

# Glacier-Permafrost Hydrology Interactions, Bylot Island, Canada

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**ABSTRACT:** A temporal study of perennial groundwater springs, icings, ice caves and subsurface tunnels demonstrates the complex interactions between glacial and terrestrial hydrology on Bylot Island, Canada. Thermal and ground-penetrating radar analysis show that the portions of the island not covered by glaciers are underlain by continuous permafrost, while some of the glaciers appear to be polythermal with subglacial taliks. Hydrological observations indicate that taliks generated beneath glaciers can extend beyond the glacial limits, thus modifying the surrounding terrestrial hydrological system.

An icing that varies in size annually was found to result from the draining of a large tunnel complex that extended from within a glacier out into the surrounding lateral moraine. Nearby, a large perennial icing grew from water flow through a subglacial talik originating beneath an ice-dammed lake. In both these cases it was found that the subsurface hydrological system was a continuum between the glacial and periglacial environments.

## 1 INTRODUCTION

Glaciers at high latitudes differ from glaciers located at lower latitudes. Most significantly, large portions of the ice in the ablation area are well below 0°C. As well, arctic glaciers are commonly surrounded by permafrost. The cold conditions dramatically influence the flow of glacial ice and the hydrological regimes of both glaciers and surrounding permafrost.

At high latitudes, large ice-cored moraines are commonly observed surrounding retreating glaciers, with the frozen core of the moraines being preserved for tens of thousands of years (e.g. French & Harry, 1988; Astakhov & Isayeva, 1988). This results in a blurring of the distinction between glacial ice and the buried ice enclosed in the surrounding permafrost.

The thermal conditions within polar glaciers result in the hydrological system being limited, whereas, the thermal structure of temperate glaciers enables surface water to establish englacial and subglacial drainage conduits (Paterson, 1994). Polythermal glaciers would fall in between polar and temperate glaciers, having liquid water flow generally restricted to the

warmer portions of the glacier. In temperate glaciers, the glacial hydrological system is linked to the groundwater system through dispersed pore-water flow within the unfrozen subglacial and proglacial sediment. Polythermal glaciers are generally surrounded by permafrost. Permafrost is generally viewed as an impermeable barrier to dispersed groundwater flow (Williams & Smith, 1989). Thus it might be presumed that the limited amount of liquid water flow in a polythermal glacial system would be isolated from the proglacial groundwater system.

However, warm zones in a polythermal glacier and taliks within ice-rich permafrost can enable the establishment of groundwater flow and the formation of subsurface conduits. Thus, it is hypothesized that interconnection between glacial and subsurface permafrost hydrological systems does occur in polythermal glacier systems.

Two glaciers and the surrounding permafrost on Bylot Island were investigated to test this hypothesis and to evaluate the influence that glacier dynamics has on the hydrological regime.

## 2 WATER FLOW IN PERMAFROST

The bulk flow of fresh water within permafrost occurs when; there is a subsurface void, or a talik within permeable sediment. In either case the water source must provide enough heat to prevent freeze-back of the locally unfrozen zone (be it an air filled cavity or sediment). In the case of groundwater flow through a talik, water flow must be constantly maintained or the pore water will freeze through heat loss to the surrounding frozen ground and the talik will disappear. The energy balance can be simply expressed by:

$$Q^* = Q_S + Q_L - Q_G$$

Where  $Q^*$  is the net heat flux,  $Q_S$  is the sensible heat with the unfrozen water in the talik,  $Q_L$  is the latent heat of fusion of the unfrozen water within the talik, and  $Q_G$  is the heat being conducted away from the talik through the permafrost.  $Q_G$  is a function of the temperature of the surrounding permafrost and its thermal conductivity.  $Q_S$  is a function of the temperature of the water and the flow rate.  $Q_L$  is a function of the porosity of the unfrozen sediment. When  $Q^*$  is negative, the talik begins to refreeze and the flow of water is restricted. If  $Q^*$  equals zero, the talik is in equilibrium. If  $Q^*$  is positive, the talik will begin to enlarge, possibly enabling greater flow, if the source is sufficient and the geologic conditions permit.

