# Hydro-physical conditions of an Arctic proglacial valley, Bylot Island

Pablo Wainstein, Brian Moorman & Ken Whitehead
*Department of Geography, University of Calgary, Alberta, Canada*

ABSTRACT
Icings are one of the most dominant forms of extrusive ice in periglacial environments, with proglacial icings commonly found in the eastern Canadian Arctic and Scandinavia. They occur as a result of the combination of cold arctic climate, continuous permafrost and polythermal glaciers. The preservation of these cryo-hydrological features, such as the one in front of Fountain Glacier on Bylot Island, depends on the availability of subglacial water and on the balance between ice accretion and hydro-thermal erosion. Geophysical and topographical surveys were conducted to study the main hydro-physical conditions of the proglacial valley that are responsible for the preservation of Fountain Glacier icing.

RÉSUMÉ
Abondants dans l'est de l'Arctique canadien et en Scandinavie, les aufeis sont l'une des principales formes de glace extrusive en milieu périglaciaire. Ils sont le résultat d'interactions entre le climat froid de l'Arctique, le pergélisol continu et les glaciers subpolaires. La préservation de ces formations cryo-hydrologiques telles que celle se situant devant le glacier Fountain dépendt de la disponibilité d'eau proglaciaire et d'un équilibre entre l'accumulation de la glace et l'érosion hydrothermale. Des études géophysiques et topographiques ont été menées afin d'examiner les conditions hydro-physiques propres à la vallée proglaciaire et qui expliqueraient la préservation de l'aufeis proglaciaire du glacier Fountain

## 1 INTRODUCTION

Proglacial icings are commonly found in the eastern Canadian Arctic and Scandinavia, as a result of the combination of cold and dry arctic climate, the presence of continuous permafrost and polythermal glaciers with warm bases where liquid water can be stored (Akerman 1982; Hodgkins et al. 2004; Wainstein et al. 2008).

Bylot Island, located north of Baffin Island (Figure 1a), presents several examples of proglacial icings of which only a few are perennial. Fountain Glacier icing is one of them (Moorman 1998; Moorman 2003; Wainstein et al. 2008).

The perennial character of a proglacial icing depends on the availability of water and on the balance between ice accretion and hydro-thermal erosion. As such, the characteristics of the feeding glacier's hydrology are essential in supplying water to the proglacial plain, enabling icings to exist and regenerate each season (Akerman 1982; Baranowski 1982; Pollard et al. 1999; Hodgkins 2001; Hodgkins et al. 2004; Pollard 2005). Specifically, polythermal arctic glaciers, such as Fountain Glacier, which present cold margins frozen to the underneath permafrost, enable a long term storage of pressurized deep englacial and subglacial water. This pressurized storage holds enough energy to allow water to flow, even during the cold winter, through a network of deep englacial, subglacial and intra-permafrost passages and to create proglacial springs through which icings are normally fed (Boulton et al. 2007; Wainstein et al. 2008).

Wainstein et al. (2008) suggested that the preservation of icings depends on the balance between the interactions of three concomitant and complementary geo-systems: glacier, permafrost and proglacial valley. The balance between them is noticeably unstable, with changes in the behaviour or conditions of any of the components often having considerable effects on the state of the icing. Within these systems, the main factors affecting the conditions of the icing are: temperature (air and ground), topography and hydrology.

Although Fountain Glacier icing has been studied by several authors (Moorman 1998; Moorman & Michel 2000; Wainstein et al. 2008), the icing's hydro-physical dynamics, their implications on its preservation and the relationship between glacier, permafrost and proglacial geomorphology have not yet been fully addressed.

It is hypothesized that the hydro-physical characteristics of the proglacial valley are critical in ensuring the preservation of the icing and its perennial character. This paper describes the hydro-physical dynamics of the proglacial icing and the conditions responsible for its annual regeneration and long-term preservation. Deep englacial and subglacial water routing is also discussed, in terms of its interaction with the surrounding permafrost and relict glacial features that support the transport of water used in the preservation of the icing.

