Cryofacies and cryostructures of massive ice found on Bylot Island, Nunavut

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Challenges from North to South
Des défis du Nord au Sud

Stephanie Coulombe [1 2], Daniel Fortier [1 2 3], Yuri Shur [3], Mikhail Kanevskiy [3] and Denis Lacelle [4]

[1]Department of Geography – University of Montreal, Montreal, Quebec, Canada
[2]Centre for Northern Studies – Québec, Quebec, Canada
[3]Institute of Northern Engineering – University of Alaska Fairbanks, Fairbanks, Alaska, USA
[4]Department of Geography – University of Ottawa, Ottawa, Ontario, Canada

ABSTRACT
Permafrost can contain massive ground ice of different origin. Identifying the origin and nature of massive ice is a challenge for permafrost science since the different types of massive ice remain difficult to distinguish on the sole basis of field observations. This paper uses different approaches to accurately characterize a massive ground-ice exposure observed on Bylot Island (Nunavut) in order to highlight its origin. Combined with the analysis of the ice crystallography, the massive-ice cores were described according to the cryostratigraphic approach. These techniques allowed for detailed descriptions of the stratigraphy, the ice crystals (shape, size, orientation) and patterns of gas/sediment inclusions. Our results suggest that the massive ice body is best interpreted as buried ice of glacial origin.

RÉSUMÉ
Le pergélisol riche en glace peut contenir de la glace massive de différentes origines. Il demeure difficile de déterminer l'origine de la glace massive sur la base de simples observations effectuées sur le terrain. Ce projet utilise différentes méthodes de description physique pour caractériser un corps de glace massive observée sur l'Île Bylot (Nunavut) pour ensuite déterminer son origine. Combinée à une description cristallographique, la glace est caractérisée selon l'approche cryostratigraphie. Ces techniques permettent une description détaillée de la stratigraphie, de la structure cristalline de la glace (forme, taille, orientation) et des patrons de bulles d'air et de sédiments dans la glace. Les résultats indiquent que la glace massive étudiée à l'Île Bylot est interprétée comme de la glace enfouie d'origine glaciaire préservée dans le pergélisol.

1 INTRODUCTION

Bodies of massive ground ice are important components of permafrost environments. Ice-cored terrains contain large masses of ground ice typically having gravimetric water content greater than 250% (percent dry weight) with thicknesses often exceeding 1 m (van Everdingen 1988). Two main hypotheses have been suggested to explain the origin of massive tabular ice: i) intrasedimental ice (segregated, intrusive, or segregated-intrusive) and ii) buried ice (French 1990; Mackay 1971, 1972; French and Harry 1990; Harry et al. 1988; Pollard 1990; Solomatin and Belova 2012; Vasilchuk 2012). It has been demonstrated that in situ freezing of soil water to the freezing front by cryosuction and/or water-injection processes could develop tabular massive ice bodies (Mackay 1971). Other hypotheses include the burial of a surface ice body under a cover of sediments sufficiently thick to act as an insulating layer (Lacelle et al. 2009; Kaplanskaya and Tarnogradskiy 1986). In the permafrost region, the sediment cover, if thicker than the active layer, subsequently allows long-term preservation of the ground ice (Solomatin 1986; French and Harry 1990; Fortier et al. 2009; Shumskii 1964a; Shur 1988). Although several types of buried ice (snow, lake, sea, river, glacier) can be theoretically found in the permafrost, remnants of glacier ice remain the most common type of buried ice reported by permafrost researchers. However, few studies have explained the occurrence of tabular massive ground-ice in terms of remnants of glacier ice (Kanevskiy et al. 2013; Murton et al. 2005; Henrikson et al. 2003; Ingolfsson and Lokrantz 2003; Vaikmäe et al. 1993; Pollard 1990; French and Harry 1990; Dallimore and Wolfe 1988; Kaplanskaya and Tarnogradskiy 1986; Lorrain and Demeur 1985; Solomatin 1986; Solomatin and Belova 2012). Shumskii (1964a) and Shur (1988) showed that practically only glacier ice has a high possibility to be buried and be preserved for a long time.

