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Report of Activities for High Arctic Large Igneous Province (HALIP) – GEM 2 Western Arctic Region Project: Bedrock Mapping and Mineral Exploration

M.-C. Williamson (Editor)

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Report of Activities for High Arctic Large Igneous Province (HALIP) – GEM 2 Western Arctic Region Project: Bedrock Mapping and Mineral Exploration

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HALIP REPORT OF ACTIVITIES:
BEDROCK MAPPING AND MINERAL EXPLORATION

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FOREWORD

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FOREWORD

The Geo-mapping for Energy and Minerals (GEM) program[1] is laying the foundation for sustainable economic development in the North. The Program provides modern public geoscience that will set the stage for long-term decision making related to investment in responsible resource development. Geoscience knowledge produced by GEM supports evidence-based exploration for new energy and mineral resources and enables northern communities to make informed decisions about their land, economy and society. Building upon the success of its first five-years, GEM has been renewed until 2020 to continue producing new, publically available, regional-scale geoscience knowledge in Canada's North.

During the summer 2015, the GEM program has successfully carried out 17 research activities that include geological, geochemical and geophysical surveying. These activities have been undertaken in collaboration with provincial and territorial governments, northerners and their institutions, academia and the private sector. GEM will continue to work with these key collaborators as the program advances.

OBJECTIVES

The volcanic terrain of Cretaceous age exposed in the east-central Sverdrup Basin, known as the Canadian portion of the High Arctic Large Igneous Province (HALIP), is the focus of an activity approved for the second phase of NRCan's Geo-Mapping for Energy and Minerals Program (Western Arctic Region Project).

The main objective of this activity, from 2014 to 2017, is to identify areas on Axel Heiberg Island and Ellesmere Island that show a high potential for Ni-Cu-PGE deposits (Figure 1). Specific activities include (1) detailed mapping of sills and dykes not included in current 1:250 000 scale geological maps; (2) the collection of samples for mineralogical and geochemical studies; (3) the development of geological models and a regional stratigraphic and structural framework to identify volcanic-intrusive complexes that could host nickel sulphide deposits; and (4) the transfer of data, maps and knowledge to decision-makers and stakeholders in northern communities, government, and industry.

2015 FIELD SEASON

This report highlights the results of field work conducted by three teams based out of the Eureka Weather Station in July 2015. Bédard et al. report field observations on five sets of HALIP–related intrusions and wallrocks that were sampled as part of a regional study of geochemical signatures indicative of Ni-Cu-PGE exploration potential. Williamson et al. describe the highlights of field investigations on the Strand Fiord Formation flood basalts and on volcanic-intrusive complexes located in western and southern Axel Heiberg Island. The paper by Neville et al. presents the results of late Mesozoic stratigraphic studies conducted in eastern Axel Heiberg Island. Finally, Thomson and Copland describe a collaborative research proposal that involves mapping of bedrock in the vicinity of White Glacier, Expedition Fiord.

As highlighted in this field report, the HALIP activity is providing a new metallogenic framework for the study areas in the Western Arctic Region, through thematic studies of the stratigraphy, structure, petrology, geochemistry and geochronology of Cretaceous igneous rocks. This knowledge is required to develop reliable models for Ni-Cu PGE and hydrocarbon potential, and to clarify the role of diapiric evaporites in the history of the east-central Sverdrup Basin. In addition to bedrock mapping and sampling of HALIP rocks, a detailed knowledge of the timing and extent of magmatic events in the Canadian HALIP is essential to develop models of Ni-Cu-PGE prospectivity and thermal models for petroleum maturation to be tested against the results obtained in the circum-Arctic HALIP.

[1] http://www.nrcan.gc.ca/earth-sciences/resources/federal-programs/geomapping-energy-minerals/10904

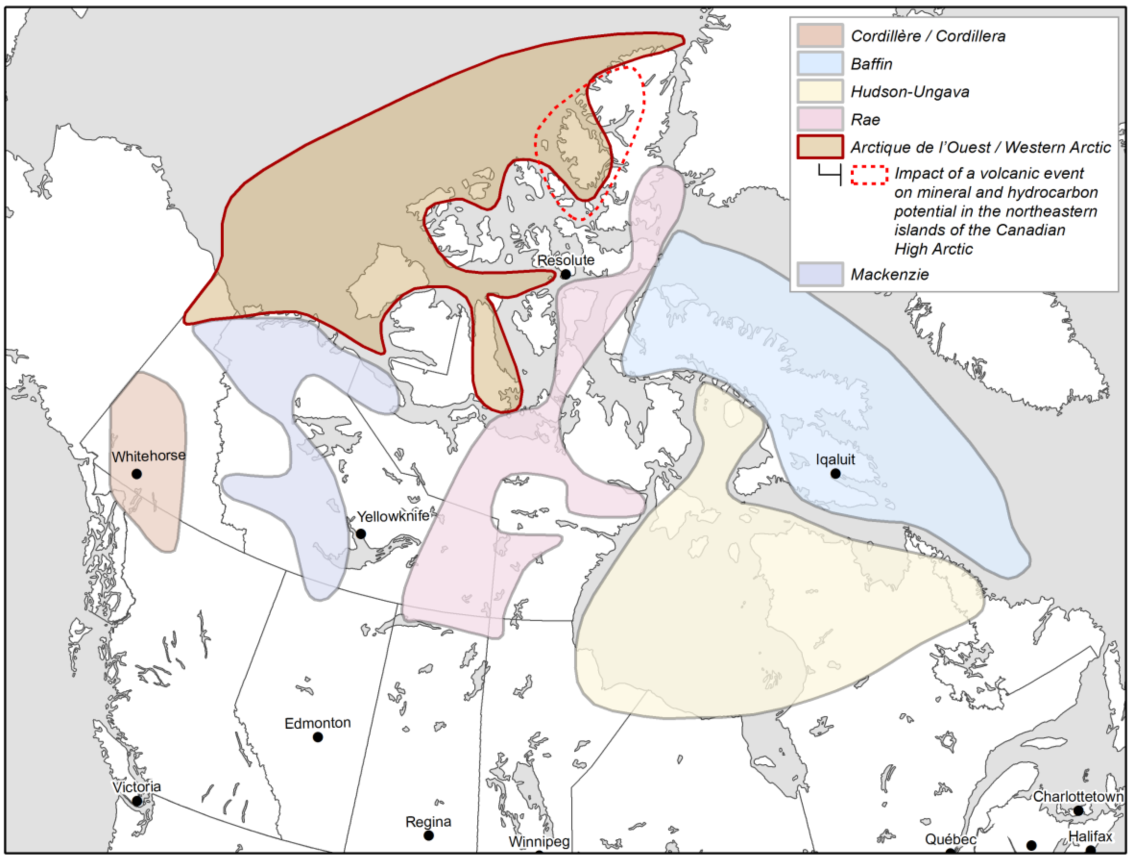

Figure 1. Regional map of the GEM 2 activities (2014-2017) showing the area covered by the Western Arctic Region Project. The area covered by the HALIP activity (red dotted line) includes Axel Heiberg Island and northern Ellesmere Islands, Nunavut.

HALIP INTRUSIONS, CONTACT METAMORPHISM, AND INCIPIENT DIAPIRISM OF GYPSUM-CARBONATE SEQUENCES

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ABSTRACT

As part of the High Arctic Large Igneous Province (HALIP) GEM2 project, five sets of HALIP-related intrusions and wallrocks were sampled for a regional-scale study of geochemical signatures indicative of PGE-Ni exploration potential. Investigation of a bedded gypsum-carbonate sequence revealed possible incipient diapiric structures with a wavelength of ~100 m and an amplitude of ~40 m. Incipient diapiric mass flow appears to be the result of a diagenetic (?) reaction between the two lithologies that generate large amounts of gas or fluid that brecciate wall rocks (decreasing strength) and increase volume (generating buoyancy). Several sample sections were collected through an oil-shale adjacent to a sill to better constrain the impact of HALIP intrusions on the basin's oil and gas potential, to quantify the volumes and species of environmentally significant gas species expelled, and to determine the impact of shale assimilation on magma chemistry and possible sulphide immiscibility.

INTRODUCTION

As part of the High Arctic Large Igneous Province (HALIP) GEM2 project, fieldwork was done on Axel Heiberg and Ellesmere islands between the 9th and 20th of July. This contribution provides a status report of fieldwork that was accomplished and some preliminary interpretations of field data. It is divided into 3 segments: 1) regional sill/lava study; 2) evaporite sequences and diapirs; 3) contact metamorphism of oil shales and contamination of sills.

Regional sill / lava study

Sets of sill and host rock samples were collected for a regional geochemical survey, as part of a global effort by the entire project team. As outlined in previous and forthcoming contributions (Bédard, 2015; Deegan et al.,in press), representative sample sets were collected to allow the team to generate a state-of-the-art geochemical dataset (including S isotope data) to allow petrogenetic interpretation of the HALIP (e.g., Evenchick et al., 2015) magma suite(s) and to define their prospectivity for Ni-Cu-PGE deposits (cf., Jowitt et al., 2014). Additional objectives included examination of contact metamorphic effects to obtain a more regional-scale view of how magmatism affected potential gas/oil producing lithologies such as organic rich shales (cf., Jones et al. 2007). We also sought field evidence that could enhance our understanding of the context and mechanisms of emplacement (e.g., sills or dykes? fault-related or passive intrusion? magma throughflow or stagnant differentiation? saucer-shaped or flat sill shapes?). Contact-metamorphosed host rock samples will be examined for mineral assemblages that could provide pressure-temperature constraints and be dateable. Selected shale/hornfels samples will be analyzed for their degree of gas depletion, thermal metamorphism, and organic matter maturation versus distance from contacts, comparing results from RockEval with temperature-step gas chromatography. Three sections were examined on Axel Heiberg Island (Figure 1): Schei Peninsula, Mokka Fiord, and North Geodetic Hills. Existing geochemical data from Axel Heiberg suggest these intrusions are probably tholeiitic and have the highest Ni–PGE exploration potential (Jowitt et al., 2014). Al section (Blue Mountains, Figure1) was collected from Ellesmere Island, for which only transitional-alkaline or alkaline basalts are known to date (e.g. Jowitt et al., 2014 ; Estrada, 2014). Schei Peninsula Section (10 July) intrusions are aphyric to weakly plagioclase glomerophyric diabase. They trend NW and some may be dykes, although many appear to be concordant with bedding. Visible (bleached) contact metamorphic haloes were commonly about 2 m wide. Observations were also made of the contacts between sills/metasediments and a small evaporite

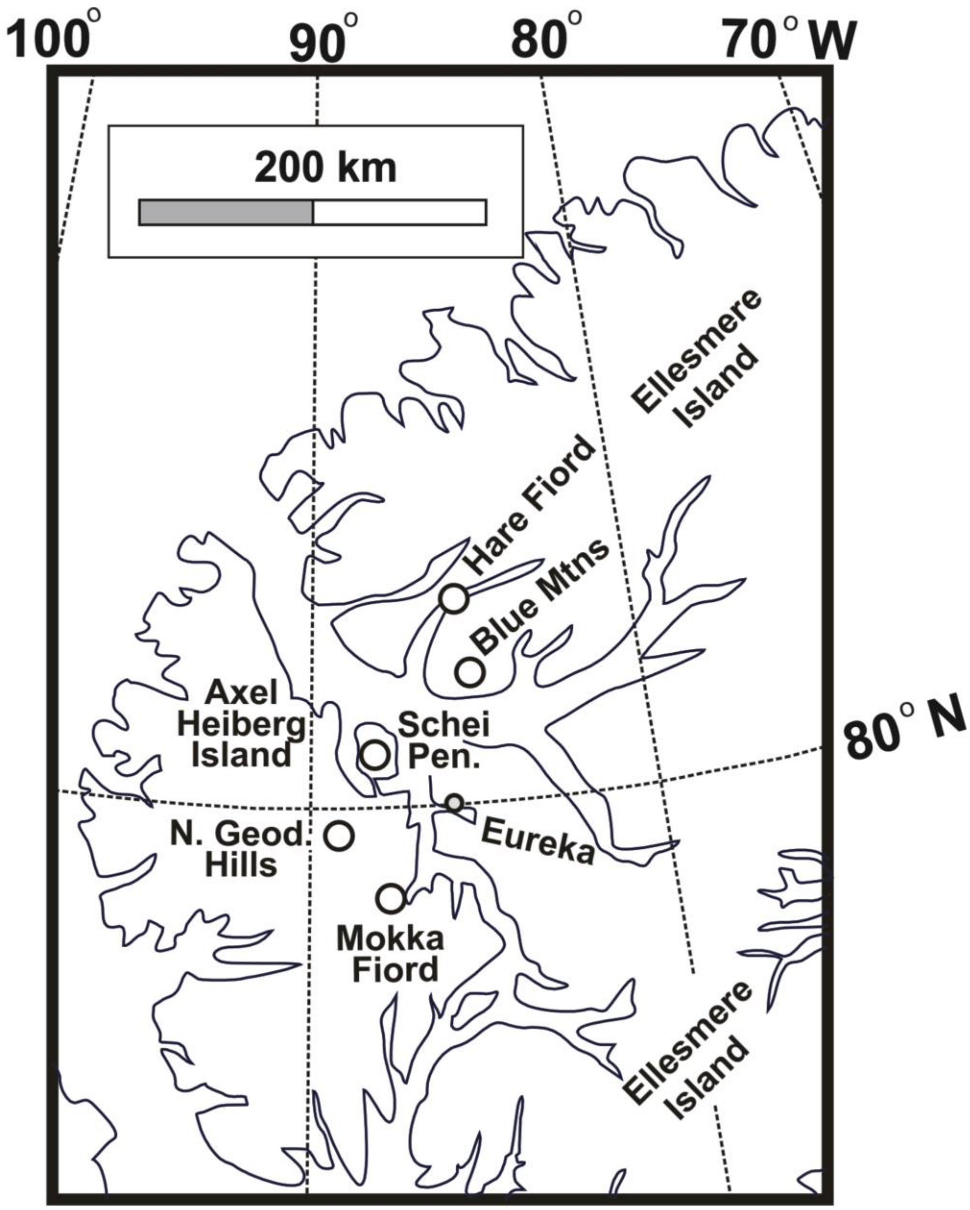

Figure 1. Location of sampled sections (N.Geod. Hills = North Geodetic Hills).

diapir. The latter was markedly chaotic, and contained significant amounts of open voids with botryoidal or faceted partial crystal infills. The nature of these secondary mineral assemblages and the types and temperatures of the gases involved remains to be determined. Other diapir contact facies appeared to be breccias with low-temperature hydrothermal cements (calcite) and minor pyrite.

The Mokka Fiord Section (11 July) examined NW trending linear diabasic / gabbroic bodies that may represent fault-guided dykes. A potential geochronology sample from an exceptionally wide contact-metamorphic halo (ca. 5m) was collected for geochronology. Samples were also collected from plagioclase-phyric capping sills that are cut by these NW trending dykes.

The North Geodetic Hills Section (12 July) sampled the northward extension of the sills from Buchanan Lake, for which previous data exist (Jowitt et al., 2014). Comparison of the two datasets may allow regional-scale (ca. 50 km), intra-sill magma flow direction to be determined. These sills ranged from weakly plagioclase-phyric to medium-grained diabasic gabbro in intrusion cores. Some sills appear to be rooted into dyke-like feeders, which may form sets (Figure 2). A sample was collected for geochronology from a metasedimentary septum sandwiched between two sills.

The Blue Mountains Section (Ellesmere Island, 13 July) is dominated by thick (>20-30m) sills emplaced into the Blaa Mountain Formation shales and overlying Heiberg Formation sandstones. Sills appear largely aphyric at the base of the section but plagioclase-phyric sills were observed further up in the section. A contact-normal section was sampled in pyritic black shales from the base of the section. Near the top of the section, a NW trending dyke sample was collected. The so-called 'Blue Mountain basalt member' of an unnamed Cretaceous Formation (Kv on map from Thorsteinsson, 1971) was briefly examined. This unit is sandwiched between the Isachsen and Christopher formations, and it was concluded that this is not an extrusive rock but more likely a sill.