## 2 STUDY AREA

Bylot Island (Figure 1a) is located at the eastern margin of the Canadian Arctic, north of Baffin Island at approximately 73°N, 78°W. It is roughly 180 km long in its NW-SE axis and 100 km wide in its NE–SE direction. The centre of the island is covered by a 4,500 km$^2$ icefield on which the majority of the valley glaciers of the island, including Fountain Glacier, have their accumulation zones.

The cold dry climate that governs Bylot Island allows for the existence of polythermal glaciers, such as Fountain Glacier, with cold impermeable margins frozen to the glacial bed and a core of warmer ice (Moorman & Michel 2000; Wainstein et al. 2008). The island is located in the zone of continuous permafrost (Zoltai et al. 1983) where low precipitation rates, subzero ground temperatures and the presence of polythermal glaciers, with well preserved hydrological networks, allow the formation and preservation of proglacial icings (Wainstein et al. 2008). The hydrology of Fountain Glacier icing is highly dependant on glacial behaviour, due to the low snow accumulation during the winter and the almost negligible rainfall events during spring or autumn.

Fountain Glacier (Figure 1b) has a catchment area of 72 $km^2$ and is approximately 16 km long, with its elevation ranging from 255 m.a.s.l. to 1758 m.a.s.l. It has an average surface slope of 5.5° (Walter 2003). Until recently, the glacier had been considered to be in equilibrium. However, field observations show that this state has changed, with increasingly faster retreat and thinning rates having been observed in the last 15 years (Wainstein et al. 2008).

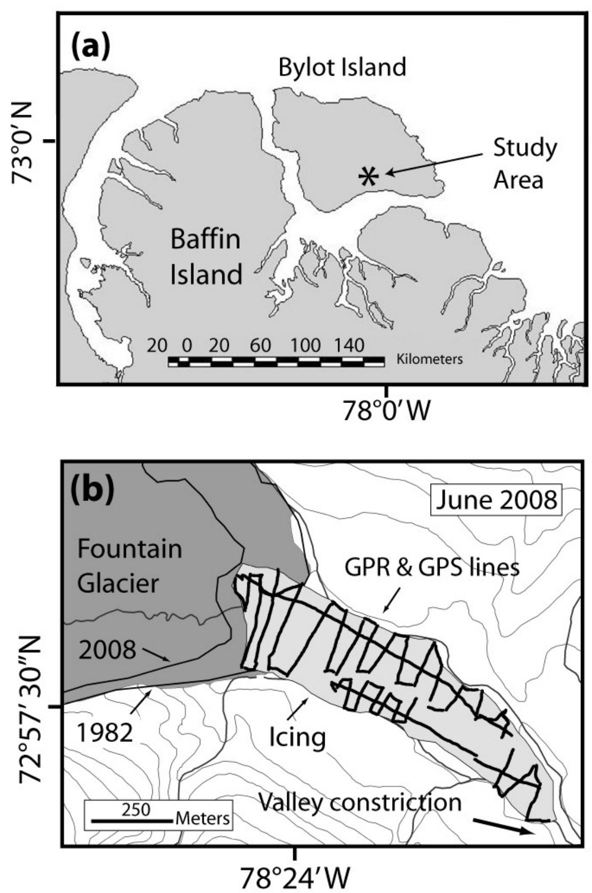


Figure 1. (a) Bylot Island, located north of Baffin Island, Canadian Arctic and (b) topography of the proglacial area of Fountain Glacier. Icing extents are shown as well as the conducted GPR and GPS lines.