In the case of a subsurface void with water flowing through it, the same energy balance equation applies, except, if  $Q^*$  is positive and a talik begins to form within the surrounding sediment, the tunnel may enlarge due to hydrothermal erosion of the sediment. As well, when  $Q^*$  is negative, and freeze-back occurs, it takes the form of ice accumulation on the tunnel walls. If the tunnel drains for part of the year, the only significant impact on its size will be creep of the cavity walls causing closure. The creep rate is a function of the composition of the surrounding material, void size, depth, temperature, the length of time it is drained, and water pressure when it is filled (Williams & Smith, 1989). For example, pure polycrystalline ice has a strength four times that of clay, however, all frozen materials experience a dramatic decrease in strength as the temperature increases. The strength of polycrystalline ice drops from over 17 MN/m<sup>2</sup> at -10 °C to less than 5 MN/m<sup>2</sup> at -0.5 °C. As a result, some subglacial cavities have been observed to disappear in a matter of days, while shallow caves in cold permafrost (such as one of the caves in this study) can exist for many years.

## 3 STUDY AREA

The study area for this research was on the southern portion of Bylot Island in the Canadian Arctic (Fig. 1). Bylot Island consists of a central ice field from which valley glaciers flow towards the coast. The Quaternary history of the island can be summarized as several extensive glaciations, the most recent being prior to 43,000 radiocarbon years ago. Glaciers on the island are currently at, or retreating from, their Neoglacial maximum positions that were attained within the last 100 years (Klassen, 1993). The distribution and character of retreating glaciers suggests that the differential retreat is the result of a lagged response to decrease in snowfall. This assertion is supported by historical climate data. Basal structure and ground-penetrating radar studies suggest that at least some of the glaciers on the island are polythermal (Zdanowicz et al. 1996; Moorman & Michel, 2000a).

Bylot Island falls well within the zone of continuous permafrost. The mean annual air temperature in the region is approximately -15 °C. The average annual precipitation is less than 200 mm, with the snow pack thickness being less than 80 cm in winter. From short-term shallow ground temperature measurements in two locations on the island, the permafrost is estimated to be in the range of 200-400 metres thick. The active layer ranges from 30 to 50 cm. Retrogressive thaw flows and thermokarst lakes on the island demonstrate that massive ice is present in the subsurface of recently exposed moraines and older sediments. Groundwater and subglacial springs have been identified in a number of locations across the is

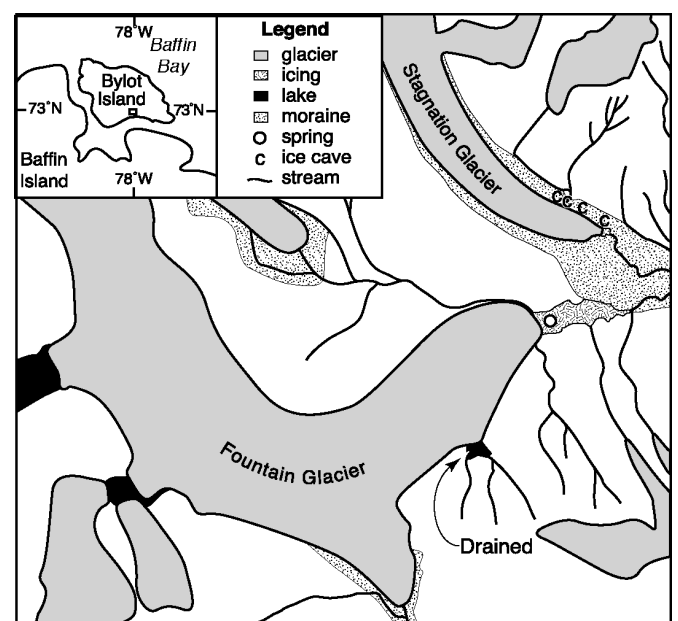


Figure 1. Southern Bylot Island, Canada study area, displaying the differences between the two glaciers.

land and icings have been observed in front of six glaciers.