Intrasedimental tabular massive ice often displays characteristics similar to those of buried ice. There are actually no reliable method or diagnosis criteria to clearly distinguish one type from another (French and Harry 1990, Mackay 1989). To overcome this difficulty, some studies have characterized massive ice by combining two or more different approaches: cryostratigraphy and crystallography (Murton et al. 2005; Pollard 1990; French 1998; French and Harry 1988; Solomatin 1986). In this study, we also combine these two approaches.

Buried glacier ice usually occurs as large ice bodies, whose melting could lead to extensive slope failures and settlement of the ground surface with formation of kettle lakes, and with significant impact on permafrost geosystem dynamics and infrastructures (Stephani et al. 2014). In recent years, numerous thaw slumps and active-layer detachment slides have exposed extensive ground-ice bodies preserved in the permafrost of Bylot Island, Nunavut. This paper presents a detailed description of the cryofacies and cryostructures of one specific massive ice exposure (site C1) and discusses its origin using cryostratigraphic and crystallographic approaches.

2 STUDY AREA

The study site (73˚09' N, 79˚57' W) is located on Bylot Island, which is located off northern Baffin Island in the Canadian Arctic Archipelago (Figure 1). In years 2011-2014, fieldwork activities were conducted in the Qarlikturvik valley glaciated during the late Pleistocene. At present time, glaciers C93 and C79 are located several km up-valley (Inland Waters Branch 1969). A local ice cap and many alpine glaciers cover the island whose total glacier-covered area is estimated at 4,783 km^2, which represents 43% of the total area of the island (Dowdeswell et al. 2007). Bylot Island is underlain by continuous permafrost that extends down to a depth of at least 400 m (Moorman and Michel, 2000). The maximum thickness of the active layer in peat and silt ranges from 0.4 to 0.6 m, while in sand and gravel it reaches ca. 1 m (Godin et al. 2014). The regional climate features long and cold winters, whereas summers are short and warm. The present climate conditions from the closest meteorological station at Pond Inlet, located about 80 km southeast from the study site, shows a mean annual air temperature of -14.6˚C for the 1981-2010 period. Long-term average for total annual precipitations reaches 189 mm, almost half (91 mm) of which falls as rain during the summer (June, July, August) (Environment Canada 2015).

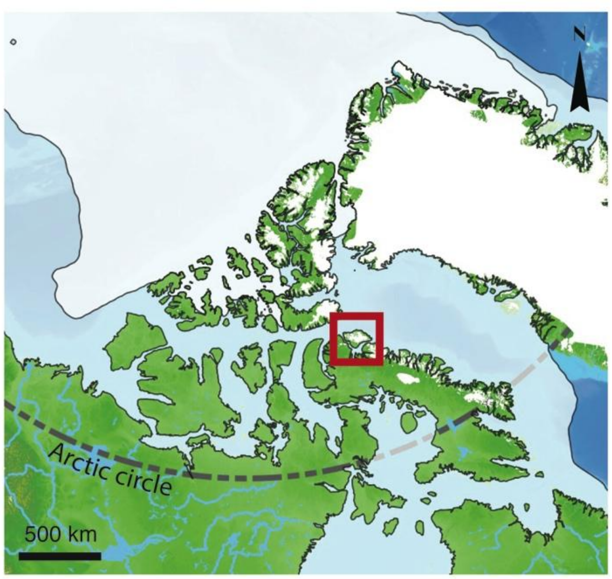


Figure 1. Localization of the study site (red square).

3 METHODS

3.1 Cryostratigraphy

The cryostratigraphic approach aims to identify «*units on the basis of thaw contacts and differences in the nature and distribution of ground-ice*» (Murton and French 1994)**.** Cryofacies are mainly defined by the volumetric ice-content from ice-poor sediment (≤25%) to pure ice (100%). Cryostructures refer to the shape and distribution of ice lenses and inclusions within the frozen sediment (French and Shur 2010; Murton and French 1994).