Evaporite sequences and proto-diapirs(?), Otto Fiord Formation, North shore of Hare Fiord

The Sverdrup Basin is pierced by swarms of evaporite diapirs, many of which are dominated by gypsum/anhydrite, and which represent oil/gas traps (e.g. Embry and Beauchamp, 2008). The mechanisms by which gypsum/anhydrite diapirs form is problematic, however, as anhydrite's high density (2.97 g/cm^3) should hinder ascent through the lower-density sedimentary rocks of the Sverdrup Basin. As halite-rich facies have been observed beneath partly gypsified anhydrite caps to diapirs (e.g. Heywood, 1955; Boutelier et al., 2011), it is widely believed that anhydrite diapirs are mainly powered by the ascent of salt (Davies and Nassichuk, 1991). However, the presence of weakly deformed partly gypsiferous anhydrite caps up to 800m thick remains problematic, as dense anhydrite should have foundered into the underlying salt (Koyi, 2001).

On July 14th, we deployed to the North shore of Hare Fiord (Figure 1) to study gypsum evaporites of the Otto Fiord Formation. The original plan was to examine *in situ* reactions between sills and hosting gypsum-dominated rocks (Bédard, 2015), but no intrusions were observed in this section. The prominent dark brown to dark grey layers intercalated with gypsum turned out to be limestone (Figure 3a) with isolated cm-scale layers of fossiliferous black chert. Nonetheless, much of interest was discovered. In the section we examined at North Hare Fiord, gypsum is largely converted to near-massive anhydrite to alabaster layers up to 50 m thick. These may represent a valuable source of carving stone, as 1-2m wide massive bodies of this material can easily be collected near the coastline (Figure 3b). The least-perturbed limestone facies, mostly brown to grey, are in the centers of the widest limestone-dominated bands (25-30 m thick). These preserve bedding, fossils and discontinuous chert layers. The amoeboid shapes of interbedded chert/limestone may record important syn-compaction flow. We observed limestone in direct contact with anhydrite-dominated layers to be extensively veined, recrystallized and brecciated (Figures 4b,c). Typically, limestone and anhydrite in the contact zones are brecciated, with open cm- to dm-scale vugs, and low-density secondary infillinfilling cements of various types (white or grey coloured, Figure 4d). Their composition remains to be determined but a sulfurous smell was common, suggesting that gypsum or S-rich gases are present. Limestone may form trains of reacted, rotated clasts in the anhydrite near contacts, indicating advective mass transfer between the two lithologies during shear deformation.

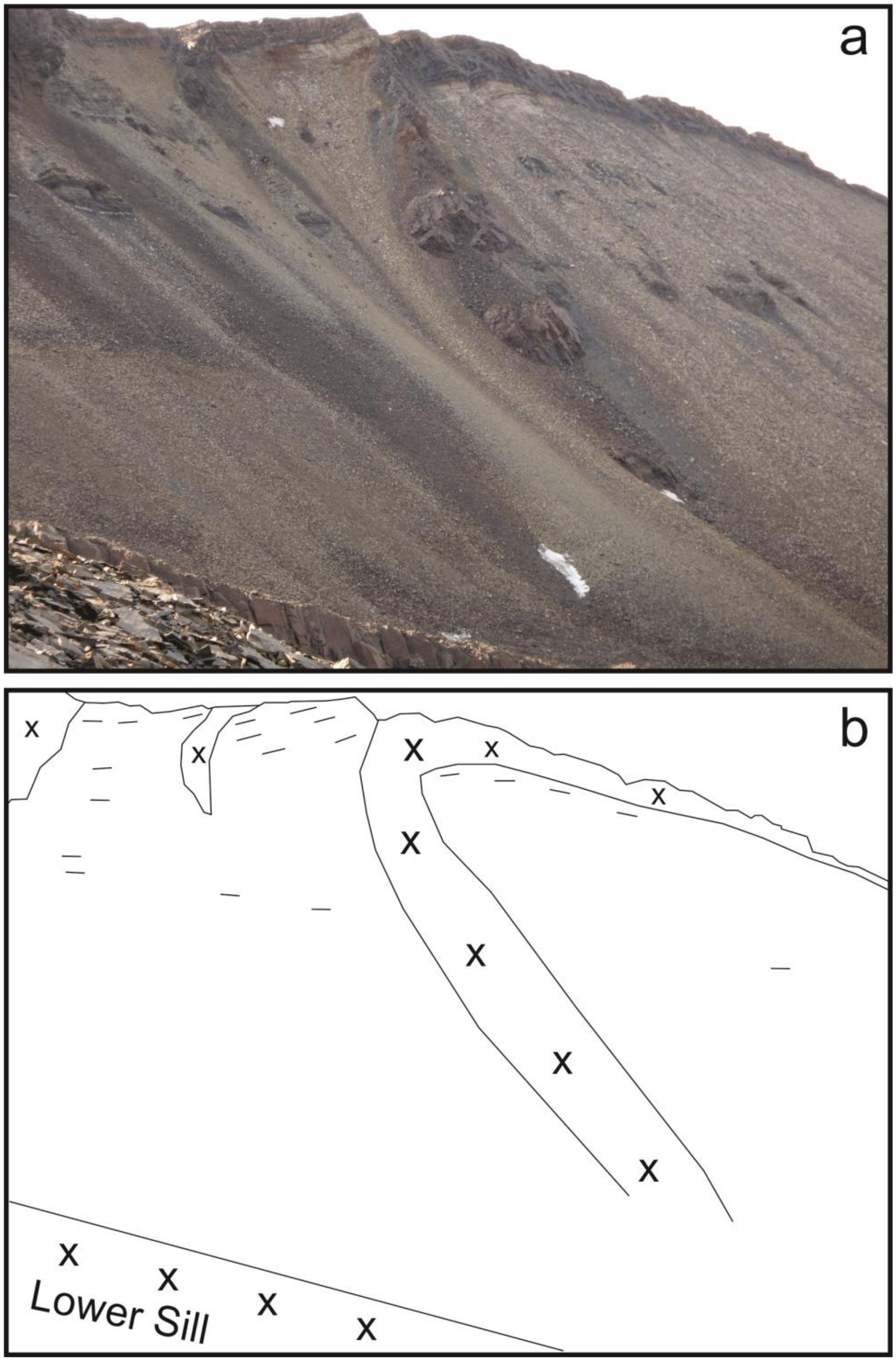

Figure 2. Photo **(a)** and interpretation **(b)** of outcrop from North Geodetic Hills Section. X symbols are for diabasic sills/dykes. Dashes track locations where bedding in intervening sedimentary rocks is visible. Note that the upper sill that caps the ridgeline appears to be rooted in a dyke-like feeder that belongs to a set of sub-parallel intrusions. The main dyke is about 10 m wide.

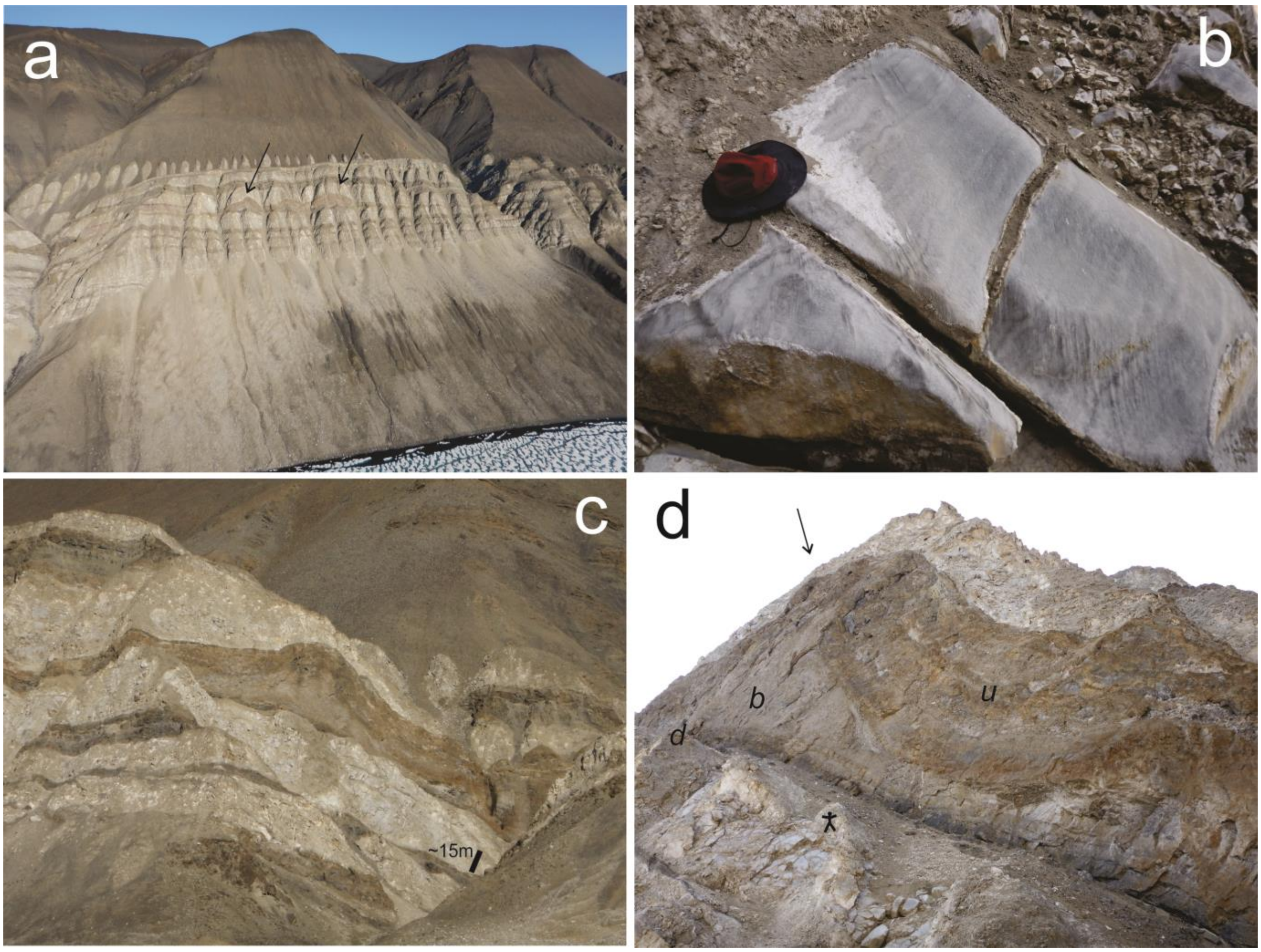

Figure 3. **(a)** General view of Otto Fiord Formation section at North Hare Fiord site (Figure 1). White is gypsum, intercalated brown/grey layers are limestone, most are ca 5-10m thick, but several (arrows) show upward bulges interpreted as biogenic mounds by Davies and Nassichuk (1975). The evaporitic rocks are capped by a shale-sandstone succession. The base of the section is a thrust fault. **(b)** Massive anhydrite, potential carving stone (hat for scale). **(c)** General view of sampling site (to the right of the exposures in 'a'). Note the prominent domal structure that we interpret to be a proto-diapir. It has an upper brown limestone with fairly constant thickness, and a lower, pale grey brecciated limestone that shows marked lateral variations in thickness, ranging from ~5 m to ~40 m. **(d)** Side view of diapir shown in 'c'. Stick-person for scale. Note the dark horizon dipping right 'd' parallel to S_0, and which contains sheared and brecciated chert and limestone (see Figure 4a), and which is interpreted to be the décollement surface along which the brecciated limestone flowed. Area with 'u' is upper brown limestone, 'b' is basal pale brecciated limestone. The arrow points to verticalized contact. Note how the upper limestone appears overturned.

Figure 4. (a) Sheared chert and limestone at the décollement beneath the proto diapir (see Fig. 3d). Note the black, rotated chert fragment. **(b)** Selenite vein in brecciated porous limestone. **(c)** Brecciated gypsum/anhydrite near contact with limestone. Breccia fill is porous, low density material**. (d)** Vuggy, porous secondary breccia fill.

There are common selenite veins in the limestone indicating transfer of SO_4-H_2O-rich gases or fluids to the limestone (Figure 4b). The outcrop-scale structures clearly record vigorous chemical exchange between these two sedimentary reservoirs. At one location an especially prominent set of limestone layers define what we infer to be proto-diapiric structures (Figures 3c,d; Figure 4d). These swellings had previously been interpreted as biogenic mounds (Davies and Nassichuk, 1975). While biogenic mounds probably exist in the Otto Fiord Formation, our observations lead us to propose a different origin for the outcrops shown in Figures 3 and 4.

Where we were able to examine one of these domal structures we observed a dark upper layer with a roughly constant thickness ('u' on Figure 4d) and a pale grey basal 'layer' ('b' on Figure4d) showing marked lateral variations in thickness, ranging from ~5 m to ~40 m over less than 100 m of strike length. The basal 'layer' is composed of strongly recrystallized, ubiquitously brecciated limestone and contains abundant gypsum veins in places (Figure 4b). In contrast, the brown upper limestone retains visible bedding, although it is contorted, brecciated and recrystallized in places. The bedded limestone in Figure 4d appears to form a synclinal structure between the major upwarp on the left (marked with an arrow) and a smaller mini-dome to the right. Bedding orientation is vertical on the highest exposed part of the dome to the left (arrow), and we do not believe that this can represent an original depositional geometry. The basal layer has a much darker zone ~2-3 m thick near its bottom ('d' on Figure 4d) with bedding-parallel shear fabrics and broken and rotated chert fragments (Figure 4a). We tentatively identify this as a décollement related to mass flow of brecciated reacted material into the apex of what we interpret to be proto-diapirs.

The field evidence shows that gypsum and limestone reacted strongly and we speculate that brecciation was caused by large volume increases associated with gas-producing diagenetic reactions. The diapiric shape of the resulting porous low-density material would then imply that the low density and viscosity of this gas-filled breccia allowed lateral and upward mass flow. We infer that these outcrops record a case where enough heat was added to stimulate gas-producing reactions and initiate diapirism, but that the absence of proximal basaltic intrusions did not allow a far-travelling diapir to form. It is perhaps significant that many far-travelled diapirs contain a frothy gas-rich brecciated facies very similar to the one described here (see previous section) but also contain metabasaltic enclaves (e.g. Boutelier et al. 2011), suggesting that magmatic heat may be necessary for diapiric structures to develop beyond what is seen in the North Hare Fiord section.

Microscope and electron-probe analysis of the secondary assemblages in vugs and breccia-fills will better constrain the P-T conditions of the gas-forming reactions. These will also be investigated experimentally. Several possible gas-forming reactions can be considered as gypsum ($CaSO_4$-$2H_2O$) breaks down via metastable intermediate forms known as hemihydrate or bassanite ($CaSO_4$-$0.5H_2O$) which then break down to anhydrite ($CaSO_4$: Freyer and Voigt, 2003). These gas-producing reactions begin at ~40^oC at 1 atmosphere, but the breakdown temperature at higher pressure is strongly dependent on pH_2O and the presence of other ionic species and is not well constrained (Freyer and Voigt, 2003). We speculate that SO_4-H_2O-rich fluids generated by breakdown of gypsum may have triggered partial decarbonation of limestone, further increasing gas pressure, enhancing brecciation and increasing porosity. There may even be a positive feedback mechanism involved, since dilution of SO_4-H_2O -rich fluids by CO_2 evolved from decarbonating limestone would lower the activity of water and sulfate in the fluid, and further destabilize gypsum. The proportion of low-density material estimated from the field exposures (ca. 20%) should be adequate to trigger a gravitational instability, leading to spontaneous evaporitic diapirism as a result of diagenesis.

Although halite is widely considered to be an important contributor to evaporite diapirism in the Sverdrup Basin (e.g. Boutelier et al. 2011); our field observations suggest incipient diapirism in a section lacking halite (cf. Davies and Nassichuk, 1975, 1991). This implies that gypsum-limestone diapirs could form despite the absence of halite, and that halite may even have been drawn in from beneath an ascending gypsum-limestone diapir. The burial depth of Otto Fiord rocks at the time of diapir initiation (Cretaceous?) will be estimated from existing stratigraphic data to determine if plausible reaction temperatures can be attained solely through burial, or whether an additional magmatic heat source is needed.

