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Annual Development Cycle of an Icing Deposit and Associated Perennial Spring Activity on Axel Heiberg Island, Canadian High Arctic

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Abstract

This paper examines the behavior of perennial saline springs and their icings at Expedition Fiord in the Canadian High Arctic during the winter months when temperatures are below the eutectic point of the solution and during the early spring when temperatures are still below freezing but above the eutectic point. The spring outflow begins to freeze when it cools from the discharge temperature which is between −3.5°C and +6°C. As ice forms it remains mixed with the brine forming a salty, icy, slush which lines the sides of the flow channel. Networks of pipes and tunnels also allow the brine to flow under and through the icing before being frozen at the icing perimeter. In late winter complete freezing occurs several hundred meters from the springs' outlets. There appears to be incomplete fractionation of salt during the freezing process and the bulk ice contains 30 to 285 ppt salt. The icing reaches its maximum extent in late winter just before temperatures rise above the eutectic point. In April 2002 the icing had dimensions of 300 m by 700 m, an average thickness of 0.5 m and a total mass of approximately 2×10^8 kg. This icing mass is consistent with the flow from the springs during the previous 6 mo.

Introduction

Two groups of cold perennial saline springs occur in the Expedition Fiord area on west-central Axel Heiberg Island in the Canadian High Arctic (Pollard, 1991; Pollard et al., 1999). One group, located at the base of Colour Peak on the north side of Expedition Fiord, consists of approximately 20 spring outlets that flow down the south-facing slope of Colour Peak into Expedition Fiord. The second group is located at the base of Gypsum Hill roughly 10 km inland from Colour Peak. At this site discharge from 40 outlets cascades down the side of the valley into the Expedition River floodplain. The locations of Colour Peak and Gypsum Hill are shown in Figure 1. In both cases year-round discharge of highly mineralized groundwater has been documented (Pollard et al., 1999; Andersen et al., 2002). During winter the extremely cold air temperatures result in the formation of icings and several seasonal frost mounds (Pollard, 1991).

The local geology surrounding the springs on Axel Heiberg Island is quite complex. The region is composed of folded and faulted sedimentary rocks ranging from Triassic to Tertiary in age. Upper Paleozoic evaporites intrude into overlying sedimentary rocks to form a series of piercement structures (Hoen, 1964; Andersen et al., 2002). The springs at both Colour Peak and Gypsum Hill are associated with these anhydrite piercement structures (Hoen, 1964).

The perennial springs on Axel Heiberg Island are noteworthy because they are among the most poleward springs known and are the only known example of cold, nonvolcanic springs in thick permafrost on Earth. The springs form the highest-latitude travertines known and have a mineralogy which includes ikiate precipitation while also hosting a variety of bacteria (Pollard et al., 1999; Omelon et al., 2001; Andersen et al., 2002). They are also notable because of the saline nature of the icings produced during winter (Pollard, 1991).

The springs at the Gypsum Hill site provide a natural setting in which to study the annual cycle of spring and icing activity under cold polar desert conditions. The Colour Peak springs are less suitable for studying the seasonal behavior of this type of system because the brine flows directly into the waters of Expedition Fiord and consequently does not develop as large or as complex an icing deposit. In this paper we report on observations of the Gypsum Hill springs and their icings at Expedition Fiord in the Canadian High Arctic during the winter months when temperatures are below the eutectic point of the solution and during the early spring when temperatures are still below freezing but above the eutectic point. We also examine the dynamics of the icing formation and the subsequent icing decay. We focus on several specific aspects of the springs system including the depressed freezing point of the springs' saline outflow and the incorporation of salt into the icing deposit.

Background

PERENNIAL SPRINGS

Perennial springs in areas of thick continuous permafrost are extremely rare. Permafrost is generally recognized as an impermeable layer that divides the groundwater system into sub- and supra-permafrost components. Research to date has focused on the hydrology and geomorphology of these spring systems at Expedition Fiord.

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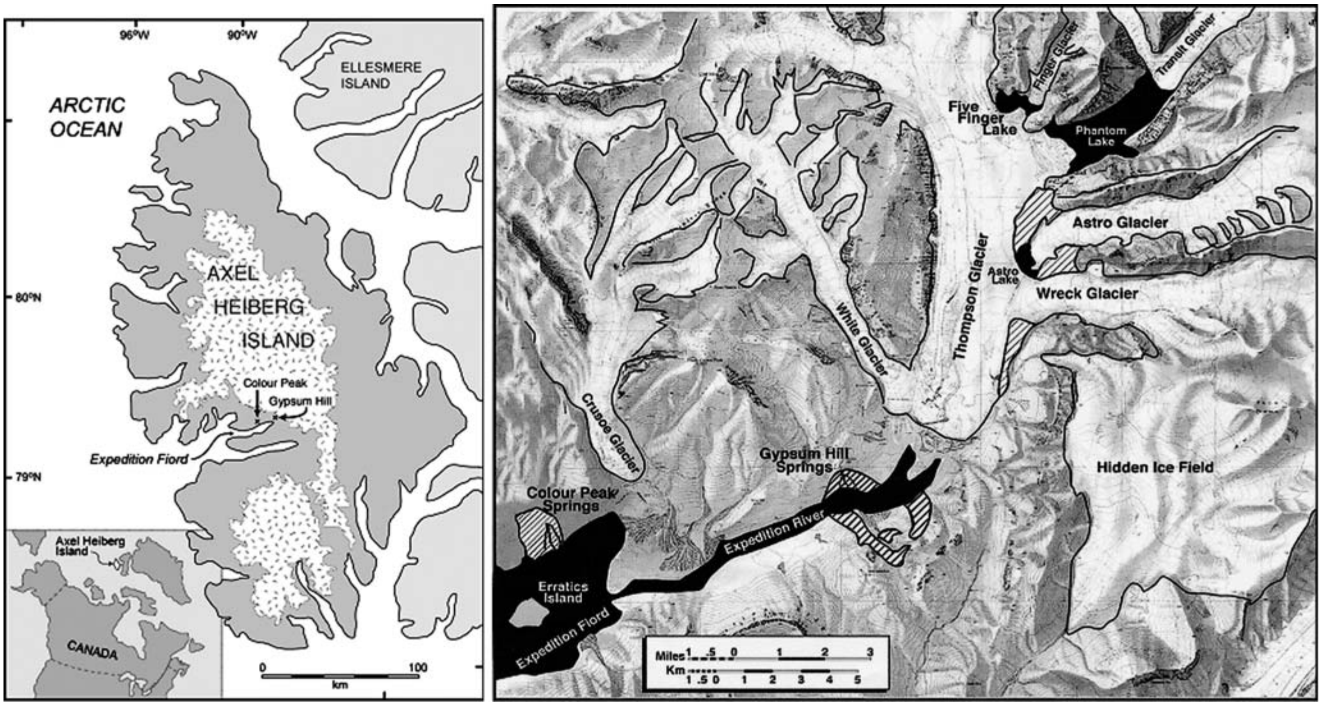