The Fountain Glacier proglacial icing is located at roughly 250 m.a.s.l. At the beginning of the summer season it extends SW for over 1 km from the terminus of the glacier. Down valley, the icing is constricted by bedrock valley walls and the presence of an old lateral moraine from Stagnation Glacier (Figure 1b). At this time, the icing occupies an area of approximately 26 ha, with an average thickness of 3.6 m. However, by the end of August, the area covered by icing ice is considerably reduced in size by melting and hydraulic erosion carried out by streams fed by glacial meltwater and mountainside runoff. During this time, the icing is comprised of well developed candle ice and is largely debris free.

## 3 METHODOLOGY

The hydro-physical dynamics of Fountain Glacier icing were interpreted based on the analysis of topographical and geophysical surveys, in conjunction with a coring campaign. Field observations were conducted over the entire extension of the icing and surrounding areas during June 2007, June 2008, August 2008 and July 2009.

Topographical surveys were carried out over the icing with the objective of quantifying the icing's thinning and spatial extent at different stages. A series of Digital Elevation Models (DEMs) of the icing surface were generated. Surveys were conducted using a combination of two Trimble Global Positioning Systems (GPS) following the transects shown in Figure 1b. In 2007 a differential GPS (DGPS) was used, whereas in 2008 and 2009 a Real Time Kinematic (RTK) unit was deployed. The DGPS survey achieved an average accuracy of 10 cm after correction, while the RTK survey achieved an average accuracy of 5 cm. All surveys were corrected against a base station installed close to the terminus of Fountain Glacier.

Shallow geophysical surveys were conducted using a Pulse EKKO Pro Ground Penetrating Radar (GPR). The system allows a non-invasive investigation of spatial changes in icing thickness and en-icing and subicing structure. Transverse, longitudinal and diagonal survey lines were established as shown in Figure 1b. The majority of the surveys were collected using 200 MHz antennae in parallel broad side configuration. Profiles were acquired in continuous mode, using a 400 V transmitter and a stacking of 8, which resulted in an average step size of 9 cm. Additionally, some survey lines were run with a 500 MHz transducer, in order to study the shallower layers of the icing ice. In both cases, a Garmin GPS was connected to the GPR unit to collect positioning data every 10 traces.

The wave propagation velocity within the icing ice was determined by Common Mid-Point (CMP) surveys and was used to convert time based profiles into depth. The CMP surveys gave an average wave propagation velocity of 0.16 m/ns. After collection, radar data was filtered for low frequency signal saturation (DEWOW) and repeated traces were extracted. The positional information acquired by the GPS was incorporated and the real step size determined. When required, profiles were enhanced with an Automatic Gain Control (AGC) algorithm.

Ice thicknesses were determined by delineating the ice / sediment interface in ReflexW, and DEM's of the subicing topography were generated using ArcMap Topo to Raster interpolation tools.

Surface and subicing hydrological models were developed using the previously generated DEM's.

Finally, ice cores were recovered using a manually turned 3 inch CRREL coring barrel. Coring sites were based on areas where GPR interpretations suggested the presence of buried glacier ice.

## 4 RESULTS AND DISCUSSION

### 4.1 Geomorphology of the proglacial valley

In the proximity of the terminus of Fountain Glacier, the proglacial valley is roughly 300 m wide and from here it tapers down to become a small and narrow canyon by the eastern end. This geomorphic constriction plays a critical role in the icing's hydrology, since it results in a natural dam which raises the water level of the proglacial plain and hence allows water to accumulate and generate a thicker icing, promoting the icing preservation. In addition, a thick icing layer acts as an insulation cover that allows liquid water to continue flowing within and under the icing, despite the cold winter temperatures. In fact, it has been observed that the icing is densely populated by en-icing and subicing channels. These channels allow the formation of injected ice and icing blisters even at a considerable distance downstream from the glacier's terminus.

During the summer season, when melt and hydro-thermal erosion dominate, the damming effect of the morainal constriction results in an overall decrease of the flow speed of glacial meltwater. This subsequently lessens the mechanical erosional power of runoff and promotes the preservation of perennial areas of the icing.

