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Ground Ice Petrography, Sand Hills Moraine, Southern Banks Island, N.W.T.

by

Alison Rothschild

A thesis presented to the School of Graduate Studies and
Research in partial fulfillment of the requirements for
the degree of Master of Arts in Geography

November, 1985

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ABSTRACT

Samples of ground ice collected from the Sand Hills Moraine, southern Banks Island, consisted of small to medium anhedral crystals which varied in size with the presence of sediment inclusions. Air inclusions were spherical to elongate and oriented vertically. Crystal fabrics were strongly oriented at approximately 15°-20° from horizontal, roughly paralleling the ground surface.

Bubble characteristics, and crystal shape, size, and dimensional orientation were all similar to those of segregated ice; however, the steep angled banding of sediment and the near horizontal c-axis orientations were similar to those of glacier ice. Since the ice is overlain by reworked Carpenter Till deposited by the Sand Hills Readvance of the Amundsen Glaciation the ice is probably buried glacier ice of mid-Wisconsin age.

Petrographic analysis of ground ice is useful when major inconsistencies exist between certain structural properties of the ice in question and those expected for a particular type of ground ice. The age of the ground ice and the possibility that it has undergone structural transformation is an important consideration when conducting petrographic analyses.

RESUME

Trois échantillons de glace de sol, qui proviennent de la moraine Sand Hills, Ile Banks, consistaient en cristaux de taille petite à moyenne, sans forme régulière, qui variaient en largeur selon la teneur de sédiments dans la glace. Les inclusions de gaz étaient de forme sphérique ou allongée verticalement. Les fabriques cristallines étaient fortement orientées de 15°-20° par rapport à l'horizon et presque parallèles à la surface du terrain.

Les caractéristiques des bulles et la forme, la largeur et l'orientation dimensionnelle des cristaux étaient semblables à ceux de glace de ségrégation. Or, la pente abrupte des lits de sédiments et les fabriques cristallines ressemblaient à ce que l'on retrouve dans les glaciers. La glace en effet se trouve en-dessous du Till Carpenter, déposé par l'Avancée de Sand Hills pendant la Glaciation d'Amundsen. La glace proviendrait probablement d'un glacier fossile du wisconsinien moyen.

Lorsque la structure de la glace en question n'est pas conforme à la structure d'un des divers types de glace de sol, les analyses pétrographiques peuvent se révéler utiles. Mais il convient d'être prudent, car les caractéristiques structurelles de la glace peuvent changer avec les années et la possibilité de l'apparition de ce phénomène est fonction de l'âge de cette glace.

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Chapter I

INTRODUCTION

1.1 Aims and Objectives

Ground ice is defined as 'ice that occurs in pores, cavities, voids, or other openings in soil or rock including massive ice' (Brown and Kupsch, 1974). It can be found in all types of frozen ground including bedrock and is widespread in regions underlain by permafrost. In places, ground ice occupies 50-70% of the upper 2-3 m of perennially frozen ground (Brown, 1967; Pollard and French, 1980). Locally, it can exceed 90% of the ground volume (Rampton and Mackay, 1971). Ground ice investigations are currently regarded as a priority research area in North America (National Academy of Sciences, 1983). Knowledge deficiencies centre around an incomplete understanding of ground ice distribution patterns and growth mechanisms (Mackay and Black, 1973; Mackay et al., 1978).

Previous studies (French et al., 1982; Harry, 1982) indicate that extensive areas of the Sand Hills Moraine, southern Banks Island (Figure 1.1) are underlain by bodies of massive ice. The origin of this ice is unknown. Accordingly, this thesis seeks to examine the petrography of this ice as one possible means of identifying its origin.

The aim of petrographic analysis is to establish the texture and fabric characteristics of ice in order to determine its growth history. Ice texture refers to the variation of crystal size, shape, dimensional orientation and inclusion characteristics in polycrystalline ice, while fabric refers to either crystal c-axis or a-axis orientation. Techniques used to study ice texture and fabric include surface rubbings of ice (as described by Bader, 1951), the partial melting of ice to reveal crystal boundaries and Tyndall figures (e.g. Mackay and Stager, 1966a, 1966b; Péwé, 1978), and the use of optical properties of ice (e.g., Langway, 1958; Shumskii, 1964b, pp. 116-133). The latter technique is used in this thesis since it allows easy manipulation of individual crystals and repeated detailed measurements for numerous different crystals. Although a petrographic approach has been used in the study of massive ice bodies in the past (e.g. Gell, 1973; 1976; 1978a; Pollard, 1983; and others) there is still a relative lack of data upon the texture and fabrics of different ground ice types.

The location of the study area is shown in Figures 1.1 and 1.2. Ground ice is exposed within several active thaw slumps, thereby permitting detailed field examination. Following reconnaissance fieldwork in the summer of 1983, three blocks of ground ice were collected from one locality and their stratigraphic positions documented. These samples were then transported to the Scientific Resource Centre, Inuvik for detailed petrographic analysis.

1.2 Southern Banks Island

Banks Island is the southwesternmost island in the Canadian Arctic Archipelago. Occupying approximately 60,165 km², it lies between 71° 10' N and 74° 30' N, thus being totally within the zone of continuous permafrost. Data obtained from an exploratory well drilled to the

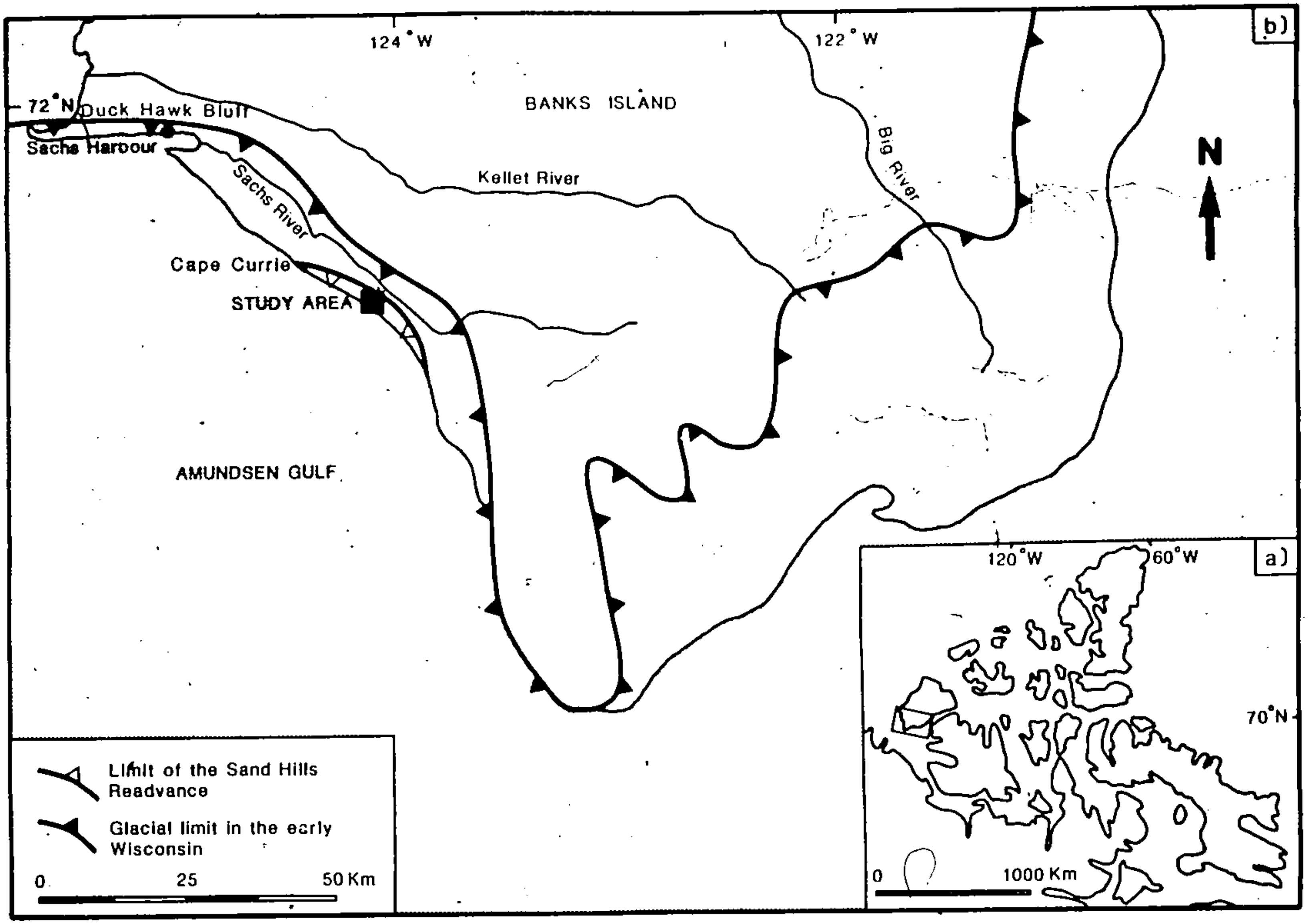


Figure 1.1 a) Location map of Banks Island.
b) The study area showing the limits of the M'Clure Stade of the Amundsen Glaciation. After Vincent (1983).

Figure 1.2 Air photo showing part of the Sand Hills Moraine, southern Banks Island (EMR, Ottawa, A16286-87). The number 1 denotes the location of the slump from which ground ice samples were taken.

southeast of Storkerson Bay on the west coast of the island indicate permafrost to be over 500 m thick and to have a mean annual ground temperature of -13° C (Taylor et al, 1982).

Climatic records kept at the Department of Transport Upper Air Station at Sachs Harbour (Table 1.1) are the most representative of conditions at the study site. The mean annual temperature is -14° C and temperatures range from a mean daily maximum of +10° C during July to a mean daily minimum of -35° C during Febuary. The mean annual precipitation is 104 mm, roughly 50% of which falls as rain during the months of June, July, and August (Maxwell, 1980). Thus, the island experiences a cold arid climate.

1.2.1 Quaternary Geology

Southern Banks Island is underlain by poorly consolidated marine and fluvial sediments of Mesozoic and Tertiary age (Miall, 1979). In the Sand Hills Moraine area an extensive cover of Ouaternary sediments overlies the Beaufort formation. The most recent sediment is Carpenter Till which was deposited during the Sand Hills Readvance (Vincent, 1983). Although no exposures revealed the sediments underlying the Carpenter Till during fieldwork in 1983 and 1984, Vincent (1983) states that the moraine lies directly over either an older till, or sand and gravel of undetermined origin.

Recent work on Banks Island (Vincent, 1980; 1982; 1983) suggests that there have been at least three separate glacial episodes which affected the island. The oldest of these, the Banks Glaciation, covered all of the island except the northwestern part. There is no apparent evidence of this glaciation in the study area although the Bernard Till

	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
(ELEVATION 85 M A.S.L.)												
TEMPERATURE (°C)												
MEAN DAILY	-30.0	-31.0	-28.5	-20.0	-9.0	1.0	5.2	3.7	-2.8	-11.5	-21.5	-27.0
MEAN DAILY MAX.	-27.0	-27.2	-25.0	-17.0	-6.0	3.7	10.0	7.0	0.2	-9.0	-18.0	-23.0
MEAN DAILY MIN.	-34.8	-35.0	-32.1	-23.0	-11.5	-1.0	2.5	0.5	-4.9	-15.0	-25.0	-31.5
PRECIPITATION (MM)												
MEAN SNOWFALL	23.0	23.0	28.0	25.0	69.0	20.0	20.0	41.0	79.0	139.0	72.0	40.0
MEAN RAINFALL	0.0	0.0	0.0	0.0	T	5.8	16.0	18.1	5.6	0.0	0.0	0.0

Table 1.1 Selected climatological data, Sachs Harbour, 1955-1978 (source: Maxwell, 1980).

and sediments associated with a post Banks Glaciation marine episode are exposed at Duck Hawk Bluff on the southwest corner of the island (Vincent, 1980, pp. 139-140; 1983).

A second glaciation, referred to as the Thomsen Glaciation, covered only the southern and eastern parts of the island. During this glaciation the limit of ice advance was just east of the study area. The associated marine event, the Big Sea, inundated eastern and western Banks Island. Although no absolute ages for the Banks and Thomsen Glaciations are known, radiocarbon dating of organic material overlying Big Sea sediments and underlying marine sediments believed to have been deposited prior to a third, younger, glaciation give a date of >61,000 years B.P., thus providing a minimum age for the Thomsen Glaciation (Vincent, 1983).

The most recent glacial episode to have affected Banks Island is the Amundsen Glaciation. During the first stade of this glaciation, termed the M'Clure Stade, three different lobes of ice overrode the island. One flowed northwards along Prince of Wales Strait, another flowed northwestwards into Thesiger Bay and a third flowed westwards along M'Clure Strait. The Sachs Till, deposited on the southern part of the island by the Thesiger lobe, has a pinkish sand/silt matrix and contains mainland erratics (Vincent, 1983).

Following the retreat of ice from its maximum position, a local readvance of the Thesiger Lobe, termed the Sand Hills Readvance, occurred and the Carpenter Till was deposited forming the Sand Hills Moraine. The exact age of this moraine is not known; however, on the basis of radiocarbon and amino-acid shell dating, Vincent (1980, pp.

208-209) considers the Amundsen Glaciation to have taken place during early or mid-Wisconsin times with an age >41,000 years. Radiocarbon dating of shells found in a raised spit believed to have been constructed in the Meek Point Sea following the retreat of the Thesiger Lobe gave an age of >19,000 years. On this basis, Vincent (1982) suggests that the Thesiger Lobe pre-dates the late Wisconsin and that the Sand Hills Moraine is probably mid-Wisconsin in age.

The recognition of both epigenetic and syngenetic ice wedges suggests that permafrost aggradation on southwest Banks Island has occurred throughout late Quaternary times, with the exception of a period of deeper seasonal thaw during mid-Holocene time (French, et al., 1982). Evidence of deeper seasonal thaw is associated with thaw lakes that occur at various localities on the island. For example, radiocarbon dating of organic materials collected from the base of lacustrine sediments at two locations in the Sachs River Lowlands yields maximum ages for the initiation of lake sedimentation of approximately 8,200-8,500 yrs B.P. (French and Harry, 1983; Vincent, 1980, p. 237). It is likely that many thaw lake basins were initiated at this time which corresponds to an early phase of the mid-Holocene climatic optimum (French and Harry, 1983; Ritchie and Hare, 1971). The growth of pingos and pingo-like mounds in the Bernard, Thomsen, and Sachs River Valleys also indicates a previous warming trend. It has been demonstrated that some of these forms developed between 4,000 and 5,000 yrs B.P. (French and Dutkiewicz, 1976; Pissart and French, 1976). A greater depth of thaw triggered by warmer temperatures is offered as an explanation for the occurrence of taliks of sufficient dimensions to ensure pingo growth.