Figure 5. General view of section at South Hare Fiord, showing locations of sections (numbered). Sections # 55, 58, and 60 are sub-sill shale sections, # 57 and 59 are super-sill sections, while # 56 is a section through the sill (ca 25 m thick). This sill pinches out ca 300 m further to the left (east).

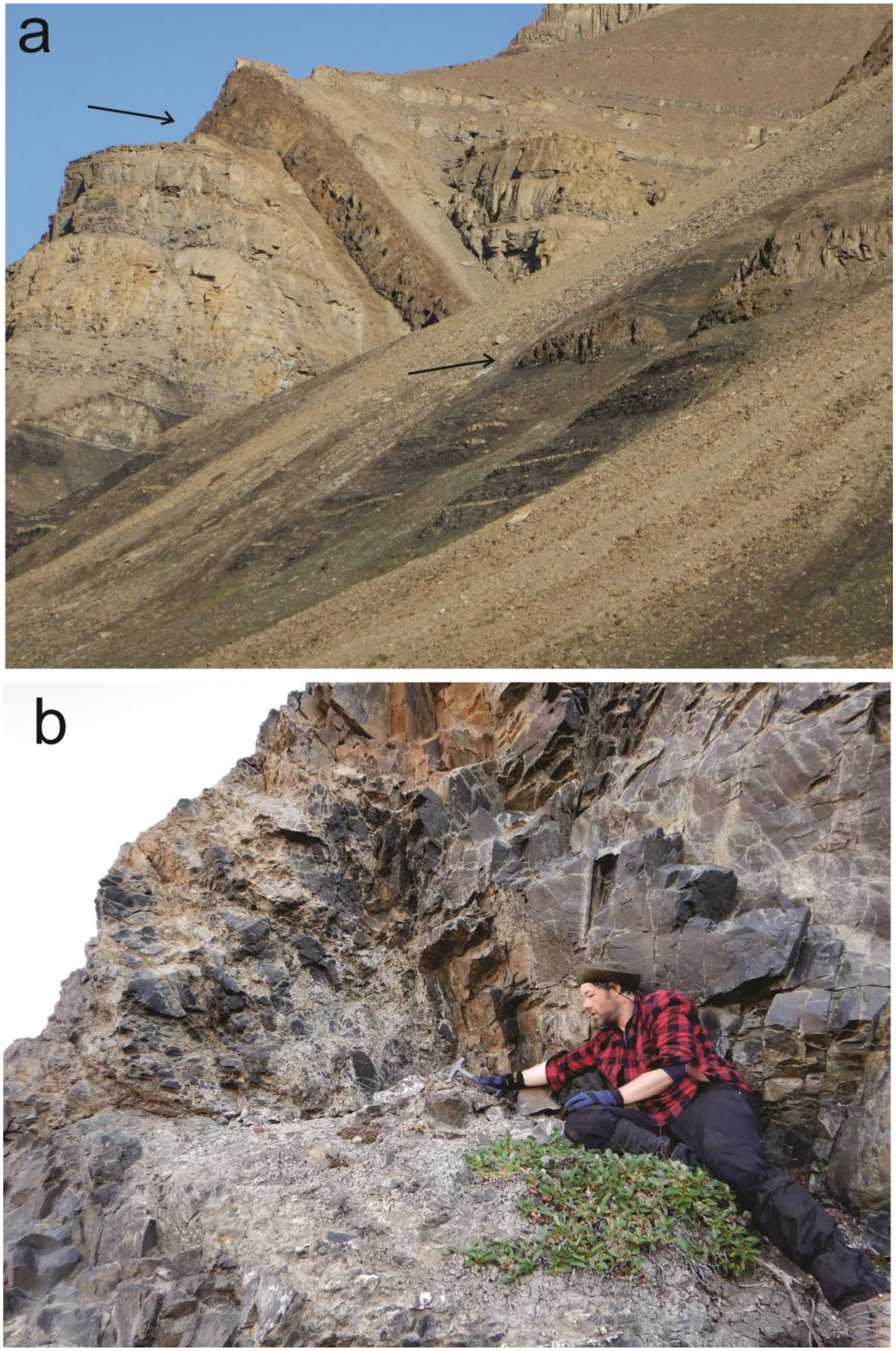

Figure 6. (a) View towards the south showing how the target sill of Fig. 5 terminates towards the east (arrow). Note also the prominent dyke that appears to feed a sill (arrow). **(b)** Close up of interior of sill sampled at section 56 (Fig. 5) located approximately 2 m above the base of the sill. Note the prominent calcite-sulfide vein systems.

Contact metamorphism of Murray Harbour Formation oil shale and contamination of HALIP sills

On the 17th of July we were moved to the south coast of Hare Fiord to examine the interaction of HALIP basaltic sills with the Murray Harbour Formation shale (Figure 5), thought to be an important source rock for oil and gas generation in the Sverdrup Basin. Most sills/dykes here are plagioclase phyric, and many of the sheet-like intrusions show lateral transitions to strongly discordant dykes (Figure 6a). Sills may pinch out along strike, or jog up or down by several meters. Three shale/hornfels sections were collected beneath a ~20-30 m thick sill and two sections were collected above it (Figure 5). These will be analyzed for geochemistry, S isotopes, metamorphic assemblages, and be fit to various thermal-cooling models. The easternmost section appears much less metamorphosed than the westernmost section, which has a wider hornfels zone. This may record variable amounts of magmatic throughflow, with the distal eastern part of this sill/dyke representing a more 'stagnant' propagator-tip. Above the most strongly hornfelsed shale, wide zones of S-rich staining were observed that concentrate at the contact and vein the overlying diabase (Figure 6b). We suspect that these record generation and migration of S-C-O-H-contact-metamorphic fluids. Igneous sulfides were observed in this sill, perhaps recording extensive magmatic contamination by the S-rich shale? The sill at this location was sampled in more detail so as to better understand its internal differentiation, and to determine if assimilation signatures are focused at sill margins or were mixed in more homogeneously.

ACKNOWLEDGEMENTS

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HALIP VOLCANIC-INTRUSIVE COMPLEXES, AXEL HEIBERG ISLAND, NUNAVUT

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ABSTRACT

Fieldwork in the summer of 2015 was carried out at various localities in the southern half of Axel Heiberg Island, and focused on volcanic successsions and sub-volcanic intrusive complexes of the High Arctic Large Igneous Province (HALIP). The ~ 950 m thick sequence of basalts of the Strand Fiord Formation occurring east of Plateau Lake represents a world-class exposure of continental flood basalts consisting of thick units of basalt flows that display well-developed colonnades and entablatures. The intrusive complex at Middle Fiord exhibits intrusions with complex geometries, cross-cutting relationships and lithological variability rarely exposed in Large Igneous Provinces (LIPs) of Mesozoic age. Highlights of fieldwork also include field observations and sampling of the Surprise Fiord dyke swarm and the documentation of showings of massive sulphide mineralization in the Expedition Fiord area. Follow-up mapping, geochemistry, mineralogy and U-Pb geochronology will fill critical knowledge gaps on the magmatic history and Ni-Cu-PGE prospectivity of the Canadian portion of the HALIP. Intrusive complexes in the Middle Fiord area, in particular, will provide a unique opportunity to elucidate the architecture and chemical variability of rarely-exposed volcanic feeder systems associated with LIPs.

INTRODUCTION

Fieldwork by the Geological Survey of Canada was carried out on Axel Heiberg Island and Ellesmere Island from July 1-29, 2015, as part of GEM 2 Western Arctic Region Project HALIP Activity (High Arctic Large Igneous Province). The field objectives included (1) detailed stratigraphic studies and physical volcanology of the Strand Fiord Formation exposed in western Axel Heiberg Island; (2) mapping the architecture of intrusive complexes in the Middle Fiord and Surprise Fiord areas with special focus on the geometry of sills and cross-cutting dykes; and (3) collecting samples of eruptive and intrusive rocks to expand the existing HALIP geochemical database (Williamson, 2015). The results of field activities and follow up research will contribute to a better understanding of magmatic Ni-Cu-Platinum Group Element (PGE) prospectivity in the Canadian portion of the HALIP. In this contribution, we highlight important results of the field activities.

STUDY AREAS

Figure 1 shows the distribution of field camps, stations and sampling localities. Field work was based out of three camps between July 4 and 21: McGill Arctic Research Station, Plateau Lake and Middle Fiord (Figure 1). Helicopter-supported fieldwork in southern Axel Heiberg Island and at numerous sampling sites in the vicinity of the Eureka Weather Station was carried out for six days at the end of the field season. Overall, over 200 samples were collected from a wide variety of eruptive and intrusive rock units consisting predominantly of basalt and gabbro. The new samples significantly expand the regional coverage available for the assessment of Ni-Cu-PGE prospectivity of the HALIP (Saumur, 2015).

McGill Arctic Research Station

Fieldwork near the McGill Arctic Research Station was carried between July 2-4, 2015 (Figure 1, locality 1). The objective was to sample a massive sulphide occurrence first reported by industry geologists (Goddard, 2010). The showing is exposed over an area of ~ 5 m by 20 m located at the intersection of White and Thompson Glaciers (Between Lake; Figure 2A). The outcrop consists of buff to grey dioritic host rocks (Figure 2B) in contact with a heterogenous deposit consisting of highly altered breccia, gabbro scree and gossanous soil (Figure 2C). Our preliminary analysis of the massive sulphide indicates that it is dominated by pyrite and pyrrhotite, with relatively minor chalcopyrite. The meter-scale exposure of fine grained diorite has been interpreted to represent the intrusive host rock to the magmatic massive sulphide body (Goddard, 2010). At various localities on Axel Heiberg Island, there is evidence for the interaction of mafic rocks with

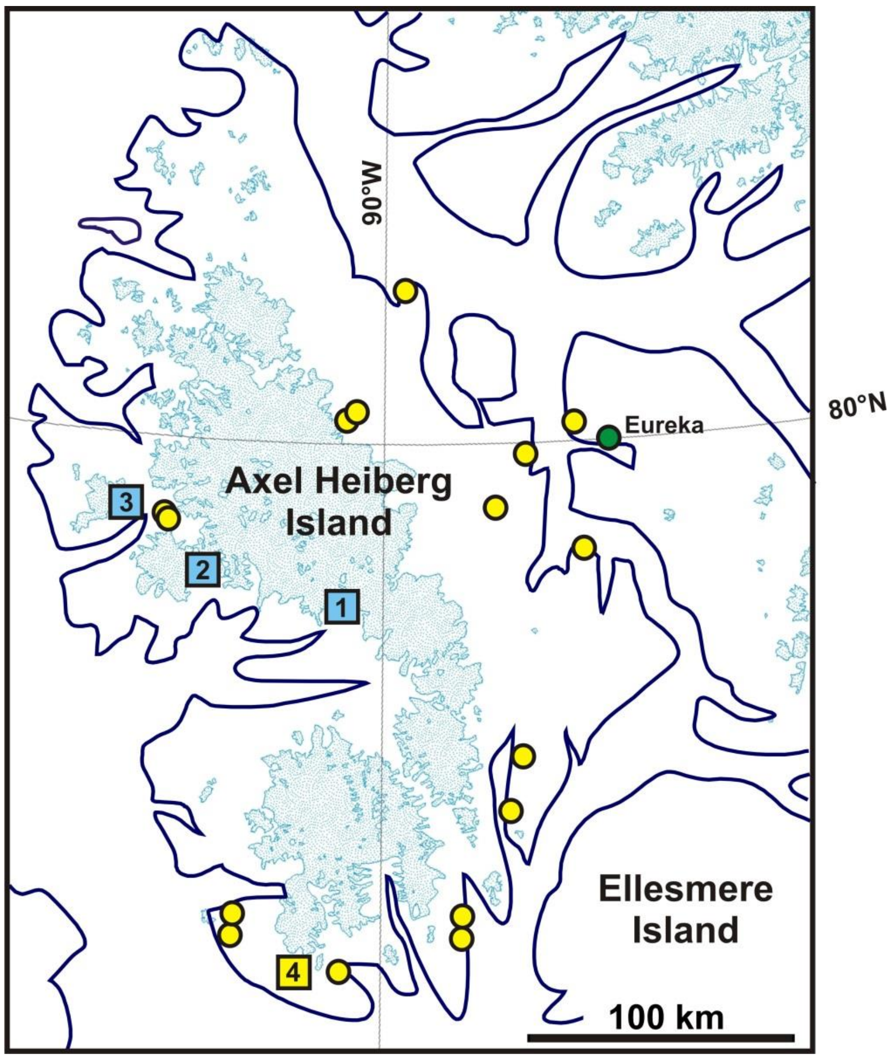

Figure 1. Study areas on Axel Heiberg Island, Nunavut. [1] McGill Arctic Research Station; [2] Plateau Lake; [3] Middle Fiord; [4] Surprise Fiord. Blue symbols indicate fly camps. Yellow symbols indicate areas investigated with dedicated helicopter support out of Eureka.

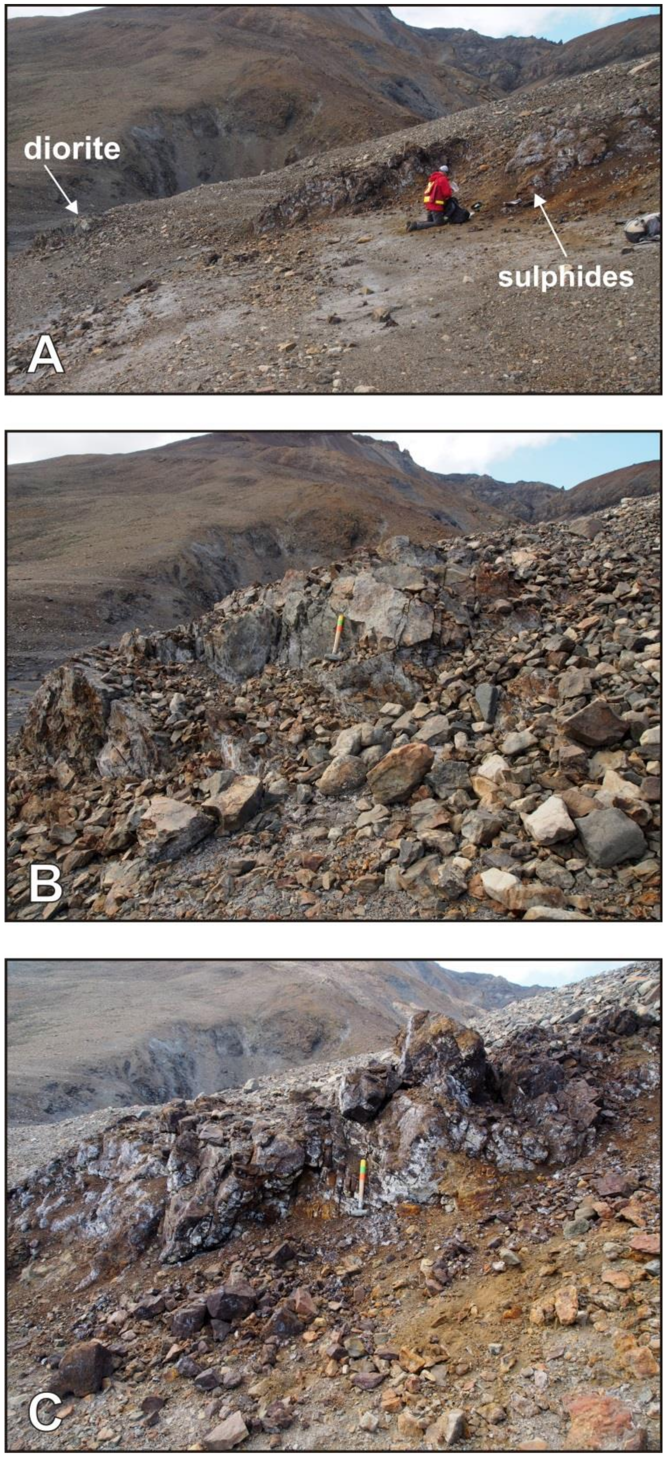

Figure 2. **A**. The Between Lake Gossan (BLG; locality 1, Fig. 1) was discovered by industry geologists who reported the occurrence of quartz diorite and massive sulphides (Goddard, 2010).
B. Fine-grained diorite interpreted by Goddard (2010) to represent the intrusive host rock.
C. Gossaneous breccia containing massive sulphides (pyrite, pyrrhotite, minor chalcopyrite). The sledge hammer is 38 cm long.

sulphidic shales, and olivine-bearing mafic to ultramafic magmas that contain up to 10% sulphide. Future work will constrain whether such units show evidence of significant sulphide saturation and enrichment in Ni-Cu, and whether important concentrations of metal-enriched sulphide could occur in the HALIP plumbing system.

