THE NATURE AND ORIGIN OF GROUND ICE IN THE HERSCHEL ISLAND AREA, YUKON TERRITORY.

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Abstract

The nature of ground ice on Herschel Island reflects the geomorphic processes and thermal conditions of the late Quaternary period. Field studies carried out from 1986 to 1988 investigated cryostratigraphic characteristics of ice-rich sections exposed in retrogressive thaw slumps and coastal bluffs in the Herschel Island area of the Yukon Coastal Plain. Sediment and ice samples were analysed for moisture content, grain size, and ice petrography. Ground ice constitutes up to 60-70 % of the upper 10-12 m of permafrost. Melting of massive ground ice and ice-rich materials have produced numerous large retrogressive thaw slumps. The petrographic characteristics of 5 types of massive ground ice were determined, including: ice-wedge ice, buried snowbank ice, injection ice, segregated and glacier ice. Ice of glacial origin is tentatively identified in areas of glacially-thrust marine sediments. The presence of very large active and inactive ice wedges, together with ice-wedge casts, multi-stage and syngenetic ice wedges in deformed sediments indicate a very long period of cold post-glacial conditions interrupted by one or two periods of deep thaw. The deformed nature of these materials reflect the glacial ice-thrust processes which formed the island and complicate cryostratigraphic interpretation.

Résumé

La nature de la glace de sol dans l'île Herschel traduit les conditions thermiques et les processus géomorphologiques de la fin du Quaternaire. Des études de terrain sur les caractéristiques cryostratigraphiques de coupes riches en glace, dégagées dans des glissements de terrain et des falaises littorales, ont été effectuées entre 1986 et 1988 sur l'île Herschel, dans la plaine littorale du Yukon. Des échantillons de glace et de sol minéral ont fait l'objet d'analyses granulométriques et pétrographiques ainsi que de mesures de teneur en eau. La glace occupe jusqu'à 70 % des 10 à 12 premiers mètres de pergélisol. La fonte de couches de glace massive et de sédiments riches en glace a engendré de nombreux glissements rétrogressifs. Les caractéristiques pétrographiques des 5 types de glace suivants ont été déterminées: glace de coin, glace provenant de combes à neige enterrées, glace d'injection, de ségrégation et d'origine glaciaire. La glace d'origine glaciaire a de façon préliminaire, été associée aux zones de sédiments marins déformés par la glacitectonique. La présence dans les sédiments déformés de coins de glace actifs et inactifs de grandes dimensions ainsi que de fentes en coin et de coins de glace syngénétiques superposés indique que la longue période post-glaciaire a été entrecoupée d'une ou deux périodes de dégel profond. L'interprétation cryostratigraphique du matériel est rendue plus ardue en raison des déformations causées par les poussées exercées par les glaciers qui sont à l'origine de l'île.

Introduction

Occurrences of massive ground ice are widely reported throughout the western Canadian Arctic (Mackay, 1966, 1989; Rampton, 1982). Several studies have been concerned with the origin and stratigraphic characteristics of ground ice in the Mackenzie Delta and the Yukon Coastal Plain (e.g. Mackay, 1971; Rampton, 1974; Rampton and Mackay, 1971). Some have included analysis of petrographic characteristics of massive ground ice (e.g. Dallimore and Wolfe, 1988; Fujino *et al.*, 1988; Gell, 1978a, 1978b; Harry *et al.*, 1989; Pollard and Dallimore, 1988). These studies show that ground ice forms an important component of permafrost sediments and plays a major role in the evolution and modification of periglacial landscapes in the western Arctic. There have been no previous detailed ground ice studies on Herschel Island, even though it was a proposed site for oil and gas exploration in 1974 and considered as a possible location for a Department of National Defence radar station.

One approach to the investigation of ground ice genesis and nature is the analysis of its cryostratigraphic and petrographic characteristics. In some cases, information about environmental conditions and geomorphic processes post-dating permafrost aggradation may also be documented. Early examples of petrographic analysis of ground ice are studies by Black (1953) in Alaska and Gell (1976) in the Mackenzie Delta. However, in recent years, the cryostratigraphic-petrographic approach has gained wider application (e.g. French and Pollard, 1986; Harry *et al.*, 1989; Pollard and Dallimore, 1988).