1.3 The Sand Hills Moraine

1.3.1 Extent and Morphology

The Sand Hills Moraine begins approximately 40 km southeast of Sachs Harbour and extends along the coast for a distance of 25 km separating Thesiger Bay from the Sachs River Valley (Figure 1.1).

Two parallel ridges may be identified (Figure 1.3). The one nearest the coast reaches a maximum elevation of 90 m a.s.l. and currently experiences considerable thermokarst activity (Figure 1.3a), usually triggered by coastal erosion. Further inland, a second, more hummocky ridge with steeply sloping hills and numerous deep kettle lakes reaches a maximum elevation of 120 m a.s.l. (Figure 1.3b). It is not presently undergoing, nor does it appear to have undergone, the same type of thermokarst activity as is found in the ridge along the coast. This may be the reason why slope angles are higher on the inland ridge. Maximum angles as steep as 29° occur, although most range between 19° and 20°. Along the coastal ridge, maximum slope angles are 10°-11° with minimum angles being 3°-4°. This gives the appearance of a more rolling topography than the hummocky topography of the inland ridge.

The Sand Hills Moraine is composed of a pinkish-beige till known as Carpenter Till, together with yellowish ice-contact sediments. Although Vincent (1983) refers to the till as consisting of gravel and cobbles in a sandy matrix, field observations indicate that the matrix is often silty. Numerous gabbro boulders are present, probably originating from outcrops of the Glenelg Formation on the southern tip of the island.

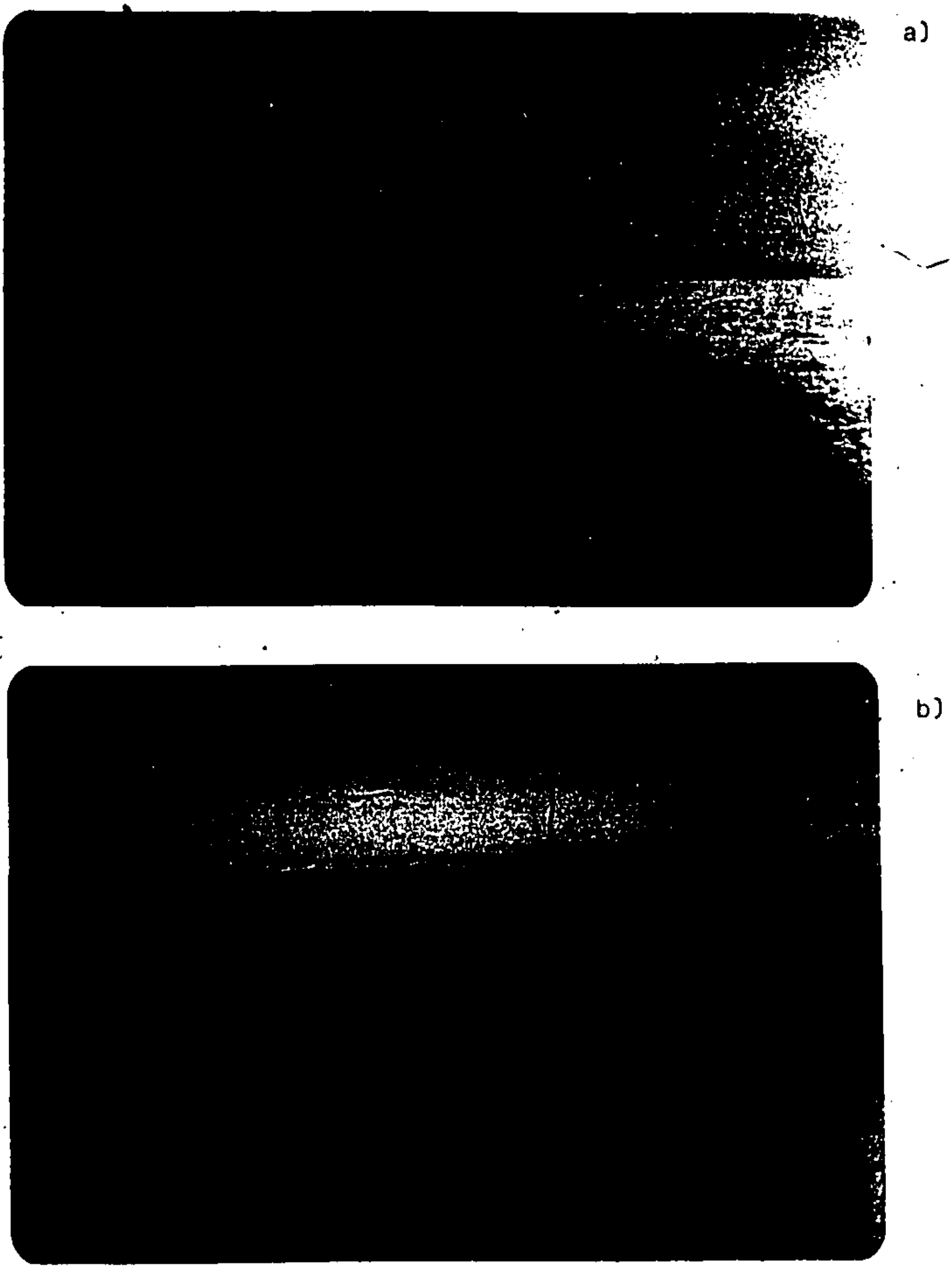


Figure 1.3 a) View looking east along the coast towards Cape Currie . Irregular terrain is due to the presence of numerous ground ice slumps.

b) View looking west along the Sand Hills Moraine. Note the high inland and low coastal ridges.

1.3.2 Vegetation

Vegetation in the Sand Hills Moraine consists of both wet and dry tundra meadows (Figure 1.4). In the former, vegetation is continuous and dominated by grasses, sedges and mosses (Figure 1.4a). On well drained ridge tops and interfluves, vegetation cover is sparse (i.e., <25%). Dominant species include Oxytropis sp., Potentilla sp., Dryas sp., and some grasses (Figure 1.4b). Many of the lower slopes have a fairly continuous vegetation cover dominated by Dryas sp., Salix sp., and grasses. Peat occurs in some low lying areas.

Patterned ground in the form of stripes and non-sorted circles is widespread (Figure 1.5). Stripes occur mainly on the lower part of slopes and are often short and broken (Figure 1.5a). Non-sorted circles are usually elongated and occur only occasionally in flat areas between hills (Figure 1.5b).

Thaw depths vary with both vegetation cover and surface material. Depths of thaw measured in mid July 1984 ranged from 35 cm in a tundra meadow to 110 cm on a gravelly ridge top, and 95 cm at the ridge base. On slopes where stripes are present thaw depths vary between 90 cm and 120 cm in the vegetated and non-vegetated areas respectively (J. Lalonde, 1984, personal communication). Although these measurements may not represent maximum active layer thicknesses, measurements taken elsewhere on southern Banks Island (Harry, 1982, p. 31) during mid August of 1979 and 1980 give similar values.

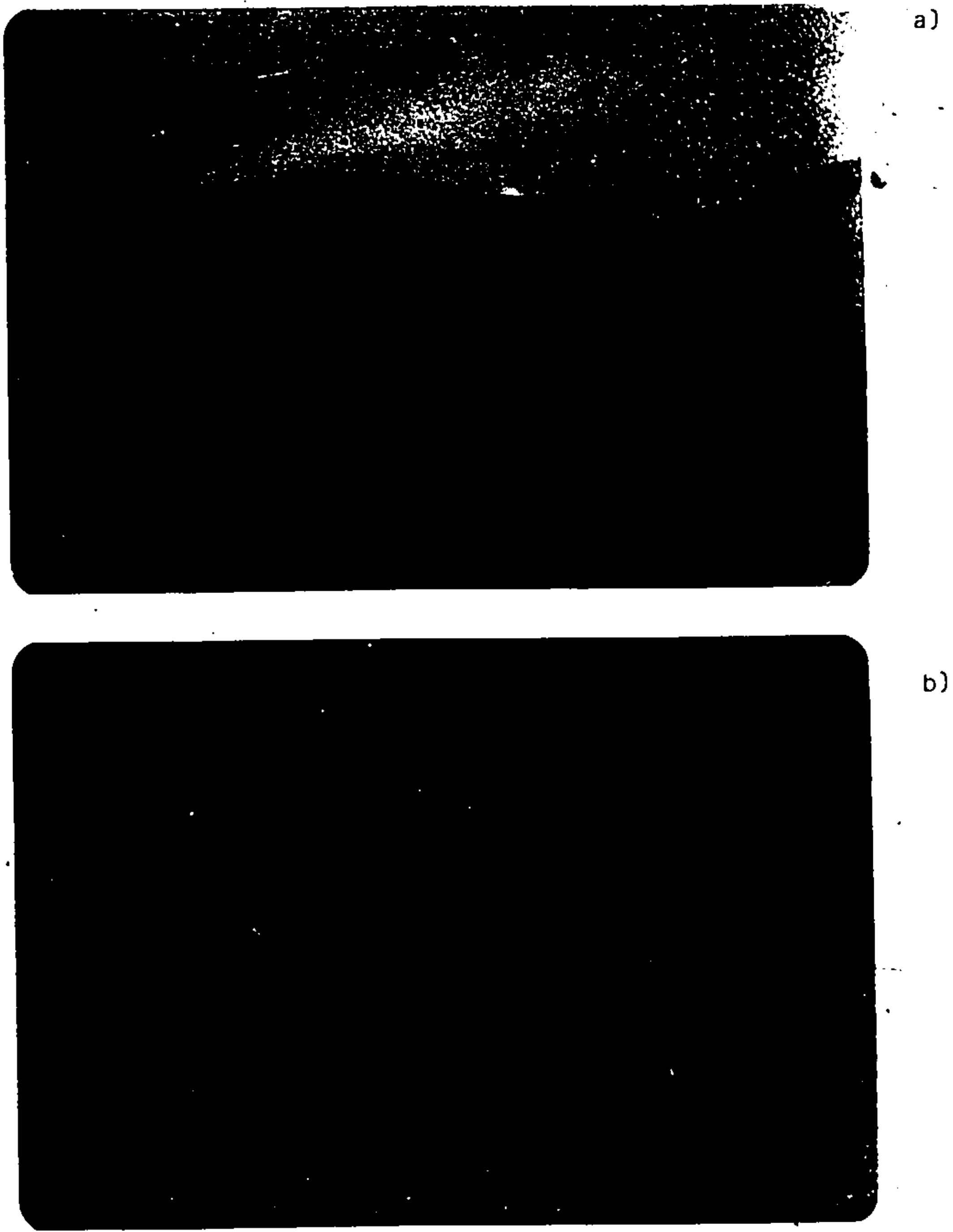


Figure 1.4 a) Typical vegetation found in wet tundra meadows is dominated by grasses, sedges, and mosses.

b) On well drained ridge tops vegetation is sparse.

a)

b)

Figure 1.5 a) -Solifluction stripes occur on lower slopes in the Sand Hills Moraine.

b) Non-sorted circles are restricted to flat areas in the Sand Hills Moraine.

1.3.3 Thermokarst Processes

Many geomorphic processes occurring in the study area are directly related to ground ice degradation. As previously mentioned, much of the Sand Hills Moraine is currently undergoing or has previously experienced thermokarst activity. Evidence of this can be seen in numerous ground ice slumps and stabilized scars which occur on the ridge closest to the coast.

Ground ice slumps are a common thermokarst form in the western Arctic (e.g., Kerfoot and Mackay, 1972; Mackay, 1966) and have been described from eastern Banks Island (French, 1974; French and Egginton, 1973). In the study area, these features commonly consist of a semi-circular or amphitheatre-shaped headwall composed of 1-2 m of ice or ice-rich material overlain by 1-3 m of overburden. They range from approximately 15 m to 100 m in width at their widest point.

Over a 4 km distance along the coast at least eleven active ground ice slumps were observed in July 1984 (Figure 1.6). Many are located within older inactive ones. The latter exhibit vegetation recolonization on the floors and headwalls. Small slumps located near the coast suggest that many of these features may have been activated originally by coastal erosion causing the exposure of ice-rich sediments or massive icy bodies.

Active ground ice slumps are the only means by which massive ice bodies are exposed naturally in the Sand Hills Moraine (Figure 1.6b). It is for these reasons that samples of massive ice were collected from ground ice slumps.

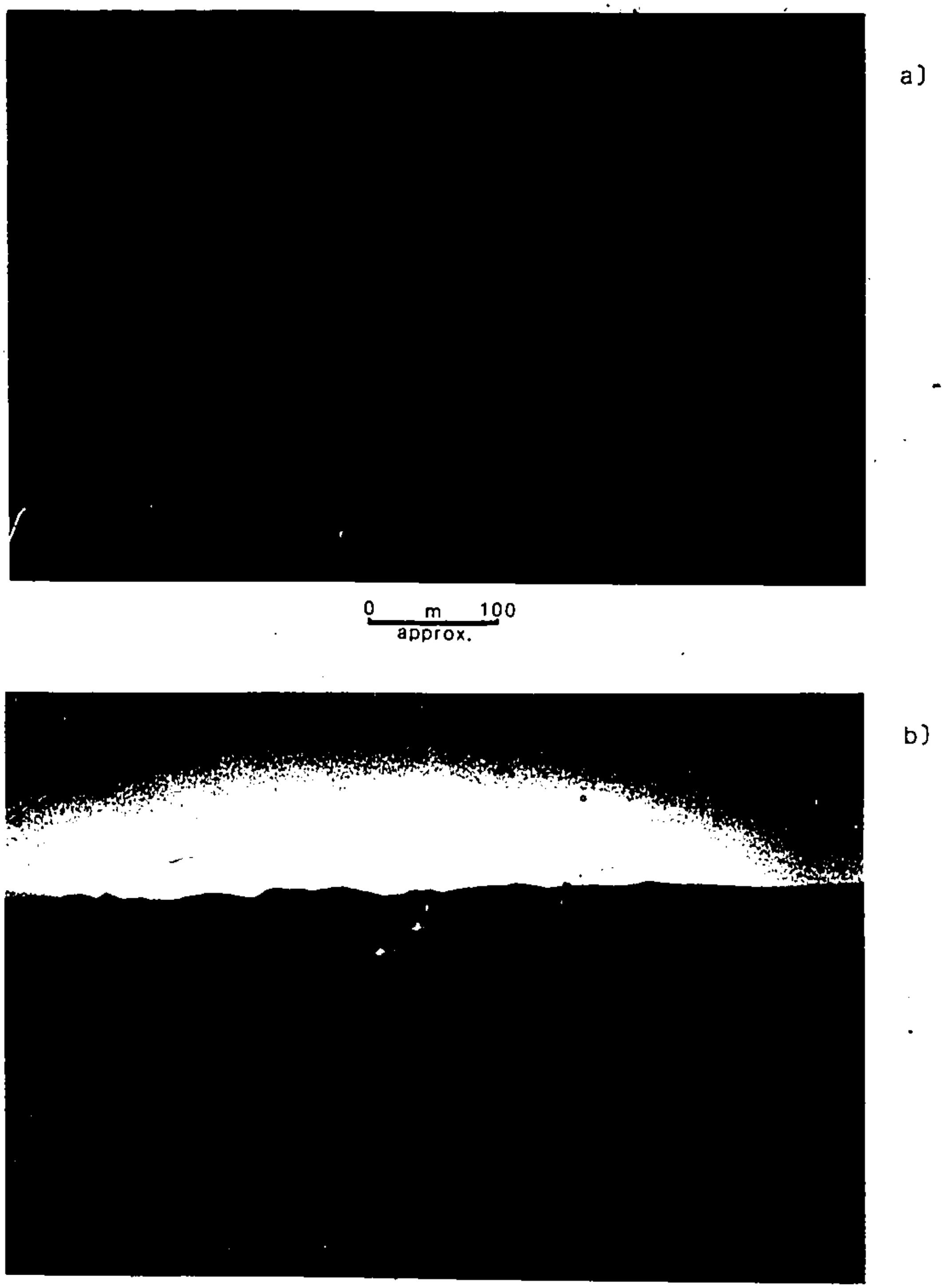


Figure 1.6 a) Oblique air view of the ridge near the coast. Note the numerous ground ice slumps.

b) View of typical ground slump (photograph taken in July 1983).

