GEOMORPHIC AND HYDROLOGIC CHARACTERISTICS OF PERENNIAL SPRINGS ON AXEL HEIBERG ISLAND, CANADIAN HIGH ARCTIC

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Abstract
This paper documents the hydrologic and geomorphic characteristics of perennial springs on western Axel Heiberg Island in the Canadian High Arctic. Two groups of mineralized springs occur near the McGill Field Station at Expedition Fiord. The first group is 3 km from the terminus of the White and Thompson Glaciers discharging at the base of the east side of Gypsum Hill adjacent to the floodplain of the Expedition River. The second site is at Colour Peak near the head of Expedition Fiord, approximately 10 km down valley from Gypsum Hill. Each spring group consists of 20-40 outlets spread over several hundred square metres. The mineralized nature of the discharge is responsible for a range of precipitates and travertine deposits. This paper documents spring discharge, water chemistry, and mineral precipitates associated with the springs.

Introduction
Permafrost exerts a profound influence on the occurrence, movement and quality of ground water in polar regions (van Everdingen, 1990). Continuous permafrost divides hydrogeologic systems into sub and suprapermafrost aquifers with permafrost acting as an impermeable barrier, the net result being that surface hydrologic and biologic systems are supplied by ephemeral waters from suprapermafrost aquifers. Deep permafrost inhibits ground water movement to the point that springs can occur only where ground water is either (1) heated and reaches the surface through a hydrothermal talik, or (2) is highly mineralized, depressing the freezing point below the temperature of the permafrost to form a hydrochemical talik. Since perennial springs are rare in the Canadian Arctic Archipelago, little is known about their impact in cold polar environments.

At Expedition Fiord mineralized ground water discharges from two groups of springs, each consisting of 20-40 vents and seeps spread over several hundred square metres. This paper documents the nature of this perennial spring activity. The aims of this paper are threefold: (1) to summarize hydrologic characteristics of perennial springs at Gypsum Hill and Colour Peak, (2) to document their geomorphic impact on the local environment, and (3) to discuss possible origins of this spring activity.

Site description
Perennial springs occur adjacent to Gypsum Hill and Colour Peak at Expedition Fiord on west central Axel Heiberg Island (Figure 1). Axel Heiberg Island lies within the Sverdrup Basin (Thornsteinsson and Tozier, ...
The geology of the area is complex, consisting of folded and faulted sedimentary rocks ranging from Triassic to Tertiary in age. Upper Paleozoic evaporites locally intrude the overlying sedimentary/clastic rocks in a series of piercement structures.

Glaciers cover 30-35% of Axel Heiberg Island, including the Stacie and Muller Ice Caps as well as numerous outlet and valley glaciers. Small ice caps and isolated cirque and valley glaciers are also widespread. Climatological research at Expedition Fiord suggests a mean annual air temperature of -15°C, approximately 371 mm of precipitation annually and approximately 500 thawing degree days in the summer (Doran et al. 1996).

Permafrost depth has not been measured at Expedition Fiord, however a permafrost thickness of >400 m was documented in an exploration well near Mokka Fiord on the east side of Axel Heiberg roughly 60 km from the study area. Other wells in the area indicate that permafrost is generally between 400-600 m deep (Taylor and Judge 1976).

The springs at Gypsum Hill were first documented by Beschel (1963) and subsequently discussed in Hoën (1964), Allan et al. (1987), Schiff et al. (1991), Pollard (1991), Pollard and van Everdingen (1992) and Pollard and McKay (1997). Spring activity at Colour Peak has not been documented in the literature previously. Apart from Beschel’s preliminary note and Pollard’s study on frost mounds, there are no other studies that focus entirely on these springs or spring-related phenomena.

**SPRING LOCATIONS AND SETTING**

The springs at Gypsum Hill are located at 79°24'30"N, 90°43'05"W on the northeast side of Expedition River approximately 3 km downstream from the terminus of the White and Thompson Glaciers. Forty springs and seeps discharge along a 300 m long, 30 m wide band, 10-20 m ASL at the base of a steep southeast-facing slope formed by the Expedition Diapir (Gypsum Hill). Several other springs discharge in the Expedition River but cannot be mapped because of thick icing cover during winter and river flow in the summer. The springs are concentrated at the break in slope where bouldery colluvial materials overlap sandy outwash. The area immediately surrounding the springs consists of small hills separated by shallow gullies.