Two adjacent valley glaciers on the southern portion of the island were investigated because of their differing character, retreat rates and hydrological conditions (Fig. 1). The larger of the two glaciers is informally named Fountain Glacier and the smaller Stagnation Glacier (Glacier Atlas of Canada designations B26 and B28 respectively; Inland Waters Branch, 1969).

## 4 METHODS

Changes to surficial features were mapped using a time series of aerial photographs and satellite images dating back 1948. During the years 1993-1996, 1999 and 2001 the site was visited and the glacier and icing extents were mapped, along with the location and characteristics of springs, caves, and icing structures. Subsurface features within the icing, glaciers, and moraines were mapped with ground-penetrating radar (see Moorman & Michel, 2000a). Dye tracing tests were carried out to determine the hydraulic connectivity of the streams in different caves.

## 5 RESULTS

Fountain Glacier has an accumulation area of 22 km<sup>2</sup>, while Stagnation's is only 8 km<sup>2</sup>. The terminus of Fountain Glacier was essentially stationary between 1948 and 1996. Since 1996, the glacier is starting to show signs of retreat, with the margins receding in the lower kilometer of the ablation zone by up to 5 m. Stagnation Glacier has retreated over 1.8 km since 1948, and has been consistently retreating at 5.0 m/a over the last eight years.

Stagnation Glacier has large lateral moraines (up to 200 m in height) within its ablation area. Fountain glacier has negligible moraines and with the initiation of its retreat in recent years, only very little glacial sediment is being exposed. A gravel outwash plain is in front of the glacier. On either side of the glacier, bare rock or a thin veneer of fluvial sediment is present.

### 5.1 Fountain Glacier Icing

Fountain Glacier hydrological system is unique on Bylot Island, in that there is a large icing (11

km long and up to 500 m wide) down valley from its terminus that has been visible on every aerial photograph and satellite image since 1948 (Moorman & Michel, 2000b). In the area adjacent to the glacier, a portion of the icing covers a rise in the valley bottom and persists throughout the summers (Moorman & Michel, 2000a). The icing thickness varies from year to year, but over the last 8 years its thickness has averaged 12 m adjacent to the glacier while thinning to less than 1 m beyond a constriction in the valley bottom 1 km from the glacier. This represents  $2 \times 10^7$  m<sup>3</sup> of winter water discharge.

Up until 1999, a spring, approximately 50 m down valley from the glacier terminus, had also been observed emerging as a fountain from the valley bottom sediments. In some years the area was covered by the icing and in the location of the spring, a large icing blister was present. It appears that this spring was the dominant source of water for icing growth. The spring is thought to have been fed by at least one of the three ice dammed lakes adjacent to Fountain Glacier (Elver, 1994).

In the summer the spring flow was responsible for some of the icing erosion, however, most of the erosion was caused by glacier lateral streams that flow down the valley sides (Moorman & Michel, 2000a). The spring flow is an order of magnitude less than the discharge of the lateral springs in the summer.

Sometime between 1996 and 1999 the lake closest to the glacier terminus catastrophically drained along the side of the glacier as the glacier retreated back from the valley edge (Fig. 1). The ensuing flood resulted in a 300 m by 500 m area of the thickest portion of the icing being covered by 0.5-3 m of sediment. In 2001 the lake was completely dry, and all of the exposed valley bottom on the south side of the glacier is devoid of glacial sediment.

During the summers of 1999 and 2001, no sign of spring flow or any other subsurface hydrological activity was observed. By 2001, thermokarst activity had made the surface of the buried portion of the icing very uneven (up to 5 m elevation variation). In contrast, the portion of the icing that was not buried, has a smooth surface. There is no evidence of icing build-up around the spring since 1999.

