**GEOLOGICAL SURVEY OF CANADA
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GEM 2 High Arctic Large Igneous Province (HALIP) activity: workshop report

M.-C. Williamson (Editor)

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Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario

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Publications in this series have not been edited; they are released as submitted by the author.

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FOREWORD

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The GEM 2 HALIP Activity

The Geo-mapping for Energy and Minerals (GEM)1 program 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 (2008-2013), GEM has been renewed for another seven years (2013-2020), with the continuing goal of producing new, publically available, regional-scale geoscience knowledge in Canada's North. 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.

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), was the focus of an activity approved for the second phase of GEM, within the Western Arctic Region Project. The main objective of the HALIP activity, from 2014 to 2017, was to identify areas on Axel Heiberg Island and Ellesmere Island that show a high potential for Ni-Cu-PGE deposits (Figure 1). Specific activities included (1) detailed mapping and documentation 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.

The HALIP Workshop

The areas investigated during the course HALIP activitities are illustrated on Figure 2. In July 2015, field work carried out by HALIP teams had yielded a wealth of information on volcanic-intrusive complexes, evaporite structures and stream sediments. As the project approached mid-life, it made sense to invite experts on the High Arctic Large Igneous Province to discuss these preliminary results. In addition, representatives from the resources industry could provide feedback on future research priorities.

The HALIP Workshop was held on February 12-13, 2016, in Ottawa, Ontario. The workshop brought together 17 participants from two divisions of the Geological Survey of Canada, the Polar Continental Shelf Program, the University of Ottawa, Carleton University, Memorial University, the University of Oslo, Newgenco, and Shell (USA). Presentations and plenaries were held at the Canadian Museum of Nature and at the University of Ottawa. This report is a compilation of extended abstracts that were submitted by participants in advance of the Workshop, and edited prior to the event. The topics are grouped into two themes: Overview of the High Arctic Large Igneous Province and Metallogeny.

Additional reporting

In addition to this report, HALIP Workshop 2016 participants agreed to propose a Special Session on Magmatic Processes Associated with

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[1] http://www.nrcan.gc.ca/earth-sciences/resources/federal-programs/geomapping-energy-minerals/18215

Large Igneous Provinces for the 2017 meeting of the Geological Association of Canada. As a result of this initiative, a team of five participants co-convened session GS1 *Magmatic and Metallogenic Processes Associated with Large Igneous Provinces*, to be held at GAC-MAC 2017 in Kingston, Ontario, on May 15-16, 2017.

A second GSC Open File will include a summary of HALIP presentations at GAC-MAC 2017 that are relevant to the Workshop results. The projected Open File will also include suggestions for future work.
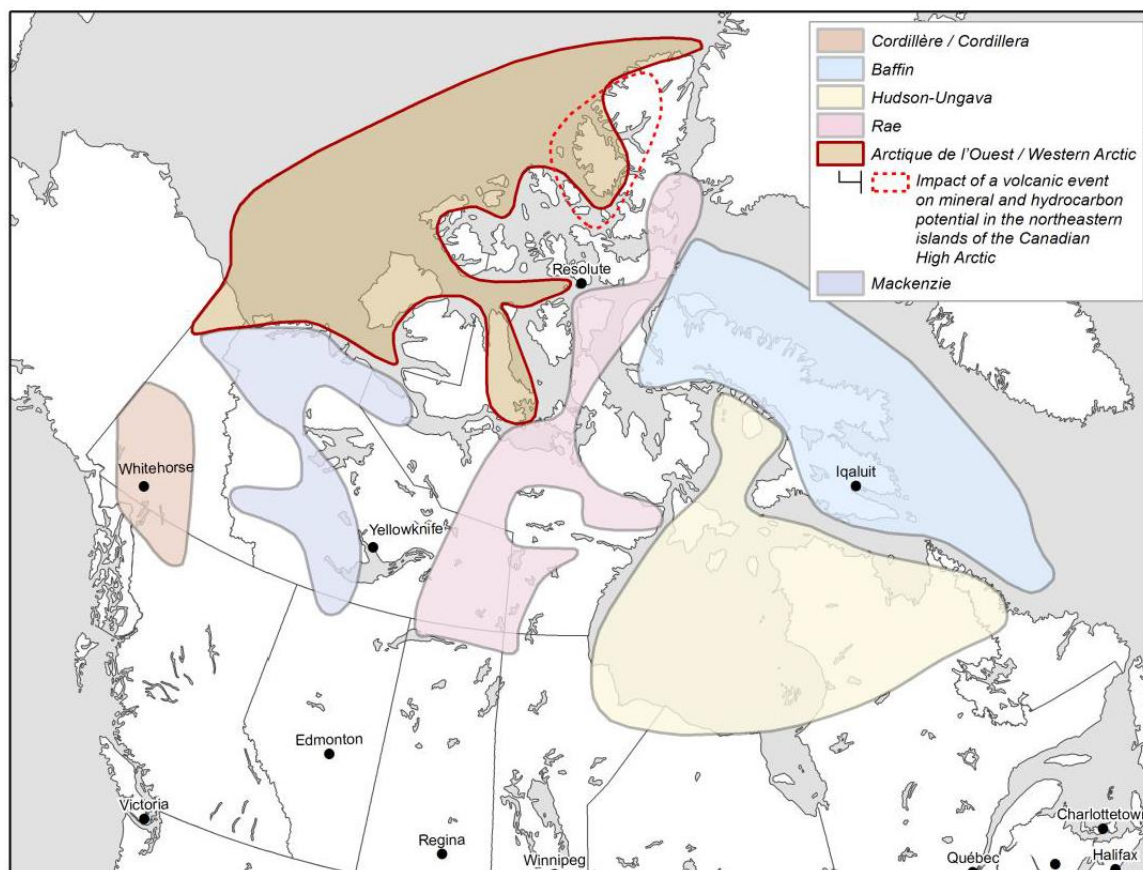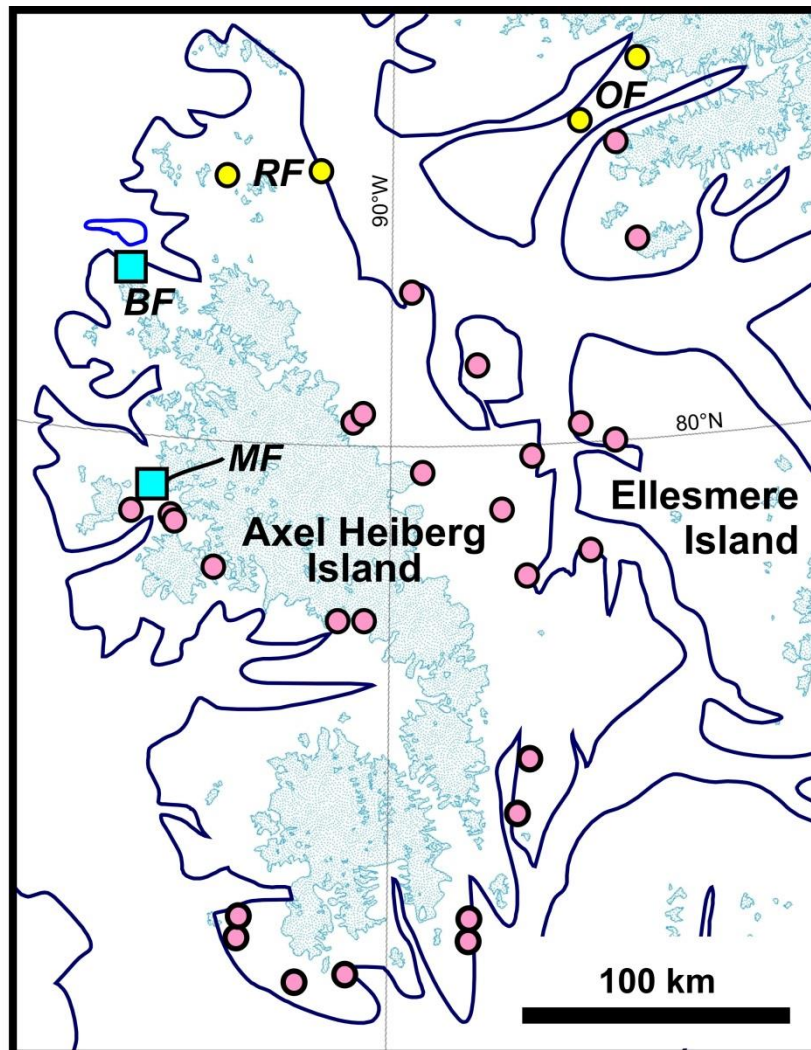
Figure 1. Regional map of the GEM 2 activities (2014-2017) showing the area covered by the Western Arctic Region Project. The red dotted line shows regional coverage for the High Arctic Large Igneous Province activity.

Figure 2. Map of Axel Heiberg Island and western Ellesmere Island highlighting GEM 2 HALIP 2015 and 2016 field sites. Sites of fieldwork were named after nearby fiords.

HALIP INTRUSIVE AND EXTRUSIVE COMPLEXES
OF SVALBARD AND THE BARENTS SEA

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Introduction

The aim of this presentation is to give a synthesis of our recent work on the distribution, age, formation and impact of the HALIP in the Barents Sea region documented in papers [1] to [6].

Distribution

Mafic igneous rocks of Cretaceous age (80–130 Ma) scattered around the Arctic Ocean are commonly referred to as the High Arctic Large Igneous Province (HALIP). We have mapped out the distribution of HALIP igneous rocks in the Barents Sea region over the past decade based on integrated seismic–gravity–magnetic interpretation, field work, review of publications, and analyses of new and vintage borehole and field samples [2, 3, 4]. The mapping reveals abundant igneous rocks in the northern and eastern Barents Sea covering an area of ~900,000 km^2 with a conservative volume estimate of 100,000 to 200,000 km^3 of intrusions. The igneous province is dominated by sheet intrusions injected into Triassic and Permian sedimentary rocks and is referred to as the Barents Sea Sill Complex (BSSC) [2]. Extrusives are less abundant, but present on Franz Josef Land (FJL) and eastern Svalbard. Hydrothermal vent complexes are rare, and only two potential vent complexes have been identified on seismic data in the eastern Barents Sea.

Age

We have done extensive radiometric dating of the igneous samples [1, 2]. New $^{40}Ar/^{39}Ar$ dating of thirteen samples from Svalbard reveal ages of crystallization and alteration. The large age span (60–140 Ma for the raw ages) is likely due to partial or complete overprint of the K/Ar system in plagioclase, and the age of the magma emplacement is better represented by U/Pb TIMS ages. Only one of the $^{40}Ar/^{39}Ar$ analyses of plagioclase yielded a statistically valid age that is in line with the U/Pb TIMS ages of 122–125 Ma. The new data clearly document that relying on published data from the K/Ar system can lead to erroneous conclusions on the age of crystallization in this province without a careful use of additional $^{40}Ar/^{39}Ar$ degassing data (i.e., K/Ca). We propose that the magmatism of Svalbard and FJL represents a distinct magmatic event near the Barremian/Aptian boundary (125 Ma).

Formation

The petrology and geochemistry of doleritic sills, dykes and flood basalts of FJL and Svalbard shows the main magma type on both islands is evolved, tholeiitic ferrobasalt, although FJL also include alkali basalt, basaltic andesite and rhyolite [6]. Major and trace element compositions indicate that their formation included two dominant mantle components: enriched mantle akin to that of plumes associated with ocean island basalt and other LIPs, and subduction modified mantle. Crustal contamination also influenced the magmas. The somewhat different compositions of magmatism of Svalbard and FJL are interpreted as a consequence of variations in the mixing proportions of mantle components and crustal contamination. The rare earth element compositions demonstrate that the melting conditions also differed slightly with a relatively stable, thick lithospheric lid in the case of Svalbard and a more dynamic, thinning lithospheric lid during FJL magmatism.

Impact

The massive injection of hot magma into potentially organic-rich sediments in the eastern and northern Barents Basin caused rapid organic matter maturation and formation of thermogenic gas and oil in contact aureoles [2, 5]. We estimate that up to 20,000 Gt of carbon were potentially mobilized, corresponding to 175 trillion barrels of

oil equivalent. The production rates and fate of the carbon gases are uncertain. However, we speculate that rapid release of aureole greenhouse gases (methane) may have triggered the Oceanic Anoxic Event 1a (OAE1a) and the associated negative δ^{13}C excursion in the Early Aptian. Some of the methane may also be trapped in the vast hydrocarbon gas accumulations found in the east Barents Basin.

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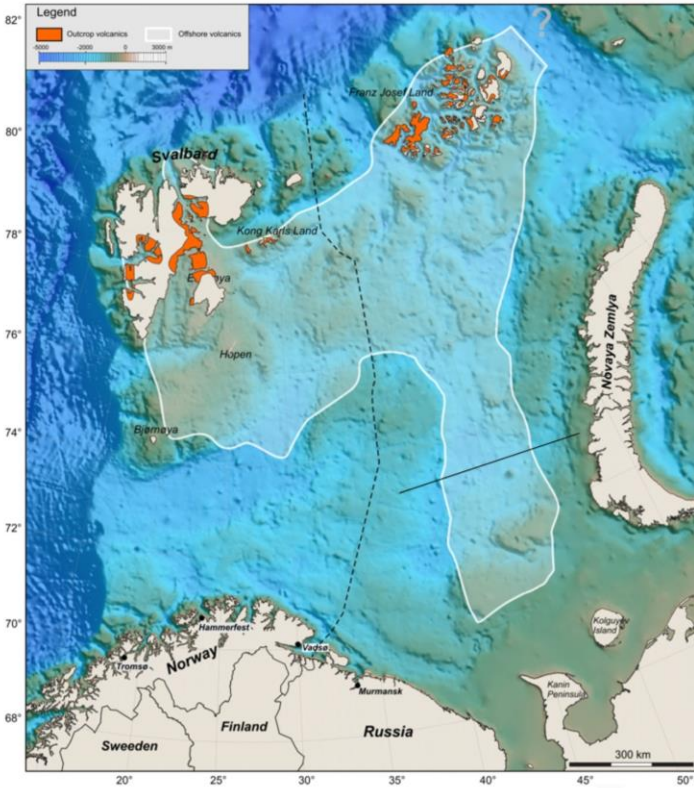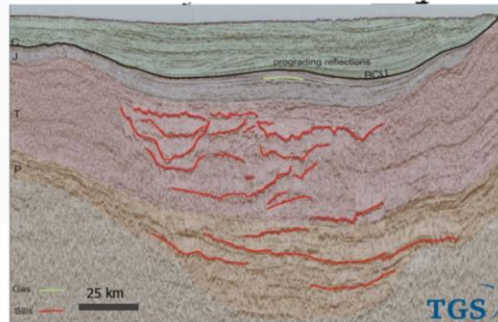
Figure 1. Barents Sea bathymetry map showing onshore and offshore distribution of Cretaceous igneous rocks, selected offshore hydrocarbon fields and wells, and interpreted seismic profiles in the Eastern Barents Sea. (from [2]).

HIGH RESOLUTION STRATIGRAPHY OF A 10 MYR CENOMANIAN-TURONIAN INTERVAL, TRANS-PECOS, TEXAS, USA: KEY TO UNDERSTANDING STARVED CARBONATE SHELF DEPOSITION IN A GREENHOUSE CLIMATE, CALDERA ERUPTIONS, AND IMPACT OF THE HALIP

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Introduction

The Boquillas Formation (Fm.) (equivalent to the Eagle Ford Group) and portions of bounding Buda Fm. and Austin Chalk were deposited at the Southern end of the Cretaceous Western Interior Seaway (KWIS) and the northwestern margin of the Gulf of Mexico Carbonate Shelf (passive margin) in a starved retroarc foreland basin setting during part of the Cenomanian and Turonian Stages (CT; 99-89 Ma). The Boquillas Fm. includes several Oceanic Anoxic Events (OAE) marked by global Carbon Isotope Excursions (CIE) and trace metal anomalies [1]. The Boquillas Fm. consists of a succession of cyclic marlstone and limestone beds and over 300 bentonites deposited in a distal, restricted, suboxic setting mostly below storm wave base [2]. Bentonites are generally homogenous, clay-rich layers 1-10 cm thick (average 5 cm, up to 1 m) showing sharp contacts and strong yellow-orange mineral fluorescence under ultraviolet light. In addition to detailed logging of roadcuts, two research wells drilled behind outcrops, Shell IONA-1 and Shell INNES-1, recovered >330 m of continuous core from the Austin Chalk at surface through the Boquillas and Buda Limestone Fm. The bentonites form ~5% of the 60-111 m thick Boquillas Fm. intervals, and are interpreted as distal pyroclastic fall deposits from large volume (>10-100 km^3) Plinian eruptions from calderas associated with the subduction-related Western North American Cordilleran magmatic arc of the Sierra Nevada and Peninsular Ranges. Some of the Boquillas Fm. bentonites can be correlated using cores, petrophysical logs, geochemistry, and biostratigraphy for more than 1000 km to the north within the KWIS at the CT global stratotype (GSSP) section at Pueblo, CO as well as many other sections in the KWIS.

