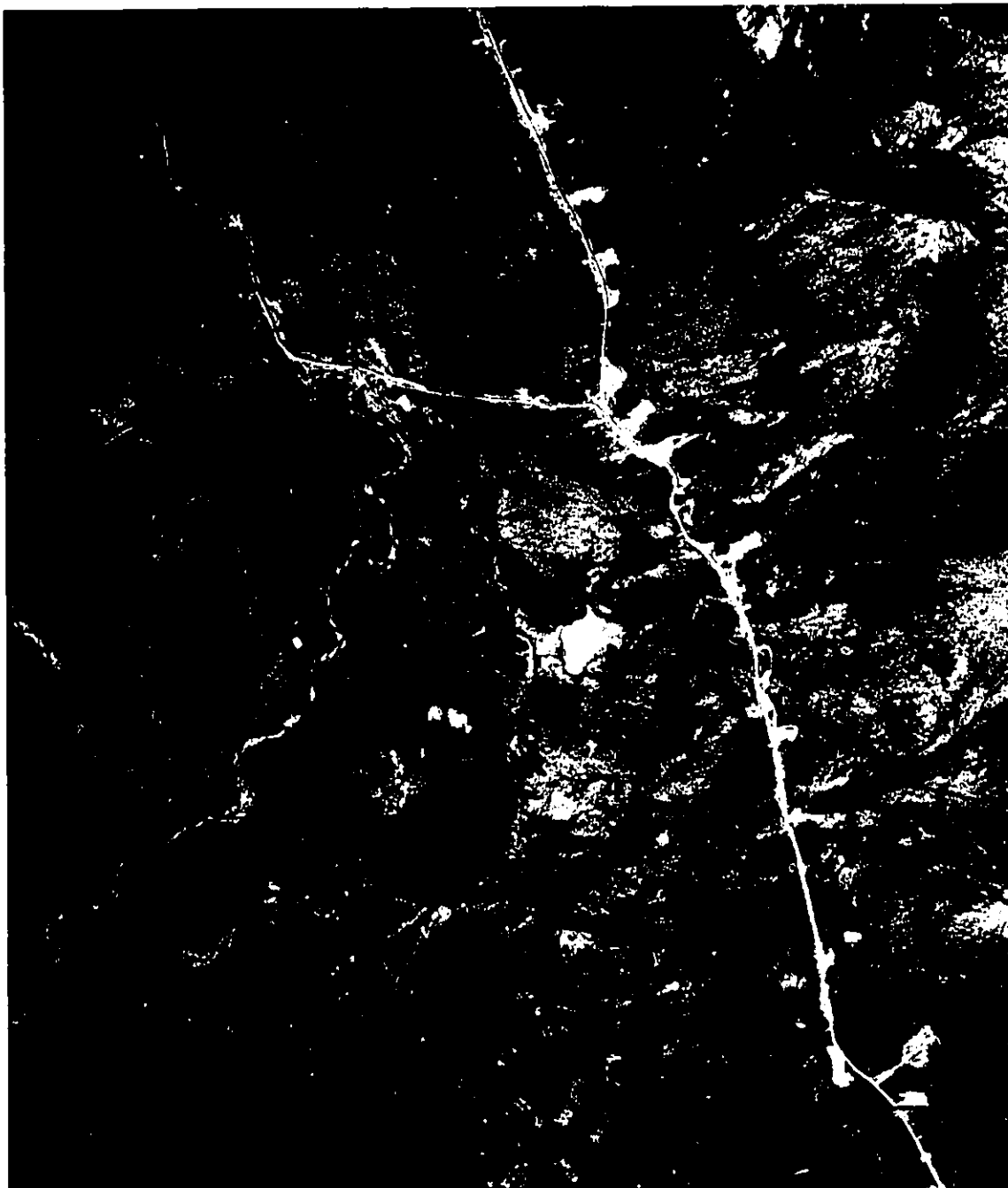


Figure 2.1 Air photo of the North Fork Pass area. The location of frost mound sites and the Dempster Highway are marked. Source: National Air Photo Library, A 18137-40.

1978; 1982).

Criteria considered during the selection of the study area included: (a) the regular occurrence of seasonal frost mounds, (b) year-round access and logistical support for a base of operations, and (c) availability of baseline data.

Research in both 1980 and 1981 was carried out at intervals during the late summer and autumn. At that time, all icing-related phenomena in the North Fork Pass had disappeared, as had several frost blisters. Those mounds that remained were either partially collapsed, in some cases revealing an ice core, or remained as residual landforms into the next winter. During 1981 and 1982, field investigations were undertaken in December and March. The specific aim was to document the various stages of a complete cycle of seasonal frost mound activity.

The Yukon territorial government strictly regulates off-highway activities within the Dempster Highway Development Area, particularly campsite locations. In the North Fork Pass area, approved base camp locations included the Tombstone campground (KM 74), an outfitters camp (KM 91) and a trailer facility (KM 82). The Dempster Highway is maintained year-round, thereby allowing both winter and summer investigations. A final consideration was the availability of general background information for the area. This included climate data for Dawson City, weather summaries for Dempster Highway maintenance camps at KM 74 (Klondike River) and

KM 196 (Ogilvie River), a number of field excursion guides describing glacial history, vegetation, surficial geology (e.g., Hughes et al., 1972; Hughes and van Everdingen, 1978; Pettapiece et al., 1978), and various geologic reports (e.g., Gray, 1968; 1973; Green, 1972; Green and Roddick, 1962; Hughes, 1969; 1972; Hughes et al., 1969; Terasmae, 1968; Templeman-Kluit, 1970; Vernon and Hughes, 1966).

## 2.2 Regional setting

Relatively few data are available with respect to the interior northern Yukon. The mountain ranges and interior plateaus of this area have long remained among the least known parts of Canada (Porsild, 1974). Accurate maps based on aerial photographs are now available, but the absence of roads and the scarcity of suitable landing strips for light aircraft have made ground exploration, including the study of permafrost, vegetation and wildlife, difficult. Most of the data presently available have been collected either since the start of highway construction in 1959, or as a result of oil and gas exploration (Campbell, 1960; 1967; MacLeod, 1979).

With a few exceptions (e.g., French, 1981; Hughes, 1969; Hughes et al., 1981; Richardson and Sauer, 1975; Ricker, 1968; Wiken et al., 1979; Zoltai and Pettapiece, 1973), the terrain, permafrost, vegetation and climatic conditions of this region have not been described in detail.

2.2.1 Quaternary history

The interior Yukon is geomorphologically interesting since a large portion escaped glaciation by the Laurentide ice sheet (Hughes, 1972; Hughes et al., 1969; Prest, 1969; Prest et al., 1968). The northwestern perimeter of the ice sheet reached the eastern border of the Yukon Territory and penetrated the southern Eagle Plain, along the Peel River valley. Elsewhere, the ice advance was contained by the Richardson and Mackenzie Mountains (Figure 2.2).

The north and west-central areas of the Yukon are thought to have remained unglaciated throughout the Pleistocene, while other parts of the Territory display a complex pattern of Cordilleran glaciation (Bird, 1967; 1972; Bostock, 1966; Hughes and van Everdingen, 1978; Ricker, 1968). A number of glacial episodes have been recognized in the Yukon:

	Contemporary	-	St. Elias Range
	Neoglacial	-	2,000 B.P. (?) expanded version of present St. Elias Range
	McConnell	-	Wisconsin
Late Pleistocene	Reid	-	early Wisconsin
	Pre-Reid	-	

(Modified from Bird, 1972)

The unglaciated portions of the Yukon, Alaska, eastern Siberia and intervening shelf areas comprise the Beringia refugia (Hopkins, 1967). Refugia are important for several reasons; not only do they offer the possibility

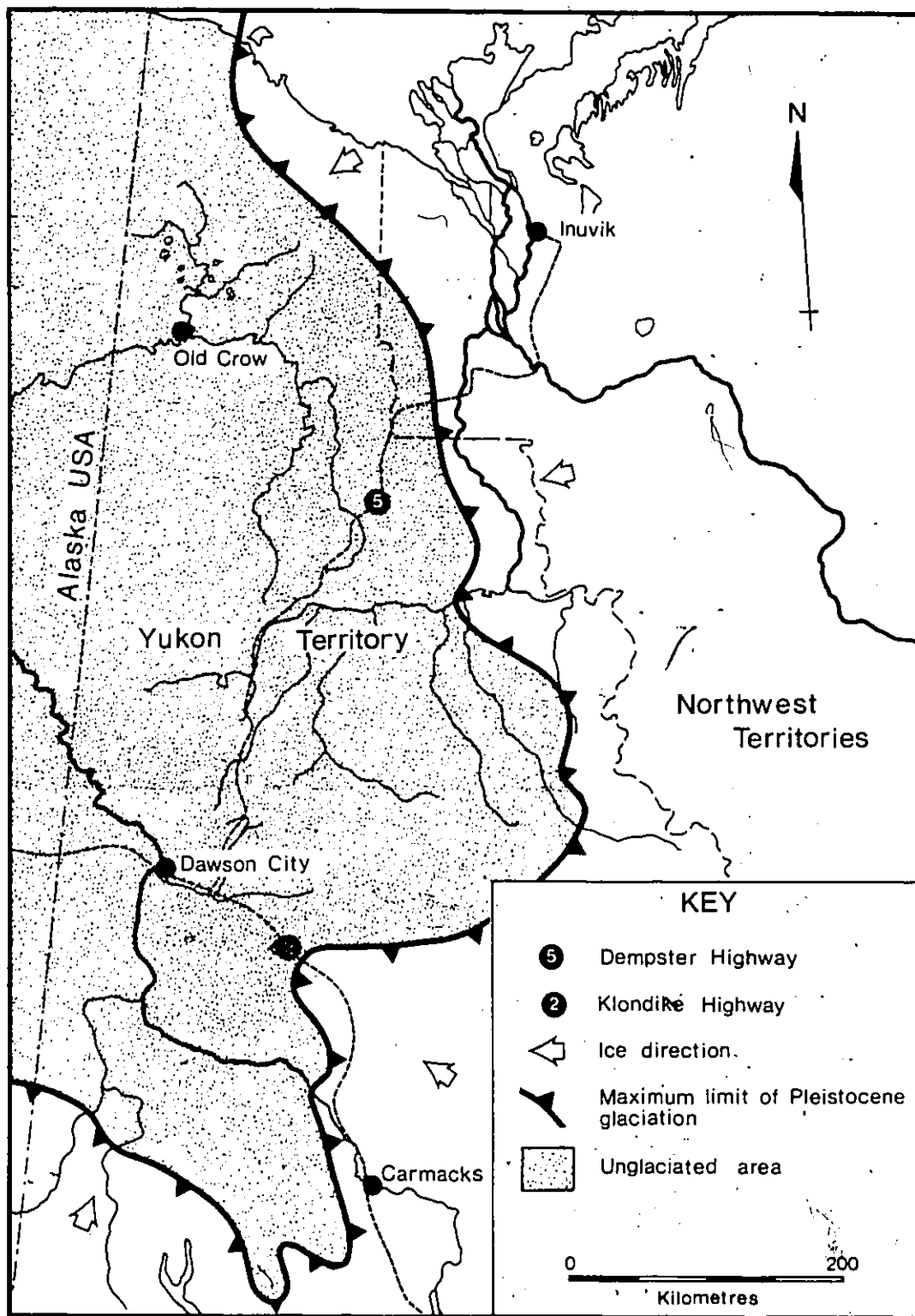


Figure 2.2 Map showing the glacial limits in the northern interior Yukon Territory. Source: Hughes, 1969; 1972; Hughes et al., 1969; 1971.

of a long and relatively continuous geologic record of non-glacial environmental change, but they also provide centres for dispersion of flora and fauna following deglaciation (Youngman, 1975). This part of the Beringia refugia displays a unique periglacial landscape, the result of prolonged cold and aridity. Many of the landforms (e.g., tors, cryoplanation surfaces and widespread felsenmeer) developed in response to a climate more severe than the present, which may or may not be related to the development of contemporary permafrost.

#### 2.2.2 Relief and geology

The study location was between KM 82 and 87 of the Dempster Highway. At this point, the highway traverses the southern Ogilvie Mountains through North Fork Pass, at an elevation of 1,290 m a.s.l. The Southern Ogilvie Mountains form a distinct physiographic unit (Bostock, 1948; 1961). This mountain system rises abruptly from the Tintina Trench and Yukon Plateau, forming an eastward trending belt of rugged fold mountains. The mountains display a close relationship between topography and underlying bedrock geology (Green, 1972). The most rugged topography and steepest relief have developed in areas underlain by porphyritic syenite stocks. A number of these stocks have been intruded to form a 60 km northwest trending belt of jagged peaks, the most striking of which is Mount Tombstone (Figure 2.3).



Figure 2.3 The North Klondike River, near Mount Tombstone (centre) is flanked on the left by The Three Sisters and Mount Campbell. Photo: September 1981.

The average mountain peak elevation is approximately 2,050 m a.s.l., with an average relief of roughly 900 m and a maximum relief of 1,800 m. Mount Frank Ray is the highest peak in the Southern Ogilvie Mountains at 2,360 m a.s.l., while Mount Tombstone and surrounding peaks exceed 2,200 m. The Cloudy Range flanks the East Blackstone River valley at North Fork Pass and ranges between 1,500 and 2,100 m in elevation. The East Blackstone River valley in the vicinity of the study area has an elevation of 1,190 m, roughly 100 m lower than the top of the pass.

The drainage of the area is described by Ricker (1968, p. 36) as 'youthful to early mature', varying regionally from a dendritic to a rectangular pattern. In the vicinity of the plutonic stocks, the drainage pattern is more radial in character. The North Klondike, Blackstone, Ogilvie and Hart Rivers comprise the main drainage systems in the North Fork Pass area. Many rivers display braided channel segments, often corresponding to sites of extensive winter icings.

The larger valleys were modified by repeated advances of valley glaciers and, as a result, have rounded cross-valley profiles (Figure 2.4). The valley floors are covered by varying thicknesses of glacial and glaciofluvial sediments. The upper valley slopes are mantled by coarse angular talus and fine colluvial materials. The smaller, unglaciated tributary valleys have steep, straight sides with v-shaped cross-profiles. Large alluvial fans occur at regular intervals on both sides of the valley where runoff channels join



Figure 2.4 General view of the East Blackstone River valley near the North Fork Pass. Note the lateral moraine on the far side of the valley (indicated by the arrow). Photo: September 1980.

the main valley.

The Southern Ogilvie Mountains display a complex Pleistocene geology, related to successive advances of Cordilleran glaciers. In this part of the Yukon, glaciation was characterized by local glaciers originating in cirques along the main axis of the Southern Ogilvie Mountains. Glaciers flowed outward from the Ogilvie Mountains in the direction of modern drainage routes (Figure 2.5; Vernon and Hughes, 1966). In the North Fork Pass area, at least three and possibly four glacial advances are recognized (Ricker, 1968; Vernon and Hughes, 1966). The glacial advances are referred to as the Old, Intermediate and Last by Vernon and Hughes (1966). They probably correlate with the pre-Reid, Reid and McConnell glaciations, identified by Hughes et al. (1969) for the central Yukon Plateau. The McConnell advance is considered to be of main-Wisconsin age and the Reid advance of early-Wisconsin or Illinoian age (Hughes et al., 1972).

Between the pre-Reid and McConnell age deposits found in the North Fork Pass/Chapman Lake area, a two-fold sequence of glacial deposits has been tentatively identified as corresponding to the Reid maximum and a Reid readvance (Ricker, 1968). The North Fork Pass area displays till and outwash deposits from glaciers occupying the North Klondike and East Blackstone River valleys. The northern slope of the North Fork Pass is covered by the southern lobe of a hammer-head shaped moraine which

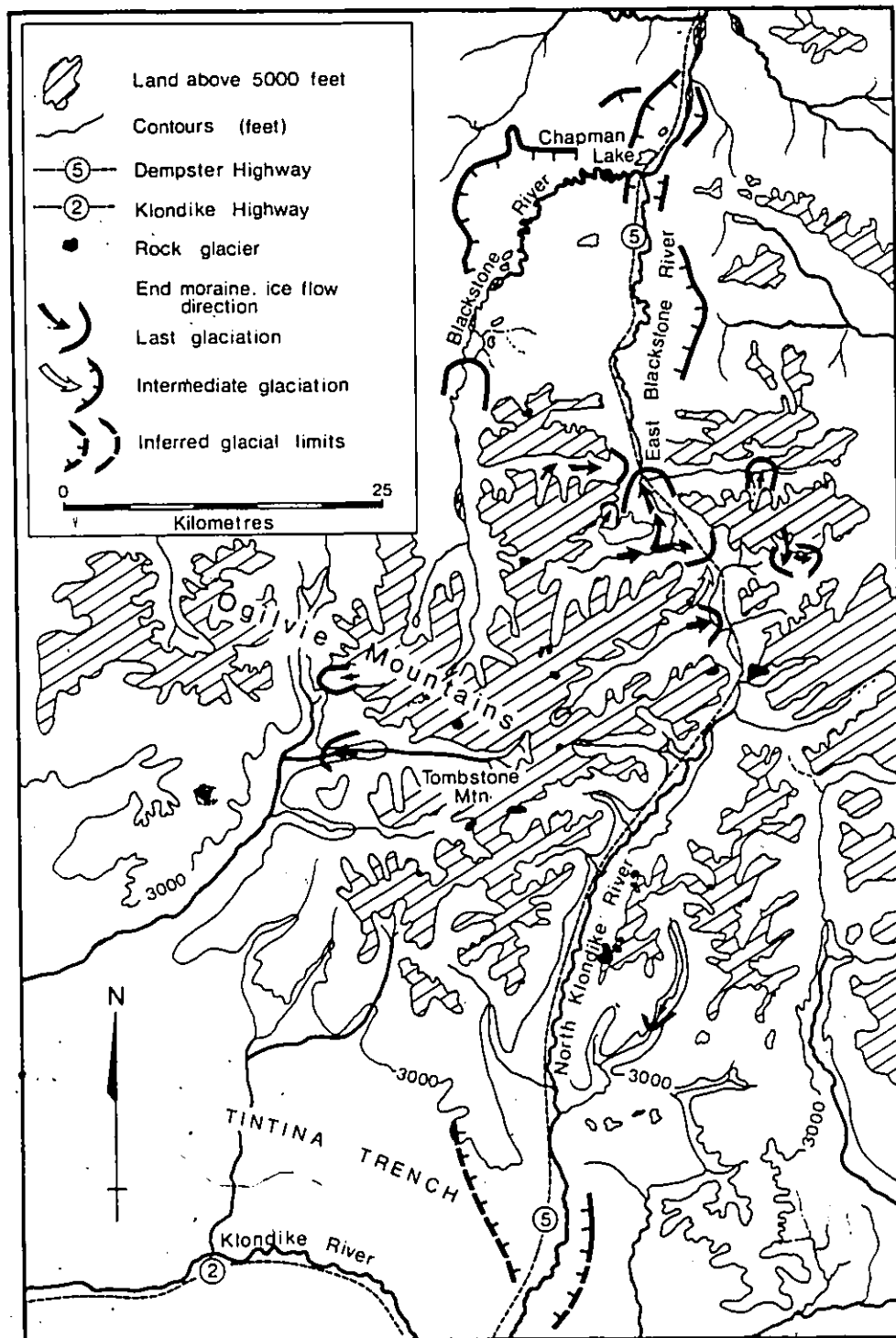


Figure 2.5 Map of landforms and surficial geology of the North Fork Pass area. Source: Vernon and Hughes, 1966.

formed by glaciers advanced into the East Blackstone Valley from the adjacent Rangeifer Valley. The moraines are hummocky and ridged with a number of closed depressions. The deposits are composed of predominantly bouldery till, with a silt-sand matrix. Zones of coarse gravel were used extensively as aggregate during highway construction. A number of large glacial erratics and areas of hummocky ground moraine exist on the valley floor.

### 2.2.3 Regional climate

The present climate of the interior northern Yukon is cold and continental. It is frequently influenced by weather systems and air masses originating over the Arctic Ocean (Burns, 1973; 1974; Hughes et al., 1981; Kendrew and Kerr, 1955; Thompson, 1967). In general, the climate is characterized by long cold winters, with prolonged (3 to 4-week) periods of intense cold during which daily maximum temperatures fail to rise above  $-35^{\circ}\text{C}$  or  $-40^{\circ}\text{C}$  (Campbell, 1961; Martin, 1973; North, 1972; 1978). Summers are short, cool and damp; however, hot and dry periods are not uncommon. Total precipitation is low, but seasonally and regionally variable. Snow may occur during any month, particularly at higher elevations, and constitutes almost half of the total precipitation. Variability and rapid change in weather conditions are typical of the northern Yukon climate. Due to the diverse topography of the region, its climate is also strongly influenced by local variation in elevation and aspect.

Long-term meteorological data are not available for the interior northern Yukon. However, an approximation of climatic conditions is provided by data from Dawson City (64°04'N, 139°24'W, elevation 323.8 m a.s.l.). Located in the Klondike River valley 10 km east of Dawson City, the climatic station is probably representative of conditions occurring to the south of the study area. The mean annual air temperature is -5.0°C but has varied between -10.1°C and 0.7°C during the period over which records have been maintained. Average annual precipitation is 328 mm, the majority of which occurs during the summer. Figure 2.6 presents a monthly breakdown of average temperature and precipitation data. Of significance are the cold winter temperatures and low snowfall in contrast to the cool wet summers. The data also demonstrate that 1981 was an average year in terms of temperature, except for a very mild period in January and February. Precipitation was above average in 1981, particularly during the late summer and early autumn.

The community of Old Crow (67°34'N, 139°50'W, elevation 253 m a.s.l.), located almost 400 km north of Dawson City, is probably more representative of temperature conditions occurring in the study area (Table 2.1). The mean annual air temperature is -10.0°C and ranges between -4.5°C and -15.2°C. Precipitation is low, averaging 212 mm per year, of which almost half occurs as snow. Average temperatures for December, January and February are below

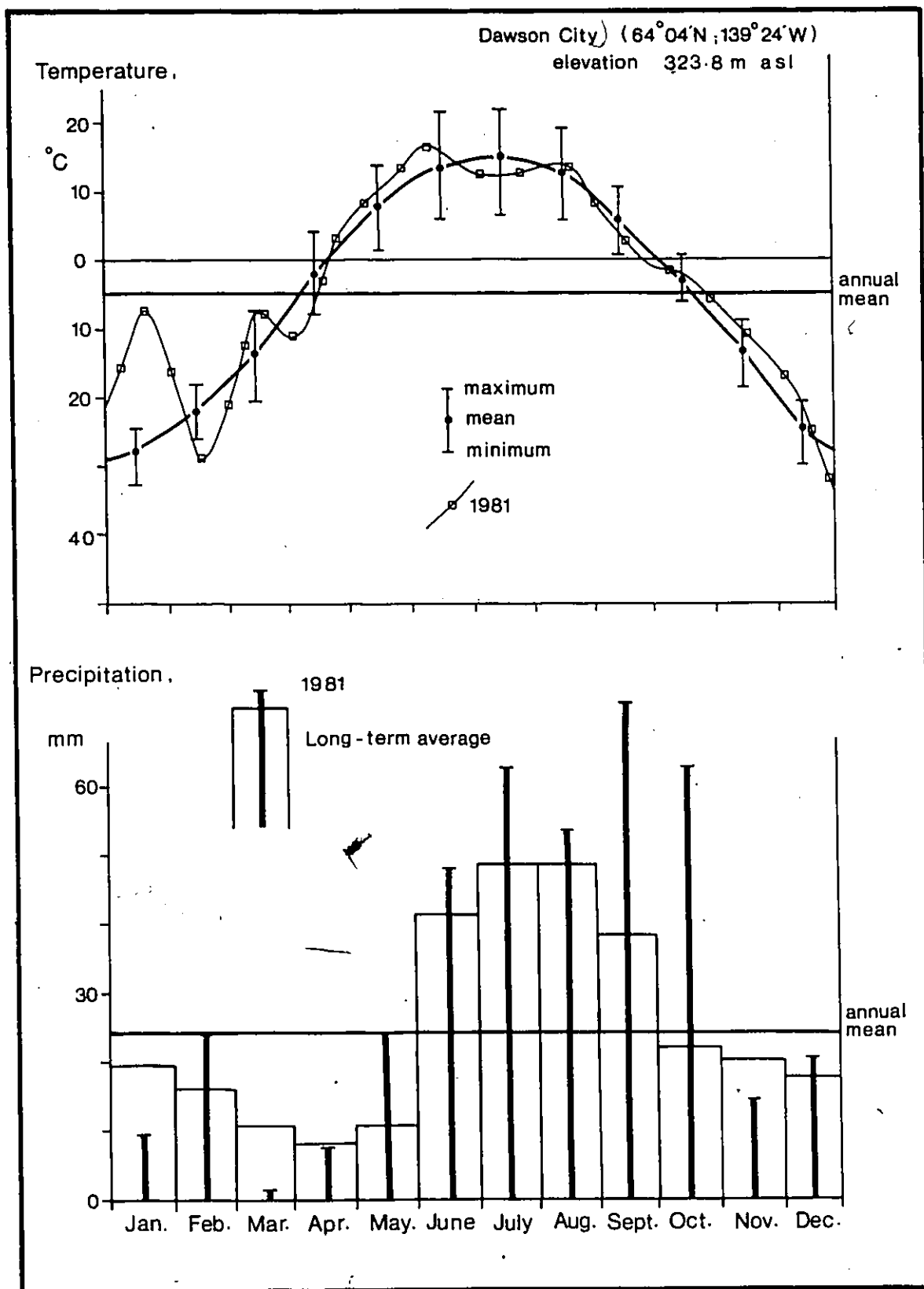


Figure 2.6 Summary of selected climate data for Dawson City, 64°04'N, 139°24'W. The mean monthly temperature and precipitation for 1981 are highlighted. Source: Atmospheric Environment Service, Environment Canada.

Table 2.1

Selected Climatological Data for the Interior Northern Yukon Territory. (A) Temperature and Precipitation Data for Old Crow, 1959-1980 (Source: Environment Canada). (B) Sporadic Temperature and Precipitation Data for Dempster Highway Maintenance Camps (Source: H. Wahi, Environment Canada).

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
<b>(A) Old Crow</b>													
67°34'N, 139°50'W (elevation 253 m)													
Temperature (0°C)													
mean daily	-33.7	-29.5	-23.5	-11.7	1.2	12.0	14.1	10.4	3.0	-8.8	-23.2	-29.7	-9.9
mean daily max	-28.8	-24.6	-17.5	-5.5	6.5	18.2	20.7	16.1	7.9	-4.9	-19.0	-24.7	-4.6
mean daily min	-38.6	-34.3	-29.4	-17.9	-4.2	5.9	7.5	4.6	-1.9	-12.8	-27.4	-34.1	-15.2
Precipitation (mm)													
mean rain fall	-	-	-	-	4.0	32.1	22.1	37.3	10.8	1.9	-	-	108.2
mean snow fall	9.1	8.5	4.0	6.2	4.9	TR	TR	1.0	13.5	24.1	19.6	12.9	103.8
mean total	9.1	8.5	4.0	6.2	8.9	32.1	22.1	38.3	24.3	26.0	19.6	12.9	212.0
<b>(B) Klondike River Camp</b>													
64°27'N, 138°13'W (elevation 960 m)													
Temperature (0°C)													
mean daily	-24.0	-17.5	-15.3	-5.9	2.4	9.2	11.5	10.0	2.6	-6.4	-16.0	-20.0	-6.0
Precipitation (mm)													
mean daily	26.8	38.2	37.8	37.3	20.4	40.0	55.5	63.1	42.3	45.1	37.6	39.0	483.1
<b>Ogilvie River Camp</b>													
65°22'N, 138°18'W (elevation 579 m)													
Temperature (0°C)													
mean daily	-30.7	-27.9	-24.1	-9.7	2.9	10.9	13.3	10.9	3.6	-11.2	-22.0	-28.5	-9.5
Precipitation (mm)													
mean daily	19.3	12.8	12.3	17.6	20.1	48.1	48.9	49.9	35.1	31.7	20.8	20.1	336.7

-30°C, and precipitation is low.

Both Dawson City airport and Old Crow meteorological stations are located in low-lying areas subject to extreme temperature inversions, resulting from katabatic conditions during the cold winter months. Temperature differences of 5 to 10°C between valley floor and upland locations have been reported at a number of sites in the Ogilvie Mountains and Eagle Plain (personal communication, A. Williams, July 1979). The North Fork Pass, at 1,290 m a.s.l., must be regarded as an upland site in which katabatic effects are frequent.

#### 2.2.4 Permafrost

Although mapped by Brown (1978) as transitional from discontinuous to continuous permafrost, very little is known about permafrost conditions for this part of the Yukon. Some of the earliest permafrost observations in the Yukon were made by miners and geologists at the time of the Klondike gold rush (e.g., McConnell, 1905; Ogilvie, 1913; Perret, 1912; Rickard, 1909). Brown's 1978 permafrost map incorporates data from only four boreholes for all of the Yukon, of which only one is located in the northern Yukon. The division between the continuous and discontinuous permafrost zones is based on the -5°C mean annual isotherm, which for the Yukon is derived from a minimum of data.

At Dawson City, permafrost is reported to depths of up to 60 m (Brown, 1967; 1970; 1978; E.B.A. Engineering Ltd., 1977; Naldrett, 1982), while limited borehole data

from the Eagle Plain suggest that permafrost is nearly continuous and may occur to depths of up to 90 to 100 m (Brown, 1970; 1978; Crampton, 1979; Johnston, 1980a; b; Judge, 1973; Taylor and Judge, 1974).

Permafrost occurrence south of the North Fork Pass area is probably similar to the discontinuous conditions known to exist in the immediate vicinity of Dawson City; however, the higher elevations in the North Fork Pass area introduce a stronger cordilleran influence. Klohn Leonoff Consultants Ltd. (1978), under contract to Foothills Pipe Line Ltd., performed shallow drilling and geotechnical analyses at several locations in the North Fork Pass area in conjunction with the Dempster Lateral Pipeline proposal. These investigations showed that permafrost occurs at depths greater than 5 m in poorly drained fluvial valley sediments south of the pass, but is absent in south- and west-facing slopes of the south lobe of the North Fork Pass moraine. North of the pass, ice-rich permafrost occurs almost continuously to depths in excess of 8 m in the fine-grained fluvial and fluvio-glacial sediments. Permafrost is probably absent beneath major drainage channels and lakes throughout the area. Ground temperature measurements in the North Fork Pass area indicate continuous permafrost with temperatures between  $-8^{\circ}\text{C}$  and  $-2^{\circ}\text{C}$  below a 3 m maximum active layer (Harris et al., 1983). However, active layer depths of 60 to 100 cm are common in poorly drained valley floor locations (Ricker, 1968).

Several landforms diagnostic of permafrost conditions occur in the vicinity of the North Fork Pass. These include well developed high-centred ice-wedge polygons, poorly sorted stone circles and stripes, beaded drainage patterns, tussock tundra and pingos (Figures 2.7 and 2.8). Frost boils, solifluction lobes and rock glaciers have been described at higher mountain and interfluvial locations (Hughes, 1969; Ricker, 1968; Vernon and Hughes, 1966).

One of the few areas in the northern interior Yukon where detailed information about permafrost is available is the Eagle River crossing and Eagle Plain area (e.g., French, 1977; 1981; Johnston, 1980a; 1981). At the Eagle River bridge, data extrapolation suggests that permafrost extends to a depth of 90 to 100 m, with a temperature gradient of  $1^{\circ}\text{C}/38\text{ m}$  ( $26\text{ mK/m}$ ).

The seasonal pattern of frost penetration in the Eagle Plain area is illustrated in Figure 2.9. At the Eagle River site, an active layer depth of 60 to 100 cm was observed during August 1981. Elsewhere on the Eagle Plain, active layer depths between 20 to 100 cm have been documented (French, 1977; personal communication, G. H. Johnston, 1981). Numerical simulation of thermal regimes predicts significantly deeper active layers in local bedrock (Pollard, 1980). In all probability, seasonal thaw penetrates to depths ranging between 2.0 and 3.0 m, depending on rock type and slope conditions.

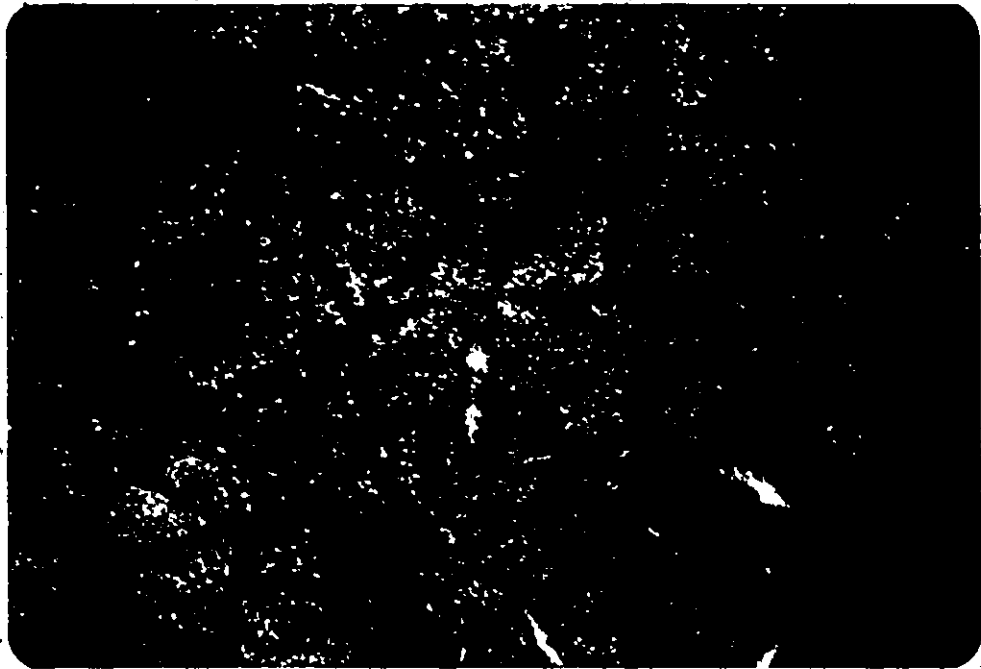


Figure 2.7. Ice-wedge polygons in lowlying valley tundra, North Fork Pass. Photo: July 1979.

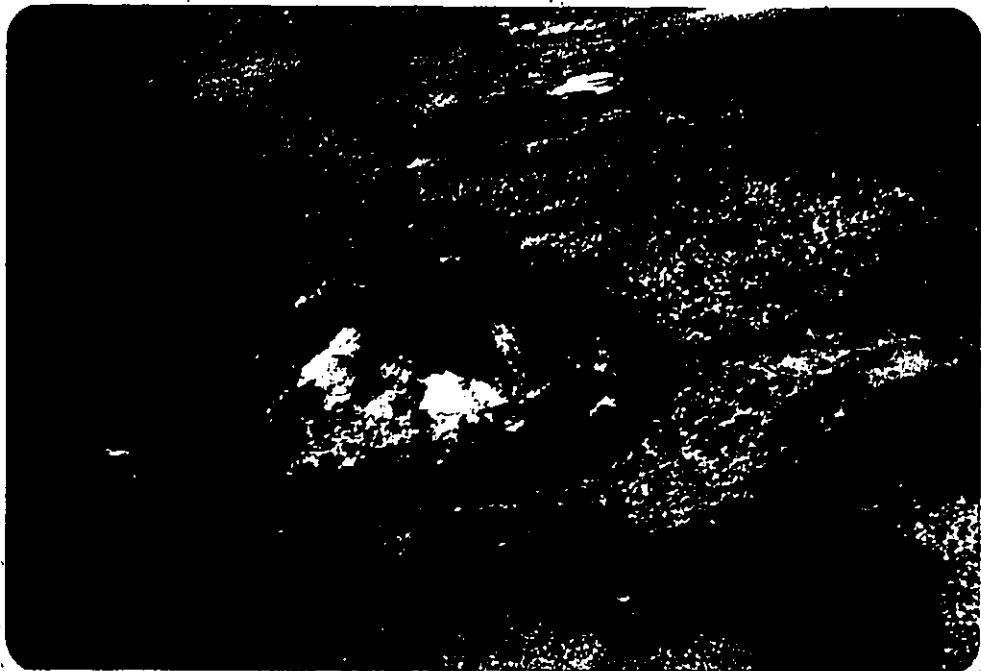


Figure 2.8. Aerial view of a closed system pingo (see Hughes, 1969) located in the main Blackstone valley. Photo: July 1979.

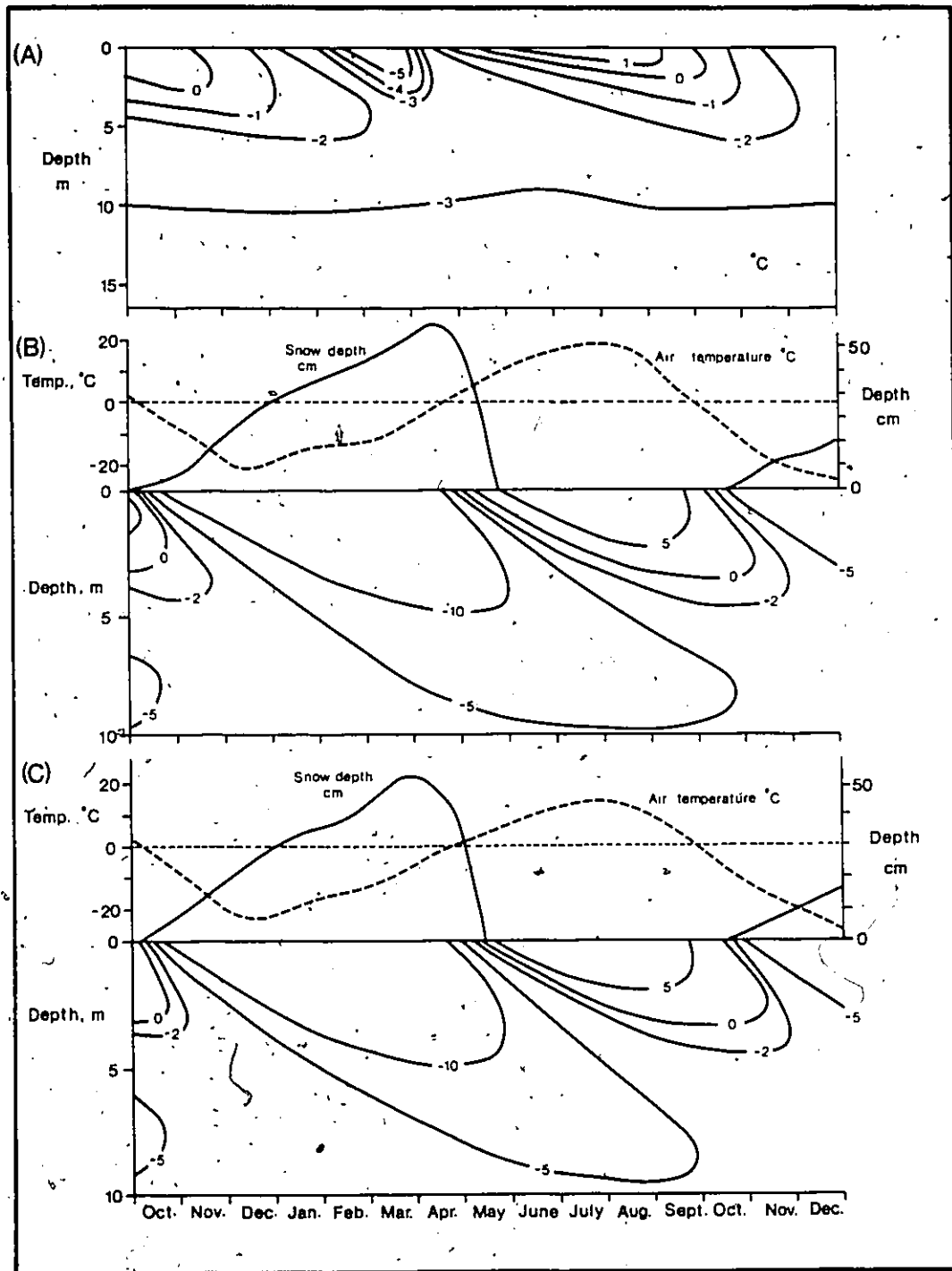


Figure 2.9 Ground thermal regimes in the Eagle Plain area. (A) Fine grained sediments, Eagle River floodplain (Source: G. H. Johnston, 1981, and unpublished data, NRCC), (B) limestone surface, and (C) sandstone surface. Graphs (B) and (C) are predicted, and taken from Pollard (1980, p. 27).