FIGURE 1. (a) Location map of Expedition Fiord, Axel Heiberg Island, Nunavut. Hatched areas indicate glacial ice cover. (b) Location map of the Expedition Fiord region. The Gypsum Hill and Colour Peak springs are labeled. The red hatched markings represent surficial salt deposits; note that such deposits are associated with the springs and suggest a connection of spring activity with the subsurface evaporite diapir structures that pierce the surface at the Gypsum Hill and Colour Peak sites. Phantom and Astro Lakes are perennially ice-covered lakes that formed following the retreat of the Transit and Astro Glaciers, respectively, and may be sources of the spring water.

Discharge temperatures are relatively constant throughout the year despite extreme seasonal variations in air temperature (Pollard, 1991; Pollard et al., 1999; Omelon et al., 2001; Andersen et al., 2002). The average discharge temperature is +3.9°C and temperatures at different spring outlets range from –3.5 to +6.6°C. However, over a 5-yr monitoring period, individual outlet temperatures have varied by less than 0.5°C, attesting to the constant nature of the discharge temperatures.

Total discharge for all the springs at Gypsum Hill combined range between 10 and 15 L s^{-1} (Pollard et al., 1999). Flow from individual springs, however, is more variable. Some seeps have barely detectable flows while others have maximum flows of 0.9 to 1.50 L s^{-1}. However, each individual seep maintains a relatively constant discharge rate throughout the year.

The chemistry of the brine solution is likewise similar for all outlets. The solution is dominated by Na and Cl dissolved solids with lesser amounts of K, Ca, Mg, and SO_4 (Pollard et al., 1999). The outflow is thus constant with respect to temperature, discharge rate, and composition.

The ultimate source of this brine solution has been enigmatic for many years. Andersen et al. (2002) suggest that the source of the Gypsum Hill brine is a combination of water from basal melting of the Muller ice sheet and water from the glacially dammed Phantom Lake located ~397 m above the outlet of the springs and the smaller lake into which it overflows, Astro Lake. Phantom and Astro Lakes are perennially ice-covered lakes that formed following the retreat of the Transit and Astro Glaciers, respectively. Phantom lake is sufficiently large to sustain a sublake talik. Faulting beneath the lake through the evaporite piercement structure may also provide a conduit to the deep subsurface and may also help to link together other piercement structures associated with the springs. Astro Lake is in direct contact with a gypsum diapir and Andersen et al. (2002) suggest that water from the lake flows beneath the permafrost through an underlying evaporite layer and then returns to the surface as spring discharge flowing through the evaporite piercement structures. The brine is warmed to the geothermal temperature within the underlying evaporite layer and loses heat to the surrounding permafrost as it flows upward to the Gypsum Hill site. The brine solution then creates the observed springs where the evaporite piercement structure reaches the surface on the lower reaches of Gypsum Hill.

ICINGS

The seasonal formation of ice in cold environments produces a variety of morphological features, including icings and seasonal frost mounds. The icing and seasonal frost mounds at Expedition Fiord were first described by Beschel (1963), Pollard (1991), and Pollard and van Everdingen (1992). The term "icing" refers to sheet-like masses of layered ice formed on the ground surface (or on river or lake ice) by freezing of successive flows of water that seep from the ground (ground icings), flow from a spring (spring icings), or emerge from below river ice through fractures (river icings) (Carey, 1973; Pollard and van Everdingen, 1992). In winter, much of the groundwater discharged through seeps, springs, and in streambeds in northern regions will freeze and form "icings." This term, in common North American usage, is synonymous to "aufeis" (widely used German term), or "naled" (Russian term) (Carey, 1973).

Ground and spring icings are produced by the freezing of successive flows of ground water. This water can initially seep into a snowpack and freeze to form a massive basal icing layer. Overflow events also contribute to the formation of the icing deposit. Overflow initially occurs as a very thin water sheet, less than 2 mm thick, flowing down slope (Hu and Pollard, 1997a, 1997b). Because of the discontinuous nature of this process, the underlying ice is usually close to ambient temperature (Hu et al., 1999). A significant amount of the heat carried by the water is conducted into the ice. Consequently, the distance of water movement during the first several minutes of an overflow event can be very limited and is less than 2 m in experiments by Hu and Pollard (1997b). As the leading edge of this thin water layer reaches the freezing temperature, a mixture of water and ice (slush) forms, and ice crystals attach themselves to underlying ice. As water flows over and within this slush section, the flow speed becomes significantly slower. The water level consequently increases in the up-slope part of the icing, resulting in an increase of the icing layer thickness. Meanwhile, a thin ice cover forms over the surface of the water which results in water flowing continuously between the top ice cover and the underlying ice. This intra-ice layer flow continuously brings heat to the slush section and introduces melt, thus allowing water to travel a greater distance. As long as the intra layer flow path is open, the ice stops forming on the surface at the upper part. Once freezing of water through heat losses into both the atmosphere and underlying ice obstructs intra layer flow, a second icing cycle occurs up slope (Hu and Pollard, 1997a, 1997b).