High resolution stratigraphy

This contribution integrates new high-precision zircon U/Pb TIMs age data from both core and outcrop samples with independent proxies derived from sedimentology, biostratigraphy, orbital cyclostratigraphy, isotope stratigraphy and trace element geochemistry (see [3] and [4] for details).

We present a robust chronostratigraphic framework for the CT stages, key to the interpretation of sediment accumulation rates (compacted rates=1.4-6.5 cm/kyr, lowest in the Boquillas and highest in the Buda and Austin Chalk); lateral variability and character of depositional environments; diagenetic effects; and sequence stratigraphy in a ~10 Myr long greenhouse climate-driven carbonate shelf influenced by explosive volcanism and Large Igneous Provinces (LIPs). We show that the OAE2 CIE coincided with an $^{187}Os/^{188}Os_i$ excursion [5] at 95.0±0.1 Ma, probably related to eruption of the High Arctic Large Igneous Province (HALIP) and/or Caribbean Large Igneous Province (CLIP), coinciding with a major change from Tethyan to Boreal marine circulation in the KWIS.

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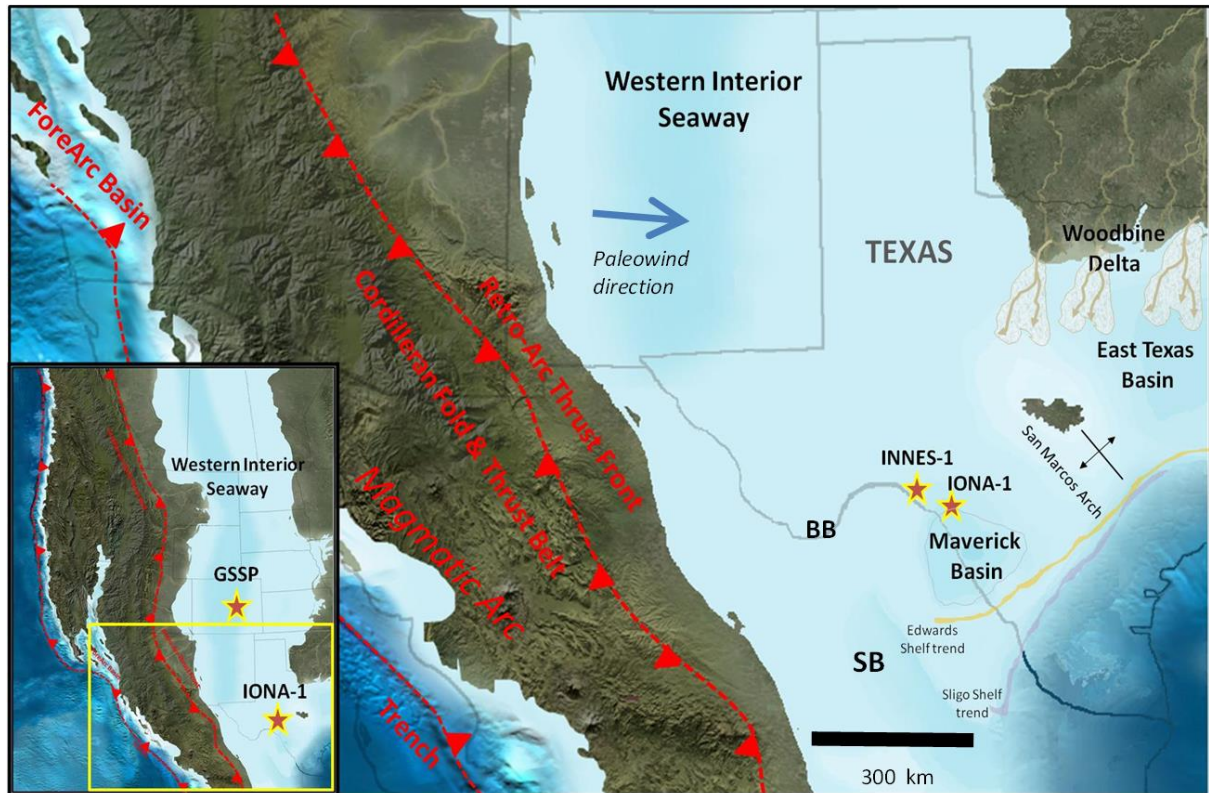
Figure 1. Middle Cenomanian (~96 Ma) palaeogeographic map showing the location of Iona-1, Innes-1, and USGS Portland-1 cores (GSSP) in the regional tectonic context; modified from Ron Blakey and the Colorado Plateau Geosystems Inc. **SB**: Sabinas Basin, Mexico; **BB**: Big Bend National Park.

GIANT CIRCUMFERENTIAL AND RADIATING DYKE SWARMS OF THE HIGH ARCTIC LARGE IGNEOUS PROVINCE

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It is thought that major dyke swarms associated with the High Arctic Large Igneous Province (HALIP) in the Canadian Arctic islands, northern Greenland and Franz Josef Land, along with a few isolated dykes in Svalbard, were emplaced as a giant radiating dyke swarm [1, 2]. However, plate tectonic processes have distorted the radiating geometry, so that the original dyke pattern is only obtained in a pre-late Cretaceous paleocontinental reconstruction (Fig. 1a). The focus of the reconstructed swarm is near the Alpha Ridge and may represent a mantle plume centre [3]. The dykes extend up to 1000 km from the focus.

Recent analysis has resulted in the identification of a second giant dyke swarm associated with HALIP, one which circumscribes the probable plume centre [4] and can best be viewed when using the reconstruction of the giant radiating swarm (Fig. 1a). Such circumferential swarms are exceedingly rare on Earth, with only a few examples having previously been described [e.g., 5, 6]. However, quasi-circular or quasi-elliptical giant graben-fissure systems (e.g., Fig. 1b, c), called coronae, are common on Venus [7], and may be underlain by dykes [e.g., 8]. In some instances coronae are also associated with giant radiating graben-fissure systems (e.g., Fig. 1c). Therefore, coronae could be analogues for circumferential dyke swarms on Earth.

Dykes of the HALIP circumferential swarm are well defined on Franz Josef Land where they are perpendicular to the radiating system. They appear sporadically on Svalbard. In northern Greenland the circumferential dykes are well mapped and intersect the radiating dykes at an angle of ~70-75^0. In the Queen Elizabeth Islands of Canada, dykes that crosscut the dominant radiating system are common. Those at a very high angle to the radiating pattern are interpreted to be part of the circumferential system.

The HALIP giant circumferential dyke swarm is slightly elliptical, with an outer diameter of ~1700 km and a width >300 km. Its centre is offset 200-250 km from the focus of the giant radiating swarm (similar to offsets of some paired radiating-circumferential systems on Venus). This offset is consistent with the fact that the circumferential dykes in Greenland are not at right angle to the radiating system. The offset may reflect a time difference between emplacement of the two systems. However, the age relationship between circumferential and radiating HALIP dykes is not well constrained.

HALIP is currently the best example on Earth of a LIP with both radiating and circumferential giant dyke swarms. The circumferential swarm is also the first to have been identified in a paleocontinental reconstruction.

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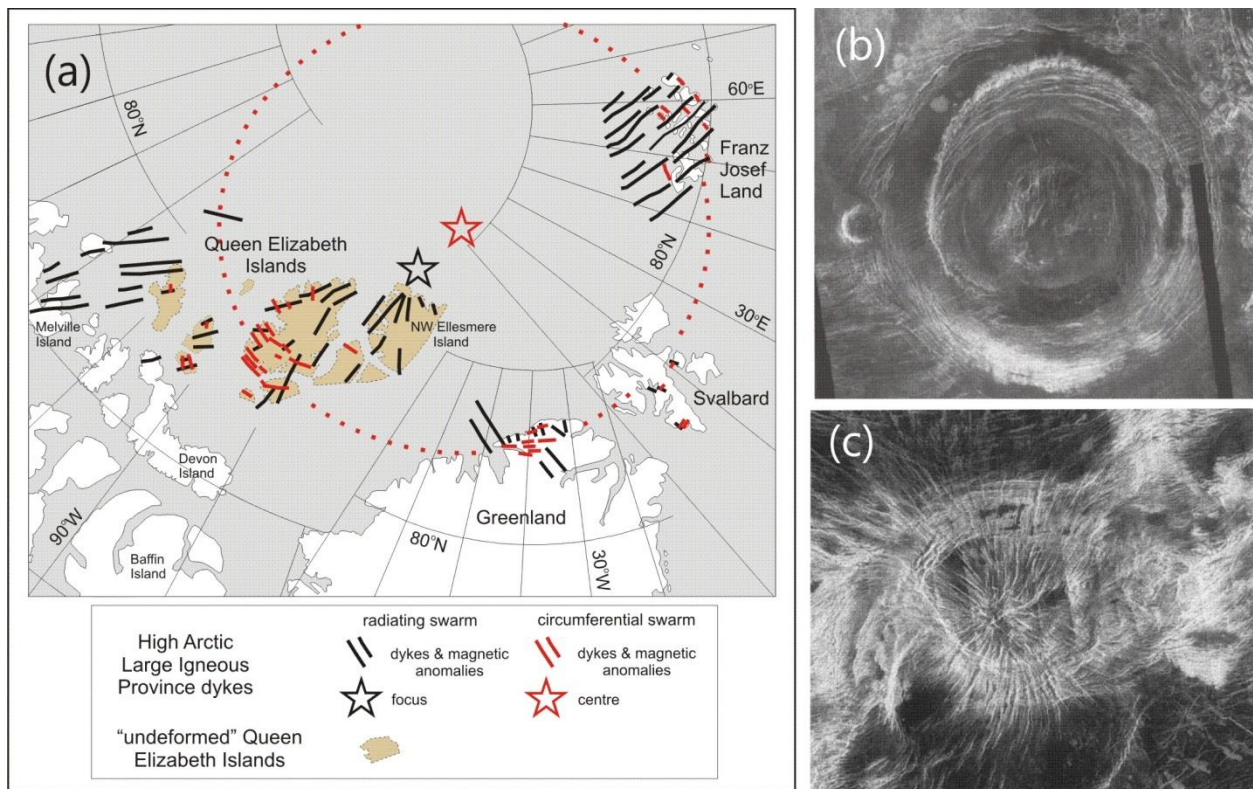
Figure 1. Comparison of giant circumferential and radiating dyke swarms of the HALIP and coronae on Venus. **(a)** Reconstructed HALIP giant dyke swarms (after Buchan and Ernst, in prep.) based on closing the Eurasian Basin, and undoing deformation in the Queen Elizabeth Island (which increases progressively to the NE) in order to best match the foci of the radiating swarms on the Queen Elizabeth Islands and other blocks. **(b)** Radar image of circular Aramaiti corona (diameter 350 km) on Venus at 26.3^0S, 82.0^0E (after [9]). **(c)** Radar image of quasi-elliptical Oduduwa corona (diameter 175 km) with an accompanying radial fracture system on Venus at 11.0^0S, 211.5^0E (after [7]).

GEOMETRY, STRUCTURE AND TECTONIC FRAMEWORK OF THE ALPHA RIDGE

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Introduction

The Alpha-Mendeleev Ridge Complex (AMRC) is a first-order physiographic and geological feature of the Arctic Amerasia Basin (Figure 1). High amplitude "chaotic" magnetic anomalies (the High Arctic Magnetic High Domain or HAMH) are associated with the complex, and extend beyond the bathymetric feature beneath the sediment cover of the adjacent Canada Basin and the Makarov-Podvodnikov basins. The HAMH is interpreted to represent the geophysical manifestation of the **Alpha-Mendeleev Magmatic Province** (AMMP). In this presentation, we outline the results of geophysical surveys carried out under the UNCLOS (United Nations Convention on Law of the Sea) Program[1], and describe how the new database contributes (1) to our understanding of the nature and origin of the Alpha Ridge and (2) links between the AMMP and Canadian portion of the HALIP as exposed in the Sverdrup Basin.

Potential Fields Data

New analysis of gravity and magnetic data have been used (1) to characterize the crustal structure of the Alpha-Mendeleev Ridge complex and (2) calculate the area and volume of the AMMP. The free-air gravity data over the AMRC shows gravity highs and lows that correlate directly with bathymetric features. Calculated marine Bouguer gravity anomalies over the ridge complex (after removal of bathymetric and long-wavelength isostatic effects) have low amplitudes which imply that the ridge complex structure has a remarkably uniform density structure [1]. Pseudogravity (magnetic potential) calculations of the

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[1] http://www.international.gc.ca/arctic-arctique/continental/index.aspx?lang=eng

magnetic field show a large positive high over a broad region, which implies that the AMRC has a deep crustal component [1]. The aerial extent of the HAMH (from a closed contour around the positive pseudogravity anomaly) is calculated at ~ 1.3×10^6 km^2.

Crustal Structure and Volume Estimates

Models of the bulk crustal structure of the Alpha Ridge portion of the AMRC are constrained by published refraction seismic studies (CESAR and LOREX) [2] [3] and recently acquired seismic reflection, wide-angle refraction, and sonobuoy refraction data collected as part of Canada's UNCLOS Program. CESAR samples of acoustic basement recovered from the Alpha Ridge [4] strongly support a volcanic origin. Forward 2D gravity and magnetic models assuming bulk lower crustal density values of 3000 kg/m^3 (velocities of 7.1 to 7.3 km/s), a mid-crustal layer of 2900 kg/m^3 (velocities of 6.7 to 7.1 km/s) and an upper crustal layer of 2600 kg/m^3 (velocities of 5.0 to 5.6 km/s) yield an calculated estimate of 5-7 km of mafic crust. Combined with the aerial extent of the complex, a total volume of (at least) 6×10^6 km^3 of volcanic crust is calculated. A comparison of the magnetic anomalies (Figure 2) and pseudogravity of the HAMH with those of LIPs globally suggests that AMMP is similar to the North Atlantic Igneous Province and Kerguelen Plateau, where deep-rooted plume-related magmatism intruded continental protoliths [5] [6] [7].

Arctic Plate Tectonic Reconstructions

Circum-Arctic stratigraphic correlations identify two key constraints for defining the age- of emplacement of the AMRC: 1) a pronounced lower Hauterivian (~135Ma or M10) circum-Arctic transgression has been

attributed to a "breakup unconformity" for the opening of Canada Basin; and 2) a major Barremian-Aptian volcanic event (~125Ma or M0) injected dykes and sills from the Canadian Polar Margin to the Barents Shelf. Additionally, a detailed evaluation of the North Atlantic plate tectonic spreading system identifies significant elements that affected the development of the Arctic, since both the Atlantic and Arctic lie between the North American and Eurasian plates. Plate reconstruction stage poles calculated for the pre-C26 (pre- Eurasia Basin) opening of the North Atlantic predict "stress fields" across the Arctic. Between C27 to C34 (56 to 84 Ma) over 450 km of regional extension is predicted to have occurred in a direction perpendicular to the Lomonosov Ridge. This extension may explain the orientation of elongated grabens on Alpha Ridge. Between C34 to M0 (84 to 124 Ma), extension is predicted to have occurred in a direction perpendicular to the Canadian Arctic margin, which is remarkably similar to the pole calculated for the opening of the central (oceanic) Canada Basin. This stress field is compatible with the orientation of the regional ~125 Ma dyke swarms. Finally, evaluation of absolute Mesozoic motion of the North American plate shows that the geometry of the AMRC is compatible with a hot-spot track and suggests a systematic age progression of volcanism with the youngest igneous event occurring close to the Canadian Polar Margin and the oldest event occurring close to the East Siberian Shelf. This leads us to conclude that the AMMP likely represents the offshore manifestation of the HALIP.

Overview

Canada and the United States collaborated in geophysical survey operations in the Amerasia Basin from 2007 to 2011 using the Canadian icebreaker CCGS Louis S. St. Laurent and the U.S. icebreaker USCGC Healy. Over 15000 km of bathymetry, sub-bottom profiles, and 16-channel seismic reflection data were acquired over the Canada Basin and Alpha Ridge. Expendable sonobuoys were deployed during seismic

acquisition, primarily to collect P-wave refraction data to define the regional velocity structure of the sedimentary successions; however, the ~35 km offsets have provided velocity information of crustal layers - and in some cases Moho depths **[8]**. Additionally, Canada conducted long-offset seismic refraction experiment in 2008, which extended 350 km from north Axel Heiberg Island along the bathymetric axis of Alpha Ridge **[9]**. Much of the material shown in this presentation (geophysical modeling) is a summary of material prepared for publication in a Tectonophysics Special Volume on "Circum-Arctic Lithospheric Evolution" [10]. The "tectonic framework" material is under development, although portions have been shown in conference presentations.