The disruption of permafrost and subsequent melt of ground ice was a problem during construction of the Dempster Highway (Claridge and Mirza, 1981; Harris et al., 1983; Pufahl et al., 1974) and also during the seismic and drilling phases of early oil and gas exploration in the Eagle Plain (Campbell, 1961) in the late 1950s.

### 2.2.5 Vegetation

The flora of the northern Yukon is as diverse and distinctive as the physiographic landscape. Prior to construction of the Dempster Highway, this area was possibly the largest remaining botanically unexplored area in Canada (Porsild, 1974). Since 1959, the extent of floral information has grown steadily (e.g., Cunningham, 1977; Douglas et al., 1981; Lammers, 1979; Pettapiece et al., 1978; Porsild, 1972; 1974; Strang and Johnson, 1981). A field survey by A. E. Porsild and R. T. Porsild in the Southern Ogilvie Mountains, during the period 1966 to 1968, resulted in the recognition of 11 species which were considered new or previously undefined, 6 species believed to be new to the flora of Canada and 38 species new to the flora of the Yukon Territory (Porsild, 1974).

Vegetation analysis does not play a major role in this thesis; however, the recognition of dominant or climax species and plant associations provides a useful tool for the analysis of geomorphic and climatic environments. Vegetation is dependent on climate, soil, moisture and slope characteristics and at the same time is a key factor

(a)



(b)



Figure 2.10 Vegetation assemblages within the northern interior Yukon range from (a) boreal forest in the North Klondike Valley to, (b) alpine tundra in the North Fork Pass area.

influencing snow distribution and ground temperature.

Vegetation within the northern interior Yukon ranges from Boreal forest dominated by Picea sp. in the south (e.g., North Klondike River valley, Figure 2.10a), to sedge tundra and shrub tundra further north (e.g., north of North Fork Pass in the Upper Blackstone valley, Figure 2.10b). The alpine treeline (i.e., timberline) varies between 1,050 m and 1,200 m a.s.l. south of North Fork Pass; north of the pass, forests are not encountered until the southern margin of the Central Ogilvie ranges, north of the Taiga Valley. At this point a Northern Woodland type of spruce forest occurs at elevations generally below the 950 m contour.

Variations in dominant species and plant communities are common between north- and south-facing slopes. On south-facing slopes in the Dawson area, vegetation usually consists of white birch forest (Betula papyrifera) with minor white spruce (Picea glauca) and aspen (Populus tremuloides) and scattered shrub and herb layers. This reflects the warmer and drier conditions on south-facing slopes which, in the Dawson area, are often free of permafrost.

On cool, moist north-facing slopes and valley floors, the typical subarctic vegetation community consists of open black spruce forest (Picea mariana) with a continuous moss-lichen ground cover (Sphagnum sp. and Cladonia sp.). In the Dawson City and North Klondike River areas, permafrost is often very close to the surface (within 50 cm). The North Fork Pass area is between 1,000 m and 1,200 m a.s.l.,

and well above treeline. With the exception of the occasional stunted white spruce in sheltered localities, the vegetation is a shrub tussock tundra dominated by dwarf birch (Betula glandulosa) with mosses in depressions. Interfluvial and exposed areas are characterized by ericaceous shrubs and lichens, typical of alpine tundra.

A series of plant associations have been described at a number of locations along the Dempster Highway (e.g., Pettapiece et al., 1978). In the North Klondike River valley, the Subarctic black spruce forest/moss association is most common, particularly in poorly drained valley bottom areas. Common plant species in this association include Picea mariana, Betula glandulosa, Sphagnum fuscum and Eriophorum vaginatum. Of local significance are peat plateaus and fen areas. In better drained valleys and on south-facing slopes, the boreal forest associations are dominated by aspen (Populus tremuloides), white birch (Betula papyrifera) and white spruce (Picea glauca). In the North Fork Pass area, the dominant plant community is Arctic-Alpine Tundra, characterized by dwarf shrubs, mosses, sedges and lichens (e.g., Betula glandulosa, Ledum palustre, Cladonia alpestris and Alectoria sp.).

CHAPTER THREE

METHODS OF APPROACH

### 3.1 Introduction

Research methodologies used in this thesis may be divided into two components. The first was the collection of field data on the physical characteristics of seasonal frost mounds and the factors that influence their occurrence. The second was the laboratory analysis of samples obtained from the field.

Several periods of fieldwork ranging between 10 and 35 days in duration were carried out between 1980 and 1982. Both summer and winter visits were made to document the complete range of seasonal frost mound phenomena. Summer fieldwork focussed on the morphological and stratigraphic aspects of frost mound occurrence. Winter fieldwork, undertaken in December 1981 and March 1982, was concerned with the hydrologic processes responsible for frost mound formation, the measurement of winter ground thermal regimes and the areal extent and thickness of icings and snow cover. Instrumentation was installed to measure the hydraulic pressures associated with the growth of mounds.

Laboratory investigations concentrated upon the analysis of ice petrofabrics, water and ice chemistry, and environmental isotope concentration.

### 3.2 Field observations

#### 3.2.1 Physical character

A primary aspect of the field program concerned the measurement of frost mound form and character. This included analysis of their setting, morphology and structure as well as their distribution. These observations provide valuable information necessary to: (a) evaluate theories of seasonal frost mound formation, and (b) distinguish them from other types of frost mound phenomena (see Chapter One).

Frost mounds are dynamic features, and since they develop over periods of days and/or months during the winter, their growth is particularly difficult to measure. Changes in their nature, shape and size over time were determined by repeated observation and measurement, primarily using surveying and photographic techniques. Investigation was at two scales. First, a meso-scale investigation concerned their distribution and occurrence in the study area as well as the general character of the surrounding terrain. Second, a micro-scale investigation involved measurement of individual frost mound size, shape and location.

The distribution of seasonal frost mounds was mapped on air photos at scales of 1:20,000 and 1:4,000. A regional map of frost mound locations in the North Fork Pass area was produced at a scale of 1:50,000 using N.T.S. Map 116 B/9 as a base.

Morphological studies were conducted by surveying the shape, height, long and short-axis profiles of more than 30 frost blisters and several icing blisters and icing mounds. Sequential surveys documented short-term changes caused by either growth or thaw degradation and long-term changes (from one year to the next) resulting from mound reactivation.

Conventional optical surveying techniques were used. Study area bench mark elevations were surveyed from geodetic survey bench marks in the North Fork Pass area. A "Wild NK2" level and a 7 m metric stadia rod were used for all surveyed measurements. A supporting tripod was also used to hold the stadia rod. Levelling accuracy is estimated to range between  $\pm 0.01$  m and  $\pm 0.1$  m depending on location and terrain conditions.

Detailed stratigraphic investigations documented the internal structural characteristics of the mounds. Two approaches were utilized: (a) the excavation of frost blisters along tension cracks using a chainsaw and an ice axe, and (b) the coring of seasonal frost mounds at several locations along a transect and in areas adjacent to it. A gas-driven coring unit (e.g., Hughes and Terasmae, 1963) was used to penetrate ice and fine-grained frozen soils to depths of 2 to 3 m (Figure 3.1). Two drilling/coring units were employed on different occasions; a "Stihl" Model 4308 drill equipped with a modified CRREL core barrel (17" - 43 cm) was used in September 1980, and a "SIPRE" ice corer with a CRREL core barrel was used in

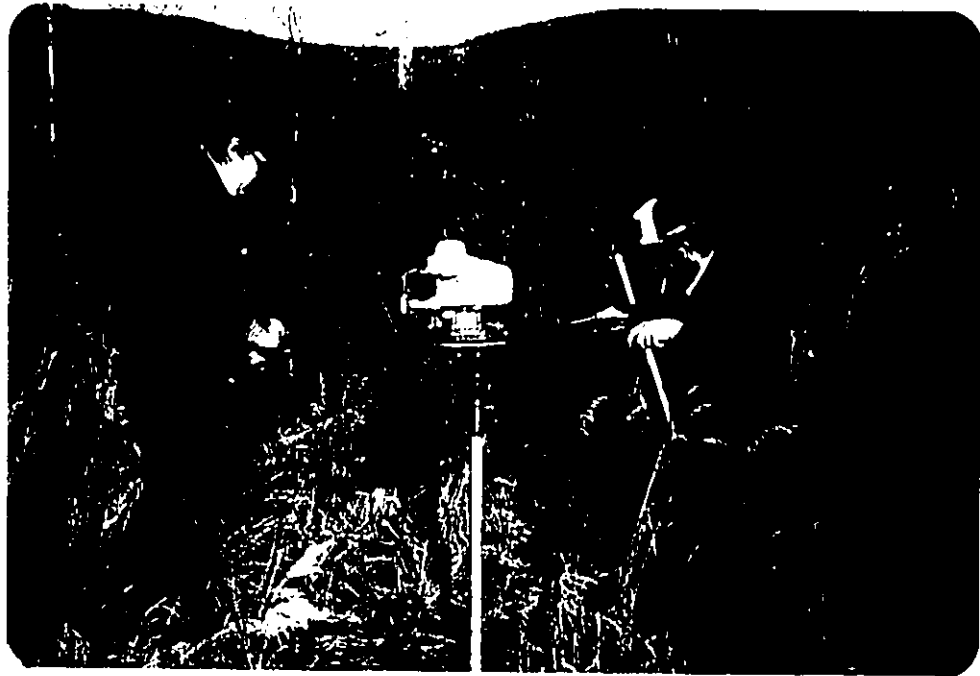


Figure 3.1 A gas driven coring unit was used for stratigraphic investigations of seasonal frost mounds and frozen ground. Photo: September 1980.

August/September 1981.

The first method was used only where adequate thaw degradation or collapse allowed easy excavation, and was the technique used to obtain oriented ice block samples for petrofabric analysis. The drilling method was much faster and facilitated the installation of bench marks, thermistor cables and piezometers. Other stratigraphic investigations included the examination of permafrost sections exposed along river banks, borrow pits and road cuts, as well as the excavation of soil pits and shallow coring to provide information on surficial geology and ground ice.

In a series of measured sections, detailed stratigraphic sequences were recorded and samples were taken for grain-size and ice content analyses. These observations provided information concerning the suitability of various materials as groundwater aquifers. Sections were described in terms of grain-size and texture (after Folk, 1966; 1968), colour (Munsell soil colour classification) and ground ice (Pihlainen and Johnston, 1963).

### 3.2.2 Measurement of thermal regimes

A program of thermal monitoring was conducted to determine active layer conditions (e.g., thaw depth, surface temperature, thermal profile for different times of the year). Since seasonal frost mounds are primarily active layer phenomena, their occurrence may be influenced by depth and spatial variations of thaw, the locations of residual thaw zones and the time and rate of active layer freeze-back.

The duration of a seasonal frost mound also depends on the rate and depth of thaw. In the case of a mound lasting two to three years, its presence temporarily modifies active layer development by creating an upward bulge in the frost table. The combined effect of active layer hydrologic and temperature conditions, plus their interaction during freeze-back and thaw are important factors influencing the location, size, time of formation, rate of growth and duration of seasonal frost mounds.

Ground temperature measurements were made in two ways. A "YSI" Model 42 SC telethermometer was used to measure ground temperature profiles to depths of nearly 100 cm. Ground temperatures were profiled at a number of locations displaying variable surficial materials and vegetation cover. During winter, the telethermometer was used to obtain temperature profiles within snow banks and to probe unfrozen ground near spring outlets. A series 400, T2625, "Banjo" surface temperature thermistor probe attachment was used to obtain water temperatures and surface temperatures.

The second method of ground temperature measurement utilized multi-thermistor cables. In 1981, cables were installed to depths of up to 2.0 m at five locations at site 1 (see Figure 6.1) in the North Fork Pass. The cable was attached to wooden doweling to keep it straight in the hole and a PVC collar was placed over the cable to protect it from foxes and porcupines.

### 3.2.3 Background hydrology

Since seasonal frost mounds result from the interaction between seasonal freezing of the active layer and suprapermafrost groundwater circulation, hydrologic investigations complement ground thermal studies. These were designed to document the characteristics of the groundwater system.

Hydrologic investigations were designed to establish general summer groundwater flow conditions in the active layer and base flow conditions from perennial springs. All spring outlet locations in the vicinity of frost mound locations were mapped together with surface flow paths. During the winter and early spring, icing and major snow bank locations were surveyed and mapped.

Approximate spring discharge values were obtained by measuring flow through culverts using a 10 litre drum and the average of ten, timed discharge runs. Spot measurements of surface flow velocities were also recorded using small styrofoam balls which were introduced into the surface flow system and photographed using a tripod and fixed shutter speeds (1/20, 1/50 second). As the target passed through a clearly defined test section corresponding to the frame of the camera, a picture was taken. The distance travelled by the target was measured using the scale included in the test section; the resulting velocity was a multiple of the exposure time. Data obtained from these tests provide a relative indication of surface flow velocities and seasonal

variations in surface discharge.

Icing volumes were calculated using winter drill and survey data. Their calculation was used to produce a minimum estimate of discharge during icing formation of a particular spring group.

#### 3.2.4 Hydraulic potentials

A piezometer apparatus was developed to measure the hydraulic potential of the water inside an active seasonal frost mound. A previous study using time lapse photography (van Everdingen and Banner, 1979) indicated that mound growth could occur at any time between January and April. However, no measurements of hydraulic potential have been reported in the literature.

Other studies which have measured pressures in freezing ground and frost hummocks (e.g., Mackay, 1980; Mackay and Mackay, 1976; Slusarchuk et al., 1973) or hydrostatic pressures in a subpingo water lens (Mackay, 1978a; 1979) used electrical pressure cells and pressure transducers. Neither of these were suitable for the present study. Slusarchuk et al. (1973) developed an instrument which consisted of a pneumatic piezometer enclosed in a protective housing and immersed in ethylene glycol. However, the complicated construction and installation procedures together with prohibitive costs precluded its use.

The apparatus used in the present study consisted of a closed hydraulic system piezometer containing an anti-freeze fluid. The main body, or the standpipe, consisted

of 0.93 cm diameter schedule 80 polyvinyl chloride (PVC) pipe fitted with a "Weiss" bronze bellows and a brass socket pressure gauge (Figure 3.2). A T-joint was used to avoid trapping gas bubbles in the pressure gauge and to facilitate filling. Dow Corning 200 Fluid, a silicone oil with 1 centistoke viscosity (near that of water) and a freezing point well below  $-40^{\circ}\text{C}$  was used as the antifreeze. The silicone fluid was retained in the piezometer by two methods (see Figures 3.3 and 3.4): (a) a brass "Nupro" checkvalve with a 1/3 psi (2.3 kPa) cracking pressure and swaglock fittings; (b) a rubber condom (surgical rubber and a latex rubber) of 0.93 cm diameter was loosely inserted into the lower end of the standpipe and sealed with a nylon wrap and self-vulcanizing rubber tape. Only the latter is a true closed system unit. The length of the pipe ranged from 120 cm to 200 cm. A CRREL ice thickness kit with a 3.8 cm (1½") auger bit was used to puncture the frost mound; afterward the piezometer was installed. A 40 cm "Rubatex" foam collar, 3.8 cm (1½") in diameter, was tightly fitted to each unit with a hose clamp to effectively seal the hole once the instrument was installed. Pressure from inside the mound expanded the lower end of the collar, effectively creating a plug until frozen in place. The lower end of the piezometer was fitted with a protective extension, 15 to 20 cm long, consisting of perforated PVC pipe designed to elevate the sensor above the floor of the frost mound chamber (see Chapter Four).



Figure 3.2 Piezometer pressure gauge assemblage.

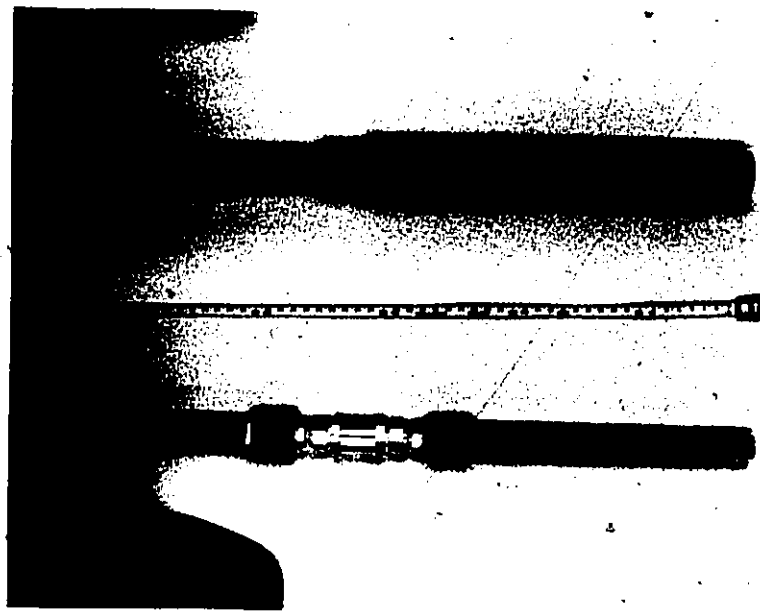


Figure 3.4 (A brass check valve (left) with a 2.3 kPa cracking pressure was tested and perforated PVC extension tubes (left and right) provided protection of the lower end of the piezometer.



Figure 3.3 The lower end of the piezometer standpipe possessed a flexible rubber condom as a sensory membrane, separating the silicone oil from the groundwater.

The requirements of the desired apparatus were twofold: the unit had to (a) measure groundwater pressure potentials analogous to the artesian pressures of a shallow confined aquifer, and (b) operate under cold subarctic conditions and withstand temperatures of at least  $-30^{\circ}\text{C}$ . A further limitation was cost, so not only did the instrument have to be sturdy and versatile, but also it had to be inexpensive. Finally, the transient and unpredictable nature of seasonal frost mound occurrence favoured an instrument which could be installed directly into the frost mound and read instantaneously.

Under noncryotic conditions, a conventional piezometer would have readily fulfilled these needs. However, in frozen ground the water would rapidly freeze in the piezometer standpipe. Reference to an antifreeze-filled piezometer in Slusarchuk et al. (1973, p. 232), although it did not describe the device, provided the idea for the unit developed.

### 3.3 Laboratory procedures

#### 3.3.1 Ice petrofabric determinations

The aim of ice petrofabric analysis in this study was to develop a better understanding of the range in freezing conditions and the mechanics of seasonal frost mound growth. Ice petrofabric analysis is a technique which utilizes the optical properties of ice and a universal stage to determine crystal size, shape, lattice and dimensional orientation. These characteristics are influenced by a

number of variables which include: (a) the nature of the water supply to the freezing front (e.g., open or closed system), (b) the direction and rate of freezing as a function of ground thermal conditions, and (c) patterns and mechanisms of solute rejection and inclusion incorporation.

Post-freezing stresses, generated by high hydraulic potential and cryostatic pressure, may result in recrystallization, ice deformation and faulting, or dilation cracking. Evidence of these stresses are visible during ice fabric analysis in the form of strain shadows, grain boundary irregularities and dislocations. Large scale deformations (e.g., fractures, faults and heaved ice layers) are distinguishable in the ice sections and block samples.

By studying variations in ice fabric characteristics in a mound, a generalized freezing history and post-freezing deformation sequence can be developed.

Petrofabric analysis was performed on thin sections cut from oriented block samples taken from three frost blisters and a surface icing, all of which formed in the North Fork Pass area during the winter of 1981-1982. A total of seven block samples, approximately 20 cm square, and up to 40 cm long, were obtained on two occasions (September 1981 and March 1982) and shipped to Ottawa packed in freezer chests specially designed for ice transport. The block samples effectively represent a complete vertical section through the core of each frost blister. Ice samples were wrapped in foil and sealed in freezer bags at the site.

Care was taken to avoid exposure to direct sunlight.

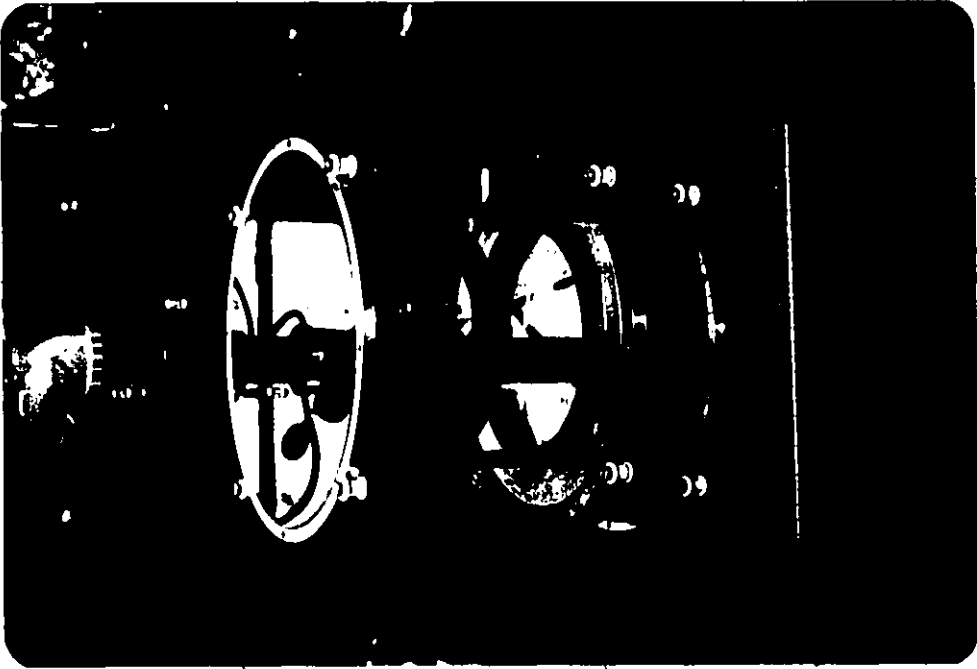
In Ottawa, the ice samples were stored at temperatures of  $< -20^{\circ}\text{C}$  in deepfreeze facilities. A number of thick section photographs taken before and after storage showed minimal losses to sublimation and no recognizable structural changes: It is assumed that stored samples were reasonably representative of field conditions.

Two methods of thin section preparation were available. In the case of clear, fine crystalline ice, a microtome (described in Langway, 1958) provided good results. For coarse crystalline ice, however, it was necessary to first cut a thick section with a bandsaw. The section was then frozen to a slide and reduced to the desired thickness using either sand and emery paper or a hotplate. Both are standard procedures described in the literature (e.g., Gell, 1976; Langway, 1958).

A universal stage (Rigsby, 1951) and cold room facilities are the main requirements for ice fabric studies; a camera with a close-up lens mounted on a polariscope (Figure 3.5a) provided a record of observations. A universal stage (Figure 3.5b) is an instrument used for orienting crystals or crystal sections so that the position of the optic axis may be measured.

Standard universal stage techniques (for details see Bader, 1951 and Langway, 1958) were used to determine ice crystal orientation. Ice crystal c-axes were measured and, where possible, at least 25 to 30 values were obtained

(b)



(a)

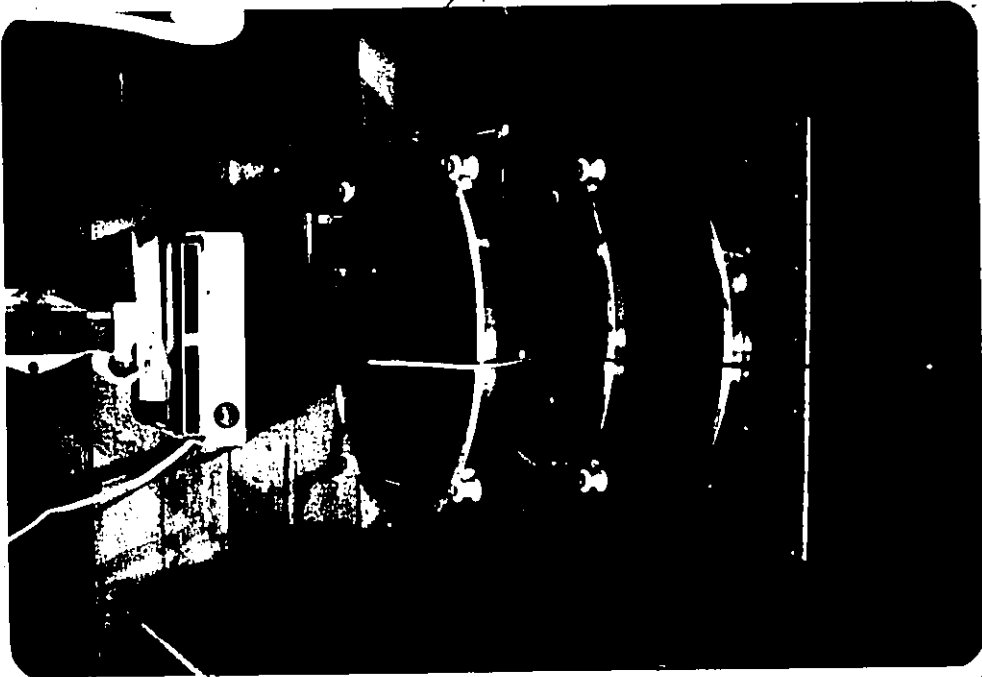


Figure 3.5 (a) Thin section photographs were taken using a Leitz camera with polaroid film mounted on a polariscope. (b) Ice fabric determinations were performed using a universal stage (4 axes).

and plotted on an equal area lower hemispheric Schmidt projection. Most of the patterns show a high degree of preferred crystal orientation and contouring was not necessary; to emphasize fabric variation, Kambs' (1959) method of contouring proved useful.

Ice petrofabrics are frequently studied. Early investigations (Black, 1953; 1963; Shumskii, 1964a; b) identified basic ice textures and crystal characteristics of wedge ice, segregation ice and injection ice. Black (1953; 1963) studied wedge ice almost exclusively, while Shumskii (1964a) analyzed textures and petrofabrics of three ground ice types: congelation ice (including wedge ice), segregation ice and injection ice. Shumskii's discussion of injection ice was most useful to this study; in it he defined injection ice as the product of the freezing of water which had been intruded under pressure between impermeable frozen layers of ground. Its formation is distinguished from that of segregation ice in that it results from the freezing of free groundwater which has migrated under pressure, with subsequent displacement of earth materials attributed to hydraulic pressure rather than to the growth of ice crystals. It is usually pure and transparent with gas inclusions of variable size and shape, and the texture is characterized by vertical prismatic granular crystals.

Corte (1962) performed petrofabric analysis on four ground ice types, namely, wedge ice, relict ice,

ice masses and lens ice, from the Thule area of Greenland. He concluded that fabric analysis provided a criterion by which specific types of ground ice could be distinguished. For example, "wedge ice" was found to have fine cracks along the wedge axis filled with very small horizontally oriented crystals. Further from the crack, crystals were larger, elongated and oriented with their c-axes and axes of elongation dipping steeply toward the axial plain of the wedge. "Relict ice" contained crystals that were generally smaller in size and oriented and elongated vertically. The strongest concentration of c-axes in "relict ice" was found in a zone of contact with an ice wedge. "Lens ice" and "ice masses" similarly exhibited a distinct pattern of crystal size, shape and orientation. Although the terminology used by Corte (1962) and others is at times confusing, it demonstrates that different types of ice develop fairly distinct petrofabric characteristics.

Other studies (e.g., Mackay, 1972b; Mackay and Stager, 1966a; b; Müller, 1963; Vtyurina and Vtyurin, 1970) have employed petrofabric studies as a means of analyzing ground ice. The work by Gell (1975; 1976; 1978) is the most applicable to the present study since one aspect focussed on the petrofabric analyses of pingo and icing mound ice. Gell observed a wide range of crystal and gas inclusion characteristics, ranging from a chill zone characterized by small crystals to areas immediately below, where crystals became more elongated. Crystal shape was also observed to vary with depth.

### 3.3.2 Water chemistry and isotope analyses

Water samples from springs in the North Fork Pass were obtained for hydrochemical and environmental isotope analyses. Ice from the surface icing and frost blisters was also collected, along with a snow sample, for similar analysis. One-litre water samples were collected for major ion analysis.

In September 1980, 126 ml water samples were collected for isotope analysis, while peat and ice samples were taken from a frost blister using a Stihl model 4308 drill equipped with a modified CRREL core barrel (7.5 cm diameter). The core was cut into 4 cm sections and sealed in heavy-duty plastic bags. The analyses for oxygen ( $^{18}\text{O}$ ), deuterium ( $^2\text{H}$ ) and tritium ( $^3\text{H}$ ) isotope content were performed using mass spectroscopy and liquid scintillation techniques in the isotope laboratory at the University of Waterloo. The analytical error for  $^{18}\text{O}$  and  $^2\text{H}$  determinations is less than  $\pm 0.1\%$ . Deuterium and oxygen isotope abundances are expressed as per mille deviation from Standard Mean Ocean Water (e.g.,  $\delta^{18}\text{O}\text{‰SMOW}$ ). Tritium content, which was analyzed by direct liquid scintillation counting, has potentially a large measurement error depending upon the counting times. Since the sample is small, enrichment was not possible and therefore the error is always stated with the tritium value, which is expressed in tritium units (e.g.,  $\text{ITU} = 10^{-18} \text{ } ^3\text{H}/^1\text{H}$ ).

Field measurements of pH, conductivity and temperature were taken regularly from spring outlets, surface water and groundwater discharge at the North Fork Pass study sites.

A portable "Harris" Model B5160, accurate to  $\pm 0.5$  pH units was used to measure pH. The unit was calibrated with a neutral buffer solution prior to use in the field. Due to the cold temperature of the water sampled, a temperature correction factor was employed. Field pH measurements minimize inaccuracies resulting from escaped  $\text{CO}_2$  from groundwater when it is exposed to the atmosphere. Carbon dioxide in groundwater normally occurs at much higher partial pressures than in the earth's atmosphere. When groundwater is exposed to the atmosphere,  $\text{CO}_2$  will escape and pH will rise (Freeze and Cherry, 1979).

Electrical conductance, which indicates dissolved solids, was measured using a "Chemtrix" type 70 conductivity meter equipped with an automatic temperature compensation. This unit measures conductivity in microsiemens per centimetre ( $\mu\text{s}/\text{cm}$ ), which were compensated to  $25^\circ\text{C}$ . To convert specific conductance to total dissolved solids, the following relation is used:

$$\text{TDS} = A \times C$$

(after Hem, 1970), where TDS is total dissolved solids (mg/l), C is conductivity (micromhos or microsiemens/cm) and A is a conversion factor. For groundwater, A is usually between

0.55 and 0.75, depending on the ionic composition. A value of 0.65 is frequently used (Rainwater and Thatcher, 1960). Error in the instrument is less than 1 percent full scale deflection, which, for the range encountered, is  $\pm 1 \mu\text{Scm}^{-1}$ .

The application of groundwater chemistry and isotope analysis to this study has a twofold purpose: (a) to develop a hydrologic and geologic history of groundwater discharging from perennial springs feeding seasonal frost mounds and icing development, and to determine that the water forming the seasonal frost mounds is actually derived from these spring sources; (b) to develop the freezing history of a seasonal frost mound based on negative isotopic shifts resulting from fractionation.

Geochemical and isotopic analyses of groundwater and ground ice have been employed by a number of researchers as a method of interpreting the hydrologic system in areas of permafrost (e.g., Michel and Fritz, 1982; Schreier, 1979). The variable chemical properties of sub-, intra- and supra-permafrost groundwater and the reasons for the variation have been discussed by Tolstikhin and Tolstikhin (1974), who also discuss the variation of suprapermafrost groundwater composition with altitude. A detailed discussion of groundwater in permafrost areas of Canada by van Everdingen (1974) describes the influence of permafrost on groundwater chemistry and flow characteristics. Another study (van Everdingen, 1981) used hydrogeochemistry and isotope analysis to trace flow systems in karst water systems near Great Bear Lake.

The role of permafrost in directly imparting a particular type of mineralization to groundwater is probably minor. However, permafrost may reduce the rate of groundwater movement or confine groundwater such that a longer residence or storage time may occur, during which reactions may take place between groundwater and the enclosing earth materials (Williams and van Everdingen, 1973). Permafrost may retard chemical reactions by low temperature conditions; however, under these conditions, saturation concentrations for calcium, magnesium bicarbonate and gypsum (anhydrite) are higher.

Mackay and Lavkulich (1974) describe the change in chemistry and oxygen isotope concentrations in pingo ice in the Tuktoyaktuk peninsula. The variation is explained by the occurrence of ionic rejection and oxygen isotope fractionation during freezing. They also suggest that electrical conductivity and ionic concentration of subpermafrost water is an order of magnitude higher than surface pond water systems. In another study (Allen et al., 1976), the chemical properties of an open system pingo in Greenland were found to be similar to those of nearby meteoric waters. In a study at Bear Rock, N.W.T., groundwater geochemistry and sulphur isotope analysis were used to trace the groundwater system feeding a series of frost blisters (van Everdingen, 1978; 1982). It was concluded that differences between the ionic concentration of spring water and of ice from the frost blister core were the result of exclusion during freezing.

CHAPTER FOUR

DISTRIBUTION, SETTING AND MORPHOLOGY

#### 4.1 Introduction

In this chapter, the physical character of seasonal frost mounds in the North Fork Pass area is addressed. Of particular interest are the distribution, setting, morphology and duration of the mounds. Since most are constantly undergoing change either by growth or degradation, and since new mounds form each year in approximately the same areas, such a discussion is essential to the analysis of growth mechanisms.

During the period 1980 to 1982, more than 65 seasonal frost mounds were observed at 7 sites in the floodplain of the East Blackstone River near the North Fork Pass. They were in various stages of growth and disintegration. Frost blisters were the most common of the three types of seasonal frost mounds and comprised 80% of the mounds which were observed.

Variation in form can be attributed to both growth characteristics and degree of degradation. For example, the maximum dimensions of both mounds and associated icing phenomena are usually observed during the winter and early spring. During May 1981 and March 1982, it was possible to document the morphology not only of icing mounds and icing blisters but also frost blisters. The former are short-lived and disappear as the icing ablates. Icing

accumulations range from a few centimetres to 1.4 m in thickness, often covering or obscuring smaller frost blisters. Seasonal frost mounds occur most frequently in areas of perennial spring discharge which are also the source for water forming icing accumulations. Sometimes, icing blisters complete a full cycle of growth and collapse within three to four months of their formation, thereby totally disappearing by early summer.

Summer field observations focussed upon the size, shape and structural characteristics of frost blisters. With few exceptions, the thaw portion of the frost blister cycle is characterized by gradual disintegration and collapse. This often takes as long as three years, thereby modifying the permafrost table and suprapermafrost groundwater circulation. The formation of frost mounds in the following winters may therefore be influenced by the distribution of previous frost blisters.

Frost mounds that are heavily fissured by dilation cracks thaw more rapidly than mounds where the integrity of the surface materials is maintained. In some cases, frost blisters disappeared totally by August or September of the year in which they formed; however, in at least one instance, a mound was observed intact during three consecutive years.

A major problem in the study of seasonal frost mounds is their ephemeral winter occurrence. This, combined with extreme cold, snow accumulation and shortened daylight

hours are probably the main reasons why so little is known about seasonal frost mounds. Random or infrequent visits to a locality may fail to identify their existence. For example, in December 1981, there were no visible indications of frost mound development in the North Fork Pass area. By March 1982 however, a large number of mounds, some exceeding 3.0 m in height, and extensive groundwater icings had occurred at a number of localities. Many of the mounds were visibly active while others were not.