Plateau Lake

Previous studies have shown that lava flows in the Strand Fiord Formation exposed on Axel Heiberg Island consist of flood basalts that are uniformly basaltic and were erupted as *aa* and *pahoehoe* flows (Ricketts et al., 1985). Williamson (1988) documented the presence of well-developed colonnades and entablatures (Types II and III; Long and Wood, 1986), and noted the similarities in eruptive style and volume of lava flows with those in the Columbia River Basalt Province (Riedel et al., 2013; Riedel, 2015). Invasive flows occur at the base of the volcanic succession indicating interaction between sheet flows and wet, unconsolidated sediments (Muecke *et al*., 1991). Lava flows in the type area at Strand Fiord display grey flow tops, suggesting rapid extrusion rates (Williamson and MacRae, 2001). In some cases, the presence of pillow lavas and tubes indicates extrusion of basaltic lava in small, ephemeral lakes.

Fieldwork on the volcanic succession near Plateau Lake (July 5-12, 2015; locality 2 on Figure 1) suggests a total thickness of ~ 950 metres (Figure 1, locality 2). The excellent quality of exposure of the Strand Fiord Formation at this site (Figure 3) is matched only by inaccessible coastal cliffs bordering Expedition Fiord. A preliminary compilation of field observations unequivocally demonstrates that this section is a world-class example of flood basalt volcanism. In addition, several types of intraflow deposits were discovered. Figures 3A and B show the contact between the Strand Fiord Formation and sedimentary rocks of the Bastion Ridge Formation. The irregular feature at the contact is interpreted to represent a ~ 10-m long sedimentary loading structure (Figure 3B). Further up section, complex, three-dimensional structures of basalt colonnades and entablatures in the lava flows are well defined (Figures 4A, 4B). Additional observations include: lapilli tuffs in shales near the base of the succession; channelized lava flows; volcanic conglomerates; and the presence of a red soil horizon at the contact between two lava flows (Figure 5A). The presence of fresh olivine in outcrop indicates that the massive, lower portions of basaltic lava flows are ideally suited for geochemical studies (Figure 5B). Follow-up laboratory studies will allow us to re-examine the significance of the Strand Fiord Formation within the circum-arctic HALIP, and will provide insight on the paleoenvironment of eruption.

Middle Fiord

Fieldwork in the Middle Fiord area was carried out from July 13-19, 2015 (Figure 1, locality 3). Figure 6A shows an example of the unusually high concentration of discordant intrusions with various emplacement styles, orientations and cross-cutting relationships, immediately east of the area examined. An important diversity of intrusive rock types was observed in outcrop, from olivine-bearing gabbro to diorite. These observations, the stratigraphic position of the dykes, their geometry (Figure 6B) and proximity to the thickest exposures of the continental flood basalts provide strong evidence that they form part of a sub-volcanic feeder system. Follow-up work, (detailed mapping, igneous petrology and geochemistry, U-Pb geochronology) will further test this hypothesis. The intrusive rocks in the Middle Fiord area may provide a unique opportunity to elucidate the architecture and chemical variability of rarely exposed volcanic feeder systems associated with continental flood basalts (Jerram and Widdowson, 2005).

SOUTHERN AXEL HEIBERG ISLAND

Surprise Fiord

The Queen Elizabeth Island and Surprise Fiord intrusions are considered to be manifestations of the HALIP (Buchan and Ernst, 2006). The latter is particularly enigmatic because there are no reports of field examination of these intrusions. Aerial reconnaissance flights carried out in a broad area centered on the Surprise Fiord dyke swarm (Figure 1, locality 4) on July 24-25, 2015, revealed subdued topography where dykes cross-cutting sills lead to the best exposures of HALIP rocks for field studies (Figures 8A, B). The compositional variability of intrusions in the Surprise Fiord area is not as wide as in the Middle Fiord area. However, leucogabbros were observed at one locality (Figure 8C).

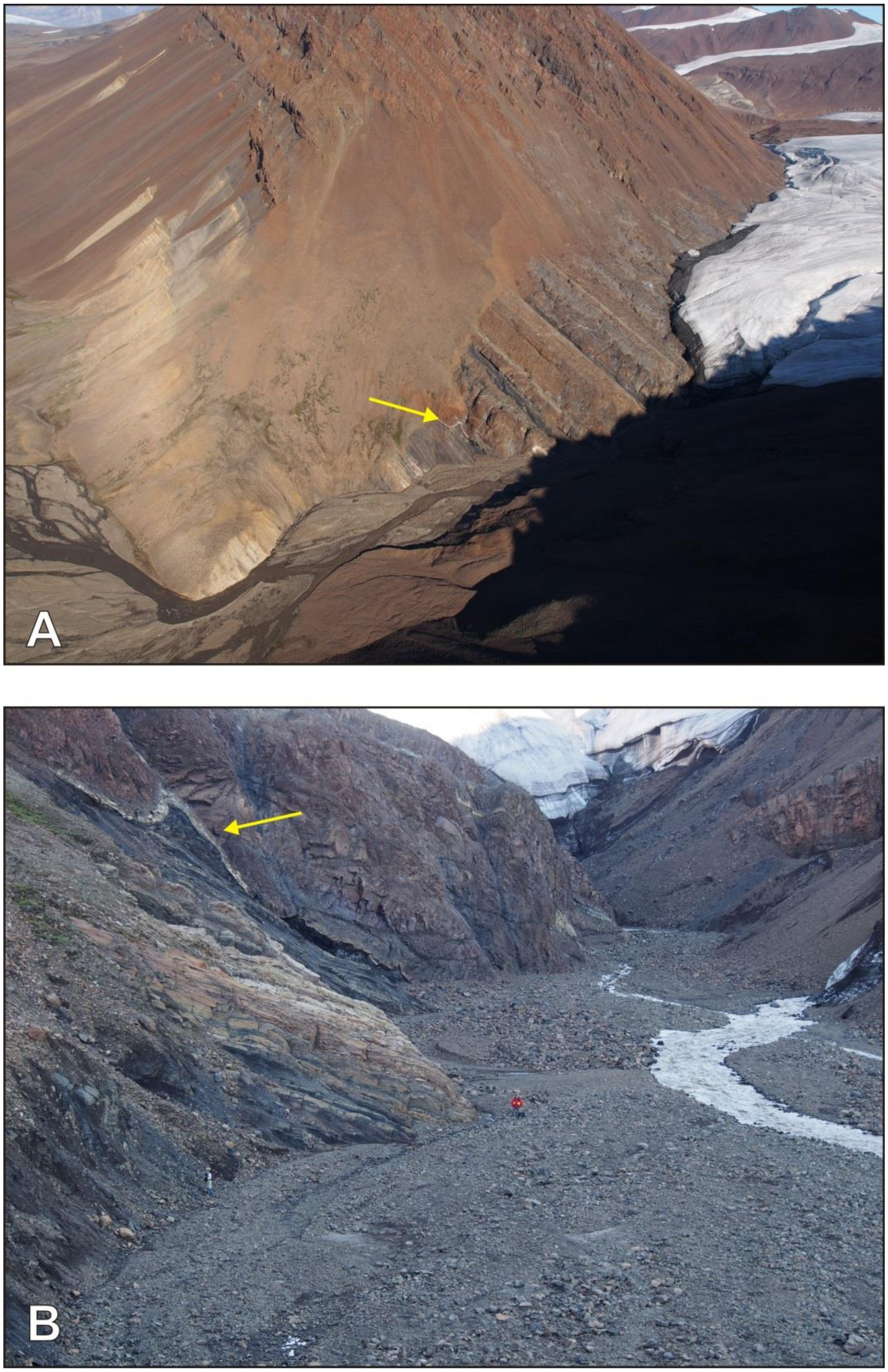

Figure 3. **A**. Aerial view of flood basalts exposed near Plateau Lake (locality 2, Fig. 1). Glacier retreat has resulted in spectacular exposure of the sedimentary rocks and overlying volcanic succession along the stream cut. The arrow points to the contact between the Bastion Ridge Formation and Strand Fiord Formation.

B. Irregular contact between shales of the Bastion Ridge Formation and a massive lava flow of the Strand Fiord Formation. The arrow points to a feature that is interpreted to represent a loading (flame) structure. Note the geologist for scale.

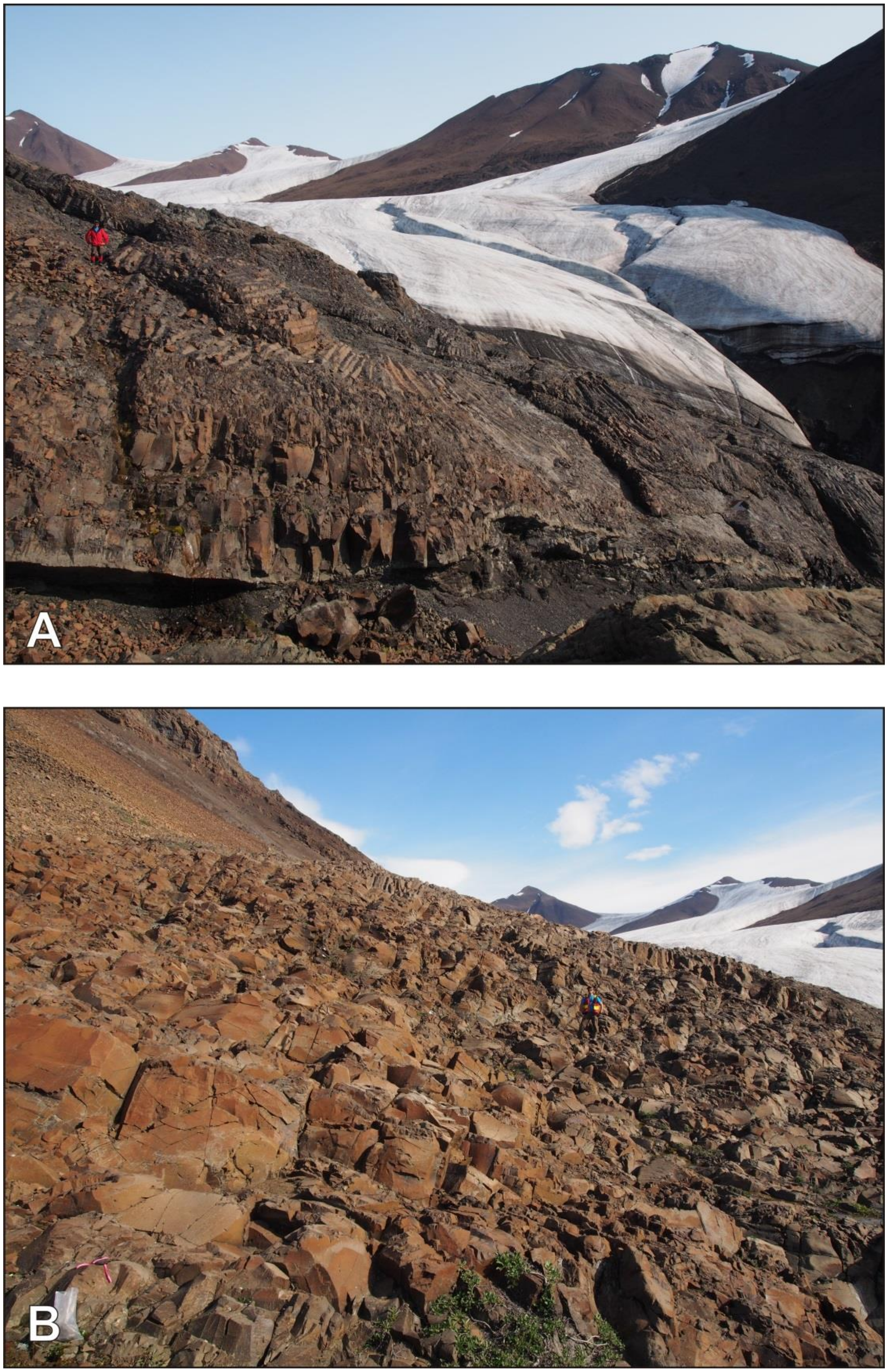

Figure 4. Eruptive style in flood basalts of the Strand Fiord Formation, Plateau Lake (locality 2, Fig. 1).
A. Colonnade and entablature in thick lava flow; geologist for scale.
B. Stubby columns typical of hackly flow structure. Note geologist for scale, at centre-right of the image.

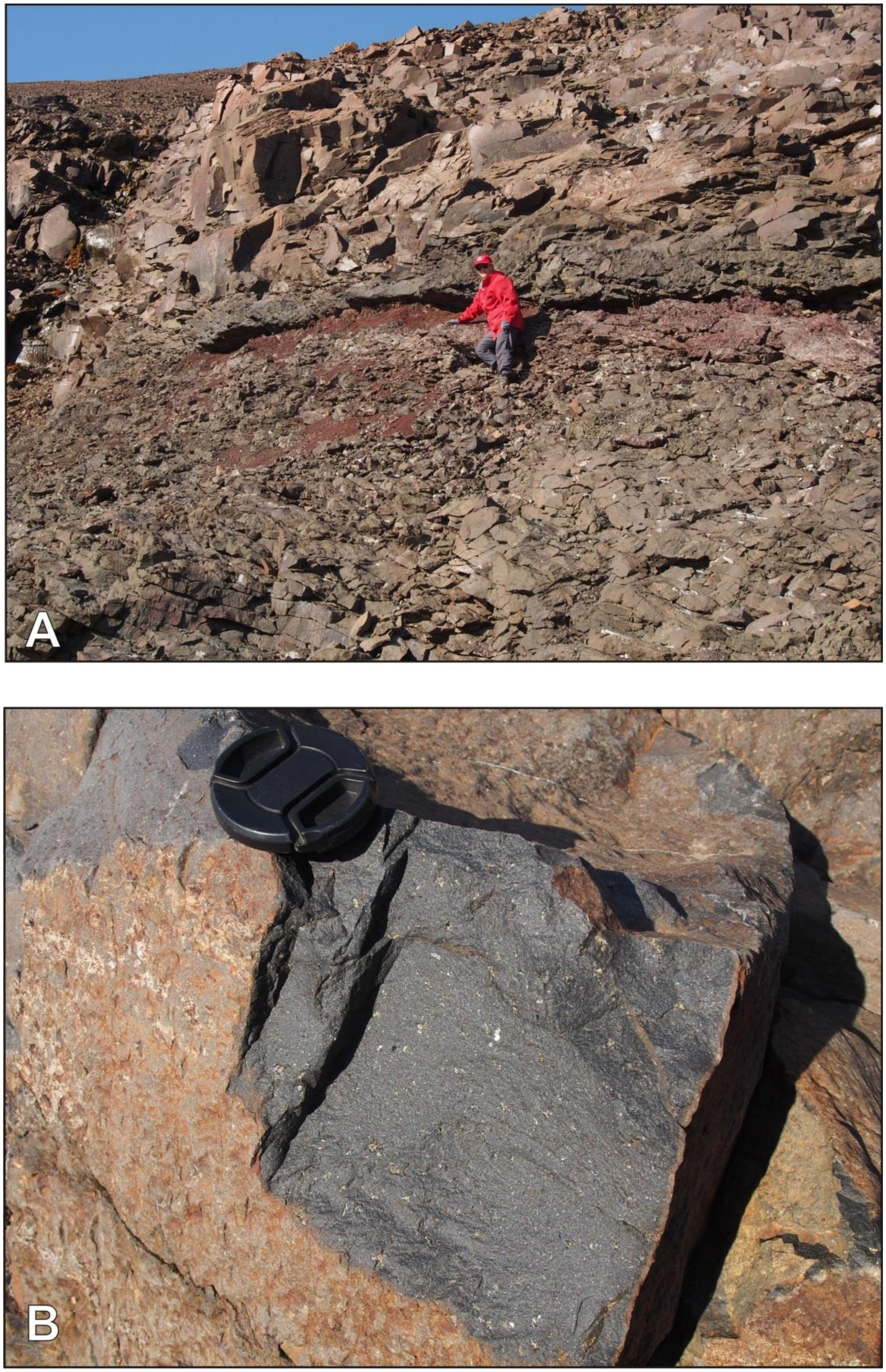

Figure 5. Examples of the Strand Fiord flood basalt succession at Plateau Lake (locality 2, Fig. 1).
A. The thin layer of terra rosa at the contact between two lava flows suggests a hiatus between eruptions.
B. Massive, fine-grained basaltic lava flow with well-preserved feldspar microphenocrysts and olivine. Note the lens cap for scale.