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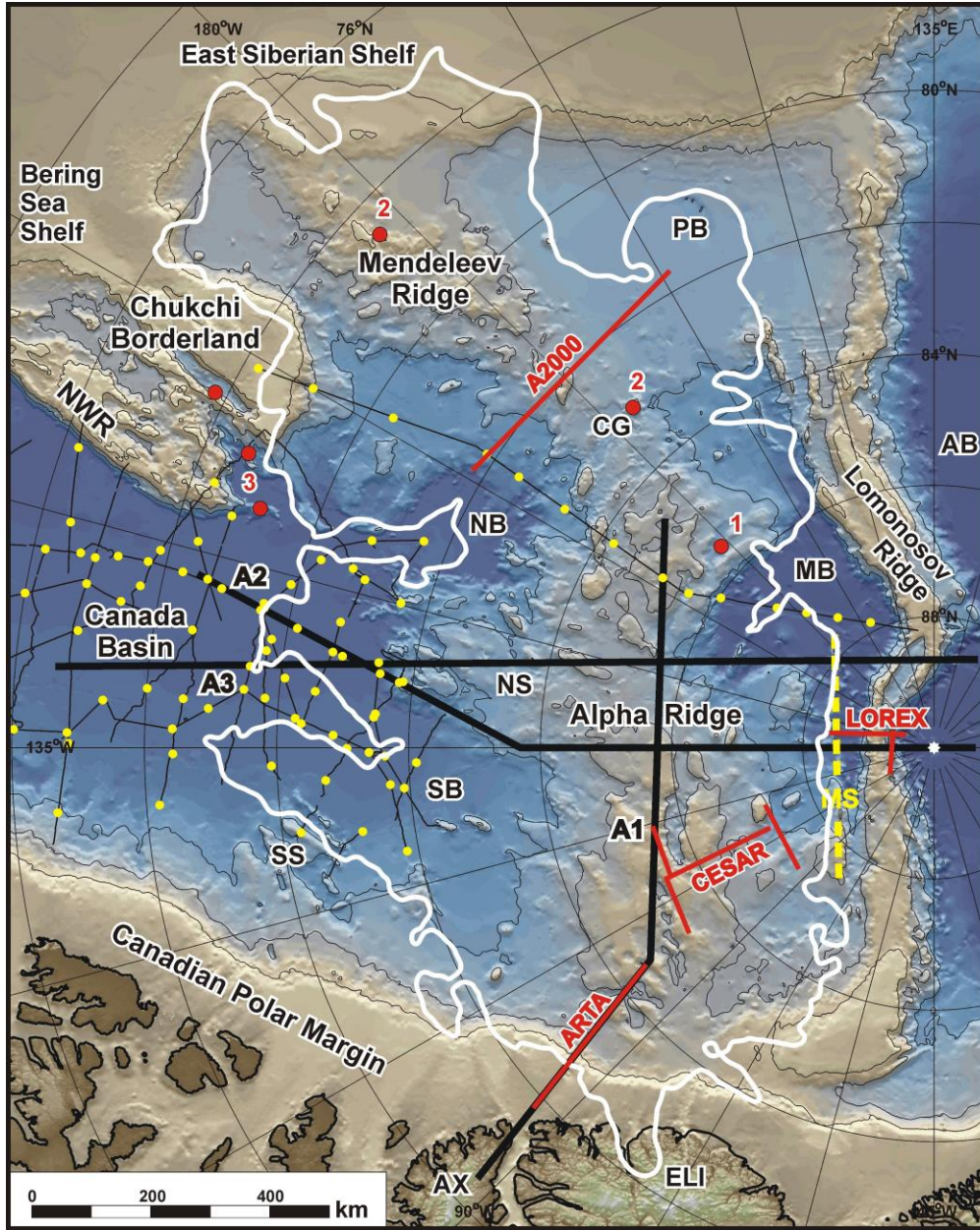
Figure 1. Bathrymetry and topography of the study area. International Bathymetric Chart of the Arctic Ocean (IBCAO; [11]). The outline of the High Arctic Magnetic High (HAMH; **white polygon**) is from [10] as well as the **heavy black lines** (labeled **A1**, **A2**, and **A3**) showing the locations of the geophysical models. **Solid red lines** show the locations of published transects across the Alpha and Mendeleev ridges discussed in the text: **A2000** [12]; **ARTA** [13]; **CESAR** [3]; **LOREX** [2]. **Thin black lines** show locations of (2007 to 2011) Louis S. St. Laurent seismic reflection data. **Yellow dots** show locations of (2007 to 2011) sonobuoy deployments [8]. **Red dots** show locations of dated volcanic samples: **1)**[13] **; 2)** [14]; **3)** [15, 16, 17]. The axis of Marvin Spur (**MS**) is shown with a yellow dotted line. **AB** = Amundsen Basin; **AX** = Axel Heiberg Island; **CG** = Cooperation Gap; **ELI** = Ellesmere Island; **NB** = Nautilus Basin; **NS** = Nautilus Spur; **NWR** = Northwind Ridge; **MB** = Makarov Basin; **PB** = Podvodnikov Basin; **SB** = Stefansson Basin; **SS** = Sever Spur.

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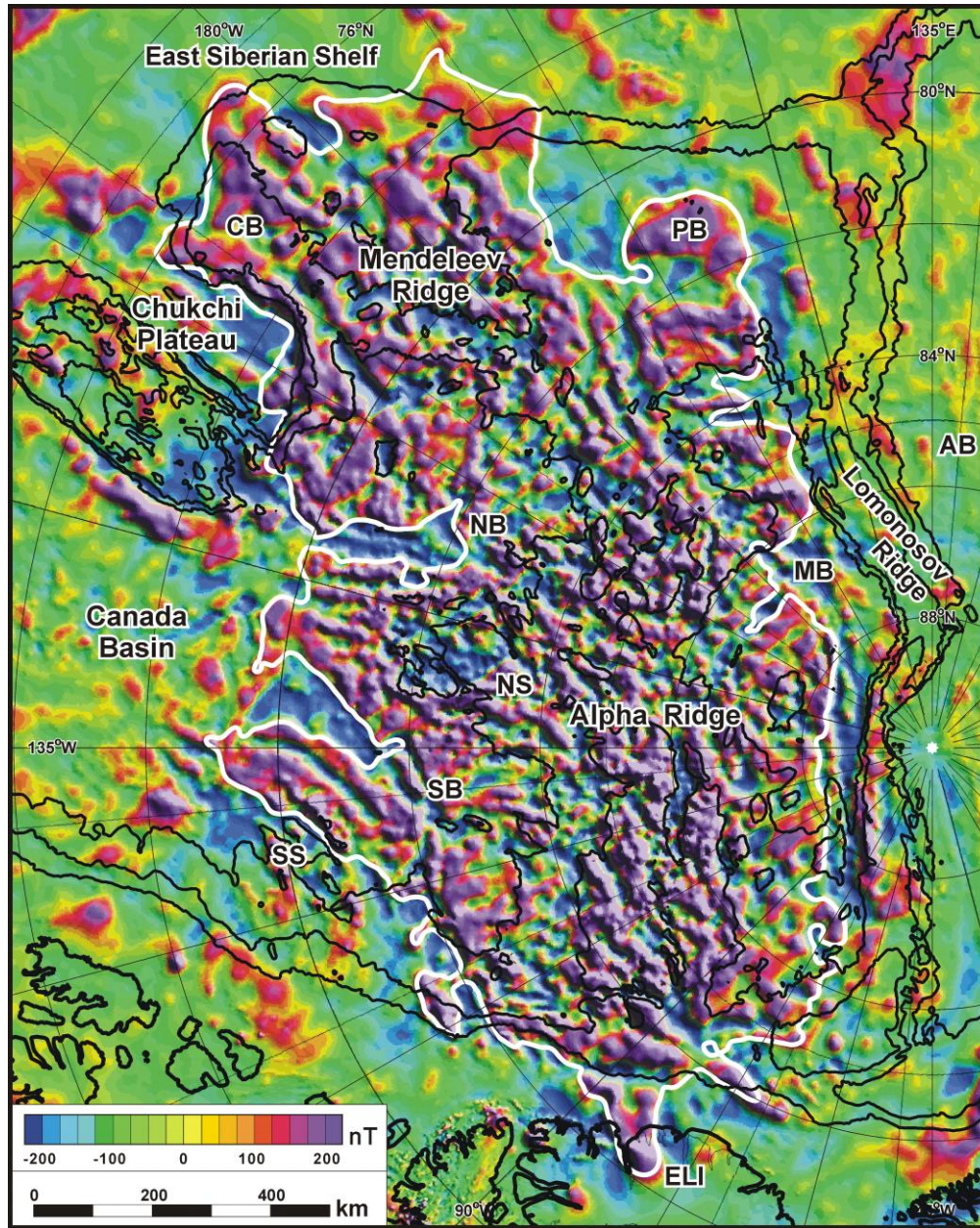
Figure 2. Magnetic anomaly map over the Alpha-Mendeleev Ridge Complex. Data from the International Polar Year compilation [18]. The outline of the High Arctic Magnetic High (HAMH) [10] and place name abbreviations are the same as in Figure 1.

U-PB GEOCHRONOLOGY OF BENTONITES FROM ELLEF RINGNES AND AXEL HEIBERG ISLANDS – A RECORD OF ALBIAN TO CAMPANIAN FELSIC MAGMATISM IN THE HALIP REGION

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Introduction

The duration and frequency of magmatic activity within the HALIP region remain poorly documented. This reflects the small number of high-precision ages, as well as uncertainites in interpretation and reliability of some of the earlier K-Ar and Ar-Ar analyses. The early history of the HALIP in the Canadian Arctic is dominated by mafic sill and dyke intrusions between 129 and 121 Ma [1,2,3] and is broadly contemporaneous with the timing of mafic magmatic events on Franz Josef Land and Svalbaard at 125-122 Ma [4]. Younger volcanic and intrusive rocks include the ~95 Ma basalts of the Strand Fiord Formation [5], the ~92-93 Ma Wootton instrusive complex and the ~83-84 Ma Hansen Point volcanics [3]. In this presentation, we summarize U-Pb ages of volcanic ash beds from the Christopher, Bastion Ridge and Kanguk formations that document frequent volcanic events within the Sverdrup basin area over a 30 m.y. period, from ~112 to 84 Ma.

Summary of Bentonite U-Pb age data

Two bentonites within the Christopher Formation at Glacier Fiord, Axel Heiberg Island yielded U-Pb zircon ages at 111.6 and 106.7 Ma [6]. Similar ages were determined for volcanic horizons on Ellef Ringnes Island with ages at <106.2 Ma and 105.7 Ma [1]. Additional volcanic events between 108 and 111 Ma are indicated by inherited or accidental zircon grains within the volcanic layers. Younger volcanic units within the Macdougall Point member of the Christopher Formation and Hassel Formation on Ellef Ringnes Island have estimated stratigraphic ages of ~103 and ~101 Ma [1]. A bentonite within the Bastion Ridge Formation at Glacier Fiord on Axel Heiberg Island provides a maximum depositional age of 98 ± 1.8 Ma, consistent with the Cenomanian age reported for Strand Fiord volcanic rocks [5].

Bentonites are particularly well preserved within the Kanguk Formation. The bentonites have alkaline chemical signatures consistent with the younger magmatic rocks of the HALIP [7]. Nine bentonite layers from Glacier Fiord, Axel Heiberg Island, and Hoodoo Dome, Ellef Ringnes Island, yield U-Pb zircon ages between 93 and 84 Ma. The lowermost bentonite layer within the Glacier Fiord section has an age of 93.03 Ma and lies ~18 m above the chemostratigraphically defined OAE2 layer (93.9 Ma) within the lower Kanguk Formation [6, 8].

Discussion

The age data indicate that volcanic activity occurred more or less continuously over a 30 m.y. period from ~112 to 84 Ma. The record of events between 112 and 93 Ma is less well documented but an eruption frequency of less than 3 m.y. over this time interval is indicated. Within the Kanguk Formation, where bentonites are best preserved, an eruption frequency of 0.5 to 2.5 m.y. is calculated over the interval between 93 and 84 Ma. For comparison, this is broadly similar to the eruption frequency of ~0.6 to 0.8 m.y. for the Yellowstone intraplate volcanic centre over the past 2.5 m.y.

The volcanic source of the ash beds remains conjectural. Ash bed thicknesses of 10-40 cm, typical of those in the Kanguk Formation, usually occur at maximum distances from source of ~500 up to 1000 km. A radius of 1000 km from the Glacier Fiord and Ellef Ringnes sections extends as far north as the proposed HALIP plume centre

on the Alpha Ridge, and to the northeast to northern Greenland in the area of the Kap Washington volcanics and Peary dykes. Included within this radius are known volcanic and intrusive centres of the Wootton intrusive complex and the Hansen Point volcanics, which are located on Ellesmere Island within a 400 km radius of the Glacier Fiord and Ellef Ringnes sections. Derivation of the ash from known igneous centres is permissible. The frequency of eruption is greater than currently documented for igneous centres on northern Ellesmere Island, such as the Wooten Intrusive Complex, or Hansen Point volcanics [5], indicating that the younger alkaline igneous activity within the HALIP region was more frequent than currently documented.

The interval between 121 Ma and 112 Ma remains as an apparent magmatic gap. There is evidence for multiple magmatic events between ~130 and 121 Ma but little evidence for magmatism between 121 and 112 [1]. Whether this represents a significant gap in magmatic activity, or is simply a preservational issue remains to be established.

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NEW U-PB AGES FROM SOUTH FIORD, AXEL HEIBERG ISLAND: IMPLICATIONS FOR HALIP MAGMATISM

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Introduction

The geologic evolution of the Arctic margins in Canada (Figure 1A) and in formally adjacent regions of Svalbard (Norway) and Franz Josef Land (northern Siberia) was extensively modified by widespread Cretaceous magmatic activity[1]. Evidence of this activity is recorded in continental flood basalts as well as the associated dykes and sills which make up their plumbing system[2]. Taken together, these volcanic and intrusive structures constitute the High Arctic large igneous province (HALIP)[2,3].

There is evidence in Canada that the initial onset of voluminous mafic magmatism of tholeiitic character was protracted, comprising two early Cretaceous pulses at 126.6±1.2 Ma and 120.8±0.8 Ma based on ages derived from subalkaline diabasic sills on Ellef Ringnes Island [4,5]. U-Pb ages from mafic intrusions on Svalbard and Franz Josef Land imply a more restricted interval of magmatism in the early Cretaceous (ca. 122 – 124 Ma) based on six age determinations[6]. A younger pulse comprising the Strand Fiord formation lavas is indicated thus far by two lines of evidence: (1) stratigraphy (either late Cenomanian – Coniacian[7] or late Albian – middle Cenomanian[8]) and (2) Ar-Ar ages of 80.7 ± 1.1 Ma to 100 ± 2 Ma [9,10]. Along the Arctic coast of Ellesmere Island, the Wootton Igneous Complex (WIC), a sill-like composite intrusion of bimodal composition marking the onset of alkaline magmatism, yields U-Pb ages of 92.0 ± 1.0 Ma[11] and 92.1 ± 0.1 Ma[12] for the gabbroic portion and 92.7 ± 0.3 Ma[12] for the microgranite zone.

With the exception of U-Pb ages derived from the alkaline WIC, there is a distinct paucity of U-Pb ages in the 90 – 100 Ma interval from HALIP magmatic rocks that envelops the eruptive timeline of the Strand Fiord formation lavas. Here we present the first two baddeleyite U-Pb ages from two samples collected in 2013 [13] from the South Fiord region of Axel Heiberg Island (Figure 1B) that are compositionally correlated with the Strand Fiord formation eruptive period (Kingsbury et al., under review).

Sample descriptions:

13-CK-16: This sample of diabase was collected from a NW-SE trending ridge from a small (~5 m x 5 m) subcrop within a talus slope of dm-sized rocks. Because ridge and mountain slopes surrounding the collection site are covered with significant talus it is difficult to discern whether this sample was collected from a dyke or a sill. This could represent a dyke on the basis of the orientation of columnar cooling joints on a ridge aligned with and to the SW of the sample location. Compositionally, this sample is of subalkaline basaltic composition based on the Pearce and Norry classification scheme[14].

13-WJA-C028-A2: This gabbroic sample was collected, via helicopter support, from the top of a sill with a thickness greater than 50 m. The unit forms a ridge exposed on the peninsula ~16 km southwest of the location where sample 13-CK-16 was collected (Figure 1B). Thorsteinsson and Tozer[15] originally mapped this as a dyke which was then subsequentially classified by Buchan and Ernst [16] as being part of the Surprise Fiord swarm. However, field observation revealed that this is a sill based on the presence of vertical sets of hexagonal cooling joints on the cliff-face. The true thickness is unknown because the sample site is medium- to coarse-grained, inferring that the upper chilled margin was removed by erosion. This sample is of sub-alkaline basaltic andesite composition based on the Pearce and Norry diagram [14].

Methods and Results

Baddeleyite grains were separated at the University of Lund using the Söderlund and Johansson method[17] and subsequently selected into fractions and analyzed at the Jack Satterly Geochronology Laboratory at the University of Toronto by isotope-dilution thermal ionization mass spectrometry (ID-TIMS).