Satellite images show that there are other proglacial icings on Bylot Island; however they are not perennial, presumably as a result of meltwater erosion. For example, the nearby Aktineq and C5 glaciers have small proglacial icings contained in narrow canyons that are severely affected by the erosional power of high flow meltwater. As a result, these icings are completely eroded away during the first part of the summer season.

Although the morphology of the proglacial valley is key in the preservation of the icing, the amount of meltwater produced and stored by the glacier is also extremely important. An insufficient water supply to the icing would result in a thin ice cover which would easily melt during the summer. Alternatively, an oversupply of glacier meltwater during the ablation season would erode the proglacial icing and thus would not allow it to perennially survive. The latter case often occurs in association with larger glaciers, such as the nearby Sirmilik Glacier. This glacier produces meltwater in amounts that are orders of magnitude higher than that produced by Fountain Glacier.

Moorman and Michel (2000) suggested that the preservation of the icing also depends on the curvature of the ice surface and of the valley bottom. They observed that the convex shape of the icing's surface drove meltwater to the valley margins and promoted the preservation of a central area (Figure 2 a & b).

Although this conceptual model held true for some decades, field observations conducted between 2007 and 2009 showed that currently, meltwater channels concentrate at the centre of the icing, allowing marginal areas to be perennially preserved (Figure 2 c & d). Results obtained from the conducted topographic surveys show that the curvature of the icing's surface has changed in recent years, causing water to be diverted from the valley sides to a more central location. Additionally, results obtained from the conducted GPR surveys and the generated hydrological models (Figure 2) suggest that the observed migration of meltwater streams results from changes in the subicing topography.

Regardless of the position of the meltwater channels (marginal or central) what is important is the fact that they maintain on average the same location for a period of time longer than a year. It is suggested that the migratory behaviour of the meltwater streams form part of a decadal cycle. As such, Moorman and Michel (2000) described half of the cycle whereas currently, field observations show the other half of it.

### 4.2 Routing of glacially fed springs

Although a number of studies e.g. (Akerman 1982; Baranowski 1982; Hambrey 1984; Pollard et al. 1999; Moorman 2003; Hodgkins et al. 2004; Boulton et al. 2007) have shown the importance of englacial and subglacial hydrology in the annual regeneration of proglacial icings; the pathways involved in the flow of water from the glacial environment onto the proglacial plain through permafrost are still not yet well understood.

In the case of both Breidamerkurjokull Glacier, southeast Iceland (Boulton et al. 2007) and of Fountain Glacier, the water involved in the regeneration of the icing was observed to emerge onto the proglacial plain as springs through glaciofluvial gravels (Wainstein et al. 2008). Similar to 1991, the current upwellings are located close to the glacier's terminus, but currently vary in numbers and distribution within the upper icing.

In the case of Fountain Glacier, it is suggested that there is a combination of two water pathways. Subglacial waters emerge on the proglacial valley by (1) through relict conduits carved within a tongue of buried glacial ice that underlies the upper proglacial valley and (2) through a proglacial talik located within the upper icing.

Water flows from the glacial environment through a network of relict conduits within the buried ice until it finds a weak point. At that location, if the ice is weak enough, it opens up to the surface and a proglacial spring develops. Relict conduits are kept open within the buried glacier ice by the heat dissipated from the flow of pressurized water. As in the case of englacial hydrology, it is suggested that bigger conduits are kept open at the expense of smaller ones (Fountain & Walder 1998). Since the tongue of buried glacier ice is not subjected to strain rates of the magnitude affecting the main body of the glacier, crevassing is very limited and the development of new conduits within the buried ice is rare.

Six lines of evidence support the proposed routing of glacially fed springs.