### 5.2 Stagnation Lateral Moraine Caves

At first appearance, the lateral moraines flanking Stagnation Glacier appear to be quite stable, with only minor active layer detachments occur-

ring the in the warmest portions of the summer and healing quickly. However, one cave system has been exposed within the eastern moraine for at least the last fifty years, two other cave systems became exposed in 1999, and another exposed in 2001 (Fig. 2).

The first cave system (Cave 1) to become exposed opens up on the outside of the moraine and a terrestrial stream enters the cave system in the summer. Aerial photographs display the opening of this cave gradually getting larger as it erodes deeper into the moraine. The erosion has currently progressed two thirds of the way across the width of the moraine. The stream entering this cave proceeds into Stagnation Glacier in a conduit beneath the east lateral stream. Dye tracing experiments have shown that there is no connectivity between the stream entering the cave and the glacier's marginal stream.

In 1999, two other caves became exposed, both on the glacial of the lateral moraine. Cave 2 is less than 50 m down valley from the Cave 1, but 75 m higher in elevation. This cave system winds its way down valley, staying within the moraine for over 100 m before it becomes too small to explore. Sections of the cave show signs of closure due to roof creep, while in another part, there is a gallery measuring 20 m by 10 m with a 5 m high roof.

Closer to the terminus of the glacier, Cave 3 was discovered in 1999, but has subsequently been

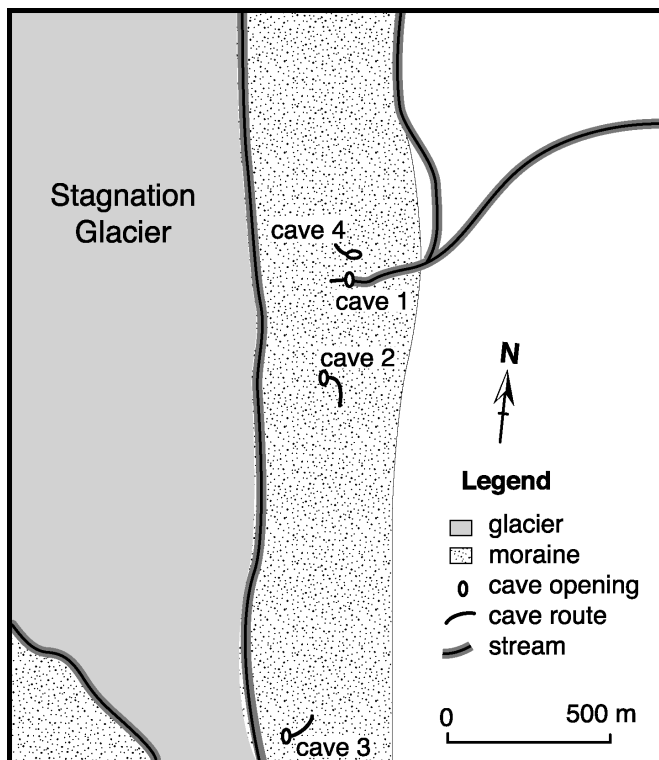


Figure 2. Caves on the eastern lateral moraine of Stagnation Glacier. Cave 1 was initiated on the outside of the moraine, while Caves 2, 3 and 4 are on the glacier facing slope.

covered by colluvium. This cave was 5 m in height and 10 m across at its opening, gradually tapering to closure 75 m into the moraine after curving up-valley (Fig. 3). This tunnel system is in direct alignment with the tunnel system originating in Cave 2.