STUDY AREA

The Gypsum Hill springs are located at 79°24′30″N, 90°43′05″W on Axel Heiberg Island in the Canadian High Arctic (Fig. 1a). Axel Heiberg Island lies within the Sverdrup Basin and is composed primarily of Triassic to Tertiary folded and faulted sedimentary rocks. Upper Paleozoic evaporite piercement structures intrude into the sedimentary layers as a result of early Tertiary orogenic activity (Thorsteinsson, 1971; Pollard et al., 1999). Currently, the island is mostly bare ground with <35% covered by glaciers or ice caps and is devoid of volcanic heat sources (Muller, 1963; Thorsteinsson and Tozier, 1970; Andersen et al., 2002). Although permafrost depths have not been measured at Expedition Fiord, a permafrost depth of greater than 400 m was reported in an exploration well 60 km from the springs site and depths of greater than 600 m have been reported at other sites in the region (Taylor and Judge, 1976).

The springs are located within a polar desert environment. The mean annual air temperature at Expedition Fiord is −15°C, however winter temperatures below –40°C are common (Andersen et al., 2002). This part of the Arctic Archipelago is characterized by cold, dry winters and cool summers with maximum precipitation occurring in July (Maxwell, 1982). Early research at Expedition Fiord indicated a mean annual accumulation of 371 mm (water equivalent) on the Muller Ice Cap (Muller, 1963). Precipitation is much less in lower areas where orographic influences are absent. This High Arctic site is therefore classified as a polar desert since potential evaporation exceeds the low annual precipitation (Andersen et al., 2002).

The Gypsum Hill springs are situated on the northwest side of Expedition River. Gypsum Hill is 2.5 km downstream from the terminus of the White and Thompson Glaciers and 7 km upstream from the head of Expedition Fiord. The spring outlets are located 10 to 20 m a.s.l.), and discharge along a region 300 m long and 30 m wide.

Data Collection

Data was collected during the 2001–2002 seasons to characterize the wintertime conditions at the Gypsum Hill springs site. At the springs site, brine and ice samples were collected for salinity measurements which were obtained using a Vista Model A366ATC salinity refractometer. Hobo H8 Outdoor/Industrial Four-Channel External dataloggers (H08-008-04) with wide-range temperature sensors (TMC6-HA) were installed at the Gypsum Hill springs at four different locations following one main exposed outlet in April 2002 to record brine, slush, and ice temperatures along the channel. Weather conditions were recorded 10 km downstream of Gypsum Hill at Colour Peak using Campbell automatic weather stations equipped with a Campbell Model 107 temperature probe from 12 July 2001 through 12 April 2002. A similar Campbell weather station was also installed at the Gypsum Hill site and monitored environmental conditions from 13 April 2002 through 12 July 2002.

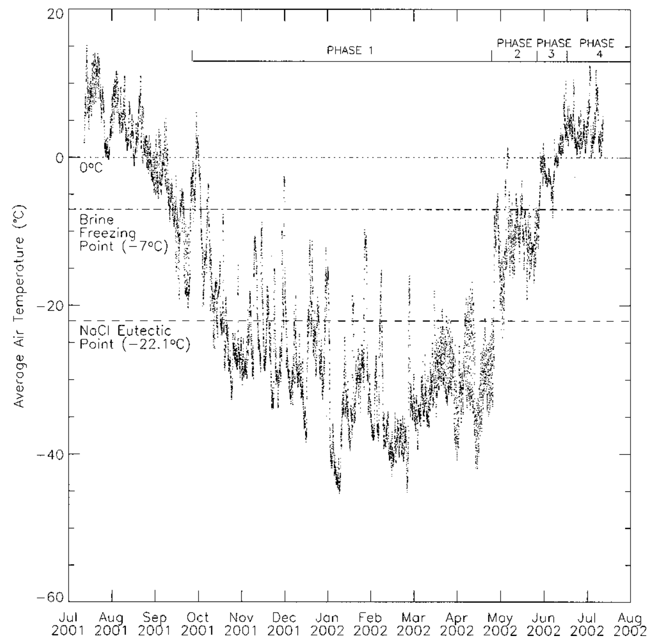

FIGURE 2. Average air temperatures for Gypsum Hill at Expedition Fiord, Axel Heiberg Island. Phases 1, 2, 3, and 4 represent different stages in the icing formation. Phase 1 occurs as air temperatures drop below the brine freezing point (–7°C) and icing of the springs' outflow begins. Phase 2 occurs when air temperatures are below the brine freezing point but above the brine eutectic point (–22.1°C) which allows for simultaneous icing melt and brine freeze. The icing completely melts during Phase 3 when temperatures rise above the brine freezing point. In Phase 4 temperatures climb above 0°C and the meltwater from the nearby White and Thompson Glaciers flows down Expedition Fiord to wash away any remaining salt and ice deposits derived from the Gypsum Hill springs.

In addition to these data collected, the general behavioral cycle of the Gypsum Hill springs has been directly observed by the co-authors for 15 consecutive years. Data from one year was collected to quantify these observed processes and correlate the yearly developmental cycle of springs with ambient environmental conditions as well as conditions describing the icing itself. Therefore the conclusions drawn are based both on multiple years worth of direct observation as well as data collected during the 2001–2002 season. Our extensive observations show that the development cycle of the Gypsum Hill springs follows a similar pattern each year and that the sequence of events described in this paper is typical.

