Hyper-saline spring dynamics and salt deposits on Axel Heiberg Island, Nunavut

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ABSTRACT
On Axel Heiberg Island in the Canadian High Arctic, low temperature perennial saline springs occur despite cold polar desert conditions marked by a mean annual air temperature close to -20°C. Distinct large scale salt deposits are associated with two hyper-saline springs. This research characterises the geomorphology and geochemistry of two hyper-saline springs on Axel Heiberg Island: the first is located at Wolf Diapir (79°07'23"N; 90°14'39"W), the deposit at this site resembles a large conical mound (2.5 m tall x 3 m diameter). The second is located at Stolz Diapir (79°04'30"N; 87°04'30"W). In this case a series of pool and barrage structures staircase down a narrow valley for approximately 800 m (several pools are up to 10 m wide x 3 m deep). A detailed methodology and preliminary results are presented.

RÉSUMÉ
De nombreuses sources d'eaux salées ont été identifiées sur l'île Axel Heiberg (Haut-Arctique canadien) et ce, malgré un climat désertique polaire et une température moyenne annuelle de -20°C. Les dépôts de sel sur l'île sont associés à deux sources d'eaux hyper salées. Cette recherche vise à caractériser la géomorphologie et la géochimie de ces deux sources d'eaux salées. La première source est caractérisée par un grand monticule conique composé de sel (2,5 m de hauteur et 3 m de diamètre) et se situe à Wolf Diapir (79°07'23 "N; 90°14'39" O). La deuxième source est située à Stolz Diapir (79°04'30 "N; 87°04'30" O) et se caractérise par une série de barrages et de bassins en forme d'escaliers dévalant une vallée étroite sur une distance de 800 m (plusieurs des bassins mesurent jusqu'à 10 m de largeur et 3 m de profondeur). La méthodologie et les résultats préliminaires sont présentés dans cet article.

1 INTRODUCTION

The occurrence of perennial springs is rare within continuous permafrost regions. Permafrost is the thermal state of ground material remaining below 0°C for at least two consecutive years. Its presence impacts the occurrence, movement and quality of groundwater and results in a distinctive hydrogeologic structure unique to Polar regions (Prowse and Ommaney, 1990). Cold continuous permafrost is largely impermeable, and therefore groundwater movement must rely on unfrozen zones known as taliks for springs to occur. Types of taliks include hydrothermal taliks (where water temperature is maintained above 0°C usually as a hot spring) and hydrochemical taliks (where highly mineralized groundwater remains unfrozen at temperatures below 0°C).

Travertines and tufas are common spring deposits occurring in non-permafrost locations around the world (well known examples include the Pamukkale Travertine Terraces in Turkey and the tufa towers at Mono Lake, California). These landforms are generated by the surface accumulation of precipitating carbonate minerals (as opposed to dissolution or erosion; Hammer, 2008) and take on a variety of morphologies (e.g. conical mounds, stalactites, stalagmites, spheres, terraces and steps).

On Axel Heiberg Island, Nunavut a series of salt formations occur at two sites that morphologically resemble travertines and tufas but do not contain carbonate minerals. These deposits are composed predominantly of salt minerals and are therefore considered travertine or tufa analogues.

This study is part of a larger investigation on the occurrence and the biophysical significance of perennial springs in the Canadian High Arctic (e.g. Pollard et al. 1999; Omelon et al. 2006**;** Andersen et al. 2002**,** Pollard, 2005**;** Pollard et al. 2009**;** Niederberger et al. 2010) and focuses on two relatively unstudied sites on Axel Heiberg Island. The aims of this paper are: (a) to outline the mix-methods approach being used to characterize the geomorphology of structures being formed by hyper-saline spring flow at Stolz and Wolf Diapirs; and (b) to present preliminary findings on the geochemistry and morphologic characteristics of both spring systems. This research hypothesizes that the extreme cold winter air temperatures cool water temperatures triggering the rapid precipitation of various salt minerals leading to the formation of the salt deposits.

1.1 Study Area

Axel Heiberg Island is located in an area of continuous permafrost within the Canadian High Arctic (figure 1). Permafrost depth was measured between 400 and 600 m at a series high Arctic oil and gas exploration wells (Pollard et al., 2009); the thickness of the active layer is between 40 cm and 60 cm.