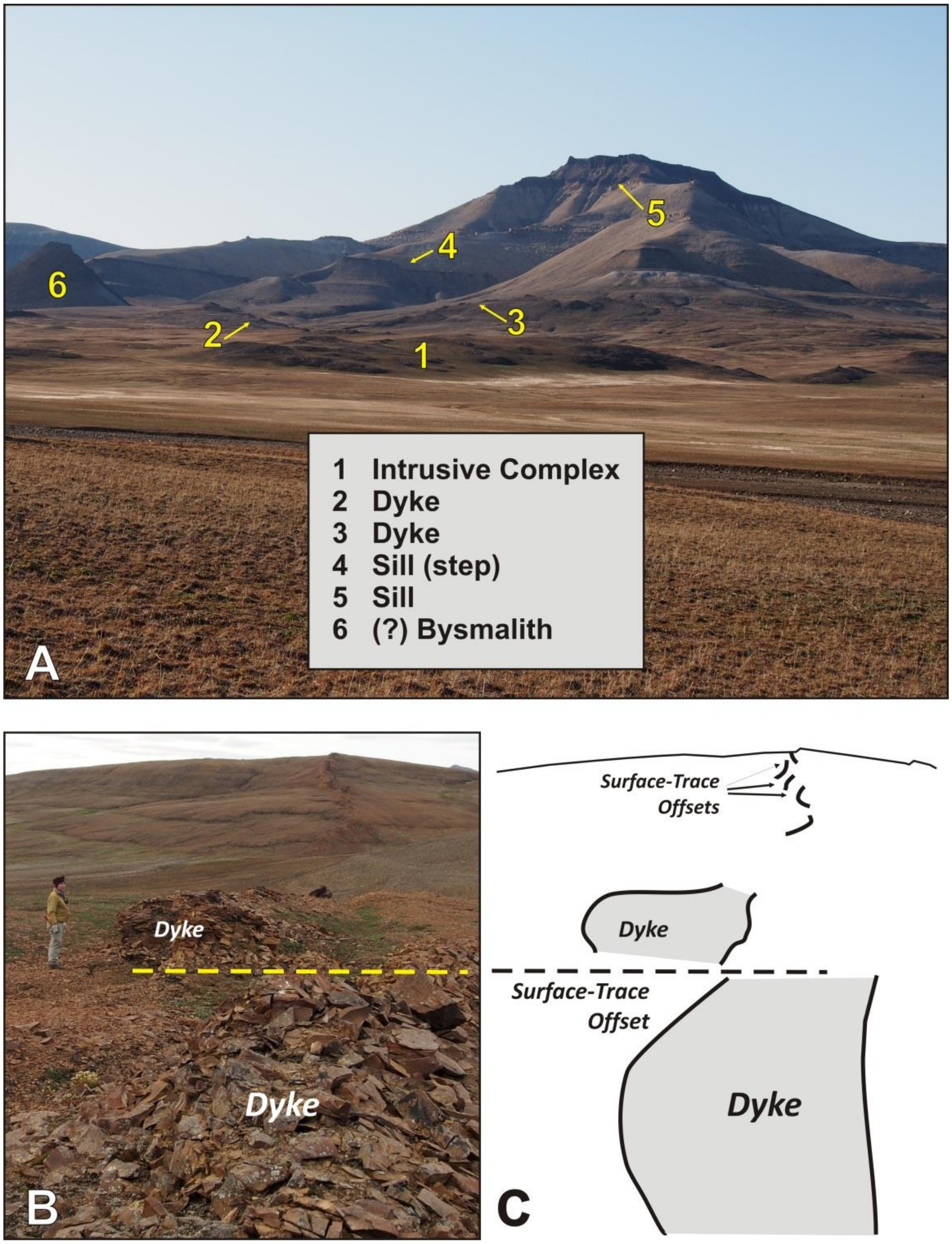

Figure 6. Geometry of sills and dykes along the north shore of Middle Fiord (locality 3, Fig. 1).
A. Intrusive rocks located on the east side of Middle River. The intrusive complex shown at (1) could represent the extension of units sampled west of the river (Fig. 6). The cylindrical intrusion shown at (6) could represent a bysmalith, a modified laccolith in which the roof has been lifted in part by peripheral faulting.
B-C. Dyke geometry observed at meter- to kilometer-scale on the western side of Middle River.The dyke (~ 2 meters thickness) crops out as hook-shaped segments and generally dips steeply towards the NNW. There is a lack of faulting in the area. Moreover, the steep dip of the intrusion rules out a topographic effect on the surface trace of individual segments. The segments are interpreted to connect at depth.

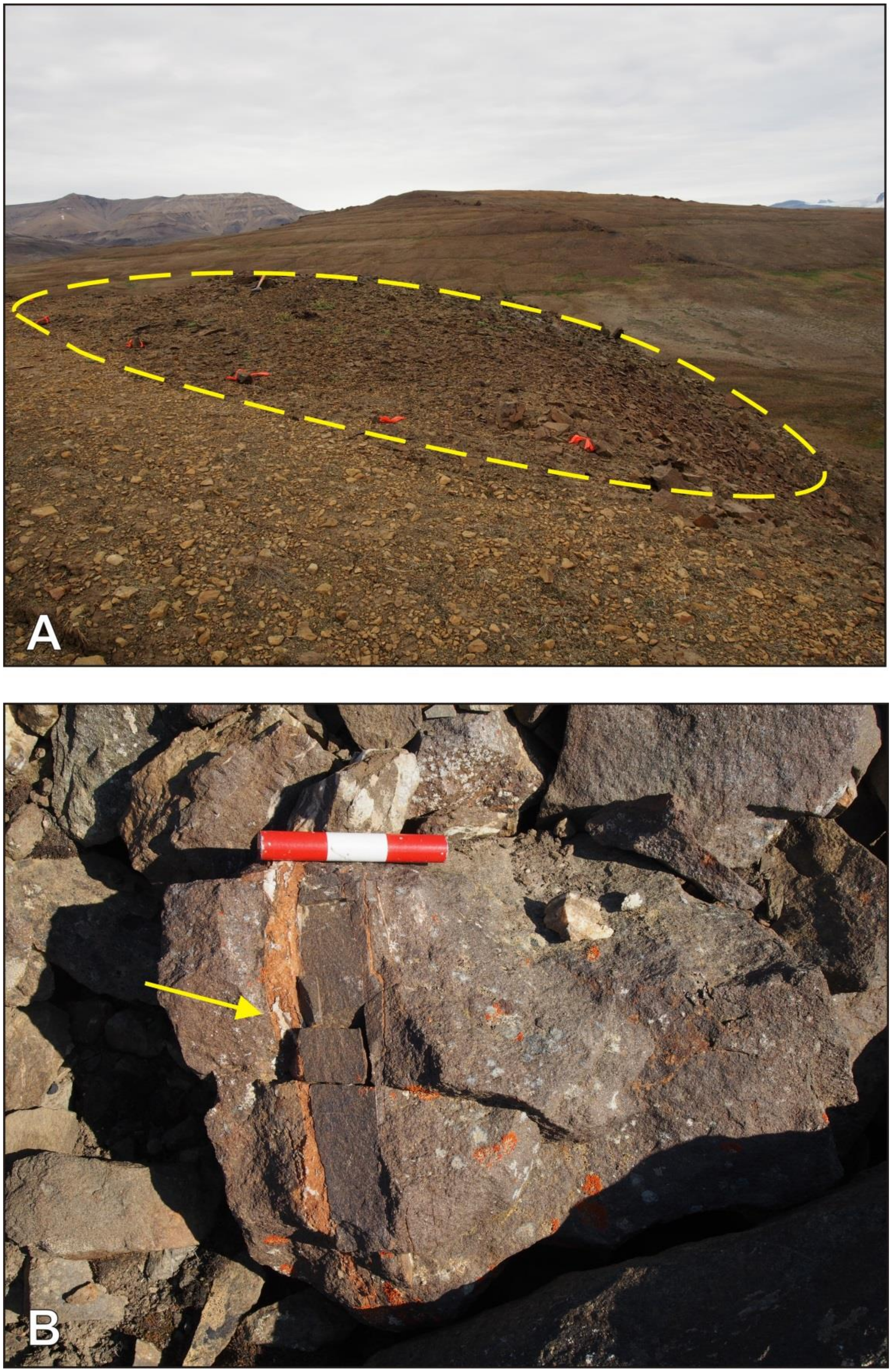

Figure 7. Field observations on the emplacement style of discordant intrusions in the Middle Fiord area (locality 3, Fig.1).
A. Poorly-exposed intrusion of mafic-(?)ultramafic rocks displaying a roughly circular pattern (diameter ~ 5 m). Rock types in the larger intrusive complex include diabase, olivine-gabbro and diorite
B. Thin dykes show evidence of late-stage fluid circulation in dilational fractures (arrow). The scale at centre is 7.62 cm long.

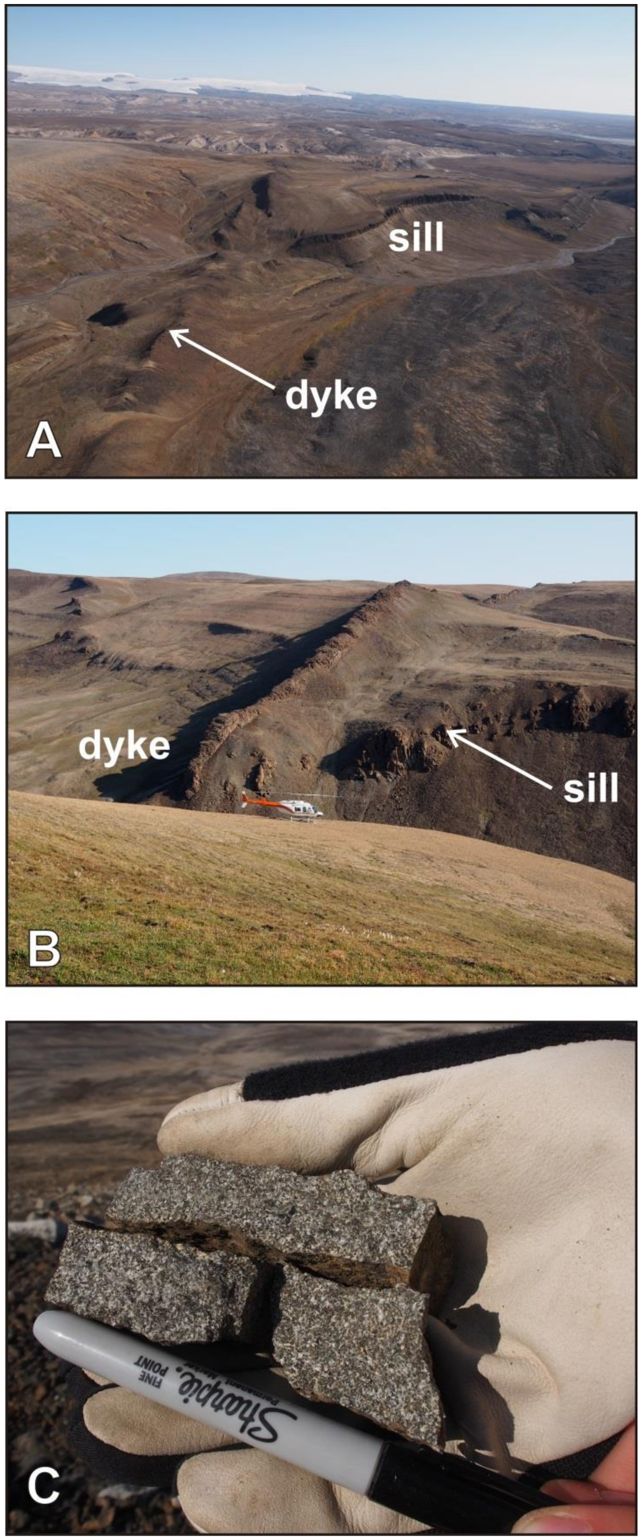

Figure 8. Geometry of sills and dykes exposed in Southern Axel Heiberg Island (locality 4, Fig. 1).
A. Aerial view of segmented dyke cutting a sill exposed along the stream cut.
B. Complex geometry of sills and dykes.
C. Samples of leucogabbro such as the one shown in this field photograph will be selected for U-Pb geochronological studies.

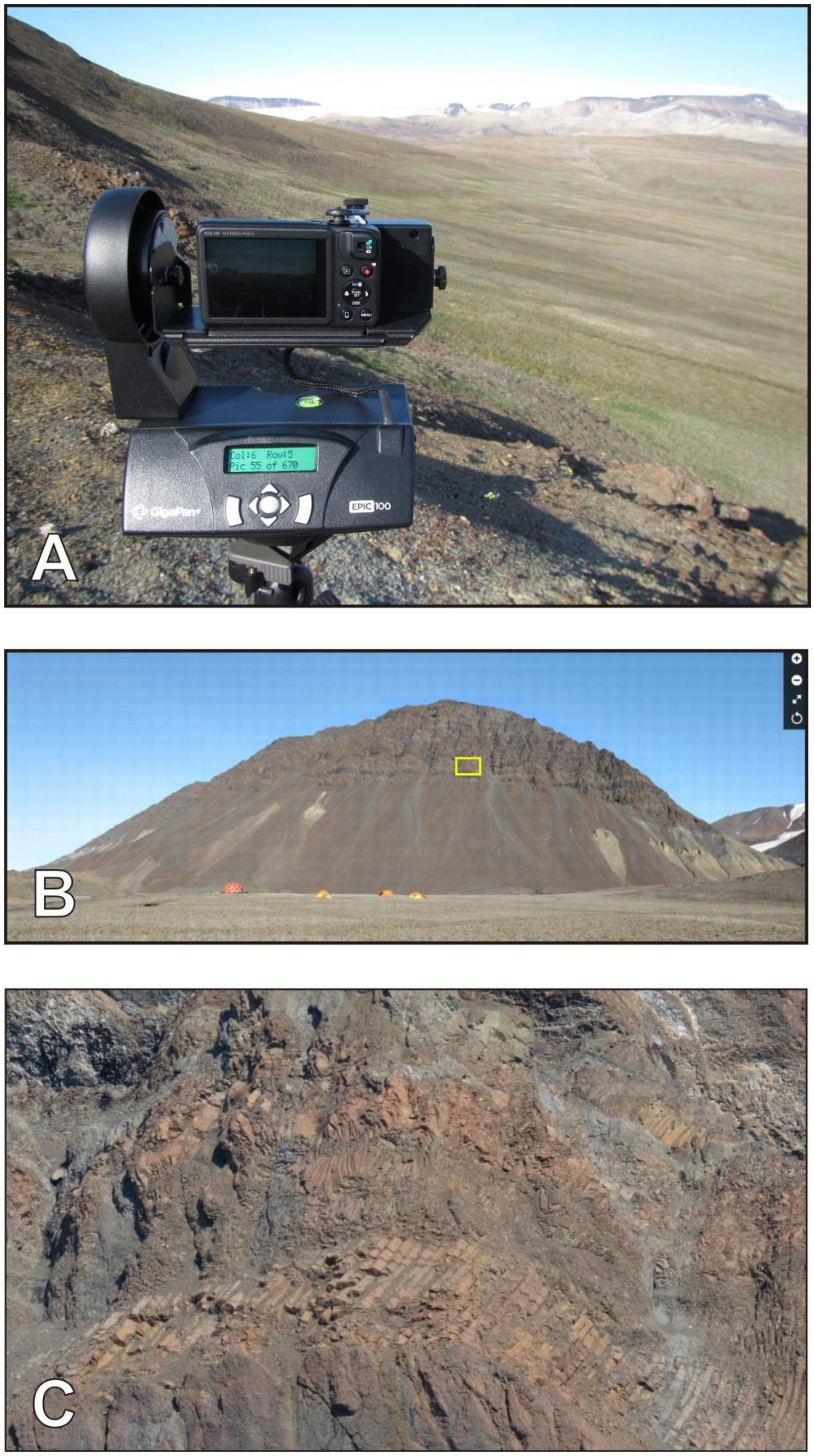

Figure 9. GigaPan© imaging system. **A**. Close up of the camera installed in the GigaPan© robotic mount, with the robot screen indicating that the defined panorama will be 670 photographs.
B. Gigapixel image (5.23 gigapixels) of the Strand Fiord Formation exposed on a cliff near Plateau Lake. This image, stitched from 900 images, each taken at maximum zoom for the camera, can be viewed at:
http://www.gigapan.com/gigapans/178076/options/nosnapshots,hidetitle,fullscreen/iframe/flash.html?height=250
The GigaPan© view controls are located at upper right. The yellow rectangle shows the location of Figure 9C.
C. Detail of the rectangle indicated in Figure 9B, showing the resolution when zoomed in to one part of the image.