#### 4.2 Distribution and setting

During reconnaissance investigations in September 1980, three areas of frost mound activity were identified on the east side of the East Blackstone River floodplain (Figure 4.1, sites 1, 2 and 3). Although spaced 500 to 700 m apart, each site is fed by a separate group of perennial springs. For example, several frost mounds formed at site 1 during each year of observation, while at site 2 frost mounds were observed only once, after the 1979-1980 winter. Sites 1 and 2 have been identified earlier (e.g., Hughes et al., 1972; Hughes and van Everdingen, 1978). Both are relatively close to the road allowing easy access. A third site was identified 500 m south of site 2 in a similar spring-discharge geomorphic setting. In May 1981, a fourth group of seasonal frost mounds was observed on the east side of the valley approximately 300 m southeast of site 3 (see Figure 4.1). At both sites 3 and 4, the mounds occur near

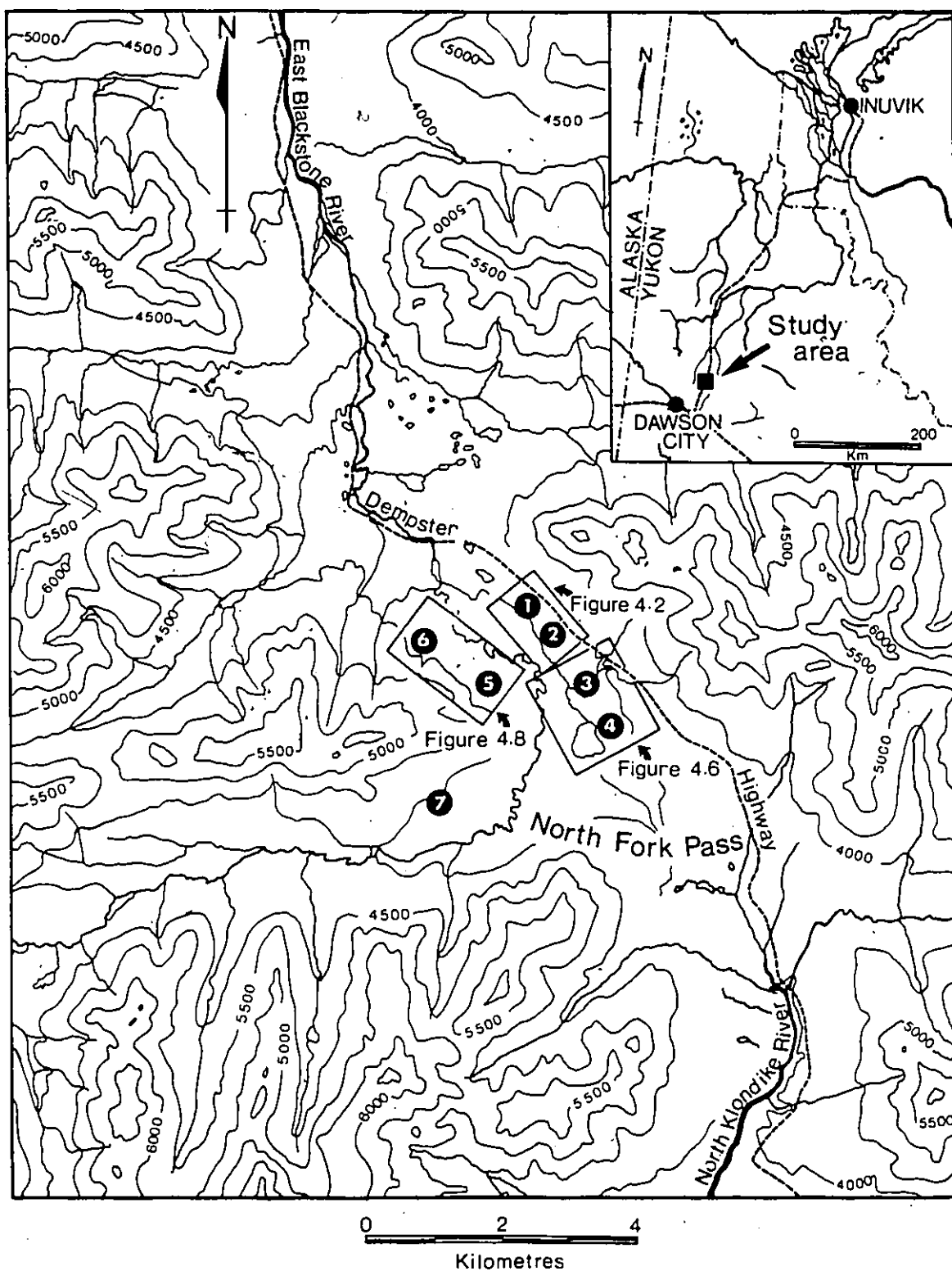


Figure 4.1. Location map of study sites, main drainage channels and spring outlets. The approximate limits of Figures 4.2, 4.6 and 4.8 are indicated. Source: N.T.S. Map 116B/9, 1970.

the base of the steep west-facing slope of the North Fork Pass.

In August 1981, a group of frost blisters occurring on the west side of the floodplain was identified (site 5) and several small and collapsed mounds were observed at another location also on the west side of the valley. During March 1982, the latter was formally identified as site 7 and another group, also located on the west side of the valley, was identified as site 6. Table 4.1 outlines the times at which observations of the various frost mound sites were made.

During winter, icings develop at a number of locations along the East Blackstone River and at several perennial spring locations. Groundwater icings regularly occur at sites 1, 3, 4, 5, 6 and 7. No icing accumulation was documented at site 2. At sites 1, 3 and 6, the icing usually covers the entire frost mound area downslope from the break of slope between the valley side and the floodplain. Further downslope it joins with the icing accumulation of the East Blackstone River. At sites 5 and 7, the icings are sporadic and sometimes associated with discharge from ruptured frost blisters. At site 6, the main spring group is situated well above the valley floor producing an icing that covers the steep slope and fans out over the floodplain. Icings observed in this part of the East Blackstone River valley form between December and April, and melt by late June and July. They are small to medium sized (Tolstikhin

Table 4.1  
 A Chronology of Site Observations in the North Fork pass.

Study Site	Geomorphic Setting	First Documentation	Subsequent Documentation			
			1980 Sept.	1981 May	1981 Aug.	1982 March
1	Base of west-facing slope.	1980 Sept.	*	*	*	*
2	Base of west-facing slope.	1980 Sept.	*	*	*	*
3	Base of west-facing slope.	1980 Sept.	*	*	*	*
4	Base of northwest-facing slope.	1981 May	*	*	*	*
5	Base of east-facing slope.	1981 Aug.	*	*	*	*
6	Base of east-facing slope.	1982 March				*
7	Base of southeast-facing slope.	1981 Aug.			*	*

and Tolstikhin, 1974, p. 15), covering between  $1.10^3$  to  $1.10^5 \text{ m}^2$ . Groundwater icings and related mound phenomena are more common on the east side of the valley where the mountain slopes appear to be hydrologically more active in mid- and late winter.

A characteristic of seasonal frost mounds is their occurrence in poorly drained alpine tundra near the break of slope between the valley side and the floodplain. The occurrence of cold mineralized springs upslope is also fundamental. The break of slope is hydrologically significant because it approximates the intersection point between the water table and the ground surface. The abundance of various discharge phenomena, such as spring outlets, seepage zones and saturated tundra, indicate its importance. The break of slope is geologically significant because it also defines the contact between colluvial materials that form the lower debris slope (e.g., talus, alluvial fan and glacial till deposits), and fluvial materials which form the floodplain. Talus and alluvial fan deposits along with fluvial sediments are generally recognized as the primary aquifers in areas of permafrost (Tolstikhin and Tolstikhin, 1974; Williams and van Everdingen, 1973). It follows, therefore, that these materials provide the most suitable media for groundwater transmission and frost mound occurrence.

Several alluvial fans, with radii of between 500 and 700 m, occur where tributary valleys feed into the main valley. Much of the runoff and snowmelt from high alpine

slopes is channeled into these alluvial fans as illustrated by the large number of spring outlets at the distal edge of the fans and the development of ephemeral stream channels on the fan surface. Upper fan segments have steep slope angles of 15 to 20°, while distal portions possess slopes between 7 to 12°. All seven frost mound sites are located either downslope or along the distal edge of alluvial fan structures.

Permafrost modifies the groundwater hydrology since it forces the intersection point further downslope and/or prevents subpermafrost groundwater from rising to the ground surface even though sufficient hydraulic head may exist.

Other fluctuations in the level of the water table and the location of spring outlets result from precipitation events and snowmelt. Although a number of terrain characteristics are common to all sites, several site-specific factors are responsible for variations in seasonal frost mound morphology. These include slope angle and aspect, surface and subsurface hydrology, surficial geology, microrelief and snow distribution.

The geomorphic and physiographic characteristics of study sites 1 to 6 were mapped at a scale of 1:8,500. The number, location and size of frost mounds (Figures 4.2, 4.6 and 4.9) and the distribution of spring outlets and seepage lines were mapped each-year along with the areal extent of icings.

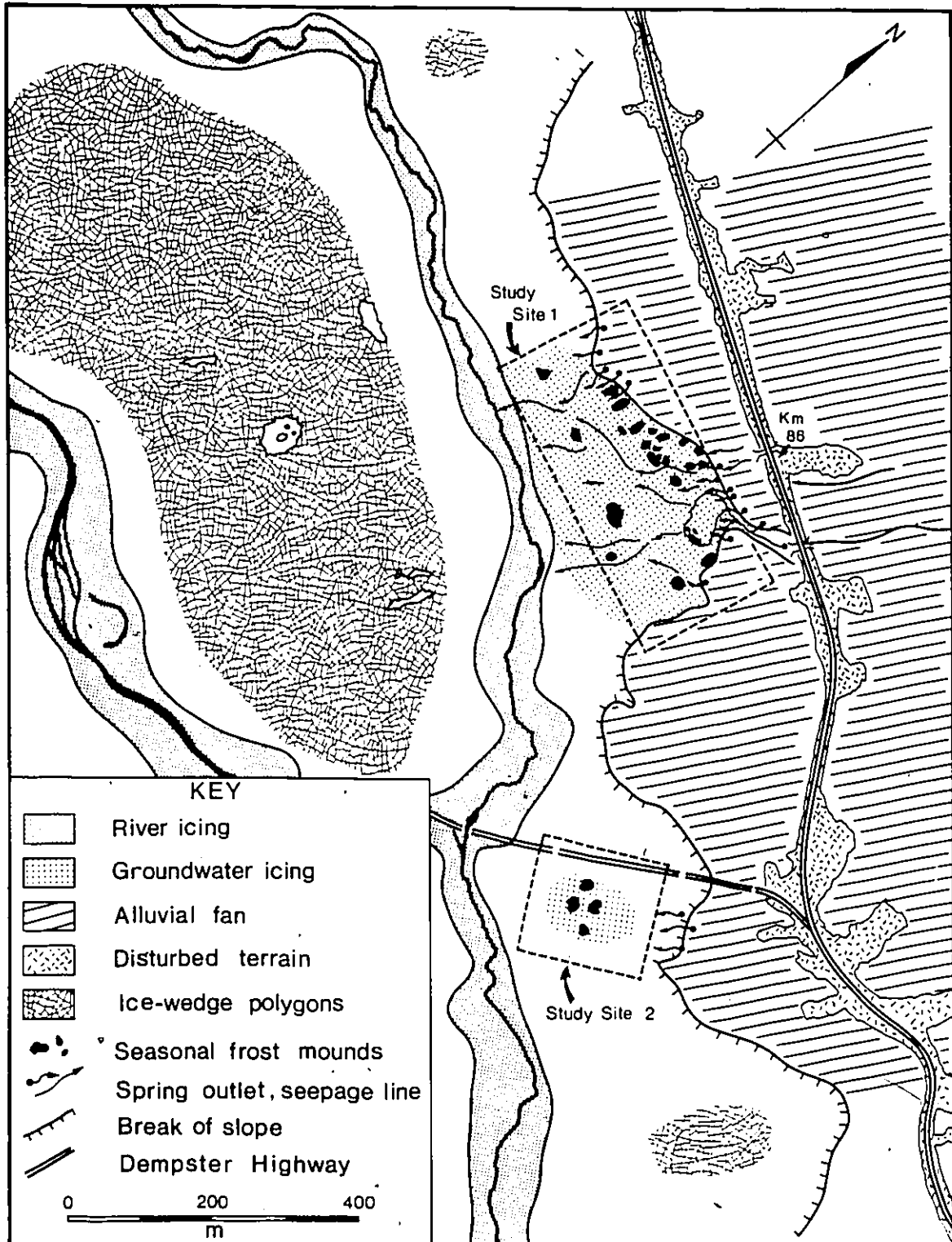


Figure 4.2 Physiographic map of sites 1 and 2, North Fork Pass, near KM 86 of the Dempster Highway. Based on field survey and air photo analysis. Source: National Air Photo Library, A 18137-41, -42.

Although study sites 1 and 2 occur in similar topographic settings (Figure 4.2), they demonstrate a strong contrast in frost mound activity. During the period 1980-1982, 28 frost mounds were observed at site 1, while only 4 occurred at site 2, all in 1980. Site 1 consists of an area approximately 400 m long and 200 m wide. Frost mounds occur in three different settings. First, they form near the break of slope at, or a short distance downslope from, a perennial spring. Some mounds extend into the floodplain. The icing covers the entire area, to a thickness of 1.4 m with the larger frost blisters protruding through the ice (Figure 4.3). Sometimes, smaller mounds are covered completely by the icing. Only a small number of icing mounds and blisters develop in this locality.

A second setting in which seasonal frost mounds occur is associated with a small pond located at the southeast corner of the study site (Figure 4.4). Several frost blisters formed in shallow water or along the pond edge. Mounds forming in this setting are usually small, flat-topped and circular to oval in plan. The third setting is along the downslope perimeter of the groundwater icing.

Site 2 (Figure 4.2) is smaller in area than site 1 and possesses fewer frost mounds. At this site, spring discharge and groundwater seepage are not as evident. Frost blisters only formed in 1979-1980. They were clustered in a saturated, oval-shaped depression approximately 60 m long (Figure 4.5).

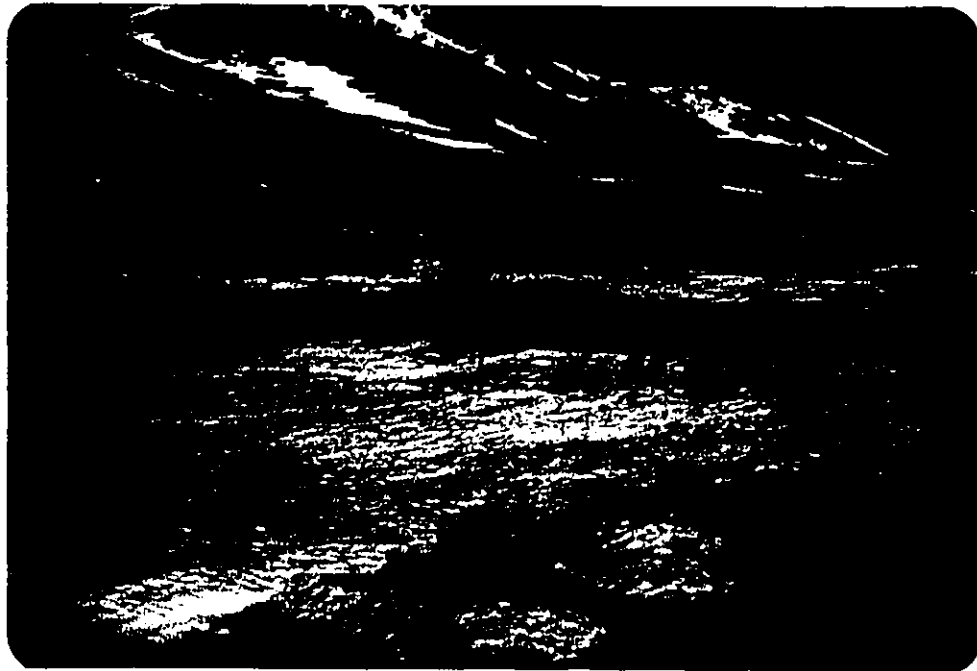


Figure 4.3 Two frost blisters protrude through the icing at site 1 (mounds 1-10 and 1-11). Photo: May 19, 1981.



Figure 4.4 A small tundra pond, located at the southeast corner of site 1, is fed by perennial spring discharge. Two seepage/stream outlets from the pond are marked by arrows. Photo: August 1981.



Figure 4.5 Site 2, as seen from the highway looking west. Only the collapsed remnants of 4 frost blisters are visible (indicated by arrows). Photo: September 28, 1980.

Frost mounds possibly form only during years of either above normal groundwater discharge or unusual freeze-back conditions, or both. Alternatively, the lack of mound activity may reflect modifications to the local groundwater hydrology in response to construction or use of an access road adjacent to the site. The silting-up of culverts passing under the main highway directly upslope may also result in reduced groundwater supply.

Sites 3 and 4 (Figure 4.6) have settings similar to the previous sites. The valley slopes are steeper however, and the alluvial fan is covered by glacial till. At site 3, most mounds occur either in or adjacent to a small pond which is sustained by seasonal runoff from two intermittent streams and continuous spring flow.

In 1979-1980, a group of frost blisters formed along the north edge of the pond in organic-rich silts and sands (Figure 4.7). They closely parallel the side of the pond, suggesting that the pond exerts a strong influence on mound location and shape. A large groundwater icing forms each year at this site, extending from the break of slope and merging with an icing that forms in the nearest tributary of the East Blackstone River. In 1982, a large icing mound formed in part of the icing covering the pond.

At site 4, frost mounds form each year in a hummocky area of gently sloping alpine tundra approximately 20 to 40 m below the break of slope. During summer, discharge from two springs maintains saturated tundra conditions. A group

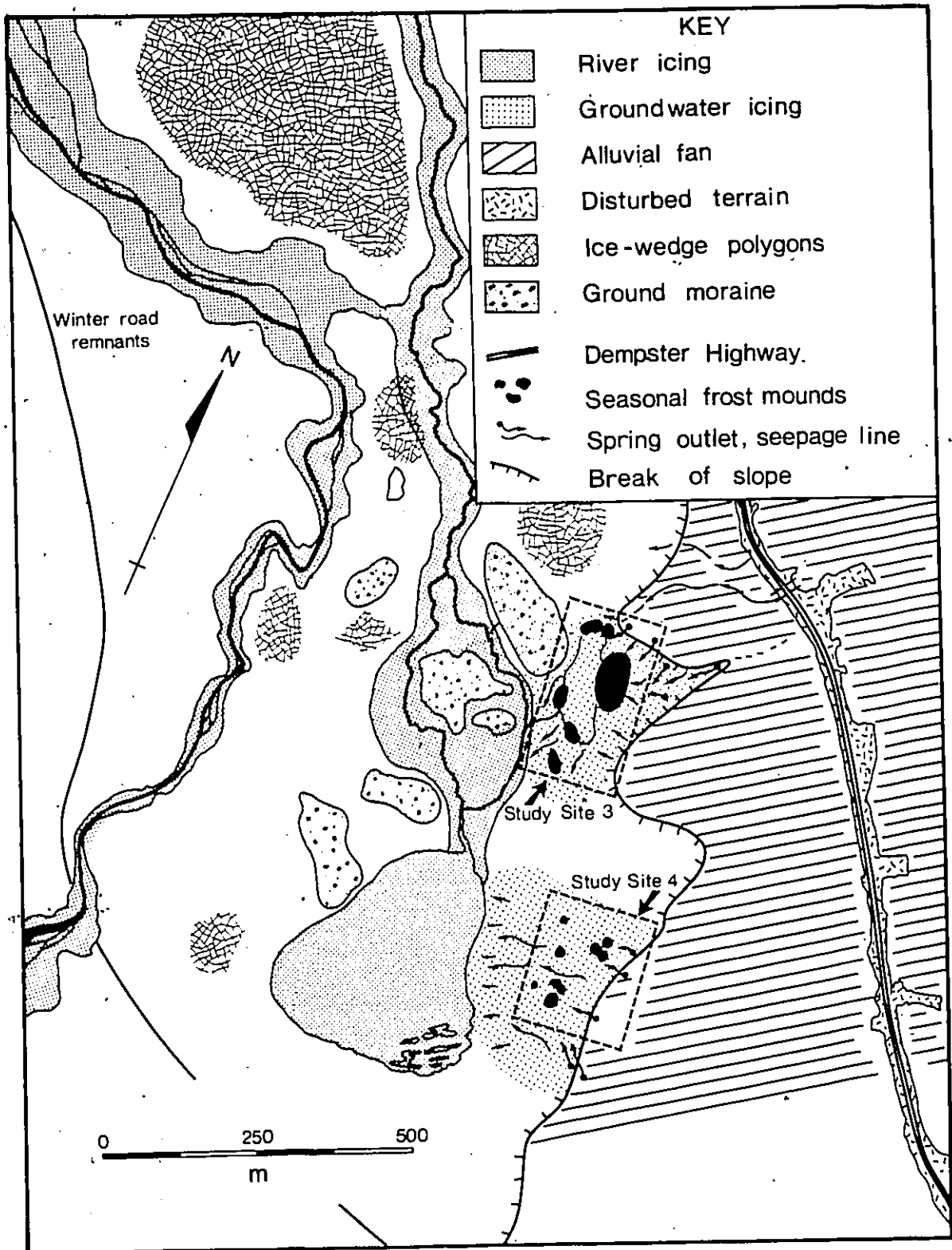


Figure 4.6 Physiographic map of sites 3 and 4, North Fork Pass, based on field survey and air photo analysis. Source: National Air Photo Library, A 18137-40, -41.

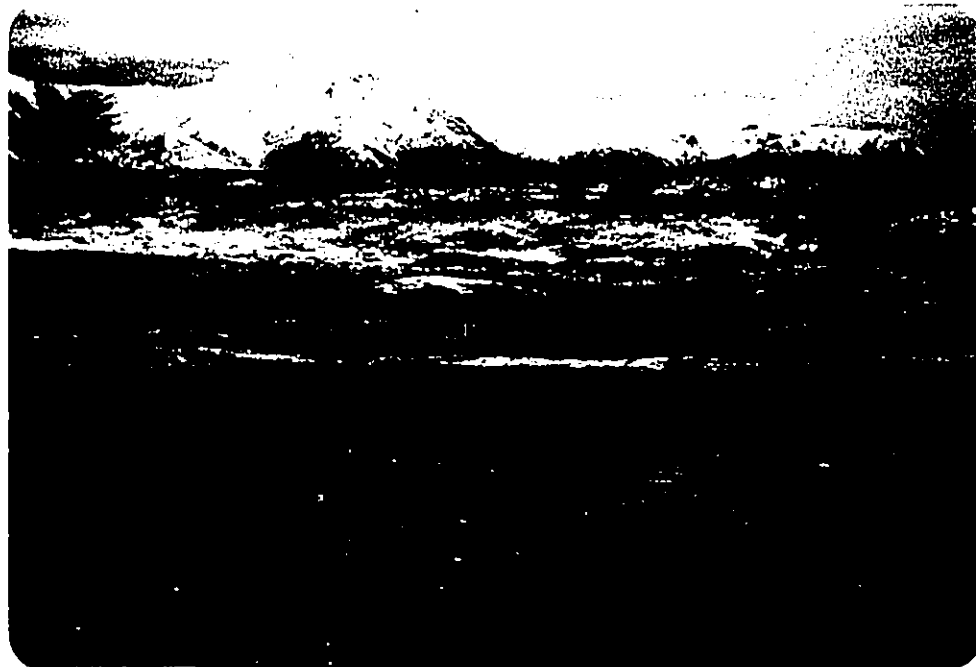


Figure 4.7 Frost mounds 3-1 and 3-2 were located at the north end of a small pond and formed in organic-rich silts. Photo: September 20, 1980.

of mounds forms directly downslope from these springs, while two or three single mounds occur further downslope. The mounds occurring at this site are the same size as the largest mounds observed at site 1. Each winter, spring discharge results in an icing accumulation that effectively covers the entire frost mound area. Mounds occurring at this site usually collapse in the summer following their formation.

Figure 4.8 shows the geomorphic and topographic characteristics of sites 5 and 6. Frost mound activity in both areas occurs within a short distance of the break of slope. The largest frost blisters observed in the North Fork Pass area were located at these sites. The terrain directly above these sites approaches  $30^\circ$  in angle, providing a potentially greater hydraulic gradient than at the other sites. This translates into potentially higher hydraulic pressures and thus, larger frost mounds. It is significant perhaps, that frost mound size decreases with increased distance from the break of slope.

Site 5 is situated along the perimeter of an alluvial fan (Figure 4.9). Spring discharge occurs at the break of slope and at several locations within seasonal runoff channels that dissect the fan. Site 6 differs in that the spring occurs at an elevation well above the break of slope between the valley side and the floodplain. Each winter an icing, together with several icing mounds and blisters, forms at the main spring outlet and spreads several hundred metres onto the floodplain. This location is characterized

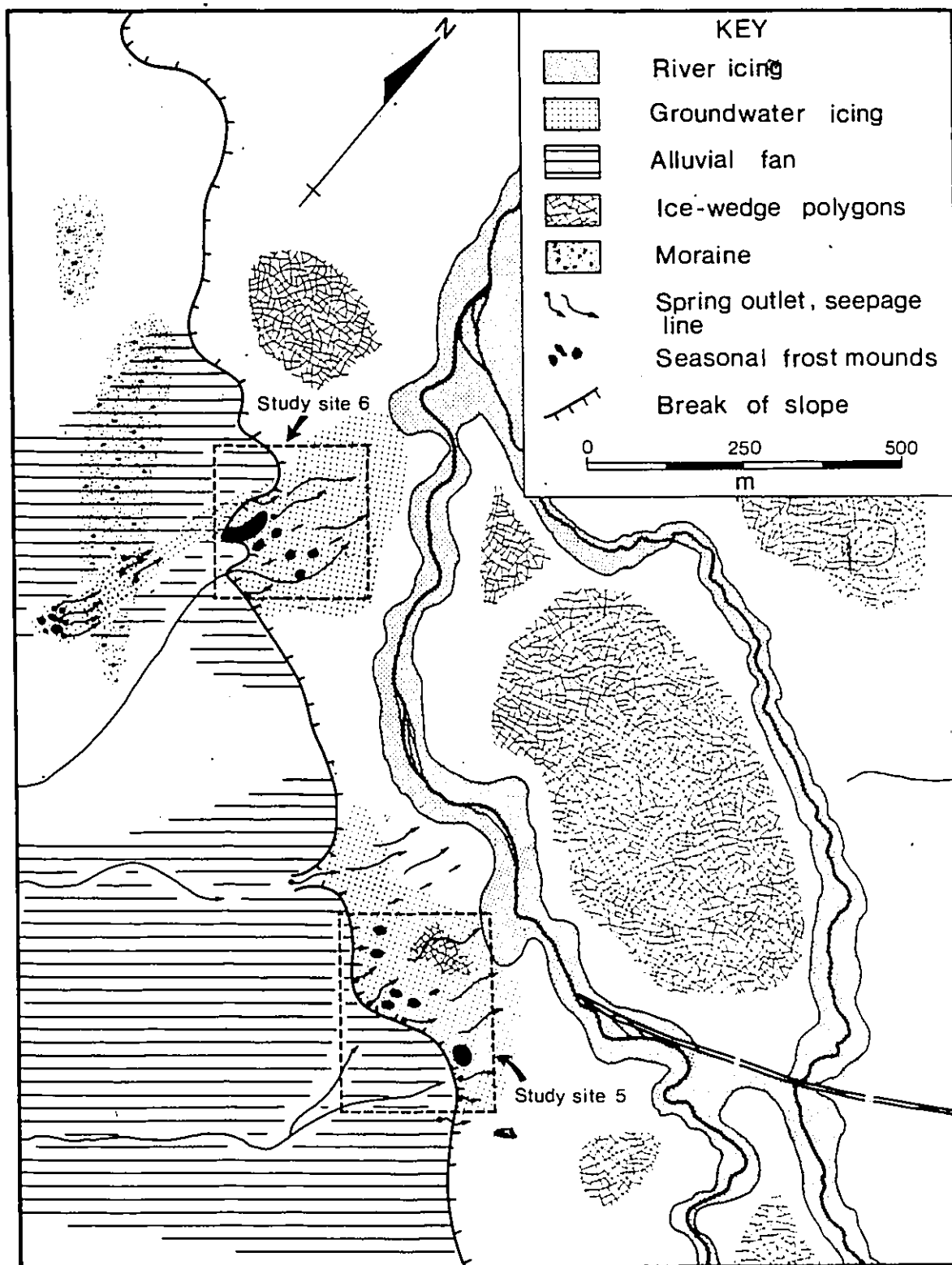
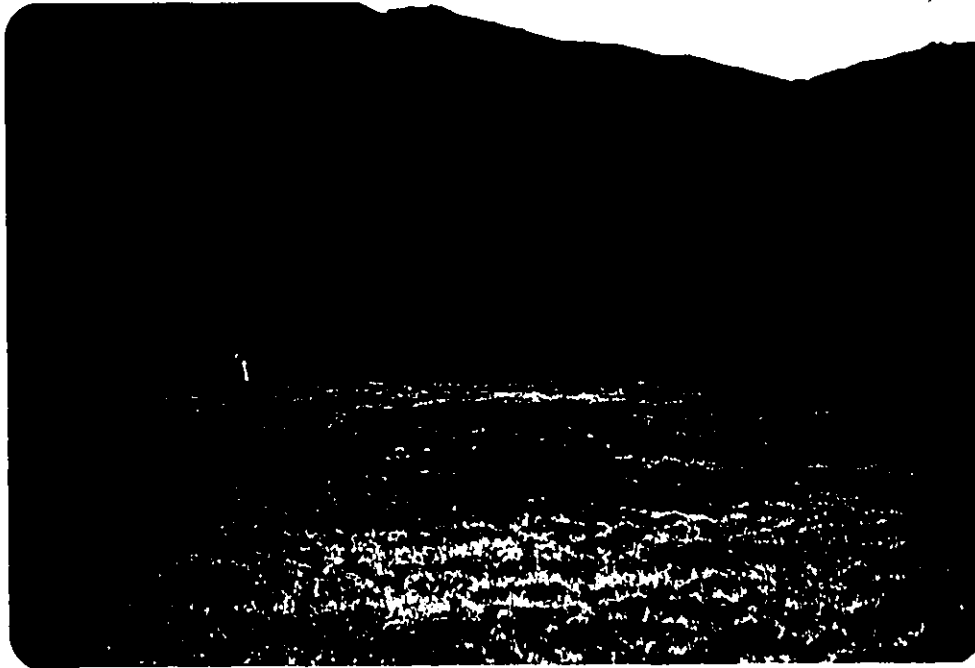


Figure 4.8 Physiographic map of sites 5 and 6, North Fork Pass, based on field survey and air photo analysis. Source: National Air Photo Library, A 18137-41, -42.



(a)



(b)

Figure 4.9 Alluvial fans provide the main aquifer materials for groundwater systems feeding perennial springs at site 5. (a) In summer (September 1981) a number of collapsed mounds are visible near the distal edge of the fan, and (b) each winter new mounds form (March 1982) in slightly different locations.

by a boulder apron much like that at site 4.

Site 7 is located further up the East Blackstone River valley. Like sites 5 and 6, it is located on the west side of the East Blackstone River. Few detailed observations were made at this site.

### 4.3 Morphology

#### 4.3.1 Introduction

Although the seasonal frost mounds in the North Fork Pass area are smaller than those described elsewhere (e.g., Lewis, 1962; Mackay, 1979; van Everdingen, 1979; 1982), their frequency is higher and morphology more diverse than others previously described.

The morphology of seasonal frost mounds reflects both the magnitude of the processes active and the physical properties of the materials in which they occur.

Seasonal frost mounds range from low, flat-topped and circular swellings to distinct lobate forms exceeding 3.0 m in height. They occur either as solitary features or in groups. The distinction between mound types is difficult to determine during winter and by mid-summer, only frost blisters remain.

Exact mound locations and sizes vary from year to year. On five occasions, frost blisters that survived the summer with only minimal degradation were reactivated during the following winter. Reactivation took the form of a minor increase in height and length, but in one case

(frost blister 1-4), reactivation resulted in a doubling of both mound height and length and the modification of mound shape. Previous studies describe mounds occurring in approximately the same location in consecutive years (e.g., van Everdingen, 1982); however, there is no mention of reactivation of previously formed mounds.

A practical problem concerns the identification of very small frost mounds which are sometimes indistinguishable from the normal tundra surface. In this study, frost mounds were identified only when they exceeded 0.5 m in height and 5.0 m in length. Table 4.2 summarizes the physical characteristics of seasonal frost mounds in the North Fork Pass area. This table is based on observations made during the study. Detailed information is presented in Appendix I (Tables AI.1 to AI.10).

#### 4.3.2 Size, shape and orientation

Sixty-five seasonal frost mounds were observed during the course of the study. This total included 46 frost blisters, 14 icing mounds and/or icing blisters and 5 combined frost blisters and icing blisters. A number were measured on successive occasions to determine rates of deterioration. The average mound height, based on the maximum height for all mounds, was 1.4 m. Since some of the mounds were surveyed in late summer after considerable collapse had occurred, a better estimate of average mound height is based on a survey of 20 mounds undertaken during March 1982 (see Table 4.2). At that time, the average

Table 4.2  
 A Summary of Seasonal Frost Mound Physical Characteristics  
 for the North Fork Pass area.

Study Site	Number of Frost Mounds	(A) Frost Blisters	(B)		Average Height (m)	Average Length (m)	Average Width (m)	Average L/W Ratio	Average Local Slope
			Icing Mounds & Blisters	Combined (A) & (B)					
1	28	18	8	2	1.40	13.74	7.38	2.30	3.7°
2	4	4	-	-	0.69	9.80	7.35	1.30	2.8°
3	6	4	1	1	1.54	23.70	10.20	2.26	4.1°
4	7	5	2	-	1.90	17.90	10.16	1.80	3.5°
5	7	6	-	1	1.50	20.30	14.61	2.02	3.8
6	7	3	3	1	1.30	17.77	7.00	1.64	4.6°
7	6	6	-	-	1.24	10.40	4.80	1.70	3.2°
TOTAL	65	46	14	5	1.40 (1.90)*	16.00	8.50	1.90	3.6°
SUMMARY OF SHAPE CHARACTERISTICS									
SIMPLE	54-83%				MAX.	65-70	35.00	3.50	10.0°
COMPOUND	7-10.7%				MIN.	3.00	1.50	1.20	2.5°
COMPLEX	4-6.3%								

\*Based on measurements for 20 mounds made in March 1982.

height was 1.9 m and some of the largest mounds seen in the North Fork Pass area were observed at that time. At site 5, for example, one frost blister (5-5) located at the break of slope between the distal part of the alluvial fan and the floodplain measured 3.5 m in height. It also possessed a long-axis basal diameter of 40.2 m oriented parallel to the local slope direction and a short-axis basal diameter of 24.0 m. A second frost blister (6-1), also located on the west side of the valley, was 3.4 m high, 53.1 m long and 15.0 m wide. It occurred in roughly the same setting as frost blister 5-5. Frost blisters 5-5 and 6-1 are shown in Figure 4.10 as observed in March 1982.

During the same period, a large icing mound (3-6) was observed at site 3 extending onto the icing covering a small pond. It was a gently sloping, oval-shaped dome of ice approximately 3.0 m high, 65.0 m long and 35.0 m wide (Figure 4.11). The freezing of groundwater overflow discharging from the top of the mound continued to add to the dimensions of both the icing mound and the adjacent icing throughout the March 1982 observation period.

It is possible that March 1982 was a period of greater than normal frost mound activity. Before then the largest mounds observed were frost blisters located at sites 1 and 4. At site 1, several were measured with heights ranging between 2.0 and 2.4 m, and at site 4 frost blister 4-4 attained a height of 2.3 m.

(a)



(b)



Figure 4.10 (a) Frost blister 5-5 formed along the distal edge of an alluvial fan at site 5, and (b) frost blister 6-1 formed in a similar setting at site 6. Photos: March 19-20, 1982.

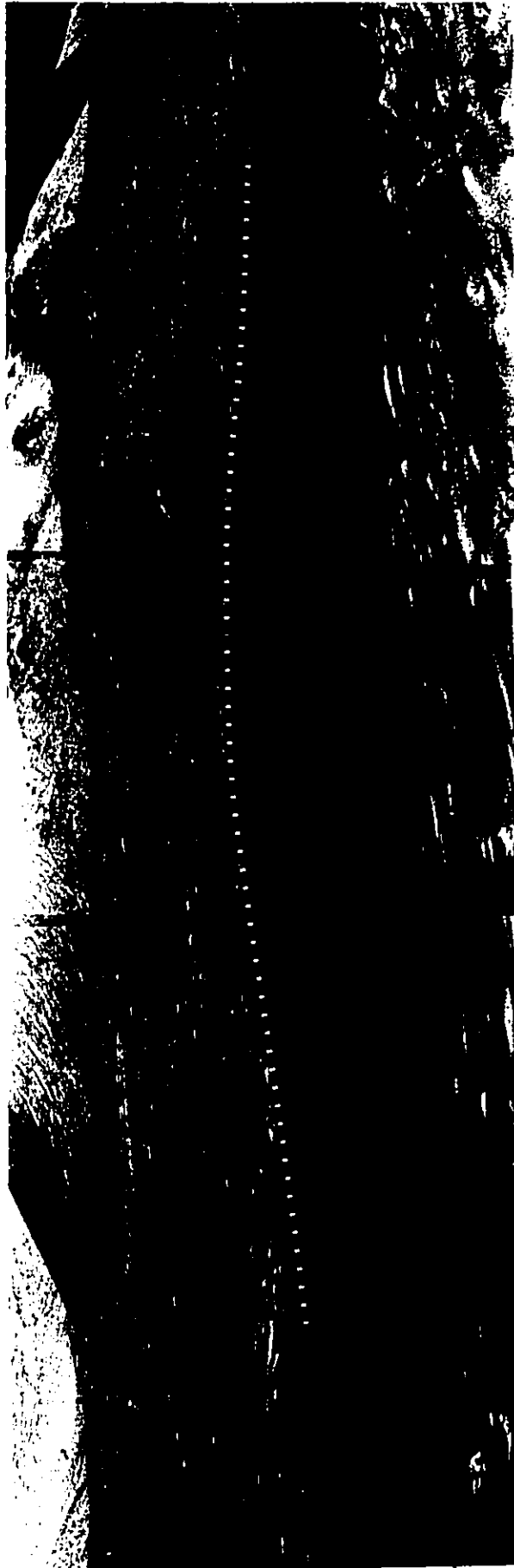


Figure 4.11

General view of icing and icing mound 3-6 located at site 3. Note the flow of water from the top of the mound, snowshoe prints in the lower left corner provide a rough scale. A dashed line identifies the top of the mound. Photo: March 20, 1982.

The average long-axis basal diameter was 16.0 m and usually oriented parallel to the slope. The average short-axis diameter was 8.5 m. Figure 4.12 illustrates the frequency distribution by height and length of seasonal frost mounds. In both cases, the distributions are skewed toward the smaller classes.

Frost mounds can be grouped into a number of shape categories (Figure 4.13):

- (1) Simple mounds are characterized by a single plan outline and a smooth unimodal profile. Oval and circular shapes are most common.
- (2) Compound mounds are irregular in plan and usually result from the coalescence of two or more mounds. They usually possess a bimodal long-axis profile. Elongate forms resembling the outline of a peanut are common.
- (3) Complex mounds include mounds which are either 'mutually interfering' or hydrologically integrated. Complex mounds may have an outline which appears lobate or crenulate. Complex mounds appear to have developed from the same source and have a common, integrated groundwater system.