13-CK-16: U-Pb analyses of three multi-grain fractions of translucent baddeleyite gave concordant and overlapping data that have a weighted mean $^{206}Pb/^{238}U$ age of 95.18 ± 0.35 Ma (2σ, MSWD = 0.02), which is interpreted as the age of magmatic emplacement of this mafic intrusion.

13-WJA-C028-A2: U-Pb analyses of three multi-grain fractions of translucent baddeleyite gave concordant data, two of which are highly precise and yield a weighted mean $^{206}Pb/^{238}U$ age of 95.51 ± 0.39 Ma (2σ, MSWD = 0.39. If the least precise and overlapping fraction is included in the mean, the interpreted age is slightly older at 95.56 ± 0.24 Ma (2σ, MSWD = 1.9).

The two ages reported above, whose samples were collected ~16 km apart, are statistically insignificant. If it is assumed that these came from the same magmatic episode, then using the two-fraction age from 13-WJA-C028-A2, a composite weighted age of 95.40 ± 0.20 Ma (2σ, MSWD = 0.73) is obtained.

Discussion and Conclusion

The two new highly precise U-Pb ages place magmatism in the South Fiord area, at least in part, firmly within the Cenomanian period (93.9 – 100.5 Ma)[18] and ~3 Myrs prior to the onset of younger alkaline magmatism, manifested initially by the WIC on northern Ellesmere Island. Furthermore, the subalkaline chemical signature of both samples strongly suggests that they are co-genetic with the Strand Fiord formation lavas (Kingsbury et al, under review). Further evidence for a common source is given by the fact that they both intrude the lower Cretaceous Isachsen formation, and were collected less than 20 km from the nearest exposure of the late Cretaceous Strand Fiord formation (East Fiord and Triangle Peninsula; Figure 1B). These new ages hereby date a magmatic episode that is consistent with the timing of magmatism associated with the Strand Fiord formation volcanic pulse.

Embry and Osadetz [8] proposed that the timing of Strand Fiord formation volcanism was late Albian – middle Cenomanian. In this context, the age determinations reported here for intrusive rocks represent a late-stage episode within the total duration of the Strand Fiord formation magmatic pulse. It is important that additional precise U-Pb age studies be carried out to further constrain the timing and duration of intrusive activity in the Canadian portion of the HALIP.

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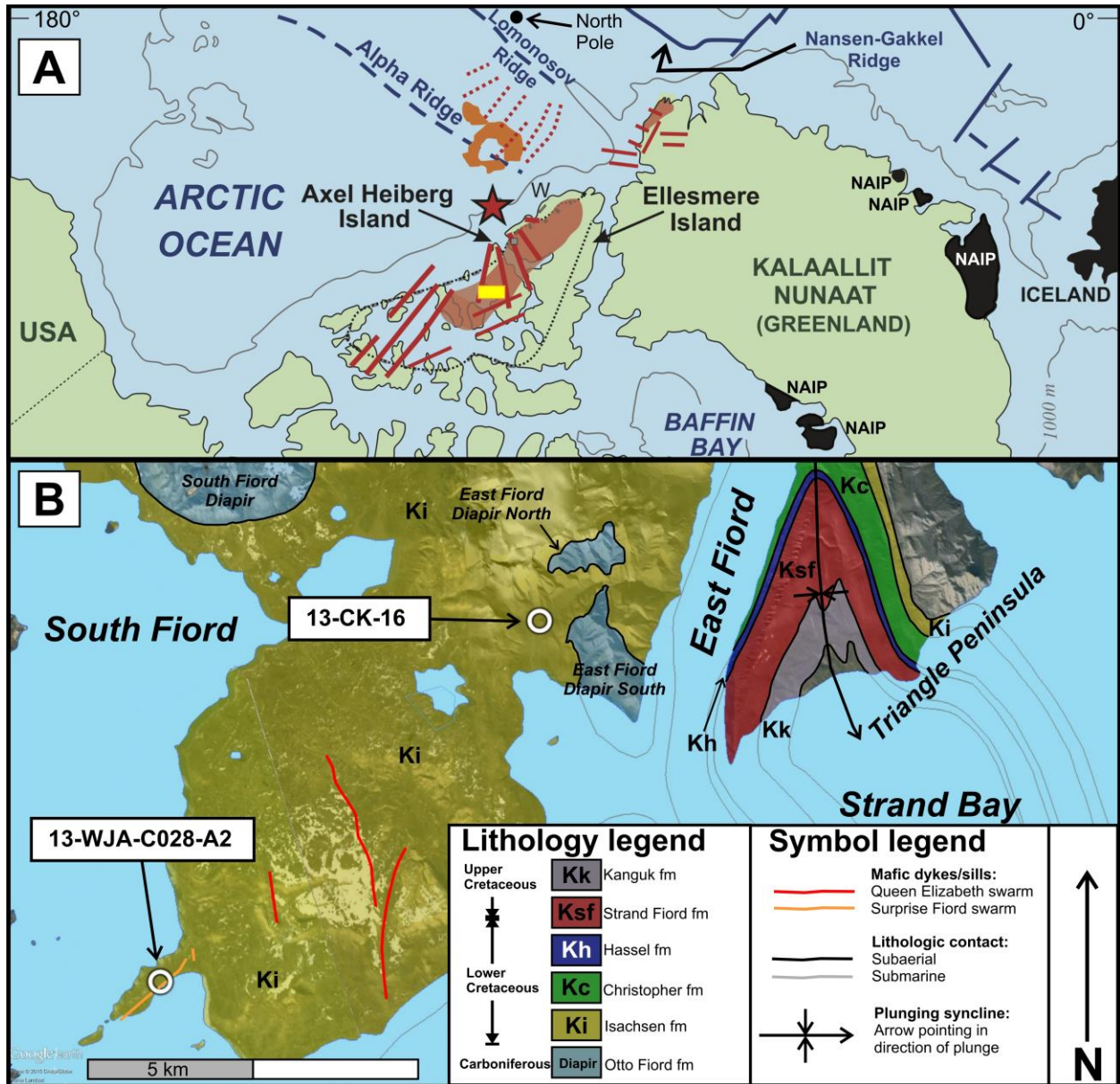
Figure 1. **A**. Map showing the distribution of magmatic units ascribed to HALIP in Canada and Greenland (red shading) along with HALIP dyke swarms (red lines). Red star denotes location of mantle plume centre as identified in [2,8]. Orange dotted lines and doughnut shaped pattern in the Arctic Ocean are geophysical anomalies that Døssing and others[19] interpret as magmatic intrusions and dykes. Thin black dotted line in the Canadian Arctic Islands represents the outline of the Sverdrup Basin. "W" indicates the location of the WIC. The yellow rectangle represents the extent of the study area shown in **B**. NAIP and black shading denotes the unrelated Paleocene North Atlantic igneous province. Map modified from [20].

B. Geologic map of the South Fiord area, western Axel Heiberg Island, draped onto Google Earth® showing sample collection locations refered to in the text. Base geology is from Harrison and Jackson [21] with the exception of the vicinity of Sample 13-WJA-C028A2 which is from Thorsteinsson and Tozer[15]. Mafic dyke data and swarm identifications are from Buchan and Ernst[16].

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MORPHOLOGY, MINERALOGY AND GEOCHEMISTRY OF GOSSANS, AXEL HEIBERG ISLAND, NUNAVUT

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Introduction

The study presents new data on gossans that were investigated during a three-year study funded by Natural Resources Canada's Environmental Geosciences Program. The main objectives of the Arctic Gossans Activity was to demonstrate that Arctic gossans constitute natural analogues of mine wastes derived from metalliferous deposits. Study protocols included (1) the identification of gossan zones using satellite imagery; (2) mapping and sampling in the field; (3) laboratory analyses to determine the mineralogy and geochemistry of gossans; (4) and complementary analysis of sediments in local streams [1].

Morphology

The two gossans discussed in this presentation are located in the South Fiord area of Axel Heiberg Island [2]. Figure 1 illustrates the bedrock geology of the area dominated by the presence of HALIP intrusive rocks and evaporite diapirs. The Ridge Gossan (L7; [3]; Figure 2) consists of a thick deposit associated with shales that is overlain by volcanic rocks of the Walker Island Member, in the Isachsen Formation (Figure 3). The deposit consists of thinly stratified sediments and is reactive with permafrost. The Stream Gossan (L6; [3]) is a thick deposit that developed within poorly-consolidated shales located beneath a mafic sill, and is reactive with permafrost (Figure 4). Many of its features, with the exception of its poor stratification and shale host are comparable to the L2 gossan on Victoria Island (Figure 5; [3, 4]).

Mineralogy

Whole rock mineralogy was completed on two representative samples from Ridge Gossan and Stream Gossan. Ridge Gossan is quartz-rich (92 wt%) with minor plagioclase, K-feldspar, kaolinite, jarosite and trace pyrite. In contrast, Stream Gossan is gypsum-rich (92 wt%) with minor quartz, plagioclase and trace mica. These examples may not be completely representative of the gossanous material at these two sites but provides a starting point for understanding major and trace element geochemistry. More samples will be required to make full characterizations.

Geochemistry

A total of nine samples were analysed for major and trace elements. The focus of the presentation is on observed variations in the concentrations of transition metals Cr, Cu, Ni and Co with depth in the Ridge and Stream Gossans. Overall, the two gossans show remarkable differences in their trace element profiles. Of particular significance is the enrichment in Cu in the Stream Gossan and inverted profiles in Ni concentrations with depth in the gossans. The results are compared with those obtained on the Sill Gossan (L2), Victoria Island, Northwest Territories (Figure 5) [3,4].

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Figure 1. Simplified geological map of the Strand Fiord-Expedition Fiord area, Axel Heiberg Island (modified from [2]). The 2013 study area is shown by the blue circle.

Figure 2. Topographic map of the 2013 study area showing the sampling stations for bedrock, gossans, and stream sediments [5]. Samples discussed in this study are the **Ridge Gossan** and the **Stream Gossan**.
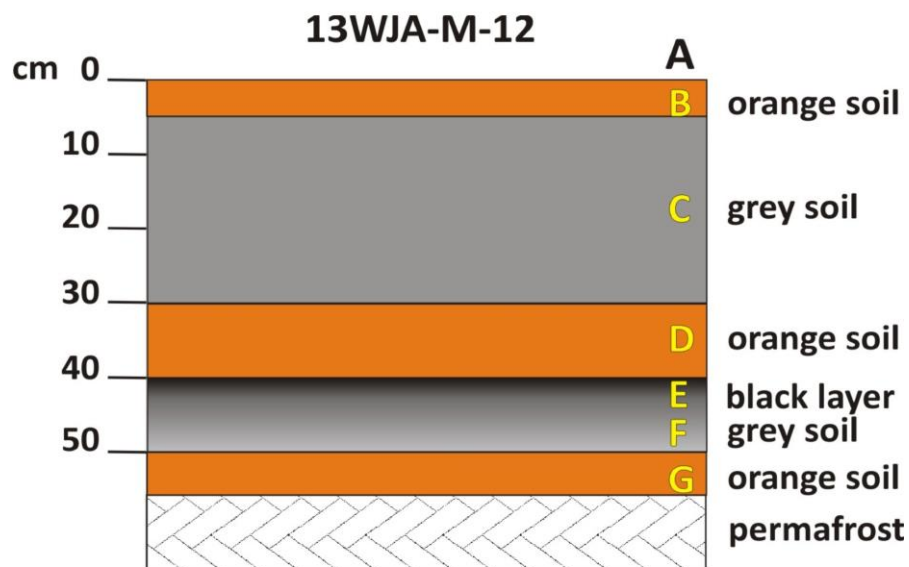
Figure 3. Schematic diagram showing the stratigraphy of the Ridge Gossan. The photograph illustrates the collection of samples A-G. Sampe A consists of loose gravel sampled at the surface of the deposit.
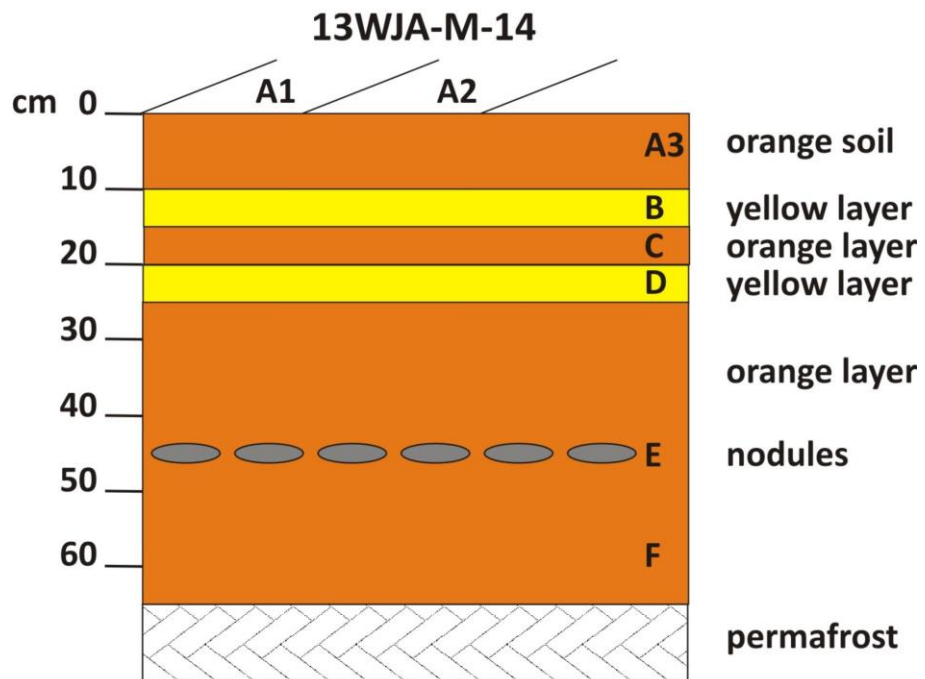
Figure 4. Schematic diagram showing the stratigraphy of the Stream Gossan. The photograph illustrates the trench where samples A-F were collected. The A-series consist of loose gravel sampled at the surface of the deposit for spectral reflectance studies. The nodules are visible on the field shot above the red and white scale.
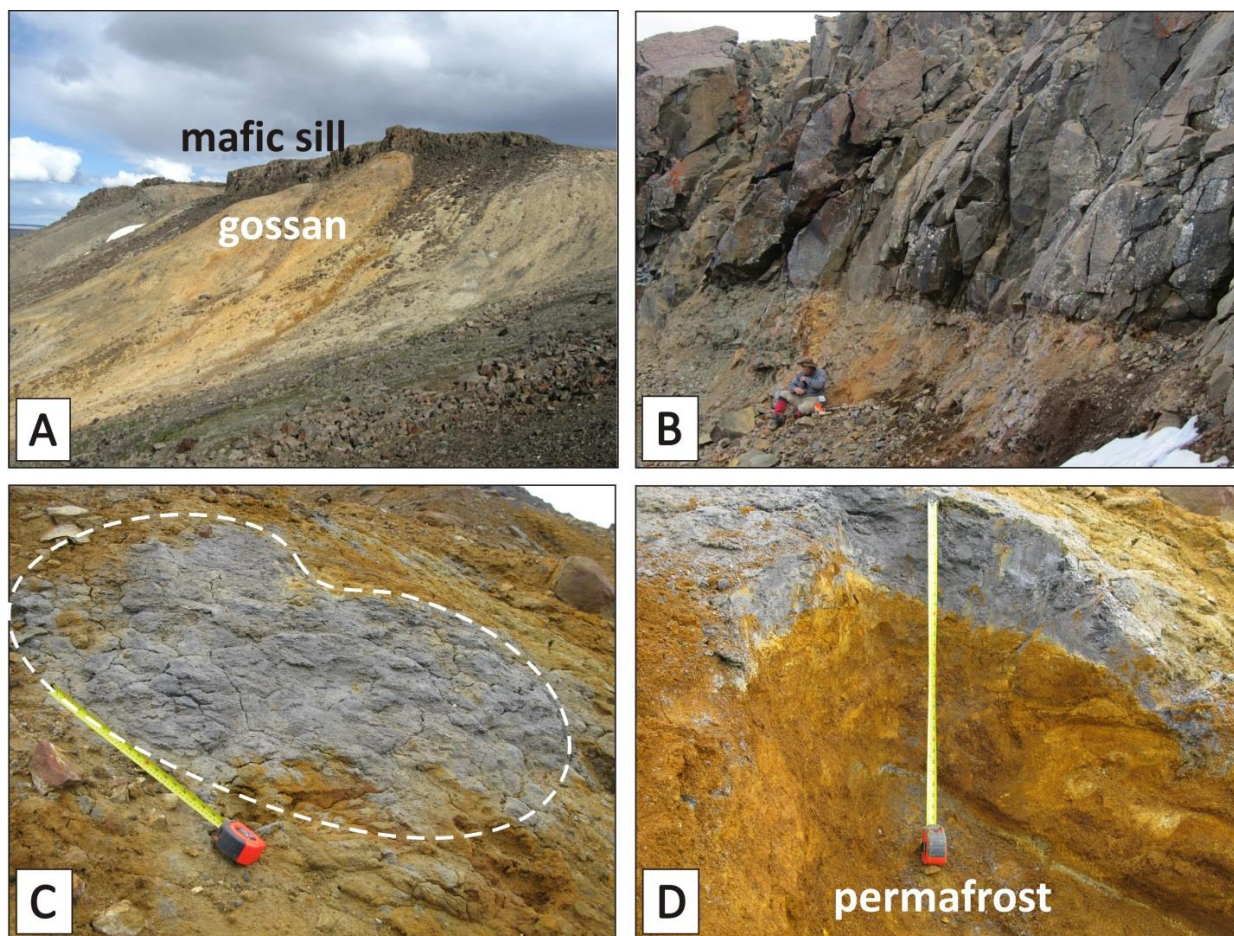
Figure 5. **A**. Aerial view of the Sill Gossan (L2; [3]) located on Victoria Island, Northwest Territories, looking southeast. The scree slope consists of loosely-consolidated pyrite sands and gossanous soil overlain by a gabbro sill and complex rheomorphic breccia. **B.** View of the contact between the massive sill and the underlying rheomorphic breccia. **C.** Plan view of alteration zone where the pit was dug. The measuring tape is 51 cm long. **D**. Close-up of the trench dug into the gossan showing inverted stratigraphy. Depth to permafrost is 80 cm (modified from [3]).