• *Glacio fluvial features.*

Two well preserved ice-cored eskers (Figure 3) run from the glacier terminus, longitudinally down valley, for roughly 100 m until they meet the main transverse water course of the upper icing. Water has partially eroded the esker's ends and as such, the current preserved length of the eskers depends on the migration of the upper icing main waterways. The presence of these eskers supports the hypothesis that Fountain Glacier has a well developed longitudinal subglacial network. Such a network is essential to the preservation of the icing since it allows stored meltwater to be efficiently transported down valley onto the proglacial plain.

• *Similarities between Fountain and Stagnation Glacier*.

Moorman (1998) already established that Stagnation Glacier presented a 10 m thick body of buried glacier ice that extended for 175 m from the glacier's terminus and covered almost the whole width of the glacier. This supports the idea that a glacier, like Fountain Glacier, subjected to very similar climatic conditions and surrounding landscape might present a comparable geomorphic feature.

• *Buried glacier ice observed within the upper icing*.

A large ice-cored sediment exposure containing the remnants of a fountain observed in 1991 divides the icing into an upper and a lower section (Figure 3). The structure, foliation marks and crystallography of the ice that forms the core of the sediment exposure suggest it is glacier ice. The overburden sediments were deposited almost 20 years ago by fluvial action of an incoming mountain stream and re-worked by the hydraulic activity of the fountain observed in 1991.