1.3.4 Lake Drainage

Lake drainage is a geomorphic process which has been operating in the study area since deglaciation. There are at least two different mechanisms by which this may occur. First, catastrophic outflow following lake tapping or truncation has been reported, especially in regions subjected to coastal retreat (Harry, 1982, p150-155; Mackay, 1979). Second, in areas of ice cored terrain, subsurface drainage may occur. Harry (1982, pp. 155-157) attributes the partial drainage of a lake in the Sand Hills Moraine during early January of 1977 to this latter mechanism, and suggests that extensive areas within the limits of the Sand Hills Readvance may be underlain by buried glacier ice.

In the study area, the recent retreat of one ground ice slump into a small lake has caused drainage of the lake. As yet, the lake floor has experienced no vegetation regrowth, thus indicating this event to be quite recent (Figure 1.7a).

Signs of lake drainage on a larger scale are also apparent. For example, a clearly defined strandline several metres above the current water level completely surrounds the largest lake in the study area (Figure 1.7b). On the north side of this lake a flat erosional surface sloping to the north (see Figure 1.3b) suggests that water probably once flowed into the Sachs River Valley.

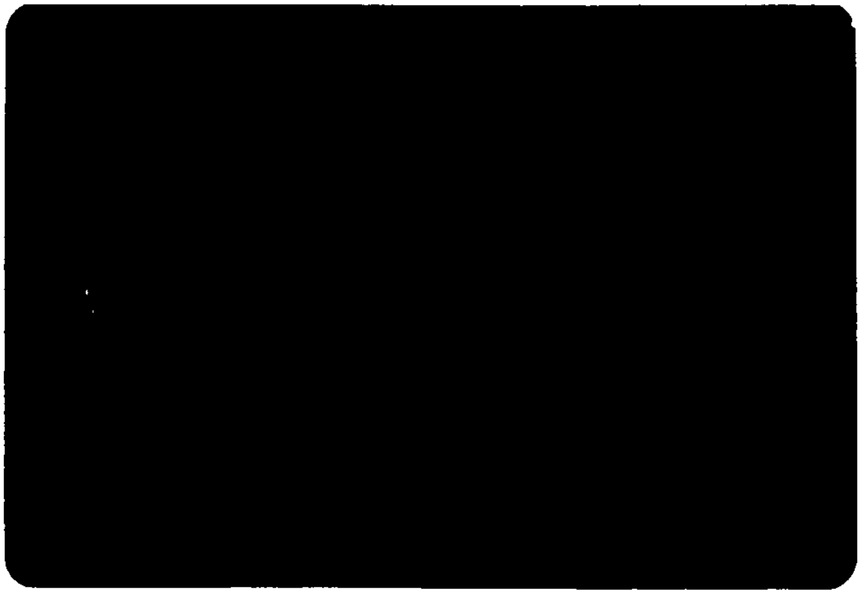


Figure 1.7 a) A recently drained lake basin caused by erosion of a ground ice slump.
b) A bench indicates a former lake level around the largest lake in the study area.

Chapter II

GROUND ICE

Ice petrography is influenced by the temperature, heat flow direction, pressure, and water supply during, and subsequent to freezing. It is necessary, therefore, to understand the mechanisms of formation of different types of ground ice in order to utilize petrographic data.

Ground ice occurs in a complex variety of forms and, as a result, many classification systems, both genetic and descriptive, have been devised (e.g., Mackay, 1972; Pihlainen and Johnston, 1963; Shumskii, 1964a, p. 14). Mackay (1972) uses the origin of water prior to freezing and its principal transfer process as criteria to distinguish ten different types of underground ice (Figure 2.1). The most important and/or widespread types of ice are briefly described below.

2.1 Pore Ice

The most important type of ice in terms of its contribution to the total volume of ice in the ground is pore ice. For example, in a 50,000 km^2 area on the Alaskan north slope pore ice represents approximately 70% of the total ice volume, the total ground ice volume being equal to 40% of the upper 7.5 m of permafrost (Brown, 1967). On Richards Island, in the Pleistocene Mackenzie Delta, pore and segregated ice together constitute 85% by volume of the upper 9.5 m of permafrost

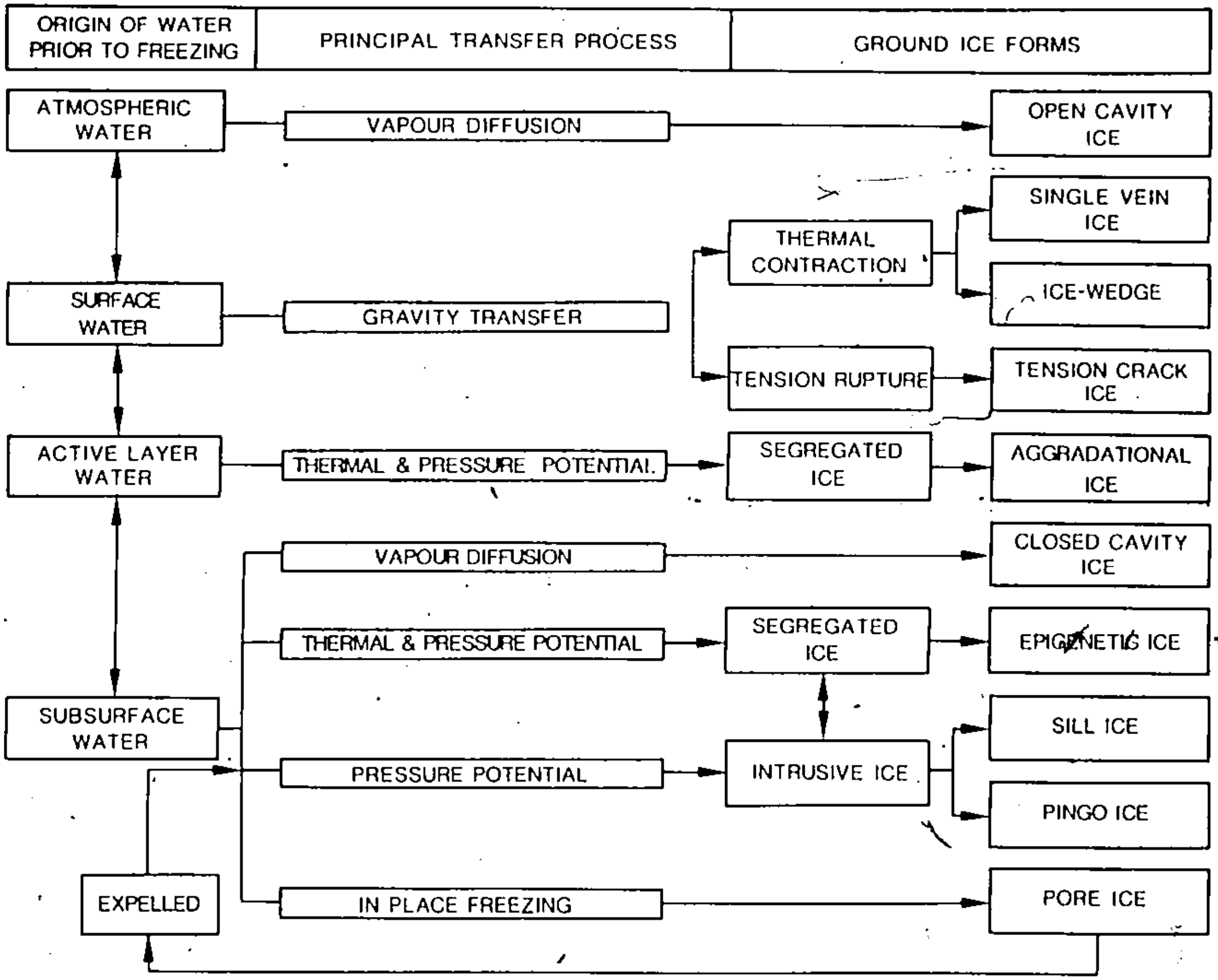


Figure 2.1 Classification of ground ice according to J. R. Mackay (1972).

(total ice volume equals 10.0 km^3 in the upper 10 m of ground) (Pollard and French, 1980).

Pore ice fills the voids between soil grains and, as such, bonds or cements them together. Pore ice is most likely to form in coarser grained materials. Where strong pore water pressures are less easily maintained than in finer grained material (Arvidson and Morgenstern, 1977).

2.2 Segregated Ice

Segregated ice is formed by the movement of water to a relatively stationary freezing front. It forms lenticular ice bodies ranging from only a few millimetres to many metres in thickness.

Segregated ice is typically found in fine grained and organic soils, although it is not necessarily restricted to such materials. Crystal c-axes and gas bubble trains are often oriented normal to the freezing front. Individual soil particles and small stones may be suspended in clear ice (Mackay and Stager, 1966b; Shumskii, 1964a p. 16).

Mackay (1971, 1973) explains the occurrence of massive ice bodies along the western Arctic coastal plain as being of a segregated origin; however, others suggest that it might be buried snow and lake ice (e.g., Fujino et al., 1983). Although these icy beds can be pure and clear in places they are usually composed of horizontal layers of dirty ice alternating with relatively pure ice. Petrofabric analyses of this ice show that crystal c-axes and elongated bubbles have a preferred orientation normal to layering. Isolated stones have icy coatings on one side, and broken soil fragments can often be matched across ice lenses

(Mackay, 1971; 1973; Mackay and Stager, 1966b; Rampton and Mackay, 1971). Petrographic analyses of other bodies of segregated ice show that crystal size often varies as a function of the presence of sediment inclusions and long axes may range from small (<0.5 cm) to several centimetres. Often, crystals are equi-granular; their shape may be irregular or slightly elongate parallel to the compositional layering (Corte, 1962; Gell, 1978b).

Penner (1961) studied the crystal structure and orientation of an ice lens induced in Leda clay. In this case crystal long axes were oriented in the direction of heat flow, crystals varied in size and had irregular boundaries, and c-axes orientations (determined by an etching technique) were random.

A special type of segregated ground ice called aggradational ice forms when the permafrost table rises. This type of ice usually occurs as lenses within the upper 3 m of the ground. Its upper surface roughly coincides with the permafrost table. Repeated yearly water migration and ice lensing has been proposed as one mechanism for the formation of aggradational ice (Cheng, 1983). Characteristics of this type of ice are 1) sediment inclusions occur both as soil particles and aggregates suspended in the ice, 2) volumetric ice contents are usually greater than 50%, 3) chemical composition is similar to that of atmosphere and surface water, and 4) it occurs mainly in fine-grained sediments (Cheng, 1983).

2.3 Intrusive Ice

Intrusive ice is formed by the movement of water under hydraulic or hydrostatic pressure. It is often accompanied by positive relief at the ground surface. It is usually distinguished from segregated ice by its clarity and purity; however, when the two types of ice appear together, such as in pingos (French et al., 1982; Mackay, 1978; 1979; Pissart and French, 1976), it may be difficult to tell them apart. If soil particles are present they occur at the base of intrusive ice in the form of streaks parallel to the movement of water at the time of intrusion. Sometimes, layering occurs in the form of distinct bubble bands parallel to the overlying ground surface. Within each band, the range in bubble size and shape may be fairly uniform, but major differences often exist between different bands (Gell, 1978a; Pollard, 1983 pp. 131-133). Bubbles may also occur in trains normal to the freezing plane.

Intrusive ice crystals vary from being small (<1 mm in dimensions) and equi-dimensional in upper 'chill' zones to large (up to 200 mm long), columnar, and dimensionally oriented parallel to the freezing direction. C-axis orientation is random in the upper 'chill' zone and becomes more concentrated with depth becoming preferred normal to the direction of crystal elongation (horizontal) (Gell, 1978a; Pollard, 1983 pp.138-140). The development of this type of texture and fabric is typical of rapid ice growth in bulk water (Ketcham and Hobbs, 1967). The upper zone of small crystals corresponds to rapid freezing and the elongate larger grains represent slower crystallization.

2.4 Vein and Wedge Ice

Vein ice is formed when water or snow penetrates and freezes in thermal contraction cracks. Single vein ice is common in the upper portions of permafrost where it may form complex networks of thread-like ice often less than 2 mm in thickness (Mackay, 1974b).

If repeated cracking occurs, vertically foliated ice masses termed ice wedges may form. Wedges are usually between 0.1-3.0 m wide at their top and 1.0-10.0 m long, in some cases, such as in central Yakutia, U.S.S.R., syngenetic wedges are reported to reach up to 60-80 m in length (Melnikov and Pavlov, 1982). Observations upon thermally-induced cracking were first reported by Leffingwell (1915) and the mechanism of formation has since been described by Black (1963), Lachenbruch (1966), Mackay (1974a) and others. Ice wedges can be distinguished from other types of ground ice by their layering and their abundance of gas and soil inclusions. They are often located beneath troughs in the ground surface which form a polygonal network when more than one wedge is present. The most striking relationship between wedge ice and its enclosing sediments is upturning of the material surrounding the wedge. This is thought to be caused by pressure due to the expanding wedge (Péwé, 1966).

The presence of many bubbles causes wedge ice to appear milky at the centre of the wedge and to be easily fractured. A typical feature of this type of ice is parallel, near-vertical, layers of bubbly ice and sediment. The petrography of ice wedges has been investigated by Black (1953; 1963; 1978), Gell (1978b), and Shumskii (1964, pp. 39-41). Due to their mode of formation, crystal size is generally larger in the upper portion of the wedge (up to 1.5 cm in diameter) than in the lower part (<0.15 cm in diameter). Within the same wedge, or for different wedges, crystal c-axis orientation may vary from chaotic to distinctly linear and normal to the foliations. Where variations occur within the same wedge they are gradual.