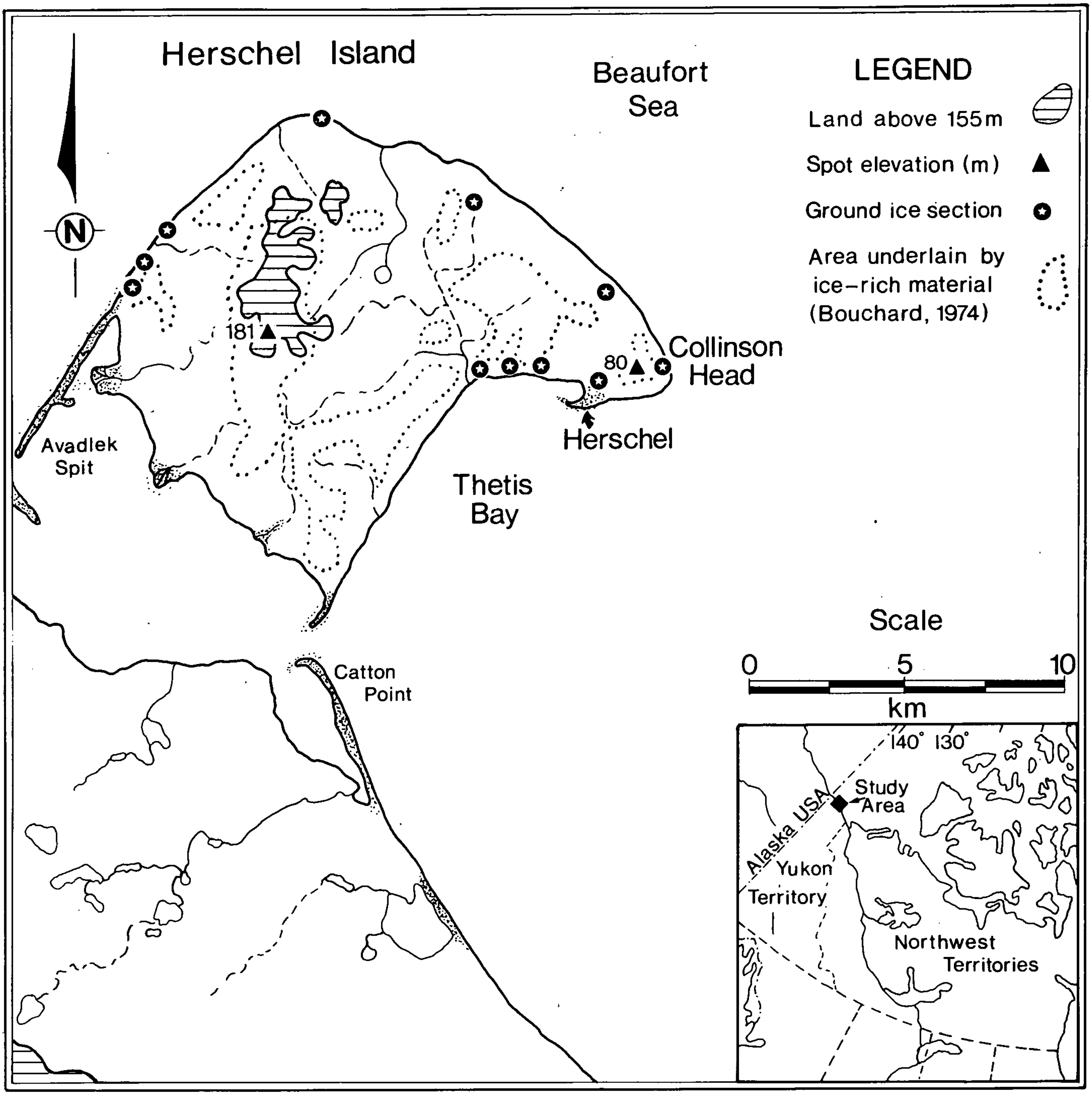


Figure 1. Study area map of Herschel Island showing the location of study sites and ice-rich permafrost.

This paper summarizes a field study carried out between 1986 and 1988 investigating cryostratigraphic and petrographic characteristics of massive ground ice exposed in retrogressive thaw slumps and coastal bluffs at Herschel Island. The primary aims of this paper are:

(1) to describe the range and nature of massive ground ice found on Herschel Island together with its petrographic characteristics, and
(2) to incorporate petrographic properties into a genetic classification for massive ground ice based on observations from Herschel Island, the Yukon Coastal Plain and Mackenzie Delta.

Study area

Herschel Island (Fig. 1) is located at 69°42'N, 139°01'W in the northern Yukon Territory within the zone of continuous permafrost, which is at least 300 m deep (Judge, 1973). The mean annual air temperature is approximately -11°C. The island is approximately 108 km² and is characterized by rolling and hummocky moraines which form ridges and hills up to 180 m a.s.l. The melting of ground ice in areas of high relief, which are often ice-cored, has resulted in extensive thermokarst. The nature of ground ice on Herschel Island reflects the complex geomorphic and climatic history of the late Quaternary period in this region (Rampton, 1982).