In order to describe the massive ground ice body and obtain detailed photographs, sections of the massive ice exposure were excavated and cleaned. The excavated section were ca. 10 meters wide and 7 meters high. The ice was sampled using a portable core-drill equipped with a 3 ¼'' diamond carbide core barrel and all the ice cores were shipped frozen to the laboratory at the University of Montreal. The cryostratigraphic sequence was determined based on detailed photographs, field observations and detailed analysis of the frozen cores in the laboratory.

High-resolution images (512-pixel matrix) of the internal structure of the frozen cores were obtained using a computerized tomography (CT) scanner *Siemens SOMATOM Sensation 64.* This technique produces two and three-dimensional detailed images of the internal structure of the permafrost core. It is a non-destructive tool that allows for effectively refining permafrost cores description. The CT-scan images reveal characteristics otherwise difficult or even impossible to observe with the naked eye. The resulting output is a series of hundreds DICOM (Digital Imaging and Communications in Medicine) images representing cross-sectional slices (0.6 mm thick) of the sample. By displaying various shades of gray, CT images generally reflect density variations in the sample. Dark shades represent low-density materials (i.e air) whereas light shades represent high-density minerals (i.e. rock, unconsolidated sediments). As for the ice component of the sample, it tends to display dark grey shades. Visualization and post-processing imaging was performed from reconstructed axial images using an image processing software (Fiji) dedicated to DICOM images (Schindelin et al. 2012).

3.2 Ice Crystallography

Crystallographic analysis emphasizes the microstructure of the ice itself. It provides information about the physical properties of the ice such as its texture (size and shape of the ice crystals), fabric (orientation of the crystals), the boundary characteristics, and the gas/sediment inclusions. The size, shape and distribution of ice crystals and inclusions give clues about the growth processes and freezing conditions (French, 2010). This technique relies on the birefringent property of the ice where individual crystal will take on a specific color according to its orientation. This method has been widely used by glaciologists to investigate the crystal structure of ice sampled on contemporary glaciers and ice sheets (Rigsby 1953; Tison and Hubbard 2000).

Horizontal (n=2) and vertical (n=1) slices cut from an ice core were thinned to about 0.2-0.4 mm thickness using a microtome. Ice thin-sections were then placed between cross-polarizing filters on a light table. Thin-section preparation follows the standard microtoming procedure developed by Langway (1958). Images were then processed using Fiji image analysis software to delineate the crystal boundaries and to calculate shape descriptors from each crystal, such as the area (mm^2), the long-axis (mm) and the circularity ratio (Schindelin et al., 2012). The area represents the amount of space inside a single crystal while the long axis measurement is the primary axis of the best ellipse that fits an irregularly shaped crystal. The circularity ratio, defined by Equation 1, is another way for quantifying crystal morphology (A=area, p=perimeter). It can be defined as the extent to which a crystal is similar to a circle. It is a dimensionless value where a value close to 0 indicates highly elongated crystal and the value 1 a perfect circle (Schindelin et al., 2012). C-axis orientations of the crystals have not been measured since the orientation of the ice core and blocks was not preserved following the sampling. In order to assess the similarity with contemporary glacier ice, thin-sections (n=4) were also made from ice blocks sampled on glacier C93 on Bylot Island.

$$\text{Circularity ratio} = \frac{4\pi A}{P^2} \qquad [1]$$

4 RESULTS AND DISCUSSION

A number of cryostratigraphic features may be used to characterize a massive ice body and infer its origin: 1) the contact between the ice and the overlying/underlying sediment (e.g., thaw unconformities); 2) the cryofacies and cryostructures; 3) the ice crystallography; 4) the gas inclusions; and 4) the deformation structures within the ice body. Below, we present results from these features and propose an origin to the massive ground ice body at site C1.