The climate is polar desert with dry, cold winters and cool summers. Historical meteorological data from the Eureka Weather Station (located on Ellesmere Island at 79°59'N; 85°56'W; the closest weather station to these sites) provides mean annual, January and July temperatures of -19.7°C, -36.1°C and +5.4°C with extreme minimum air temperatures frequently reaching -55°C (Pollard et al., 2009). Long term measurements at the McGill Arctic Research Station (MARS) offer a mean annual air temperature of -15.5°C (Andersen et al., 2008). Mean annual precipitation recorded at the Eureka Weather Station is roughly 64 mm with over half of the precipitation occurring as snow (Pollard and Bell, 1998).

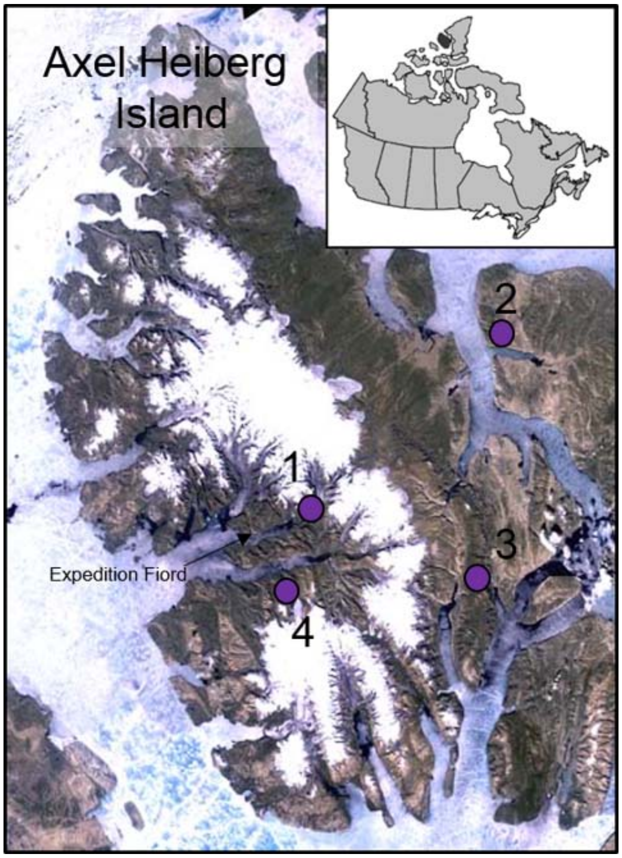

Figure 1. A false colour Landsat mosaic of Axel Heiberg Island showing ice caps, glaciers and fiords with map insert modified from Grasby et al., 2003). Purple circles indicate the location of the following: (1) McGill Arctic Research Station (M.A.R.S); (2) Eureka Weather Station on Ellesmere Island; (3) Stolz Diapir study site and (4) Wolf Diapir study site (also known as Lost Hammer).

The Eureka Sound fold belt on Axel Heiberg Island contains the thickest Mesozoic sequence of the Sverdrup basin. The Sverdrup Basin is a 12-15 km thick sedimentary basin composed of varying marine lutaceous and non-marine arenaceous deposits ranging from lower Pennsylvanian to early Tertiary in age (Pollard, 2005**;** Jackson & Harrison, 2006). Orogenic activity during the Tertiary produced the mountainous topography as well as widespread diapirism around the basin.

Diapirs are "*masses of salt that has flowed ductilely and appear to have discordantly pierced or intruded the overlying sedimentry-clastic rocks*" (Hudec & Jackson, 2012). At least 100 diapirs have been identified within the Sverdrup basin, of these about 60 are exposed including 46 on Axel Heiberg Island (Thorsteinsson, 1974; Jackson & Harrison, 2006). The Island has the second greatest concentration of exposed diapirs in the world, second to Iran (Harrison and Jackson, 2014). Stolz diapir, located close to Whitsunday Bay, is the only diapir on the island with an exposed halite (NaCl) core **(**Hugon & Schwerdtner, 1982). The source material for the diapirs within the Sverdrup Basin is the Otto Fiord Formation, an evaporative belt 800 km long and 240 km wide where evaporites accumulated during Carboniferous rifting (Thorsteinsson, 1974; Davies & Nassichuk, 1975; Jackson & Harrison, 2006).