SE Axel Heiberg Island and Fosheim Peninsula

Additional helicopter-supported fieldwork was carried out from July 26-29, 2015, at several field sites along Eureka Sound (e.g., near Glacier Fiord, Skaare Fiord, Whitsunday Bay, Gibs Fiord) and on Fosheim Peninsula, Ellesmere Island (Figure 1). The objectives were (1) to expand the regional sampling coverage of the Canadian HALIP; (2) to complement the investigations of Bédard et al. (this volume) and (3) to groundtruth ongoing remote predictive mapping focused on the regional distribution of sills (K. Dewing, Pers. Comm, 2015).

Gigapans

A specialized camera system was employed in the field to assist in recognizing macro- and megascopic relationships between rock bodies, and to explore the benefits of this technology to regional studies. GigaPan© images are gigapixel digital images that allow ultra-zoomability of the subject. The system includes a camera, a GigaPan© robotic mount that the camera sits in, and a tripod to hold the GigaPan© robot (Figure 9A). The seven GigaPan© images acquired during the 2015 field season can be viewed on the Gigapan© website[1]. As an example, Figure 9B shows part of the section of Strand Fiord Formation near Plateau Lake. This image was stitched from 900 individual images. Figure 9C is a 'snapshot' of the part of Figure 9B outlined by the rectangle. The process, pitfalls, and benefits of using the GigaPan© system in remote fieldwork will be explored in a future report.

CONCLUSIONS

Fieldwork carried in western and southern Axel Heiberg Island in July 2015 achieved all the planned objectives. Highlights include detailed stratigraphic studies of the thickest volcanic succession in the Strand Fiord Formation at Plateau Lake; mapping of the potential feeder system of the Strand Fiord Formation near Middle Fiord; a comprehensive geoscientific survey of the Surprise Fiord dyke swarm; the documentation of local sulphide mineralization previously reported by industry; and acquisition of Gigapan© images that will assist in mapping volcanic and intrusive rocks. Ongoing and future work include (1) detailed physical volcanology and petrology of the Strand Fiord Formation; (2) follow-up mapping of the Middle Fiord area with a focus on the stratigraphy and the structure of the locally exposed intrusive complex; (3) U-Pb geochronological studies of HALIP rocks in the Middle Fiord and Surprise Fiord intrusive systems with particular attention to leucograbbros; and (4) expansion of the regional geochemical database (whole rock lithogeochemistry and assays). This work will significantly improve our understanding of the economic prospectivity of the HALIP and also provide insight on the volcanology of continental flood basalts and the sub-volcanic architecture of LIPs.

ACKNOWLEDGEMENTS

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[1] http://gigapan.com/gigapans?query=evenchick

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SUMMARY OF PALEONTOLOGICAL WORK CONDUCTED ON AXEL HEIBERG ISLAND, NUNAVUT, SUMMER 2015 – STRATIGRAPHY OF THE LATE MESOZOIC

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BACKGROUND AND RATIONALE

Paleontological collections were acquired as part of a mapping program undertaken by the Geological Survey of Canada on Axel Heiberg and Ellesmere islands, Nunavut, in support of the Geo-Mapping for Energy and Minerals (GEM) Western Arctic Project, High Arctic Large Igneous Province (HALIP) Activity. The paleontological samples collected will contribute to the overall objectives of the project by determining the age of rock units studied and characterizing their depositional environments. One of the key gaps in the geological knowledge of HALIP is that there is very little age control from fossils on the Jurassic-Cretaceous interval (160 to 65 million years ago). Large fossils (ammonites and clams) are rare, and aside from several short reports in the late 1960s and early 1970s, there are few studies of microfossils from this key interval anywhere in the Arctic Islands (Galloway et al., 2013, and references therein). Additionally, a high-standing late stage of fragmenting Pangaea was associated with widespread unconformities and non-marine deposition, and restricted marine connections, adding to the challenge of global correlation (Wimbledon, 2008). The difficulties involved in the definition of the Jurassic-Cretaceous boundary and the designation of a global stratotype result in this being one of the last systemic boundary to be defined to modern GSSP standards. Extreme marine faunal provincialism and the lack of any recognized global geochemical “event” have prevented agreement on detailed global correlations.

The work of our team was aimed to specifically fill these knowledge gaps by collecting small samples of rock that will be investigated for microscopic remains of plants (pollen and spores – Dr. J.M. Galloway and Ph.D. candidate K.C. Sulphur) and amoebae (foraminifera – Dr. L.A. Neville) as well as for organic and elemental geochemical signatures (such as trace metals and isotopes). Using micropaleontology integrated with other geological techniques we hope to provide information on the age of the rocks and on the types of plants and environmental settings that were present in the Arctic during this time.

PALEONTOLOGICAL COLLECTION TEAM

Paleontological samples were collected by Dr. J.M. Galloway (GSC research scientist), Dr. L.A. Neville (GSC Visiting Fellow) and K.C. Sulphur (GSC and University of Calgary Ph.D. candidate).

DESCRIPTION OF WORK

Lithostratigraphy

The Sverdrup Basin is an east-west trending, Carboniferous to Paleogene sedimentary basin that stretches from Melville Island in the west to Ellesmere Island in the east. It is approximately 1,000 km long and 350 km wide. During the Jurassic, the Sverdrup Basin was occupied by a shallow sea, with a series of wave-dominated deltas of the Awingak Formation (Late Jurassic) prograding overtop of the shelf mud and silts of the Ringnes Formation (Late Jurassic) (Figure 1). Covering these Awingak Formation sands, are the shelf muds and silts of the Deer Bay Formation (Late Jurassic to Early Cretaceous), which covered much of the basin in latest Jurassic and earliest Cretaceous time. The Deer Bay Formation is then overlain by the delta front sandstones of the basal Isachsen Formation (Embry and Beauchamp, 2008).

The Deer Bay Formation was originally named for a succession of medium to dark-grey shale that underlies the Isachsen Formation on northwestern Ellef Ringnes Island, but no type section was designated (Heywood, 1955, 1957). Succeeding work has expanded the definition of the Deer Bay to include a grey, silty shale with interbeds of siltstone and very fine-grained sandstone. Concretions of various composition, size and shape occur throughout. Most obvious are large, buff, calcitic and sideritic mudstone concretions (or Glendonites) which are most common in the lower portion of the formation. This formation is interpreted to have been deposited in an offshore shelf setting (Embry, 1985). It is of Upper Jurassic-Lower Cretaceous in age, and lies between the Isachsen Formation and either the Awingak Formation or its shale-siltstone equivalent, the Ringnes Formation (Balkwill, 1983; Embry, 1985).

Sampling Information

Fieldwork occurred between July 5th and July 11th, 2015. Two stratigraphic sections of Late Jurassic to Early Cretaceous-aged Deer Bay formation were measured, described and sampled at Buchanan Lake and Geodetic Hills on Axel Heiberg Island, Nunavut (Figure 2). At both locations sampling commenced and ended at the upper (Isachsen formation) and lower (Awingak formation) lithostratigraphic contacts.

Buchanan Lake

Shales of the Deer Bay formation outcropping down the side of a mountain at Buchanan Lake (Figure 2 and Figure 3; Table 1) were sampled over 2 days from July 5th – 6th, 2015. The formation was sampled at an approximate 4 m resolution covering 255 m. At this location 157 samples were collected for pollen and geochemical analyses, and 32 for foraminiferal analysis. Macrofossils were sampled at 6 intervals and consist of bivalves, belemnites, ammonites and wood (Table 2). Weathered Glendonites were abundant at this location.

Geodetic Hills

Shales of the Deer Bay formation outcropping along a river cut at Geodetic Hills (Figure 2 and Figure 4; Table 1) was sampled over 3 days from July 9th – 11th, 2015. The formation was sampled at an approximate 3 m resolution covering 345 m. At this location 93 samples were collected for pollen and geochemical analyses, and 19 for foraminiferal analysis. The only macrofossil collected at this location was a belemnite at 142.5 m. Glendonites were abundant at this location and were collected at 7 intervals (Table 3).

At both Buchanan Lake and Geodetic Hills, high resolution sampling (4 m and 3 m respectively) was conducted for pollen, spores and geochemistry (both elemental and organic), while sampling for foraminifera was less frequent. Samples for foraminifera were collected approximately every 5th sample, therefore every 20 m at Buchanan Lake and 15 m at Geodetic Hills. Collections consist of ~200 grams of material for pollen and geochemical analysis and ~200 grams for foraminiferal analysis. Samples were collected whenever possible from a small pit dug less than 10 cm deep to avoid collecting weathered material. See Tables 2 and 3 for measurement and sampling information on the geological section.

Macrofossils were collected when encountered. These collections consist of the specimen itself and the rock it is hosted in. See Tables 2 and 3 for information and macrofossils collected and corresponding depths.

Table 1. Section location information. Latitude and longitude are recorded in NAD83 format.

Section Name	Age	Stratum	Latitude	Longitude
Buchanan Lake	Late Jurassic – Early Cretaceous	Deer Bay Formation	79.3552391	-87.7209194
Geodetic Hills	Late Jurassic – Early Cretaceous	Deer Bay Formation	79.8149714	-89.8178493

Table 2. Macrofossils collected at Buchanan Lake with corresponding sample names (internal), and depths collected.

Sample Name	Sample Depth (m)	Macrofossils and Other Collection
A15	54	bentonite
A20	74	bivalve, belemnite, ammonite
A25	79	wood, belemnite
A26	80	wood, belemnite
A74	128	wood
A80	134	wood, 2 ammonites
A115	175	ammonite

Table 3. Macrofossils collected at Geodetic Hills with corresponding sample names (internal), and depths collected.

Sample Name	Sample Depth (m)	Macrofossils and Other Collection
B43	142.5	belemnite
B52	191.5	glendonites
B65	237	glendonites
B70	252.5	glendonites
B72	259	glendonites
B73	262	glendonites
B75	268	glendonites
B84	324	glendonites (red weathering)
B85	327	glendonites

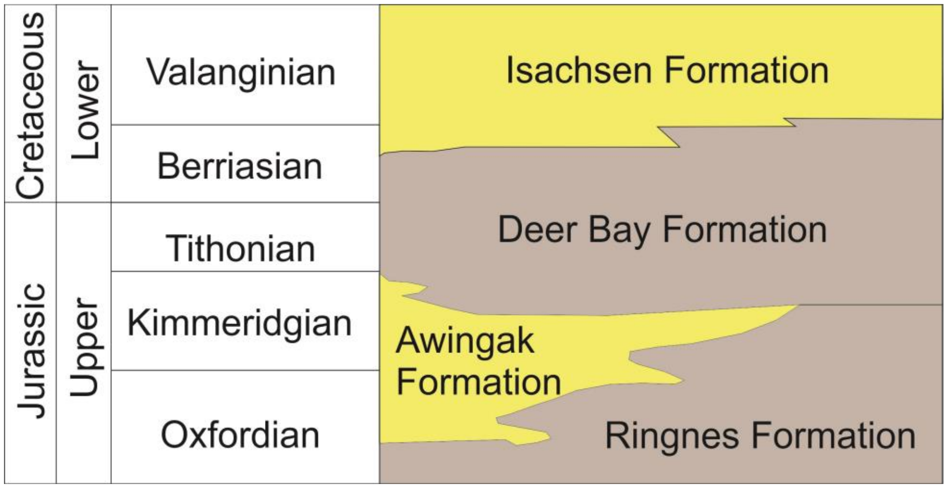

Figure 1. Jurassic-Cretaceous stratigraphy of Sverdrup Basin (after Embry 1991; Dewing and Embry 2007; Obermajer et al. 2007; Embry and Beauchamp, 2008).

Figure 2. Location of the study areas on Axel Heiberg Island, Nunavut. Topographic base source: Government of Canada; Natural Resources Canada; Earth Science Sector; Canada Centre for Mapping and Earth Observation.

Figure 3. Buchanan Lake. **A.** Image of the sampled section of the Deer Bay Formation outcropping down the side of the mountain, with a trail of sample bags containing shale samples. The orange sediments at the top of the mountain belong to the Isachsen Formation, where sampling commenced. **B**. Image of fossil wood collected from the Deer Bay Formation (see Table 2 for sample depth in formation). **C**. Image of an ammonite collected from the Deer Bay Formation (see Table 2 for sample depth information).

Figure 4. Geodetic Hills. **A**. Image of the sampled stream cut section of the Deer Bay Formation. **B.** Image of glendonites which are abundant in the lower portion of the Deer Bay Formation at both this location and at Buchanan Lake. Glendonites are pseudomorphs of Ikaite, which is the hexahydrate of calcium carbonate, and they are characteristic of the Deer Bay formation.

Preparation, Processing and Analyses

Upon arrival at the GSC-Calgary samples will be sub-divided for various analyses and catalogued with GSC Catalogue numbers. The microfossil preparation and analyses will be conducted at the GSC-Calgary, where matrix will be removed and the microfossils (fossil pollen, spores, algae, and foraminifera) will be isolated and mounted on microscope slides. The microscope slides will then be examined under a microscope by a paleontologist who can identify the organisms and determine the age and environment during which the rock was deposited based on the types and amounts of microfossils present. This is a very time consuming process.

Additional analyses to be conducted on the collected material include macrofossil interpretation, geochemistry, organic carbon isotope analysis, Rock-Eval pyrolysis and organic petrology. Macrofossil specimens will be identified by Dr. J. Haggart (GSC-Vancouver) or Dr. T. Poulton (GSC-Calgary) and then be curated. Macrofossil specimens will undergo no destructive process. Rock-Eval pyrolysis and organic petrology will be conducted at the GSC-Calgary, to determine the amount and source of organic matter in the rock and its chemical characteristics. Bureau Veritas Laboratories, Vancouver, BC, or a similar commercial laboratory, will be used to conduct geochemical analysis to provide additional information on the environmental setting in which the rock was deposited. Carbon isotope analyses will be conducted at the Institute of Geosciences (Goethe-University Frankfurt, Germany), using MAT 253 gas source mass spectrometer.

REPORTING

A series of government reports and publications will be produced using this data by the Geological Survey of Canada. These will be distributed to the Minerals and Petroleum Resources Divisions of the Department of Economic Development and Transportation, Government of Nunavut and to the Canada-Nunavut Geoscience Office. All reports will be available for free download on the internet. Results will be discussed at the Yellowknife Geoscience Forum and at future Nunavut Petroleum Workshops (in Iqaluit).