2.5 Buried Surface Ice

The classification of ground ice shown in Figure 2.1 does not include buried surface ice. This is because it is thought to be relatively rare (Mackay, 1972; Mackay et al., 1978). Nevertheless, there remains a problem in distinguishing between massive segregated bodies of ice and buried surface ice. The latter has been identified on Ellesmere Island (e.g., Christie, 1967) and, more recently, on Victoria Island (Lorrain and Demeur, 1985).

Buried surface ice may be either glacier, river, or lake ice, or it may be metamorphosed snow. In studying the nature of buried ice it is necessary to consider both the source of ice and the conditions of burial. The primary features of the ice composition and structure are controlled by the growth mechanisms of the ice, while the conditions for ice preservation are controlled by the mode of burial. However, the structure of ice may change subsequent to burial. This might occur from the following: additional stresses (e.g., overburden pressures), major changes in temperature such as those experienced during the mid-Holocene (Ritchie, 1972), and/or a change in groundwater flow. As a result, the ice may undergo recrystallization and develop a secondary structure which bears little resemblance to the original texture and fabric, thus making it difficult to identify the original source of ice.

The longer the ice has been buried, the greater are the chances it has undergone transformation. Indications that this has happened are the presence of faults, dilation or contraction cracks, strain shadows, grain boundary irregularities and dislocations, and crystal substructure. Crystal substructure includes grain boundary migration, incorporation of smaller crystals within larger ones, and recrystallization.

It is generally assumed that ice found in ice-cored moraines associated with modern glaciers has originated from glacier ice or has a complex origin. Few petrographic studies have been done on this ice, although one such study found that the ice in question consisted of crystals ranging in area from a mean of 0.3 cm² to 12.0 cm² and having preferred c-axis orientations perpendicular (or very nearly so) to dirt layers within the ice (Östrem 1963). Mean crystal size was usually small (around 0.05 cm²) but areas which had a high sediment content were found to have larger crystals. Östrem (1963) compared the moraine ice to massive snow-bank ice and glacier ice. Based on crystal size measurements he concluded that the buried ice was superimposed snow-bank ice.

Hambrey (1984) found buried ice in association with several glaciers in Spitsbergen. He identified the ice as being both buried aufeis (naled ice) and buried glacier ice. The aufeis was typically comprised of long vertical crystals as well as laminated granular ice which, Hambrey suggests, was formed by recrystallization or freezing slush. The buried glacier ice, on the other hand, was deformed and coarsely crystalline with crystals several centimetres long and of irregular shape.

There are many crystallographic studies of glacier ice (eg. Bader, 1951; Hambrey, 1976; Koerner, 1968; Koerner and Fisher, 1979; Rigsby, 1951; 1955; and others). These show that crystal characteristics vary greatly depending on the location within the glacier. For example, ice near the top of a glacier is generally more granular with less pronounced crystal orientation patterns. As one progresses through the glacier a preferred crystal orientation reflects ice flow. Finally, in areas of stagnant ice such as near the tongue or edges (the parts which are most likely to be buried in a moraine) crystals are usually large (several centimetres in diameter) and exhibit multimaxima preferred orientations.

Deep ice cores taken at Byrd Station, Antarctica and Camp Century, Greenland provide additional examples of crystalline textures of an ice cap. For both glaciers average crystal size increases over the first several hundred metres. Throughout this interval crystal shape changes from elliptical and anhedral with sutured boundaries to complex and interlocking (Gow and Williamson, 1976). The glacial-interglacial transition at these two sites is marked by a significant decrease in crystal size and strengthening of crystal orientation (Herron and Langway, 1982). At levels of greater antiquity, crystal size increases reaching a maximum cross sectional area of 9 cm^2 at the base of the glacier at Byrd Station (Gow and Williamson, 1976).

The fact that ice cores from both the Greenland and Antarctic ice caps reveal that ice structure undergoes a sudden change has prompted the speculation that Wisconsin ice may bear a unique textural and fabric signature (Herron and Langway, 1982). Fabric diagrams indicate a strongly preferred c-axis orientation sometimes having a 'diamond fabric' near the base of the glacier (Herron and Langway, 1982).

2.6 Optical Properties of Ice

Of the nine phases of ice that are known to exist, only ice I is found at pressures below 2,000 atm and temperatures above -70° C. Ground ice is therefore ice I in type. Structurally, ice I has hexagonal crystal symm~~etry~~. Three axes, (the a-axes) lie at 60° angles to each other in a basal plane. A fourth axis, the c-axis, runs perpendicular to the basal plane.

When a beam of light passes through a thin section of a transparent mineral belonging to the hexagonal system it experiences double refraction as it splits into a 'fast' and 'slow' ray according to two different indices of refraction. The difference between the indices of refraction for these two rays is referred to as the birefringence.

Ice has a very low positive birefringence (0.0014). As a result, the difference in speed between the two rays is small, and double images are not seen unless light is emerging from a fairly thick piece of ice. Differences in speed, however, are sufficient to produce interference colours when ice is viewed between crossed polarizers. Thus, individual crystals are easily distinguished by their interference colours which vary with crystal dimensions and orientation. When a crystal appears black, light emerging from it has been blocked by the second polarizing sheet and the crystal is said to be in an extinction position. This occurs at 90° intervals in a 360° rotation about the line of sight.

Being uniaxial, ice crystals have one axis through which light may pass without experiencing double refraction. This is referred to as the optic axis and corresponds to the c-axis. Therefore, birefringence is zero along the c-axis and increases to a maximum of 0.0014 at right angles to it. Because ice is optically anisotropic the position of the c-axis may be measured using a universal stage (Rigsby, 1951).

2.7 The Growth of Ice in Bulk Water

An understanding of how the more common types of ice textures and fabrics form aids in the interpretation of petrographic data.

Experimental investigations into the growth of ice from pure water reveal that large columnar crystals usually form with horizontally oriented c-axes (Ketcham and Hobbs, 1967); however, the availability of nuclei and the speed at which freezing takes place are important factors in determining exact ice texture and fabric.

A small temperature gradient causes slow crystallization. Initial crystals will have random c-axis orientations and will tend to grow more along the basal plane (Shumskii, 1964b, pp. 68). As crystals grow into long needles they either grow together and maintain their orientation or they turn over and float, like flat plates on the surface of the water with their c-axes taking a vertical orientation. These crystals act as seeds for other crystals growing in a downward direction, thus producing ice composed of long columnar crystals with vertical c-axes. Gow and Langston (1977) record lake ice with this crystal structure having single grains up to 40 cm in length.

With a large temperature gradient crystallization of bulk water proceeds quickly and there is a large increase in the number of crystals. Initial crystals grow together before they have time to develop the plate-like shape described above. As a result, randomly oriented equi-dimensional crystals develop. Because crystals grow more rapidly along their basal planes, crystals with their basal planes oriented vertically eventually wedge out others so that larger columnar crystals with horizontal c-axes lie below a 'chill' zone of smaller equi-dimensional crystals. This type of crystal structure has been observed by Gell (1978a) and Pollard (1983, p. 138) in injection ice.

Most substances other than ammonia and hydrogen fluoride are insoluble in ice and are rejected, therefore, when water freezes (Glen, 1974, p. 23). Thus, impurities accumulate at the ice/water interface causing enrichment of the remaining melt and depression of the freezing point. The manner in which air bubbles are included in ice is particularly important as they can indicate the relative speed of freezing and the direction from which freezing occurred. In many studies distinct layers of ice having different bubble characteristics are identified and these are used to help reconstruct the freezing history of the ice (Corte, 1962; Gow and Langston, 1977; Pollard, 1983, pp. 131-138).

As crystallization takes place air is rejected from the freezing water and accumulates at the ice/water interface until its concentration is high enough for bubbles to nucleate. In relatively slow freezing a bubble will continue to grow as the ice moves forward thus forming a cylindrical bubble parallel to the direction of ice growth. Slightly faster freezing produces egg, or pear-shaped, bubbles oriented with their fat end away from the freezing interface (Bari and Hallett, 1974; Carte, 1961). Fast freezing produces small spherical bubbles as there is insufficient time for more air to diffuse into the initial bubbles. Very slow freezing, and freezing in flowing water, produce ice without bubbles since, in the former, air is able to diffuse away from the ice, and, in the latter, the continuous removal of water prevents the build-up of a concentration of air bubbles sufficient for nucleation (Chalmers, 1959). Finally, very high freezing rates initially give clear ice but over a period of time bubbles nucleate and grow at grain boundaries within the ice (Bari and Hallett, 1974).

2.8 Ice Transformation

As the structure of ice is not stable even under constant external conditions (Glen, 1974, p. 32; Voytkovskiy and Golubev, 1973), the dimensions, shape and orientation of crystals may vary with the length of time that the ice has been in existence. The presence of a temperature gradient and a deforming force will accelerate the process of structural rearrangement of the ice. As temperatures approach the phase transition point the rate of increase in crystal size decreases with the length of time spent at that temperature (Voytkovskiy and Golubev, 1973). Conversely, the average grain size in ice that has undergone severe strain is smaller than the average grain size before the load was applied. For example, Gold (1963) has conducted laboratory experiments on the response of polycrystalline ice to an applied load. Thin sections cut from ice deformed under loads between 5 and 10 kg/cm² for at least 70 hours at a temperature of -9.5° C showed extensive recrystallization with a tendency for columnar crystal structure to be transformed into a granular one. The first evidence of grain boundary migration and slip occurred after one half hour of the load application. Slip occurred along the basal plane.

It is also known that crystal fabric is influenced by stress. Ice under stress recrystallizes in such a way as to produce a preferred orientation which is favorable to the direction of stress (Glen, 1963).

Changes in size and shape of inclusions are also possible. For example, irregularly shaped bubbles associated with frozen snow become more rounded as recrystallization occurs (Quervain, 1963). When ice approaches its melting point impurities such as gases, liquids, and solids, have a tendency to congregate along crystal boundaries (Glen, 1974, p. 32).

It is clear, therefore, that the number of changes which may occur in ground ice, and the reasons for them, are numerous. It must be kept in mind therefore, that the structure of ice examined in this study may be significantly different from its original structure.

Chapter III

FIELD AND LABORATORY METHODS

3.1 Field Methods

3.~~1~~.1 Introduction

In permafrost regions there are often strong geologic controls on the origin, characteristics, and distribution of ground ice (Mackay et al., 1978). As a result, stratigraphic observations may reveal a relationship between the amount of ground ice present, its physical characteristics, and the nature of the enclosing sediments (e.g., French and Harry, 1983). Deformation of surrounding sediments, their grain size distribution and ice content, the nature of the ice/sediment contact, and the presence or absence of bedding and organic material are factors which help place the formation of the ice in a sequence of events and thus suggest one or several modes of origin for the ice.

3.1.2 Field Sampling

Opportunities for stratigraphic observations in the study area were scarce as many ground ice slumps exposed only colluvium and other natural exposures were rare. When ice was visible within a slump, debris usually covered its lower and side contacts as well as the surrounding sediments.

At two slumps exposing massive ice different stratigraphic units were identified according to their grain size, colour, and the presence or absence of bedding and organic material. Unit thickness was estimated with a tape measure at 5 m intervals along the face. Where possible the amount of excess ice was calculated by measuring the volume of supernatent water in a sample as a percentage of the whole sample.

The amount of ground ice exposed in a slump at any given time is unpredictable due to rapid melting in favorable weather and to covering of the ice by slumped material. As a result, only one slump was sampled while detailed stratigraphic information was recorded at a second slump approximately 400 m to the west.

Sketches were made and photographs taken of the ice and its surrounding sediments prior to sampling. Information recorded included the appearance of the ice in stratigraphic section, descriptions of the enclosing sediments, the ice/sediment contact, apparent sediment distribution within the ice body, and the nature of the ice itself. The latter included observations on ice clarity, the presence or absence of fractures, and the abundance, size, and shape of air inclusions. Exact sample locations were recorded on sketches and photographs of the ice body were taken so that sample orientation could be verified at a later date.

A rough estimate of crystal size was made by allowing pieces of ice to melt slowly thus revealing grooves along crystal boundaries (Bader, 1951). It was found that crystal size was small, apparently 0.5-2.0 cm long, therefore enabling sample size to be small.

A total of 3 blocks were cut from one slump (see Figure 3.1). Blocks 1 and 2 were cut side-by-side approximately 3.0 m below ground surface just above a boulder embedded in the ice, and block 3 was cut approximately 8 m to the east and 1.5 m above the first two. Figure 3.1 shows the general stratigraphy exposed at the slump.

3.1.3 Transportation and storage of samples

Immediately after being cut samples were wrapped in plastic and paper, their orientation marked on the paper, and stored with freezer packs and loose chunks of ice in an insulated box. They remained this way for approximately 16.5 hours before being transferred to the cold room at the Scientific Resource Centre in Inuvik.

When samples were unwrapped in the cold room they showed no signs of melting. As they were to be stored for 3 months at -15° to -20° C before being analyzed each block was sketched and photographed so that at the end of the storage period it could be determined if any major changes had occurred. They were then stored in plastic bags which were tightly sealed after the air was removed.

3.2 Laboratory Methods

3.2.1 Preparation of Samples

Before cutting the blocks of ice into thin sections their outer 2-4 cm were trimmed and detailed sketches and descriptions were made of the ice. There were three reasons for doing this. First, additional observations on distribution characteristics and size variations of inclusions were more easily made on a trimmed block. Second, the sketches and descriptions were preliminary ice texture observations and as such were useful to refer to during texture and fabric analysis of thin sections.

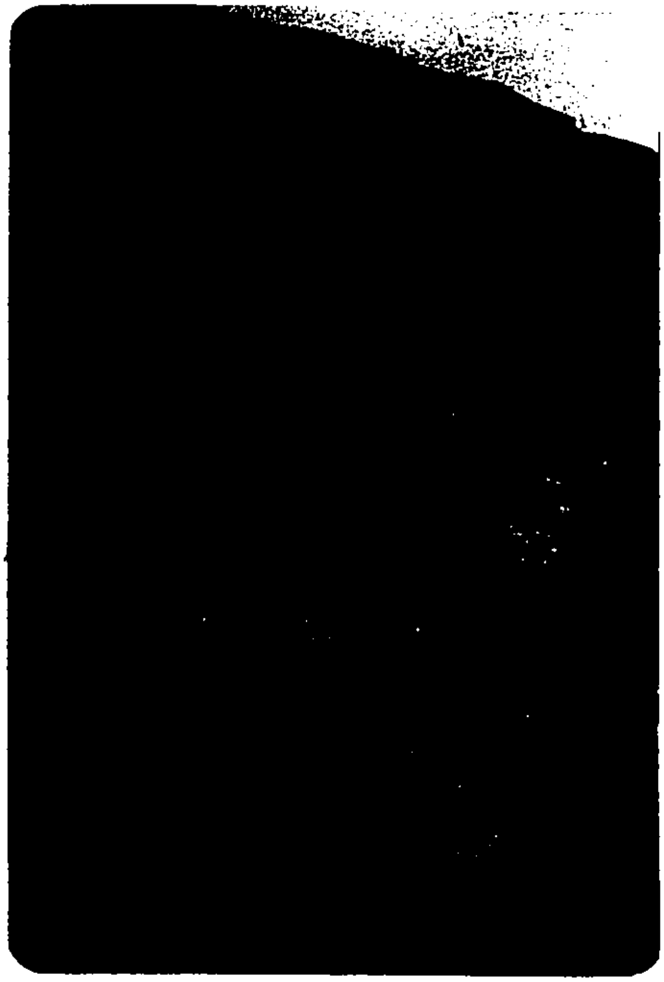


Figure 3.1 Photograph of ground ice exposed at sampling location, July 1984. The numbers indicate the locations sampled for blocks 1, 2, and 3 respectively.