Icing Development

The annual development cycle of the Gypsum Hill spring system can be divided into four distinct phases. These phases include (1) icing formation, (2) simultaneous icing melt and brine freeze, (3) total icing melt, and (4) icing washout. The timing of these events depends mainly upon air temperatures. Air temperatures were collected every one minute and averaged over 30-min intervals. Figure 2 shows these average air temperatures recorded at Gypsum Hill. Phases 1, 2, 3, and 4 of the springs' development are labeled. In the following sections we consider each of these phases in more detail.

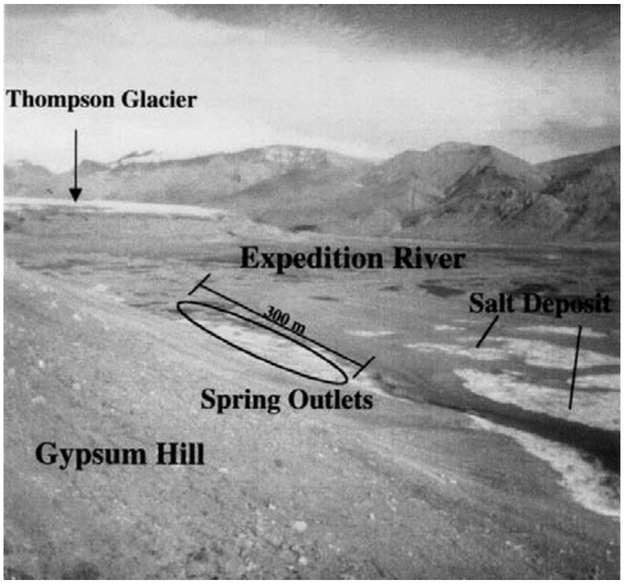

FIGURE 3. Image taken 16 July 1995 showing the relative locations of Expedition River, Gypsum Hill, Thompson Glacier, and the spring outlets. The spring outlets are located at the base of Gypsum Hill. The salt deposits within the river show the location of the wintertime icing. These remnant salt deposits are being washed away by meltwaters emanating from the Thompson Glacier which flow down the Expedition River during the summer months. Washout is typically complete by the end of June.

PHASE 1: ICING FORMATION

At the start of the winter, the Expedition River floodplain has been cleared of any residual ice or salt by glacier meltwater that sustains the Expedition River. The river stops its flow as the White and Thompson Glaciers cease melting and the river bed becomes dry. Residual melt water continues to drain from the White and Thompson Glaciers after the onset of freeze-back and results in small localized freshwater icings near the glacier termini. The springs continue to flow into the dry riverbed. Icing of the springs' outflow begins when ambient air temperatures fall below the freezing point of the brine solution. Freezing point depression experiments using Gypsum Hill brine show that freezing consistently begins around –7°C (Pollard, 1991; Pollard et al., 1999). These experiments also indicate that continued freezing causes fractionation which increases the salinity of the residual brine and further depresses the freezing point. As seen in Figure 2, air temperatures fall below the freezing point of the brine in late September. At this point ice starts forming but the liquid does not completely freeze since temperatures are above the eutectic point of the concentrated brine. Freezing depression experiments found residual brines still present at –20°C. The brine solution freezes slowly as air temperatures first drop below –7°C and hence most of the salt is excluded from the ice lattice, resulting in a relatively low salt content in the ice deposits that form at this time and a more concentrated residual brine. The flow continues to freeze as air temperatures continue to drop during the winter months. Hence through this process, more ice is added to the deposit as the ambient temperatures decrease. Under normal freezing the rejection of salt from solid solution yields ice salinities generally lower than the solution from which it is derived.

As the icing grows during the winter, its shape is dictated by the local topography of Expedition River floodplain and the self-leveling process that develops as ice accumulations obstruct down stream flow. The geometry of the brine flow and icing development from Gypsum Hill is mainly downstream towards Expedition Fiord. This geometry is shown from both a ground-based perspective (Fig. 3) and an aerial perspective (Fig. 4). The spring outlets are located on the sloping shores adjacent to the Expedition River which results in the downslope movement of the icing in the southern direction into the river. The riverbed slopes towards the southwest and once the icing enters the riverbed, it flows down river. Once the icing body is established there is a minor upstream development as flow from the most upstream outlets is partially obstructed. Hence the icing is elliptical in shape with the long axis in the south-southwest direction and the spring outlets are located in the northeast quadrant of the icing.

During the winter, the icing reached a maximum size of approximately 300 m wide by 700 m long and extended into the floodplain at the base of Gypsum Hill. Once the icing had reached its maximum extent the average icing thickness was 0.5 m. The icing dimensions are generally the same year after year.

Icing growth is a complex process that initially involves seepage into the snowpack and freezing to form a massive basal icing layer. The snowpack is typically 10 cm thick on the floodplain where the icing forms. This basal layer lacks the banding that reflects repeated overflow. The salinity of this layer is often lower due to the dilution effect of the snow. Based on a comparison of snow crystals versus ice crystals trapped by overflow within the icing, we estimated that snow may comprise as much as 10% of the volume of the ice mass. Once there is a basal layer, the icing grows primarily by episodic overflow events where water is forced to the icing surface. The large lateral extent of the icing is understood in terms of both the lowered freezing point of the brine as well as the internal structure of the icing itself. The freezing point depression allows the brine to flow as a liquid when its temperature is as low as –20 to –25°C (NaCl eutectic point is –21.1°C) (Pollard et al., 1999). As air temperatures drop below the eutectic point in the winter, the brine is capable of flowing significant distances laterally outward from the spring outlet before freezing since it flows beneath an insulating cover of the icing. As the icing develops, direct observations over 15 yr indicate that a network of pipes and channels develops to help distribute the water. Both active and abandoned channels are observed within the icing which demonstrates the dynamic nature of these conduits. The icing thereby grows in horizontal extent throughout the cold winter instead of having a more restricted, choked flow closer to the spring outlet.