DRAINAGE GEOCHEMISTRY SURVEYS, AXEL HEIBERG ISLAND, NUNAVUT

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Introduction

A stream sediment and water geochemistry survey covering parts of the Sverdrup Basin was carried out in August 2015 in three areas of central Axel Heiberg Island, Nunavut, as part of the second phase of the GEM 2 High Arctic Large Igneous Province (HALIP) activity. Bulk sediment samples were also collected for the recovery of indicator minerals from the heavy mineral contents at selected sites. In this presentation, we describe the rationale for site selection and a summary of field activities.

2013 Orientation Survey

Previously, in July 2013, an orientation survey was carried out in the East Fiord area of western Axel Heiberg Island as part of the Arctic Gossans activity of the Environmental Geoscience Program [1] (Figure 1). The objectives were to (1) generate the first baseline stream sediment and water geochemical data for this area in proximity to evaporite diapirs and gossans; and (2) use the data to evaluate mineral prospectivity. This area is host to a cluster of Tertiary Otto Fiord Formation diapirs which intrude the Mesozoic sedimentary-volcanic succession [2]. Sills and dykes are abundant and were investigated in a separate study [3]. Samples from the 2013 drainage survey yielded moderately elevated base metal values in sediment and water. Elevated indicator mineral counts, specifically chalcopyrite (29 – 553 grains), sphalerite (4 – 565 grains) and galena (1 – 40 grains) as well as barite and pyrite were noted in the heavy mineral concentrates (HMC) in samples collected proximal to the East Fiord north and south diapirs. The discovery of abundant chalcopyrite, sphalerite and galena combined with the presence of other indicator minerals in the HMC [4] [5] prompted the follow up studies described here.

2015 Reconnaissance survey

In August 2015, a helicopter supported reconnaissance regional drainage survey was carried out in central and eastern Axel Heiberg Island in three geologically distinct areas located between Expedition Fiord and Lightfoot River (Figure 1).

Two types of sampling sites were targeted during this study with a focus on mineral resources: (1) smaller first and second order streams in the upper reaches of the drainage for silt and water, and (2) larger third and fourth order streams for silt, water and bulk sediment for the recovery of indicator minerals.

Lightfoot River

The Lightfoot River area is characterized by the absence of evaporite diapirs, the predominance of shales in the Triassic Blaa Mountain Formation and the presence of the Lightfoot River dyke swarm (Figure 2). The rationale for selecting the Lightfoot River area for a drainage survey was to investigate the potential effects of a well-documented mafic dyke swarm on the mineralogy and geochemistry of sediments and waters away from evaporite structures. A total of 26 sites were sampled for silt and water, and 10 sites for indicator minerals.

Geodetic Hills

This area is characterized by the presence of Tertiary Otto Fiord Formation evaporite diapirs intruding Cretaceous and Triassic sedimentary successions as well as being intersected by multiple fault structures such as the major NW-SE trending Stolz Thrust Fault (Figure 3). The rationale for selecting Geodetic Hills for a drainage survey was to investigate the combined effect(s) of evaporite diapirs and faulting on mineral prospectivity.

Expedition Fiord

The bedrock geology of the Strand Fiord-Expedition Fiord region is dominated by the presence of Triassic through Lower Cretaceous mudrocks and coarse clastic rocks intruded by HALIP volcanic and intrusive rocks, and overlain by Late Cretaceous through Eocene

sediments (Figure 4). Regional anticlines, which formed during the Paleogene Eurekan Orogeny, trend roughly north on a regular ~ 20 km wavelength and probably detach on the autochthonous Carboniferous Otto Fiord Formation evaporites [6]. A massive sulphide occurrence first reported by industry geologists [7] recently investigated by Williamson et al. [8] is found in the White Glacier Basin at the head of Expedition Fiord. The rationale for selecting this area for a drainage survey was to evaluate base metal prospectivity on a regional scale. A total of 27 sites were sampled for silt and water, and 7 sites for bulk, silt and water.

Whitsunday Bay

A fourth reconnaissance survey was identified in the Whitsunday Bay area. Due to inclement weather, attempts to reach the area for sampling were unsuccessful.

Conclusions

New regional stream sediment and water geochemistry coverage combined with indicator mineral samples will assist in the evaluation of the economic potential of HALIP rocks on Axel Heiberg Island, Nunavut. Stream sediment and water geochemical datasets represent a critical part of the geoscience knowledge required to establish environmental baselines pre-dating economic development and related activities in this region of Nunavut.

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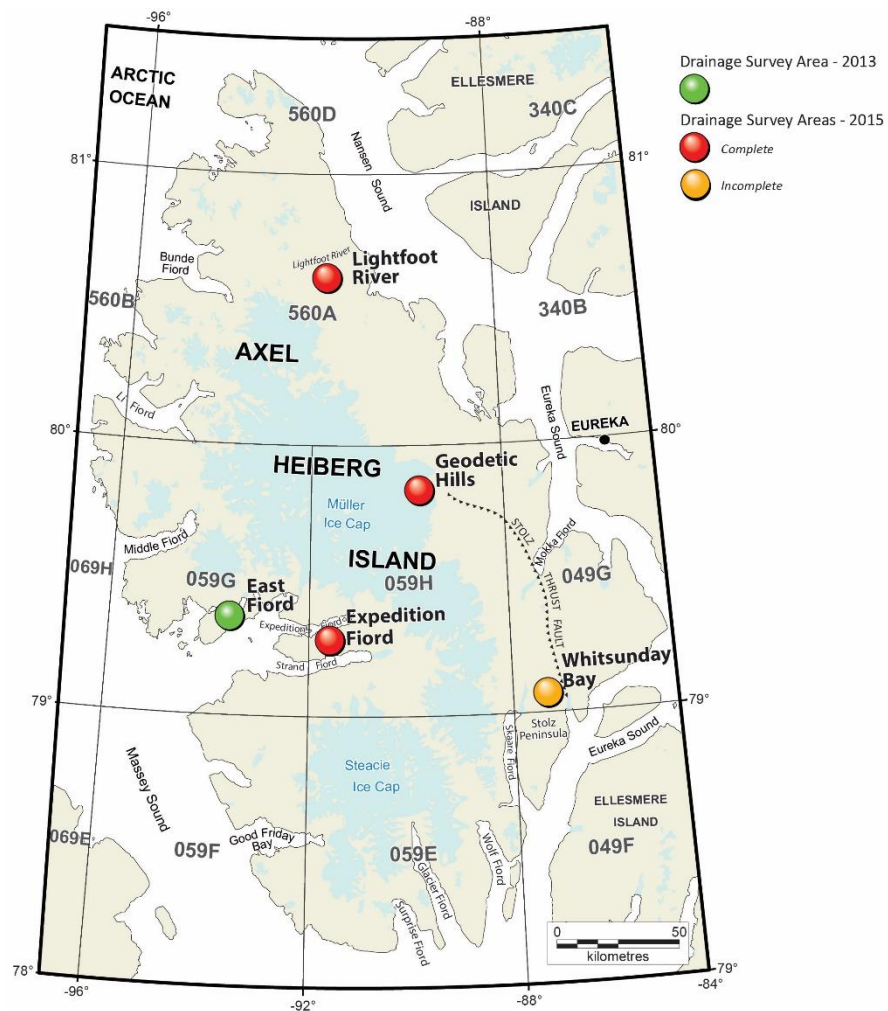
Figure 1. Location map showing the 2013 drainage study area near East Fiord and the 2015 drainage study areas in east-central Axel Heiberg Island. The map is overlain with the 1:250,000 NTS grid.
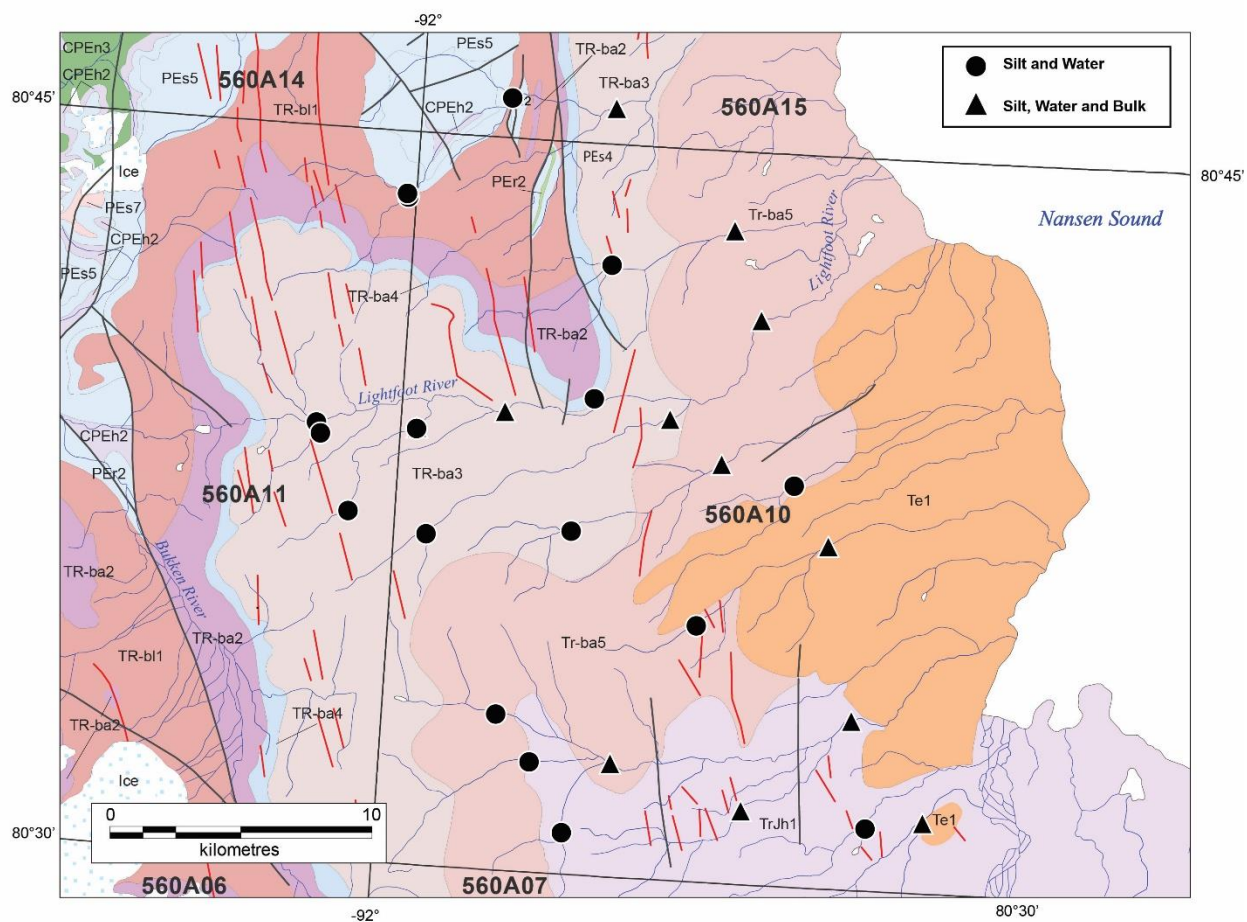
Figure 2. Bedrock geology of Lightfoot River area showing the location of 2015 sampling sites. Geology is modified from [9]. See Figure 5 for lithological legend. The map is overlain with the 1: 50 000 NTS grid.
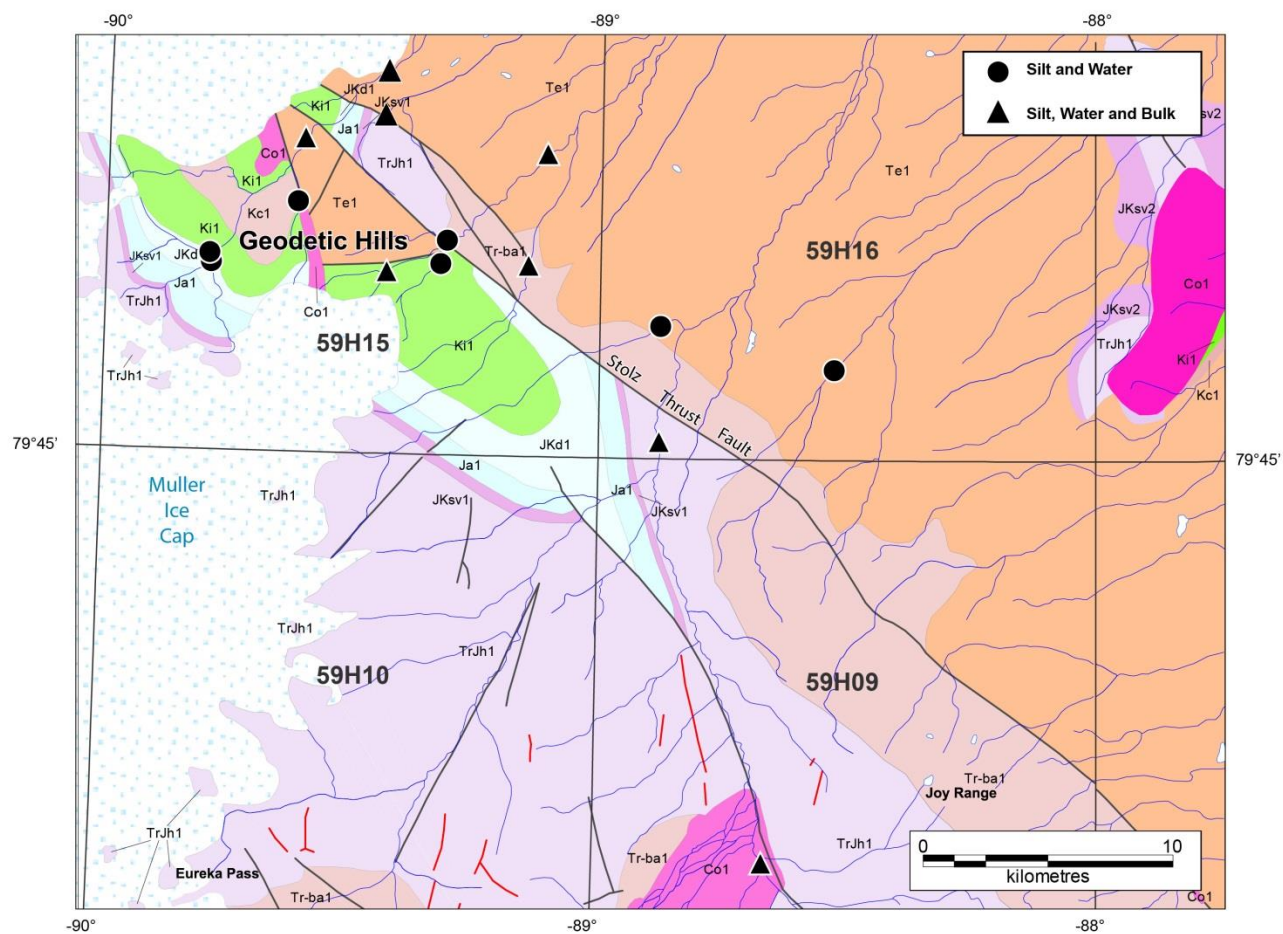
Figure 3. Bedrock geology of the Geodetic Hills area showing the location of 2015 sampling sites. Geology is modified from [10]. See Figure 5 for lithological legend. The map is overlain with the 1:50 000 NTS grid.
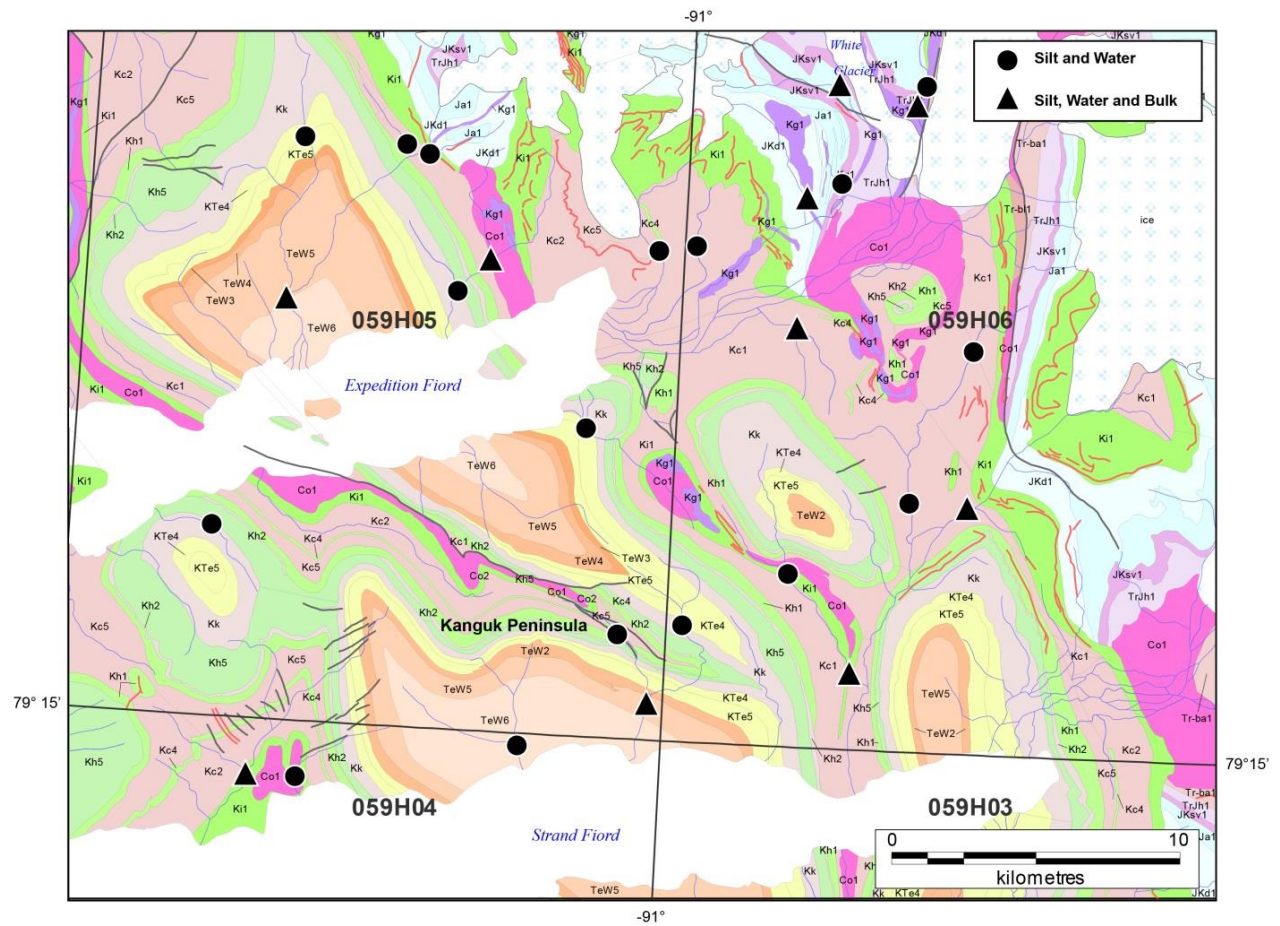
Figure 4. Bedrock geology of the Strand Fiord-Expedition Fiord area showing the location of the 2015 sampling sites. Geology is modified from [10]. See figure 5 for lithological legend. The map is overlain with the 1:50 000 NTS grid.