4.1 Thaw unconformity

The excavated section at the study site reveals up to 10 m of massive ice overlain by 1.7 m of glacio-fluvial sand and gravel deposit. The contact between the ice and the overlying material is sharp and unconformable whereas the lower contact is not visible (Fig. 2). It indicates a thaw or erosional contact along the top of the ice unit, which is consistent with the buried ice theory (Mackay, 1989, French and Harry, 1988; Mackay and Dallimore, 1992). The top of the ice body could have been truncated by erosion due to fluvioglacial processes or by the thawing front as it reaches the ice at the base of the active layer (Dallimore and Wolfe, 1988). On the contrary, an intrasedimental ice body should usually have a gradational and conformable upper contact, which indicates downward freezing (French and Harry, 1988).

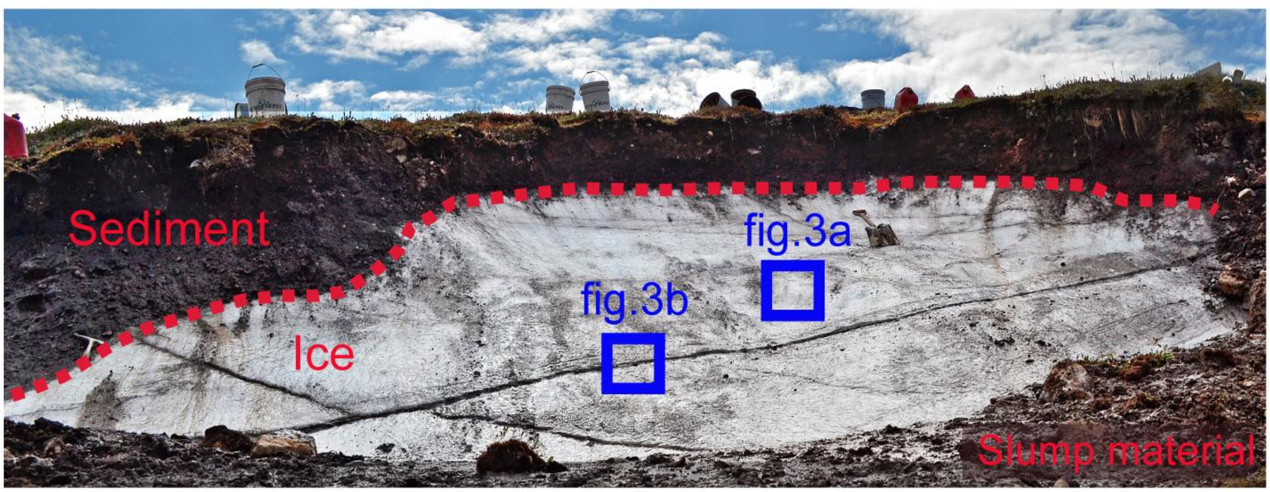


Figure 2 Massive ice exposure found on Bylot Island (ca. 13 m x 5 m in dimensions). The red-dotted line represents the sharp and continuous ice-sediment contact. The blue squares refer to the localization of the ice samples shown in the figures 3b and 3b.

4.2 Cryofacies

The ice body is homogeneous and it is mainly composed of clear to milky ice with 2 to 5% soil inclusions (Fig. 3a). According to the classification developed by Murton and French (1994), it refers to the «pure ice» cryofacies. The ice also features occasional thin bands of ice-poor sediments (sands and gravel) with a variable thickness of a few millimeters to a few centimeters (< 3 cm) (Fig. 3b)

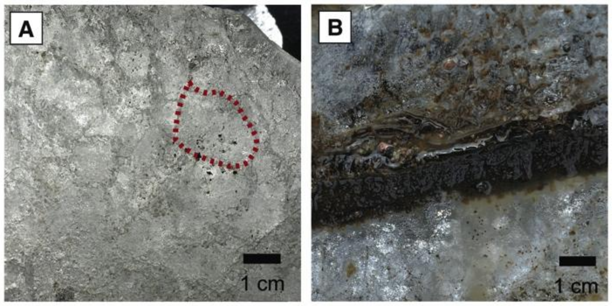
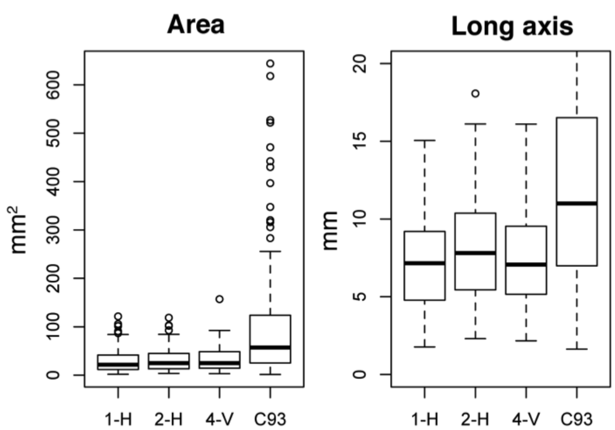