1.2 Site Descriptions

Stolz Diapir is located at 79°04'30"N; 87°04'30"W at the head of Whitsunday Bay on the eastern side Axel Heiberg Island. A series of salt encrusted pool and barrage structures staircase down a narrow valley for approximately 800 m. At the mouth of the valley, the salt deposit forms a salt pan within the Whitsunday River floodplain. Perennial spring discharge flows into the snowmelt fed Whitsunday River which flows into the Arctic Ocean via Whitsunday Bay.

There have been sporadic observations of the Stolz Diapir spring but few results have been published. Hugon and Schwerdtner (1982) note the presence of a spring within the context of their study of the geologic structure of Stolz Diapir. It is similarly mentioned in Schwerdtner and Van Kranendonk (1984). The only paper that notes the presence of unusual salt structures and the perennial nature of the spring is Pollard (2005).

The Wolf Diapir spring is located at Strand Fiord on the Western side of Axel Heiberg Island at 79°07'23"N; 90°14'39"W. The spring at Wolf Diapir was discovered by Pollard in 2004 during an aerial survey in the Strand Fiord area and first reported in the literature in 2010 microbiological study by Niederberger *et al*. The salt deposit at this site resembles a large hollow cone-shaped mound 2.5 m tall and 3 m in diameter at the outlet and a large 100 m by 15 m salt pan down slope whose size varies each year (Pollard, personal communication). This site is also referred to as Lost Hammer or Wolf Spring (e.g. Harrison et al. 2008**;** Niederberger et al. 2010**;** Lay et al, 2012; Battler et al., 2013).

2 METHODS

The research design for this study consists of three parts: (1) field-based morphologic measurements and sampling (deposits and spring water); (2) laboratory based geochemical and mineralogical analyses; and (3) the application of an equilibrium chemical thermodynamic model to simulate mineralogical processes.

2.1 Fieldwork

This paper reports on work in progress and includes an overview of recent summer and late winter sampling programs designed to confirm the perennial nature of spring discharge and the seasonal pattern of geomorphic processes.

Spring water samples were collected using 250 mL acid washed polyethylene bottles. Summer sample locations were chosen to represent changes at regular downstream intervals. At the Stolz site samples were also collected from the inflow stream located on the opposite side of the diapir as well as perennial snow deposits that feed the inflow stream in addition to the spring outlet, the downstream halfway point, the valley mouth and the salt pan on the Whitsunday floodplain (figure 2). Winter samples were collected from the outflow and most of the active pools. Samples for the Wolf Diapir site (figure 3) included: the outlet and the spring channel 5 m away from the outlet. Water samples were collected at the same locations during each field season. The location of the main spring outlet at the Stolz site migrates between summer and winter seasons and from one year to the next, in July 2014 the outlet was covered by a recent debris slide so a water sample was taken at the first point of exposed flow down valley (this sample is considered to be from the summer outlet position; figure 2).