The ratio of length to width (L/W) provides an index of elongation. As a mound becomes more circular, the

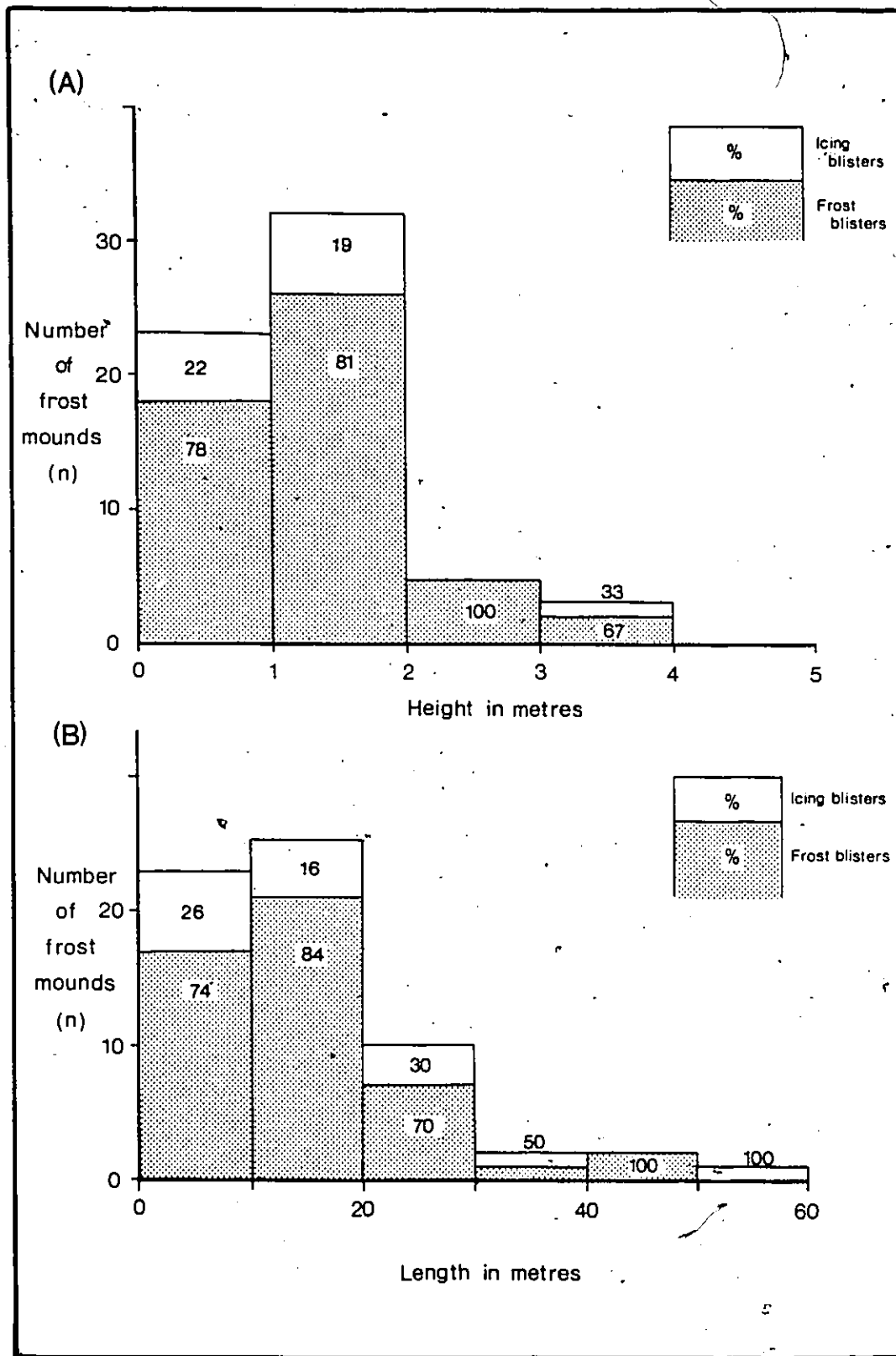


Figure 4.12 Frequency distribution histograms of seasonal frost mounds (a) by height and (b) by length.

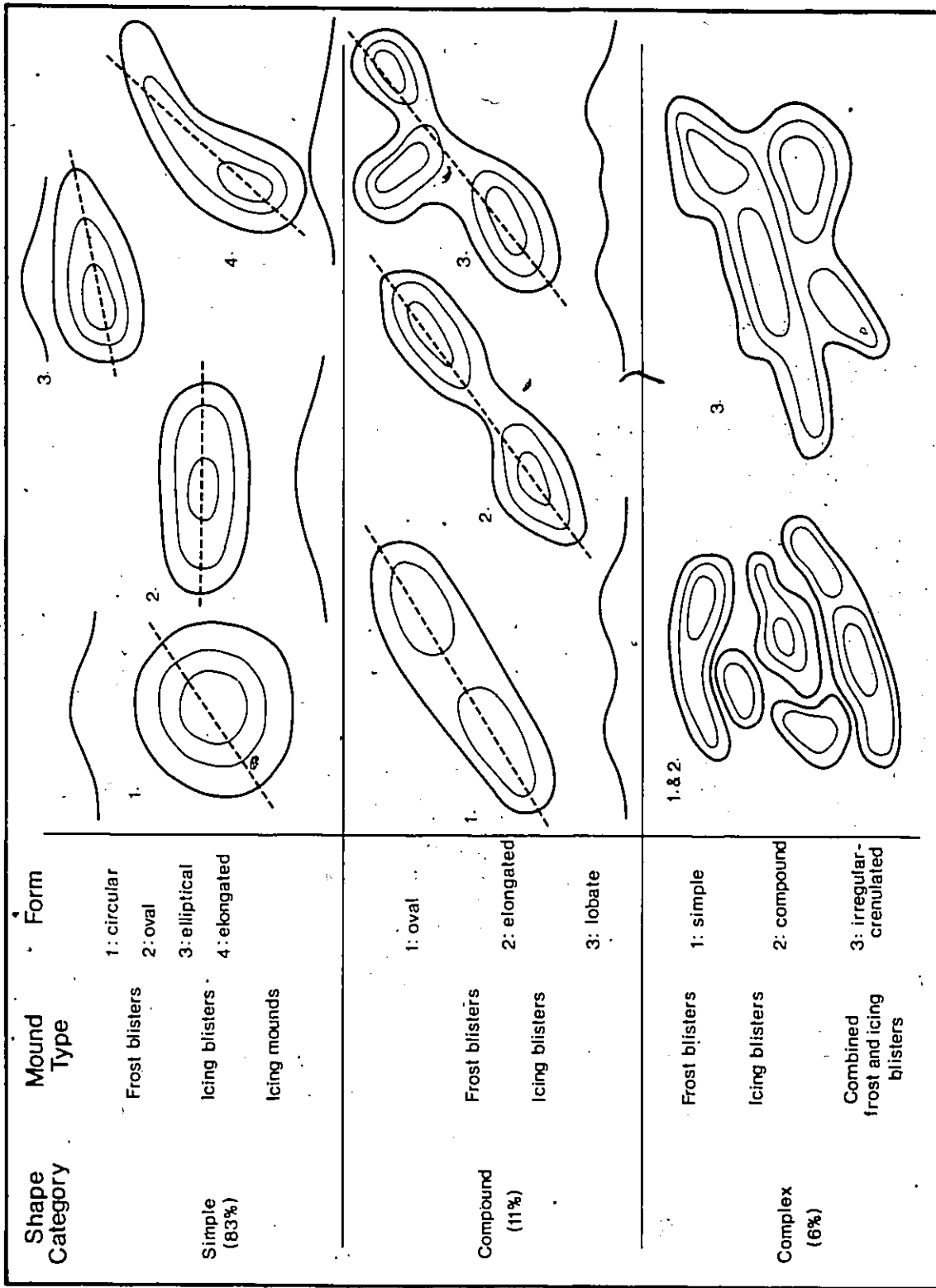


Figure 4.13 A morphologic classification of seasonal frost mounds based on plan shape and long-axis profile.

length to width ratio approaches unity. In actuality, very few mounds have L/W ratios of 1.0 and the average for all mounds was 1.9. The majority (almost 60%) are characterized by L/W ratios of between 1 and 2. Ratios between 2 and 3 characterized 34% of the observed population. Mounds having ratios greater than 3 (strongly elongated) are usually large but this applied to only 6% of the population.

Most mounds (83%) display a simple shape from which long and short axes are readily identified. In general, the long axes show a preferred orientation parallel to the local slope direction. Deviation of the long-axis orientation from the local slope direction was usually within  $\pm 15^\circ$ . Only in a few cases did deviation exceed  $\pm 40^\circ$ , mainly in areas of very low slope angle. Regression analysis indicates a strong positive correlation between slope direction, slope angle and frost mound long-axis orientation (Figure 4.14). This implies, although does not prove, that slope may be an important factor influencing mound orientation and, subsequently, morphology. This hypothesis is supported by a progressively smaller variance between mound orientation and slope direction as slope angle increases. For example, where larger mounds occur, such as 6-1 and 5-5, slopes approach 7 to  $10^\circ$ . Deviation of the long-axis orientation from the local slope direction is less than  $3^\circ$ . Conversely, mounds that occur on gentler slopes (2 to  $3^\circ$ ) consistently display a wider variance of long-axis orientations and are usually smaller.

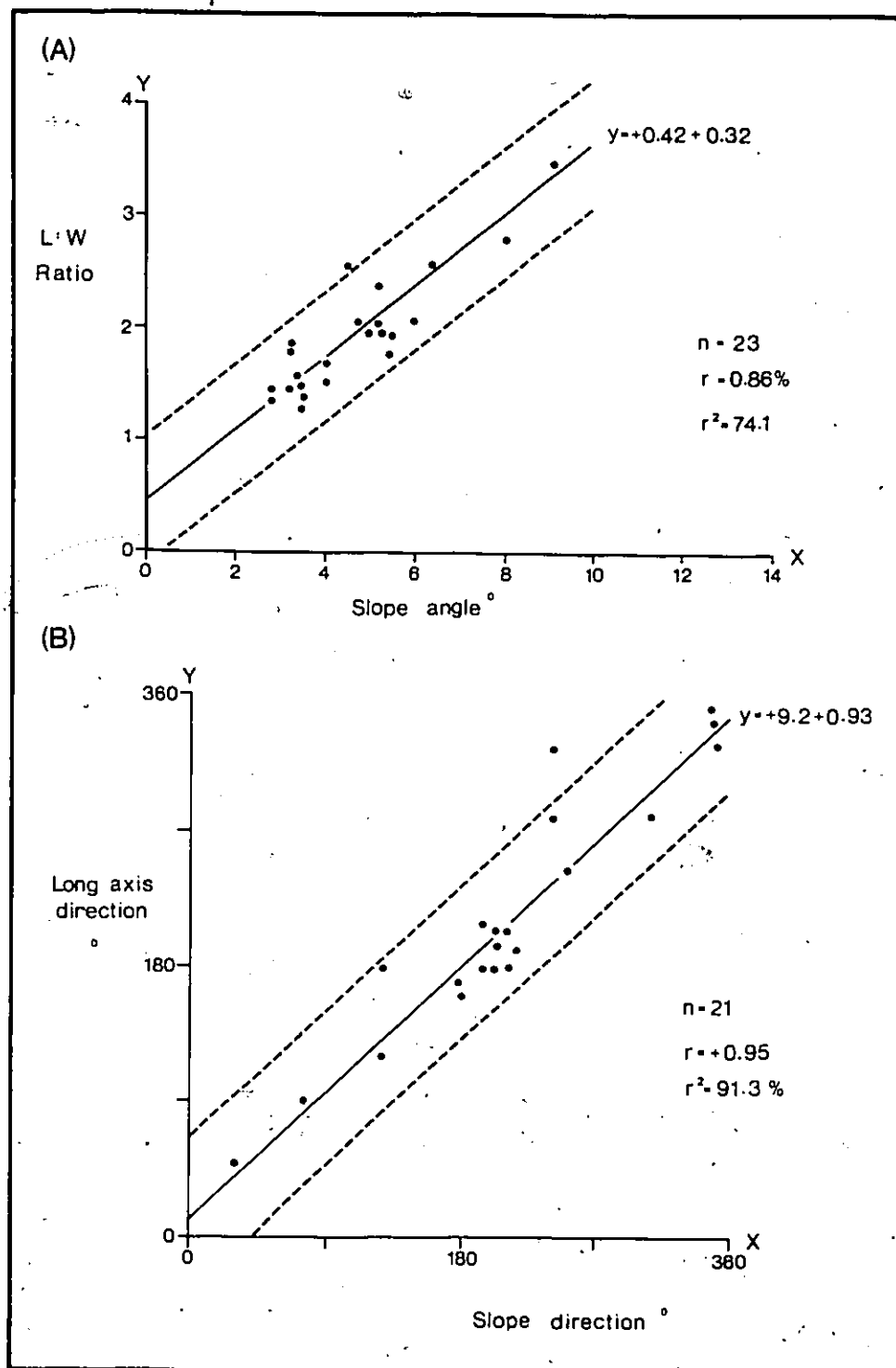


Figure 4.14 (a) Correlation of slope angle and L/W ratio. (b) Correlation of slope direction and seasonal frost mound long-axis orientation.

Mound shape and orientation may also reflect the pattern of groundwater movement. For example, during winter freeze-back, the zone of greatest water transmission would freeze more slowly than surrounding areas. By delaying freeze-back, a thermal channel or pipe is created along which groundwater transmission may occur. As the channel gradually freezes, mounds form reflecting the shape of the channel.

#### 4.3.3 Cross-profile characteristics

Most structurally intact or active seasonal frost mounds display a smooth and often gentle cross-profile. During winter, when seasonal frost mounds are growing, their profile characteristics are constantly changing. The presence of icing cover or hard packed snow tends to streamline the profile.

A number of typical frost mound cross-profiles are presented in Figure 4.15. The mounds range from small simple frost blisters and icing blisters (e.g., 1-6, 6-3, 6-4) to large simple (e.g., 5-5, 6-1) and compound (e.g., 1-7) frost blisters. Sequential surveys of the same mound show the change in form associated with degradation (e.g., 1-4, 1-7, long and short-axis profiles). It is clear that mound morphology varies with the time of year and the state of the mound.

In most cases, mounds exhibit an asymmetrical profile with the downslope side of the mound being steeper than the upslope side. The side slopes of seasonal frost mounds commonly range between 5 and 15°. Low side slope angles

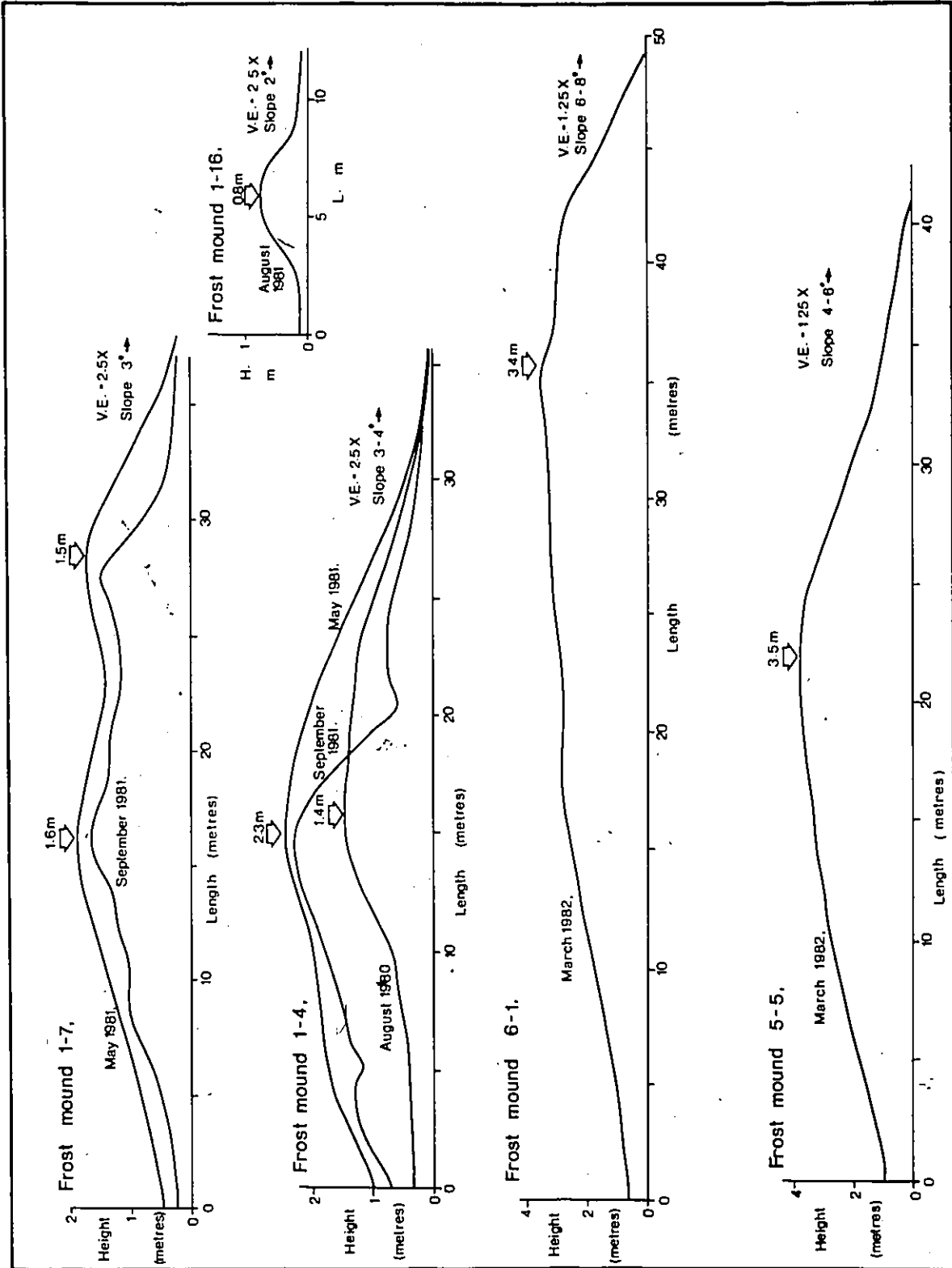


Figure 4.15 Typical mound cross-profiles, based on survey data obtained during 1980, 1981 and 1982.

are encountered in (a) small incipient frost mounds, (b) mounds with large basal diameters often located farthest from the spring outlet, and (c) relatively large frost mounds occurring on steep slopes where the upslope side of the mound tends to reduce the local slope (e.g., frost mounds 5-5 and 6-1). Small frost mounds, 1.0 to 1.5 m high, display steep side angles where the mound rises abruptly to its maximum height over a horizontal distance of 4 to 5 m.

While frost blisters consistently exhibit smooth cross-profiles, icing blisters more often possess an angular summit with dilation cracks at the point of maximum inflection. Icing mounds frequently have irregular and uneven profiles with rippled and fissured surface ice. Typically, icing mounds and blisters have straight to convex-upward side slopes, while frost blisters have mainly convex-upward side slopes. As frost blisters decay their slopes gradually become concave-downward, sometimes displaying downslope slumping and creep of materials overlying the ice core. Also, the top of the mound frequently collapses inward to expose the ice core. Icing mounds and icing blisters, on the other hand, disappear rapidly as the icing ablates; icing blisters also collapse inward.

Dilation cracks which form during winter growth accelerate spring and summer degradation. Dilation cracks may be up to 35 cm wide and form discontinuities in the mound profile.

CHAPTER FIVE

INTERNAL STRUCTURE AND ICE

CHARACTERISTICS

## 5.1 Introduction

The examination of the internal structure of frost mounds together with detailed process studies provide the most conclusive means of distinguishing seasonal frost mounds from other frost mound phenomena (e.g., pingos, palsas, hydrolaccoliths). In this chapter, the stratigraphy of several frost blisters and an icing blister is examined, with particular attention paid to lithology and contact relationships. Second, a detailed examination is made of the ice crystal and gas inclusion characteristics of frost mound and icing ice. Ice fabric analysis is used to interpret the freezing conditions under which the ice formed and the stresses, if any, acting upon the ice after it formed.

Frost mound stratigraphy was determined either mechanically using a motor driven coring unit and light drilling equipment, or manually by excavating along dilation cracks and areas of collapse. In total, the stratigraphy of eighteen seasonal frost mounds was investigated and fabric analyses were performed on ice from four of the mounds.

## 5.2 Internal structure

Not only were there marked stratigraphic differences between mounds, but also there were considerable variations in vertical sequences within each mound.

### 5.2.1 Frost blisters

Typical frost blister stratigraphy is summarized by the following generalized sequence and illustrated in Figures 5.1, 5.2 and 5.3. With few exceptions (discussed later), frost blisters are usually covered by a surface vegetation mat which provides strength and insulates the surface layers. During winter, the mound surface is also covered by varying thicknesses of packed snow or icing ice. In either case, the presence of these materials influences the ground thermal regime and subsequently, the formation and degradation of the mound. In the case of icing ice, its presence increases the hydraulic potential required to form the mound by increasing the soil overburden strength. Beneath the surface organic litter, there is usually a thin (10 to 50 cm thick) layer of peat grading into organic-rich silt. This unit unconformably overlies a body of clear layered ice. The contact between the ice and silt is sharp and concordant. Frequently, the ice appears layered, composed of bands of gas bubbles and, sometimes, sediment inclusions. Gas inclusions range from small, spherical bubbles to vertically oriented elongated bubbles, sometimes 1 cm in diameter and 3 to 4 cm long. In some blisters less than 1.0 m high, the mound is often solid and the ice forms an epigenetic body unconformably overlying frozen ice-rich sediments. By contrast, other mounds have cores consisting of one or more layers of clear ice arched over a water-filled chamber. Typically, the thickness of ice varies between

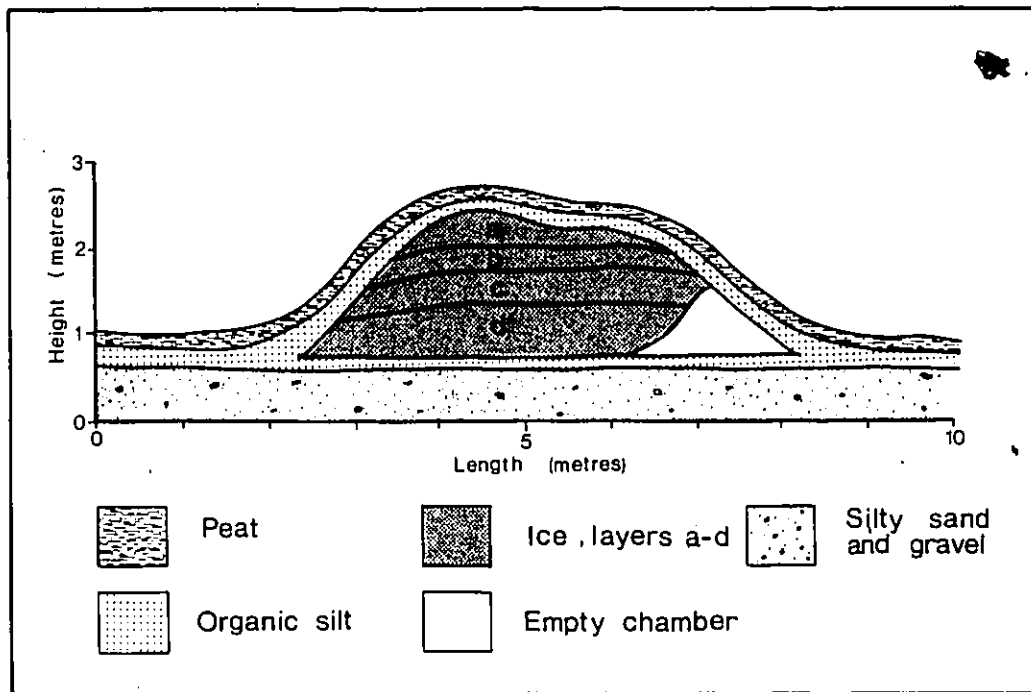


Figure 5.1 A cross-section through frost blister 1-2, observed in September 1980. \*

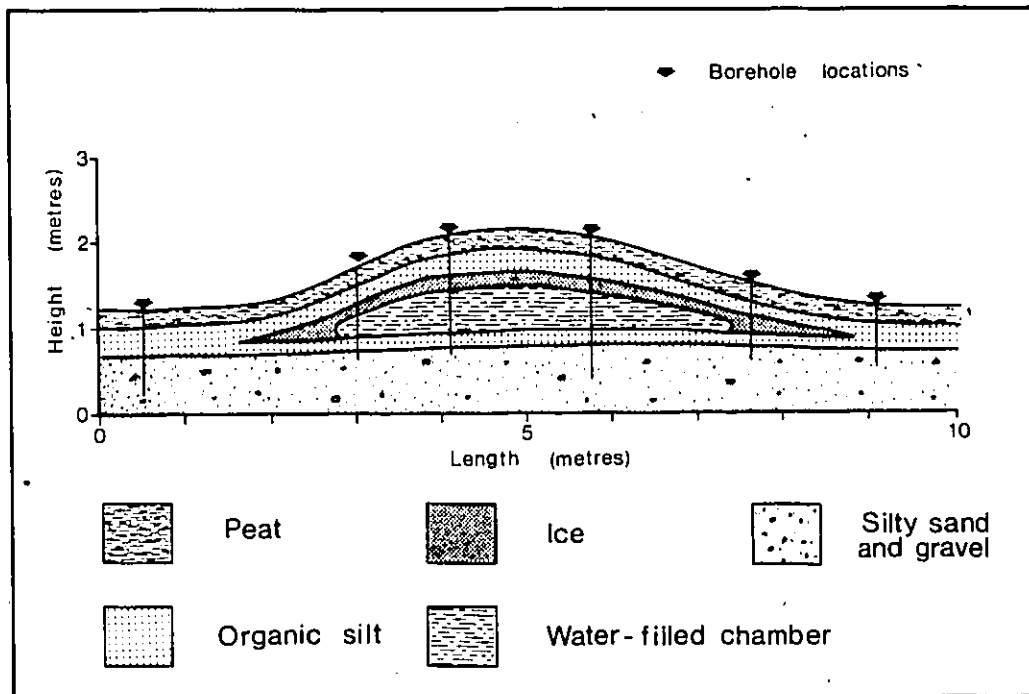


Figure 5.2 A cross-section through frost blister 1-16, based on drill data obtained in September 1981.\*

\*Frost table not indicated.

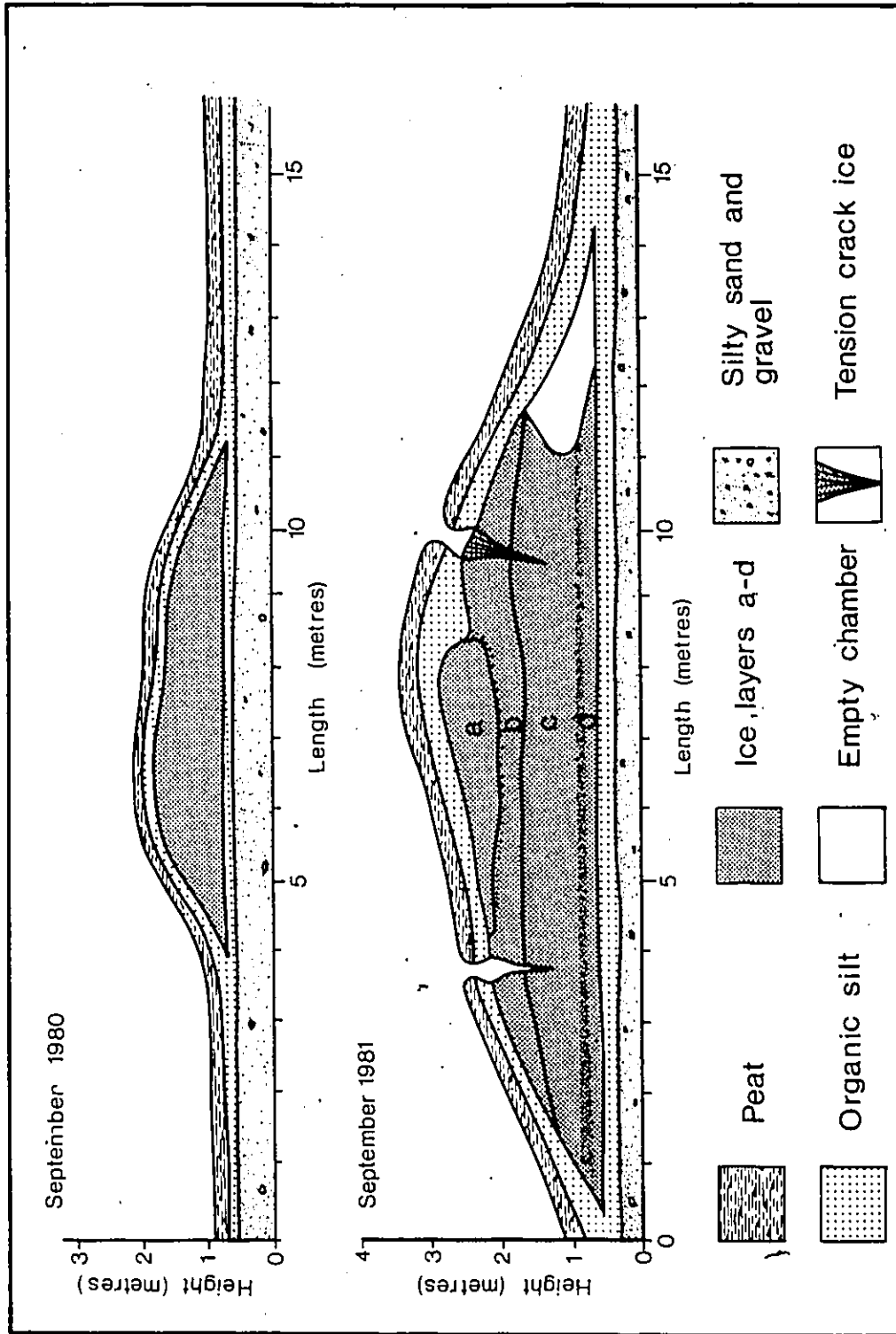


Figure 5.3 Vertical cross-sections through frost blister 1-4, (a) based on coring performed in September 1980, and (b) based on an excavated section observed in September 1981. Frost table not indicated.

30 and 80 cm and the height of the chamber varies between 20 and 90 cm. The horizontal dimensions of the ice core are difficult to determine as are the size and shape of the interior water chamber. From drilling and sections, it appears that the shape of the ice core resembles the surface expression of the mound, while the water chamber is low and lens-shaped. During winter, water in the chamber is clear and sometimes slushy, but during the summer, the water in the chamber is murky and dirty. On several occasions, an empty chamber was observed where frost mound rupture had resulted in drainage. A thin layer of ice usually covered the floor of chambers which had drained. The sediment directly beneath the ice core consists of in situ layers of frozen organic silt and silty sand with gravel. Horizontal ice lenses up to 1.5 cm thick were observed in frozen organic and fine mineral soils, while visible ice coatings and ice crystals were present in frozen sand. The flat, horizontal and unconformable nature of the base of the ice core probably correlates with the top of the frost table at the time the mound was initiated.

Since stratigraphic data relating to the internal structure of seasonal frost mounds are rare, and because the generalized stratigraphy outlined above allows for a wide range of local variability, several mounds are now described in detail.

(a) Frost blister 1-2 (Figure 5.1)

Frost blister 1-2 was first observed in September 1980, at which time the mound had partially collapsed. It was located in a low-lying area of saturated tundra downslope from a small pond. The mound was sectioned to expose a thin layer, 25 to 30 cm thick, of peat and organic silt overlying a solid ice core, 100 to 110 cm thick. The contact between the ice and the overlying material was sharp and uneven. In some places, fragments of peat, root material and fine silt were incorporated into the ice core. The ice adjacent to the contact displayed small spherical bubbles and small randomly arranged ice crystals characteristic of rapidly frozen water. Other layers of ice, ranging between 20 and 30 cm in thickness with distinct bubble patterns, were observed at different depths within the ice core. A slight downwarping of the ice layers was visible in some locations near the side of the mound. Only 60 to 70 cm of the ice core were exposed, since the remainder was below the water table. An empty cavity represented either the remnants of a water chamber or a possible zone of accelerated thaw. Organic-rich silt underlay the ice core and rested upon coarse frozen sandy silt and sand.

(b) Frost blister 1-16 (Figure 5.2)

Frost blister 1-16 was a small frost blister observed in August/September 1981. In contrast to mound 1-2, this mound had experienced little collapse, and thaw had penetrated only 30 cm. It was morphologically simple, being flat-topped,

and was almost 1 m high and 7 m in maximum plan dimension. The stratigraphy (Figure 5.2) consisted of a surface layer of peat and organic silt, 40 to 50 cm thick, which was thawed to a depth of 30 to 35 cm. Beneath the organic silt was 25 to 30 cm of clear, layered ice containing gas bubbles and root fragments. The ice was arched over a water-filled chamber, almost 30 cm high. The water had a high suspended sediment content, creating a turbid, dirty appearance. When the chamber was penetrated by the drill, there was a release of trapped gases. Sufficient pressure remained in the mound to force the water 15 cm up the borehole. The ice core and water chamber were underlain by frozen organic silt, 10 to 15 cm thick, containing visible segregation ice lenses. Layers of interbedded sand and gravel lay beneath.

(c) Frost blister 1-4 (Figure 5.3)

Frost blister 1-4 was first observed as a small, partially collapsed mound in September 1980. At that time, it was cored to obtain ice and sediment samples for hydrochemical and isotope analyses. The stratigraphy, as determined by coring, consisted of 26 to 30 cm of peat and organic silt, thawed to a depth of 20 cm, overlying 60 cm of clear, layered ice. In turn, the ice core overlay ice-rich organic silt and silty sand (Figure 5.3a).

During the 1980-1981 winter, the mound experienced a second period of growth during which it doubled in size. The shape of the original mound was no longer visible; however, survey stakes installed the previous year provided

fixed points from which change was interpreted. In 1981, the reactivated mound was excavated along a large dilation crack, 30 to 35 cm wide and over 1 to 4 m deep. The structure of the reactivated mound is shown in Figure 5.3b. An ice core, 150 to 190 cm thick, was composed of a sequence of alternating bubble-rich and bubble-free layers, with an upper layer appearing as a distinct ice lens. The upper ice lens was interpreted to be the remnants of an earlier frost mound. The various ice bands, between 20 and 40 cm thick, with distinct bubble inclusion patterns, were warped downward near the sides of the mound. At the bottom of the ice core, a thin (3 to 6 cm) zone of sediment-rich ice, overlay a second (10 to 20 cm) thin layer of clear ice. Beneath the ice core, 5 to 10 cm of ice-rich organic silt were underlain by grey-green coarse sand.

The sequence of sediment-rich and clear ice layers at the base of the core may represent a multiple cycle of mound growth, where water with a high suspended sediment content was injected either between existing layers of ice or into a nearly totally frozen ice core. The sediment-rich layer pinches out near an empty cavity located on the upslope side of the ice core. The cavity is possibly the remains of a water-filled chamber which may have been the source of the sediment-rich water, or equally, it may be a melt feature formed by groundwater flow.

Deviations from the type structures, as outlined in the previous paragraphs, were encountered in several

other frost blisters that formed in organic sediments adjacent to shallow tundra ponds at sites 1 and 3. The size of these mounds ranged between 40 and 140 cm in height and 3 to 10 m in length. The most striking characteristic was their unvegetated surface which consisted of dark brown to black, fine organic silt (muck). In May 1981, a complex of these mounds was observed at the south end of a pond at site 1 (frost mound complex 1-8). In detail, the complex consisted of four small mounds protruding through the icing surface. The stratigraphy of each was similar, consisting of 5 to 10 cm of organic silt overlying 40 to 60 cm of clear massive ice. Layering was not observed within the ice core. Once exposed, the mounds collapsed very rapidly as their mud cover liquified upon thawing and exposed the ice core. By August, all traces of these mounds had disappeared.

Similar features of larger size and longer duration formed during the 1979-1980 winter in organic silt and sand deposits at the north end of a small pond at site 3 (mounds 3-1 and 3-2). Mound 3-1, shown in Figure 5.4, was excavated in the summer of 1980. The structure of this mound was distinctive in that a more complex and thicker sequence of sediments overlay the ice core. The surface layer consisted of 10 to 15 cm of peat and dark organic silt, the next unit was composed of 33 to 36 cm of black organic clay-silt 'muck'. This was underlain by a 10 to 15 cm thick layer of bedded grey-green sand containing ice crystals and ice-coated sand grains which in turn overlay 11 to 15 cm of ice-rich silty

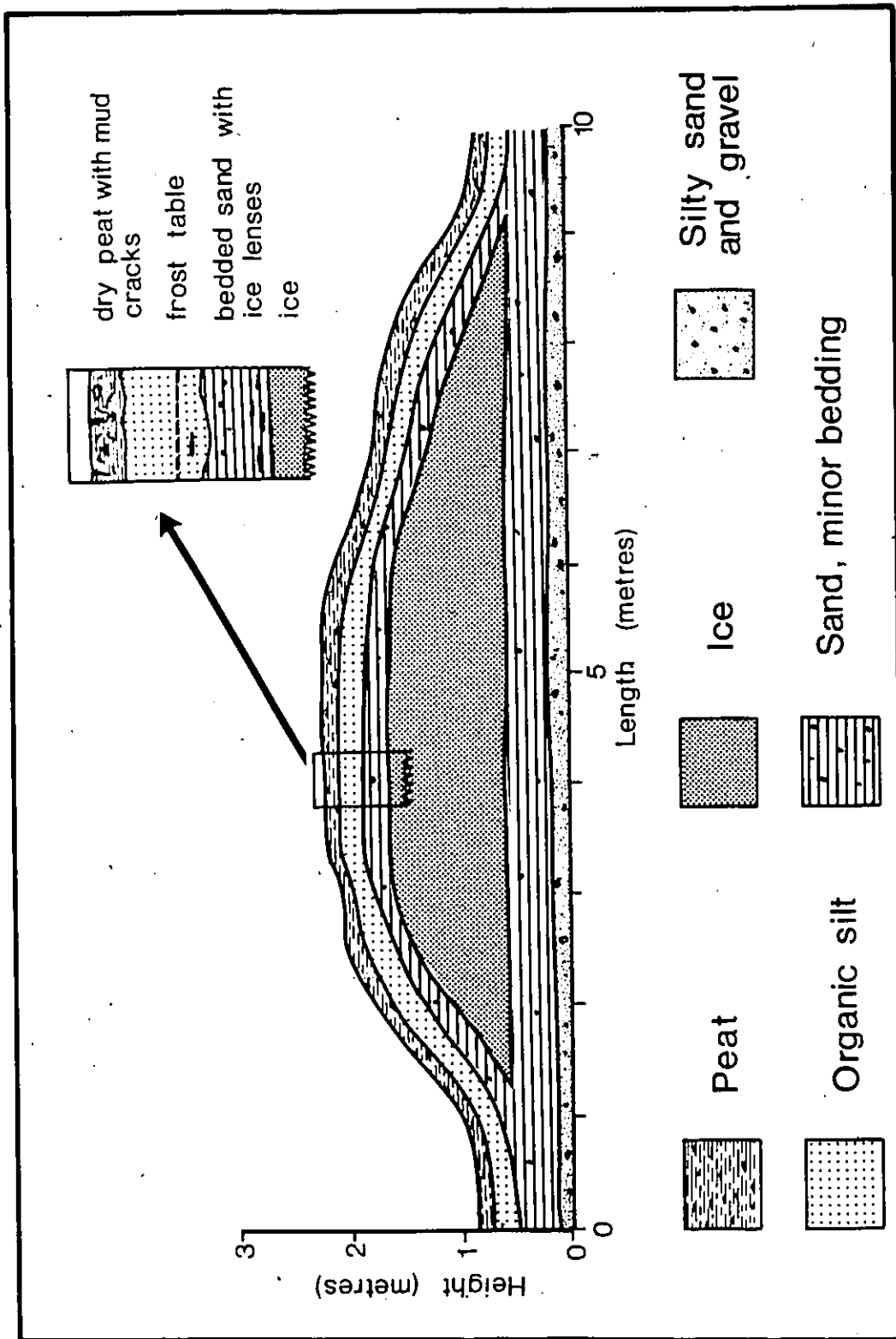


Figure 5.4 A vertical cross-section through frost blister 3-1, sectioned in September 1980.

clay. The base of the silty-clay unit unconformably overlay a massive ice core. Only 30 to 40 cm of ice were visible above the water table. The well-drained peat forming the surface layer of the mound provided excellent insulation, limiting thaw penetration to less than 40 cm and preserving the ice core.