Figure 3. Cryofacies and cryostructures observed in the massive ice body. A) Pure ice facies. The red-dotted line highlights one crystal. B) Ice-poor sediment facies with a porous cryostructure (pore ice, not visible by naked eye) forming a band in the massive-ice body. The sediments are sand and gravel.

4.3 Ice crystallography

Petrographic analysis of the ice shows medium- to coarse-grained crystals with interlocked crystals boundaries. The ice displays a wide range of crystal sizes (0.18-1.57 cm^2) that average 0.32 $\pm$ 0.26 cm^2 in area (Figure 4). Their long axes have a mean of 0.76 $\pm$ 0.26 cm (Figure 4). Their mean circularity ratio indicates relatively rounded crystals, with an average ratio of 0.65 $\pm$ 0.11. Figure 4 also indicates no significant differences in crystal size or shape between the horizontal and vertical thin sections. As mentioned before, the exact c-axis orientation could not be measured because the block samples were not oriented. However, most of the crystals in the thin section exhibited similar colours toward blue tones, which suggests the crystals have a preferred direction although some variability in crystal orientation exists.



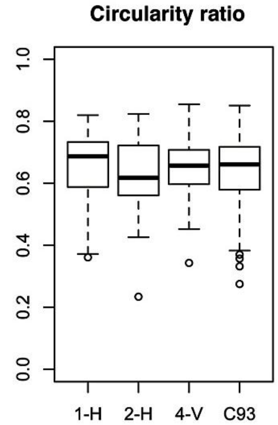


Figure 4 Box-plots displaying the distribution of ice crystal characteristics of two horizontal thin-sections (1h, 2h) and one vertical thin-section (1v) obtained from ice samples sampled at site C1. C93 represents data obtained from a sample of modern glacier ice extracted from glacier C93.

Since both intrasedimental ice and buried massive ice display a great range of grain size and shape, it cannot be used alone for inferring the genesis massive ice at this site. Pollard (1990) have reported that the appearance and petrography of segregated massive ice vary greatly owing to the «*large number of factors influencing its growth*». Ice crystal size of segregated ice depends on the freezing front advancing rate and the soil water content. For instance, a continuous water intake combined with a stationary freezing front will allow a greater crystal growth (Dallimore and Pollard 1988). To sum up, crystal size from massive segregated ice are quite variable, but large equigranular crystals generally characterized this type of ice (Pollard 1990). It is usually transparent and marked by the absence of soil particles inclusions. Furthermore, ice crystals tend to be slightly elongated with a weakly preferred near-vertical oriented c-axis parallel to the heat flow direction. (Shumskii 1964a; French and Harry 1990; Dallimore and Wolfe 1988; Pollard 1990).

Glacier ice is also characterized by a great variation in ice crystal size, ranging from sub-mm to tens of cm (Rigsby, 1960; Gow, 1963). Cores samples taken in deep glaciers have shown an increase in crystal size with increasing depth due to recrystallization under considerable pressure (Thorsteinsson et al. 1997, Tison and Hubbard 2000). Also, smaller crystals are expected in zones of high stress, while very large crystals are found in stagnant ice and areas of significant melt-water (Rigsby 1960). The crystal structure of glacier ice is influenced by the age of the ice, the sediment content of the ice, the flow dynamic and past temperature variations (Menzies 2001). There is also a close relationship between the orientation of the main crystal axes of glacier ice and zones of high stress (Paterson 1994). Ice crystals from the upper layers of a glacier are usually randomly oriented according to the original random orientation of the snowflakes. In zones of high stresses, the ice crystals have strong preferred orientations in the inferred ice flow direction of a moving glacier.