The Quaternary stratigraphy of Herschel Island is divided into pre-glacial, glacial and post-glacial deposits (Bouchard, 1974). Although much of the northern Yukon remained unglaciated throughout the Pleistocene, the Yukon Coastal Plain near Herschel Island was glaciated at least once. A glaciotectonic origin is assigned to Herschel Island (Mackay, 1959). Topographic and structural characteristics support a glacier ice-thrust hypothesis. In theory, a lobe of Laurentide ice moved northwestward from the Mackenzie Valley during the early Wisconsin and excavated marine sediments from the current location of the Herschel Basin. As the ice impinged on the coast, it produced an ice-thrust moraine and formed the main body of the island (Rampton, 1982).

During deglaciation, a major stillstand or re-advance, termed the Sabine Phase, produced a moraine-outwash complex that lies southeast of Herschel Island. Marine and mixed terrestrial deposits predating glaciation are exposed at the base of coastal bluffs on Herschel Island and the western Yukon coastal. Reworked glacial, glacial-fluvial and lacustrine deposits are overlain by pre-Buckland sediments. Post-Buckland time has been marked primarily by alluviation, thermokarst, mass wasting and ground ice formation (Rampton, 1982).

Ground ice

Massive ground ice is defined by a gravimetric moisture content exceeding 250% (percent dry weight) or approximately 85-90% by volume. According to Mackay (1989), massive ground ice can be divided into 2 categories, (1) buried ice and (2) ground ice formed in place or *in situ* ground ice. *in situ* ground ice is subdivided into epigenetic and syngenetic types, reflecting the relationship between ice formation and stratigraphic position. These ice types can be further subdivided on the basis of genetic processes (Mackay, 1972).

Massive ground ice and ice-rich sediments are common on Herschel Island and are readily observed in coastal sections, stream valleys and retrogressive thaw slumps. The most common types of ground ice, based on stratigraphic and petrographic analyses, are massive or horizontally-foliated segregated ice and ice-wedge ice (Fig. 2). A long history of ice-wedge development can be inferred from extremely large ice wedges, deeply buried relict ice wedges and multistage ice wedges. Ice-wedge polygons are visible on aerial photographs for approximately 15% of the island's surface. Since ice wedges do not always have a clear surface expression, the true value is probably much higher. Other forms of massive ice documented include buried snow bank ice, intrusion ice and irregularly-shaped ice bodies in highly deformed materials within ice-thrust ridges on the north and west sides of the island. The latter has abrupt unconformable upper and lower contacts, is overlain by diamicton and is faintly foliated and contain thin bands of fine sediment (Fig. 2c). It is tentatively interpreted as buried glacier ice. Pore ice, vein ice and reticulated ice occur in most sections and contribute to the ice-rich nature of permafrost.