### 5.2.2 Icing mounds and blisters

The structure of icing mounds and icing blisters investigated in the North Fork Pass area closely resembled the structure of similar features described elsewhere (e.g., Carey, 1973; Frederking, 1979; Muller, 1945; van Everdingen, 1978). Both types of mounds are composed entirely of layered ice and occasionally include zones or lenses of water. The uniform nature of the ice and the lack of stratigraphic variation sometimes make the stratigraphy difficult to identify. Occasionally, however, layers of mineral precipitates, bands of bubble inclusions and variation in ice crystals provide useful marker horizons.

In May 1981, three small icing blisters were investigated (mounds 1-18, 1-19 and 1-20). Two had large dilation cracks running longitudinally along the spine of the oval-shaped features (Figure 5.5). Excavation along the dilation crack of mound 1-19 revealed a sequence of 30 to 40 cm of layered ice arched over an empty chamber 25 to 35 cm high and underlain by 30 to 40 cm of horizontally layered ice. The upper ice layers were distinguished by the presence of candled ice, yellow coloured mineral precipitate

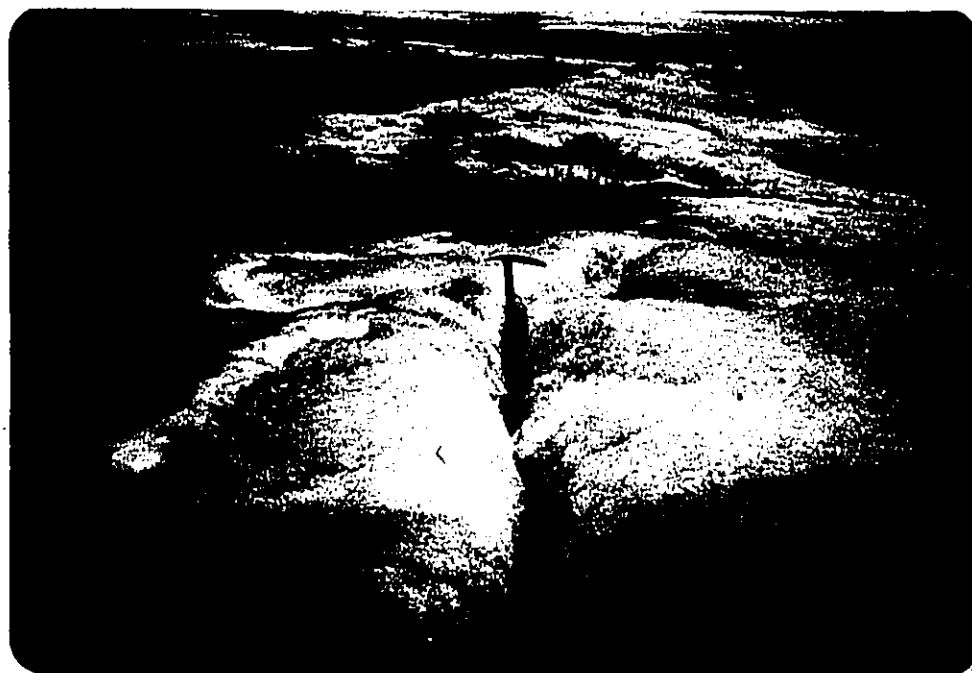


Figure 5.5 A dilation crack runs the entire length of icing blister 1-19. Photo: May 1981.

(Figure 5.6) and variable bubble inclusions. Each layer was characterized by a zone of fine gas bubbles at its upper contact, in contrast to large elongated bubbles occurring toward the lower part of the ice layer. At one time, the chamber probably contained water under pressure which heaved the overlying ice layers. The chamber drained when the confined pressures exceeded the strength of enclosing ice and rupture followed.

Some of the largest icing mounds were observed during March 1982. One, approximately 95 to 100 cm high, was composed entirely of a sequence of ice layers formed by the freezing of successive flows of groundwater discharging from a crack in the icing surface. The surface of the mound, and in some cases the internal layers, was often uneven or irregular, and sometimes rippled. In the case of a high discharge from a point source combined with rapid freezing, a knob-like plug formed in the top of the mound (Figure 5.7). At this site, the combined thickness of icing mound and icing ice was almost 200 cm. Mound 3-6 was the largest icing mound observed (Figure 5.8). It formed during the 1981-1982 winter at a perennial spring outlet near the break of slope between the valley side and the valley floor. Discharge throughout the 1981-1982 winter resulted in an icing mound accumulation over 60 m long and 3 m high. During the entire period of observation in March 1982, water discharged from the top of the mound, forming small drainage channels on the ice.

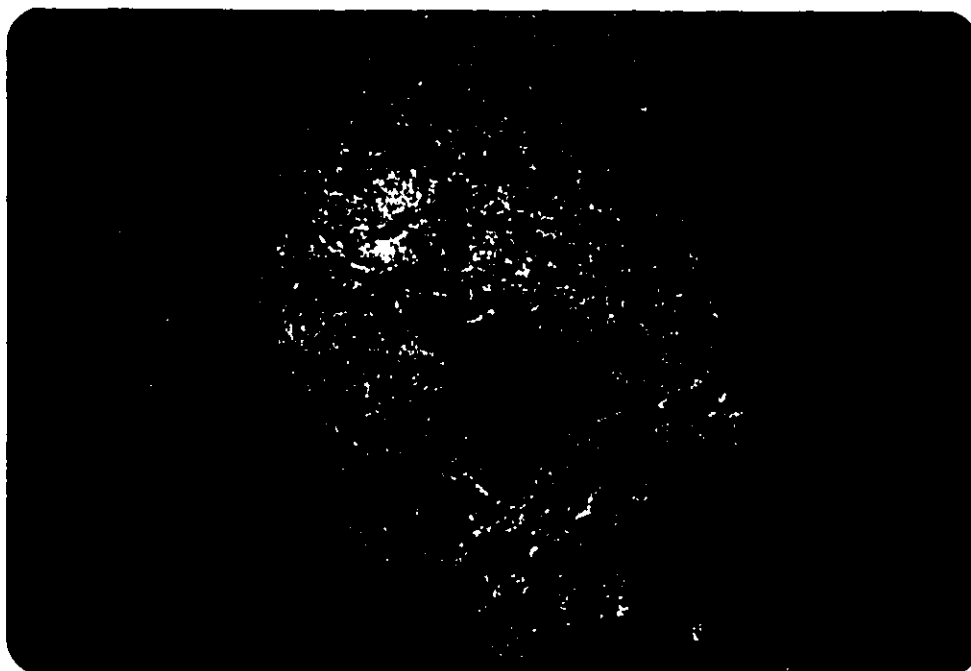


Figure 5.6 Patches of powdery yellow precipitate are often observed on the icing surface. Photo: May 1981.



Figure 5.7 An icing mound formed part of frost mound complex 1-23. Photo: March 1982.



Figure 5.8 . In March 1982, a large icing mound was observed at site 3. Note the recent overflow from the top of the mound.

### 5.3 Ice characteristics

Ice forms an integral component of the structure of seasonal frost mounds. Information concerning their growth processes can be obtained by examination of ice crystal and gas inclusion characteristics (Carte, 1961a; b; Harrison and Tiller, 1963). Although it is widely known that frost blisters form as a result of freezing of groundwater injected between layers of frozen soil (e.g., Muller, 1945; Shumskii, 1964a; van Everdingen, 1978; 1982), a detailed description of the freezing-injection process is lacking. Another important type of ice, particularly in the case of icing blisters and icing mounds, is icing ice. Since icings form by the freezing of successive layers of groundwater overflow, they possess completely different ice texture and petrofabrics. The distinction between injection and icing ice may provide a means of differentiating mound types and formative processes. Accordingly, a summary of petrofabric analyses and textural observations for ice from three frost blisters and one icing blister is presented in this section. The physical and optical properties of ice are also briefly reviewed. The petrofabric and textural analyses are intended to complement stratigraphic observations.

#### 5.3.1 Crystallography and optical properties

The size, shape and orientation of ice crystals and gas inclusions observed in polycrystalline ice are a function of temperature and water supply conditions during

freezing, and temperature and deformation processes after freezing. The examination of ice petrography can provide a basis for reconstruction of freezing and past consolidation histories of a frost blister ice core. Four factors may affect the orientation of crystals found in ice bodies; these are: growth rate, heat flow, stability and shear stress.

Petrofabric analysis is facilitated by the optical properties of ice crystals. Ice in general is transparent in the visible region of the electromagnetic spectrum. In the case of ground ice, it may, however, appear opaque to translucent, depending on the volume and type of materials incorporated. Ice displays a weak, positive birefringence and is optically uniaxial. The optic axis corresponds to the c-axis of crystallographic symmetry. Because of its birefringent properties, ice crystal orientation can readily be determined using polarized light and since ice is so weakly birefringent, crystal characteristics can be determined using relatively thick sections of ice (up to 0.5 mm).

Nine phases of ice have been identified (Glenn, 1974; 1975; Shumskii, 1964a). However, only one phase, known as Ice I, is stable at normal pressures. Ice I has two structural variants; a hexagonal crystal symmetry which is most common, and a cubic crystal symmetry which requires very cold temperatures for nucleation and is subsequently rare. Ground ice, including injection ice found in frost blister cores, belongs to the hexagonal crystal system.

Minerals having hexagonal crystal symmetries are characterized by three equal axes ( $a_1$ ,  $a_2$ ,  $a_3$ ) forming angles of  $60^\circ$  occurring in a common plane, referred to as the basal plane. A fourth, uneven, crystal axis ( $c$ ) occurs normal to the basal plane.

Most bulk ice or massive ice in nature is termed polycrystalline ice; that is, ice composed of a large number of single crystals in various orientations. The extent to which there is any pattern or preferred crystal orientation, or any special grain shape, is the subject of ice petrography (Percy and Pounder, 1958). In terms of its physical properties, there are two main reasons why polycrystalline ice behaves differently from a single crystal of ice: (a) single crystals are anisotropic, and (b) the boundary conditions in polycrystalline ice influence its net physical characteristics. Since individual ice crystals are anisotropic and hexagonal in symmetry, their physical properties are different in directions parallel and perpendicular to its  $c$ -axis. Thus, the  $c$ -axis is an important structural axis.

There are three commonly occurring polycrystalline petrofabrics for which specification is relatively simple, and easily identifiable:

- (1) Randomly oriented polycrystalline ice composed of approximately equidimensional crystals;
- (2) columnar ice with  $c$ -axes parallel to

- column lengths; and
- (3) columnar ice with c-axes perpendicular to column lengths.

Columnar ice with c-axes parallel to column lengths is the ice fabric which occurs normally when water freezes. This kind of ice is the most anisotropic form of polycrystalline ice. Columnar ice with c-axes perpendicular to column lengths occurs when a layer of randomly oriented ice grains provides nuclei for ice crystals growing in water at 0°C or just slightly cooler. Since growth of ice crystals occurs more rapidly in the direction perpendicular to the c-axes, the crystals with their c-axes horizontal soon wedge out the others and produce columnar ice (Pounder, 1963; 1965). This type of preferred orientation has been discussed by Ketcham and Hobbs (1967) for lake ice, and by Gell (1978) for icing mound ice.

Grain boundary character also influences the physical properties of polycrystalline ice. Low angle grain boundaries are those in which the boundaries between grains have approximately the same orientation as their crystalline axes. High angle grain boundaries are described as regions between two grains where the crystalline arrangement breaks down (Glenn, 1974). If ice is heated by solar radiation, the grain boundaries may act as centres of melting. For example, a body of icing or lake ice during spring frequently consists of ice crystals disaggregated by melting along grain boundaries; this is sometimes referred to as

candled ice or candling.

### 5.3.2 Crystal growth and bubble characteristics

With regard to seasonal frost mounds, the majority of ice forms from the freezing of a groundwater reservoir injected between layers of frozen ground. Once an ice nucleus is present, ice growth from the surrounding water varies, depending on hydrochemistry and whether the water is supercooled or not. At large supercoolings ice grows in a dendritic pattern. When water temperature is close to the ice temperature, dendritic growth does not occur. Instead, as ice grows down into water under natural conditions, a strong preferred orientation with c-axes vertical gives way to one in which c-axes are horizontal (Gell, 1976; Ketcham and Hobbs, 1967; Michel and Ramseier, 1971; Ramseier, 1968). In polycrystalline aggregates, two texturally distinct zones are frequently encountered; (a) a zone of competitive growth near the cooling surface characterized by small randomly oriented crystals (i.e., a chill zone) and (b) a zone of elongated columnar crystals aligned parallel to the heat flow direction. In the columnar zone, the textural zonation has been accompanied by a higher frequency of preferred c-axes orientation.

During ice formation, most impurities are rejected from solid solution. There are a few exceptions (e.g.,  $\text{NH}_3$  and HF). It follows, therefore, that the formation of ice from groundwater is a more complex process than from

pure water since the various dissolved impurities in the aqueous solution are redistributed during solidification. Solute rejection occurs at the ice/liquid interface and the remaining solution experiences an increased concentration of dissolved impurities; some incorporation does occur at zones of disorder such as grain boundaries and lattice defects.

An important type of solute rejection with respect to the interpretation of ice growth and freezing conditions is that which forms gas bubbles. The occurrence of gas inclusions in the form of bubble-rich layers and single bubble trains in massive ice have been described by several researchers (e.g., Gell, 1976; Mackay, 1971) and in lens ice (e.g., Gold, 1957; Penner, 1961). The range in gas bubble size, shape, orientation and layering characteristics are a function of the freezing conditions under which the ice formed and may be used as an indicator of both freezing rate and direction. Gases accumulate at the advancing ice/water interface until their concentration is high enough to nucleate bubbles. Once a bubble has formed, it grows because air diffuses into it. The distribution coefficient for air in the ice/water system is 0.01 (Gell, 1976); therefore, a strong concentration is established ahead of the ice/water interface in the air saturated liquid. Nucleation may occur on particles, or at points of high solute concentration. After nucleation, if the interface continues to move forward, the bubble grows with it to form cylindrical

bubbles, and intermediate growth generates cylindrical shaped bubbles parallel to the growth direction (Chalmers, 1951). In rapid freezing, bubbles are quickly entrapped and result in small spherical bubbles with bubble trains. Where freezing is extremely rapid, there is insufficient time for bubble nucleation and a clear bubble-free ice body results.

#### 5.4 Frost blister ice character

##### 5.4.1 Frost mound 1-10

Frost mound 1-10 is the first of three frost blisters for which detailed analyses of ice characteristics are presented.

Mound 1-10 was an elongated, compound frost blister. It was located in a low area of saturated tundra at site 1. It formed during the 1980-1981 winter and was first observed in May 1981. Mound 1-10 attained a height of 2.2 m and a length of 30.2 m, oriented with its long axis parallel to the local slope. The ice core was exposed in a longitudinal dilation crack (Figure 5.9a) which resulted in minor thaw subsidence by late summer. In September 1981, the mound was cored and excavated (Figure 5.9b) to obtain an oriented block of ice for fabric analysis.

##### (a) Ice core character

The ice core was solid and composed of 115 cm of layered ice (Figure 5.9b). The layered appearance was the result of interstratification of clear and bubble-rich ice. The gas bubbles occurred within distinct bands parallel to

(a)



(b)



Figure 5.9 Frost blister 1-10, (a) protruding through the icing, May 1981, and (b) excavated in September 1981.

the mound surface. Within each layer, the range in bubble size and shape was fairly uniform; however, major differences existed between different bands. Some of the compositional layering was visible in the ice samples obtained for fabric analysis. Figure 5.10a shows a large block of ice, 40 cm thick, the upper 20 cm of which were nearly bubble-free except for a narrow band of fine bubbles at the ice/soil contact. Bubble concentrations increased in the lower part of the block (Figure 5.10b). At a depth of 20 cm to 30 cm, a number of single bubbles and bubble trains were visible. Bubble shapes ranged from small and spherical to elongated tubes. Bubble size ranged from 1 to 9 mm in diameter. Also present were filament-like bubbles and bubbles that widened downward into bulbous shapes. According to Gell (1976, pp. 48-49), this type of inclusion occurs along crystal boundaries and provides a useful "way-up" indicator. It has also been suggested that, where bubble distributions are random and where bubble shape is highly variable between spherical and filament forms, gas concentrations in the melt are locally variable and the supply for nucleation is uneven. In contrast, a number of bubble-rich layers were observed where bubble concentrations were so high that the ice took on a milky appearance (Figure 5.10c). The bubbles in these layers were small, 1 to 3 mm in diameter, and ranged between spherical and oval in shape, frequently arranged into vertical bubble trains and sometimes long filaments. Bubbles of this nature often form as the result

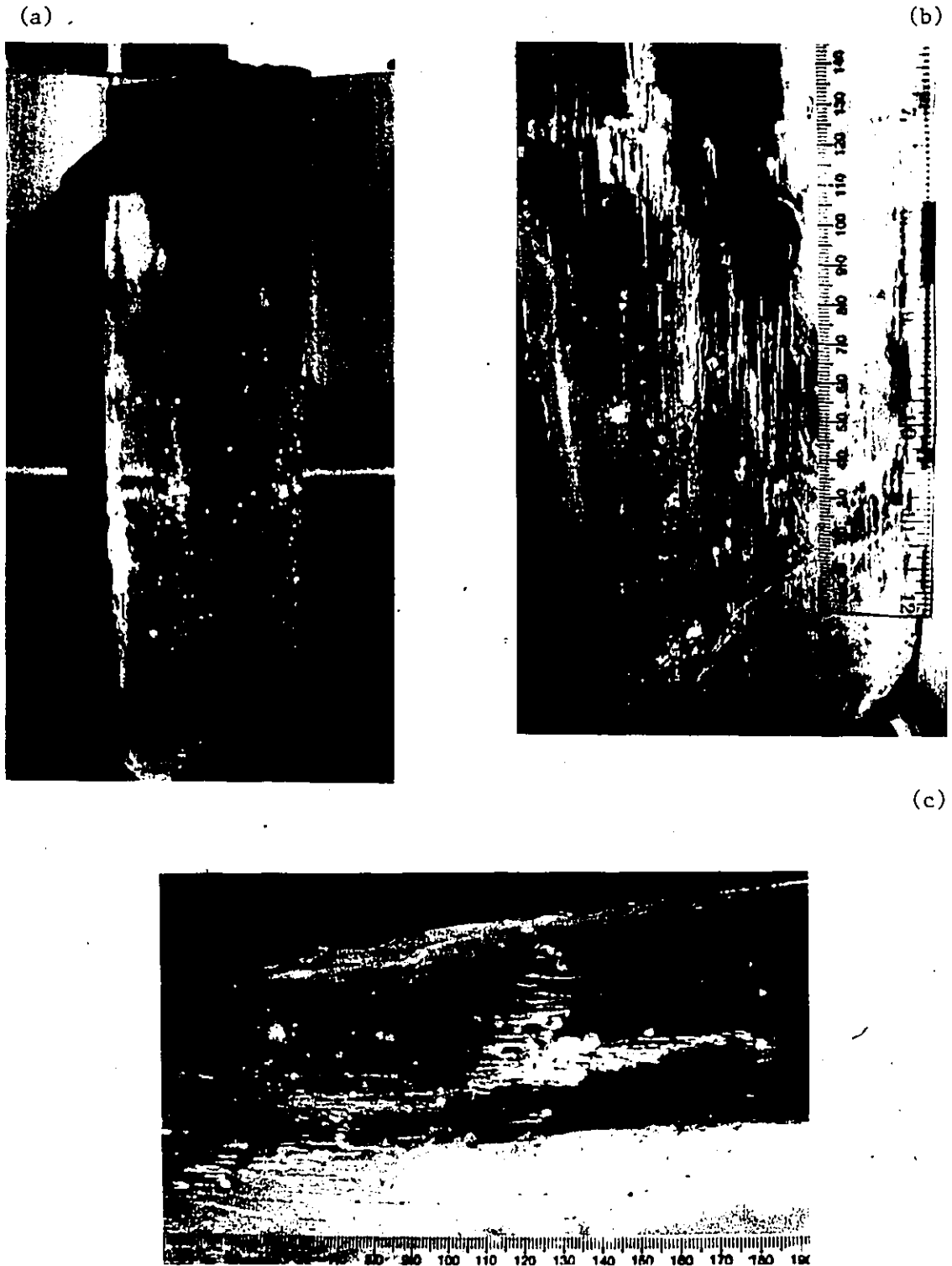


Figure 5.10

Ice from frost blister 1-10, (a) a 40 cm high block from the top of the ice sequence, including the upper segment contact, (b) a close-up of the lower portion of the block, and (c) elongated to bulbous gas bubbles.

of rapid freezing and saturation of the remaining water with respect to the gases rejected. In all cases, bubble elongation was normal to the direction of compositional layering, and parallel to the freezing direction and to the crystalline basal plane. The alternate banding of bubble-free and bubble-rich layers has been interpreted as the result of either a change in gas concentration in the water or possibly a change in freezing rate.

(b) Ice fabric and texture

A number of vertical and horizontal thin sections were prepared from ice at depths of 7, 20 and 40 cm beneath the upper ice-sediment contact. Figures 5.11 and 5.12 present data for the 7 and 40 cm depths.

At the 7 cm depth, a distinct texture of narrow columnar crystals was clearly distinguishable. Crystal diameters ranged from 2 to 15 mm and vertically-oriented crystals ranged from 30 to 90 mm in length. Crystal shape was anhedral and boundaries were essentially straight.

The columnar texture was better defined at depths of 20 and 40 cm. Crystal size increased dramatically at 20 cm; crystal diameters of 15 to 25 mm were common with corresponding column lengths that sometimes exceeded the 200 mm length of the glass slide. At a depth of 40 cm, crystal diameters had increased to 25 to 35 mm and again, column lengths of greater than 200 mm were common. At both depths, crystal shapes were mainly anhedral to slightly subhedral and no lateral irregularities were observed.

(a)



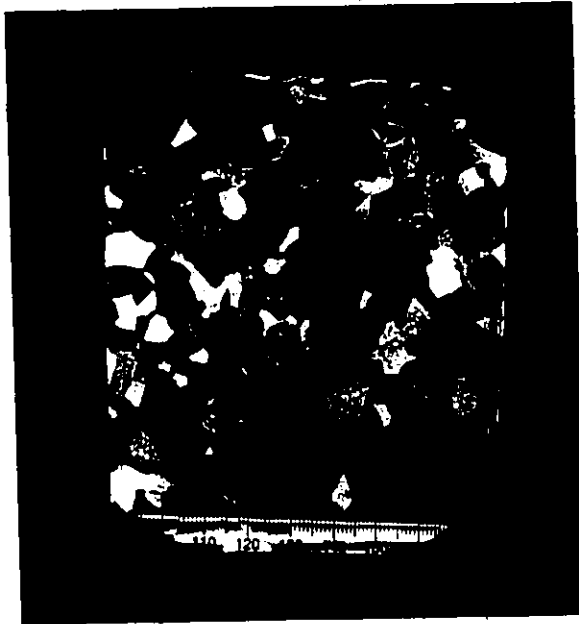
1cm

(b)



Figure 5.11 Vertical thin sections of frost blister ice from mound 1-10 at depths of (a) 7 cm, and (b) 40 cm below the upper sediment contact. (Crossed polarizers).

(a)



1cm

(b)



Figure 5.12

Horizontal thin sections of frost blister ice from mound 1-10 at depths of (a) 7 cm, and (b) 40 cm. Note the greater grain size with depth. (Crossed polarizers).

Irregular and serrated grain boundaries occurred in horizontal sections, while in vertical sections, serrated boundaries in the upper part of the section became smoother and gently curved at depth. For the most part, the main body of the ice core was composed of large, very elongated crystals which grew parallel to the freezing direction. There is little evidence of change in the freezing direction as illustrated by both the crystal texture and the gas bubble patterns which are also elongated, and parallel to freezing direction.

Based on textural characteristics, it appears that initial rapid freezing at the sediment contact resulted in a 'chill zone' of small randomly arranged ice crystals from which the main body of water gradually froze into long tubular crystals. The relationship between crystal and bubble characteristics is such that in the upper zone of high bubble concentration, bubbles are both inter- and intragranular. At depth, the larger elongated bubbles frequently occur along vertical boundaries. From this evidence, it appears there was only one period and direction of growth through the upper 50 cm of ice. Freezing direction was downward from the upper contact. The very large crystal size is distinctive and suggests a constant freezing rate.

Petrofabric analyses were performed on vertical thin sections from three levels in the upper 50 cm of the ice core (Figures 5.13a and 5.13b). In the upper chill zone, the crystal lattice was characterized by a random pattern of c-axis orientations. This corresponds to the

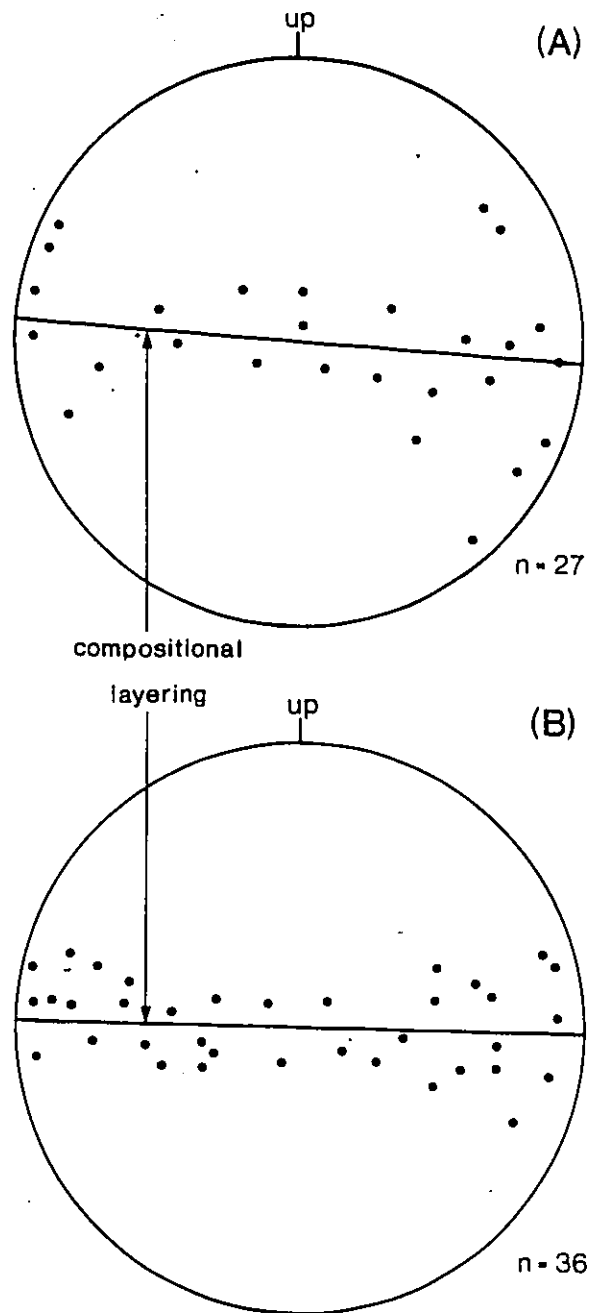


Figure 5.13 Petrofabric diagrams for frost blister ice (mound 1-10) based on crystal orientations of vertical thin sections from depths of (a) 7 cm, and (b) 20 to 40 cm. Horizontal line represents the plane of compositional layering. Dots indicate C-axes of ice crystals.

almost random crystallographic orientation. The main body of the ice core, where the texture was distinctly columnar, was characterized by preferred c-axis orientations forming a girdle around the horizontal plane and normal to crystal elongation (see Figure 5.13). At shallower depths (7 to 17 cm), the girdle of horizontal c-axis orientations was not as well developed as at greater depths within the mound (20 to 30 cm and 40 to 50 cm). The observed lattice orientation where vertically oriented columnar ice has c-axis orientations normal to crystal elongation is one of the three common polycrystalline textures identified by Glenn (1974). This petrofabric is characteristic of the rapid growth of ice in bulk water with crystal growth along the basal plane in a-axis directions.

#### 5.4.2 Frost mound 1-17

Frost mound 1-17 was a small, simple frost blister, circular in plan and round in profile. It was considered typical of many small mounds which formed during the 1980-1981 winter. It attained a maximum height of 0.6 m and a length of 5.7 m and was located at the northern edge of site 1, protruding through the surface of a groundwater icing in May 1981.

##### (a) Ice core character

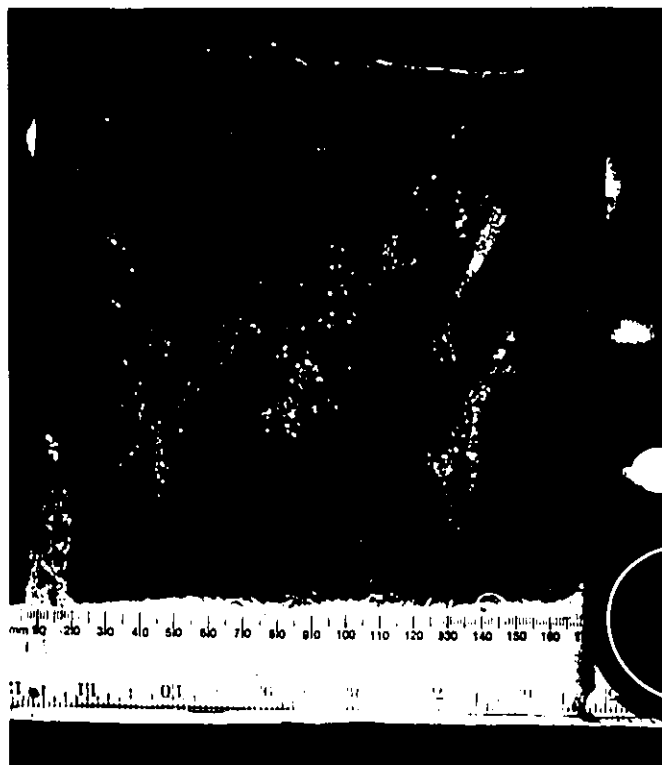
The core consisted of a hemispherical body of clear ice, 60 cm thick. There was no evidence of an air or water-filled cavity. In section, the ice body had a massive appearance with minimal compositional layering. An oriented block

sample, 40 cm thick, was taken from the upper part of the ice core from the apex of the mound profile. The sample included the upper contact with overlying peat and minor compositional layering. Other structures (i.e., faults, ice-filled dilation cracks) were not observed in the ice core.

The transparent characteristics of this type of ice (see Figures 5.14a and 5.14b) are due to the lack of internal melting figures (Tyndall figures, Péwé, 1978) and minimal gas inclusion content. However, the greatest concentration of gas inclusions occurred in the upper 20 cm of the ice core in a layer parallel to the ice/peat contact. Gas bubbles were small (less than 1.5 mm) and spherical, occasionally forming either short bubble trains (up to 10 to 20 mm long) or elongated tubular bubbles. Also included in the upper layer were large pieces of organic matter and fine mineral grains (Figure 5.14a). Gas inclusion content increased in association with these solid inclusions and, frequently, a film of gas enclosed organic and mineral particles. Both sediment and gas bubble content decreased at depth within the ice where only occasional and randomly distributed gas inclusions occurred (Figure 5.14b).

The upper ice/sediment contact varied from sharp to irregular and transitional. The incorporation of fragments of peat was observed in other mounds but not to the same extent as in mound 1-17. The lower contact between the ice and underlying coarse sandy silt was abrupt and planar.

(a)



(b)

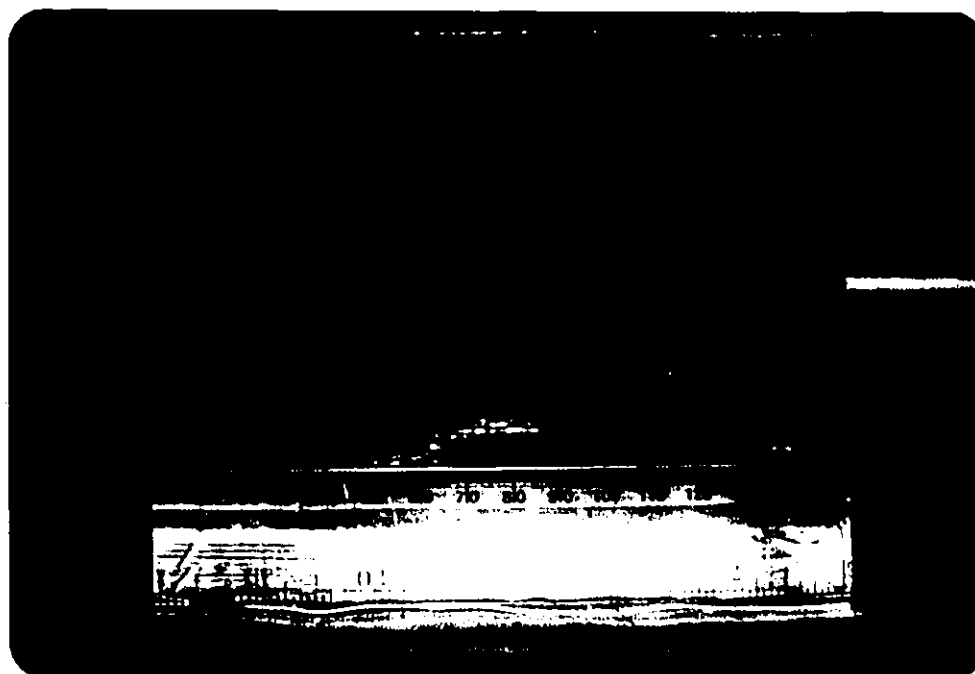


Figure 5.14 Oriented block samples obtained from frost mound 1-17.  
(a) The upper sediment contact, and (b) clear massive ice from deep in the mound core.

(b) Ice fabric characteristics

Ice crystal characteristics were determined from a series of vertical and horizontal thin sections prepared from ice samples from depths of 2 cm, 20 cm and 35 cm in the ice core. The most noticeable characteristic was the wide range in ice crystal size and orientation through the vertical section.

Adjacent to the upper contact, at a depth of 2 cm, a zone of small randomly oriented anhedral ice crystals was observed. Crystals were slightly elongated, average length was 10 mm with maximum lengths of 20 mm and an average diameter of 4 mm. Grain boundaries varied from straight to irregular. They were occasionally modified by the presence of sediment inclusions. This narrow zone is interpreted as a chill zone formed by rapidly freezing water. In all probability, competitive crystal growth and copeous nucleation resulted in a random crystal orientation and the inclusion of a zone of small bubbles where rapid freezing prevented growth of larger bubbles.

Below this upper chill zone, ice crystals became larger and took on a columnar texture. At 20 cm below the contact, long columnar crystals up to 80 mm long and 12 to 15 mm in diameter were not uncommon. At 35 cm, the columnar texture was better defined and ice crystals were larger, up to 150 mm long and 25 mm in diameter. At both depths, the ice crystals were anhedral to subhedral in shape. Grain boundaries were usually smooth or gently curved, but

serrated and feathery boundaries were also observed. The long axes of the tabular crystals were normal to bubble layers and parallel to the assumed thermal gradient and growth direction. The absence of a strong compositional layering and gas inclusions leaves little room for correlation between crystal and inclusion patterns.

Petrofabric analysis was performed on a series of vertical thin sections. In the upper section, a random to slightly preferred pattern of c-axis orientations was observed (Figure 5.15a); however, in the zone of columnar ice crystals, c-axes showed a strong preferred orientation normal to the crystal long axis and the freezing direction (Figure 5.15b). This pattern is similar to that observed in mound 1-10 and, as before, interpreted as characteristic of the rapid freezing of bulk water.

#### 5.4.3 Frost mound 1-4

Frost mound 1-4 is interesting since it experienced growth in two consecutive winters. For this reason, detailed analysis of the ice core was undertaken. The mound first developed during the 1979-1980 winter and, when observed in September 1980, existed as a partially collapsed, simple, oval-shaped frost blister. When observed in 1981, it had doubled in both height and length, and displayed a strongly modified shape and a heavily fractured surface. A description of the location and structure of this mound has already been presented (section 5.2.1c, pp. 116-117).

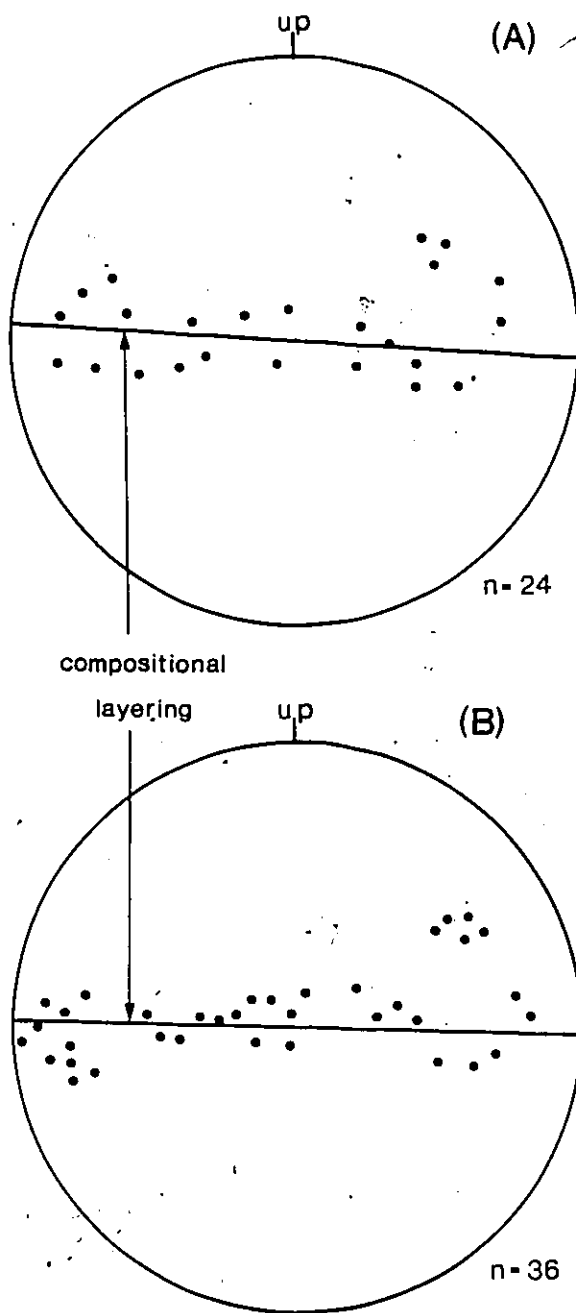


Figure 5.15

Petrofabric diagrams based on vertical thin sections of frost blister ice from mound 1-17 at depths of (a) 2 cm, and (b) 20 to 35 cm. Horizontal line corresponds to the plane of compositional layering. Dots indicate C-axes of ice crystals.