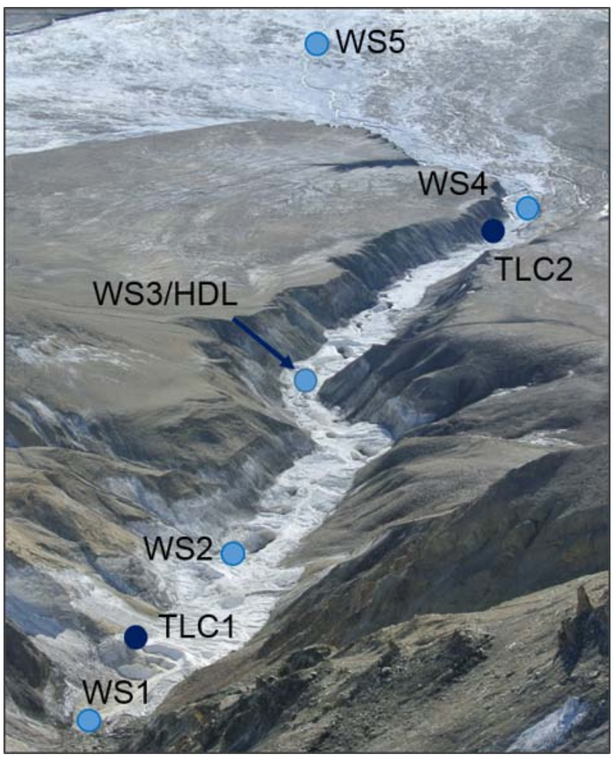

Figure 2. Water samples (WS), time lapse cameras (TLC) and Hobo data logger (HDL) locations at Stolz Diapir site. WS1 represents the winter outlet, WS2 is the summer outlet, WS3/HDL is the halfway point of the deposit for water sampling and the location of the hobo data logger, WS4 is the valley opening and WS5 is the salt pan within the floodplain.

Figure 3. Water sample locations at Wolf Diapir site. WS1 (Water Sample 1) represents the outlet, and WS2 is the spring channel located 5m away from the outlet.

Mineral (salt precipitate) samples were collected to reflect as full a range of precipitate locations, structures and settings within the spring systems. Samples were collected aseptically and placed in sterile Whirl-Pak® sample bags. July samples were transported and stored at 5-10°C while winter samples were stored and shipped at -20°C.

A series of 4-channel Hobo® data loggers (sensor accuracy is ±0.25°C) were used to collect air and water temperatures at both spring locations. At the Stolz Diapir site the logger sensors were installed at different levels within the flow system to record the air temperature and changing water levels in one of the lower pool and barrage structures (Figure 2). Initially all the sensors record air temperature but as the pool fills during winter 3 sensors sequentially deviate from the air temperature providing a time series record of water level change (figure 4B). A second 4-channel Hobo® data logger was located next to the spring to record air and shallow soil temperatures. At Wolf Diapir a logger was installed inside the salt mound at the spring outlet to collect temperatures in a vertical profile with each sensor spaced 65 cm apart. These loggers were installed in July and are collecting a full cycle of spring activity. Each logger was programmed to record temperatures every 6 hours.

Two time-lapse cameras (Bushnell Trophy Cam) installed at Stolz diaper are collecting daily (at solar noon) images of surface hydrologic processes. These cameras have a good reliability record and operate for approximately one year on one set of lithium batteries, even under extreme cold temperatures (figure 2). One camera was installed at the spring outlet and the second lower in the salt structure downstream from the temperature logger (figure 4A). Both cameras are oriented in the direction of spring flow.

Figure 4. Set up for (A) the time lapse cameras and (B) the Hoho data logger, see figure 2 for exact locations within the Stolz deposit.

2.2 Laboratory Analyses

Water samples were analyzed for major ion concentrations (Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{2-}, NO_3^- and PO_4^{3-}) by Ion Chromatography using a Dionex DX-00 Ion Chromatography in the Department of Materials Engineering at McGill University. Hyper-saline samples have to be diluted 100x for Ca^{2+}, Mg^{2+}, K^+ ions to be detected and 1000x to detect Na^+ and Cl^- ions. Neither NO_3^- nor PO_4^{3-} were detected in any of the water samples analyzed.

Bulk analysis of mineral precipitates are analyzed by X-Ray diffraction using a Bruker D8 Discovery X-Ray Diffractometer in the Department of Materials Engineering at McGill University. Mineral sample preparation involves oven drying for two days and then grinding the sample into a fine powder.

2.3 Chemical Modelling

This study uses Frezchem, a FORTRAN version of the Spencer-Møller-Weare model to calculate the changing composition of solids and liquids under freezing conditions. Other water chemistry models are capable of calculating compositions only above 0°C. Frezchem uses chemical thermodynamic principles over a -60°C to +25°C temperature range and Pitzer equations (specific ion interaction equations) to calculate activity coefficients for water and ions in complex solutions and at high ionic strengths (Marion, 1997).

Currently there are 16 versions of the model available (http://www.dri.edu/frezchem) with different features and environmental parameters options for each version. The model's author recommends using earlier more robust versions if features added in the later configuration are not required (Giles Marion – personal communication). In this study version 5.2 was employed because it is parameterized for Na-K-Mg-Ca-Cl-SO_4-H_2O systems, which is what was needed in this study. Table 1 lists the minerals calculated by this version of the Frezchem model.