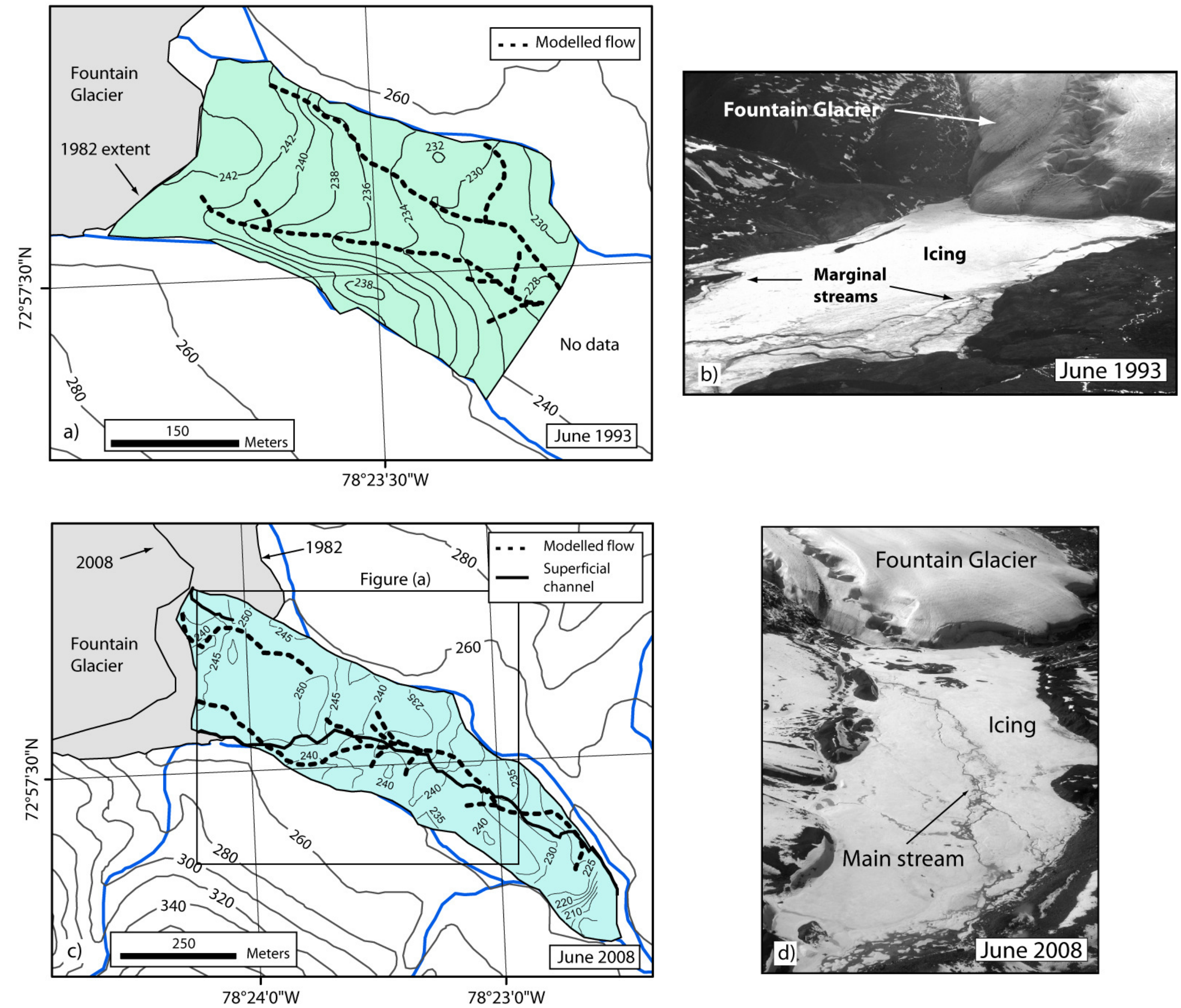


Figure 2. Meltwater streams within the proglacial icing have migrated from being marginal in 1993 to being central in 2008. a) and c) show the hydrological models generated from the surface and subicing DEMs, whereas b) and d) show oblique aerial photos of the modelled area. Field observations confirm the model results.

Field observations show that in addition to the ice-cored sediment exposure, there are several other locations, within the upper icing, where glacier ice has been found. It is usually found underlying a 20 – 30 cm thick cover of fine and coarse gravel. Small water upwellings have been observed within this zone of buried glacier ice, supporting the hypothesis that buried ice can be used as a medium to transport water through a continuous permafrost environment (Figure 3).

• *Active springs.*

During August 2008, an incipient circular sediment feature was found approximately 35 meters down valley from the glacier terminus (Figure 3). It was observed that the new feature lays slightly south of the east-west alignment between the ice-cored sediment exposure and the outlet of a major supraglacial stream. A small upwelling was observed at the southern end of the circular feature. Although flow rates were low at the time, presumably due to the fact that the ablation season was coming to an end, its presence is most important since it shows that there are active, newly developed, groundwater connections between the glacial and the icing environment. Water flow marks within the circular feature suggests that water coming from the observed upwelling is responsible for carving such a shape. Flow marks radiating out from the feature suggest that water flows in a circular pattern within the feature and then exits to the southeast of the outwash plain.

• *Proglacial talik.*

The upper section of the icing presents a concave topography that allows for water to accumulate and form a ponding area. This pond is kept unfrozen throughout the winter as a result of the un-interrupted water supply coming from the glacial environment. Subsequently, the presence of year round liquid water has promoted the preservation of a talik that covers approximately the whole upper icing zone. Downstream from the sediment exposure, the subicing topography is considerably flatter and water is driven down-slope in the form of meandering streams.

• *Ground penetrating radar and ice coring.*

Radar surveys conducted within the upper icing were particularly important since the understanding of the area's geomorphology and current hydro-physical processes are fundamental to comprehend the hydraulic mechanisms by which the icing is replenished during the winter. Results from the GPR surveys revealed interfaces interpreted as the limiting boundaries of a body of buried glacier ice underlying the outwash plain within the upper icing and the northern side of the ice-cored sediment exposure.

Figure 4 shows a GPR line surveyed following an east direction starting from the glacier's terminus, where the contact line between the glacier ice and the icing ice was clearly visible. The profile has an appropriate vertical resolution and deep enough penetration which allows the visualization of three main interfaces. The shallowest interface located at roughly 30 ns is very strong and has been interpreted as the boundary between icing and glacier ice.