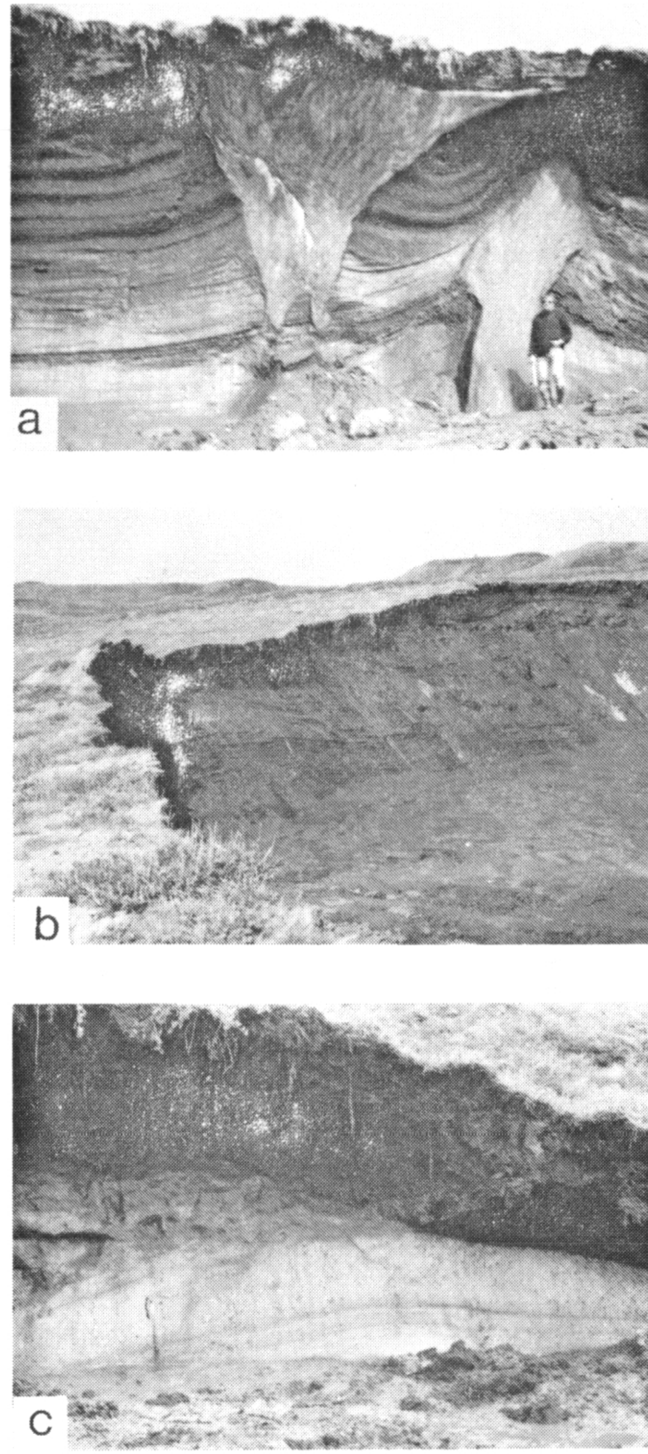


Figure 2. Photographs illustrating (a) large active and inactive ice wedges, (b) horizontally bedded massive segregated ice and (c) buried glacier ice.

Stratigraphy

The cryostratigraphic approach can be useful in the reconstruction of permafrost conditions. Stratigraphic observations were undertaken at 10 ice-rich exposures located in coastal bluffs and retrogressive thaw slumps. The deformed nature of Herschel Island sediments make regional interpretation and correlation very difficult. The following is