The Colour Peak springs are located at 79°22'48"N, 91°16'24"W on the north side of Expedition Fiord, roughly 3 km from the mouth of the Expedition River. At least 20-30 springs discharge into a series of gullies located 30-40 m ASL near the base of a south-facing slope of Colour Diapir. The springs are grouped into 3 distinct topographically controlled areas with the central group being the largest. Morainic deposits mantle the slopes immediately above the springs, while sandy beach and alluvial fan deposits cover the slopes along the edge of the fiord. The surface near the springs is composed of a combination of weathered bedrock and grey silty mud covered by a range of grey and black coloured precipitates. Spring outlets occur from 15 m up to 45 m ASL, although underwater discharge into the fiord has not been ruled out.

Both groups of springs occur in topographically and geologically similar settings but are 11 km apart and are associated with different piercement structures. The Gypsum Hill site is characterized by icings and frost mounds reflecting the interaction between spring flow and permafrost. Colour Peak, however, is marked by gullies and travertine deposits reflecting the complex interaction between water chemistry and flow conditions.

**Methods**

Temperatures of individual spring discharges were measured periodically between May and July 1997 in situ using a Cole-Parmer handheld digital thermometer with a Digi-Sense type K thermocouple. Selected outflows were also monitored for temperature using thermistors with Branker XL 800 and Campbell CR-10 data-logger systems, providing continuous records throughout the winter months. Spring water pH was measured in situ using a handheld Cole Parmer 3900-50 pH meter calibrated prior to each sampling period with pH 4, 7, and 10 standard buffer solutions. Water samples were collected using precleaned, EPA approved polyethylene bottles. The samples were maintained at ~4°C until laboratory analyses were conducted. Mineral precipitates were collected for SEM/microprobe analysis at selected points along the entire length of flow at the sites and placed into individually sealed bags. Preliminary discharge measurements were made by averaging 10 individual spot measurements channeling water flow through a portable weir and recording the time intervals required to fill a 4l container.

Gas bubbles emanating from several spring outlets were sampled by inverting 150 ml glass serum vials filled with spring water over discharging gas and allowing the bubbles to displace the water in the vial. To prevent exchange with the atmosphere the vials were fitted with flange style, red rubber stoppers and sealed with aluminum crimps under the water.

Water samples were analyzed for total ions using a Dionex 4500i gradient ion-chromatograph and a Perkin Elmer 3100 atomic absorption spectrometer. Alkalinity and conductivity were analyzed in accordance with Standard Methods for the Examination of Water and
Wastewater (AWA, 16th Edition, 1985). SEM/microprobe analyses were conducted at McGill University’s Department of Earth and Planetary Sciences using a JEOL 8900 electron microprobe. Dissolved gases were analyzed by injecting 10 or 250 µl aliquots of head space gas into a Hewlett Packard 5890II gas chromatograph (GC) fitted with a J&W Scientific molesieve column (#115 3632) and a thermal conductivity detector. Oxygen and hydrogen isotopes were analysed at the Environmental Isotope Laboratory (University of Waterloo). Stable isotopes results are reported in (18O% Vienna Standard Mean Ocean Water (ViennaSMOW).

Spring discharge samples were analysed for 3H by the electrolytic enrichment method (±0.3 T.U.) while other locally collected samples were measured using the direct count method (±8.0 T.U.).

Results

Spring Discharge

Discharge rates from the Gypsum and Colour Peak Springs are relatively low. Total discharge is estimated between 10-15 l/s at Gypsum Hill and 20-25 l/s at Colour Peak. At Gypsum Hill several outlets are located in the Expedition River and cannot be measured. Flow from individual vents is highly variable, ranging from seeps with barely detectable flow rates to maximum flows between 0.9-1.0 l/s at Gypsum Hill and 1.5-1.8 l/s at Colour Peak. Periodic measurements of flow rates made between May and July 1997 suggest that discharge from the larger springs is reasonably constant.

Observed temperatures range from 3.5 to +6.4°C at Gypsum Hill and 4.0 to +6.7°C at Colour Peak. Average temperatures are 3.9 and 3.6°C, respectively, and given that the vents with higher flow have the warmest temperatures these values could be at least 0.5°C higher if weighted by discharge. Of particular interest is the constant nature of discharge temperatures for specific spring outlets at both sites. In one case, a temperature sensor installed 60 cm into the spring vent measured only ±0.1°C variation over a 2-year period.

Spring Chemistry

Outflow pH at Gypsum Hill ranges from 6.9 to 7.4 and at Colour Peak from 7.3 to 7.9. Alkalinitities are also high ranging from 1511 mg/l for Gypsum Hill to 1064 mg/l at Colour Peak (measured as total CaCO3). Conductivity values range from 105 to 170 mS/cm for the spring water. The ionic chemistry of water from

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<th>Na</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>Cl</th>
<th>SO4</th>
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<td>62.6</td>
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<td>115</td>
<td>44079</td>
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<td>190</td>
<td>42225</td>
<td>3980</td>
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*From Table 1 in mg/L. bFrom Table 1 in mg/L. cFrom Table 1 converted to mg/L. Conductivity, pH and alkalinity were measured in the field. Alkalinity is expressed as total CaCO3.