Third, characteristics such as strain shadows and fractures were helpful in subsequent verification of thin section orientation.

For a complete three dimensional idea of crystal size and shape it was necessary to cut horizontal thin sections and vertical thin sections both parallel and perpendicular to the ice face. Thus, thin sections having three different orientations were cut from each block. Because crystal size was small to medium most sections contained over 100 grains. Therefore, only a few thin sections of each orientation were required for each block. In order to observe any possible variation of texture and fabric within a block, sections were cut from various locations throughout each block; however, where sections were cut close to each other the chance of repeated measurement of any ice crystal was minimized by cutting sections at least 2 cm apart.

Texture and fabric data were collected from 14 thin sections cut from block 1, 12 thin sections from block 2, and 2 thin sections from block 3.

3.2.2 Thin Sections

Thin section preparation was as described by Rigsby (1951). Thick sections (about 5 mm thick) were cut and frozen onto plates of glass which had been previously marked with the correct orientation. These were then trimmed to a thickness of about 2 mm with a bandsaw and further thinned to less than 1 mm with a hotplate. Abundant sediment inclusions often resulted in uneven thickness across a thin section but this was minimized by picking out large clumps of sediment where possible. A high sediment content in block 3 prevented more than two thin sections from being prepared for this block.

3.2.3 Ice Texture

For a detailed description of ice texture thin sections were viewed through cross-polarized light. Long axes of largest and smallest crystals were measured with a ruler and average crystal size was approximated by measuring several crystals and calculating their average size. Where there were two distinct groups of crystals having different sizes an average size was calculated for each group. As in Hambrey (1976), a crystal was considered large if its long axis measurement was more than 3 cm, and small if it measured less than 1 cm in length. Crystals falling between these two categories were medium in size.

Characteristics of grain shapes in monomineralic materials have been studied by metallurgists, geologists and glaciologists. A wide variety of descriptive terms exist. Shumskii (1964b) describes ice texture and fabric with a range of terms from prismatic-granular for long columnar crystals in which the geometric and optic axes coincide and are parallel to the direction of growth, to allotriomorphic granular in which crystal shape is without regular faces and optic axis orientation is random. A range of complicated terms apply to textures between these extreme types.

To avoid confusion it was decided to use the simplest terms possible to describe grain shape and not to group texture and fabric characteristics into one term. Thus, crystals are described as being either anhedral (having no regular faces), subhedral (having some regular faces and bearing some resemblance to a hexagonal shape), or euhedral (having a hexagonal shape). This is the CIPW (Cross, Iddings, Pirsson and Washington) classification system. Ice crystal shape is commonly described in this way (e.g., Black, 1978; Péwé, 1966; 1978; and others).

To describe grain boundaries in ice Gell (1973) used the following classification; straight, curved, sutured, and cuspate (Figure 3.2). Other terms such as irregular, smooth, serrated, and jagged have also been used frequently (e.g., Gell, 1976; Rigsby, 1955; and others). Descriptions of grain boundaries in this thesis use similar terminology.

3.2.4 Ice Fabric

Ice fabric was determined by measuring c-axis orientations using a Universal stage (Rigsby, 1951). Description of the standard technique for orienting crystals on the Universal stage may be found elsewhere (Langway, 1958). Orientations were corrected for the error introduced by the different indices of refraction for air and ice using a correction table (Langway, 1958). Petrofabric diagrams were then plotted on a Schmidt equal area net in order to illustrate the 3-dimensional orientations of fabric elements in a complete and concise manner. Conventionally, orientations are shown relative to a reference plane (the plane of the diagram) in lower hemisphere equal area projection. Contouring of the density of points in 1% of the area of the projection was done to emphasize the orientation pattern.

The number of points plotted in ice petrofabric diagrams varies greatly. In some works as few as 20-30 orientations were plotted (e.g., Bader et al., 1939; Pollard, 1983); however, most researchers plot between 100 and 200 grains in one diagram (e.g., Black, 1978; Corte, 1962; Herron and Langway, 1982; and others). The relationship between the number of grains plotted and the reliability of the resulting

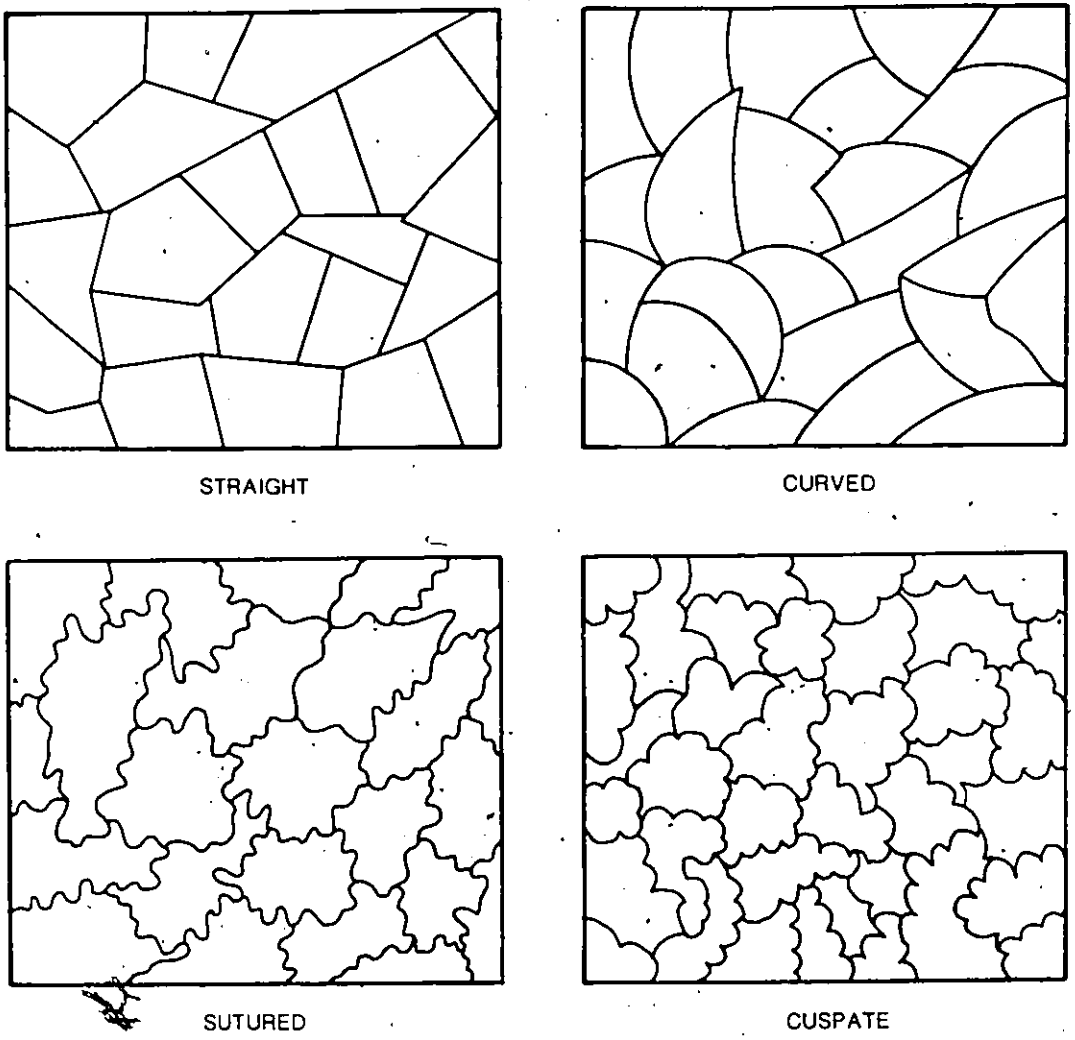


Figure 3.2 The classification of grain boundary types used by Gell (1973).

fabric patterns was investigated by Kamb (1959). He discovered that for greater reliability of results at least 200 orientations should be measured for one diagram. Thus, where possible a minimum of 200 c-axis orientations were measured; however, in the case of block 3 a limited number of thin sections allowed for only 100 c-axis orientations to be measured for each diagram.

The problem of general interpretation of a fabric diagram is whether or not a preferred orientation exists. Flinn (1958; 1963) examined several of the tests used to infer the statistical significance of preferred orientations and found that a reliable way to establish whether or not a preferred orientation exists is to compare fabric diagrams to a prepared random diagram. The probability that point diagrams contain concentrations deviating from a random distribution is approximated by the Poisson distribution (Chayes, 1949, pp. 313). Comparison can be made by means of a χ^2 test. In this study all fabric diagrams showed obvious preferred orientation and statistical significance tests were not necessary.

3.2.5 Sources of Error

Sources of error in measuring c-axis orientations using a Universal stage have been discussed by Langway (1958) and Gell (1973, pp. 51). These and other difficulties encountered in this research are as follows;

1) Measurement of exact extinction position at high angles to the line of sight.

2) A possible parallax effect when the eye is not quite normal to, and in line with, the grain being measured.

3) Operator error in reading the dials of the stage.

4) Inherent mechanical errors of the stage itself. According to Langway (1958) reproducibility of readings from the same grain is about 2°.

5) Measurement of crystals in the polar position where extinction is less distinct than in the equatorial position.

6) When the c-axis is normal to the line of sight it is difficult to determine if it lies in the east-west or north-south plane.

7) Due to high sediment content some thin sections were uneven in thickness. Thus, the uneven thickness of some larger crystals made it difficult to determine their extinction position. Similarly, some smaller crystals in areas of high sediment content were too thick to be measured.

8) Perfect orientation of thin sections may not have been maintained due to inaccuracies in cutting the original blocks from the ice face and subsequent sectioning of the blocks.

All c-axis measurements were read on the same Universal stage by one operator thus eliminating errors due to inconsistency.

Chapter IV

ICE PETROGRAPHY

4.1 Introduction

The body of massive ice which was sampled for petrographic work was located in the retreating face of an active ground ice slump. This was, in turn, located within an older and inactive slump. Due to slumped debris the exact dimensions of the ice body are unknown; however, it is estimated that the ice extends over a distance of several tens of metres and is at least 1.5 m thick in places. From August 1983 to late July 1984 retreat of the slump headwall was over 14 m (A. G. Lewkowicz, 1984, personal communication) indicating that the body of ice extended at least this far into the headwall. Excess ice measurements taken at regular intervals along the exposure of massive ice were usually above 90% (A. G. Lewkowicz, 1984, personal communication).

Contact between the ice and overlying sediments was abrupt and appeared to be in the form of a straight or slightly wavy line, suggesting a thaw unconformity. The overlying material consisted of 1.5-2.5 m of previously slumped, pinkish- grey gravel and boulders in a silty matrix. The lower contact and underlying sediments were not observed.

The ice characteristics (clarity, colour, bubble content, and sediment content) varied greatly without any apparent regularity. In small areas the ice appeared clear and relatively free of bubbles and sediment; however, it was more common to find clear ice with small bubbles and suspended clumps of sediment or else opaque brown or white ice. In places, sediment inclusions occurred in wavy horizontal bands dipping downward into the body of ice (Figure 4.1a). Often sediment occurred in short streaks having apparently random orientations. Sediment inclusions were for the most part silty; however, pebbles and boulders were observed occasionally. Air inclusions were fairly numerous and small.

4.2 General Description of Ice Samples

Block 1 was roughly rectangular in shape and measured 20 X 12 X 15 cms. A large boulder lay directly beneath the locality from which the sample was collected (Figure 4.1b). The bottom of the block contained small pebbles in a silty matrix. The ice immediately above this silty matrix was opaque and yellowish brown in colour due to the high content of suspended sediment. The majority of the ice sample consisted of more or less clear ice with vague horizontal streaks of silt running parallel to the ice/sediment contact. Silt clumps ranged from less than 1 mm to 4 mm in diameter, the average size being approximately 1 mm (Figure 4.2a).