(a) Ice core characteristics

The two dominant ice characteristics were; (a) the candled columnar nature of the exposed ice similar to that observed in other mounds, and (b) the well-developed layering in which some of the layers were separated by distinct unconformities. Figure 5.16 shows both these characteristics.

Candled ice is frequently associated with the melting of lake ice (Andrews, 1962; Knight, 1962). However, in the case of mound 1-4, only the outer 15 to 20 cm of ice exposed in a large dilation crack had decomposed to a candled state. The preferential melting along crystal boundaries in this case clearly defined the crystal structure and texture.

The layering and contact characteristics of the ice core of mound 1-4 presented a number of ice relationships not observed in the other mounds previously described. The irregular nature of the contact between the overlying peat and the upper layer of ice was marked. The greatest irregularities corresponded with two ice lenses that formed the upper layer of the core. The lower contact of these lens-shaped bodies was also distinct, in that the ice lenses unconformably overlaid the ice below. In addition, within the contact was a band of sediment grains.

Initial interpretation was that the upper layer of ice represented the remains of the ice core formed during 1979-1980. With this hypothesis, the irregular upper contact represents a thaw unconformity since, in the previous year,



Figure 5.16 The solid ice core of frost blister 1-4 is characterized by an irregular contact with overlying sediments, unconformities between ice layers and candling of exposed ice. Photo: August 1981.

the mound had partially collapsed. The lower contact represents the boundary between ice of two different years. During growth in 1980-1981, the existing ice was heaved upward by injection of groundwater. The sediment included in a number of places, along the lower contact of the first year ice had frozen to the base of the previous year's ice.

This interpretation is supported by both crystal fabrics and gas inclusion patterns. With respect to gas inclusions, a layer of small spherical gas bubbles occurs in the upper portion of the ice core. At depth, the bubbles are larger and form long bubble trains parallel to the former direction of ice growth. The trains are oriented at angles of  $25^{\circ}$  to  $35^{\circ}$  from the vertical and terminate abruptly at the lower contact with the more recent ice. Immediately beneath the contact, small spherical bubbles (less than 2 mm in diameter) and bubble trains up to 20 mm long are vertically aligned (Figure 5.17).

Crystal textures show a similar pattern (Figures 5.18a and 5.18b). The ice remaining from the original mound has a coarse columnar texture typical of injection ice observed in other mounds. Grain diameters were in the order of 10 to 20 mm and crystals were 150 to 200 mm long. Their long axes are oriented 25 to  $30^{\circ}$  from the vertical as a result of heaving during growth in 1980-1981. Petrofabrics for the older ice show a wider distribution of c-axis orientations. In all probability the slightly modified crystal structure and matrix orientation resulted from the thermal



Figure 5.17 An ice sample from frost blister 1-4 showing the contact between first and second year ice. Note the variation in the direction and pattern of gas bubbles.

(a)



(b)



1cm

Figure 5.18 Sections cut from the ice sample shown in Figure 5.17: (a) thick section, and (b) thin section. Both show the relationship between the gas bubble pattern and ice texture along the contact between first and second year ice. (Crossed polarizers).

and tensile stresses generated during the 1980-1981 period of reactivation.

Petrofabric analysis of thin sections prepared near the contact shows a wide girdle of preferred c-axis orientations normal to crystalline long axes. At depth, the preferred nature of the c-axis orientations forms a girdle closer to the horizontal and normal to crystal long axes. Figure 5.17 shows the gas inclusion patterns in a block of ice taken from the contact between the first and second year ice. Similarly, Figures 5.18a and 5.18b illustrate the different crystal textures observed at the same contact. In some cases, nucleation of crystals in the more recent ice utilized the crystals from above the contact. Crystal boundaries above the contact were serrated and occasionally curved. Anhedral crystals with gently curving grain boundaries occurred below the contact. Petrofabric diagrams for the main ice core show c-axis orientations that compare with petrofabrics observed in mounds 1-10 and 1-17.

### 5.5 Icing blister ice

Mound 1-24 was the only icing blister examined for ice texture and fabric analyses. It formed at site 1 during the 1981-1982 winter. Frost mound activity had been minimal in this area during previous years of study. In March 1982, the icing blister was a simple, oval-shaped feature 1.8 m high and 13.0 m long. Initially, the mound

was cored to determine its internal structure and to install instrumentation to measure hydraulic pressures. The distinction between icing ice and injection ice within the mound is often difficult to make because both may have a layered appearance. Mound 1-24 consisted of 80 cm of layered ice domed over a water-filled chamber, 35 cm high at the apex of the mound. Beneath the water-filled chamber, 10 to 15 cm of clear ice overlay the ground surface vegetation mat. The only visible difference between icing and injection ice observed in the field was the close spacing of layers and opaque appearance of icing ice, in contrast to the transparent appearance of injection ice.

Excavation was undertaken in a portion of the mound containing a solid ice core (Figure 5.19a). At a depth of approximately 65 cm, the distinct layering of the icing ice was replaced by 10 cm of clear injection ice (Figure 5.19b). The latter contained randomly distributed spherical to tubular bubbles and long bubble trains. The layered appearance of the upper section of icing ice consisted of a series of bubble-rich and low bubble content bands forming layers parallel to the icing surface. Upon close inspection, individual layers could be distinguished. The contact was marked by a narrow band of small, closely spaced, spherical bubbles (less than 1 mm in diameter) and bubble trains. Bubble size increased and content decreased upward through each layer. Typically, the bubbles were spherical to tubular in shape and between 5 and 7 mm in diameter. The top of

(a)



(b)

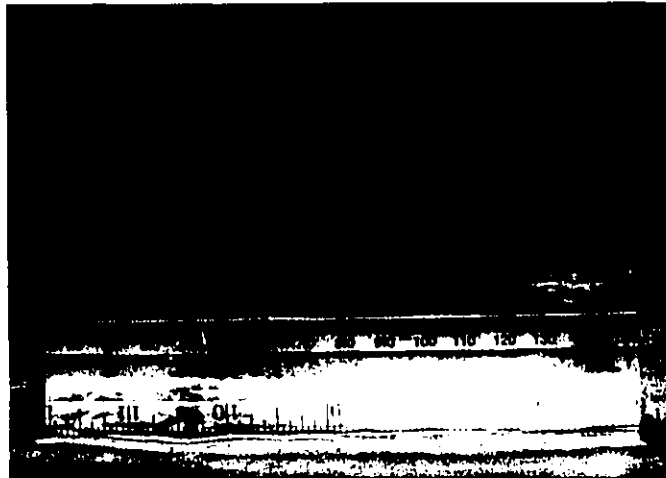


Figure 5119 Ice samples obtained from icing blister 1-24. (a) The upper part of the mound was characterized by opaque, layered ice while, (b) at greater depth the ice was clear with a low bubble content.

each layer was almost bubble-free, providing a marked contrast with the bubble-rich zone beginning the next layer. Layer thicknesses ranged from 1.5 to 5.0 cm and were interpreted as representing one episode or overflow event in icing accumulation.

During periods of peak solar radiation, a film of flowing groundwater will cover sections of the icing. Overflow is localized and may incorporate snow or frost mantling the icing surface. Subsequently, this may influence textures within icings. During the initial stages of icing growth, several tens of centimetres of snow may form the base, while heavy snow accumulation during subsequent growth may result in granular porous zones within the icing. The overflow event usually ends with the onset of colder temperatures. Sometimes, an ice layer forms on top of the overflow and water movement continues underneath. It might be anticipated, therefore, that freezing takes place in two directions; (a) from the icing surface upward, and (b) from the upper overflow downward. This is supported by ice crystal characteristics.

Horizontal and vertical thin sections (Figure 5.20), made from icing ice, indicate ice crystals to be small and anhedral in shape, and elongated in the same place as the horizontal layering. Very small crystals occur in the zone of relatively rapid freezing along the lower contact of the layer. Ice grains along the lower contact tend to be oriented with their long axes vertical. A horizontal section

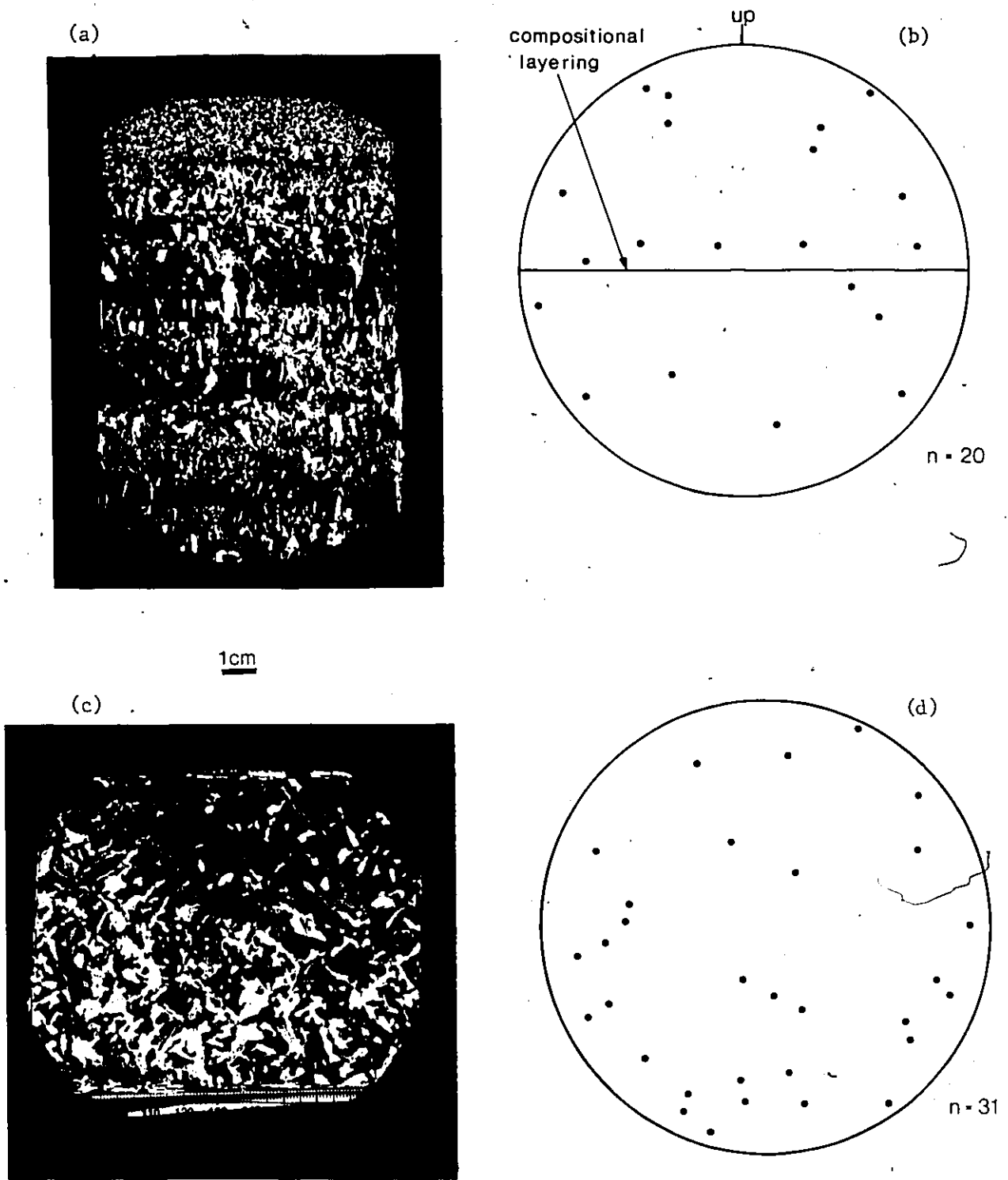


Figure 5.20

Photographs (cross polarizers) of thin sections of icing ice and corresponding fabric diagrams: (a) vertical thin section showing the layered nature of icing ice, (b) fabric diagram based on this thin section, (c) horizontal thin section showing a slight flow pattern, and (d) fabric diagram based on the horizontal thin section. The ice sample was from a depth of 20 cm.

(Figure 5.20a) shows a distinct directional orientation of horizontally layered, small, tabular crystals. This pattern may be a flow texture imparted by the rapid freezing of flowing water. The layered texture is more pronounced when thin sections are examined through polarized light. The layer boundaries are distinct and often defined by an abrupt termination of the larger ice crystals. Conceivably, each sequence of overflow and freezing modifies or partially destroys the underlying ice layer.

Petrofabric analysis of icing ice reveals a random distribution of c-axis orientations (Figures 5.20b and 5.20d). In contrast to icing ice, the clear injection ice occurring inside the mound is composed of large columnar crystals 7 to 15 mm in diameter and 100 to 200 mm long. The columnar crystals are oriented at an angle  $15^\circ$  from the vertical and effectively normal to the compositional layering. Crystal shapes are anhedral to subhedral and grain boundaries are serrated near the upper contact with the icing ice but mainly straight or curved deeper in the section. The columnar texture is similar to the injection ice found in the frost blisters described earlier. Similarly, petrofabric analysis revealed a strong preferred orientation of crystal c-axes normal to the crystal columns.

CHAPTER SIX

GROUNDWATER HYDROLOGY

## 6.1 Introduction

The occurrence of groundwater in areas underlain by permafrost is essentially similar to its occurrence in areas where permafrost is absent (Church, 1974). However, the introduction of permafrost produces several important modifications to groundwater hydrology:

- (1) In permafrost areas, quantities of groundwater are removed indefinitely from circulation and retained in storage as ground ice;
- (2) Low temperatures lead to increased groundwater viscosity (sometimes by a factor of 1.2 to 1.8) which results in reduced rates of groundwater circulation;
- (3) The freezing of soil materials significantly reduces their hydraulic conductivity, and therefore increasing the number of impermeable barriers (aquitards) to groundwater flow;
- (4) The irregular nature of the permafrost table may create drainage divides that do not correspond to either topographic or geologic structures;
- (5) Permafrost may result in perched water tables and confined aquifers.

In summary, even though permafrost does not change the occurrence of groundwater, it may alter its hydrodynamic behaviour. A comprehensive treatment of groundwater in permafrost areas is given by Tolstikhin and Tolstikhin (1974).

The interactions between groundwater circulation and seasonal freezing of the active layer are unquestionably important processes influencing seasonal frost mound occurrence. Although seasonal frost mounds are widely reported from the Arctic and Subarctic (e.g., Frederking, 1979; Leffingwell, 1919; Lewis, 1962; van Everdingen, 1978; 1982), there is a general lack of process observations regarding their occurrence. Usually an understanding of their formation is based either on inferred, indirect or qualitative observations. This chapter focusses therefore on two aspects of groundwater hydrology:

- (1) The determination of groundwater history and circulation patterns, based on hydrochemical and isotopic analyses of water and/or ice associated with perennial spring discharge, icings and frost blisters; and
- (2) The measurement of groundwater hydraulic potentials inside frost and icing blisters.

Study site 1 was chosen for most of these observations. Not only was it the most accessible but also it was the most active from a hydrologic standpoint. Each year, several medium-sized mounds and an extensive icing develop.

## 6.2 Background conditions

Areas of mountainous relief, like the North Fork Pass, have groundwater hydrologic systems that differ from those found in areas of gentler relief. Mountain areas initially benefit from higher precipitation inputs and relative ease of recharge through coarse unconsolidated slope deposits. High hydraulic gradients result in rapid groundwater flow and short residence times. These factors contribute to the abundant occurrence of perennial groundwater springs. Their site-specific behaviour, however, is subject to seasonal and spatial variations in geomorphic conditions.

### 6.2.1 Discharge and runoff

The North Fork Pass receives over 430 mm of precipitation per year, of which 60% occurs as snow. Snowmelt and peak discharge are concentrated in late April and early May. During early summer, groundwater discharge and seepage occur throughout the lower valley-side slopes, but by late summer and fall, spring discharge is limited to perennial sources and is concentrated in the lower 50 to 100 m of the valley sides. During winter, perennial spring discharge is concentrated at the break of slope and within the lower portions of seasonal runoff channels. Seasonal frost mounds form in areas of greatest spring discharge and where there is continuous year-round flow. In each case, mound activity occurs immediately downslope from a spring outlet. Spring locations and seepage lines at site 1 are shown in Figure 6.1,

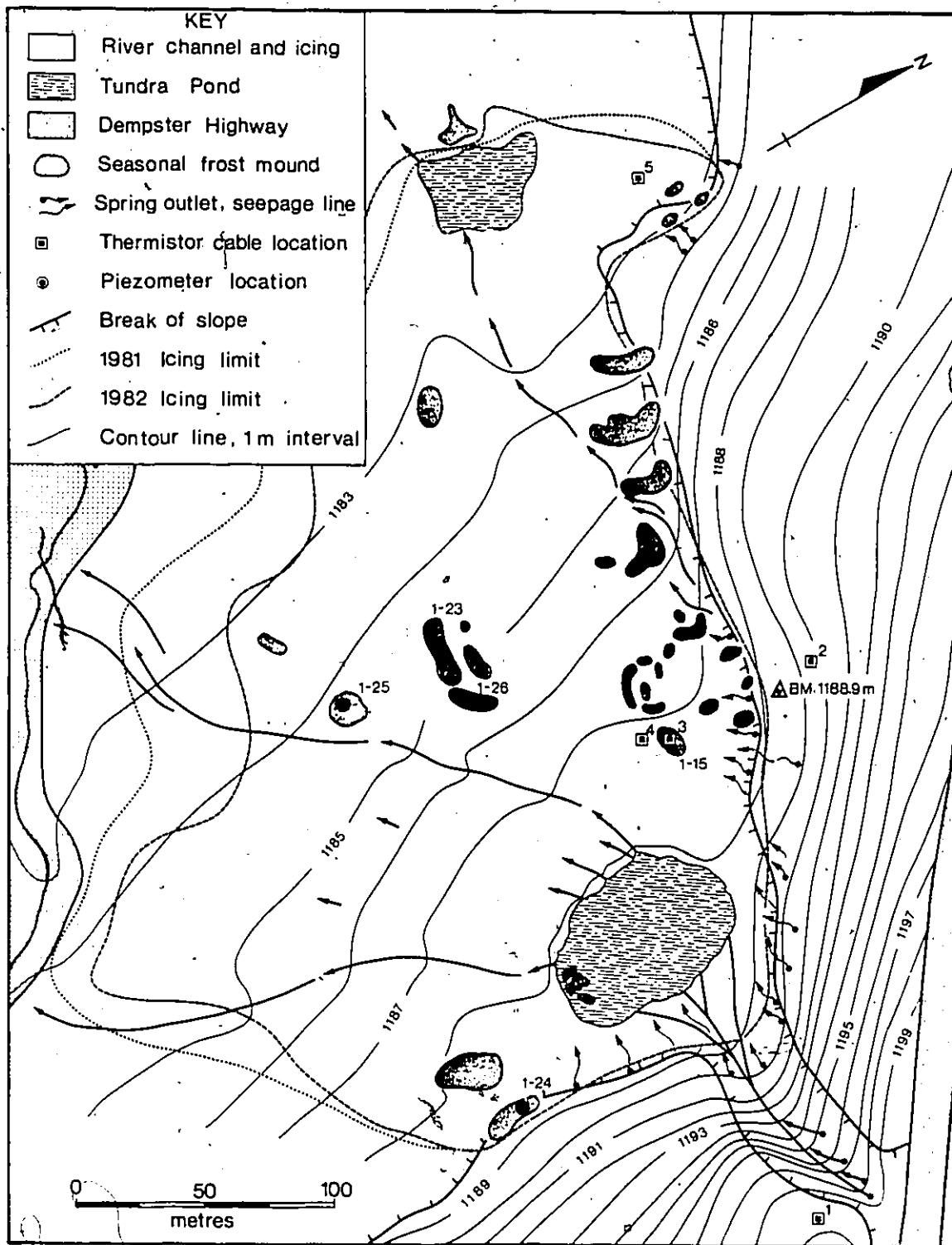


Figure 6.1. Detailed physiographic map of study site 1, North Fork Pass, showing location of instrumentation, seasonal frost mounds, spring outlets, seepage lines and icing distributions. Based on field survey data for 1980, 1981 and 1982.

along with major physiographic features.

The average temperature of groundwater discharge at site 1 is 1.1°C, ranging between -1.0°C in winter and 3.0°C in summer. Throughout the three years of observation, records of pH and conductivity were maintained. Spring discharge tends to be neutral to slightly alkaline with pH values of between 7.0 and 7.9, while pH of surface water and seepage is neutral to slightly acidic (pH 6.9 to 7.4).

Conductivity measurements display a greater seasonal and spatial variation, indicating the influence of dilution by spring runoff. Conductivity ranged between minimum values of 90 to 100  $\mu\text{S cm}^{-1}$  during the spring to over 700 to 750  $\mu\text{S cm}^{-1}$  during late winter. Values concentrate between 450 to 600  $\mu\text{S cm}^{-1}$  during late summer and fall. Solute rejection during freezing tends to increase conductivity in the winter.

At KM 86, spring discharge passes through a culvert under the highway allowing accurate gauging. In May 1981, a flow rate of 3.7 to 4.0  $\ell/\text{sec}$  was measured. In August 1981, flow had decreased to 0.9 to 1.0  $\ell/\text{sec}$  and, when visited again in December of that year, had ceased completely. Elsewhere, typical surface flow velocities near spring outlets on slopes of between 4 to 6° were in the order of 0.20 to 0.30  $\text{m sec}^{-1}$ . On gentler slopes, surface flow velocities ranged between 0.15 and 0.25  $\text{m sec}^{-1}$ . Flow velocities between 0.18 and 0.25  $\text{m sec}^{-1}$  were observed for groundwater overflow on icing surfaces with slopes of 3 to 5°. Prior

to icing formation at site 1, surface runoff and spring outlets are usually indicated by 'breathing holes' in the deep snow cover (Figure 6.2). By late winter, icing accumulations cover the floodplain area downslope from the spring outlets and only some of the spring outlets are still visible through the snow. Snow accumulation in the drainage channels provides excellent insulation allowing spring outlets to remain open beneath the snow. In open areas, removal of snow by wind exposes the ground surface to colder temperatures and promotes freezing. By late March, the depth of icing accumulations usually exceed 1.0 m in places.

The extent of icings at site 1 in May 1981 and March 1982 is presented on Figure 6.1. Also shown are a number of spot measurements of ice thickness based on drilling and surveying. In March 1982, the ice covered approximately  $6.76 \times 10^4 \text{ m}^2$  with an average thickness of roughly 0.7 to 0.9 m. A maximum icing thickness of 1.4 m was observed near the break of slope and it thinned gradually toward its downslope perimeter. The volume of the icing was approximately  $4.73 \times 10^4 - 6.09 \times 10^4 \text{ m}^3$ . In May 1981, the surface area was approximately  $7.5 \times 10^4 \text{ m}^2$ , but the average thickness was only 0.6 to 0.7 m. The volume of ice was roughly  $4.5 \times 10^4 \text{ m}^3 - 5.3 \times 10^4 \text{ m}^3$ .

#### 6.2.2 Ground thermal and physical conditions

Groundwater circulation in frozen materials is controlled, in part, by the thermal characteristics of the

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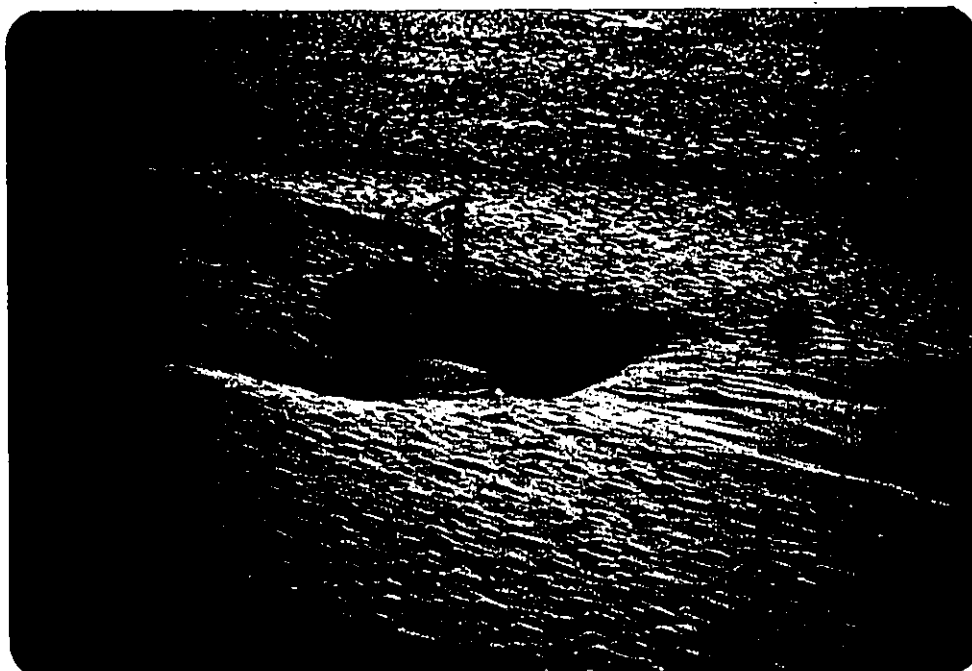


Figure 6.2 A breathing hole through the snow marks the location of perennial spring discharge and a zone of near-surface groundwater transmission in winter. Photo: December 1981.

materials present. Unfrozen water content decreases and pore ice content increases when the bulk temperature of material is lowered from 0°C toward -1°C, and hydraulic conductivity declines by several orders of magnitude as temperature drops below 0°C (Burt and Williams, 1976; van Everdingen, 1976).

These properties are particularly important when considering the hydrodynamics of groundwater circulation through the active layer and the effect of winter freeze-back (Hoekstra, 1966; Mackay, 1983). The manner in which freeze-back occurs (i.e., freezing direction and rate) plays a major role in determining the response of the groundwater system. The relationship between temperature, represented by either the 0°C isotherm or the freezing front, and zones of groundwater transmission is a factor influencing frost mound location and shape. It is probable that the depth of freeze-back at the time of frost blister growth is represented by the thickness of soil materials heaved upward.

During 1981-1982, a program of active layer measurements was undertaken at site 1 to identify areas of greatest groundwater transport potential. The average active layer thickness in the floodplain near the break of slope varied between 51 and 63 cm. On well-drained, southwest-facing slopes, thicknesses averaged between 85 and 95 cm. In areas of groundwater discharge, the bottom of the active layer could not be probed while seepage lines downslope from springs were characterized by thaw depths ranging between 70 to 120 cm.

Typical late summer thermal profiles measured with a YSI telethermometer are presented in Figure 6.3. In addition, thermistor cables were installed to depths of 150 cm at various locations to measure winter ground temperatures (Figure 6.4). A coarse gravel unit found in four of the five locations limited deeper installation of cables.

By December 1981, freeze-back of all cable locations was nearly completed, although, in three cases thin residual active layer zones were still apparent. At that time, air temperatures were between  $-20$  and  $-25^{\circ}\text{C}$  and ground surface temperatures were between  $-3$  and  $-7^{\circ}\text{C}$ . At one location (cable 1), temperatures at depths between 30 and 100 cm were close to  $0^{\circ}\text{C}$ . By the following March, three of the five sites were covered by icings up to 1 m thick. During a two-week period, the cables were read on a number of occasions during which air temperatures varied between  $-7$  and  $-32^{\circ}\text{C}$ . Locations characterized by thick icing accumulations experienced ground surface temperatures that were consistently 3 to  $5^{\circ}\text{C}$  cooler than locations that were either bare or snow covered. At depths 1.0 m below the ground surface, the temperature at icing covered locations was 2 to  $3^{\circ}\text{C}$  cooler. These data, if typical, suggest that lower ground temperatures are maintained beneath the icing surfaces.

Aquifer grain-size is an important variable influencing hydraulic conductivity within a groundwater system. Coarse sediments (e.g., fluvial sands and gravels) are

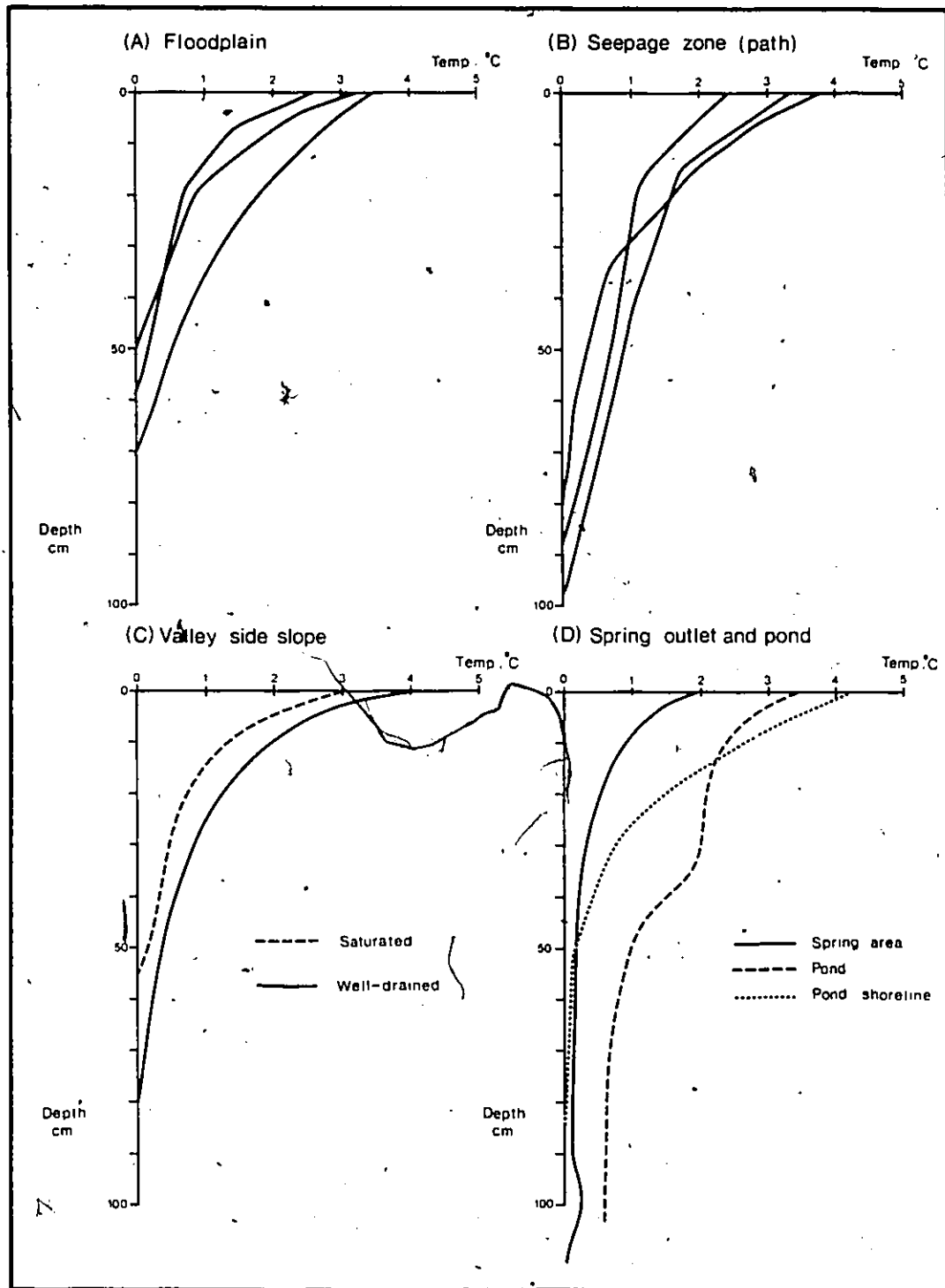


Figure 6.3 Measured active layer temperature profiles at site 1, North Fork Pass. (a) Floodplain, (b) seepage zone, (c) lower valley side slope, and (c) spring outlet and pond area. Measurements made in September 1982.

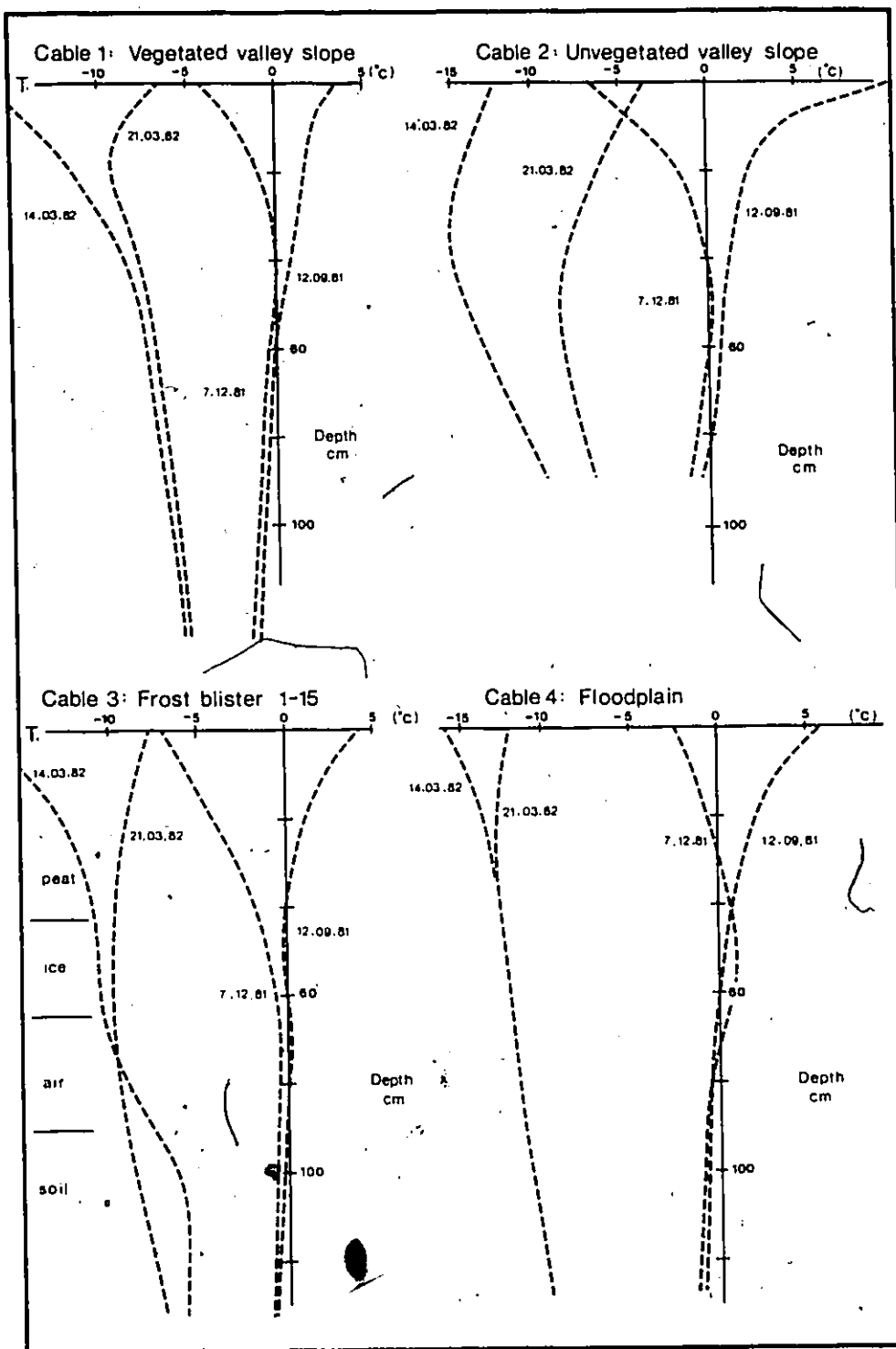


Figure 6.4 Summary of thermistor cable observations at (a) vegetated side valley location, (b) gravelly unvegetated side valley location, (c) frost blister 1-15, and (d) saturated floodplain location during 1981-1982.

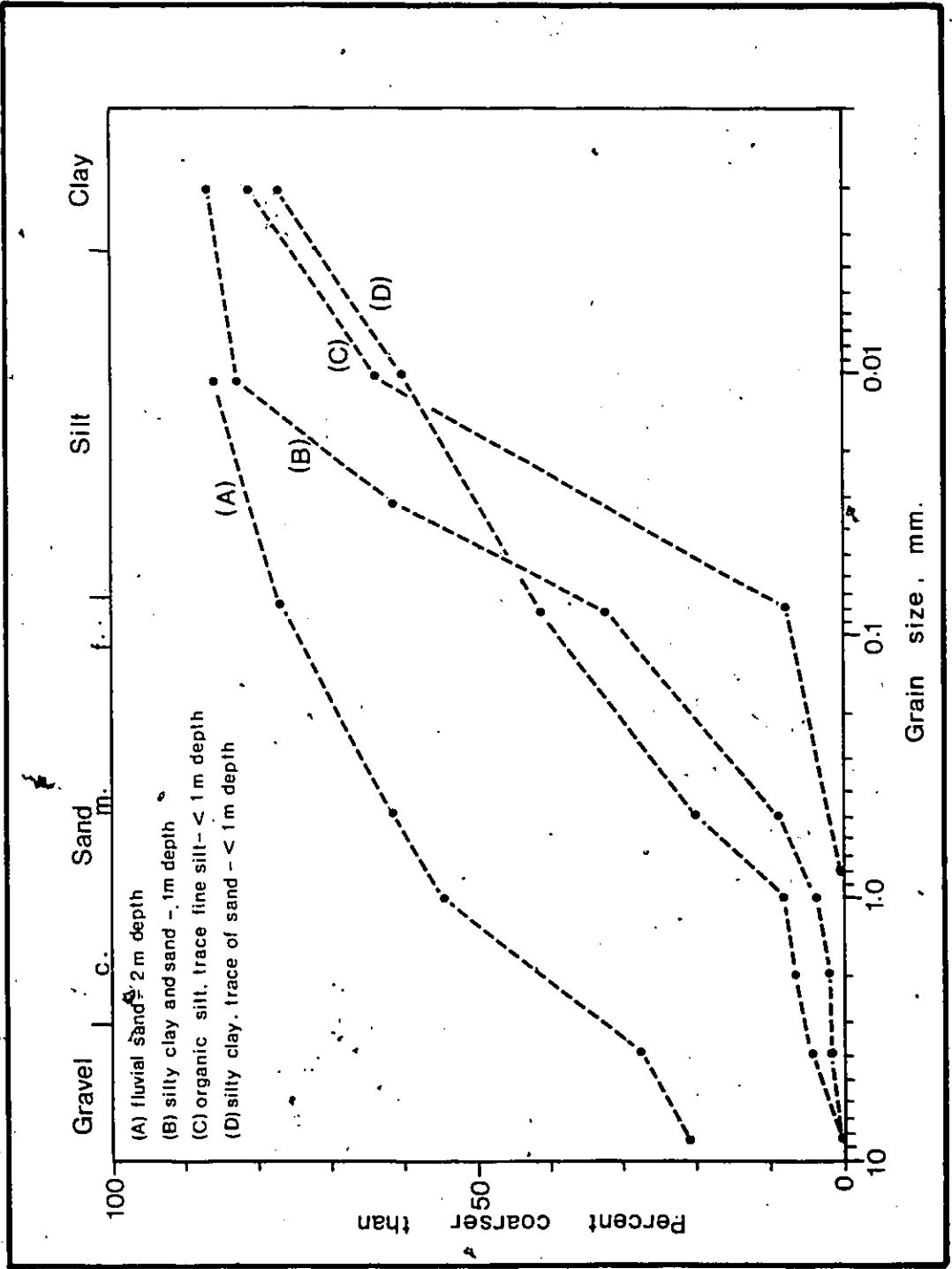
better aquifer materials than fine-grained sediments (e.g., fine silts and clays). Grain-size analysis of surficial materials from the floodplain and lower slopes near study site 1 indicates a relatively high amount of sand and silt-sized materials (Figure 6.5). The main aquifer in the active layer of the valley floor is a sandy silt (Figure 6.5, plots B and D). These materials form both the heaved and underlying sediments in the frost blister structure. The uppermost strata are composed of organic silt and peat (Figure 6.5, plot C).