Table 1. Composition of the spring waters at Gypsum Hill and Colour Peak in addition to other local sources

Table 2. Isotope data for the spring waters at Gypsum Hill and Colour Peak in addition to other local sources

<table>
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<td>Schiff et al. (1991)a</td>
<td>-</td>
<td>51 to 96c</td>
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<td><strong>Crusoe Lake</strong></td>
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<tr>
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<tr>
<td>Schiff et al. (1991)a</td>
<td>-</td>
<td>15c</td>
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*From Table 3. aAccuracy of ± 0.3 T.U. bAccuracy of ± 0.3 T.U. cAccuracy of ± 8.0 T.U. 1 T.U. defined as 3H/³H x 10^-3.
both springs is characterized by very high dissolved solids concentrations (Table 1). An interesting aspect of the chemistry is that if all the ions are normalized to Na+, the water has the same basic signature as seawater. Beschel (1963) noted a similar pattern.

Samples were collected from both Gypsum and Colour Peak springs for oxygen and hydrogen isotope analyses (Table 2). $\delta^{18}O$ values for the Gypsum Hill and Colour Peak springs are considerably lighter than water from Colour and Crusoe Lakes suggesting recharge during a period of colder climate. Tritium ($^3H$) concentrations for spring discharge are much lower than values from other local sources indicating that the spring waters have been out of contact with the atmosphere since before 1952. Schiff et al. (1991) reports sulphate isotopic signatures of $^{34}S$ 15-24% for Gypsum Hill, typical of marine sulphates.

Gas released as bubbles were analyzed from a spring located at the Gypsum Hill site (Figure 2). The gas was analyzed for $N_2$, $O_2$, $CO_2$, $CH_4$, and $H_2S$. $O_2$ was undetected in the samples indicating that air had not leaked into the sample containers prior to analyses. The gas was composed primarily of $N_2$ with 0.4% $CH_4$ and 0.2% $CO_2$. The absence of $H_2S$ within the samples is surprising since there is a noticeable smell near the springs. This may be an indication that sediments next to the springs may be a more important location for the production of $H_2S$. Additional measurements of the dissolved gases emanating from the springs will be necessary in order to better understand the origin and fate of the groundwater.

**SPRING VENT MORPHOLOGIES**

Three basic vent structures are observed at the spring outlets: pools, seeps and pipes. Pool-type vents occur only at Gypsum Hill and are marked by shallow circular pools 1-2 m wide and 20-50 cm deep. Loose black sand and gravel from which water and gas bubbles up, cover the pool floor. This upwelling maintains several small fountains of sand that are disrupted by embulations of large gas bubbles. In all cases the pools are within the Expedition River floodplain and a small channel flows from the downslope side. Seeps are points where saturated sediments yield a very slow and continuous flow of water. They are usually shallow depressions open on one side and marked by a black stain. The most common vents have pipe-like structures; some are situated in steeply sloping ground while others occur in gullies or on flat surfaces. They usually have a hard precipitate that defines the outlet and in a few cases they occur in flat lying ground where they produce a fountain of water 3-4 cm high.

**MINERAL PRECIPITATES**

Mineral precipitates occur in association with spring activity at both Gypsum Hill and Colour Peak ranging from simple salt crusts to complex channels, terraced mounds, and cascade structures. In some cases, the travertine develops distinct forms such as elevated channels and tunnels; however at other locations, mineral precipitates are thin and poorly developed. Most of the structures observed satisfy morphologic criteria described by Pentecost and Viles (1994) and Chafetz and Folk (1984), however some are sufficiently different that they lie outside known classification criteria. Precipitates are mainly black to pale grey in colour, and in a few locations are orange and yellow. They display a wide range in hardness depending on their structure and mineralogy. Preliminary microprobe analysis shows these precipitates to be composed of calcite and gypsum.

Precipitate morphologies at the springs can be generally defined as (1) hard channel and (2) terraced mounds. Hard channel precipitates are the most dominant forms of travertine observed at the Gypsum Hill and Colour Peak springs (Figure 3). They commonly develop into U-shaped channels with steep sides and a rounded bottom. Water depths range from centimetres to decimeters. Where slope angle is low ($5-15^\circ$), the channels are generally wide and flat, contrasting with more deep and narrow channels observed in steeper sections. Precipitate constantly submerged under water has a shiny black colour, and is extremely smooth, hard and brittle. Rounded steps are observed along the base of the channel, formed in response to changes in slope.