Numerous air inclusions occurred randomly throughout the ice. Bubbles were mostly oval and circular measuring approximately 1 mm in diameter; however, some were vertically elongated being either linear or pear-shaped (fat end at the bottom). The latter measured between 2 and 3 mm in length. Often, cylindrical or linear bubbles extended

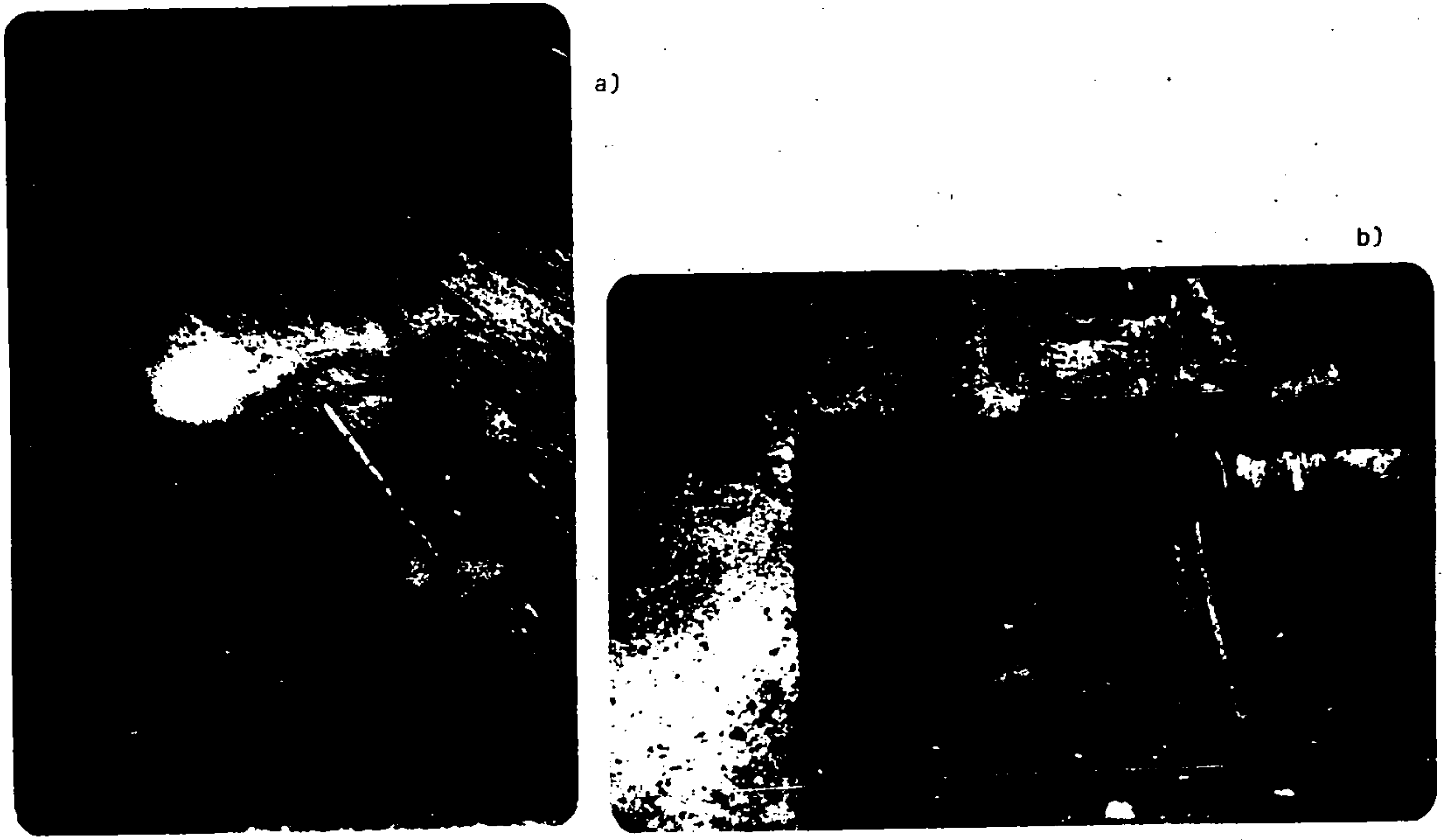


Figure 4.1 a) Wavy horizontal bands of sediment inclusions are visible in the area from which ice samples were collected.

b) A large stone lay directly beneath the locality from which block 1 was collected.

upward from a sediment clump. Near the upper right corner of the block small horizontal strain shadows were present.

Block 2 was sampled from the area immediately adjacent to block 1 and measured 21 X 12 X 20 cms. The ice was fairly opaque and light grey with some transparent areas where there were fewer air and sediment inclusions (Figure 4.2b). The top of the ice sample was white due to an abundance of small spherical, oval, and occasionally pear-shaped bubbles. The latter were always oriented with their long axes vertical and the fat end at the bottom. Occasional crescent-shaped bubbles were also observed, usually oriented with the opening towards the top of the ice block. This portion of the ice also contained some suspended sediment clumps similar to those in block 1.

The middle portion of block 2 consisted of a band of opaque brownish-grey ice. It had a high sediment concentration occurring both as very fine suspended particles, giving the ice a cloudy brown appearance, and as clumps similar to, but slightly larger than, those in the overlying ice. Sediment clumps were clearly arranged in streaks dipping approximately 15° to the left. The bottom portion of the block contained sediment clumps intermixed with clear ice. The sediment clumps continued to be arranged in parallel streaks. Small vertical strain shadows occurred perpendicular to the face but no fractures were apparent.

Block 3 measured 12.5 X 10.0 X 9.0 cms. This block had a high amount of fine suspended sediment particles dispersed unevenly throughout the ice giving it a cloudy yellowish-brown to opaque, dark brown colour (Figure 4.3). As in the other two blocks, sediment

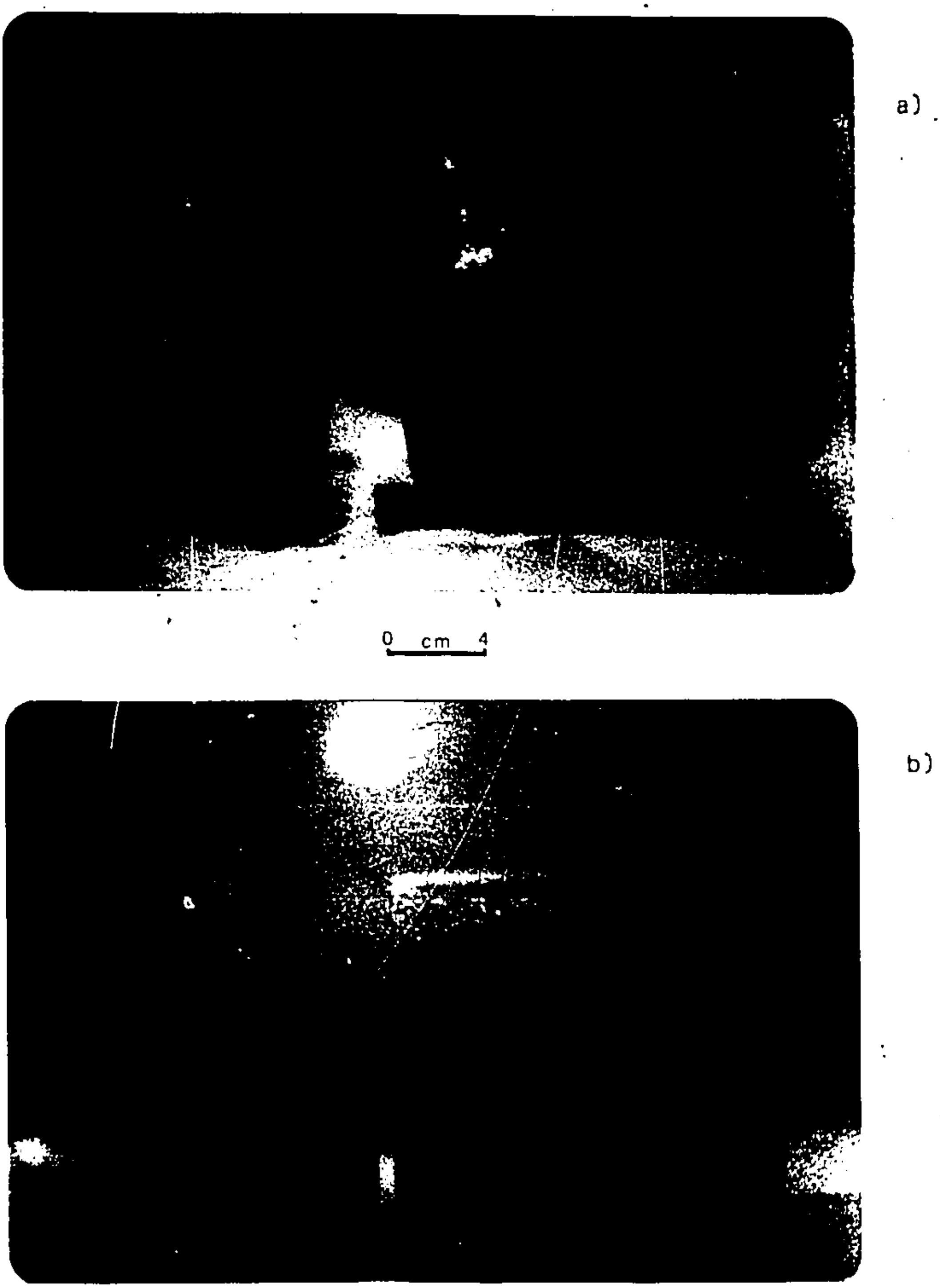


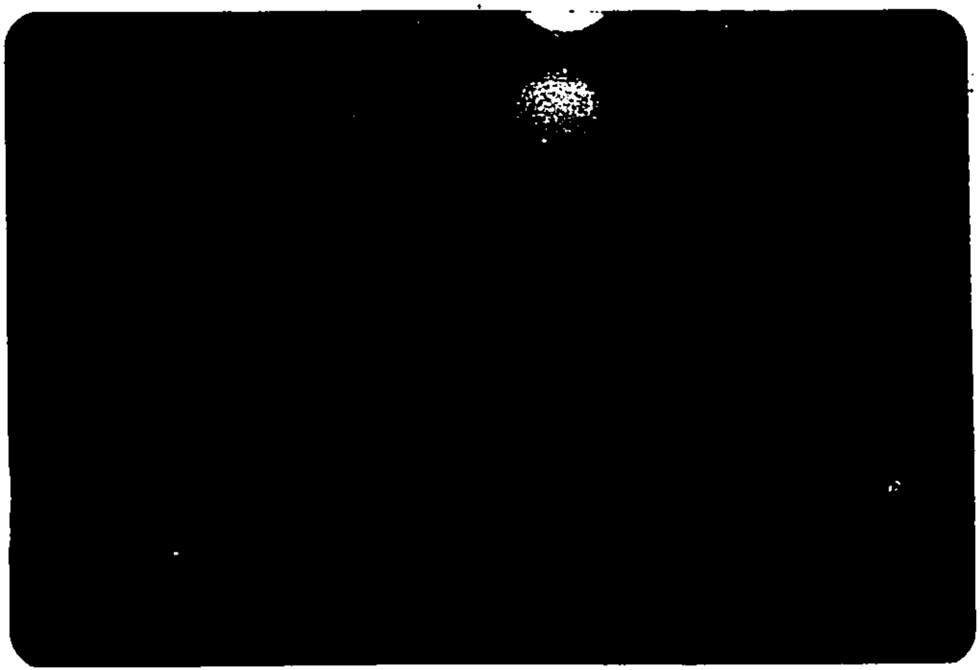
Figure 4.2 a) View looking into the face of block 1.
b) View looking into the face of block 2.

clumps were numerous and unevenly distributed, although cloudy sediment bands dipping into the ice at an angle of 45° and having a strike of 18° were identified. A large central band of opaque brown ice with the greatest concentration of dirt was enclosed by a band having fewer sediment inclusions above and a small bubble-rich layer below. The bubbles were both spherical and pear-shaped and ranged from less than 1 mm in diameter to 2 mm in long axis. A vertical/perpendicular-to-the-face plane of bubbles (less than 0.5 mm in diameter) divided the block into two parts. A layer of silty sand, 0.5 cm in width, was observed above the central band of dirty ice (Figure 4.3a). Of note was a single pebble (2.2 cm in long axis) visible in the upper right corner of the block near the face (Figure 4.3b). Also, a single horizontal strain shadow was visible in the lower left corner near the face. There were no visible fractures.

4.3 Crystallography

Blocks 1 and 2 are discussed together as they were taken from adjacent areas.

Crystal size was small to medium, the smallest crystal being less than 1 mm in diameter and the largest being 2.1 cm along its long axis. Average crystal dimensions varied between 5-8 mm. Towards the bottom of block 1 crystal size was very small (less than 1 mm) and sediment particles were uniformly inter- and intragranular (Figure 4.4a). In other parts of both blocks sediment inclusions occurred as intergranular clumps of fine material and crystal size was only affected when several clumps occurred near each other (Figure 4.4b). Many of



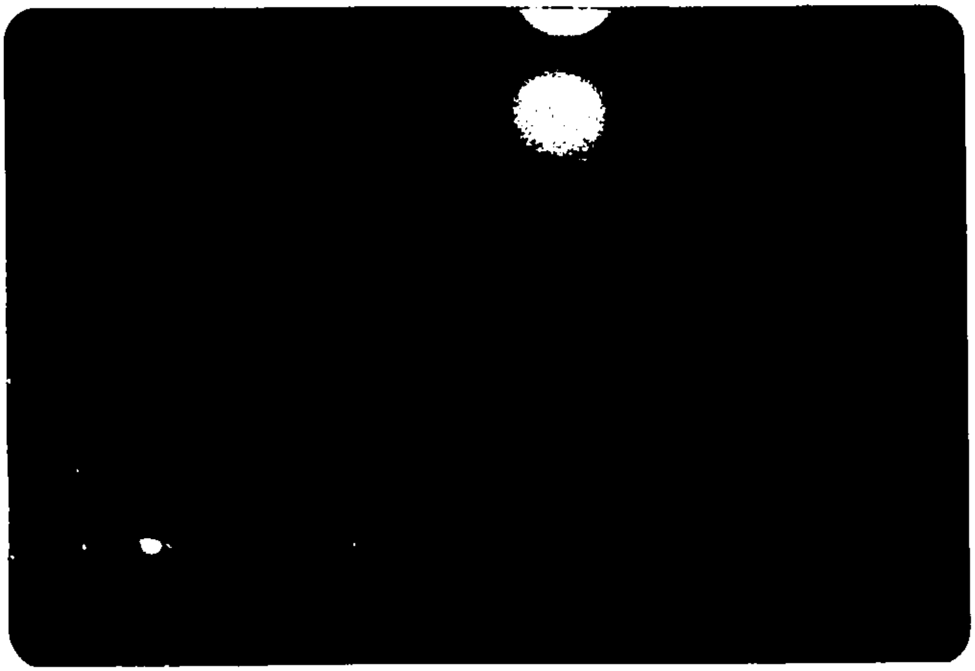


Figure 4.3 a) View looking into the right side of block 3. Cloudy sediment bands can be seen dipping down from the face at approximately 45°.

b) View looking into the face of block 3. Note the pebble in the upper righthand corner.