Using the size of the Gypsum Hill icing as well as flow rates from the spring outlets, we performed mass-balance calculations to compare the amount of brine discharge with the total amount of ice formation. We estimated the total icing volume by treating the icing as an ellipsoid with axes of 700 m and 300 m, and a thickness of 0.5 m. The total ellipsoid volume was calculated and then divided by two to consider only the upper half of the ellipsoid which approximates the shape of the icing deposit and simulates the flat icing bottom which rests on the floor of Expedition Fiord. Using this method, the total icing volume at Gypsum Hill is $\sim 2.2 \times 10^5$ m^3. Assuming an ice density of 0.931 g cm^{-3} then the total icing mass is $\sim 2.0 \times 10^8$ kg. This calculation uses our best estimates for the icing dimensions and hence is our standard Gypsum Hill icing case. An uncertainty in the horizontal icing dimensions of ± 10 m would imply an uncertainty in the icing volume of 7.5%. An uncertainty of 5 cm in the vertical thickness of the icing would result in an uncertainty of the icing of 20%. It is possible that the density of the icing is lower than that of pure ice due to the presence of bubbles trapped in the ice formed from snow. We estimate that the icing may be up to 10% snow and so using an icing density of 0.831 g cm^{-3} the total icing mass would be 1.84×10^5 kg.

We now calculate the required flow rates necessary to be consistent with the estimated icing mass assuming the icing deposit is formed from the springs' brine. Temperatures are below the freezing point of the spring brine for approximately six months per year (see Fig. 2) and hence a brine flow rate of 12.9 L s^{-1} is required to create an

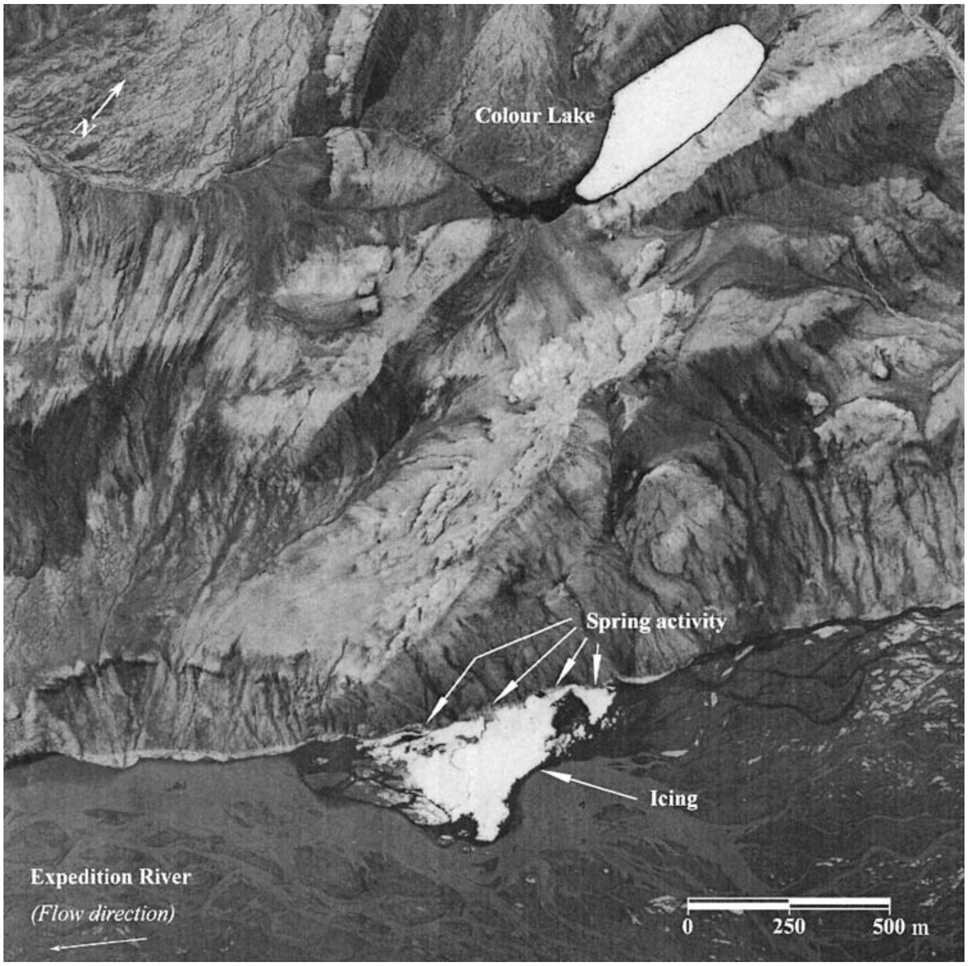

FIGURE 4. Gypsum Hill study area showing location of springs activity and icing deposit; note the size and shape of the spring icing. Airphoto A30860-139 ©1973 Her Majesty the Queen in Right of Canada, reproduced from the collection of the National Air Photo Library with permission of Natural Resources Canada.

icing of $\sim 2.0 \times 10^8$ kg in this timeframe. This calculated flow rate is within the range of flow measurements of 10 to 15 L s^{-1} as reported by Pollard et al. (1999). We estimate that the icing may contain up to 10% snow content, and in this case a flow rate of 11.6 L s^{-1} is needed to create the icing. These values are consistent with the icing representing the flow from the springs for 6 mo. We estimate that minimal amounts of water have sublimed because the icing deposit is typically covered by snowfall; approximately 20 cm of snow accumulates on the icing during the winter season which shields the ice from the atmosphere.