Later in travel time at approximately 100 ns, a second strong interface is resolved. This has been suggested to be the glacier ice / sediment boundary. At roughly 140 ns, a third and weaker interface is observed which is suggested to be the lower boundary of a layer of glacio fluvial sediments deposited by the action of the icing hydrology.

Figure 4 also shows the location of the ice coring site, which provided further evidence to support the radar interpretation. The extracted core (1.8 m long) revealed a series of layers of different crystallography, strength, water and bubble content and transparency within the icing ice column. Since the coring site was located within the upper icing, in an area of annual icing ice, the majority of the observed ice layers correspond to different freezing episodes of local flooding or injections of water that took place during the previous winter. However, at 1.6 m deep, the core reveals a substantially different type of ice. An extremely hard surface was encountered. At this time, the coring speed decreased substantially.

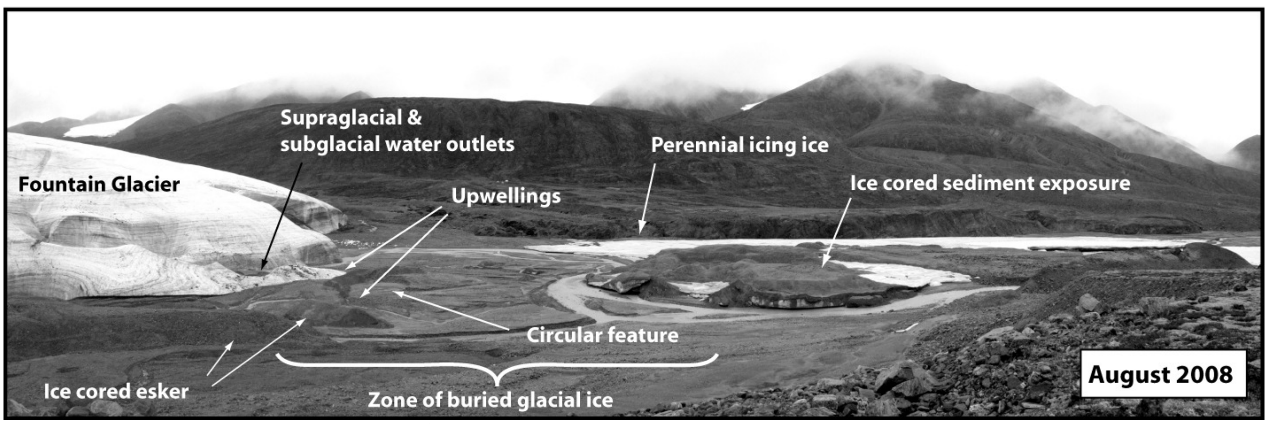

Figure 3. North bound view of Fountain Glacier's proglacial valley.

A 15 cm core section was able to be extracted. It was composed of strong cohesive drier granular ice with clearly visible rounder crystals populated by bubbles. Crystals varied in size but the average measured diameter was approximately 3 cm. Based on the above characteristics especially the crystallography and the drastically different hardness of the layer, it is suggested that this last layer was composed of hard cold glacier ice. Unfortunately, the coring could not be continued because the equipment got frozen stuck and was damaged during its extraction. The depth of the boundary between icing and glacier ice, found from the extracted core, closely matches the depth of the first interface visible on the GPR profile at roughly 30 ns (Figure 4).

The combined results of the GPR and the coring survey conducted in June 2009 support the hypothesis that a roughly 5 m thick body of buried glacier ice underlies the upper area of the proglacial icing and extends from the glacier terminus to at least 80 m down valley. Although some GPR lines do show these interfaces extending further down valley, the connectivity between the buried body of glacier ice and the ice cored sediment exposure cannot be made with confidence. The radar profiles are unclear close to the latter geomorphic feature.