Table 1. Minerals in Frezchem model v. 5.2 (Marion, 1997)

	Mineral formula		Mineral formula
1.	$Na_2SO_4*10H_2O$ (cr) (mirabilite)	16.	H_2O (cr, I) (ice)
2.	Na_2SO_4 (cr) (thernadite)	17.	$Na_2SO_4*MgSO_4*4H_2O$ (cr)
3.	K_2SO_4 (cr) (arcanite)	18.	$CaSO_4*2H_2O$ (cr) (gypsum)
4.	$MgSO_4*6H_2O$ (cr) (hexahydrite)	19.	$CaSO_4$ (cr) (anhydrite)
5.	$MgSO_4*7H_2O$ (cr) (epsomite)	20.	$MgSO_4*12H_2O$ (cr)
6.	$MgSO_4*K_2SO_4*6H_2O$ (cr) (picromerite)	21.	$Na_2SO_4*3\ K_2SO_4$ (cr)
7.	NaCl (cr) (halite)	22.	$CaCO_3$ (cr) (calcite)
8.	$NaCl*2H_2O$ (cr) (hydrohalite)	23.	$MgCO_3$ (cr)
9.	KCl (cr) (sylvite)	24.	$MgCO_3*3H_2O$ (cr)
10.	$CaCl_2*6H_2O$ (cr) (antarcticite)	25.	$MgCO_3*5H_2O$ (cr)
11.	$MgCl_2*6H_2O$ (cr) bischofite)	26.	$CaCO_3*6H_2O$ (cr)
12.	$MgCl_2*8H_2O$ (cr)	27.	$NaHCO_3$ (cr)
13.	$MgCl_2*12H_2O$	28.	$Na_2CO_3*10H_2O$ (cr)
14.	$KMgCl_3*6H_2O$ (cr) (carnallite)	29.	$NaHCO_3*2H_2O$ (cr)
15.	$CaCl_2*2MgCl_2*12H_2O$ (cr) (tachyhydrite)	30.	$NaHCO_3*Na_2CO_3*2H_2O$ (cr)

Our water chemistry data (table 2) was used to determine the sequence of mineral precipitates for both the Wolf Diapir and Stolz Diapir spring systems. Each sample (chemistry) was run through the model twice, first simulating evaporation precipitation at +7°C (the average summer temperature) and then using the freeze-drying precipitation mechanism over a temperature range of +15°C to -45°C). To ensure the functionality of the model, input water chemistry had to be charge balanced using chloride ions requiring the addition of chloride ions to each sample.

3 RESULTS

Pollard has made general observations of the Stolz Diapir site since 1995. Focused research for this study began in 2014. The following presents results based on one year of observation along with prior observations made by Pollard for comparison. With these results we have been able refine our sampling and analytical protocols.

3.1 Spring Discharge & Chemistry

Discharge measured at Stolz Diapir is quite variable ranging from 11.33 *l*/s in July 2014 to as high as 30.5 *l*/s in June 2008. Discharge at Wolf Diapir forms a small pool (1 m in diameter) hidden within the salt mound and could not be measured directly. Based on the amount of flow in seeps from the side of the mound within the salt deposit downstream it is estimated to be only a few (1 to 2) litres per second. Battler et al. (2013) report a discharge of 4-5 *l*/s however based on our observations (since 2011) this seems to be an overestimation.

Observed water temperatures at the spring outlets are consistently between -1°C and -2°C at Stolz and approximately -4.3°C at Wolf regardless of air temperature. Spring temperatures downstream reflect either warming or cooling by ambient conditions. Of particular significance was a liquid water temperature of -24.5°C in the salt pan in April 2007.

Table 2. Summer outlet chemistries for spring sites located a Stolz Diapir and Wolf Diapir.