Salinity Patterns

To quantitatively characterize the brine and ice derived from the springs, temperature and salinity data were collected on 12 April 2002. Sample temperatures were recorded at the time of Hobo installation by a hand-held thermometer. Samples were collected and measured in the lab using a Vista Model A366ATC salinity refractometer.

Each sample was collected from a different location within the Gypsum Hill icing to determine spatial differences in icing temperature and salinity. Locations of data collection are described in Table 1. Sample 1 from the spring outlet was the liquid brine solution at the head of the channel. Sample 2 was collected ~12 m from the spring outlet and was a slushy material of liquid brine and ice crystals which was completely melted in the lab to determine the bulk slush salinity. The final two ice samples, Samples 3 and 4, were collected ~28 m and ~70 m from the spring outlet, respectively. These were both ice samples collected from several centimeters below the icing surface. These samples were likewise melted in the laboratory in order to determine the ice bulk salinity. Temperatures reported in Table 1 were gathered using both the hand-held thermometer as well as the Hobo dataloggers. The loggers successfully collected data from 12 to 16 April 2002 and indicated constant brine and ice temperatures at each location.

Based on the measured temperature and salinity of the Gypsum Hill slush we calculated the relative proportions of ice and brine in the system. The brine initially cools after it leaves the spring outlet because it is exposed to the lower ambient air temperatures. The liquid is exposed to the cold ambient conditions near the spring outlet because here an open-channel of water often exists that is not covered with ice. Further from the outlet and the open channel the icing grows from subsurface flow. Ice forms once the brine cools to the freezing point and this ice remains mixed with the brine forming a salty, icy, slush which lines the sides of the flow channel. As shown in Table 1, the slush region within the icing had a temperature of –9.5°C and an overall salinity of 64 ppt. During the freezing process, the brine portion

TABLE 1

Locations of data collection, sample temperatures, and sample salinities from the Gypsum Hill springs.

Location	Sample temperature	Salinity (ppt)
1. Spring outlet	Brine −6.6°C	72
2. Slushy tongue on icing, ~12 m from outlet	Slush −9.5°C	64
3. Tongue of ice in middle of icing, flanked by two tongues of slushy material, ~28 m from outlet	Ice −24°C	30
4. End of icing, ~70 m from outlet	Ice −32°C	285

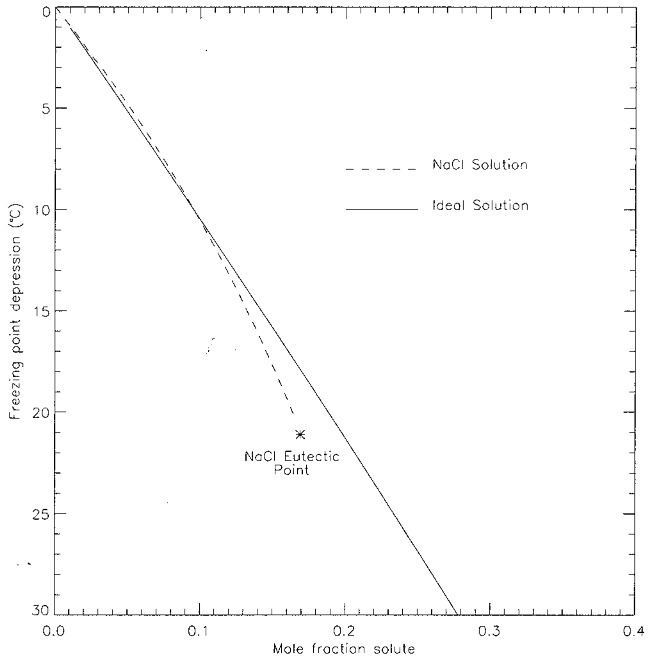

FIGURE 5. Freezing point depression curves as a function of mole fraction solute. The freezing point depression of a salt solution increases with an increased mole fraction of solute. The solid line shows the freezing curve of an ideal salt solution and the dotted line shows the freezing curve of a sodium chloride solution based on the data of Clark and Glew (1985).

of the slush must follow the equilibrium freezing point depression curve shown in Figure 5. Since the freezing point of seawater is –2.1°C then the slush temperature of –9.5°C implies a slush salinity 4.5 times greater than seawater. However, the measured bulk salinity of the slush was only 1.8 times greater than seawater salinity, and so a fraction of the slush material must be in the form of relatively pure ice which would increase the salinity of the remaining brine. The dilution effect of snow can also cause salinities lower than those predicted by the freezing curve, but snowfall at this time was minimal and so this effect is negligible in this case. The concentration of the brine portion of the slush must be increased by a factor of 2.5 with respect to the bulk slush salinity, and hence ~40% of the slush is liquid and ~60% of the slush is ice 12 m from the spring. These relative concentrations of brine and ice are consistent with the observed composition of the Gypsum Hill slush during April 2002.

The liquid brine contains significant quantities of salt (Pollard et al., 1999) and the salt concentrations within the icing itself varies but is always substantial. All of the ice within the icing contained some fraction of salt as shown in Table 1 and so there was no complete separation of salt and ice, and measurements along a transect of the icing shows that the icing was not homogeneous with respect to salt content. Salt concentrations were lowest near the center of the icing and increased farther from the spring outlets. The initial outlet salinities of the Gypsum Hill springs which contribute to the overall icing do not vary substantially (Pollard et al., 1999) and so the variations in icing salinity are not due to different contributions of salty water from different spring sources. Likewise the variations in icing salinity are not primarily due to sublimation of water which could increase the salinity of the remaining ice because the icing is covered by a layer of snow throughout the winter months which inhibits sublimation. Instead the pattern of salinity within the icing reflects the dynamics of the icing formation with respect to salt inclusions in the icing and may be somewhat affected by variations in snow content.