## 5 CONCLUSIONS

Although evidence shows that the preservation of the Fountain Glacier icing depends mainly on three systems: glacier, permafrost and proglacial valley, the degree of dependence on each is not equal. Wainstein et al. (2008) presented evidence supporting the fact that

Fountain Glacier is the dominant system, able to drive the icing out of equilibrium; whereas permafrost is the component that dampens down the disturbances caused by the glacier and brings the icing into a new state of equilibrium.

It is believed that the geomorphology of the proglacial valley influences the development of the icing, subject to the bounding conditions established by the interactions between the glacier and the underlying permafrost.

Considering the conditions that are subjected to change in the proglacial valley, it has been recognized that the most important are the hydro-physical conditions. A changing geomorphology will affect the shape of the valley and subsequently the characteristics of the icing. Similarly, changes in the hydrological conditions will have important consequences on the supply and routing of water and therefore will also impact the state and regeneration of the icing.

More specifically, it was found that:

• The morphological characteristics of the valley, particularly the presence of a natural dam at the eastern end, allow the formation of a thick perennial icing that sustains erosion during summer. Additionally, the width of the outwash plain decreases the flow speed of meltwater, which lessens its erosional power during the ablation season.

• A tongue of buried glacier ice, well populated by relict glacial conduits, likely acts as the supply medium through which water flows from the glacial environment to the outwash plain.

• Although the presence of a buried body of glacier ice is extremely important for the hydrologic connectivity of the icing, the combined action of a proglacial talik, within the upper icing sediment layers, is key in allowing subglacial water to effectively emerge onto the proglacial outwash plain, especially in an environment of continuous permafrost.

• The finding of active springs, within the area underlain by buried glacier ice, supports the hypothesis that there are active hydraulic connections between the glacial environment and the outwash plain that use buried glacier ice as a transport mechanism.

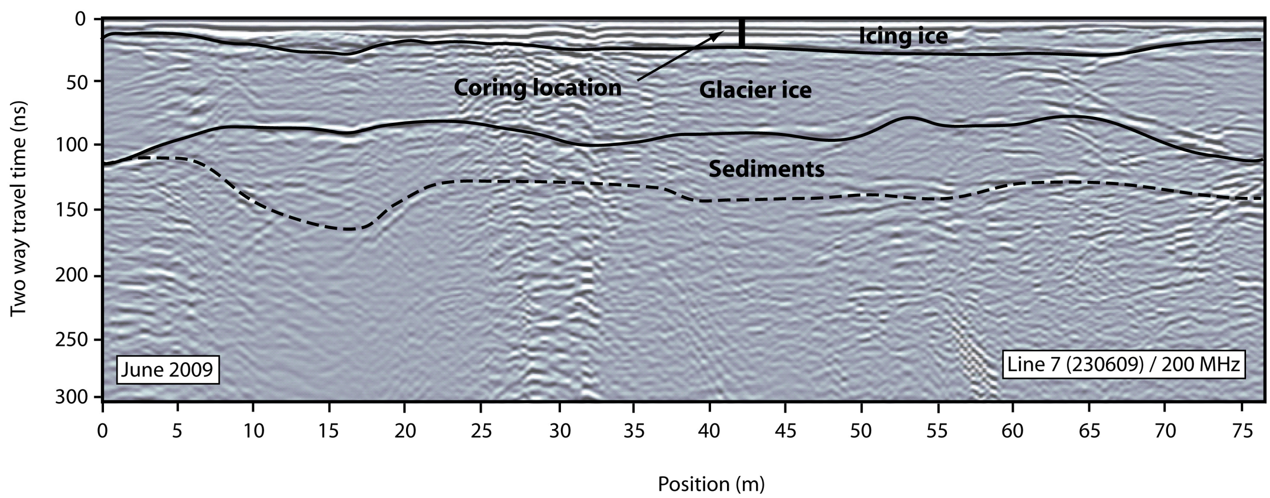


Figure 4. 200 MHz GPR line surveyed eastward following the centre line of the upper icing outwash plain. Survey was conducted in June of 2009.


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