### 6.3 Hydrochemical and isotope analyses

#### 6.3.1 Introduction

Groundwater circulation is an important factor determining the chemical composition of spring discharge. The distribution of permafrost contributes to the complexity of both local and regional groundwater circulation systems and, in consequence, its dissolved constituents. Furthermore, local variation in permafrost (e.g., thickness, temperature, ground ice content) and active layer conditions (e.g., depth, moisture content, rates of thaw and freeze-back) complicate groundwater circulation patterns. Finally, the occurrence of taliks, assumed to underlie major river channels and lakes, as well as slope and sediment characteristics also influence groundwater circulation.

Hydrochemical and environmental isotope analyses were undertaken to better define the groundwater system



contributing to perennial spring discharge and seasonal frost mound development at the North Fork Pass. In a separate experiment, isotope analysis was performed on an ice core from a frost blister to identify the freezing and hydrologic conditions responsible for mound formation.

#### 6.3.2 Springs and supra-permafrost groundwater

Water samples were collected for chemical analysis from perennial springs, surface runoff and discharge from the icing and a frost blister at site 1. Samples from springs were collected on several occasions during the period 1980-1982. Ice samples were also collected from both icings and frost blisters in March 1982. Results of chemical analyses for samples obtained from site 1 are presented in Table 6.1. Water temperature, pH and conductivity were measured in the field at the time of sampling.

In general, the dissolved solid concentrations for spring water are approximately constant throughout the year, indicating a fairly stable groundwater system. The very low dissolved solids concentrations found in ice samples are the result of solute rejection during freezing. However, the water sample obtained from inside the frost blister exhibits higher dissolved solids concentrations because the unfrozen portion of a frost mound water chamber is enriched with the solute rejected during freezing by the advancing freezing plane. It seems that a similar enrichment would account for the high concentrations found in water

Table 6.1

Hydrochemical Data for Spring Waters, Icing and Frost Mound Ice at Site 1, North Fork Pass.

Sample Source	Spring Area at Site #1		Runoff Through Culvert Above Site #1		Icing Area Site #1		Icing Ice Site #1		Frost Blister Ice Site #1		Frost Blister Dis-charge Site #1	
	Date	19/03/80 <sup>1</sup>	30/03/81 <sup>1</sup>	15/08/81	16/03/82	19/09/80 <sup>1</sup>	18/08/81	22/03/82	22/03/82	21/03/82	21/03/82	21/03/82
Temperature (0°C)	0.9	0.7	1.0	0.5	2.0	1.3	0.0	0.0	0.0	0.5	0.3	
Conductivity (µS/cm)	540	560	590	600	345	480	110	97	920	860		
pH (units)	7.5	7.3	7.7	7.5	7.7	7.7	-	-	8.0	7.9		
Ca (mg/ℓ)	64.2	66.0	62.0	67.4	60.5	62.1	9.1	12.8	98.2	82.2		
Mg (mg/ℓ)	32.0	33.6	35.2	37.1	11.3	14.2	1.2	2.1	51.0	43.1		
Na (mg/ℓ)	5.6	6.3	6.7	7.1	2.0	2.5	2.4	2.9	10.1	8.1		
K (mg/ℓ)	1.9	2.0	1.5	2.2	0.8	1.5	1.9	n/a	3.0	2.5		
HCO <sub>3</sub> (mg/ℓ)	310.8	314.8	323.0	317.1	214.5	210.0	n/a	n/a	n/a	n/a		
SO <sub>4</sub> (mg/ℓ)	39.0	48.0	44.1	52.8	9.0	27.5	4.3	n/a	54.0	41.0		
Cl (mg/ℓ)	0.4	0.4	0.7	0.6	0.5	0.4	1.9	n/a	0.5	0.7		
F (mg/ℓ)	0.07	0.05	TR	TR	0.08	0.07	TR	n/a	0.1	TR		
SiO <sub>2</sub> (mg/ℓ)	8.7	9.0	6.0	6.6	6.5	6.0	1.0	n/a	9.0	7.9		
Total	462.7	480.1	488.2	490.9	305.2	332.0	-	-	-	-		

<sup>1</sup>Analysis supplied by R. O. van Everdingen, National Hydrology Research Institute, Calgary. Other analysis performed by the author.

beneath the icing.

The generally low dissolved solids concentrations indicate that springs discharge from local flow systems and presumably receive their recharge at higher elevations in the mountains east of the Dempster Highway. It also seems evident that the water found inside seasonal frost mounds and beneath the icing are derived from spring groups immediately upslope.

The results of the isotope analyses for spring waters and snowpack are presented in Table 6.2, and illustrated in Figure 6.6. The range in  $^{18}\text{O}$  and  $^2\text{H}$  values for these data show a reasonably good correlation with the global meteoric water line (GMWL) described by Craig (1961). These results support the hypothesis that local unaltered precipitation is the source of water for the flow systems discharging from springs at sites 1 and 3.

Tritium ( $^3\text{H}$ ) concentrations in spring waters (see Table 6.2) are higher than those in precipitation that fell during the study period. These higher values suggest that the spring waters may represent precipitation that fell between ten and fifteen years earlier, during the period when  $^3\text{H}$  concentrations in precipitation were gradually decreasing from the 1963 peak resulting from atmospheric testing of nuclear weapons. The pH of the groundwater is neutral to slightly alkaline. Since the bedrock in this area is characterized by cherty conglomerate with a calcite matrix, this may partly account for the alkaline pH.

Table 6.2

Isotope Data for Spring Waters and Snow Pack Samples  
from the North Fork Pass Area.

Sample Source and Date	Isotopes		
	$\delta^2\text{H}$ , ‰ SMOW	$\delta^{18}\text{O}$ , ‰ SMOW	$^3\text{H}$ , T.U.
Spring Area 1, 19-09-80	-166	-21.8	110±10
Spring Area 2, 19-09-80	-166	-22.0	161±10
Spring Area 2, 30-03-81	-169	-22.8	139±10
Steam from culvert, 19-09-80	-159	-21.1	122±10
Snow pack, 30-03-81	-157	-21.0	-3±10
Rain, Whitehorse, 16-09-80	-125	-17.2	30±10
Snow, Little Fox Lake, 20-09-80	-194	-26.0	14±10

Analysis supplied by Dr. Fred Michel; Department of Geology, Carleton University.

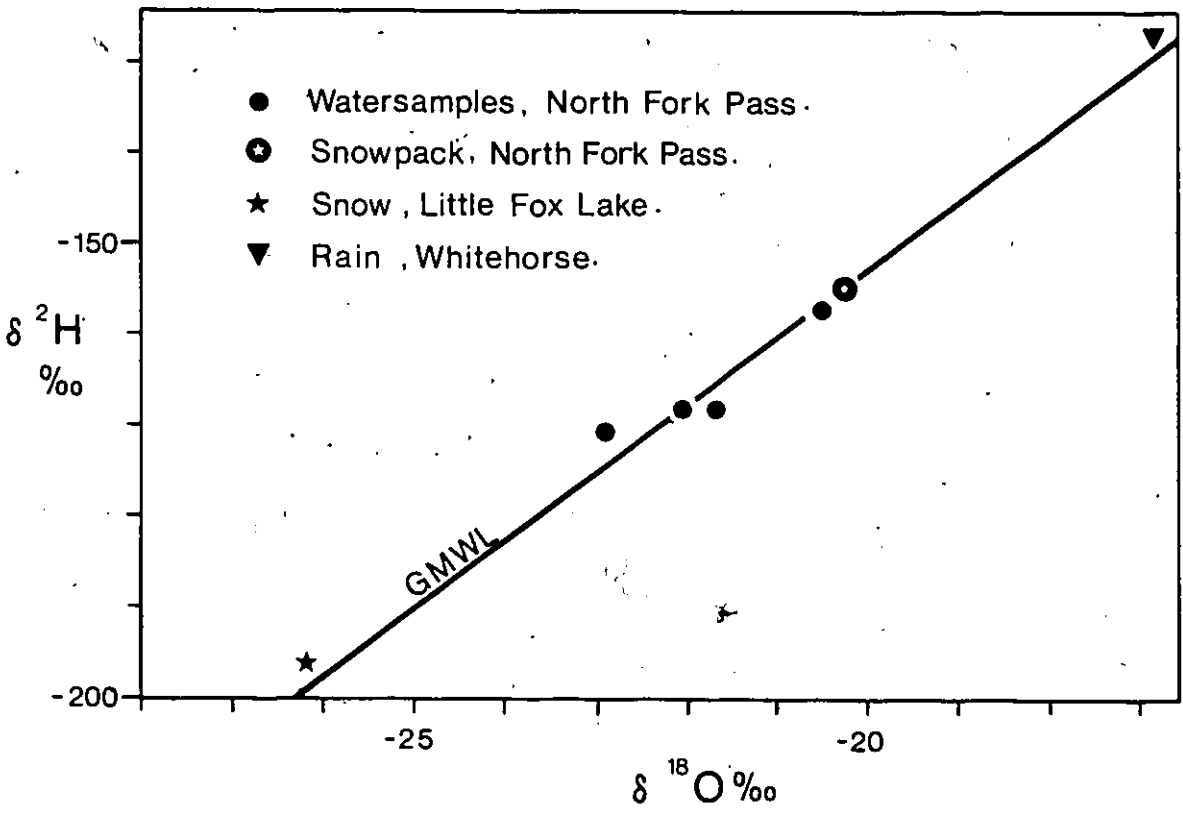


Figure 6.6 Isotope data for water and snowpack samples plotted against global meteoric water line.

During fieldwork in both May 1981 and March 1982, mineral precipitates were observed on icing and plant surfaces, and contained within icing layers (Figure 6.7). In May 1981, the precipitate formed a yellowish stain at several locations on the upslope side of the icing. In March 1982, a fine white powdery residue was noticed at locations where groundwater had recently discharged.

The occurrence of salt and mineral precipitates in association with icings has been documented in many parts of the arctic (e.g., Ackerman, 1980; 1982; Hall, 1980; van Everdingen, 1978; 1982). They may occur in two ways; (a) by evaporation from the water flooding the ice surface, and (b) by solute rejection during freezing.

During May 1981, the thickness of the precipitate ranged from 1 to 5 mm and x-ray diffraction revealed that the precipitate was mainly calcium carbonate (calcite) with minor amounts of quartz. The calcium carbonate is thought to be derived from solution of the local bedrock. The River Road Formation, a cherty-argillaceous conglomerate of Ordovician-Silurian age has a calcite-rich matrix and calcite-filled fractures (Green, 1972). This formation outcrops directly upslope. Weathered talus and alluvial deposits derived from this formation probably constitute the main aquifer materials through which local groundwater systems circulate. The cold perennial springs, ranging between 0.0°C and 3.0°C have a high capacity for dissolved CO<sub>2</sub>, since the amount of CO<sub>2</sub> increases with decreasing temperature.

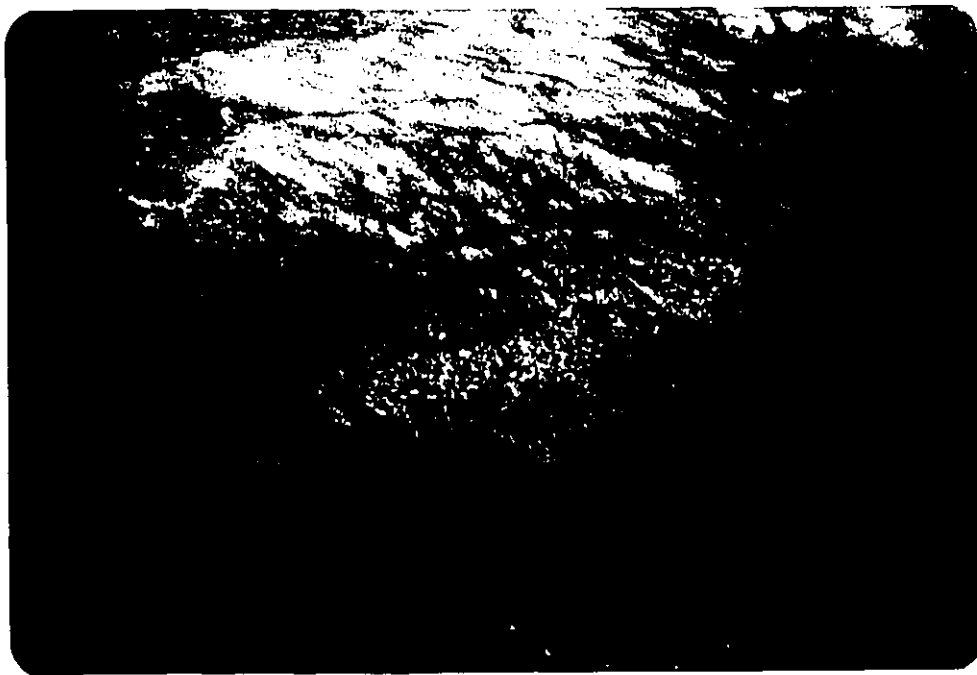


Figure 6.7 Mineral precipitate deposited on the icing surface during freezing. Photo: May 1981.

As the  $\text{CO}_2$  combines with the cold water, carbonic acid ( $\text{H}_2\text{CO}_3$ ) is formed. The carbonic acid is then available to dissolve calcareous bedrock. The solubility of  $\text{CaCO}_3$  increases with increasing  $\text{CO}_2$ . Calcium carbonate dissolved from the bedrock and talus is carried in solution by groundwater. During winter, groundwater discharges form icings and calcium carbonate is rejected during freezing. As the icing ablates, calcium carbonate accumulates on the icing surface as a residual deposit. The  $\text{CaCO}_3$  precipitate indicates, therefore, that the groundwater systems supplying perennial springs and icings flow through the weathered talus and fractured bedrock of the River Road Formation.

### 6.3.3 Isotope fractionation

Since water molecules containing the heavy isotopes  $^{18}\text{O}$  and  $^2\text{H}$  are preferentially incorporated into the solid phase during freezing, ice is enriched with these environmental isotopes. If freezing occurs in a closed system, the residual liquid is depleted with respect to its isotope content, and subsequent freezing produces lower levels of enrichment since the liquid within the shrinking reservoir is constantly being depleted. This effect accelerates as the volume of the reservoir decreases and is most strongly displayed in the youngest ice.

The analysis of heavy isotopes in a frost blister core provides one way of inferring the hydrologic conditions (e.g., open or closed system) during freezing of the ice

core. Therefore, in September 1980, frost blister 1-3 was cored and sampled for the purpose of isotope analysis. The results of these analyses are presented in Figure 6.8, where  $\delta^{18}\text{O}$ ,  $\delta^2\text{H}$  and  $^3\text{H}$  concentrations are plotted against depth.

Figure 6.9 presents a plot of weighted mean values for  $\delta^{18}\text{O}$ ,  $\delta^2\text{H}$  and  $^3\text{H}$  in ice sample numbers 1 to 20. The values (-22.5‰, -171‰ and 149 T.U. respectively) are similar to values obtained from spring waters at site 1. These data provide further evidence to suggest that local spring discharge was the source of water that formed the ice core of frost mound 1-3.

The  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  values in the upper portion of the core are less negative than those for spring water, reflecting small positive fractionations of  $^{18}\text{O}$  and  $^2\text{H}$  during freezing. The differences are, however, less than the equilibrium fraction values suggested by Suzuoki and Kimura (1973) and are problematic. They may indicate rapid freezing and inadequate mixing or leakage from a partially closed system. The increasingly negative values found in the lower part of the core are thought to reflect continued freezing of a gradually shrinking reservoir that was progressively being depleted with respect to the heavier isotopes. The implication is that freezing occurred in a closed system. In the frozen peat lying beneath the ice core,  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  values were similar to those of spring water, indicating that they did not freeze at the same time as the ice core, and consequently, may represent shallow permafrost. The  $^{18}\text{O}$  and  $^2\text{H}$

Sample number

179  
Depth. cm

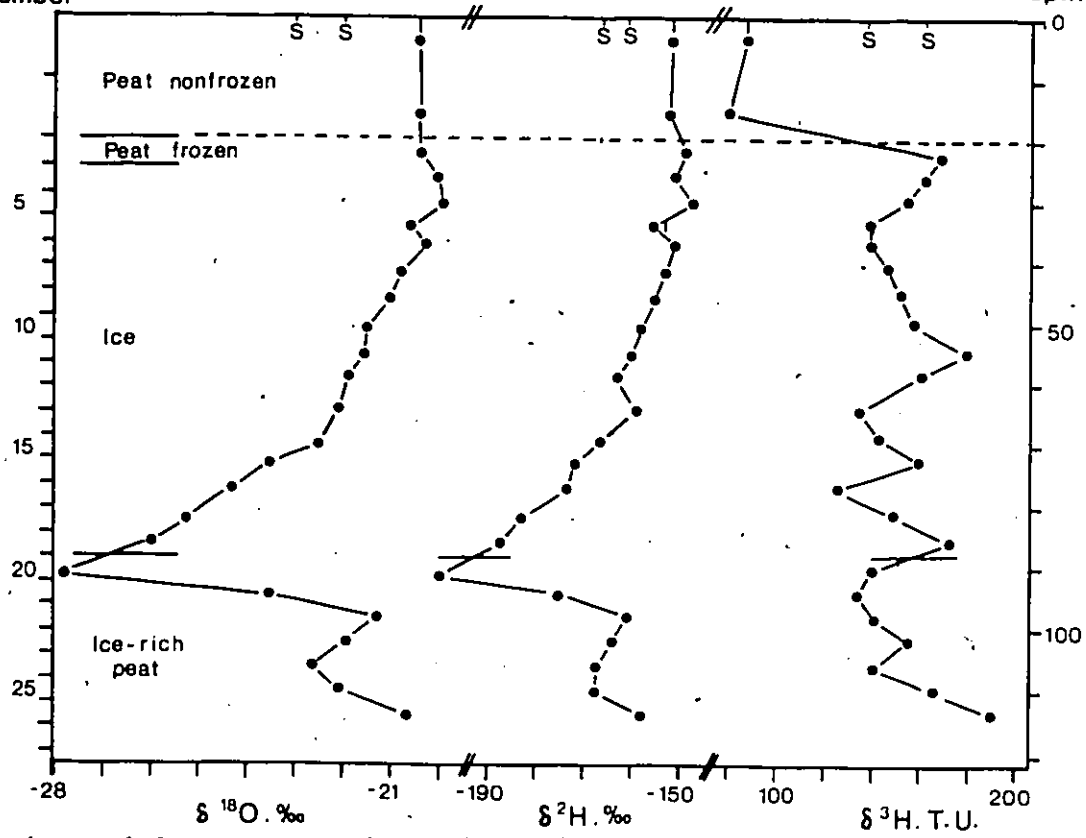


Figure 6.8 Plot of isotopic variation against depth.

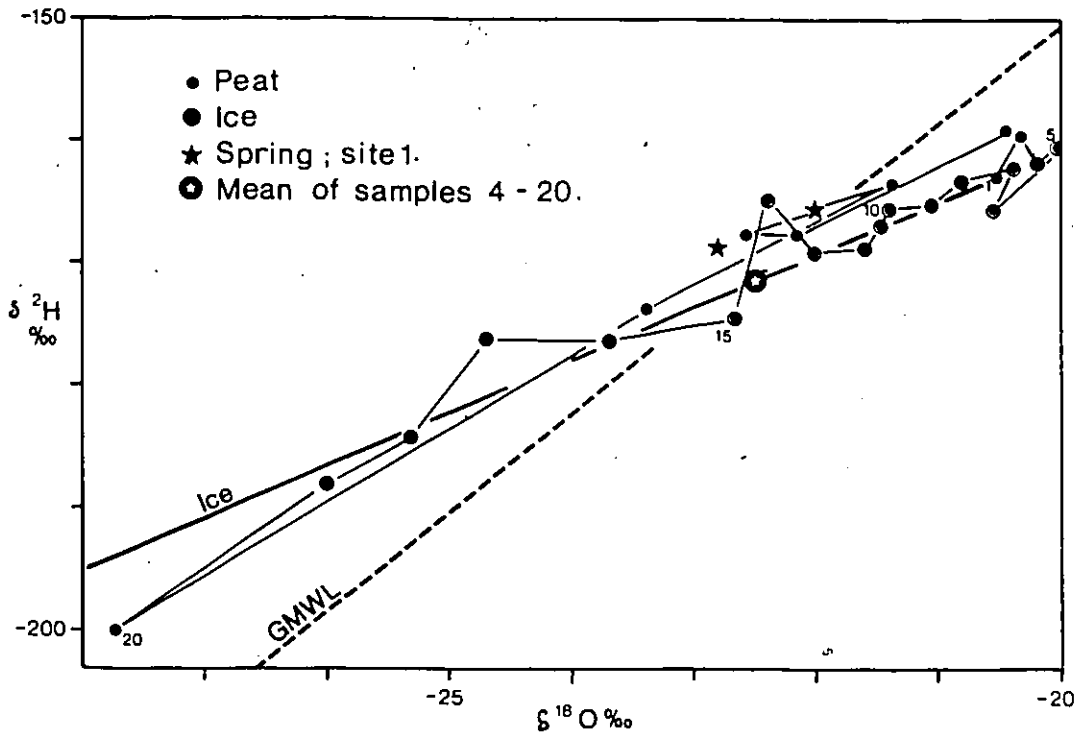


Figure 6.9 Plot of weighted mean isotope values for frost blister ice samples compared with isotope data for springs.

data indicate that the uppermost sample of ice-rich peat from below the ice core, contained the last remaining water to freeze. The isotope profiles indicate that the upper 93 cm of the core formed by freezing downward in a hydrologic system that was initially open but subsequently closed. Freezing occurred in response to seasonally negative air temperatures rather than upward aggradation of permafrost.

The plot of  $\delta^2\text{H}$  against  $\delta^{18}\text{O}$  in Figure 6.9 shows that values for individual ice samples are close to the global meteoric water line described by Craig (1961) and defined by the equation:

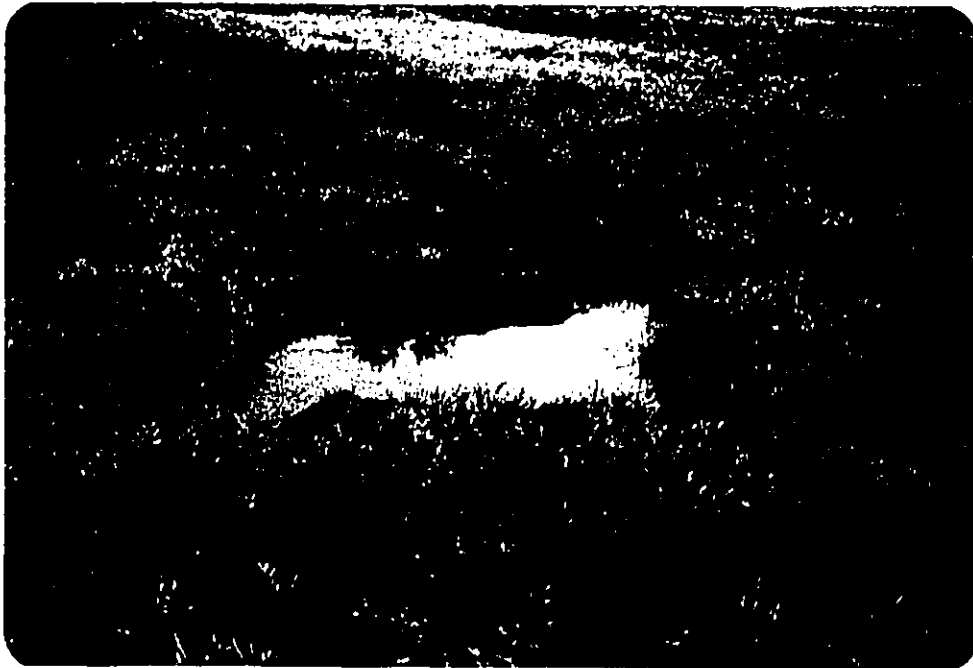
$$\delta^2\text{H} = 8.0 \delta^{18}\text{O} - 10$$

Least squares regression applied to the data for ice samples from the core of frost blister 1-3 is represented by the equation:

$$\delta^2\text{H} = 5.1 \delta^{18}\text{O} - 56.4 \quad (r = 0.99)$$

Similar results have been obtained by van Everdingen (1978; 1982) and also reported by Fritz and Michel (1977) and Michel and Fritz (1978).

(a)



(b)




Figure 6.10 Evidence of explosive frost blister rupture occurs in the form of (a) a water-filled depression (September 1980), and (b) displaced and overturned blocks of peat (May 1981).

## 6.4 Hydraulic potential

### 6.4.1 Introduction

One of the characteristics which distinguishes seasonal frost mounds from morphologically similar features (e.g., palsas) is the dominant moisture transfer processes associated with ice core growth. The duration of the mound is of only secondary importance. Frost blister formation is usually attributed to the development of high hydraulic potentials in suprapermafrost groundwater. When sufficiently high hydraulic potentials occur, the overlying frozen materials are deformed upward and a reservoir, or chamber, of water is formed. Initially, the pressure within the mound is a function of the hydrologic system, but later in the growth cycle, it may be attributed to the hydrostatic and cryostatic pressures associated with closed system freezing.

Little is known concerning the groundwater hydrodynamics and the range of hydraulic potentials associated with seasonal frost mound formation. Present theory is based mainly on indirect evidence (e.g., groundwater discharge from a ruptured mound or explosive mound rupture). For example, recent work by van Everdingen (van Everdingen, 1982; van Everdingen and Banner, 1979), using time-lapse photography, provides data regarding the time and rate of mound growth for the Bear Rock area, N.W.T. Growth rates of up to  $0.55 \text{ m.day}^{-1}$  (van Everdingen, 1982) far exceed potential growth rates expected by ice segregation.



At present, only rough estimates of minimum hydraulic potentials are available. They are obtained by calculating the pressure required to vertically displace the various heaved materials to the heights observed in vertical sections and using assumed density values (weight per unit volume). These calculations assume that resistance to deformation is negligible and therefore provide only minimum estimates.

In the following section, both measured and calculated hydraulic potential data for the North Fork Pass features are discussed. The significance of these observations is that they clearly identify the genesis of mound formation.

#### 6.4.2 Hydraulic potential measurement

During coring of several mounds in September 1981, water-filled chambers were penetrated and trapped gases were released. In one case, in a mound less than 1 m high, sufficient pressure was present to force water 15 to 20 cm up a 7.5 cm diameter borehole, and approximately 50 cm above the level of standing water in the surrounding tundra (requiring approximately 5 kPa of pressure). Presumably, these pressures represented residual pressures associated with the hydraulic potential developed during mound growth in the previous winter. These observations support the hydraulic potential model of mound formation. In addition, the presence of gases, which were probably the product of solute rejection during freezing, raises the question of the role of compressed gases during explosive rupture.

In the case of explosive rupture, loud noises may accompany the displacement of large blocks of ice and frozen sediments (Shumskii, 1964b). No such noises were heard during periods of winter study. However, during the summer of 1980, and again in May 1981, at sites 1 and 4, water-filled excavations/depressions in the tundra surrounded by overturned blocks of peat, or large blocks of peat scattered on the icing surface were observed. These were believed to be the result of explosive rupture (Figure 6.10).

Other circumstantial evidence supports the concept of the gradual build-up of hydraulic potential inside frost mounds. On March 21, 1982, for example, water was observed flowing from a dilation crack in an icing blister at site 1. Discharge continued for two hours and stopped when refreezing had closed the crack. The constant discharge over such a period of time indicates an integrated hydrologic system linked to a perennial spring source, in contrast to a limited flow that would be expected if the water chamber had been part of a closed system. Late in the winter, the integrated nature of the hydrologic system may give way to a series of closed systems with a corresponding change from hydraulic to hydrostatic pressure conditions.

Although the concept of constricted groundwater developing sufficient hydraulic potential, to deform and uplift overlying sediments is fundamental to the present interpretation of seasonal frost mounds, there has been very little success in obtaining pressure values. With

this objective, instrumentation was designed and installed. During March 1982, 24 small and medium-sized (up to 2.5 m high) seasonal frost mounds were drilled to obtain hydraulic potential values. Fourteen were found to be either frozen solid or had empty interior chambers (i.e., the mounds were hydrologically inactive). The remainder were characterized by water-filled chambers under pressure and/or the movement of water up the borehole from zones of water movement within or below the surface icing (Table 6.3). The most active site hydrologically was site 1; it was also characterized by the largest and thickest icing accumulation.

Six antifreeze-filled, closed system piezometers were installed in drillholes where water under pressure had been encountered (see Figures 6.11a and 6.11b). A foam collar (Rubatex) surrounding the piezometer standpipe provided a seal preventing groundwater seepage from the drill-hole and, in each case, the piezometer rapidly froze into place. Of the six units installed, only one failed to yield pressure data. The other five mounds consisted of three icing blisters and two frost blisters. Figure 6.12 shows the range in pressure potentials obtained for a ten-day period from March 14 to 24, for the five functioning units.

The largest mound instrumented was icing blister 1-23. It ranged between 2.19 and 2.30 m in height and at the point where the piezometer was installed, was 2.07 m high. This mound also exhibited the highest pressure values, reaching a maximum of 80 to 81 kPa. Figure 6.12 shows a

Table 6.3

Summary of Hydrologic Conditions for Each Seasonal  
Frost Mound Type Encountered During  
Drilling in March 1982.

	Frost Blister	Icing Blister	Icing Mound	Total
Drilled	9	11	4	24
Solid or drained	6	6	2	14
Instrumented values	2	3	-	5
H <sub>2</sub> O under pressure	3	5	2	10
Failed to recharge	1 (2)	2	-	3 (4)
Displayed seepage from within or beneath the icing mound	-	-	2	2

(a)



(b)



Figure 6.11 Antifreeze-filled piezometers were installed in 5 seasonal frost mounds during March 1982: (a) icing blister 1-24, and (b) frost blister 1-26.

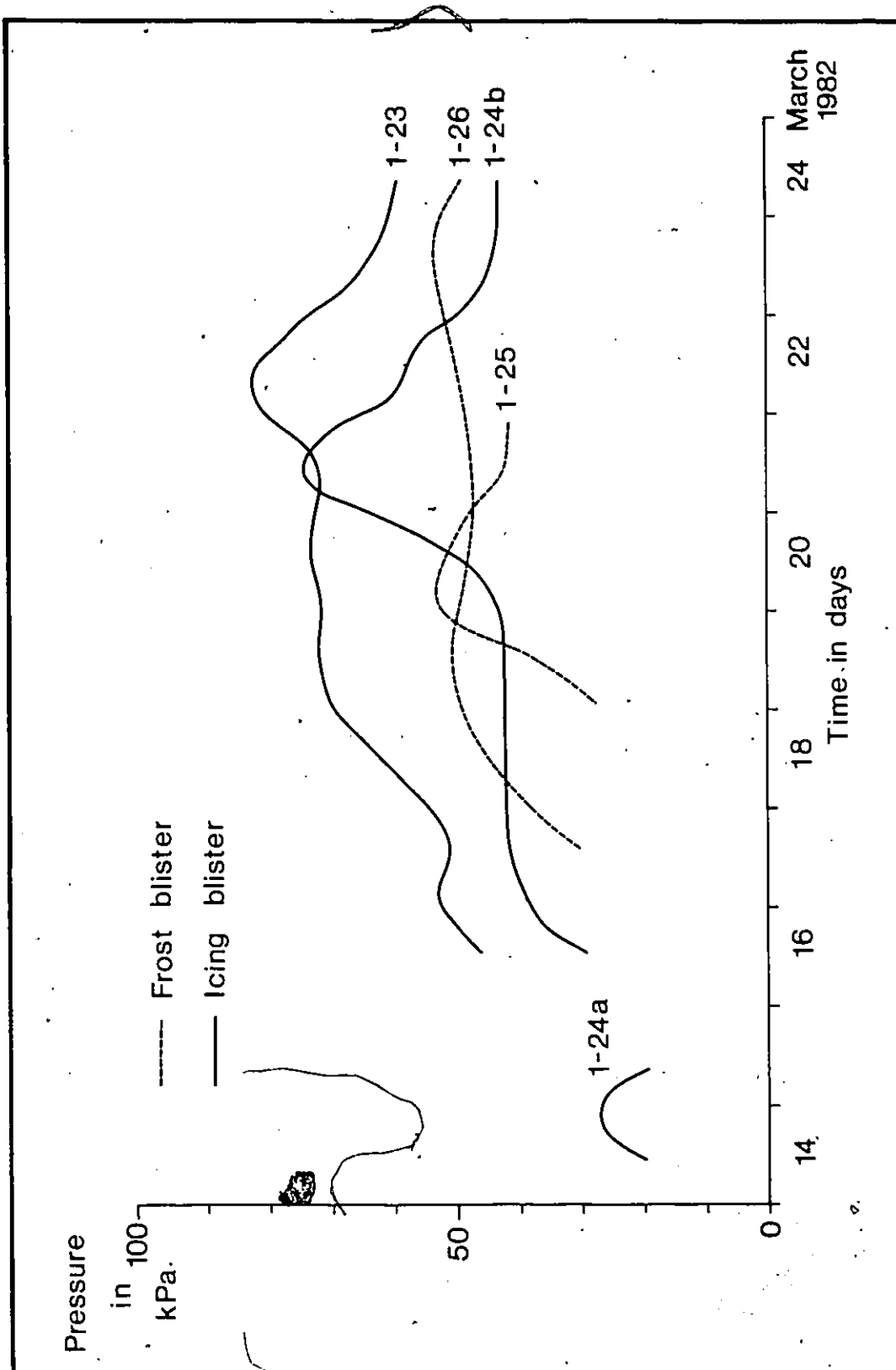


Figure 6.12 Plot of hydraulic potential values measured in the North Fork Pass area.

variable pressure profile for this mound, rising from 50 kPa to 80 kPa over a six-day period and then decreasing. A similar variable trend was also observed for icing blister 1-24. This mound was 1.2 m high and displayed a range in pressure potential between 30 and 75 kPa. In both cases, pressures rose to a peak and then declined. The pressures observed in these two mounds demonstrate (a) a range in hydraulic potential between 30 and 80 kPa, and (b) the variability of hydraulic potentials, possibly reflecting the irregular nature of icing hydrologic activity. On two occasions during the measurement of hydraulic potentials in icing blister 1-24, a second hole was drilled to penetrate the water-filled chamber. On both occasions, a slight loss in pressure (4 to 6 kPa) was registered during the period when water discharged from the mound. However, full recovery was attained two hours after the drillhole had completely refrozen. Additional holes were drilled at various times into the icing surrounding mound 1-24; those located upslope and some adjacent to the mound intercepted water under pressure and flowed freely for periods of one to three hours. However, at no time did the pressure in mound 1-24 change appreciably.

A third icing blister (mound 1-28, 1.2 m high) was also instrumented, but after registering initial pressure potentials of 50 to 55 kPa, no further data were recorded. The loss of hydraulic potential in this mound could be the result of either instrument failure or possibly, mound de-activation.

Hydraulic potentials measured inside frost blisters 1-25 and 1-26 were generally lower and more constant than those documented in the icing blisters. Frost blister 1-26 formed part of a mound complex that also included icing blister 1-23. It was 2.0 and 2.07 m high and covered by a 25 to 35 cm layer of icing ice (Figure 6.11b). The thickness of the icing ice is important because it adds to the resistance to deformation during mound growth, thus requiring higher pressure potentials for mound formation. The icing covering mound 1-26 was considerably thinner than the icing surrounding it. This indicates that formation of the mound predates the main period of icing accumulation. In contrast, icing blister 1-23, which formed near to mound 1-26, possessed a thick icing cover (1.0 to 1.3 m), suggesting that it formed after the formation of the icing. The variable thickness of icing cover provides an indication of the order of occurrence of mounds 1-24, 1-26 and the surrounding icing. The pressures observed in 1-26 ranged between 50 and 60 kPa and displayed less variation than the icing blisters which were instrumented.

Hydraulic potential measurements for frost blister 1-25 were obtained for only a three-day period after which gauge readings dropped to 0 kPa, indicative of either instrument failure or complete loss of pressure in the mound. During that 72-hour period, hydraulic potentials ranged between 30 to 50 kPa.

On several occasions during drilling, a fountain or discharge of water occurred when a water-filled chamber was penetrated. In one case, a jet of water spurted at least 1.2 m into the air and subsided to a fountain of continuous flow 9 to 12 cm in height then decreasing to a simple outflow that continued for nearly two hours and ultimately stopped due to infreezing of the borehole. This case was interesting for another reason; the outflow was charged with gas bubbles producing a foamy appearance. This probably accounts for the explosive nature of the initial jet of water. If these observations are converted to a pressure potential at the base of the water-filled chamber, it would be equivalent to the height of the mound (1.07 m) plus the height of the fountain (1.2 m), which is 2.27 m or approximately 22 kPa, subsiding to roughly 11.0 kPa. In other cases, water fountains ranging between 5 and 15 cm discharged from boreholes in both icing and frost blisters.

#### 6.4.3 Theoretical calculations of hydraulic potential

The direct conversion of fountain height to hydraulic head is not realistic for a number of reasons. For example, the height of the fountain is a flow level and not necessarily the equivalent of a static column of water. Second, the water discharging from the borehole is forced to overcome the weight and downward energy of the collapsing fountain of water. Third, water discharging from the drillhole must overcome the resistance and irregularities of the drillhole,

air pockets within the enclosing ice and ice chips and snow blocking the outlet. Fourth, the low temperature of the water increases its fluid viscosity and cold air temperatures cause refreezing of the borehole. Finally, the constant release of gas bubbles interrupts flow.