Springs with the greatest discharge produce the largest mineral precipitates and commonly develop to form elevated channels. The most extensive examples of these channels occur at Colour Peak. In addition, sections where the mineral precipitate completely encompasses the water to form tunnels are observed. These tunnels develop both entirely within the soil and above the surrounding substrate. Precipitate wall thickness ranges from several millimetres to centimetres.
A second form of travertine referred to as terraced mounds or barrages (Pentecost and Viles, 1994) are commonly observed at large breaks in slope where the water fans outwards and water depths decrease. The mounds consist of rimstone pools (Figure 3) ranging in size from 5-15 cm in lateral dimensions and 25 cm deep. Each flatfloored, shallow pool receives water from above. The travertine forms a raised rim around the edge of each pool due to mineral precipitation as water flows over the pool edge and down the vertical side to the next terrace. Travertine also accumulates on the floor of each terrace or pool, much of it as microbumpy, circular masses (Chafetz and Folk, 1984).

In May 1997, individual crystals were found coating the pools and terraces. These crystals, white in colour, measured 0.2-0.5 cm in length, and were most commonly observed standing upright along one edge. These submerged crystals had degraded by July 1997 as a result of higher surface water temperatures due to increasing in solar radiation inputs. However because of short warm weather periods experienced in the High Arctic, mineral precipitation rates exceed mineral dissolution rates leading to net mineral accumulations.

**Discussion**

There is limited information on saturated ground water flow in thick continuous permafrost, particularly in the High Arctic. It is generally assumed that thick permafrost, common in the Arctic islands, provides an effective aquitard preventing ground water discharge and resulting in the separation of ground water into sub, intra and suprapermafrost systems (Williams 1965; Williams and van Everdingen, 1973). Determination of ground water source is therefore a priority of this research. At this stage we must consider a number of possible ground water sources and recharge mechanisms, including: [1] ancient ground water, possibly relict sea water, rising under artesian pressure from a deep confined subpermafrost aquifer, [2] ancient or juvenile geothermal origin, [3] juvenile water derived from local runoff and seasonal infiltration into the open structure of the diapir, and [4] direct linkage with surface water bodies through open taliks (e.g. Colour Lake). A number of complimentary lines of evidence support the possibility that both spring groups are ancient ground water derived from a deep subpermafrost aquifer, possibly relict seawater. The high concentrations of dissolved ions in these waters would normally require a long residence time, as is confirmed by isotopic analyses. The chemistry also points to a possible relict seawater origin. The gypsum and anhydrite deposits that comprise diapiric structures are marine in origin; thus chemical indicators may also indicate a strong link between spring water, dome structures and subpermafrost ground water. The domes not only provide a mechanism for ground water accumulation, but also provide structures that could enhance the formation of a piezochemical talik. One of the most significant geomorphic impacts of the spring chemistry is the depression of the freezing point of the system, which alters the basic cryological conditions controlling northern hydrologic systems. Freezing experiments were conducted on water samples collected from both Gypsum Hill and Colour Peak to determine the degree to which observed high concentrations of dissolved solutes effectively depress the freezing point of the waters. Experiments involved sequentially dropping the temperature of 4 litre samples from +5°C to -20°C at various cooling rates under constant agitation. Preliminary results suggest that surface freezing of the waters begin between -7 and -10°C.

**Conclusions**

The perennial springs occurring near Expedition Fiord are the only features of this type reported in the Canadian High Arctic. These springs differ dramatically from other arctic hydrologic phenomena including the ground water seepage that has been described in the Nanisivik mine on northern Baffin Island and the
Polaris mine on Little Cornwallis Island (Weyer 1981), and the ephemeral subglacial meltwater discharge which is common around many high arctic glaciers. Preliminary field work has revealed a number of interesting and significant facts; [1] constant and perennial discharge occurs at two locations in the Expedition Fiord area of west central Axel Heiberg Island; [2] discharge temperatures tend to be constant for most vents and range from 4.0 and +6.7°C between vents for both spring groups; [3] spring water is highly mineralized, its salinity is roughly 3X seawater, and when dissolved ions are normalized to Na+, the spring water from both sites displays a marine signature, also supported by sulfurs which is common around many high arctic glaciers. Preliminary field work has revealed a number of interesting and significant facts; [1] constant and perennial discharge occurs at two locations in the Expedition Fiord area of west central Axel Heiberg Island; [2] discharge temperatures tend to be constant for most vents and range from 4.0 and +6.7°C between vents for both spring groups; [3] spring water is highly mineralized, its salinity is roughly 3X seawater, and when dissolved ions are normalized to Na+, the spring water from both sites displays a marine signature, also supported by sulfur isotopic data (Schiff et al. 1991); [4] odoriferous gases associated with discharge are predominantly N₂, and oxygen is absent.

References


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