Another plausible origin for the tabular massive ice includes buried snowbanks (Fox 2011; Lacelle et al. 2009; Pollard and Dallimore 1988; Shumskii 1964a). The burial by debris of snowbanks produces clear to milky white ice as well as the massive ice found at Bylot Island. However, the characteristics of buried snowbanks in permafrost mostly differ from the ice described in this paper. Buried snowbanks have a loosely compacted structure with randomly oriented small crystals whose area usually reaches a few mm^2 (Lacelle et al. 2009; Pollard and Dallimore 1988; Petrenko and Withworth 1999). Besides, bands of nearly horizontal pale brown ice have been observed in buried snowbanks. These bands contain fine-grained sediment inclusions suspended within the ice (Lacelle et al. 2009; Pollard and Dallimore 1988). Source material can be either of windblown or slump origin.

The crystallographic structure of Bylot Island massive ground-ice body may fall within the range of characteristics associated with both glacier ice and intrasedimental ice. Nonetheless, figure 5 shows the comparison between the massive ground-ice body studied and a sample of modern glacier ice extracted from glacier C93 located in the same valley at a few kilometers from the study site. Ice crystals belonging to the modern glacier ice are slightly larger, but the overall appearance of the structure appears quite similar to that of the massive ground-ice (Figure 4, 5).