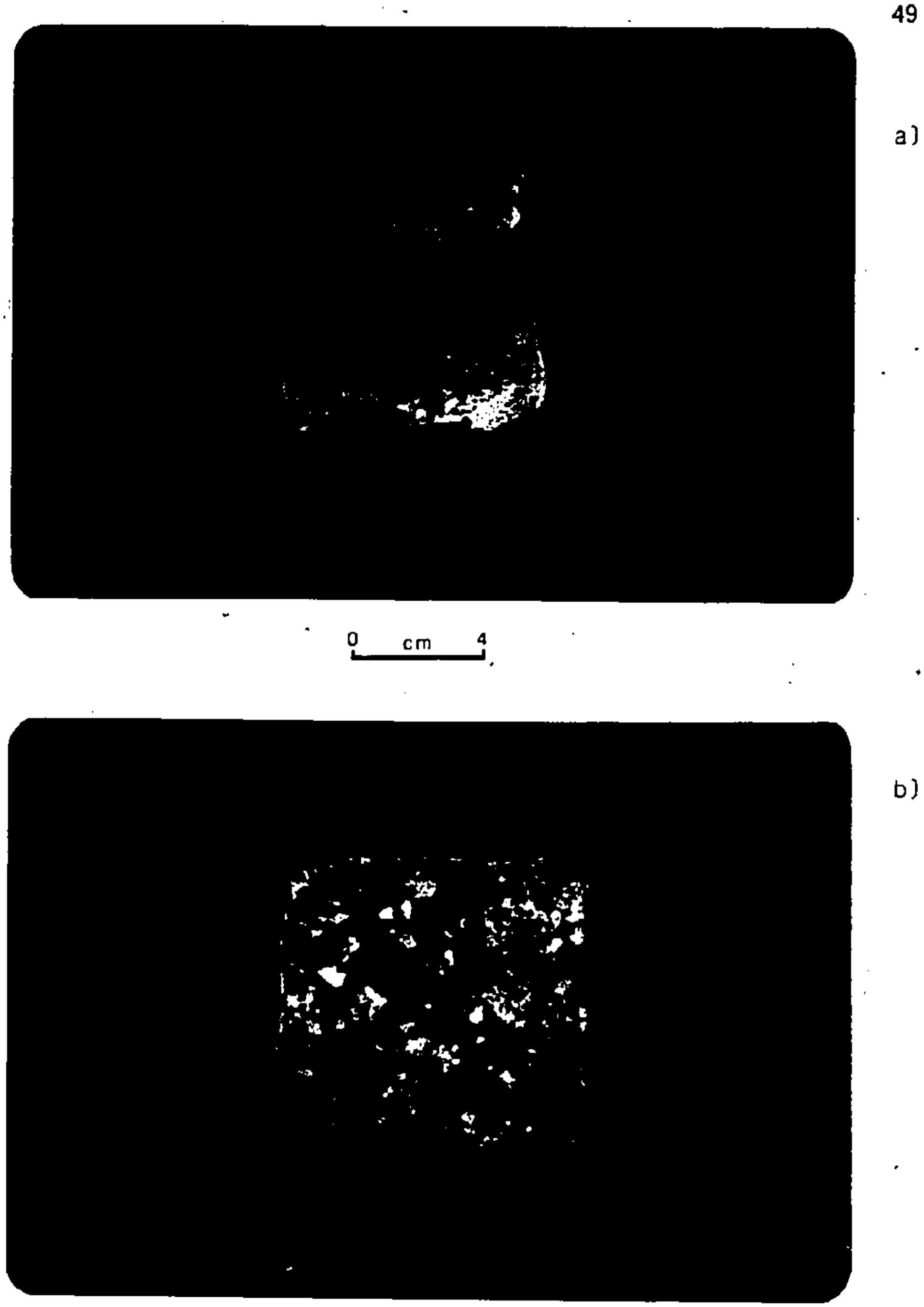


Figure 4.4 Thin sections viewed in cross-polarized light show the difference in crystal size with change in sediment content.

a) Vertical thin section parallel to the face of block 1.

b) Vertical thin section parallel to the face of block 2.

the larger crystals had substructure, suggesting the coalescence of several smaller crystals.

Crystal shape was for the most part anhedral but occasionally it was subhedral. Some crystals showed dimensional orientation, being slightly vertically elongated (Figure 4.5). Grain boundaries were usually curved or straight, although some minor embayment of smaller crystals into larger ones resulted in boundary irregularities.

Air inclusions, although usually intergranular were occasionally observed to be intragranular; however, the latter were always round flat discs and were interpreted to be the result of internal melting. Two strain shadows from block 1, and one from block 2 were observed through cross polarized light. These ran either along crystal boundaries or through crystals indicating some dislocation of crystal boundaries. Fractures that occurred either while the blocks were being removed from the main body of ice or while thin sections were being made were intragranular having no effect on grain boundaries.

Crystal size in block 3 was smaller than in blocks 1 and 2 but also variable depending on sediment content. Where there were few sediment inclusions, or inclusions in the form of clumps, average crystal size was about 4 mm in diameter. Wherever dispersed fine particles occurred crystal size was usually less than 1 mm (Figure 4.6). The dispersed sediment was both inter- and intragranular whereas sediment clumps were always intergranular. Air inclusions were almost always intergranular. Once again, crystal shape was dominantly anhedral and boundaries were straight and curved. Due to the small crystal size boundaries were fairly regular.

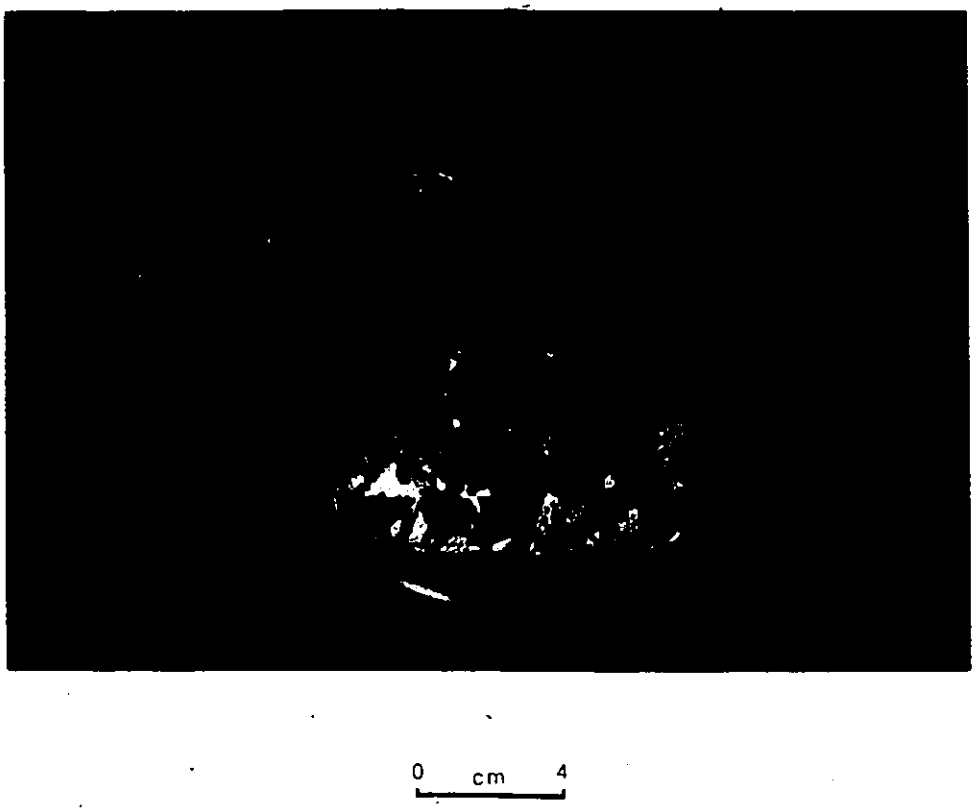
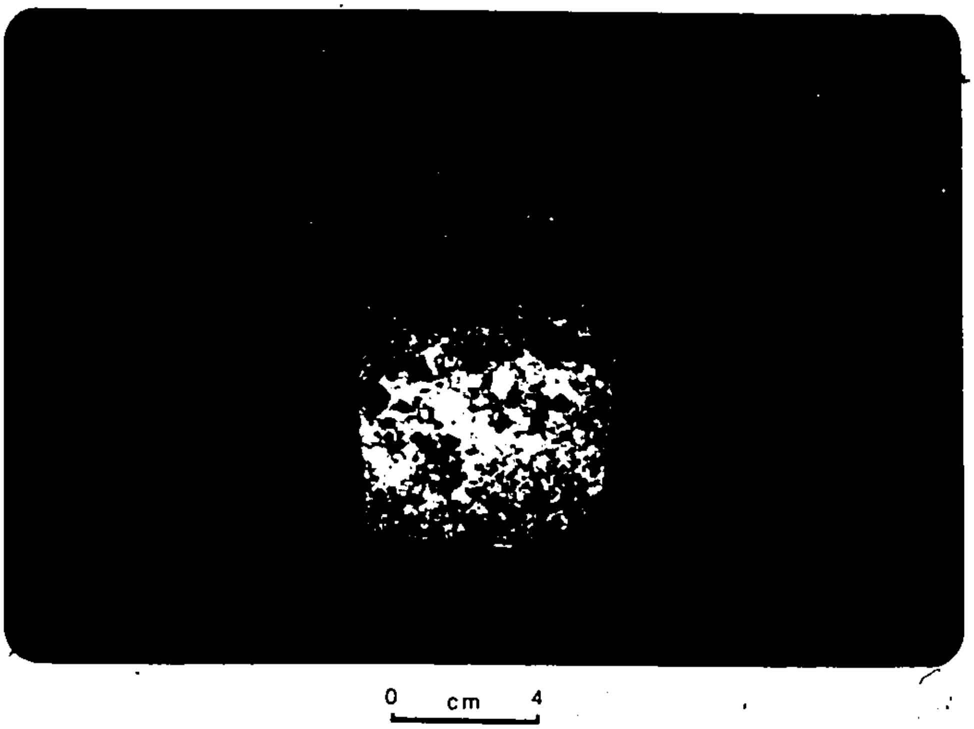


Figure 4.5 Vertical (perpendicular to the face) thin section from block 2 shown through cross-polarized light.



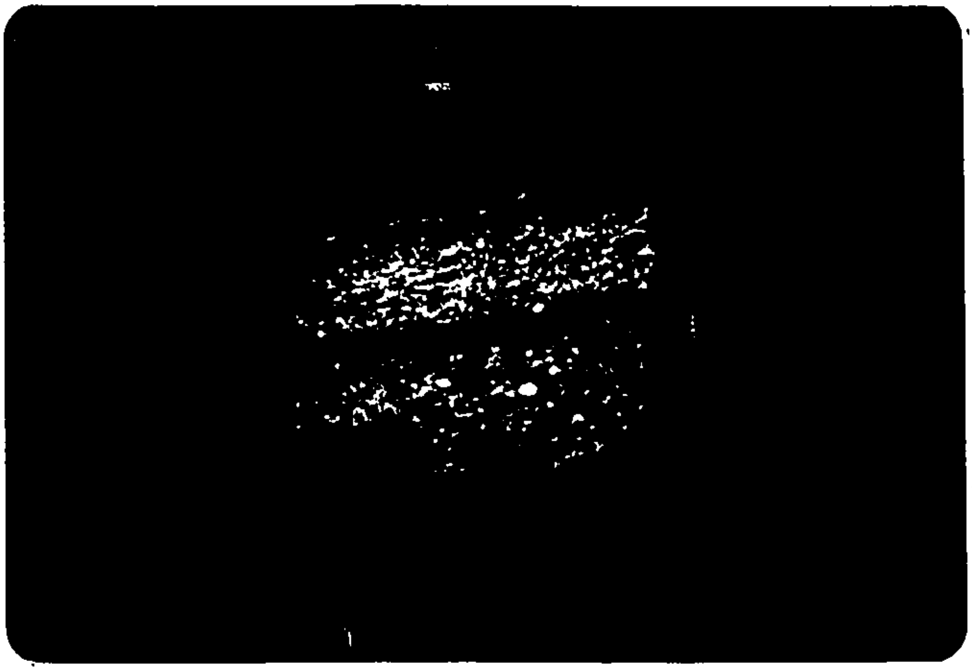


Figure 4.6 Crystal size in block 3 was small and varied with sediment content. Thin sections are viewed through cross-polarized light.

a) Horizontal thin section.

b) Vertical thin section, cut parallel to the face.

4.3.1 Ice Fabrics

Fabric diagrams are similar for all three blocks and have for the most part strong single maxima (Figure 4.7). In all cases crystal c-axes are oriented at approximately 15°-20° from horizontal. Their azimuths, however, are slightly different for each block. In most cases, the c-axes dip up into the ice. When one considers that the slope of the ground surface is approximately 11° in the same direction, the c-axis orientation becomes almost exactly parallel to the ground surface.

A slight double maximum is discernable on the horizontal diagram for block 2 (Figure 4.7b). The second maximum shows crystal c-axes to be approaching horizontal but with their azimuths rotated slightly to the east of the larger maximum. A line indicating the compositional layering in block 3 is shown in the fabric diagram for that block (Figure 4.7c). From this one can see that c-axis orientation is at approximately 115° to the sediment banding.

4.4 Discussion

The massive ice is obviously not pore ice since the excess ice content is usually over 90% and the ice is not restricted to the voids between soil grains. No further discussion is required to eliminate this type of ice as a possible origin.

It is also unlikely that the ice is intrusive ice. The size of the ice mass is large, at least 30 X 1.5 X 14 m, and similar bodies of ice occur widely in the study area. Although there is positive relief in the adjacent area, there is no reason to believe that freezing was the result of water movement under hydraulic or hydrostatic pressure. In addi-

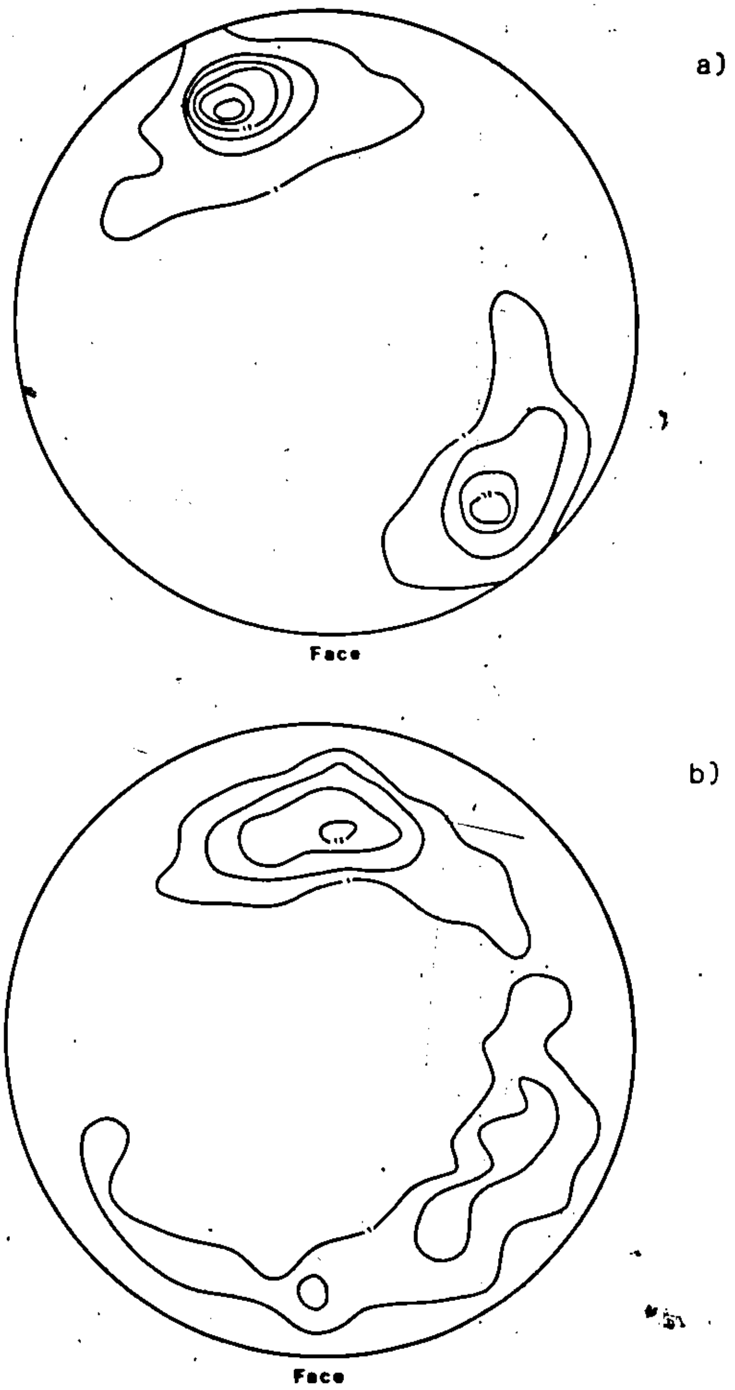
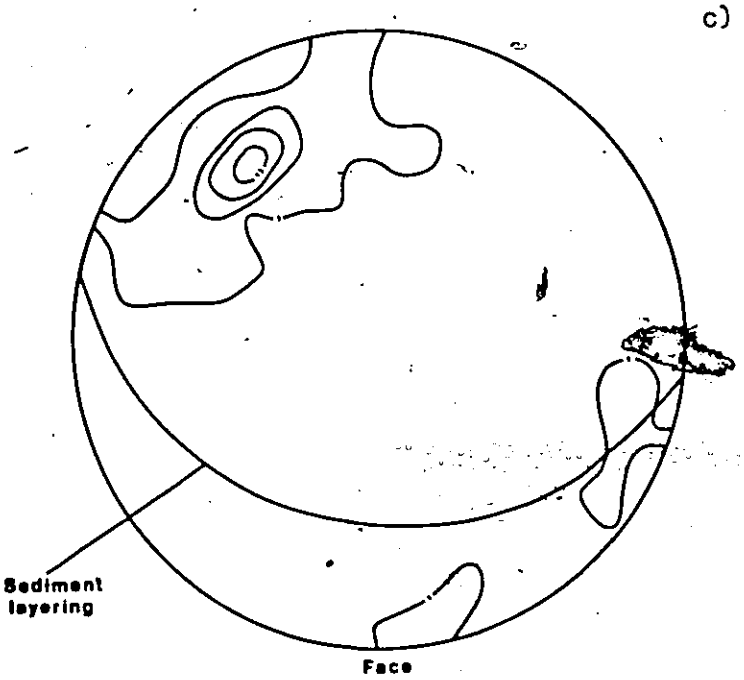