The varying salinity concentrations of the icing are mainly due to the behavior of the salt crystals as the brine freezes. Given the low flow rates and minimal flow turbulence, the freezing process of the icing is similar to sea ice formation which is dominated by the downward freezing of an ice sheet. Saline sea ice freezes through a well-understood process whereby relatively pure ice is formed and excess salts remain in the liquid since salts (including NaCl) are insoluble in ice (Petrenko and Whitworth, 1999). As salts are excluded from the ice during freezing, the remaining liquid brine becomes more highly concentrated in salt and hence the freezing point is correspondingly lowered as shown in Figure 5. Depending on the freezing rate, this brine can be trapped as inclusions in the sea ice. As temperatures continue to decrease, more pure ice as well as more highly concentrated residual brine should form. This freezing process and continual rejection of salt from the ice lattice continues until the eutectic temperature is reached and salts precipitate from the system.

The above sequence of events predicts an increasing salinity of the brine down the length of the channel as well as a distinct ice pan (formed when temperatures are between the freezing point and eutectic point) and a distinct salt pan (formed when temperatures are below the eutectic point). However, these predictions do not agree with observations with respect to the measured salinities as shown in Table 1 as well as the absence of separate ice and salt pans. This suggests, as observed above, that trapping of the brine in the ice occurs during the freezing process which prevents the separation of salt and ice as would occur in a slowly freezing system in which ice is segregated from the brine.

One possible explanation for the variation in the salt content of the ice is that ice of different bulk salinities forms during different times of the year when the degree and rate of freezing varies. The ice in the center of the icing deposit forms early in the season when the air temperatures are below the freezing point but above the eutectic. The Gypsum Hill brine freezes at ~–7°C according to the freezing point depression curve (see Fig. 5) as well as the experimental data of Pollard et al. (1999). Therefore the initial ice formation begins in early October. But at this temperature the solution will not freeze completely. Furthermore the ice begins forming only after the liquid has collected in the river bed. As the solution gradually freezes, residual brine remains and the ice that forms has a relatively low salinity as the salts should be efficiently excluded from this ice that forms early in the season. However, as shown in Table 1, the ice which freezes from the Gypsum Hill brine contains considerable amounts of salt. This unusual inclusion of salt within the icing deposit can be explained in terms of the variable freezing rates during the period of icing growth.

The Gypsum Hill icing increases in size due to the channelized brine flow within the icing and changing freezing rates during the season. One main channel develops within the icing fed by flow from several spring outlets. The channels develop only after there is a fairly large icing pan—the icing grows initially by seeping into the snowpack—diffusing along brine films and through overflow.

Overflow is a slow process and is spatially discontinuous so the icing is more or less self leveling, except for the icing mounds, icing blisters, and frost blisters. The icing mounds are formed from a point discharge where the flow moves upwards by hydrostatic pressure through a pipe-like channel through the icing. The mounds thus grow due to localized icing accumulation (Pollard and van Everdingen, 1992). Icing blisters are formed by confined water which causes the icing surface to dome upwards and results in arching fractures on the icing blister surface from the vertical ratcheting of the icing blister. These blisters grow due to the upwarp of ice layers by hydrostatic pressures (van Everdingen, 1978). The frost blisters occur when water is injected into the soil causing the frozen soil layer to dome upwards. Figure 6 shows a frost blister at Gypsum Hill. The icing mounds, icing blisters, and frost blisters attest to the fact that there is some constriction of flow around the spring outlets since at the two largest icing mounds the icing

FIGURE 6. Frost blister at Gypsum Hill. Blister is approximately 1 m in height, 2 m in length, and is located within the Expedition River floodplain. The frost blister formed as discharge from the Gypsum Hill springs was injected into the soils of the Expedition River floodplain causing uplift of the frozen soil.

FIGURE 7. Image of the Gypsum Hill icing taken 16 April 2002 looking towards the south. As air temperatures climb above the eutectic point, the icing begins to melt and mobilize to expose underlying brine channels. Brine leaves the outlet and travels along the exposed meandering channel which is flanked on either side by an extensive icing deposit. Exposed channel at spring outlet is approximately 15 cm in width.

is more than 3 to 4 m thick. The presence of frost blisters also shows that spring water is injected into the floodplain sediments. Such features form up to 100 m from the edge of the floodplain (Pollard and van Everdingen, 1992) and an average of eight to nine mound and blister features are formed each year at the Gypsum Hill site. These features mainly change the morphology of the icing and have negligible effects on the icing volume. The icing is large enough that the mounds and blisters only account for ~0.5% of the entire icing volume.

The icing grows as the brine flows underneath the preexisting icing and new ice freezes at its outer edges. Hence the younger ice typically forms later in the season and freezes at a distance further from the spring outlet when ambient temperatures are substantially lower. However, there is also an element of new ice near the spring outlets, and growth can occur simultaneously along the perimeter and near the spring outlets. Freezing occurs much more quickly later in the winter season because the air temperatures are colder. However, the brine is insulated from the air by flowing under the existing icing until it reaches the edge of the icing and then is abruptly exposed to the cold air. Under these conditions freezing occurs much more quickly than earlier in the season and there is less time for salt and ice separation. For higher freezing rates, salts cannot flow away from the freezing boundary before being trapped within the forming ice. The salt is not incorporated into the crystalline lattice of the ice but rather is caught as inclusions or brine pockets between ice crystals. Closer to the perimeter of the icing the ice incorporates higher quantities of brine solution, thereby raising the overall ice salinity. This process of icing growth predicts an increase in salinity radially outward from the center of the icing, consistent with observation of the icing salinity. The salt content of the icing is therefore determined by the varying freezing rates encountered at different locations within the icing itself.