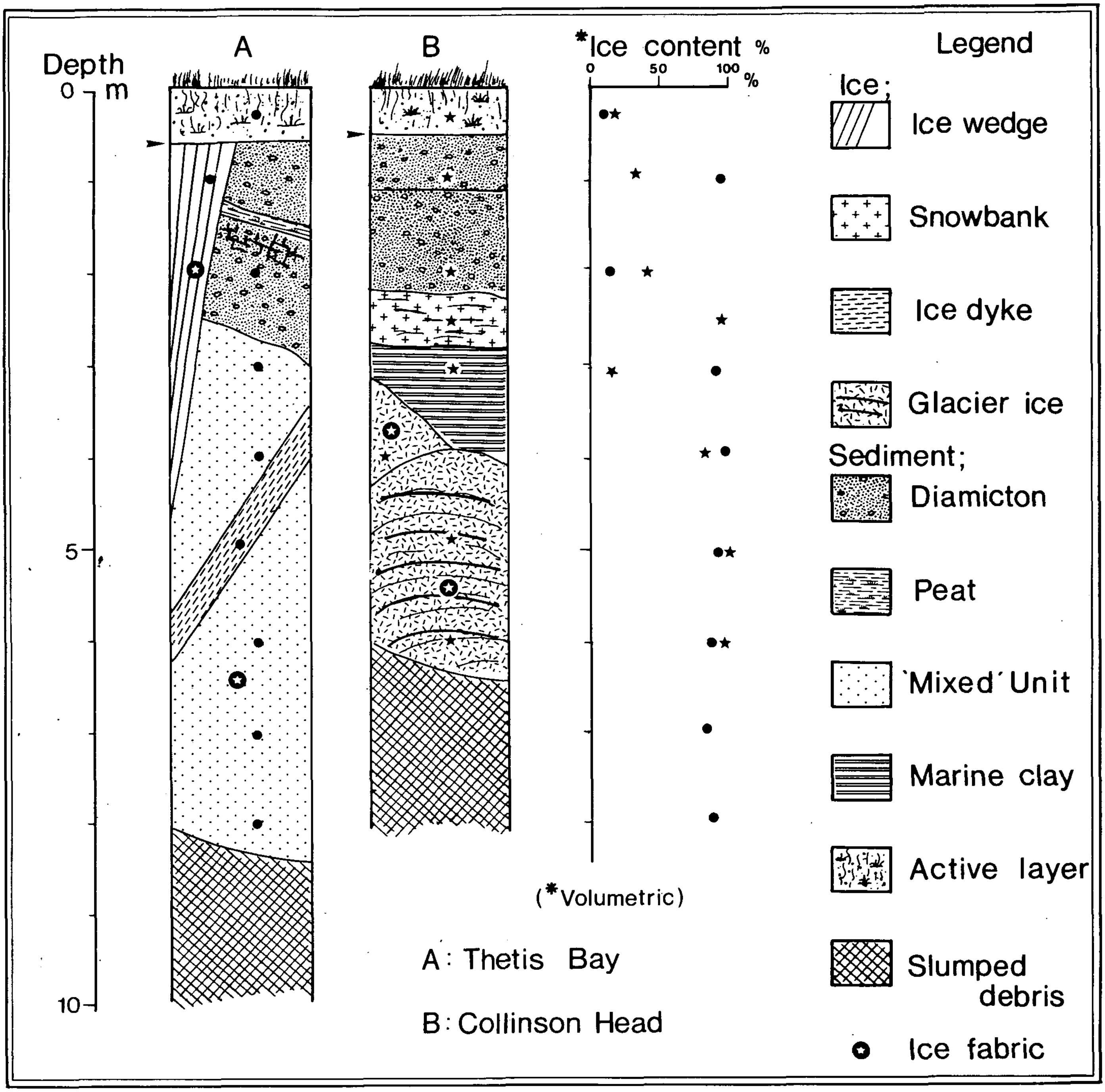


Figure 3. Stratigraphic sections illustrating the relationship between ground-ice bodies and enclosing sediments at Collinson Head and Thetis Bay.

a summary of stratigraphic characteristics associated with each massive ice type. Stratigraphic relationships from two measured sections are presented in Figure 3.

Large masses of segregated ice occur most often within the "mixed" sediment unit composed of sandy silt with gravel and clay-rich beds. The ice bodies, typically 3-6 m thick (9 m maximum), are either conformably overlain by 2-2.5 m of "mixed sediments" or unconformably overlain by up to 2.5 m of silty diamicton containing cobbles and small boulders. In the Thetis Bay area, a peat unit up to 2 m thick overlies the diamicton. The date for the peat unit was 9 300 + 170 years BP (GSC-1483). Detrital peat and wood fragments found in an ice-bearing mixed sediment unit dates >40 000 years BP (WAT-1921). In some locations, segregated ice is underlain by a silty marine clay unit. Segregated ice comprises up to 70 % of the upper 10-12 m of permafrost.

Modern ice wedges penetrate the surface diamicton , peat and underlying mixed sediments. However, some relict ice wedges are truncated at the top of the mixed sediment sequence. Others display 2-3 stages, reflecting thaw to a depth of 2 m and subsequent upward aggradation of permafrost to the current position of the active layer (approximately 50-70 cm). At one location, an ice dyke cut discordantly across the sequence to the base of the active layer. Maximum thickness of segregated ice is 10 m and ice wedges penetrate to a depth of 15 m.

Near Collinson Head, deformed bodies and layers of pale brown to dirty massive ice were observed in grey marine silts and clays. The ice in some cases displays abrupt unconformable upper and lower contacts suggesting a buried origin. At this site, a mass of faintly-layered massive ice with an arched structure and pale brown in color is found in glacially-thrust materials (Fig. 2c). An irregular body of dirty massive ice covers part of the arched ice mass. Both units are unconformably overlain by 1-2 m of icy diamicton and are tentatively interpreted as buried glacier ice.

Buried snowbank ice occurs at several polycyclic thaw slump locations. It occurs as faintly layered, white to pale brown, irregularly shaped ice bodies. In each case, both upper and lower contacts are unconformable. The upper contact is a thaw unconformity where the overlying sediments has melted the upper part of the ice unit. Buried snowbank ice comprises 4-7% of exposed ice.

Ice wedges are limited to the upper 10-15 m of frozen material and are associated with a wide variety of sediments. Ice wedges comprised up to 60% of frozen materials in the top 10 m of one location at Thetis Bay where 31 wedges were exposed over a 150 m section.

Ice appearance and petrography

Oriented block samples were taken from several ground ice bodies and transported by helicopter in refrigerated containers to Inuvik where petrographic studies were undertaken.

The nature and pattern of gas and sediment inclusions determine the color and appearance of the ice. Inclusion characteristics reflect the thermal and hydrologic conditions during freezing. The rate and direction of freezing influences the size, shape, orientation and bulk pattern of gas inclusions as well as crystal characteristics. Sediment inclusion pattern is determined by freezing rate and the source and rate of water supply.

Segregated ice has the greatest range in appearance because of the large number of factors influencing its growth. A complete spectrum from clear and colorless ice to dirty foliated ice was observed. In some cases, sediment bands form brecciated layers in an ice matrix. Gas inclusions range from vertically-oriented planes of small, flat bubbles to horizontal bands of large circular and vertically-oriented tubular bubbles. By comparison, ice-wedge ice is milky white to pale brown in color with vertical to steeply inclined folia. Bands of sediment-rich and bubble-rich ice produce the foliated appearance. Buried snowbank ice also has a milky white to pale brown appearance, but has faint horizontal layering caused by thin bands of sediment and bubble-rich ice. Gas inclusions are very small and vertically-oriented. Intrusion ice found in a frost blister is clear and colorless, but dyke ice is brown and massive. Gas inclusions are small and spherical near sediment contacts, but become larger and elongated several centimetres away from the contact. The axes of elongation are normal to the contact and parallel to the assumed freezing direction. Ice found in the ice-thrust ridges is dark brown with white layers.