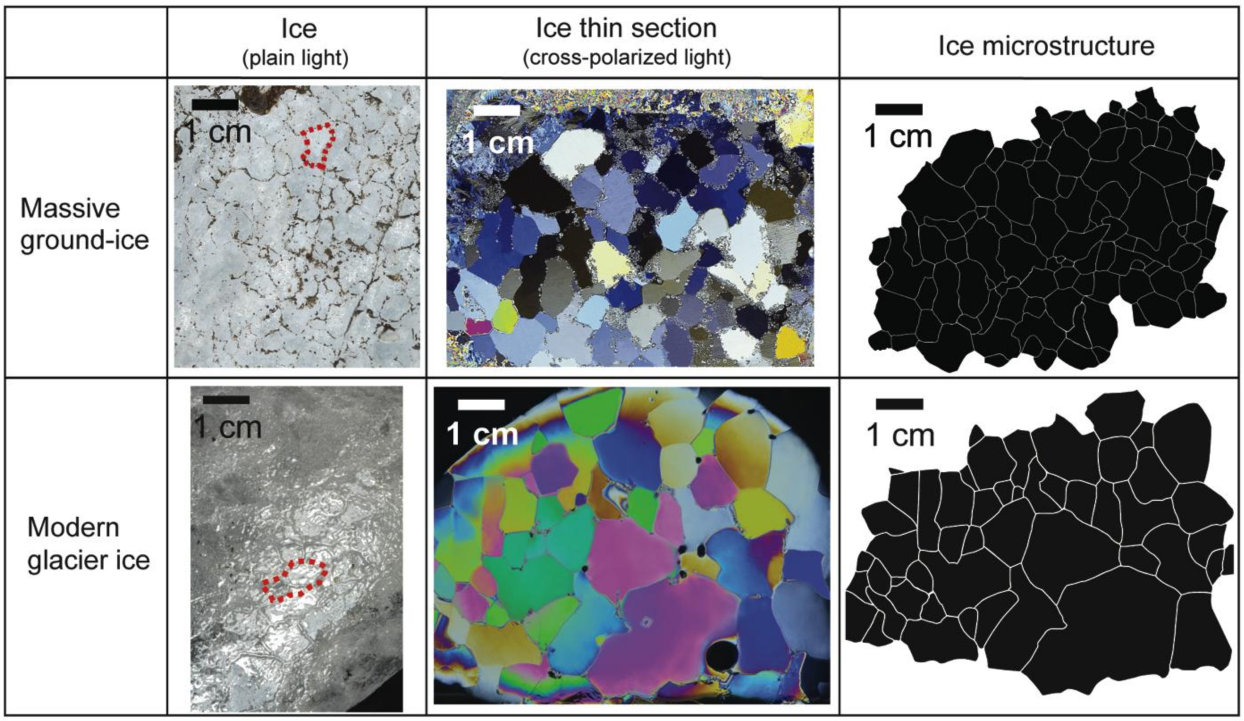


Figure 5. Comparison between the massive ground-ice body and modern glacier ice (glacier C93, Bylot Island). The first column shows unprocessed photographs of the ice taken directly in the field with surficial sediment inclusions highlighting the crystal boundaries. Sediments are not part of the ice. The red-dotted line highlights one crystal. The second column shows thin-sections of ice sample viewed under direct cross-polarized light. The third column shows the microstructure (crystal boundaries) extracted from the thin section photograph.

4.4 Gas inclusions

The massive ground ice body displays a high concentration of gas inclusions, mainly located at crystal junctions (Figure 6, 7). Bubbles are generally confined in the peripheral zone of crystals and highlight their shape. Horizontal and vertical cross-sectional views of the same ice core allow observing the absence of elongated bubbles (Figure 6). Three distinct shape patterns of gas inclusions occur within the ice: 1) Small spherical bubbles; 2) Coalescent bubbles and 3) Small disks flattened parallel to the plane of foliation of the ice body (Figure 8). These patterns and organisation differ from those usually found in intrasedimental ice. The latter typically has vertical elongated tubular gaseous inclusions, indicative of downward freezing from the surface (Shumskii 1964a, Rampton and Mackay 1971; Mackay and Dallimore 1992). Buried snowbanks also displays thin elongated tubular bubbles (mm-scale) (Lacelle et al. 2009; Pollard and Dallimore 1988)

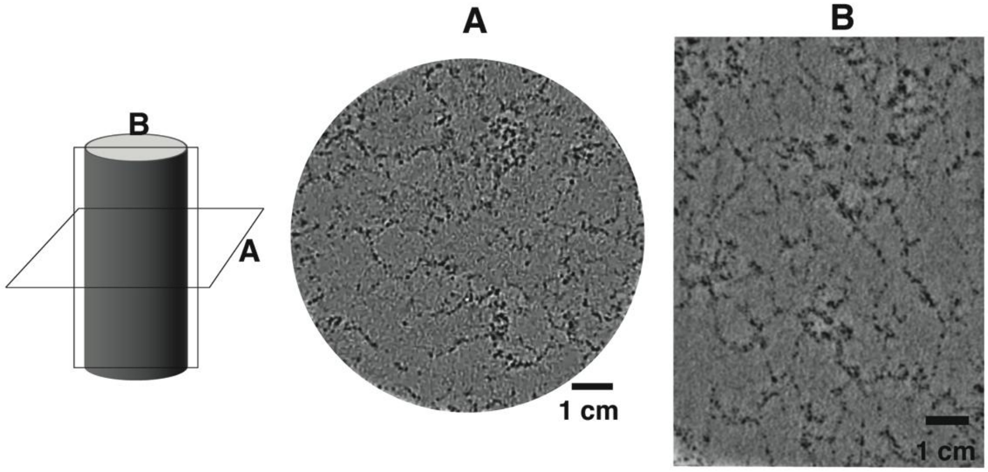


Figure 6. Transverse (A) and coronal (B) cross-sectional view of an ice core showing the gas inclusions using micro-computed tomography. (Air = black; Ice = dark grey)

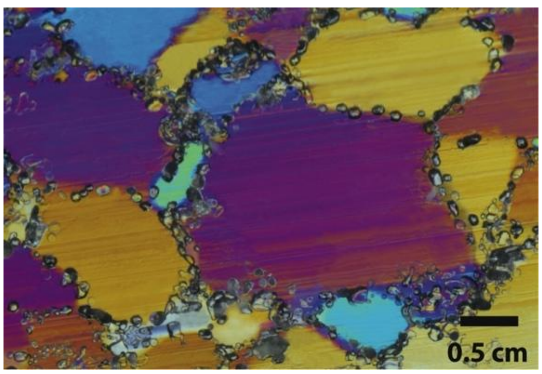


Figure 7. Ice sample viewed under cross-polarized light.