CONCLUSIONS

The shale samples collected during the July 2015 field season from the Deer Bay formation outcropping at Buchanan Lake and Geodetic Hills on Axel Heiberg Island and subsequent analyses will contribute to GEM by providing insight on basin development and Mesozoic time systems. We expect our interpretation of the paleontological and geochemical data retrieved from these samples to continue throughout the 2016/2017 fiscal year.

ACKNOWLEDGMENTS

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COLLABORATIVE BEDROCK MAPPING OF WHITE GLACIER BASIN, AXEL HEIBERG ISLAND, NUNAVUT

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ABSTRACT

This article outlines a collaborative project in development involving participants in the GEM 2 HALIP Activity and the Laboratory for Cryospheric Research, University of Ottawa. Glaciological research in the vicinity of White Glacier, Expedition Fiord, has recently involved the combined use of Structure from Motion photogrammetry methods and ultra-high resolution GigaPan© images to study landscape evolution. Here we propose to apply these techniques to generate a detailed geological map of the area centred on the Between Lake massive sulphide showing. The requirements include (a) sufficient camera resolution, (b) the availability of high-resolution satellite imagery, and (c) ground-based measurements using differential GPS systems. A 4-step approach is proposed that involves limited helicopter survey work to establish ground-control markers; the acquisition of high-resolution, spectrally-rich satellite images such as SPOT6 or WorldView3; the use of panoramic photography using GigaPan©; and targeted sampling of ridges and nunataks to ground truth a preliminary remote predictive geological map. The requirements as well as the mutual benefits to be gained in glaciological and geological research are discussed. For example, improved bedrock mapping could help to better delineate the extent of the massive sulphide deposit, and improve understanding of controls on the subglacial hydrology and basal motion of White Glacier.

INTRODUCTION

Recent communications with field geologists involved in GEM 2 HALIP field work on Axel Heiberg Island (Williamson et al., 2015) revealed the potential for collaboration between our research teams[1]. Our glaciological mapping included an air photo survey conducted in July 2014 of White Glacier and surrounding regions, with the resulting 400+ oblique photographs processed using Structure from Motion photogrammetry methods to create a new high-resolution digital elevation model (DEM; 5 m resolution) and orthoimage mosaic (1 m resolution) of the region (Thomson and Copland, in press). Comparison of this DEM and orthoimage with historical maps and photographs enables quantification of changes in the volume and structural elements of White Glacier over the past half-century. This work has been supplemented with the recent use of ultra-high resolution panoramic images produced with a GigaPan© system, which have been taken at various locations around the margin of White Glacier to provide a record against which future changes can be compared.

In this paper, we propose to apply similar methods, combined with more extensive coverage provided by high resolution satellite imagery, to: (1) improve the spatial mapping of massive sulphides exposed in the Between Lake area located ~ 1 km north of the White Glacier terminus, and (2) extend the capacity for geological mapping at higher elevations where enhanced melt conditions have increased the exposure of nunataks in recent decades. While supporting the objectives of HALIP, improved geological maps of the White Glacier basin will also advance glaciological research by revealing the potential geological controls on glacier processes including ice flow dynamics, subglacial thermal and hydrological regimes, and the surface expression of these factors (e.g. crevasse and fault patterns).

[1] Laboratory for Cryospheric Research, University of Ottawa (http://cryospheric.org)

STUDY SITE

White Glacier is a 14 km long alpine glacier that terminates adjacent to the Thompson Glacier (40 km long) at the head of Expedition Fiord on western Axel Heiberg Island, Nunavut (Figure 1). To the north of this junction is the location of Between Lake (Figure 2), an ice-dammed lake which historically formed during the onset of melt conditions in the early summer (June) (Maag, 1969). However, this lake has failed to form since approximately 2010 due to the creation of a new drainage channel between White and Thompson Glaciers. On the south-easterly facing slope above the current lake bed, a showing of massive sulphides first documented during an industry exploration program (Goddard, 2010) was sampled by the HALIP team in 2015 (Williamson et al., 2015). Evaporite structures are ubiquitous in the area (Harrison and Jackson, 2014) as well as gossans and hydrothermally altered rocks, Upper Triassic to Lower Jurassic sandstone, siltstone and shales, and diabasic and gabbroic sills and dykes assigned to the HALIP (Harrison and Jackson, 2010). However, the detail of the most recent geological mapping has been limited by the presence of glacier ice and associated hazards.

PREVIOUS WORK

The following section describes methods currently being used for glaciological research in the Expedition Fiord region with a primary focus on the capabilities of Structure from Motion 3D mapping as a resource for geological mapping, which has been demonstrated successfully in previous studies (Westoby et al., 2012). As an example, on July 10, 2014, an air photo survey was conducted over White Glacier from a Bell 206L helicopter for the purpose of determining changes to the glacier extent and volume since earlier mapping campaigns in the early 1960s. Average flying height was ~1800 m above sea level, which equated to ~300 to ~ 1500 m above ground level in the White Glacier basin. The project used the Structure from Motion software PhotoScan by Agisoft LLC of St. Petersburg, Russia, to produce the topographic model for a new 1:10,000 map of the glacier (Thomson and Copland, in press). For this survey of White Glacier, camera settings such as low-exposure and low-angle lighting were specifically tuned to enable detection of snow and ice-surface features. As a result, the surrounding rock face and bedrock outcrops were often in shadow or displayed relatively low internal contrast. Despite this, the model output reveals significant details in the exposed bedrock, highlighting the potential of Structure from Motion for geological mapping (Figure 3).

The Structure from Motion method for deriving topographic information from stereo imagery operates on the principles of classical photogrammetry, but with the added advantage of computer automated image correlation analysis. As a result, it is possible to integrate hundreds of photographs, which may be taken at oblique angles and at a variety of scales, into a photogrammetry project. The main components of a Structure from Motion project include:

(1) Designing the air photo survey (including setting ground-control markers);
(2) Conducting the air photo survey using camera settings tuned to optimize contrast and feature detection on the target;
(3) Post-processing digital photographs in a photo editor to further enhance feature contrast;
(4) Importing select photos into Structure from Motion software and removing regions of photographs outside the target area (e.g. cloud features above the horizon);
(5) “Aligning” the photographs through automated feature detection and manual entry of ground-control points (known x, y, z, coordinates);
(6) Bundle adjustment of the photographs, which builds the initial point cloud (points with x, y, z coordinates);
(7) Quality assessment and filtering of the point cloud;
(8) Interpolation between points to build a continuous digital elevation model (DEM);
(9) Overlay of photograph-derived colour to create a 3D orthoimage.

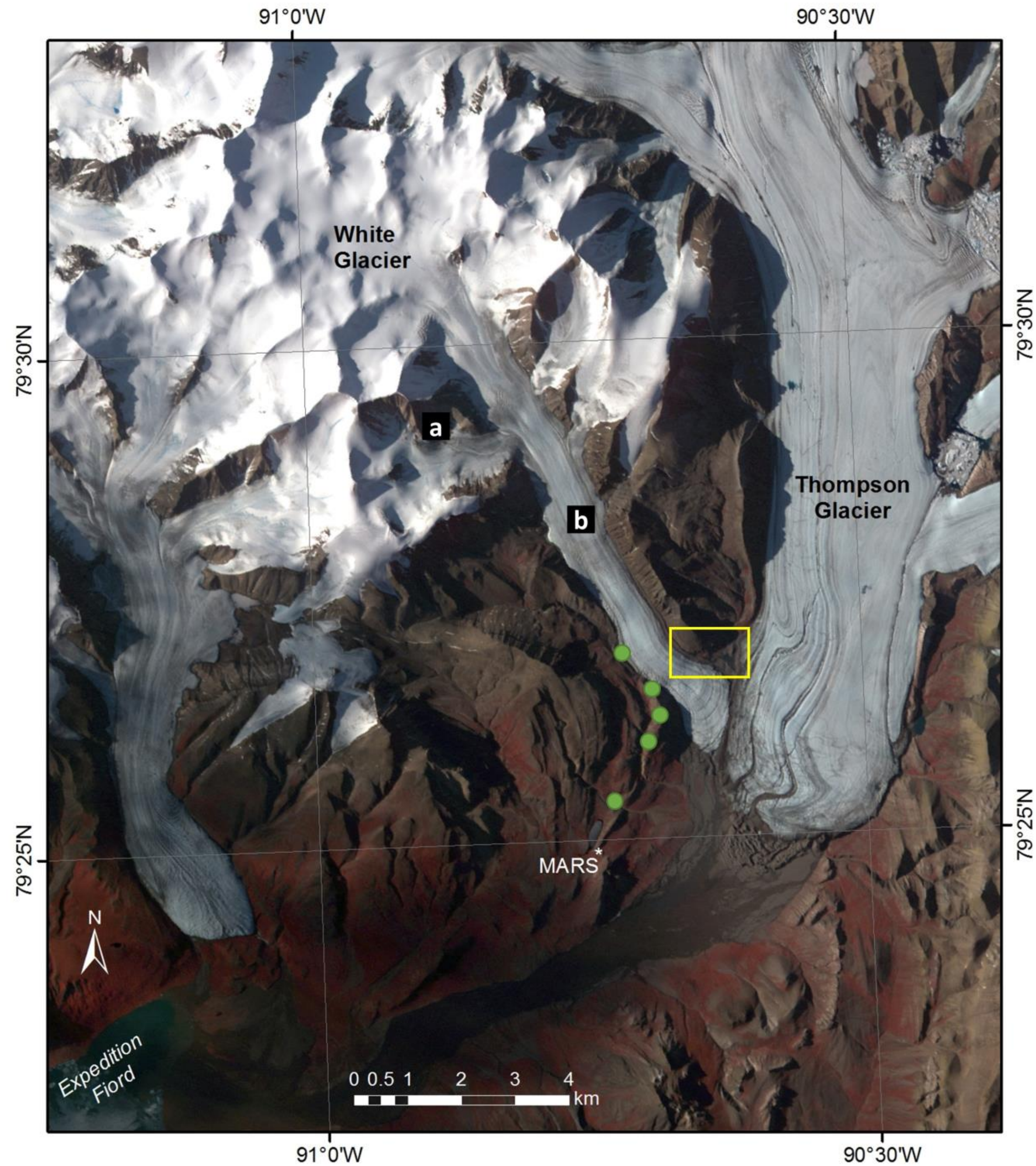

Figure 1. Satellite image of the White and Thompson glaciers region showing the locations of the McGill Arctic Research Station (MARS), the massive sulphide region shown in Fig. 2 (yellow box), the example sites in Fig. 3 (a, b), and the locations of 2013 GigaPan© surveys (green circles). Background image: ASTER L1B composite, July 5, 2010.

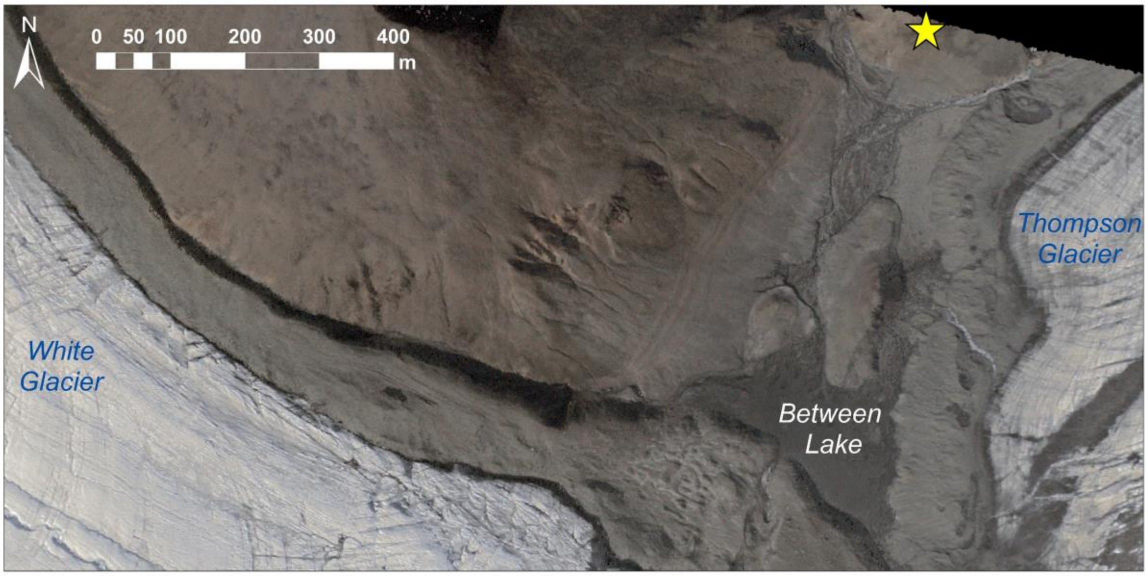

Figure 2. High angle oblique view of Between Lake with White Glacier to the west and Thompson Glacier to the east, with the location of massive sulphide showing indicated by the yellow star symbol. The background orthoimage (1 m resolution) was produced using Structure from Motion software, from approximately 20 photographs collected in July 2014.

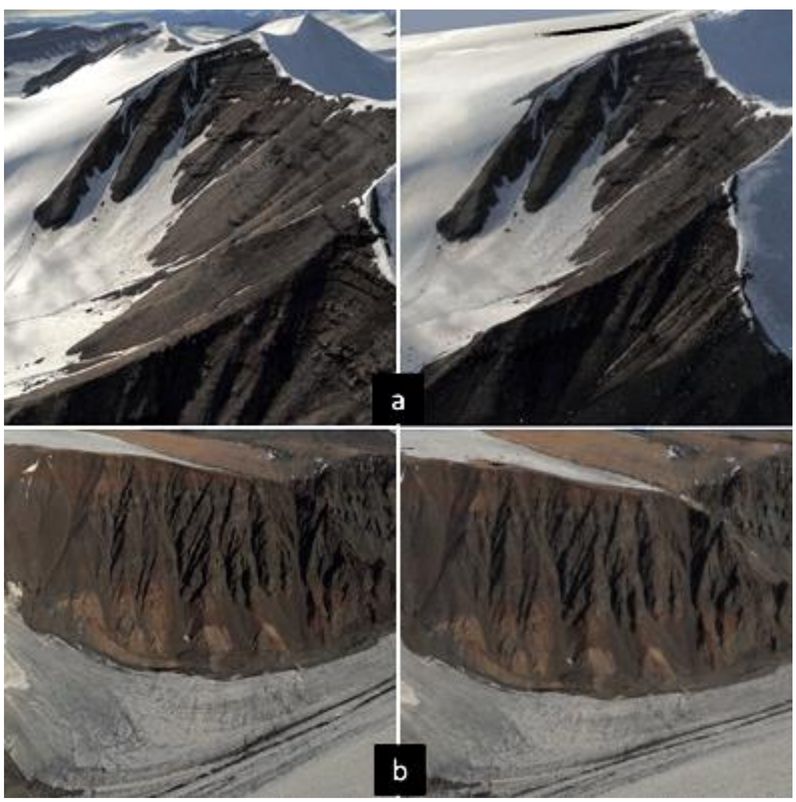

Figure 3. Examples of photographs collected during the July 2014 helicopter survey (left), and the 3D model results (right). Image locations are indicated in Figure 1.

The two products created in steps (8) and (9) can then be exported for use in other geospatial mapping software (e.g. ESRI ArcGIS). The accuracy and resolution of the model depend on the amount of ground control and image resolution. For example, the 2014 air photo survey was used to generate topographic products with 10 m vertical and 5 m horizontal errors, and an orthoimage product with 1 m resolution with minimal ground control (Figure 4; Thomson and Copland, in press).

PROPOSED METHODS

Application of Structure from Motion techniques to geological mapping within the White Glacier basin has the potential to significantly enhance knowledge concerning bedrock and surficial features within this region via the production of new high resolution DEMs and orthomosaics. Additional imagery from satellite platforms and the merging of high-resolution ground based photography (GigaPan©) are also presented as supporting methods.