Petrographic analysis of ground ice is based on the assumption that the pattern of crystal size, shape, boundary characteristics and c-axis orientations reflect growth processes and conditions. Thin sections were prepared from each ice block and c-axis orientations were measured using a Rigsby universal stage under cross-polarized light (following Langway, 1958). Fabric diagrams are plotted as lower hemisphere projections on a Schmidt equal area net with a contour interval of 2% (Fig. 4). These data suggest that each ice type displays a characteristic range of fabric and texture patterns, which when incorporated with stratigraphic and inclusion observations, can be used to identify different types of massive ground ice.

Segregated ice obtained from thick, clear layers tends to be composed of large, equigranular anhedral crystals. Occasionally, crystals are elongated in the direction of growth. C-axes form either point maxima, or a loose girdle oriented normal to the plane of the ice layer and more dispersed patterns in areas of high inclusion content (Fig. 4a). Petrographic characteristics of foliated segregated ice are closely related to sediment banding. Crystals display distinct textural breaks at sediment bands and are characterized by irregular shapes that tend to extend from one band to the next. C-axes are more dispersed, but display a weak preferred orientation normal to the sediment layers.

Ice-wedge ice displays a gradual change in texture and fabric from the center of the wedge (usually young ice) to the wedge sides (older ice). Ice from the middle of the wedge is composed of small equigranular anhedral crystals oriented perpendicular to the wedge axis. C-axes form a horizontal girdle roughly perpendicular to the wedge axis. Crystals become considerably larger toward the side of the wedge and tend to be elongated parallel to the wedge boundary (Fig. 4c). C-axes range from dispersed patterns to point maxima oriented perpendicular to the side of the wedge. Crystal and inclusion patterns reflect the foliated structure produced by repeated infilling of vertical thermal contraction cracks near the wedge centre.

Buried snowbank ice is composed of small, euhedral equigranular crystals with a high concentrations of vertically oriented intercrystalline bubble trains and tubular bubbles. Sediment inclusions form thin discontinuous layers or a fine suspension randomly distributed through the ice layer. Larger crystals were observed in buried snowbanks that are thought to have a longer period of burial. C-axes form a dispersed primary fabric with weak secondary maxima oriented roughly normal to the plane of foliation (Fig. 4d). In older snowbanks, ice fabrics display a stronger preferred vertical orientation.

Intrusion ice petrography reflects the ground water transfer mechanism and freezing conditions. In concordant