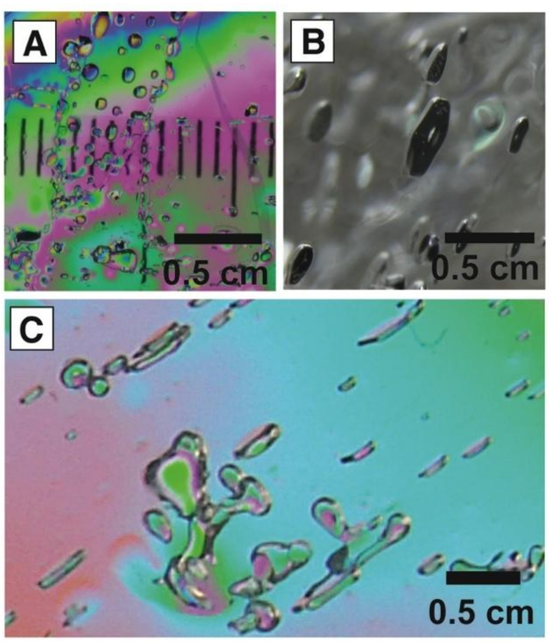


Figure 8. Patterns of gas inclusions observed through thin section analysis and detailed photographs. A) Small (mm to sub-mm) spherical bubbles (vertical bars are from measuring ruler of microscope stage); B) Coalescent bubbles and small disks all flattened in the same direction; C) Small disks up to 6 mm in diameter

4.5 Deformation structures

The ice contains very little sediment. When present, the sediments (sand and gravel) appear in micro-fractures (mm-thick) and macro-fractures (cm-thick) filled with coarse sediments (sands and gravels) (Figure 2). The banding is usually parallel and shows a consistent direction that dips towards the southeast direction. The sediment layers exhibit a gentle inclination that ranges between 21˚ and 31˚. The disposition of the sediment in discrete continuous bands suggests a subsequent deformation of the ice where sediments could have been incorporated predominantly through shearing in englacial ice. Folds, faults and boudinage structures of varying dimensions are commonly found through glaciers. These structures reflect the deformation history of the ice caused by the motion of the glacier (Benn and Evans 2010; Shumskii, 1964b).

5 CONCLUSION

On the basis of cryostratigraphic and crystallographic analyses, we interpret the massive ground-ice exposed at the headwall of thaw slump found on Bylot Island as buried glacier ice. It shows great similarities to englacial ice facies formed on glacier by the progressive compression of snow and ice and subsequent deformation caused by glacier flow. There is actually no single diagnosis criterion to accurately assess the origin of massive ice, but the overall physical characteristics of the ice such as the texture, fabric, sediment and gas inclusions, and deformation structures in the ice lead us to this conclusion. Our findings suggest additional criteria to distinguish buried glacier ice from intrasedimental ice, based on the cryostratigraphic properties of buried glacier ice of englacial origin, which is different than buried sediment-rich glacier ice formed at the base of the glacier (basal ice) (Lawson, 1979; Hubbard and Sharp, 1995;). Knight, 1997; Fortier et al. 2012)

Evidences in support of the englacial origin of the massive ice are the following: 1) The upper contact between the ice and the overlying sediment is sharp and unconformable; 2) Clear to whitish ice, with large crystals; 3) The ice is rich with small gas inclusions at crystal junctions; 4) Gas inclusions appear either as small flattened disks or spherical bubbles; these shapes are usually associated with glacier ice rather than intrasedimental ice; 5) Occasional debris bands of sand and fine gravel are cross-cutting older debris-free ice and 6) the study site is located in a valley that was occupied glaciers C93 and C79 until the late Holocene and they have now receded several km up-valley. Together, these cryostratigraphic characteristics support the buried glacier ice hypothesis.

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