Although these fountains cannot be accurately converted to a pressure value, they demonstrate clearly the hydraulic nature and, in some cases, the open nature of the hydrologic system. On other occasions, drilling encountered water under pressure but, following the initial release of pressure, no further discharge was observed. In these instances, it was felt that the hydrologic system feeding the mound had been cut off and it had effectively become a closed system and pressure potentials were hydrostatic in nature.

A series of holes were drilled through the icing around instrumented frost mounds and at a number of locations between the mounds and the break of slope. Three types of water circulation were observed; (a) supra-icing flow in the form of regular overflow, (b) intra-icing flow through channels (pipes) and porous zones within the icing, and (c) sub-icing water flow below the icing and occasionally through surface sediments. Sub- and intra-icing water movement contained pressure potentials equivalent or approximately equal to the level of the icing which in some cases was greater than 1 m above ground level.

Two different theoretical approaches to the calculation of hydraulic potential have been described in the literature. The first was originally presented by Petrov (1934) and is abstracted in Williams (1965, pp. 160-161). Although this procedure requires field measurement using a specially designed apparatus, the approach is still theoretical since the data are used to calculate a resultant mound pressure. In his study, Petrov attempts to measure the difference in freezing temperature between the inside and the outside of a frost blister. A freezing point  $0.4^{\circ}\text{C}$  lower inside the mound was attributed to a depression of the freezing temperature due to a higher pressure. Assuming a depression of  $0.01^{\circ}\text{C}$  corresponds to a pressure of 1.3 atmospheres (131.7 kPa), Petrov estimated that the pressure required to depress the freezing temperature  $0.4^{\circ}\text{C}$  was 52 atmospheres ( $5.27 \times 10^3$  kPa).

This value seems high in comparison with the results obtained in this study and with values reported elsewhere; for example, Shumskii (1964a, p. 229) indicates that pressures of 0.4 to 0.5 atmospheres (40 to 50 kPa) occurred in small icing blisters, and Mackay (1979, p. 23) measured approximately 22 m of hydraulic head (216.5 kPa) for a sub-pingo water lens in a pingo 12 m high. Possible error in Petrov's calculations may be associated with temperature measurement, or the failure to consider fully the role of high concentrations of dissolved solids resulting from solute rejection during freezing.

A second theoretical approach is described by van Everdingen (1978, p. 224; 1982, p. 261). Using an assumed average density value of  $0.9 \text{ gm cm}^{-3}$  for ice,  $1.6 \text{ gm cm}^{-3}$  for frozen saturated soil and  $1.0 \text{ gm cm}^{-3}$  for water, and using an observed stratigraphic sequence and mound height, a minimum required hydraulic potential at the bottom of the water-filled cavity can be calculated. This value is equal to the weight per unit area of overburden plus the water column in the frost blister. It intentionally disregards the resistance to deformation of overlying ice and frozen materials. As such, it represents a minimum required value. For mounds ranging between 2.9 m and 4.9 m high, van Everdingen (1982) calculated minimum pressures of 35.5 kPa and 56.8 kPa, respectively.

Hydraulic potential calculations similar to those by van Everdingen (1982) were made for mounds observed in the North Fork Pass area. A minimum hydraulic potential of 33.6 kPa was calculated to occur at the base of the water-filled chamber of frost blister 1-26 (2.07 m high). Similarly, a pressure of 12.1 kPa was calculated for frost blister 1-25 (1.0 m high). In the case of icing blisters 1-23 (2.3 m high), 1-24 (1.2 m high) and 1-28 (1.2 m high), hydraulic potentials of 21.0 kPa, 10.35 kPa and 11.4 kPa were calculated in the same manner. Table 6.4 summarized both calculated and measured hydraulic potential values for the same mounds. In all but one instance, the measured pressures far exceed calculated values. The difference

Table 6.4

A Comparison of Calculated and Measured Pressure Values for Frost Mounds in the North Fork Pass  
Based on Data Obtained in March 1982.

Frost Mound	Type	Height (m)	Ice	Soil	Water	Total Thickness of (m)			Pressure Difference
						Calculated Pressure	Measured Pressure	Pressure	
						kPa	kPa	kPa	
1-23	Icing blister	2.30	1.60	-	0.70	21.0	50-80	29-69	
1-24	Icing blister	1.20	0.90	-	0.30	10.4	30-75	20-65	
1-25	Frost blister	1.00	0.45	0.30	0.55	33.6	30-50	-3.6-16.4	
1-26	Frost blister	2.07	0.95	0.90	1.12	12.1	50-60	37.9-47.9	
1-28	Icing blister	1.20	0.43	-	0.77	11.4	50-55	38.6-43.6	



may be partly attributable to the tensile strength of the overburden and its resistance to both plastic and elastic deformation.

CHAPTER SEVEN

CONCLUSIONS

## 7.1 Seasonal frost mound occurrence

Seasonal frost mounds are a relatively common phenomena in the East Blackstone River valley near the North Fork Pass. Between September 1980 and November 1982 at least 65 frost mounds were identified at seven locations. Frost blisters are the most common type of seasonal frost mound. The majority of seasonal frost mounds are simple in plan and heights usually range from less than 1.0 m to 3.5 m.

Their distribution in the North Fork Pass area indicates a number of geomorphic characteristics common to each site. All are situated within the floodplain portion of the valley near the break of slope between the debris slopes of the valley side and the lower angled slope of the floodplain. Cold perennial springs discharge near the break of slope maintaining saturated active layer conditions during the summer and sustaining groundwater icing development during the winter. In each case, the valley slopes immediately above the area of frost mound activity are covered by small alluvial fan deposits which serve as aquifers. The alluvial fans are formed by ephemeral stream discharge from small tributary valleys fed by runoff from the nearby mountains. The distal edge of the alluvial fan corresponds to the break of slope.

Stratigraphic investigations demonstrate convincingly that mound formation results from one or more cycles of groundwater injection and freezing. Evidence is provided by the macro-scale structural characteristics of the mounds. Typically, they consist of a concordant body of layered epigenetic ice which forms an unconformable contact with overlying and underlying sediments. Micro-scale structure, in the form of ice lattice and textural characteristics, indicates freezing of bulk water in contrast to ice segregation processes. The crystal and gas inclusion characteristics are similar to those described for lake ice (Gell, 1976; Knight, 1962; Lyons and Stoiber, 1962) and icing mound ice (Gell, 1978). The occurrence of a thin band of bubble-rich, small, anhedral crystals at the ice-soil interface is indicative of a short period of rapid freezing and competitive crystal growth. This layer presumably corresponds to the period of mound growth when groundwater circulation becomes constricted and injection processes initiate the formation of a groundwater reservoir. The presence of a chill zone, the abrupt nature of the upper contact, and the low mineral content of the ice core are evidence that the overlying materials were frozen when heaving began.

The results of  $^{18}\text{O}$ ,  $^2\text{H}$ ,  $^3\text{H}$  and major ion analyses of spring waters and frost blister ice demonstrate that frost blister formation is favoured by local groundwater flow discharging through springs. The flow system is recharged by local precipitation and has a residence time

of 10 to 15 years. The analyses of  $^{18}\text{O}$  and  $^2\text{H}$  from ice samples indicate that ice cores within the mounds were formed predominantly under closed system freezing conditions. As well, isotope analysis indicates downward advancing freezing fronts. This pattern is more typical of freezing of a confined reservoir of water than a body of ice formed by ice segregation.

The drilling of seasonal frost mounds frequently encountered water under pressure within the mound. During summer, water rose 10 to 20 cm into the borehole to a level almost 50 cm above the surrounding water table, possibly reflecting residual hydraulic potentials from the previous winter. During winter, significantly higher pressures were encountered. In some cases, the pressure was sufficient to produce a fountain of water above the top of the mound. Antifreeze-filled piezometers, installed in five frost and icing blisters 1 to 2 m high, registered maximum pressures ranging between 40 to 80 kPa. These values are significantly higher than the minimum required pressures which can be calculated theoretically. The difference is interpreted partly to the resistance to deformation of the enclosing materials. On occasion, the water discharging from a borehole in a frost or icing blister continued to flow for up to two hours and stopped only when freezing closed the outlet. When the same feature was drilled again one to two days later, a similar discharge was observed. This behaviour is interpreted as evidence that seasonal frost mounds are

part of an open hydrologic system where water is constantly being supplied by gravity flow. The tendency for measured pressure values to recover 5 to 15 kPa several hours after piezometer installation reinforces this interpretation.

## 7.2 Recommendations for future research

In recent years, the amount of data available concerning seasonal frost mounds has increased significantly. However, more research is required before the level of understanding currently available for pingos and palsas is reached. Above all, there is need for improved terminology, such that seasonal frost mounds may be clearly distinguished from pingos and palsas.

A second need is for more measurements of frost mound hydraulic potentials. It would be particularly useful if pressures could be obtained for a wide range of frost mound sizes, shapes and types over long periods of time for different geomorphic settings and in different types of soil materials. The results would allow analysis of the relationship between mound size and pressure and provide further insight into the factors influencing frost mound morphology and genesis. The development of more durable pressure measuring devices is also necessary. Extreme cold, rapid changes in temperature and extreme pressure range are the problems facing new instrumentation. Complete encasement by ice and high pressures encountered in ice crystal growth readily damage sensitive pressure cells and unless

instrumentation is very cheap, a throw-away approach is too expensive.

There is also a need for documentation of the relationship between the rate of active layer freeze-back and the timing of frost mound formation. The hypothesis that freeze-back is retarded in zones of groundwater transmission, thereby influencing groundwater supply and mound location, needs to be fully investigated. Also, the depression of the freezing temperature due to increased pressure and dissolved mineral content should receive closer scrutiny.

Experimental investigations could attempt to assess the role of icing accumulation and snow cover upon seasonal frost mound formation by artificially controlling their thickness and distribution on a number of test plots located in known frost mound areas. As a hydrologic phenomena, seasonal frost mounds will be affected by any activity that modifies the normal groundwater circulation pattern. Therefore, further research into groundwater hydrologic processes, particularly those that influence the development of hydraulic potential, would contribute to a better understanding of frost mound occurrence.

A final area for future research is the development of theoretical models for frost mound growth. Using concepts developed for laccolith intrusion in a classic geological sense (e.g., Gilbert, 1877; Johnson, 1970; Johnson and Pollard, 1973; MacCarthy, 1925; Pollard and Johnson, 1973), a theoretical relationship between heaving pressure, ice core

geometry and overburden thickness may be possible. If resistance to deformation of the overburden can be incorporated, such a model would form a useful predictive tool, capable of identifying growth thresholds under varying circumstances. These models would thus provide a unique opportunity to examine the interaction between man's activities in permafrost regions and seasonal frost mound occurrence.

APPENDIX I

FROST MOUND MORPHOLOGY

NORTH FORK PASS, YUKON TERRITORY: SITE 1

FROST MOUND	TYPE	YEAR	STATE	MORPHOLOGY	SYMMETRY	HEIGHT	DIMENSIONAL CHARACTERISTICS			COMMENTS
							LONG AXIS LENGTH L	SHORT AXIS WIDTH W	L/W RATIO	
1.1	frost blister	1980	intact	simple; circular-oval	slightly asymmetrical	1.05m	23.0m - 190°	13.9m - 287°	1.7	local slope angle 4-5°, low flat topped mound 8-10m from the break in slope, isolated.
		1981	-	-	-	1.24m	-	-	-	reactivated during 1980/81 winter, slightly larger with new dilatation cracks
		1982	-	-	-	-	-	-	-	no change
1.2	blister	1980	intact/ partially collapsed	complex; oval	na.	(a) 1.30m (b) 1.60m	18.0m - 136° 7.0m - 120°	6.6m - 237° 3.1m - 300°	2.7 2.3	a group of several intact and partially collapsed mounds located in low saturated area of alpine tundra in a zone of ground water transmission
		1981-82	collapsed	-	-	<1.0m	-	-	-	during 1981 - 82 all mounds in this complex experienced severe thaw subsidence
1.3	blister	1980	partially collapsed	simple; elongated	slightly asymmetrical	1.42m	9.6m - 180°	4.3m - 770°	2.2	local slope angle 3-4° located downslope from 1.2, subsidence along longitudinal dilatation crack
		1981	collapsed	-	-	-	-	-	-	small residual mound and water filled depression
1.4	blister	1980	intact/ partially collapsed	simple; oval	asymmetrical	1.4m	14.0m - 290°	8.0m - 020°	1.8	local slope angle 4-5°, low flat topped mound with minor dilatation cracks, covered in 1980 for isotope analysis
		1981	intact/ new growth	compound; elongated	-	2.3m	27.0m - 290°	18.0m - 020°	1.5	last years mound incorporated into much larger mound, extensive growth upslope to form a compound feature, longitudinal dilatation crack, sampled for ice fabric
		1982	inactive/ collapse	-	-	1.5m	-	-	-	-
1.5	blister	1980	intact	simple; circular	asymmetrical	1.2m	11.0m - 200°	3.7m - 285°	2.9	adjacent mound 1.4, low rounded profile
		1981	-	-	-	1.4m	-	-	-	new growth, slightly higher, dilatation cracks
		1982	no change	-	-	-	-	-	-	has become a stable residual frost mound



## NORTH FORK PASS, YUKON TERRITORY: SITE 1: continued

FROST MOUND	TYPE	YEAR	STATE	MORPHOLOGY	SYMMETRY	DIMENSIONAL CHARACTERISTICS				COMMENTS
						HEIGHT	LENGTH AND ORIENTATION OF THE LONG AXIS	LENGTH AND ORIENTATION OF THE SHORT AXIS	L/W RATIO	
						LENGTH L	WIDTH W			
1.6	frost blister	1980	intact	simple; elongate	asymmetrical	1.5m	13.6m - 160°	5.7m - 260°	2.3	long low mound adjacent to small pond
1.7	frost blister	1980	intact	simple; oval	symmetrical	1.3m	5.8m - 266°	3.7m - 352°	1.6	small rounded mound near 1.6
1.6/7	frost blister	1981	intact	compound; lobate	bimodal	1.6m	15.0m - 260°	13.0m - 340°	1.1	mounds 1.6 and 1.7 reactivated to form a single compound feature
1.8	frost blister	1981	intact	complex; lobate-crenulated	symmetrical & asymmetrical	(a)0.9m (b)0.9m (c)0.7m	3.0m - 140° 5.0m - 021° 5.0m - 180°	1.5m - 030° 2.0m - 340° 3.5m - 180°	2.0 2.5 1.4	a group of low, small mounds developed in the silty organic rich sediments in the south end of the small pond.
1.9	frost blister and icing mound	1981	intact/ partially collapsed	compound; elongated - semicircular	asymmetrical	1.3m	23.7m - 210°	10.0m - 130°	2.3	local slope angle 3-4°, elongated arc shaped frost blister and icing mound located near the break in slope, totally collapsed by August 1981.
1.10	frost blister	1981	intact	compound; elongated	asymmetrical bimodal	2.2m	30.2m - 180°	15.0m - 092°	2.0	local slope 5-6°, long bimodal frost blister located near the break in slope, longitudinal dilation crack upto 35 cm wide
1.11	frost blister	1981	intact	compound; elongated	asymmetrical, bimodal	(a)1.2m (b)1.6m	19.5m - 186°	10.0m - 105° 7.0m - 100°	1.9 2.8	local slope 5-6°, long bimodal frost blister with two main bodies of ice, longitudinal dilation crack, collapsed in 1982
1.12	frost blister	1981	intact	simple; circular	symmetrical	1.1m	16.2m - 185°	12.8m - 091°	1.3	local slope 3°, low flat topped mound no dilation cracking
1.13	frost blister	1981	intact	simple; oval	symmetrical	1.0m	14.5m - 193°	8.5m - 280°	1.5	local slope angle 3-4°, low flat frost blister located in a zone of ground water transmission, collapse in 1982
1.14	frost blister	1981	intact	simple; oval	symmetrical	0.8m	6.0m - 160°	2.3m - 750°	2.6	small low frost blister, collapsed in 1981

NORTH FORK PASS, YUKON TERRITORY: SITE 1 continued

FROST MOUND	TYPE	YEAR	STATE	MORPHOLOGY	SYMMETRY	HEIGHT	DIMENSIONAL CHARACTERISTICS			COMMENTS
							LONG AXIS LENGTH L	SHORT AXIS WIDTH W	L/W RATIO	
1.15	frost blister	1981	intact partially collapsed	simple; circular	symmetrical	0.7m	7.1m - 180°	5.4m - 270°	1.1	local slope angle 3-4°, low small mound near the break in slope, cored in 1981, almost totally collapsed by 1982
1.16	frost blister	1981	intact	simple; oval	asymmetrical	0.7m	6.7m - 211°	3.3m - 130°	2.0	small oval mound adjoining the break in slope collapse started in 1981 and continued in '81,
1.17	frost blister	1981	intact	simple; circular	symmetrical	0.6m	5.7m - 175°	3.8m - 280°	1.5	small mound located at the break in slope, sectioned and sampled in 1981
1.18	icing blister	1981	intact	simple; oval	asymmetrical	0.8m	10.0m - 160°	5.0m - 250°	2.0	a group of 3 icing blisters were observed in May 1981, each displayed a longitudinal dilation crack exposing the interpal structure of mound, all three were located near the break slope in the north part of the study area
1.19	-	-	-	-	symmetrical	0.9m	11.5m - 120°	6.0m - 210°	1.9	
1.20	-	-	-	-	asymmetrical	1.0m	10.7m - 180°	5.5m - 273°	1.9	
1.21 1.22	icing blister/ mound	1981	ruptured	na	na	na	na	na	na	the remnants of 2 icing mounds/blisters occur red immediately downslope from 1.18-20, only a low rim and a water filled depression remained
1.23	frost/icing blister	1982	intact	complex; oval-elongated	asymmetrical	2.3m 2.0m 1.7m	17.0m - 309° 21.0m - 220°	8.1m - 220° 9.5m - 110°	2.1 2.2	during March 1982 a large area was heaved with several separate mounds visible, drilled and instrumented with piezometers
1.24	icing blister	1982	intact	simple; oval	symmetrical	1.8m	13.0m - 300°	6.2m - 211°	2.1	small icing blister located near the break in slope near mound 1.1
1.25	frost blister	1982	intact	simple; circular	symmetrical	0.9m	13.6m - 180°	9.6m - 290°	1.4	March 1982, low flat frost blister, piezometer #4
1.26	frost blister	1982	intact	simple; circular	symmetrical	1.0m	18.2m - 160°	13.1m - 260°	1.4	low, rounded frost blister, minor dilation crack
1.27 1.28	icing blisters	1982	intact	simple; oval	asymmetrical	1.2m 1.0m	10.2m - 200° 6.2m - 300°	3.4m - 300° 3.2m - 220°	3.0 1.9	2 small icing blisters observed in March 1982, both drilled and contained water under pressure

NORTH FORK PASS, YUKON TERRITORY: SITE 2

FROST MOUND	TYPE	YEAR	STATE	MORPHOLOGY	SYMMETRY	HEIGHT	DIMENSIONAL CHARACTERISTICS			COMMENTS
							LONG AXIS LENGTH L	SHORT AXIS WIDTH W	L/W RATIO	
2.1	frost blister	1980	partially collapsed	simple; circular	symmetrical	0.7m	9.2m - 165°	7.3m - 247°	1.3	the frost mounds observed at site 2 consisted entirely of frost blisters, they occurred in 1980 and no other time during the period of observation, all the forms observed in 1980 were located in a relatively confined small basin approximately 80-100m in diameter open on one side, the mounds observed in 1980 gradually collapsed during the following 2 years
2.2	frost blister	1980	partially collapsed	simple; circular	symmetrical	0.9m	10.3m - 180°	8.4m - 259°	1.2	
2.3	frost blister	1980	partially collapsed	simple; elongated	asymmetrical	0.8m	12.0m - 200°	7.7m - 270°	1.6	
2.4	frost blister	1980	partially collapsed	simple; oval	symmetrical	0.5m	8.0m - 192°	6.0m - 110°	1.3	

NORTH FORK PASS, YUKON TERRITORY: SITE 3

FROST MOUND	TYPE	YEAR	STATE	MORPHOLOGY	SYMMETRY	HEIGHT	DIMENSIONAL CHARACTERISTICS			COMMENTS
							LONG AXIS LENGTH L	SHORT AXIS WIDTH W	L/W RATIO	
3.1	frost blister	1980	intact	simple; oval	asymmetrical	1.2m	8.6m - 120°	4.6m - 210°	1.9	local slope angle 5-6°, a mud covered frost blister located beside a small pond, blister developed directly downslope from spring outlet.
		1981/82	-	-	-	-	-	-	-	the size and shape of the mound remained constant through 1981 and began to collapse in 1981/82.
3.2	frost blister	1980	intact	simple; elongated	asymmetrical	1.1m	16.0m - 180°	4.5m - 90°	3.5	similar to mound 3.1, mud covered situated adjacent to pond, remained stable until August 1981, collapsed late summer 1981 and 1982
		1981	-	-	-	< 0.8m	-	-	-	after thaw subsidence
3.3	frost blister	1981	intact cracked	simple; elongated	symmetrical	1.1m	14.3m - 186°	6.0m - 267°	3.4	typical frost blister located on the edge of a small pond near an outlet channel, large longitudinal dilation crack, collapsed by September 1981
3.4	frost blister	1981	partially collapsed	simple; elongated	symmetrical	1.2m	21.1m - 167°	13.2m - 237°	1.6	long, low frost blister top partially collapsed with longitudinal dilation crack pattern collapse complete by end of summer
3.5	frost blister icing blister	1982	intact	simple; elongated/lobate	symmetrical	1.3m	17.6m - 160°	7.4m - 247°	2.4	located downslope from pond near outlet channel, low, ice (icing) covered, dilation cracks upto 30cm wide
3.6	icing mound	1982	intact	simple; circular/oval	asymmetrical	3.0m+	65.0m - 120°	35.0m - 215°	2.1	local slope angle of 4-5°, large icing mound extending from the break in slope near a perennial spring outlet and extending to the middle of a small pond, observed in March 1982, a constant overflow of water was observed

## NORTH FORK PASS, YUKON TERRITORY: SITE 4

FROST MOUND	TYPE	YEAR	STATE	MORPHOLOGY	SYMMETRY	DIMENSIONAL CHARACTERISTICS				COMMENTS
						HEIGHT	LENGTH AND ORIENTATION OF LONG AXIS	LENGTH L	SHORT AXIS WIDTH W	
4.1	icing mound/blister	1981	ruptured	simple; circular	na	1.3m	21.0m - 170°	16.8m - 260°	1.3	* local slope angle 6-7°, a partially collapsed icing blister/mound situated in an icing accumulation near the base of a steep side valley slope
4.2	frost blister	1981	partially collapsed	compound; elongated	asymmetrical bimodal	1.7m 2.2m	24.2m - 181°	13.2m - 270°	1.8	* local slope 4-6°, long, fairly large frost blister situated downslope from 4.1 near the downslope edge of the icing, collapse and melting had occurred along a longitudinal dilation crack, probable original height 3m+
4.3	frost blister	1981	intact/partially collapsed	simple; circular/oval	symmetrical	1.7m	17.0m - 200°	8.6m - 295°	2.0	* local slope 4°, smaller conical mound with an elongated downslope basal diameter, dilation cracks upto 23cm wide
4.4	frost blister	1982	intact/cracked	simple; elongated	asymmetrical	2.3m	21.0m - 250°	7.7m - 145°	2.7	* all the mounds observed in May 1981 had collapsed entirely by 1982
4.5	icing blister	1982	intact/cracked	simple; oval - elongated	asymmetrical	2.4m	22.2m - 277°	8.4m - 160°	2.6	frost blister 4.4 and icing blister 4.5 form part of a complex or group of several mounds situated near the upslope edge of the ground water icing formed by potential spring discharge at the base of a steep side valley slope, both displayed ice filled dilation cracks
4.6	icing blister	1982	intact/cracked	simple; circular	symmetrical	1.4m	7.4m - 169°	6.5m - 260°	1.1	small conical mound with a radial pattern of dilation cracks
4.7	frost blister	1982	intact/cracked	simple; circular/oval	symmetrical	1.9- 2.0m	12.7m - 165°	9.9m - 257°	1.3	local slope angle 3-4°, conical frost blister thin icing cover, radial dilation crackline pattern, drilled - solid ice core-inactive

several small icing, and frost blisters less than 1.0m were also visible during March 1982.

NORTH FORK PASS, YUKON TERRITORY: SITE 5

FROST MOUND	TYPE	YEAR	STATE	MORPHOLOGY	SYMMETRY	HEIGHT	DIMENSIONAL CHARACTERISTICS			COMMENTS
							LONG AXIS LENGTH L	SHORT AXIS WIDTH W	L/W RATIO	
5.1	frost blister	1981	intact/ partially collapsed	simple; oval/elongated	asymmetrical	0.7m	12.2m - 20°	6.5m - 121°	1.8	local slope angle 3-6°, this mound was one of a group of several partially collapsed mounds observed in 1981(Aug), they were situated along the north edge of an alluvial fan 5.1 had totally collapsed by 1982
5.2	frost blister	1981	intact/ partially collapsed	simple; oval	symmetrical	0.7m	5.2m - 360°	1.1m - 77°	1.7	low, flat topped frost blister, longitudinal dilation crack along which subsidence had occurred, surface vegetation included dwarf willow and poplar shrubs
5.3	frost blister	1981	intact/ partially collapsed	simple; elongated	symmetrical	1.2- 1.5m	17.2m - 340°	6.7m - 80°	2.6	local slope angle 4°, long feature in which dilation cracks had exposed the ice core, and standing water in the mound interior, situated in shrub tundra near a runoff channel, collapse complete by 1982
5.4	frost blister	1981	intact	simple; circular	symmetrical	1.0m	7.8m - 300°	5.8m - 21°	1.3	low, flat topped frost blister with a radial pattern of dilation cracks no change in 1982
5.5	frost blister	1982	intact	simple; elongated	asymmetrical	1.5m	40.0m - 33°	15.0m - 300° (24.0m)	2.6	local slope angle of 6-8°, largest mound observed during the study, situated at the break in slope at the distal edge of an alluvial fan, thin icing cover, longitudinal and radial dilation cracking pattern
5.6	frost blister	1982	intact	simple; circular	symmetrical	1.3m	9.6m - 357°	8.1m - 83°	1.2	small conical mound located in the vicinity of the site of mounds 5.1 and 5.2, local slope angle of 3-6°, minor dilation cracking in a radial pattern
5.7	frost/icing blister	1982	intact	compound; elongated lobate	asymmetrical	1.5m	27.0m - 359°	10.0m - 80° (13.4m)max	2.7 2.1	long mound containing both icing and frost blister characteristics, bimodal profile longitudinal dilation cracking pattern

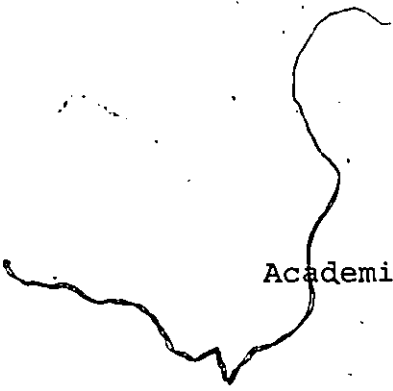
NORTH FORK PASS, YUKON TERRITORY: SITE 6

FROST MOUND	TYPE	YEAR	STATE	MORPHOLOGY	SYMMETRY	HEIGHT	DIMENSIONAL CHARACTERISTICS			COMMENTS
							LENGTH AND ORIENTATION OF THE LONG AXIS	LENGTH AND ORIENTATION OF THE SHORT AXIS	L/W RATIO	
							LENGTH L	WIDTH W		
6.1	frost blister	1982	intact	simple; oval	asymmetrical	3.4m	53.0m - 350°	15.0m - 80°	3.5	local slope angle 9°, this frost blister shows the greatest combined dimensions, it was situated on sloping ground near the break in slope, longitudinal dilation crack 35cm wide ran the entire length of the mound, covered in icine ice, caused snow accumulation on ice
6.2	icing blister	1982	intact	simple; oval/circular	asymmetrical	1.2m	11.1m - 358°	5.0m - 83°	2.2	local slope 5°, located further downslope in low flat area, area covered by icine, dilation cracks 25cm wide
6.3	icing blister	1982	intact	simple; circular/oval	symmetrical	0.8m	7.9m - 360°	6.0m - 94°	1.3	small icine blister with radial dilation cracking pattern, part of main icine area
6.4	icing blister	1982	intact	simple; circular	symmetrical	0.7m	5.2m - 10°	4.1m - 83°	1.3	small icine blister located with a group of other mounds in a flat area near the downslope edge of the icine, local slope 1-5°
6.5	frost blister	1982	intact	simple; oval	slightly asymmetrical	0.8m	8.1m - 360°	5.9m - 80°	1.4	small flat topped frost blister part of the group including mounds 6.4 and 6.6
6.6	frost/icing blister	1982	intact	simple; oval/elongated	symmetrical	0.8m	9.2m - 349°	6.5 - 75°	1.4	
6.7	icing mounds/blisters	1982	intact	complex & compound; circular - oval	-	0.5 to 1.5m	40.0m - 360°	30.0m - 90°	na	SITE 6b: part way up west side of the Blackstone Valley a group, complex of icine mounds and blisters occurred at a periglacial spring outlet well above the valley floor, spring discharge has formed an area of washed gravel and a drainage channel downslope, each year this area develops a large icine containing several mounds

NORTH FORK PASS, YUKON TERRITORY: SITE 7

FROST MOUND	TYPE	YEAR	STATE	MORPHOLOGY	SYMMETRY	HEIGHT	DIMENSIONAL CHARACTERISTICS			COMMENTS
							LONG AXIS LENGTH L	SHORT AXIS WIDTH W	L/W RATIO	
7.1	frost blister	1981	intact	simple; elongated	asymmetrical	1.7m	9.1m - 120°	4.1m - 200°	2.2	local slope angle 7-6°, low gently rounded mound, longitudinal dilation crack along the spine of the mound, minor icing development
7.2	frost blister	1981	partially collapsed	simple; elongated	asymmetrical	1.0m	7.2m - 102°	3.1m - 181°	2.3	low, flat topped mound, advanced stages of collapse at its downslope end
7.3	frost blister	1981	partially collapsed	simple; circular	symmetrical	0.9m	7.0m - 127°	6.4m - 230°	1.1	low circular mound, radial dilation crack pattern, collapsed in the centre
7.4	frost blister	1982	intact	simple; elongated	asymmetrical	1.5m	12.1m - 130°	5.4m - 210°	2.3	the above mounds were observed in either May or August 1981, by March 1982 only collapsed remnants were observed
7.5	frost blister	1982	intact	compound; elongated	asymmetrical bimodal	1.6m	21.0m - 124°	9.3m - 224°	2.2	located 20m downslope from the site of 7.1, 2, & 3, a small icing accumulation but no obvious spring outlet, longitudinal dilation crack
7.6	frost blister	1982	intact cracked	simple; circular	symmetrical	1.2m	7.2m - 100°	6.0m - 200°	1.2	local slope angle 3-5°, in some locations exceeding 7°, this mound displayed 2 main bodies of ice, a longitudinal dilation crack ran the complete length of the mound small conical mound, radial dilation cracking pattern, mound had possibly ruptured because dilation cracks were ice filled and the area surrounding the mound was covered by a small icing

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## ABSTRACT

Seasonal frost mounds are a groundwater discharge phenomenon resulting from increased hydraulic potentials developed by suprapermafrost groundwater in the active layer during winter freeze-back. They form a distinct group of ephemeral and unstable winter landforms. Only a few studies describe them in detail and in some instances, seasonal frost mounds have been confused with palsas. They should also be distinguished from other types of short-lived ice-cored mounds which occur in tundra regions.

This thesis documents the occurrence and internal structure of a number of seasonal frost mounds in the North Fork Pass area of the Ogilvie Mountains, interior Yukon Territory ( $64^{\circ}35'N$ ,  $138^{\circ}18'W$ ). At intervals between September 1980 and March 1982, the growth and decay patterns of more than sixty-five (65) mounds were observed.

Seven localities of frost mound activity were identified, all of which were associated with cold mineralized springs. The mounds occur at or below the break of slope between the valley side and the floodplain of the East Blackstone River. The break of slope is hydrologically significant since it approximates the intersection point between the water table and the ground surface. In all

localities, alluvial fan deposits, formed where small tributary channels join the main valley, cover the lower valley slopes and serve as primary aquifers. Slope angles at all sites range between  $2^{\circ}$  and  $10^{\circ}$  and, since the mounds occur on both sides of the valley, aspect does not appear to be a critical factor in their distribution.

Typically, mounds are covered by a surface vegetation mat which, during winter, is also covered by varying thicknesses of packed snow or icing ice. Beneath the surface organic layer is a thin layer of peat, grading into organic-rich silt. In many mounds, the ice is layered and includes bands of gas bubbles and sediment inclusions. In some small mounds less than 1.0 m high, the core forms a solid epigenetic ice body unconformably overlying frozen ice-rich sediments. By contrast, the larger mounds have cores consisting of one or more layers of clear ice which are usually arched over a water-filled chamber.

Ice fabric studies suggest that the mounds result from the injection of groundwater rather than ice segregation, as might be expected if they were palsas. Two fabric patterns are differentiated: first, a chill zone of small ice crystals with c-axis orientations that form a loose "girdle" parallel to the compositional layering and perpendicular to the growth direction; and second, the fabric is characterized at depth by large vertically oriented long columnar crystals formed parallel to their growth direction. This fabric pattern is similar to that described for lake

ice or injection ice and might be expected in the freezing of a closed water-filled chamber. Hydrochemical and isotopic analyses of frost blister ice and water suggest that mounds are formed by water supplied by local spring groups.

Isotope analysis indicates that these springs are fed by local meteoric recharge with a 10 to 15 year residence time. In some cases, the isotopic profiles indicate that freezing inside the mound occurs under closed system conditions.

Piezometers were inserted in several actively growing mounds during March 1982. The piezometer consisted of a PVC standpipe containing silicone oil which was closed at the top and had a flexible rubber diaphragm at the bottom. A simple pressure meter was attached to the top. Maximum values recorded in four frost mounds, all between 1.0 and 2.0 m high, ranged between 40 and 80 kPa.

It is concluded that seasonal frost mounds of the North Fork Pass area are formed under conditions of high hydraulic potential in which groundwater is injected under pressure into the active layer as it is refreezing. Therefore, seasonal frost mounds are quite distinct from palsas.

## RESUME

Les hydrolaccolithes saisonniers constituent un phénomène d'écoulement d'eau de fond dû à l'augmentation du potentiel hydraulique dans la couche active par l'intrusion d'eau souterraine provenant du suprapergélisol, pendant la progression du front de gel hivernal. Ils composent un groupe distinct de formes de relief hivernales éphémères et instables. Peu d'études les décrivent en détail et, à l'occasion, les hydrolaccolithes ont été confondus avec les palses. Il est également important de les distinguer d'autres types d'hydrolaccolithes de courte durée qui sont présents dans les régions de toundra.

Cette thèse documente l'existence et la structure interne d'un certain nombre d'hydrolaccolithes saisonniers dans la région du col de North Fork dans les montagnes Ogilvie, au Yukon central ( $64^{\circ}35'N$ ,  $138^{\circ}18'W$ ). Entre septembre 1980 et mars 1982, nous avons observé par intervalles les caractéristiques de formation et de dégradation de plus de soixante-cinq (65) hydrolaccolithes saisonniers.

Sept emplacements d'hydrolaccolithes actifs ont été identifiés et tous étaient associés à des sources minéralisées froides. On trouve les hydrolaccolithes juste en dessous ou au niveau de la concavité qui sépare le

versant de vallée et le lit majeur de la rivière East Blackstone. La rupture de pente est importante au point de vue hydrologique puisqu'elle est proche du point d'intersection entre la nappe phréatique et la surface du sol. Dans tous les sites d'observation, des dépôts de cônes alluviaux, formés aux endroits où de petits affluents rejoignent la vallée principale, couvrent les pentes inférieures de la vallée et servent d'aquifères primaires. L'angle des pentes de tous ces sites varie entre  $2^{\circ}$  et  $10^{\circ}$ . Etant donné que les hydrolaccolithes sont présents sur les deux versants de la vallée, l'exposition ne paraît pas jouer un rôle critique dans leur distribution.

L'hydrolaccolithe typique est recouvert d'une couche végétale qui, à son tour, est recouverte pendant l'hiver d'une couche de neige tassée ou de glace givrante d'épaisseur variable. La couche organique de surface repose sur une mince couche de tourbe qui passe graduellement à un limon organique. Dans plusieurs hydrolaccolithes, la glace est disposée en couches superposées et comprend des bulles de gaz en bandes et des inclusions de sédiment. Dans quelques petits hydrolaccolithes mesurant moins de 1 m de hauteur, la glace forme une masse épigénique discordante sur des sédiments gelés et également riches en glace. Par contre, le centre des monticules plus grands est constitué d'une ou de plusieurs couches de glace transparente en forme de dôme, surmontant dans la majorité des cas une cavité remplie d'eau.

L'analyse de la trame glaciaire suggère que les monticules sont le résultat de l'injection d'eau de fond plutôt que de la ségrégation de glace, ce à quoi on pourrait s'attendre s'il s'agissait de paises. Deux types de trames glaciaires se distinguent: premièrement, une zone figée, composée de petits cristaux de glace orientés sur l'axe «c» de façon à former une espèce de ceinture parallèle aux couches de glace et perpendiculaire à la direction de croissance; deuxièmement, la trame est caractérisée au fond par de gros cristaux prismatiques, d'orientation verticale, qui se sont formés dans une direction parallèle à celle de leur croissance. Ce type de trame est semblable à celui qui est décrit en rapport avec la glace lacustre ou d'injection et peut être anticipé lorsqu'il y a congélation dans une cavité fermée remplie d'eau. Des analyses hydrochimiques et isotopiques de l'eau et de la glace d'hydrolaccolithe suggèrent que les monticules sont constitués d'eau qui provient de sources locales. L'étude isotopique révèle que ces sources sont alimentées par les apports météorologiques, avec un temps de résidence de dix à quinze (10-15) ans. Dans certain cas, les profils isotopiques indiquent que la congélation à l'intérieur du monticule se produit en situation de vase clos.

En mars 1982, des piézomètres ont été enfoncés dans plusieurs monticules en formation. Le piézomètre était constitué d'une colonne verticale en PVC qui contenait de l'huile de silicone et dont la partie supérieure était

fermée et l'ouverture inférieure recouverte d'une membrane en caoutchouc souple. Un simple pressiomètre était attaché à la partie supérieure. Les valeurs maximales enregistrées pour quatre hydrolaccolithes, tous entre 1 et 2 m de hauteur, ont varié de 40 à 80 kPa.

Nous concluons que les hydrolaccolithes dans la région du col de North Fork se forment sous des conditions de potentiel hydraulique élevé dans lesquelles l'eau de fond est injectée sous pression dans la couche active pendant que celle-ci est en train de se recongeler. C'est pourquoi les hydrolaccolithes saisonniers sont tout à fait différents des paises.