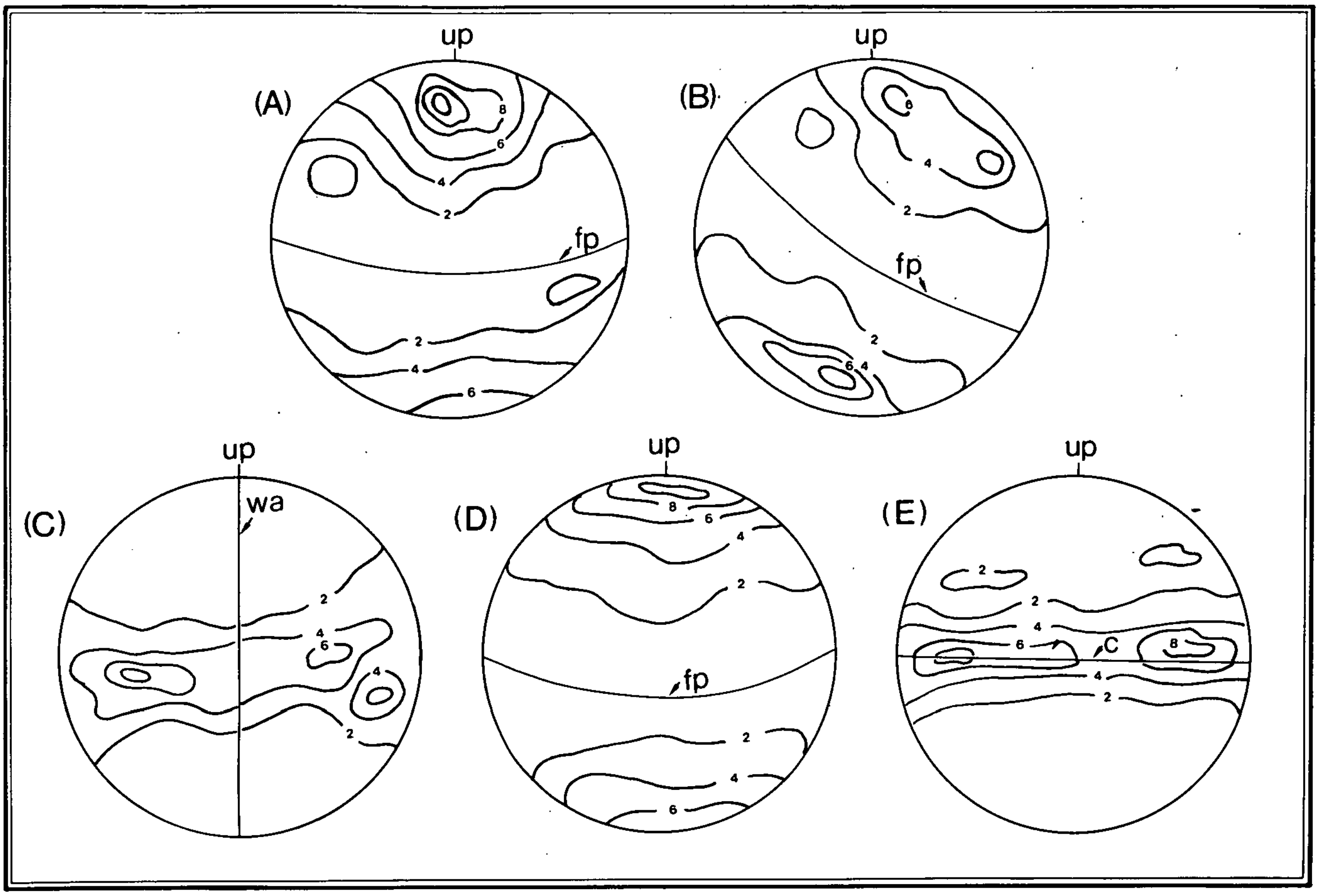


Figure 4. Fabric diagrams for (a) clear segregated ice, (b) foliated segregated ice, (c) ice-wedge ice, (d) buried snowbank ice and (e) injection (intrusive) ice. (The letters fp mark a foliation plane, wa - wedge axis, c - plane of compositional layering).

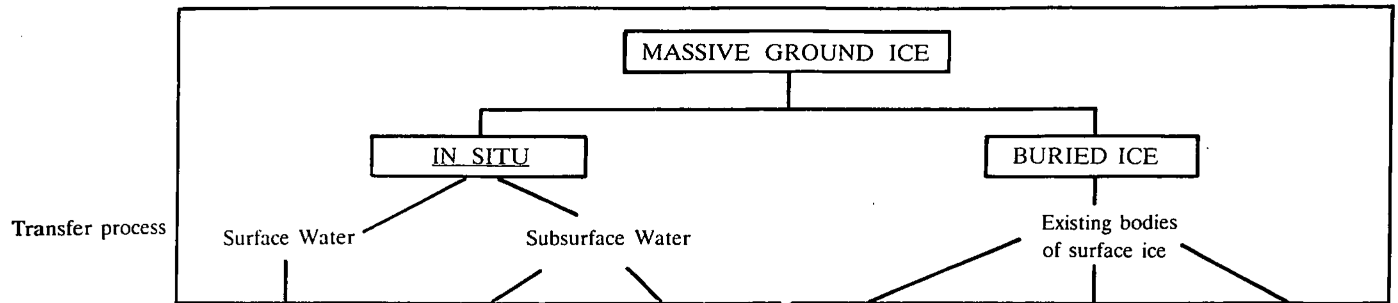
ice injections, like frost blisters, the ice mass is composed of large tabular crystals oriented normal to the freezing direction with c-axes forming a horizontal girdle normal to the long axes of the crystals (Fig. 4e). Crystal size increases away from a chill zone of small, equigranular euhedral grains at the upper contact. Dyke ice is composed of small, equigranular subhedral crystals near the dyke wall. Large elongated crystals with their long axes normal to the plane of the dyke occur in the middle of the structure. Fabric diagrams display a random pattern of c-axes with a weak secondary maxima normal to the dyke wall.

Buried glacier ice has a medium to fine equigranular crystal texture with a fabric dominated by c-axes oriented normal to the internal structure of the ice body. Limited fabric data are available because only two blocks of glacier ice have been analysed to date.