PALEOGENE
  Paleogene and Eocene

Te1 — Eureka Sound — Sandstone, siltstone, conglomerate shale; minor coal

  Eureka Sound-West Group

TeW6 — Iceberg Bay_Coal member — Sandstone, quartz arenite; minor grey shale, coal

TeW5 — Iceberg Bay_Lower member — Sandstone, quartz arenite; minor siltstone, grey shale

TeW4 — Strand Bay_Upper Part — Medium to dark grey shale; minor sandstone, quartz arenite; minor coal

TeW3 — Strand Bay_Lower Part — Medium to dark grey shale

TeW2 — Strand Bay — Medium to dark grey shale; minor sandstone, quartz arenite; minor coal

CRETACEOUS
  Late Cretaceous to Early Paleogene
    Expedition Group

KTe5 — Upper member — Sandstone, quartz arenite, fine- to medium grained; minor siltstone, shale and coal

KTe4 — Lower member — Sandstone, quartz arenite, fine- to medium-grained; minor siltstone, shale and ironstone

  Late Cretaceous

Kk — Kanguk — Dark coloured shale, minor sandstone, siltstone and mudstone

  Early and Late Cretaceous
    Hassel Group

Kh5 — Strand Fiord — Dark grey to black mafic flows and pyroclastic rocks; weathering red; minor coal, shale and conglomerate

Kh2 — Bastion Ridge — Dark grey silty shale; minor siltstone; minor sandstone; minor ironstone and volcaniclastic sandstone.

Kh1 — Hassel — Sandstone, quartzose, fine- to coarse-grained; siltstone; minor shale; local mafic volcanic flows

Kg1 — Queen Elizabeth swarm — Gabbro; minor granitoid and hybrid rocks, diabase

  Early Cretaceous
    Christopher Group

Kc5 — Macdougall Pt. member — Dark grey to brownish black shale, minor limestone concretions, volcaniclastic sandstone

Kc4 — Invincible Pt. member, Junction beds — Grey to greenish grey sandstone, feldspathic quartz arenite; siltstone

Kc2 — Invincible Pt. member — Dark greenish grey and brownish grey shale, grading upwards to lesser sandstone; local volcaniclastic sandstone

Kc1 — Christopher — Dark coloured shale, minor siltstone, sandstone and mudstone

Ki1 — Isachsen — Sandstone, minor shale, siltstone and conglomerate

JURASSIC AND CRETACEOUS
  Late Jurassic and Early Cretaceous

JKd1 — Deer Bay — Dark coloured shale, minor siltstone, sandstone and mudstone

JURASSIC
  Late Jurassic

Ja1 — Awingak — Sandstone, partly shaly; local coal

JURASSIC AND CRETACEOUS
  Early Jurassic to Early Cretaceous

JKsv2 — Savik — Awingak Formation: Sandstone, siltstone, minor shale; Savik Formation: sandstone, dark coloured shale, siltstone; Borden Island Formation: sandstone

JKsv1 — Savik — Jameson Bay formation: medium to dark grey shale and siltstone; red weathering ironstone nodules; Sandy Point formation: thin ledge of very fine to fine grained, burrowed sandstone with ironstone

TRIASSIC AND JURASSIC
  Late Triassic and Early Jurassic

TrJh1 — Heiberg — Sandstone, siltstone; minor shale

TRIASIC
  Middle and Late Triassic
    Blaa Mountain Group

Tr-ba5 — Barrow — Medium to dark grey shale and siltstone

Tr-ba4 — Gore Point — Medium to dark grey limestone; medium grey, brown weathering, calcareous siltstone with minor shale

Tr-ba3 — Hoyle Bay — Medium to dark grey shale and siltstone, very fine to fine grained sandstone

Tr-ba2 — Murray Harbour — Gravel, sand and mud

Tr-ba1 — Blaa Mountain — Dark coloured shale, siltstone, light grey calcareous siltstone; minor sandstone

  Early Triassic

Tr-bl1 — Blind Fiord — Siltstone; minor shale, sandstone and conglomerate

PERMIAN
  Guadalupian
    Sabine Bay Group

PEs7 — Trold Fiord — Siltstone, sandstone; minor bioclastic limestone, conglomerate and chert

PEs5 — Degerbols — Light coloured limestone and chert

PEs4 — Esayoo — Basalt flows, minor pyroclastic rocks

  Cisularian

PEr2 — Raanes Great Bear Cape — Light grey chert, weathers white; cherty, medium bedded limestone

CARBONIFEROUS AND PERMIAN

CPEh2 — Hare Fiord Trappers Cove — Dark grey to black shale and chert; minor limestone

CPEn3 — Nansen — Light coloured limestone, minor sandstone, siltstone and shale

CARBONIFEROUS

Co1 — Otto Fiord — Anhydrite, gypsum, minor limestone and shale

Co2 — Otto Fiord — Gypsum, with included blocks and masses of anhydrite, dolomite and limestone

Figure 5. Lithological legend for Figures 2, 3 and 4. Modified from [9] and [10].

THE USE OF STRUCTURE FROM MOTION TO PRODUCE A HIGH RESOLUTION DIGITAL ELEVATION MODEL OF THE WHITE GLACIER BASIN, AXEL HEIBERG ISLAND

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Introduction

High resolution digital elevation models (DEMs) are valuable for mapping and understanding geological and glaciological processes in alpine basins, but are frequently unavailable for locations in the Canadian Arctic. In this study we describe the use of a series of oblique aerial photographs using the Structure from Motion method to derive a new DEM (5 m resolution) and orthoimage mosaic (1 m resolution) of the White Glacier basin, Axel Heiberg Island. Data collection was based on a helicopter-based air photo survey in July 2014, which acquired >400 oblique photographs with a Canon EOS 6D SLR camera set to a focal length of 24 mm. Camera exposure settings were optimized for the bright conditions typical of a heavily glaciated region, and images were taken every 3 seconds to ensure overlap of at least 80% between adjacent scenes.

Results

The photos were input into the Structure from Motion software Agisoft, and initially processed by 'aligning' them through automated feature detection and manual entry of 15 ground-control points and 38 tie points. The initial point cloud (locations with x, y, z coordinates) were built, and then filtered to remove erroneous values. For the final DEM, >225,000,000 matching points were automatically identified in the photos by Agisoft, and interpolation was undertaken between match points to create a continuous topographic surface. The photos were also orthorectified with this DEM to produce a new high resolution record of surface conditions across the study area. This process enabled the production of a new 1:10,000 map of the White Glacier basin (Figure 1) [1], and highlights the potential of the Structure from Motion method to improve mapping of the Between Lake massive sulphide showing for the HALIP project [2].

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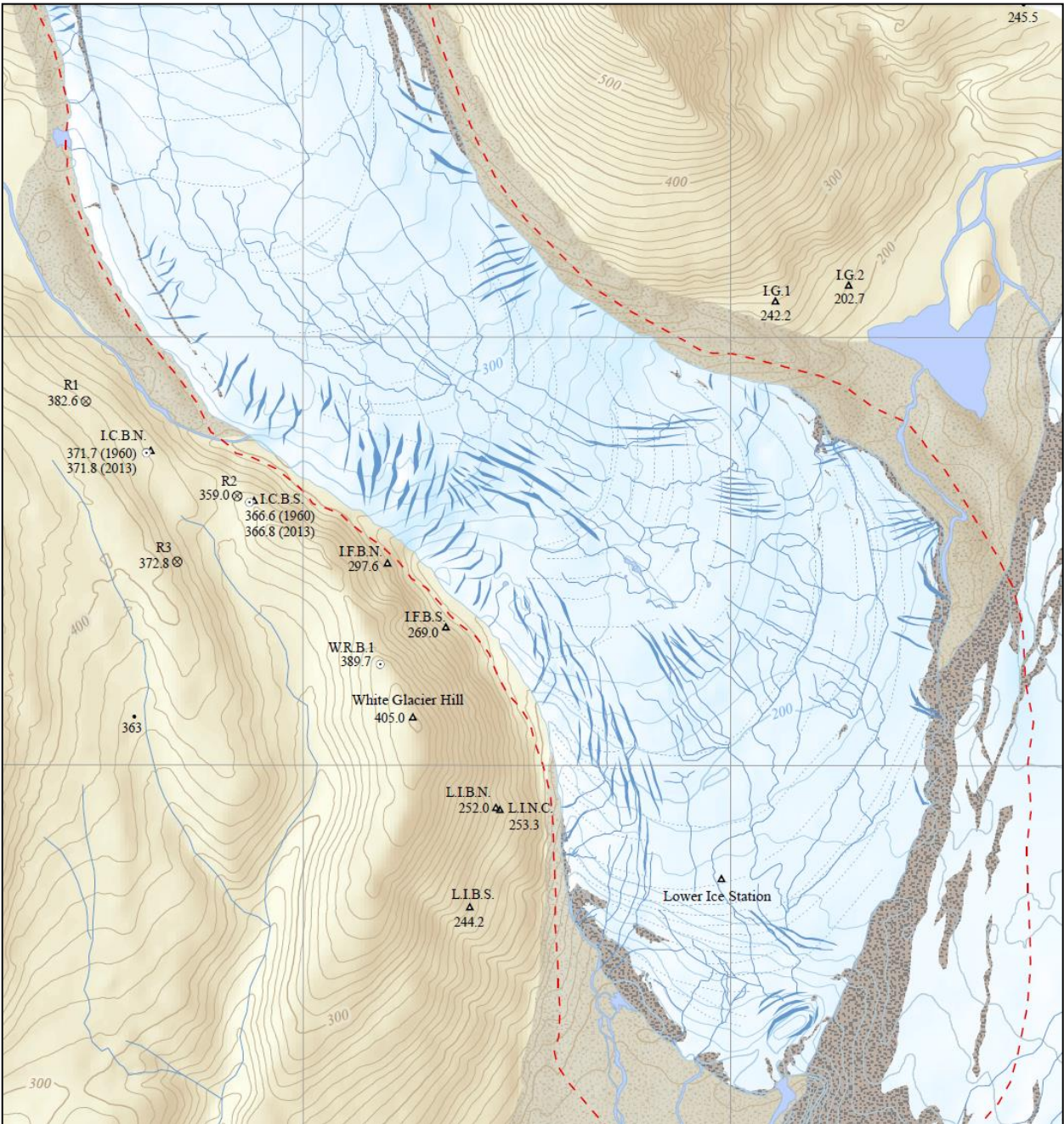
Figure 1. Example of a section of the new 1:10,000 map of the White Glacier basin derived from processing >400 oblique photographs using Structure from Motion software.

LARGE SCALE TARGETING FOR NI-CU-PGE SULPHIDE DEPOSITS USING A MINERALS SYSTEMS APPROACH: AN EXAMPLE FROM WEST AFRICA

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Introduction

Can we enhance the discovery success rate by the way we explore for magmatic sulphide deposits? In order to identify the footprint of an economic deposit there is a need to understand the entire system. The mineral systems concept was introduced in 1991 by the petroleum industry [1]. This approach was subsequently adopted by a number of companies exploring for Ni-Cu-PGE deposits, including Falconbridge Ltd in the late 1990's. The objective was to reduce the risks associated with exploration by only exploring in the most prospective areas. The concept has been refined in recent years and is now widely applied in mineral exploration for most deposit types [2].

Mineral system approach and recent advances in magmatic mineralisation

Mineral systems analysis means understanding the combination of geological processes required to form and preserve ore deposits at all scales [3, 4]. Mineral systems are complex dynamic systems and using a mineral system approach focusses on answering the question of "where" deposits form rather than "how" they form [2].

In the case of magmatic Ni-Cu- PGE systems, a world class deposit can be present if the following four conditions are met (Figure 1, [2]):

1- **Fertility**: mafic and ultramafic rocks, sulphide saturation, presence of sulphides and favourable magma sources [5, 6].

2- **Favourable whole lithospheric architecture**: Paleo architecture, subcontinental lithospheric mantle (SCLM), trans lithospheric faults. These features provide focused melt transport to the upper crust [7,8].

3- **Favourable (transient) geodynamics**: focused magma conduits (chonoliths), high magma volume, early magmatic events, e.g. roots of Large Igneous Provinces (LIPs) [5,6,7,8].

4- **Preservation** (primary depositional zone).

Targeting for Ni-Cu-PGE magmatic sulphides in West Africa

Newgenco Pty Ltd and First Quantum Minerals Ltd started a three and a half years target alliance in 2010 over West Africa. This alliance covered three countries: Mali, Côte d'Ivoire and Burkina Faso. The first phase consisted in craton-scale targeting.

The initial exploration phase involved gathering and compiling all available datasets and reports; establishing in-country contacts, collaborations with research groups (WAXI-AMIRA) and local governments; and finally creating local companies in order to apply for and obtain permits.

Both in West Africa and in other parts of the world that have similar laterite coverage, the number of magmatic Ni-Cu-(PGE) sulphide deposits discovered is minimal compared to similar non-lateritised terrains. In West Africa, favourable lithospheric architecture for magmatic Ni-Cu-PGE was present. However, knowledge of the geodynamics, favourable magma sources and fertility was unavailable mostly because of lack of information at the time. There had also been little or no base metal exploration since the mid-60's when the BRGM (Bureau de Recherche Géologique et Minière) and the UNDP (United Nations Development Program) conducted large scale stream sediment and soil geochemical surveys. Exploration was always strongly focused on gold.