A 5-10 cm thick veneer of clear ice covered the insides of the cave. Beneath this ice was the sediment-rich basal ice that made up the core of the moraine. This is indicative of minor amounts of freeze-back occurring within the tunnel when it was full of water. On the floor of the cave large blocks of ice (1-3 m diameter) lay in a jumbled pile on the outside of the bend near the entrance to the cave. Outside the entrance to the cave, four large blocks of ice (2-3 m diameter) lay randomly oriented on the ground, and the surface sediment was water washed. This is indicative of a large discharge of water through the tunnel in the past (estimated to be in the order of  $100 \text{ m}^3/\text{s}$ ). In the summer of 1999, there was only a small trickle of water along the floor of the cave and associated 1 cm high ice terraces.

The shape of the cave is in accordance with the gradual contraction associated with creep. The smaller portions of the cave were deeper in the moraine where the thickness of overlaying ice and sediment was much greater.

Cave 4, exposed in 2001, opened into a tunnel with a perfectly round cross section and a diameter of 2.8 m that extended more than 30 m into the moraine before an ice plug blocked the tunnel. The ice plug appears to be the result of the partial freezing of standing water when the conduit was approximately half full before it drained. The resultant feature is a horizontal ledge at the mid point in the tunnel with a reduction in the tunnel size beneath the ledge on one side. In the summer of July 2001 the cave was well below  $0^\circ\text{C}$  and there was

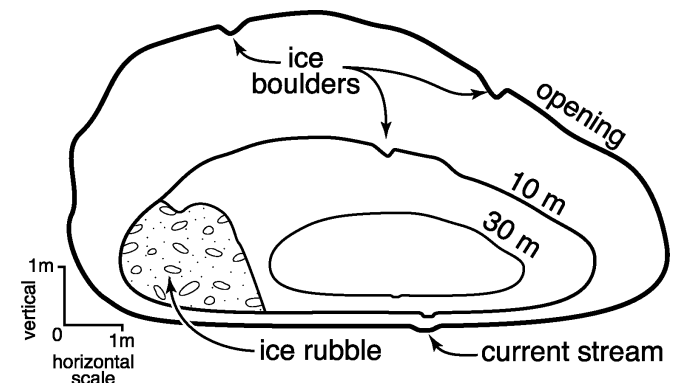


Figure 3. Cross sections through cave 3 at the opening, 10m and 30 m from the entrance, showing the relative position and shape of the cave as it extends deeper into the moraine. Note the rubble pile extended from 5-25 m along the left wall.

no flowing water within it. Hoar frost had formed on the walls, and beneath that the sediment-rich basal ice could be seen.

There are many massive ice bodies on Bylot Island, however, the ground surrounding the Stagnation Glacier moraines is very ice-poor and there is no indication that the tunnels within the moraine extend into this terrain.

## 6 DISCUSSION

The timing of lake drainage and of drying up of the spring in front of Fountain Glacier suggests that the ice-dammed lake closest to the terminus was probably the source of the spring water. The aerial photographs indicate that the spring in front of Fountain Glacier experienced the greatest discharge when lake levels were highest. In some years the summer spring discharge was great enough to completely erode the icing within 150 m of the glacier. As lake levels dropped so did discharge from the spring, such that it still effectively built up the icing during the winter but was incapable of eroding it in the summer.

The spring emerged 50 m beyond the terminus of the glacier, thus the water must have flowed through a talik within the coarse-grained valley-bottom sediments, and was constrained by the glacier and surrounding permafrost. There was no evidence that tunnel flow. The schematic diagram in Fig. 4 illustrates how the routing of the water and how the thermal structure provides a major constraint on the subsurface hydrology.

Since the spring dried up at the same time as the draining of the nearest lake, it is suggested that the other two ice dammed lakes which are further up glacier are not connected to the subglacial talik that fed the spring.

The cave system preserved in the Stagnation Glacier lateral moraine is a clear indication of channelized water flow in the subsurface. Cave 1 still has water from a terrestrial stream flowing into it and on into the glacier system. This drainage system has shown to be very stable, slowly eroding the ice-cored moraine a little more every summer, but never changing its routing dramatically. The sediment in the stream bed leading to the cave is composed of well sorted cobbles. This is much larger than can be moved during most of the flow season, suggesting that periods of extreme flow do impact the system. However, an extreme flow has yet to be observed.