	Stolz Spring Outlet	Wolf Spring Outlet
Temperature	-1.3°C	-4.3°C
pH	7.06	6.87
Ca^{2+} (g/L)	1.10	1.50
K^{+} (g/L)	0.39	0.36
Mg^{2+} (g/L)	0.07	0.35
Na^{+} (g/L)	132.84	108.71
Cl^{-} (g/L)	156.37	126.38
SO_4^{2-} (g/L)	4.18	5.28

Water chemistry for outlets at both sites is presented in table 2. Figure 5 is a piper diagram that includes all water samples collected at both sites. The discharge at both sites is classified as hyper-saline. The Total Dissolved Solids (TDS) within the water exceeded the range of the YSI 63 field conductivity meter (>999 ppm) and pH values ranged 6.70-8.16 at Stolz and 6.87-7.18 at Wolf.

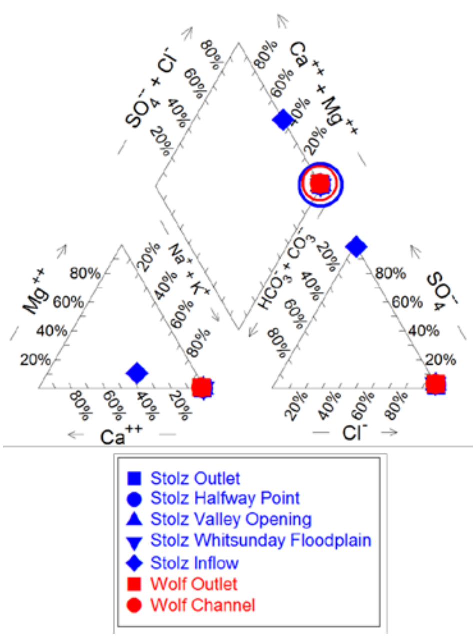

Figure 5. Piper diagram of all summer water samples collected at both sites

3.2 Mineral Precipitates

The salt precipitates at both sites form thick white crystalline mineral deposits. At Stolz, the morphology of the deposit and mineral precipitates gradually changes downstream from the outlet. The upper barrage structures near the outlet are characterized by loosely packed cubic crystals and hexagonal pseudomorphs in the summer and are the largest barrage structures documented, measuring approximately 30 m in width and 2 m in height. The pools that form behind the barrage structures during the winter vary in size year to year and their depth is usually two to three meters (figure 6). From the halfway point downstream, a fine white powder forms a light dusting on the surface of the deposit and is present all the way into the Whitsunday Bay Floodplain. Precipitates become progressively more compact with increasing distance away from the outlet. Smaller barrage structures (a few meters in length and approximately 30 cm in height) occur in this part of the valley. Within the valley opening a distinct hard crustal layer develops (<1 cm thick), with a mixture of white precipitates and sediments mixed in. In addition, the deposit itself is thicker (approximately 2.5 m) in the upper reaches of the valley and gradually thins out until the plain is reached.

Figure 6. Pools formed during winter at the Stolz site. The pool furthest away measures 12 m x 28 m and the pool in front measures 11.5 m x 26 m. Each pool is contained by a barrage structure (travertine/tufa analogue) composed of salt.

At Wolf Diapir, the cone-shaped deposit is extremely hard and rigid; and is covered with the same fine white powder as seen at Stolz Diapir. An elevated (~50 cm thick) terrace formed from accumulated salt occurs along the direction of spring flow (61 m x 22m) is also highly compact. In the spring surface channels, white crustal layers of a few millimetres to centimeters thick are present covering underlying gravel sediments (similar to Stolz). These crystals form distinct clusters of individually precipitated crystals resembling a cauliflower-like floret (figure 7).

Preliminary simulations with Frezchem using water chemistries from both sites as inputs show that the mineralogy is dominated by various salt minerals. Halite (sodium chloride NaCl) is simulated most abundantly, thernadite (sodium sulfate (Na_2SO_4), mirabilite (sodium sulfate decahydrate Na_2SO_4*$10H_2O$) and gypsum (calcium sulfate CaSO.$2H_2O$) also precipitate.