Figure 4.7 Fabric diagrams show a strongly preferred orientation of c-axes approximately 15-20° from horizontal. All diagrams are from horizontal thin sections, contour interval is 4%.

a) Block 1.

b) Block 2, note the slight second maximum.



c) Block 3.

tion, inclusion characteristics do not resemble those of intrusive ice. In intrusive ice sediment inclusions are rare and occur as streaks parallel to the movement of water. In the ice examined, sediment is irregularly distributed, sometimes in bands at 45° angles to the ground surface (block 3) and at others in short streaks parallel to the ground surface. Banding of sediment inclusions such as is shown in Figure 4.1a is atypical of intrusive ice. Furthermore, layering associated with distinct bands of bubbles is common in intrusive ice but is not found. Finally, when side-contacts with adjacent materials were observed there was no deformation of sediments.

Crystal characteristics further confirm that the ice is not intrusive ice. Average crystal size is 5-8 mm with a maximum of 21 mm. A preferred c-axis orientation exists throughout the three blocks of ice. In intrusive ice small crystals are usually found in the upper 'chill' zone and their c-axis orientations are random. Below this zone crystals are usually columnar, measuring several centimetres in length or, if they are small, they are layered (e.g., Pollard, 1983, p. 154).

The ice cannot be interpreted as wedge ice for a number of reasons. First, it lacks the characteristic wedge shape and foliations which are usually seen when wedge ice is viewed in cross section. Second, in most places, the ice lacks the milky appearance due to the abundance of bubbles which are commonly found in ice wedges. Third, there is no deformation of adjacent sediments. Fourth, the ice/sediment contact at one end of the body of ice at one slump is gradual.

In some ways, the characteristics of the ice resemble those of segregated ice. Segregated ice may be both pure and clear or composed of bands of dirty ice alternating with relatively pure ice. As previously mentioned, bands of dirty ice were present in the ice but usually the ice was clear with horizontal streaks of sediment clumps. Isolated stones were found in both the ice in this study and the segregated ice identified by Mackay (1971).

Spherical, cylindrical, and pear-shaped bubbles were observed throughout all three samples. Cylindrical and pear shaped-bubbles were consistently oriented vertically with their fat end at the bottom. This is an indication that freezing occurred from the top in a downwards direction and is consistent with the formation of segregated ice. The fact that most bubbles were similar in size indicates a fairly uniform rate of freezing (Bari and Hallett, 1974); however, bubble-rich areas such as the top of block 2 and the lower part of block 3 could indicate areas which experienced slightly slower freezing or areas of higher gas content.

Bubble characteristics similar to those in the ice studied have been described elsewhere for massive ice bodies believed to be of segregated origin (Mackay, 1966; Mackay and Stager, 1966b). In fact, the bubble size, variation, and orientation seem to be typical of segregated ice (Cheng, 1983; Corte, 1962; Penner, 1961).

Crystal texture also bears some similarity to that of segregated ice. First, crystal size is closely linked to sediment content. For example, where sediment content is higher, crystals are small. Second, crystal shape and size are similar to those documented for segregated ice and the vertical elongation of crystals has also been observed (Penner, 1961).

On the other hand, similarities between sediment inclusions in segregated ice and those in this study are only superficial. Sediment inclusions are more irregular and banding at 45° angles, observed in block 3, cannot be explained by a response to a thermal gradient normal to the ground surface. It is known that at some localities in the western Arctic (e.g., Herschel Island, Garry Island, Kay Point, and others), segregated ice does not resemble the regular horizontal beds of dirty ice alternating with clear ice that are exposed near Peninsula Point, Tuktoyaktuk (Mackay, 1971), but these have been interpreted to be the result of glacier ice-thrusting (Mackay and Stager, 1966b; Mackay, 1963). If the banding in the ice were the result of glacier ice-thrusting, then this would imply that a glacier overrode the area since ice segregation took place. Since ice segregation must have taken place after the enclosing material (Carpenter Till) was deposited this implies that a glacier overrode the area since the Sand Hills Readvance. There is, however, no evidence to suggest this. An additional consideration is that crystal fabric is not similar to most segregated ice fabrics. The preferred c-axis orientation in segregated ice is usually perpendicular to the freezing front (vertical); however, in the Sand Hills samples, the crystal c-axes are parallel to the ground surface. Since the freezing front in segregated ice would parallel the ground surface, c-axis orientations are at 90° angles to what one would expect if the ice were of a segregated origin.

Chapter V

CONCLUSIONS

Since the purpose of this thesis is to examine the petrography of ground ice as one possible means of identifying its growth mechanism, any conclusions must bear in mind 1) the stratigraphic occurrence and age of the ice, and 2) the different origins of ground ice.

5.1 Age and Stratigraphic Occurrence of the Ice

The stratigraphy at the slump was simple consisting of reworked Carpenter Till overlying an exposure of massive ice. The overburden must be reworked till since it is located in the floor of an older inactive slump. Unfortunately, the exact age of the Carpenter Till is unknown. Based on radiocarbon dating of shells, Vincent (1982) assigns an age of at least 19,000 years to the marine transgression following the retreat of the Thesiger Lobe. Although Vincent (1982; 1983) refers to the Sand Hills Moraine as 'young looking' in comparison to the Sachs Till surface he nevertheless associates the Carpenter Till with the Thesiger Lobe and not a younger ice advance. Thus, it appears that the Carpenter Till was deposited over 19,000 yrs B.P. Therefore, any ground ice found within or beneath Carpenter Till would be 19,000 years old or younger.

5.2 Origin of the Ice

Two lines of evidence support the hypothesis that the ice is segregated ice. These are: 1) bubble characteristics, similar to those found in segregated ice, which indicate freezing from the top downwards, and 2) crystal shape, size, and dimensional orientation, which are similar to those of segregated ice. Two considerations which cast doubt upon this hypothesis are: 1) the 45° dip of banding observed in block 3, which is too steep to be explained by the ice segregation process, and 2) the preferred orientation of crystal c-axes parallel to the freezing front. If the ice were segregated ice, then bubbles should be oriented perpendicular to sediment banding.

Bodies of massive ice having similar descriptions to the massive ice seen in this study are present elsewhere on Banks Island, particularly along the east coast where they are found underlying Big Sea sediments and overlying Jesse Till (Egginton, 1976; Vincent, 1983). Vincent (1983) attributes their origin mostly to segregated and wedge ice but he does not rule out the possibility that some of them could be buried glacier ice.

Lorrain and Demeur (1985) have suggested recently that buried Wisconsin glacier ice may be present on Victoria Island. It is useful therefore, to compare descriptions of the ice discussed by Lorrain and Demeur to the ice found in the Sand Hills Moraine.

The ice found on the northeastern tip of Prince Albert Peninsula, Victoria Island, is exposed over a distance of 450 m and overlain by 1.0-2.0 m of till which was deposited during the M'Clure Stade of the Amundsen Glaciation (Lorrain and Demeur, 1985). The ice has a massive subvertical banding due to an alternation of dirty and relatively clean ice and bubbly and bubble-free ice. The thickness of these bands is usually from 3-100 cm, the dirty ice being in thick layers and the clean ice being in thin ones often interbedded with thin sediment layers. The dip of the ice beds is so steep that Lorrain and Demeur (1985) interpret it as the result of glacier ice-thrusting. Oxygen isotope analysis of fifty six ground ice samples give values 11 ‰ lower than those of present-day surface waters. Because this shift is the same as that found by Dansgaard et al. (1971) at what is interpreted to be the transition from Wisconsin to Holocene ice in the ice core from Camp Century, Greenland, Lorrain and Demeur believe that the ground ice was formed during the Wisconsin. Furthermore, a graph of deuterium versus oxygen isotope values gives a straight line corresponding to the meteoric water line. This is consistent with the hypothesis that the ice formed as a result of the metamorphism of snow during a glaciation. Based on this, Lorrain and Demeur (1985) conclude that the ice is buried Wisconsin glacier ice.

Although no vertical banding was observed in the ice in the Sand Hills Moraine, dirty ice dipping 45° into the ice was seen in block 3. When viewing the top of block 3 this band appears to be subhorizontal. In the area where blocks 1 and 2 were collected (approximately 1 m below and 8 m to the west of block 3), horizontal bands of sediment correspond to the type of banding found in block 3. These bands are overlain by milky white ice with a high bubble content (see Figure 4.1a). The ice therefore, may have a similar banding structure to the ice on Victoria Island but because the bands appear horizontal at the ice face an exposure of several metres would be required to be certain. If banding did occur at 45° angles into the face (as suggested by block 3), then retreat of the ice should reveal changes in the relative clarity and purity of ice at the same elevation. This was observed to be the case.

In summary, the ice sampled in the Sand Hills Moraine area bears a resemblance to that studied by Lorrain and Demeur (1985). It is also overlain by till deposited during the M'Clure Stade of the Amundsen Glaciation. As a result, the possibility exists that this ice is buried glacier ice. Other types of buried surface ice (i.e., lake, river, sea, snow) are not possibilities since most of the massive ice bodies were located in high terrain.

The ice should also be compared to the characteristics of unambiguous glacial ice. For example, the average crystal diameter of 5-8 mm observed in the Sand Hills ice is much smaller than the average size observed in the cores of glacier ice taken at Byrd Station Antarctica and Camp Century, Greenland. Although crystal size in the first several hundred metres of the cores resembles that of the ice in this study crystal shapes are quite different. Crystals in this study are anhedral occasionally tending to be vertically elongated, and, unlike the glacier ice, no sutured boundaries or complex interlocking crystals were observed. Crystal size and shape at the glacial-interglacial transition of the cores resemble the ice in the Sand Hills samples with the exception of the elongated crystals observed in blocks 1 and 2. Crystals below this stratigraphic point are much larger than those found in this study. Finally, fabric diagrams shown in Figure 4.7 have strongly preferred c-axis orientations reminiscent of those found at the galcial- those found at the glacial-interglacial transition of the ice examined at Byrd Station and Camp Century. This lends support to the speculation that the Sand Hills ice is buried glacier ice.

5.3 Summary

Several factors indicate that the Sand Hills ice has, or is undergoing changes since its original formation. First, many of the larger crystals have barely visible subdivisions which are made up of several smaller crystals having almost, but not quite, identical c-axis orientations. This crystal substructure is possibly due to the amalgamation of small crystals into a single larger one. It is thought, therefore, that average crystal size has probably increased due to recrystallization. Second, minor grain boundary dislocation observed along strain shadows also indicates change in the ice structure. This could contribute to the anhedral shape of crystals as well as to the irregularity of some crystal boundaries. However, if major boundary dislocation had occurred followed by recrystallization, the effect would have been to reduce crystal size and change crystal dimensions.

It is also interesting to note that most inclusions found in the ice are intergranular. Although it is natural for impurities (gaseous and solid) to congregate along crystal boundaries when forming, they also have a tendency to migrate to this position when ice approaches its melting point. This is particularly important if the ice is of some antiquity since it would have been subjected to warmer temperatures during the mid-Holocene climatic optimum.

Since it is evident that the ice has undergone some changes, it is unwise to state with certainty the origin of the ice based solely on its crystal structure. This is especially true if the ice is old since the longer the ice has been in existence the greater are the chances that it has undergone transformation. Petrographic analysis of ground ice is useful when major inconsistencies between certain structural properties of the ice in question and those expected for a particular type of ground ice cannot be explained without ruling out that type of ice. In this instance petrographic analysis helps to eliminate certain types of ice.

In summary therefore, the petrography of ground ice collected from the Sand Hills Moraine resembles that of glacier ice. It is not possible to explain the steep angled banding of dirty ice and the preferred orientation of crystal c-axes parallel to the freezing front in terms of ice segregation. The most likely alternative possiblity is that the ice is buried glacier ice related to the Amunsden Glaciation. Further research should be conducted to confirm this. Isotope analyses of samples taken at regular depth intervals should be conducted and results compared to those obtained by Lorrain and Demeur (1985) for ground ice on Victoria Island. Other chemical analyses should also be done since Cragin et al. (1977) have found that Wisconsin ice in Greenland and Antarctica has a higher concentration of sulfate inclusions than modern ice. The texture and fabric of the ice on Victoria Island should be compared to the texture and fabric in this study and to others (e.g., Corte, 1962; Gell, 1973; 1976; Gow and Williamson, 1976). Although sediment inclusions within the ice appear to resemble the overlying material, grain size analysis should be done to confirm this. Finally, other bodies of ground ice in the Sand Hills Moraine should be examined to ensure their similarity to the ice studied in this thesis.

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