Helicopter Survey

To undertake this work would require dedicated helicopter time to: (1) establish ground-control markers, and (2) conduct the air photo survey with camera settings tuned for bedrock areas. The amount of helicopter time required for objective (1) depends on how many new ground control points need to be installed (e.g., some existing ones on White Glacier Hill, to the southwest of the glacier terminus, could be re-used; see Figure 4), but an allowance of 2 hours of helicopter flight time to put out markers and retrieve them afterwards should be sufficient. The flight time required for objective (2) depends on the spatial extent of the target area, but approximately 1 hour should be sufficient. For context, the helicopter survey in 2014 that covered the entire glacier basin (~40 km^2, Figure 5) was conducted in ~1.5 hours. Regarding (2) it may also be beneficial to conduct the air photo survey over two sessions (e.g. early and late in the day) to allow for differing sun illumination over targets. The time required for photo processing, the manual entry of ground-control points, and model building is variable depending on the complexity of the survey, but 80-160 hours is a reasonable estimate for a project with <200 photographs.

Satellite Imagery

High-resolution satellite remote sensing products (e.g. IKONOS, WorldView, GeoEye, QuickBird with spatial resolutions of 1 m or less) have the potential to augment geological mapping endeavours that incorporate Structure from Motion techniques. Besides the obvious benefits of providing information on conditions in locations that are difficult to access on the ground, these images can offer geospatial context at the onset of Structure from Motion model building (e.g. by aiding the alignment of problematic photos), and by providing an easy and comparatively cost effective source for ground-control information. While some optical satellite imagery is already freely available over this region (e.g. ASTER, Landsat, SPOT4), the resolutions of these products (15 m for ASTER and Landsat, Figure 6a; 10 m for SPOT4, Figure 6b) are insufficient for Structure from Motion ground-control. Commercial high resolution satellite imagery can provide sufficient resolution for Structure for Motion and geological mapping (Figure 6c), and approach resolutions available from terrestrial photography (Figure 6d), but existing imagery that we possess is limited and out of date. New acquisitions and/or the purchase of archived high resolution satellite imagery would provide a record of current conditions and enable improved mapping.

GigaPan© Images

The recent development of robotic motorized mounting heads and automated photo stitching software has enabled the production of ultra-high resolution panoramic photos via the merging of many individual photos. Companies such as GigaPan© offer commercial systems that can be used for this purpose, and in summer 2013 a GigaPan© Epic Pro system was used with a Canon© EOS6D SLR camera to take a series of images in the White Glacier region. For a complete 360° panorama, these images typically consisted of approximately 70 to 226 individual 20.1 megapixel photos taken at focal lengths of 70 to 105 mm.

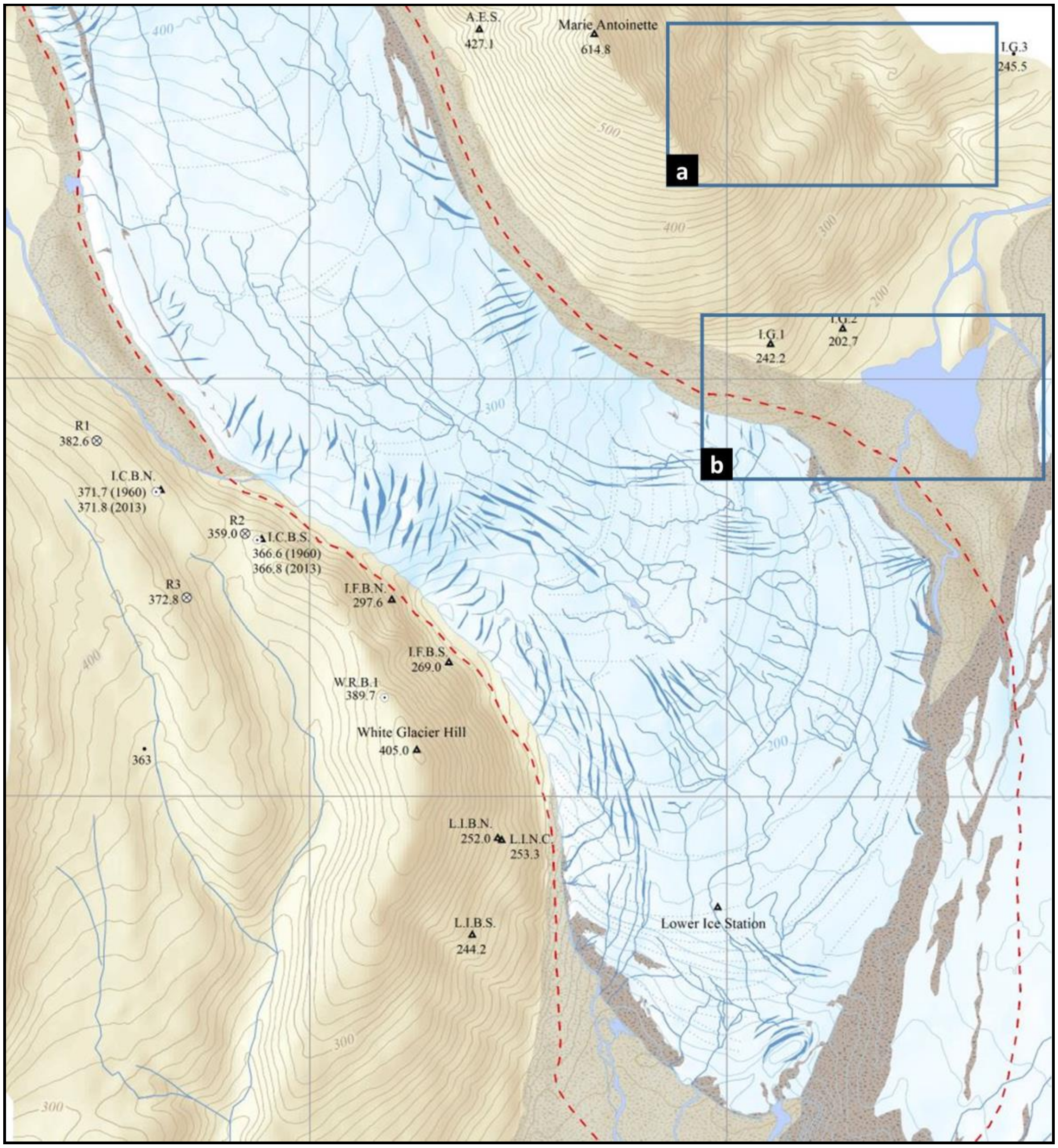

Figure 4. The terminus region of White Glacier and Between Lake, extracted from the new 1:10,000 map of the glacier (Thomson and Copland, in press) produced from >400 oblique aerial photographs in AgiSoft PhotoScan and ESRI ArcGIS. **(a)** Indicates the region of high interest for metallogenic studies and **(b)** indicates the region displayed in Figure 2.

Figure 5. Flight path for helicopter survey, July 10, 2014 with northbound flights in red, southbound flights in blue, and a reconnaissance flight indicated in orange.

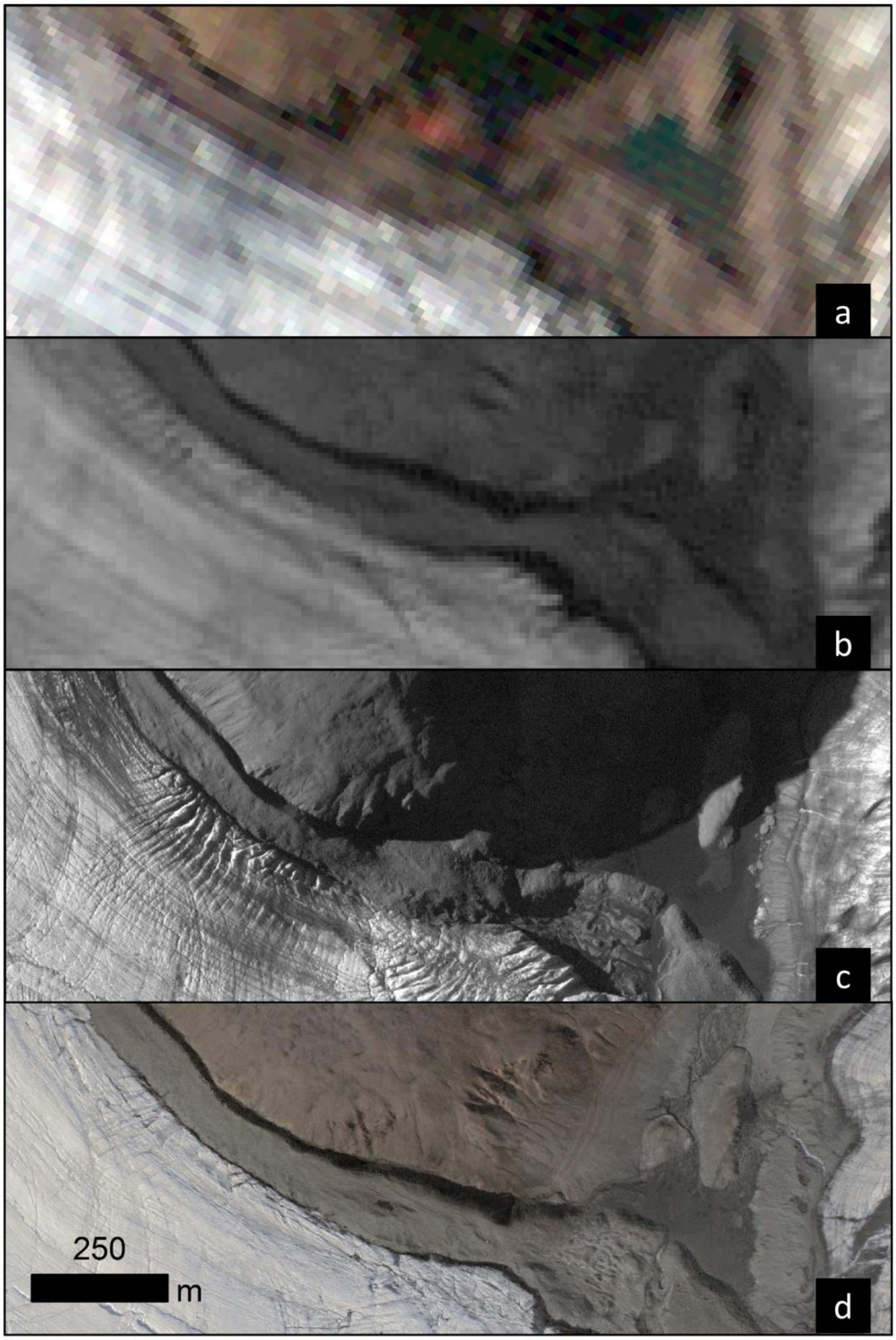

Figure 6. Comparison of satellite imagery at a range of resolutions: **(a)** ASTER L1B composite, July 5, 2010, 15 m resolution; **(b)** SPOT4 panchromatic, July 28, 2006, 10 m; **(c)** GeoEye panchromatic, July 20, 2002, 80 cm resolution; **(d)** Structure from Motion derived orthoimage from July 2014 photography, 1 m resolution.

All GigaPan© imagery taken by members of the Laboratory for Cryospheric Research is publicly available[2]. These images offer unprecedented resolution over large areas (Figure 7), and are useful for monitoring changes in glaciers and associated features (e.g., proglacial channels) over time. New GigaPan© acquisitions in selected areas, such as adjacent to the massive sulphide deposit in the Between Lake area, would provide an excellent data source for enhanced geological mapping of features.

Bedrock Sampling

Under this collaboration, members of the Laboratory for Cryospheric Research could collect geological samples on behalf of HALIP from regions in the White Glacier basin that are inaccessible during the summer but can be reached by snowmobile in April and May. Due to relatively low snow accumulation (<1 m depth) and high-winds, nunatak outcrops in the high accumulation area are typically snow-free during the spring field season. An automatic weather station is established on one of the larger nunataks near the top of the White Glacier basin that is visited on a regular basis for servicing and data acquisition, and as such these visits could provide an opportune time to also collect rock samples.

CONCLUSIONS

The application of mapping and survey techniques recently applied to White Glacier could be used to produce an updated and improved geological map of the White Glacier basin. Specifically, the following methods would be applied:

1. A new air photo survey, requiring a total of approximately 3 hours helicopter flight time, focused on bedrock exposures in the area of interest, with a particular focus on the massive sulphide showing recently discovered at Between Lake. This would produce a new high resolution photo orthomosaic of these bedrock areas, and potentially a new high resolution DEM for these areas if proper ground control points are established prior to the survey.
2. Acquisition of new high resolution (<1 m resolution) optical satellite imagery of the study region from sensors such as WorldView, QuickBird, GeoEye and Ikonos.
3. Production of new ultra-high resolution panoramic photo mosaics (‘GigaPans’) of areas of interest. Helicopter access would need to be provided for most locations at high elevations on either side of the basin, although access to most of the massive sulphide deposit could be made on foot.

BENEFITS AND OUTCOMES

In addition to aiding and improving the geological history and setting of western Axel Heiberg Island in support of the HALIP activity (Dewing, 2015), this mapping would aid in interpreting ice flow patterns and the terraced topography of White Glacier. Ice flow and glacier topography (i.e., hypsometry) are important factors controlling the sensitivity and stability of glacier response to changes in regional climate. By overlaying a new geological map on the 1:10,000 map of White Glacier (Thomson and Copland, in press), it will be possible to observe the spatial associations between geological boundaries and observed glacial features (e.g., icefalls, crevasse zones, terrace breaks). A preliminary example of such a map overlay is shown in Figure 8, with the Harrison and Jackson (2010) geological map overlain on an ASTER satellite image. The study of geological features impacting ice flow and hypsometry will be supported by ice-penetrating radar measurements of the glacier bed topography acquired during the spring 2014 and 2015 field seasons. In addition, a better understanding of the geological setting will help determine the nature of the bedrock underlying White Glacier. Glacier basal conditions are an important control on both subglacial hydrology and glacier sliding processes, but to date the subglacial geological conditions of White Glacier are largely unknown.

[2] Laboratory for Cryospheric Research GigaPan© images: http://gigapan.com/profiles/cryospheric

Figure 7. **(a)** Example of a GigaPan© image of White Glacier taken on July 18, 2013). The original image can be viewed at http://gigapan.com/gigapans/136016. **(b)** Close up of the region indicated by the white box in part **(a)**.

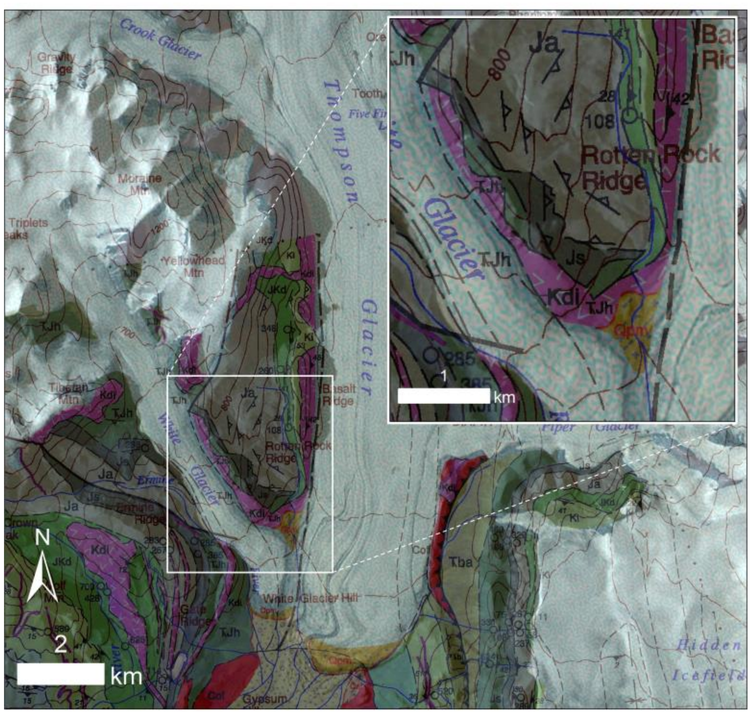

Figure 8. Geological map by Harrison and Jackson (2010) overlain on ASTER L1B composite from July 5, 2010. The inset map shows the location of a massive sulphides exposed near Between Lake in a region currently mapped as **Qpm** (Quaternary push moraine) and **Kdi** (diabase and gabbro sills and dykes, 129-113 Ma).

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