The large ice blocks and other rubble strewn in front of Cave 3 is indicative of high energy hydro-

logical activity within the moraine, with water catastrophically draining out of the moraine. The relatively small amount of deposition or erosion further down stream from the cave entrance suggests that the high discharge levels were limited in duration.

In 1999 there was approximately 40 m<sup>3</sup> of ice rubble within Cave 3. Some of this rubble was formed of 20-30 cm diameter slabs of ice formed from the freezing of a still water surface (e.g. ponded water within a partially filled tunnel). A large portion of the rubble was rounded boulders of glacial ice. It is likely they originated from a collapse within the tunnel system, but the high degree of rounding, their random orientation, and the smoothness of the nearby tunnel walls indicates the rubble was not locally derived.

Of the four caves, there were indications that two drained completely before the water within had a chance to freeze (Caves 1 & 2). Cave 3 showed signs that freeze-back was occurring while the cave was full of water and then it completely drained with limited further freezing. The ice plug in Cave 4 indicates that it was half full for a long period of time in which all of the standing water in it froze in place.

The interconnectivity of the caves has not been absolutely determined, however, it has been confirmed that some do connect with the glacial system. Thus it is reasonable to suggest that these caves reflect relict englacial drainage channels from periods of more extensive glaciation.

## 7 CONCLUSIONS

The hydrological features in the vicinity of Fountain and Stagnation Glaciers on Bylot Island demonstrate that the permafrost and glacial environments are directly linked by their common hydrological system. Fountain Glacier had a proglacial spring that was being fed by an ice-dammed lake via groundwater flow through a talik. This system was found to be dynamically stable while the glacier stability was maintained, but is thought to be statically unstable once water flow stopped.

The caves within the ice-cored lateral moraine of Stagnation Glacier demonstrate that englacial tunnels originally formed when the glacier was larger can be preserved in the ice-rich permafrost surrounding the glacier. Some of the tunnels are still intermittently active, either directing water into or out of the glacier. Due to the high hydraulic pressures that develop in some of these tunnels they can become dynamically unstable, resulting in

catastrophic outburst flows. One of the main ways these tunnels are sealed off is through ice creep when they are empty. Since the creep of sediments and ice in these cold permafrost conditions is very slow, these tunnels can be preserved for a long time (i.e. statically stable).

Although it is not anticipated that the conditions studied in this investigation are extremely prevalent elsewhere, these examples do demonstrate some of the complex interconnectivities of the glacial/permafrost hydrological system.

## 8 ACKNOWLEDGMENTS

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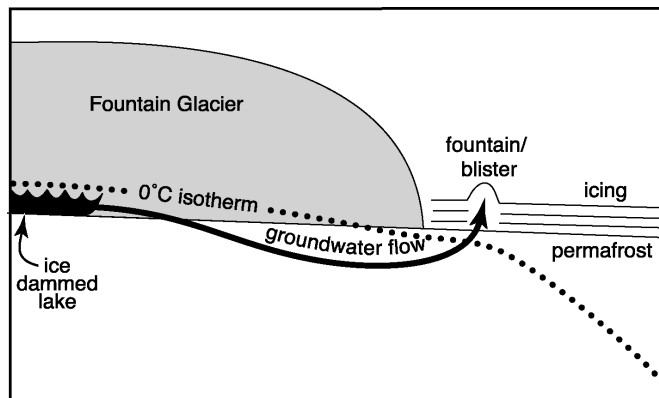


Figure 4. Schematic of the ground water flow feeding the icing in front of Fountain Glacier. The isolation of the fountain from the glacier indicates that there must be continuous groundwater flow. See Figure 1 for the location of the now drained lake.

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