Using all the available information from previous compilations and using a mineral systems approach, we selected 54 Areas of Interest (AOI) for follow-up work. After conducting field reconnaissance and analysing grab samples taken from priority targets, a total of 9 projects were

generated. Three Joint Ventures (JV) were then created over the best projects.

Many difficulties were encountered during the targeting phases in West Africa. These include: the lack of good geological and geophysical coverage; frequently difficult access; poorly-developed infrastructure; and civil wars, social unrest and local violence.

The objectives were achieved in spite of these issues. Eight new areas with multiple clusters of mafic and ultramafic intrusions, several of which are PGE-Ni-Cu-anomalous, were identified. The most significant new area is located in north central Burkina Faso where magmatic PGE-Ni-Cu-rich sulphides were identified in outcrop and subsequently in diamond drilling. Exploration work is ongoing on this project.

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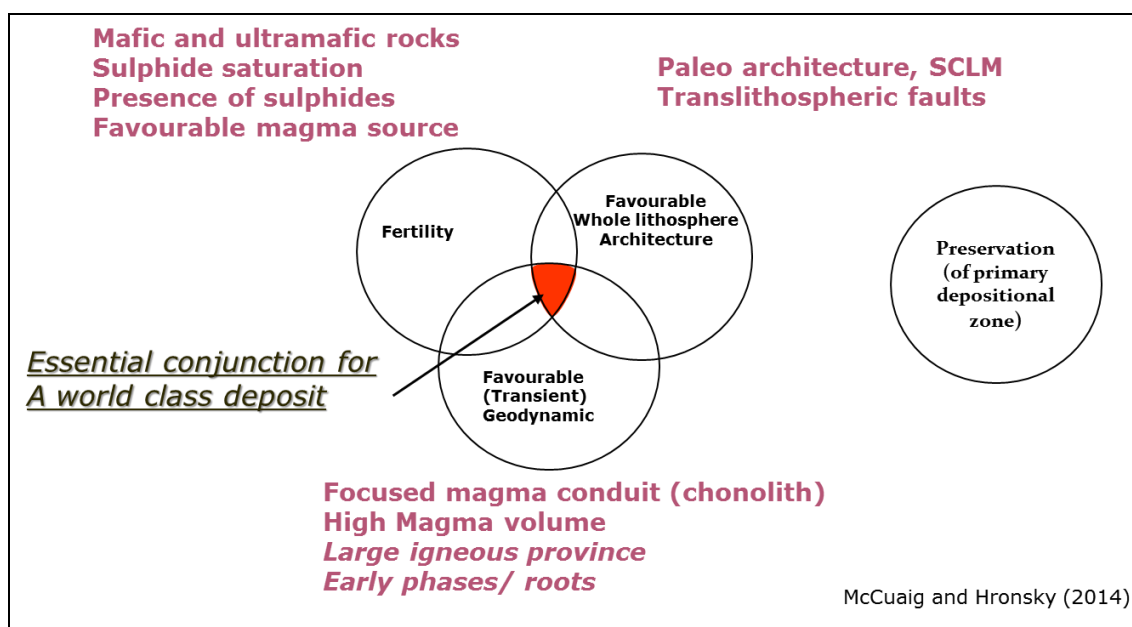
Figure 1. Regional targeting – Mineral systems approach.

LARGE IGNEOUS PROVINCES AND RESOURCE EXPLORATION: IMPLICATIONS FOR MINERAL AND HYDROCARBON EXPLORATION IN THE HIGH ARCTIC

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Large Igneous Provinces (LIPs)

LIPs represent large volume (>0.1 Mkm^3; frequently above >1 Mkm^3), mainly mafic (-ultramafic) magmatic events of intraplate affinity, that occur in both continental and oceanic settings, and are typically of short duration (<5 m.y.) or consist of multiple short pulses over a maximum of a few 10s of m.y. [1, and references therein]. They comprise volcanic packages (flood basalts), and a plumbing system of dykes, sills and layered intrusions. They can also be associated with silicic magmatism, carbonatites and kimberlites. LIP events are linked with continental breakup, global climate change including extinction events, and represent significant reservoirs of energy and metals that can either drive or contribute to a variety of metallogenic systems. In addition, LIPs can also affect hydrocarbon and aquifer systems.

Five-Part Classification System of LIPs and Resource Exploration

The relationships between LIPs and resource exploration can be condensed into five distinct categories with partial overlap[1,2]:

(1) LIP magmas that directly generate mineral deposits (e.g., orthomagmatic Ni-Cu-PGE sulphides, or Nb-Ta-REE and diamonds for often LIP-related carbonatites and kimberlites, respectively);

(2) LIP magmas that provide energy, fluids, and/or metals for ore types such as hydrothermal volcanogenic massive sulphide (VMS) and iron oxide-copper-gold (IOCG) deposits (the latter also including the silicic components of LIPs or SLIPs) and as a heat source that drove hydrocarbon source rocks to maturation or over-maturation;

(3) LIP rocks (particularly sills and dykes) that act as barriers to fluid flow and/or as reaction zones that control mineralising events (e.g. during the formation of some Au deposits), acted as structural traps within hydrocarbon systems, or formed impermeable barriers that controlled water flow and hence aquifer formation;

(4) weathering of LIP rocks that forms Ni–Co laterites and Al bauxites from exposed LIP mafic-ultramafic rocks in tropical climates and residual Nb, Ta, and REE laterites from LIP-associated carbonatites; and

(5) indirect genetic links between LIPs and ore deposits, where LIP events linked to continental breakup generate a 'barcode' record that can be used to correlate between crustal blocks and reconstruct Precambrian supercontinents. This barcode enables the tracing of metallogenic belts between presently separated but formerly contiguous crustal blocks. In addition, links can be recognized between major continental breakup events (associated with LIPs) and distal compression and transpression in the plate tectonic circuit (leading to the formation of orogeny-related deposits, such as orogenic Au mineralisation).

Application to HALIP

The proposed five-part classification system provides a framework for assessing metallogeny and hydrocarbon potential associated with the High Arctic Large Igneous Province (HALIP).

Metallogenic Implications: Applying geochemical criteria that can be used to discriminate between mafic-ultramafic rocks and LIP events that are prospective and unprospective for magmatic Ni-Cu-PGE sulphide mineralisation (e.g., [3]) strongly suggests that the older tholeiitic portions of the HALIP are prospective targets for exploration for magmatic Ni-Cu-PGE sulphide mineralisation [4]. A giant radiating dyke swarm defines a plume centre for this event (e.g. [5,6]) and areas proximal to plume centres are known to be favourable for Ni-Cu-PGE deposits [2], sug-

gesting these areas should be prioritised for mineral exploration. A large layered intrusion has also been identified geophysically on western Ellesmere Island (81°30'N, 92°W) ~ 100 km SSE of the plume centre [7] and the gabbroic sections of the Wootton intrusion [8] on NW Ellesmere (82°10'N, 85°W) about 100 km ESE from the plume centre may also be prospective for magmatic sulphide mineralisation.

In addition to the magmatic sulphide prospectivity of this LIP, some of the sedimentation within the Sverdrup basin was coeval with the HALIP event, presumably during a pulse of rifting in this area, suggesting that this contemporaneous sedimentation and magmatism may have generated sedimentary exhalative (or even volcanogenic massive sulphide) -type mineralisation in this region, although further investigation is required.

The presence of gossans hosted by evaporites, siliclastic sediments, and mafic breccias in this region (e.g., [9-11]) also suggests potential for hydrothermal-type mineralisation linked with the HALIP event. However, this relationship need to be further examined, both to determine whether these gossans are indicative of high mineral exploration potential and to determine what (if any) relationship there is between the HALIP event and the generation of these sulphides, either as a source of heat and energy, as a source of metals, or as reaction zones that enable the precipitation of sulphides (i.e. classification types 2 and 3 above).

The potential for HALIP-associated carbonatites and kimberlites should also be considered (see classification type 1; [1, 2, 12]).

Hydrocarbons: It is unclear whether hydrocarbons in the Sverdrup basin are affected by the HALIP event, for example by a thermal influence on their maturity or overmaturity (e.g. [13] cf. [14]). Another aspect is the potential for HALIP magmatism to contribute to the mafic trace element geochemistry of the Cenomanian-Turonian boundary and more broadly to the anoxia event recorded at this time (e.g. [15]), suggesting that this LIP (and potentially others) may have distal influence on hydrocarbon systems (as suggested in [1]).

Conclusions

The five-part classification system outlined above provides a framework for assessing metallogeny and hydrocarbon potential associated with the HALIP as well as foci for future research. Such research is vital in terms of furthering our understanding of the prospectivity of this LIP, prioritising areas and commodities for exploration and research, and overall assessing the role of this LIP in generating and influencing mineral and hydrocarbon resources in the Arctic and beyond.

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NI-CU-PGE PROSPECTIVITY OF THE HALIP, CANADIAN ARCTIC ISLANDS: FIELD-BASED EVIDENCE OF STRUCTURAL CONTROLS ON INTRUSIVE STYLE

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Introduction

Pioneering work by researchers such as A.J. Naldrett, R.R. Keays and P.J. Lightfoot has led to hundreds of contributions on the petrological geochemical controls on the genesis of magmatic Ni-Cu-PGE deposits. In contrast, the importance of physical controls (i.e., wall rock structure, intrusion emplacement and assembly, magma fluid dynamics) on their genesis has only recently been appreciated, and these controls are still poorly constrained. In order to properly evaluate the Ni-Cu-PGE potential of any magmatic system, at any scale, such controls must be fully considered.

Geologic Context

Portions of the Cretaceous (~ 130-80 Ma) High Arctic Large Igneous Province (HALIP) occurring in Canada's Arctic Archipelago is prospective for magmatic Ni-Cu-PGE (platinum group element) mineralization, based on geochemical evidence [1] and similarities to world class mining camps such as Norils'k-Talnakh, Russia [2]. Recent and ongoing research on the HALIP focuses on further constraining areas of prospectivity based on the structure and architecture of the system [3], from the provincial scale to that of 1-10 km volcano-intrusive complexes.

At regional scales, the distribution of components of the HALIP provides a first order constraint on prospectivity. Although extrusive components (i.e., basalts) of the HALIP are generally restricted to exposures on Axel Heiberg Island and northwestern Ellesmere Island, updated mapping of intrusive components of the HALIP (i.e., diabasic to gabbroic sills and dykes) indicates that these extend far southwestwards and southwards beyond these Islands, and are 3-5 times more important in volume [4] (Figure 1). Regional-scale prospectivity will be further constrained by the availability of legacy samples [5], recent field work [6], mapping and sampling performed in the summer of 2015 [7] and future fieldwork.

Structural Context

The prospectivity of the HALIP can also be constrained by considering the local-scale architecture of volcano-intrusive complexes. Ni-Cu magmatic sulfide deposits are typically hosted within 1-10 km scale, structurally complex feeder systems [8]. These must be uplifted to be exposed, and therefore post-emplacement structure of the HALIP (i.e., the Eurekan Orogeny) strongly constrains the potential of the HALIP. Structurally complex feeder systems can occasionally have irregular to tube-like geometries that are informally known as "chonoliths" ([8], Figure 2); however, irregular intrusion geometries can often be explained by structural processes (e.g., intermittent fault activity) or the amalgamation of dykes and sills. Such feeder systems are ideal sites of Ni-Cu-PGE mineralization because they promote high magma fluxes and protracted magma flow-through, thereby favouring the interaction between metal-bearing mafic magmas and sulfide liquids that are progressively enriched in metals. Several km-scale magmatic complexes of the HALIP show first-order architecture that would favour Ni-Cu-PGE potential; two notable examples include the intrusive complexes exposed at Middle Fiord (Western Axel Heiberg Island) and on the Wootton Peninsula (Northern Ellesmere) (Figure 1). Intrusive complexes at Middle Fiord are currently the focus of detailed studies [7]. Additional field work in this area is planned for the 2016 field season on Axel Heiberg Island.

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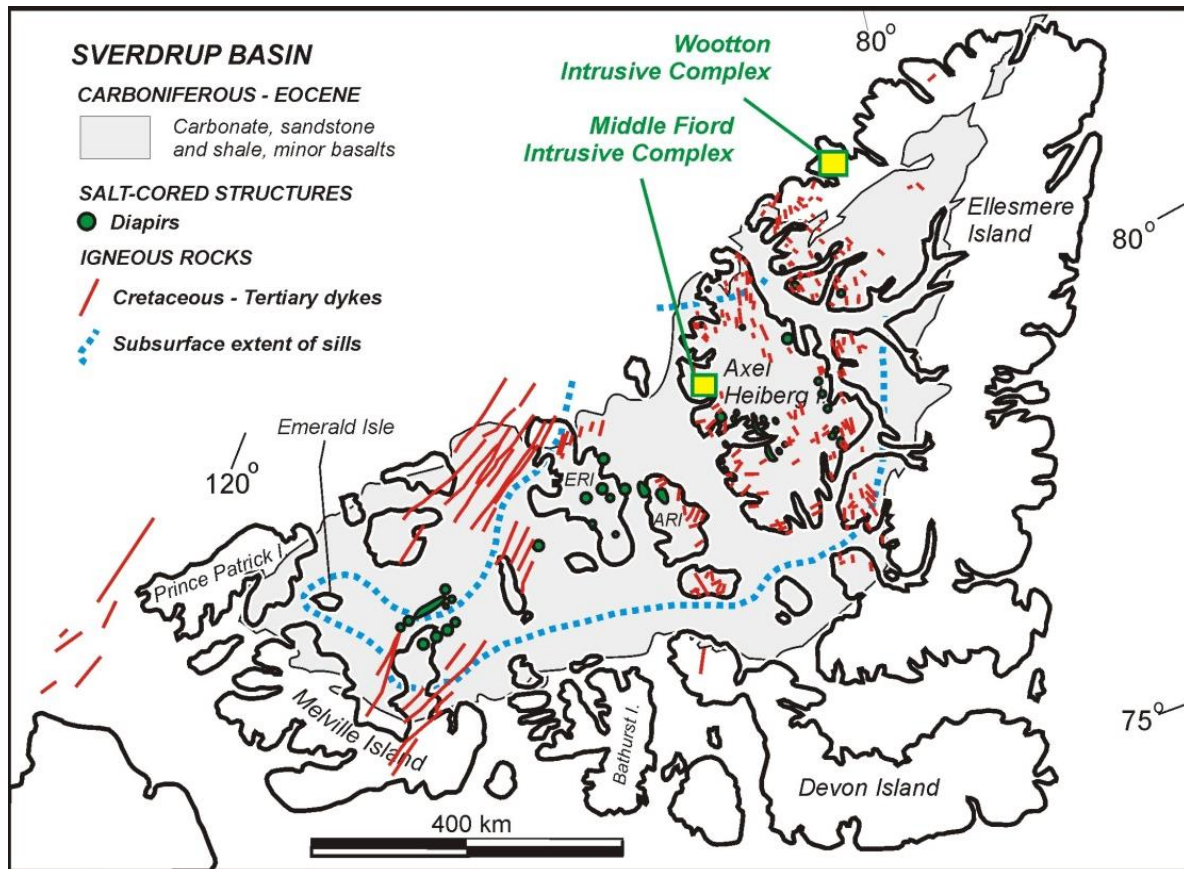
Figure 1. Simplified map of the Sverdrup Basin and the intrusive components of the HALIP (after [4]). **ERI**: Ellef Ringnes Island; **ARI:** Amund Ringnes Island.
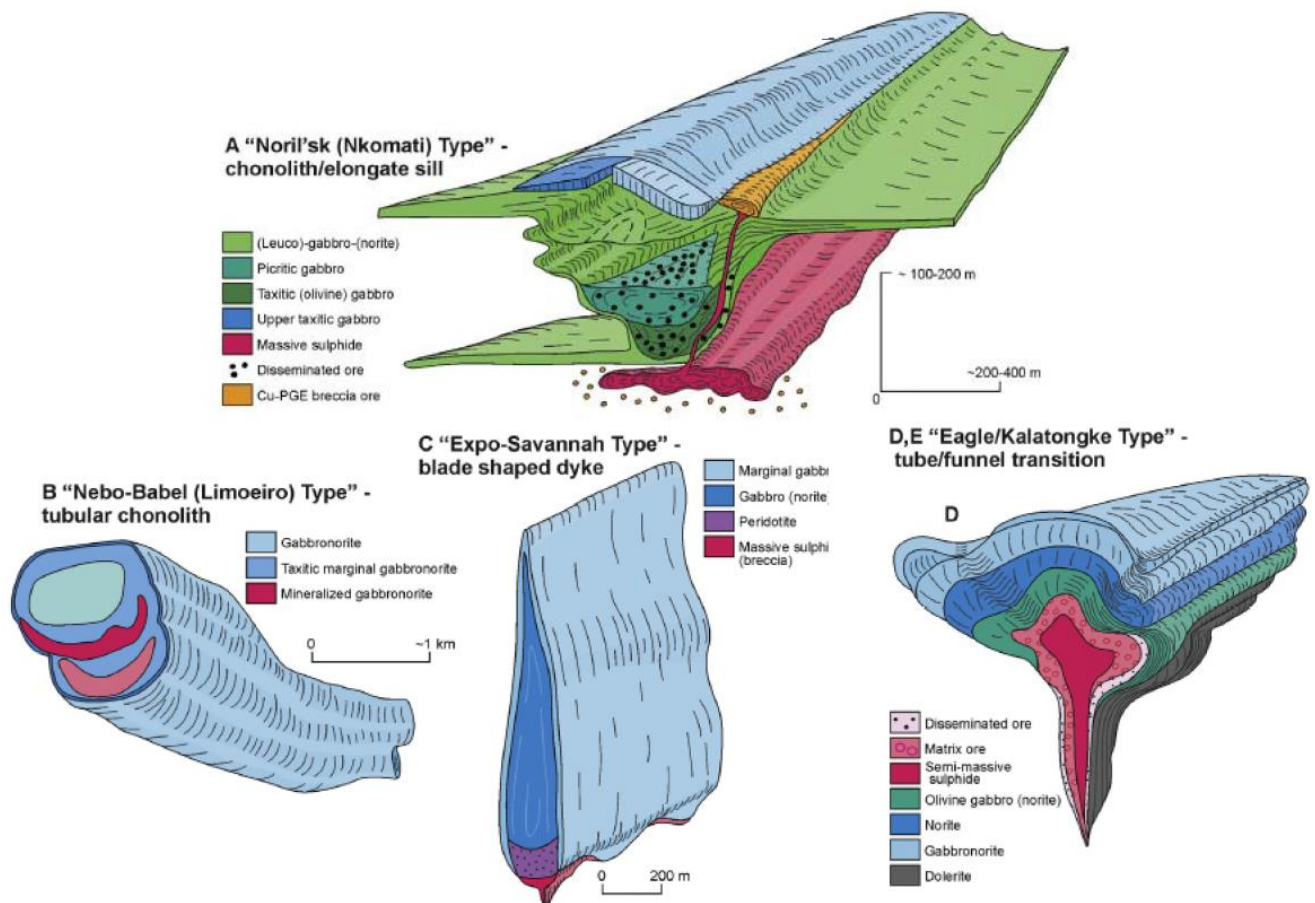
Figure 2. Characteristic geometries of intrusions hosting Ni-Cu-PGE mineralization (after [8]).