4 DISCUSSION

Perennial springs within areas of thick continuous permafrost like within the Canadian High Arctic are rare and their hydrogeology remains poorly understood. A priority of our broader research program is the determination of the groundwater source and its flow dynamics. The Stolz Diapir spring is unique in comparison with the other springs on the island in that it is the only spring where the groundwater source is known. A seasonal stream fed by snowmelt flows from the Joy Range and flows directly into a solution cavity on the western side of the diapir approximately 400 m from the spring outlet on the east side of the diapir and 40 m higher (figure 8) The inflow water is fresh but is highly mineralized (hyper-saline) when it emerges from the outflow, reflecting its interaction with the salt core of the diapir (figure 5). Extensive salt karst occurs marked by sink holes and collapse structures exposed on the surface of the diapir. Stolz Diapir is the only dome structure on Axel Heiberg Island with an exposed halite core and its water chemistry further validates this (Figure 5 and table 2).

Figure 7. Mineral precipitates along the stream channels at the Wolf Diapir Spring site, 20 mm camera lens cap for scale.

Another unique feature of both study sites is the presence of extensive thick salt accumulations and the unique morphology these minerals develop similar to structures more typical of carbonate travertines and tufas. The boundary between tufa and travertine forms is unclear. Pentecost and Viles (1994) distinguish the two based on degree of lithification, while Ford and Pedley (1996) differentiate tufas based on low Mg-content and temperature of the water it precipitates in regardless of the degree of cementation. The tufa and travertine classification debate is ongoing. Table 2.1 from Capezzuoli et al. (2014) offers a summary of main distinguishing characteristics between travertines and tufas. Regardless of how travertines and tufas are classified, the salt dominated deposits on Axel Heiberg Island cannot be classified since they lack the diagnostic mineralogy (namely calcium carbonate minerals). The occurrence of morphologically-similar structures at Stolz and Wolf Diapirs might justify recognition of a new sub-classification of travertine and tufas deposits. It seems probable that hyper-saline flows of ground water under extreme cold constrained by suitable slopes could be analogous to carbonate-rich hydrothermal groundwater systems. Nevertheless the factors controlling the formation of these deposits is not entirely understood, this study progresses and the analysis of more data continues new conclusions could be drawn to understand how these deposit form and could be comparable to carbonate travertine and tufas.

Figure 8. Oblique aerial view of Stolz diapir showing the location of the inflow stream and the outlet on the other side that where the salt precipitate occurs. The water of the inflow is fresh whereas the water in the outlet is highly mineralized (dominated by sodium and chloride ions) indicating contact with evaporates within the diapir (circled in black).

Recent observations based on data collected during late winter (i.e. under extreme cold conditions) indicate a strong seasonal pattern to the geomorphic processes associated with these features. During winter freezing concentration of these brines lead to rapid precipitation and deposition of salt minerals causing dam-like barrage structures that produce deep pools, as the pools overflow the sequence cascades down the valley producing a sequence of pool and barrage structures. Similarly the lower flow rates at Wolf diapir lead to the gradual growth of a rim structure that over time has grown into a cone-shaped mound. Subsequent overflow has added additional salt layers to the structure growing much like a shield volcano. Furthermore, winter temperatures at both sites appear to decrease enough for low temperature meta-stable hydrated salt minerals to occur although it is yet unclear exactly which minerals form, and in what order or their role in forming the travertine/tufa-like deposits. During summer both systems are dominated by solution driven erosion of the deposits that in some cases cause entire barrage structures to collapse only to be rebuilt the following winter.

5 CONCLUSIONS

Unlike other perennial springs sites identified on Axel Heiberg Island (e.g. Gypsum Hill and Colour Peak) the springs located at Wolf and Stolz Diapirs form large scale salt dominated deposits. Following the methodology outlined in this paper we are building a case for a unique winter dominated system of freezing crystallization of salt minerals that could be applicable and to other geomorphic systems. The synergistic benefit of this mixed methods approach combining cold season field measurements and sampling; laboratory analyses and computer simulations provides the basis for a realistic geomorphic interpretation of processes and landforms that might otherwise be overlooked. Preliminary results of this research have revealed some interesting facts: (1) discharge temperatures at outlets remain constant despite air temperatures; (2) cold winter temperatures and hyper-saline groundwaters are driving the seasonal precipitation of various salt minerals leading to large scale deposits; (3) springs waters become highly mineralized from contact with the evaporates that form the geologic core of these diapirs; (4) that freezing crystallization of hyper-saline brines lead to the formation of features that are more typically seen in carbonate hydrothermal systems.

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