PHASE 2: SIMULTANEOUS ICING MELT AND BRINE FREEZE

From late April through late May the air temperatures are below the brine freezing point but above the brine eutectic point. The brine emerges from the spring outlets with temperatures between –3.5 and +6°C and freezes as it cools down below the brine freezing point of –7°C. The preexisting ice within the icing, however, begins to melt as its temperature is raised above the eutectic point of the concentrated salt solution (–22.1°C) since significant quantities of salt are incorporated into the icing deposit during Phase 1. Consequently there is simultaneous freezing of the new brine and melting of the old salty ice within the icing, and this situation leads to the very dynamic activity of the icing at this time of year.

Once air temperatures climbed above –22.1°C during the 2002 field season, the icing became extremely active with partial melting of the icing and subsequent movement of the resulting liquid solution. A long winding channel of liquid brine which had been flowing under the protective ice cover cut through the icing as shown in Figure 7. Thermal erosion was concentrated along the central channel since the ice over the channel was the first to melt within the icing due to the higher temperatures in the region of the flowing brine. The ice cover then collapsed to expose the underlying stream of liquid brine. The icing along this brine channel became very active and mobile as ice began to melt and the resulting liquid brine continued to flow.

Additional surficial brine flows also emerged as air temperatures reached –22.1°C. The seasonal frost mounds which formed as a result of the springs and were located within several meters of the spring outlet became more active. Brine began flowing from the mounds and merged with brine derived directly from the springs. New spring outlets also opened up literally overnight as the ice overlying the channels melted, and within 24 h had formed a new surficial liquid brine channel flanked by slush on either side. Even though melting rates were still minimal for the bulk of the icing, freezing rates were reduced during this time of higher ambient temperatures. Instead of the brine quickly collecting as ice, it was flowing freely through the icing as a surficial channel and upon reaching the icing perimeter, some of the brine was diluted by snow and froze. Brine flows from such various sources became more abundant once the ambient temperatures were above the eutectic temperature. Also, as the sun reached the valley floor, increased solar heating caused the icing to expand and helped keep some of the brine from freezing within the icing.

Such increased activity of the icing is understood in terms of the equilibrium-phase diagram for a sodium chloride and water system. Because the bulk ice that formed during Phase 1 was not pure water ice but rather incorporated a significant fraction of salt, parts of the icing were able to melt when the air temperature reached the eutectic temperature of –22.1°C instead of the warmer freezing point of 0°C for pure ice. The dramatic manifestation of this warming occurred as the melting and mobilization of the preexisting salty ice.

PHASE 3: TOTAL ICE MELT

Air temperatures continue to rise in the spring months and once the temperatures are consistently above the brine freezing point of –7°C in late May, the icing completely melts and moves downstream along Expedition Fiord. Icing mobilization occurs when ambient air temperatures first rise above the eutectic temperature of –22.1°C during Phase 2. However, since most of the icing has salinities far below saturation, most melting will occur during Phase 3 when temperatures reach ~–5°C. As this icing meltwater flows downstream, a lag salt deposit is left behind within Expedition Fiord where the salty icing used to exist. This salt deposit persists throughout Phase 3 because the Expedition Fiord riverbed is dry and the Expedition River is not yet flowing with glacial meltwater to wash away the salt.

PHASE 4: ICING WASHOUT

The onset of increased temperatures which begins the mobilization of the ice in Phases 2 and 3 continues throughout the late spring and summer months. Ideally the icing melts completely and throughout the summer the briny discharge could be monitored for the duration of its flow. However, this situation is complicated by the meltwaters from the nearby White and Thompson Glaciers. Water from the glacier rushes along Expedition Fiord and thermally and mechanically erodes the icing. Meltwater also flushes the springs' discharge during the summer months when temperatures rise above 0°C in early June. This meltwater washes away any remnant salt deposits from the old salty icing which has already melted. Erosion of the springs' discharge by glacier runoff has been observed over several field seasons and consistently begins by early June. Therefore any remnants of the icing which develop within the floodplain during the winter are removed by the glacial meltwater flow in the summer. Air temperatures fall below 0°C in early September and so at this time glacial meltwater ceases to flow in Expedition Fiord and the Gypsum Hill spring discharge again begins to collect within the Expedition River floodplain. The seasonal cycle of icing formation, melt, and subsequent removal then begins once again.

Summary and Conclusions

The wintertime behavior of the Gypsum Hill springs has been observed and data collected has been used to improve our understanding of the dynamics of salty ice flows. The presence of the cold perennial saline springs in the High Canadian Arctic demonstrates that liquid brine can exist even as air and ground temperatures are well below the freezing point for a significant fraction of the year.

The evolution of the icing occurs on an annual basis and can be divided into four distinct phases. The icing formation, icing melt, and icing washout processes are dependent upon ambient air temperatures. The icing deposit begins to form in late September once the spring water cools from its outlet temperature to the freezing point of –7°C (Pollard et al., 1999). The ice has a great deal of internal plumbing and grows in lateral extent via channelized brine flow under the insulating ice cover. The icing deposit had grown to its maximum size of 300 m by 700 m in late April 2002. Mass balance calculations show that the total mass of the icing is consistent with the amount of total discharge from the spring outlets. The ice is not homogeneous, however, since the furthest reaches of the ice have higher salinities. The ice farthest from the spring is generally the ice that formed last during the winter, and it will typically be more saline due to faster freezing rates induced by cold temperatures causing increased salt inclusion within the ice during the colder winter months.

As temperatures climb above the eutectic point in late April, the icing begins to melt and mobilize. The icing melts at this low eutectic temperature because of the inclusion of salt within the ice during ice formation. Temperatures rise above 0°C in early June and meltwater from the Thompson Glacier washes away any spring discharge from Expedition Fiord.

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