Petrographic categorization in ground ice classification

Figure 5 is a genetic classification of massive ground ice incorporating petrographic characteristics. It draws mainly on ground ice studies at Herschel Island, the Yukon Coastal Plain (Pollard and Dallimore, 1988) and the Mackenzie Delta (Gell, 1976). The organization of this classification combines aspects of Mackay's (1989) description of buried and *in situ* ground ice, his ice classification based on origin and transfer mechanisms of contributing water (Mackay, 1972), as well as a ground ice classification presented by Shumskii (1964). Three aspects of massive ground ice occurrence are stressed: its appearance in plain light, its texture (crystal size, shape and geometric pattern) under cross polarized light and the fabric pattern of c-axis orientations. These characteristics are directly related to the processes and conditions associated with ice formation and therefore provide a good indication of ice genesis. However, since ice undergoes petrographic alteration with changes in pressure and temperature, this approach is far from conclusive. The degree of modification experienced by ground ice under the range of permafrost conditions during Quaternary time is not known. However, the available petrographic data suggest that this approach can be used in relatively young ground ice deposits and *in* situations where there is good stratigraphic control. Even where there is a complex permafrost aggradational history, including both epigenetic and syngenetic ground ice occurrence, petrographic analyses provide useful information. Where possible, petrographic studies should be supported by other lines of investigation.

This is a preliminary attempt to combine existing genetic ground ice classifications with petrographic properties. A similar classification was appended at the end of Gell's Ph.D. thesis based on his detailed petrographic studies of massive



	Ice-wedge ice (a) middle of wedge, (b) side of wedge.	Segregated ice (a) clear massive (b) foliated	Injection ice (a) frost blister (b) dyke ice	Glacial	Snowbank	River/Lake/Sea/Icing
Appearance	white to pale brown vertically foliated	(a) clear - no inclusions. (b) dirty to clear, bubble and sediment layers	(a) clear with tabular vertical bubbles horizontal bubble bands (b) brown to pale white, opaque, high gas inclusion content	clear to pale brown foliated, variable orientation sediment bands bubble-rich	white to pale brown, fine suspended sediment, faint horizontal layering	
Texture	(a) small horizontally oriented crystals (b) large vertically oriented crystals	(a) large anhedral crystals variable crystal size (b) medium to small subhedral to euhedral crystals elongated perpendicular to layering	(a+b) chill zone (a) large tabular vertically oriented crystals (b) small crystals elongated normal to dyke wall	medium to small subhedral crystals	small to medium sized subhedral equigranular crystals no chill zone	
Fabric	(a) horizontal girdle (b) clustered and point maxima perpendicular to wedge side	(a) maximum parallel to heat flow (normal to layering) (b) similar to (a) but more dispersed	(a) horizontal girdle (b) girdle normal to the dyke walls	maximum normal to internal layering loose girdle parallel to layering	random primary fabric with weak vertical maxima	

Figure 5. A proposed genetic classification of massive ground ice incorporating petrographic properties based on studies undertaken at Herschel Island, the Yukon Coastal Plain (Pollard and Dallimore, 1988) and studies by Gell (1976) in the Tuktoyaktuk area.

ground ice in the Tuktoyaktuk area and Mackay's (1972) genetic ground ice classification (Gell, 1976, p. 259). The current classification differs in that it adopts a slightly different categorization, it includes buried ice sources and is based on data from a broader area. Some of Gell's observations are incorporated in Figure 5.

Conclusions

The results of field studies at Herschel Island and on the Yukon Coastal Plain permit the following general conclusions to be made about ground ice occurrence in this area.

(1) At least two episodes of ground ice formation are represented in Herschel Island sediments, including: (a) Recent/Holocene ground ice <10 000 years BP, (b) mid to late Wisconsinan >10 000 years BP. The presence of deformed massive ice found in pre-Buckland sediments deformed by Buckland glacial activity suggest the possible presence of early Wisconsinan ground ice.

(2) Permafrost conditions have been interrupted by at least two periods of deep thaw. One was associated with buried snowbanks and another (approximately 10 000 years BP) was associated with peat formation.

(3) Segregated ice is the most common massive ground ice type in this area and in places constitutes up to 70% of the upper 10-15 m of permafrost. Ice-wedge ice is locally significant and in places makes up 60% of the upper 8-10 m of permafrost. However, the possible occurrence of glacier ice associated with ice-pushed ridges suggests that it may be locally significant.

(4) Various forms of massive ground ice have petrographic characteristics that reflect the processes responsible for their formation. In most cases their petrographic signatures may be used to help identify ice type. Based on these characteristics, a modified genetic classification incorporating petrographic properties is proposed. Segregated ice displays the widest range of petrographic characteristics reflecting the complex relationship between moisture supply and heat loss during freezing.

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