QUANTITATIVE MLA-SEM MODAL MINERALOGY OF GOSSANS AND STREAM SEDIMENTS IN THE HALIP: IMPLICATIONS FOR ECONOMIC POTENTIAL

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Introduction

A series of thirteen gossan samples and ten Heavy Mineral Concentrates (HMCs) of stream sediment samples from the South Fiord area, Axel Heiberg Island were analysed by Mineral Liberation Analysis – Scanning Electron Microscope (MLA-SEM) at the Memorial University CREAIT laboratories. The gossan samples and the stream sediment samples were collected in 2013 by the Geological Survey of Canada as part of the Arctic Gossans Activity of the Environmental Geoscience Program [1]. The MLA-SEM research was conducted as part of a reconnaissance project examining mineral phases developed in gossans and stream HMCs from Axel Heiberg Island.

The gossan samples were collected from two different locations in the South Fiord region (Figure 1; see [2] for detailed stratigraphic framework). Four samples were collected from the Dome Gossan and nine samples from the Ridge Gossan (Figure 2; see [3] for details on the morphology and classification of gossans). The HMCs were collected from streams in the study area (Figure 2) with the objective of determining the influence of gossans on the mineralogy of sediments and chemistry of waters (Figure 3) [4,5].

Approximately 0.3 g of material from each sample was mounted in an epoxy puck and polished for MLA-SEM analysis following the method described by Wilton [6,7]. The resulting sample surface essentially represents a mono-layer of the sample material.

MLA-SEM Data

HMC Samples: Results of the MLA-SEM analyses indicate that the stream sediment HMC samples consist predominantly of diopside, ilmenite, pyrite, quartz, and hornblende mixtures; with the pyrite generally containing a minor arsenic content. Diopside is the most common mineral in all samples with one exception. Ilmenite is the second most common mineral in all samples with one exception as well.Quartz is the third most common mineral in all but two samples. All samples contain pyrite ranging from 1 to 20% of the HMC minerals. Barite is a "top ten" mineral phase in four samples and seems to be inversely related to the presence of Celestine ("top ten" mineral in two samples with low barite). Both hornblende and Fe-Hornblende are common in most samples.

Previous indicator mineral analyses by visual picking [4] indicated the predominance of clinopyroxene (62 to 83% of grains) and ilmenite (4 to 19% of grains) in the HMC's, suggesting that these minerals were derived from basalts in the region. The substantial presence of barite and pyrite in the HMC's was described as being indicative of local evaporite diapirs [4]. The significant celestine and anhydrite components detected by MLA-SEM were presumably derived from the diapirs as well.

MLA-SEM analysis maps confirm the presence of cinnabar in one sample (Figure 4A) as well as chalcopyrite, sphalerite and galena in other samples. In two samples, the MLA-SEM identified partly oxidized, framboidal pyrite (Figure 4B); presumably indicative of low temperature sulphide deposition. Chalcopyrite, sphalerite, galena and cinnabar had been reported from tradional indicator mineral analyses of the HMC's[1].

Gossan Samples: In the Dome Gossan samples (Figure 2), three samples were found to be predominantly composed of anhydrite (76 to 83 modal %) and the fourth mainly contained albite (30%) and perthite (15%) with 10% anhydrite. These samples contained 0.36 to 2.69% gossan grains (oxidized Fe sulphide) and 0.9 to 1.15% slightly oxidized pyrite; the 1.15% sample also contains 0.03% pyrite with arsenic contents similar to that observed in the stream HMC's. Interestingly, 0.22 to 1.72% Rare Earth Element

mineral grains were also observed in these samples.

The greatest variations in mineralogy were observed in the Ridge Gossan samples (Figure 2). One subgroup of four samples contained from 77 to 84% modal quartz with albite and tourmaline as common components. Within the remaining five samples, three are composed of 15 to 28% quartz with nearly equivalent amounts of perthite and lesser significant amounts of clay and albite. The final two samples contain 19 to 29% gossan grains with 9 to 10% slightly oxidized pyrite. These later samples also contain 4.81 to 4.92% jarosite; jarosite is also present (0.5 to 0.52%) in Dome Gossan samples (Figure 5A). Magnetite (at 0.55 to 2.12%) is more common in the last five samples.

One cinnabar grain was identified in one Ridge Gossan sample and as was one cobaltite (CoAsS) grain in another Ridge Gossan sample (Figure 5B).

Conclusions

The MLA-SEM technique applied to HMCs and gossans from the HALIP on Axel Heiberg Island provides a quantitative measurement of mineral phases present in each type of sample. The MLA-SEM data defined considerable differences in the mineralogical compositions of the different gossans which reflected the protolithologies of each gossan. This study suggests that MLA-SEM analysis of gossan samples from regional reconnaissance surveys can provide timely and cost-effective economic potential evaluations of gossans. In a regional sense, examination of gossans specifically associated with HALIP magmatic systems might be able to pinpoint areas of particular economic potential.

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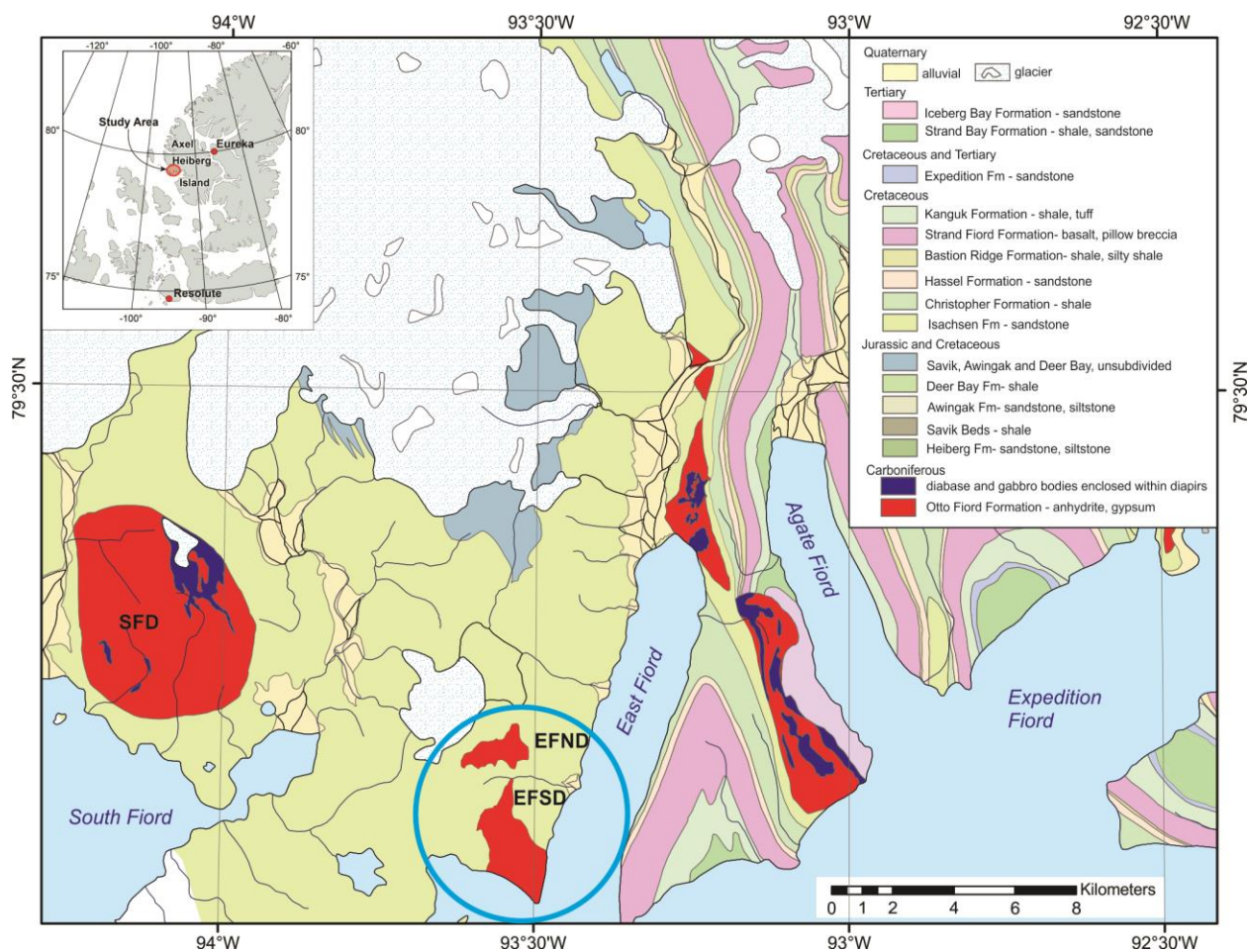
Figure 1. Simplified geological map of the Strand Fiord-Expedition Fiord area, Axel Heiberg Island (modified from [2]). The 2013 study area is shown by the blue circle.
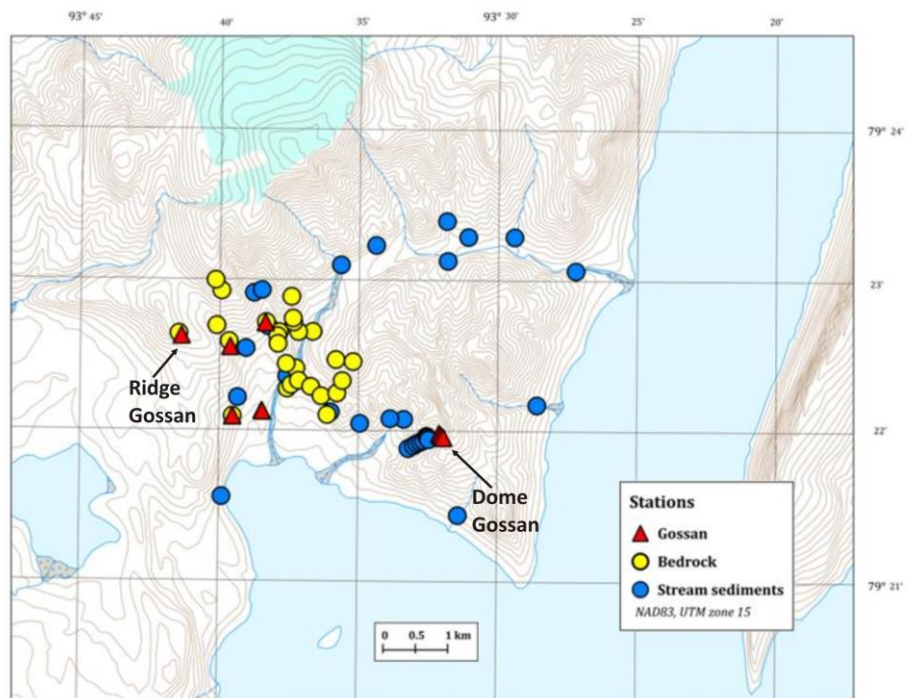
Figure 2. Topographic map of the 2013 study area showing the sampling stations for bedrock, gossans, and stream sediments [5].
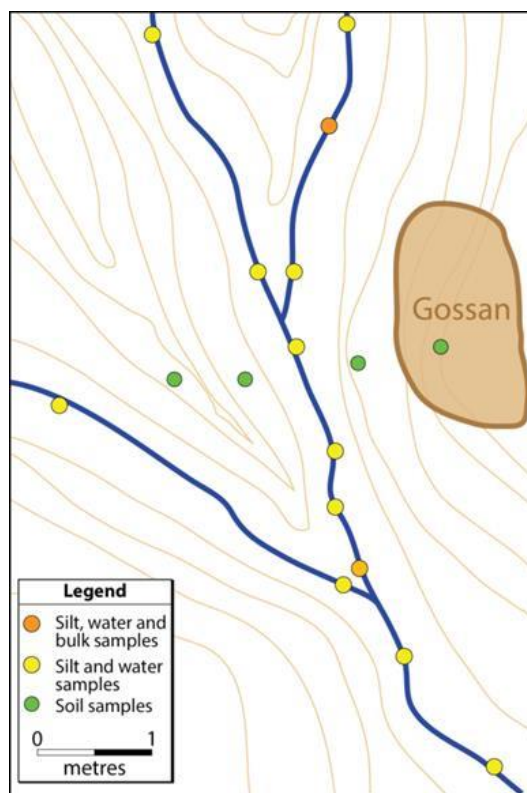

Figure 3. Idealized sampling plan of a detailed drainage study to identify the areal extent of the geochemical and mineralogical signature and dispersion down drainage of a known gossan [5].
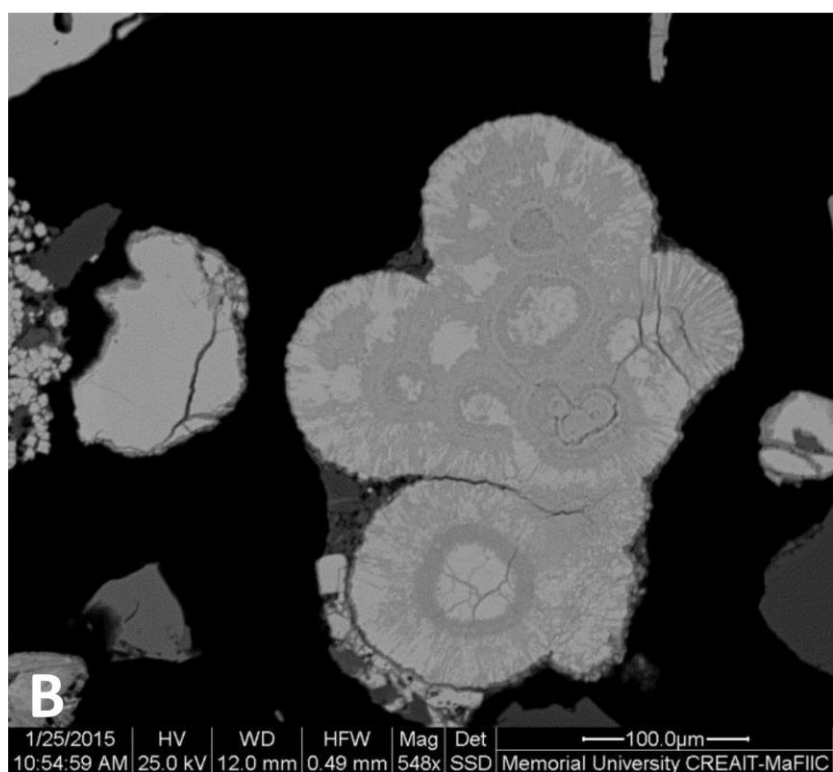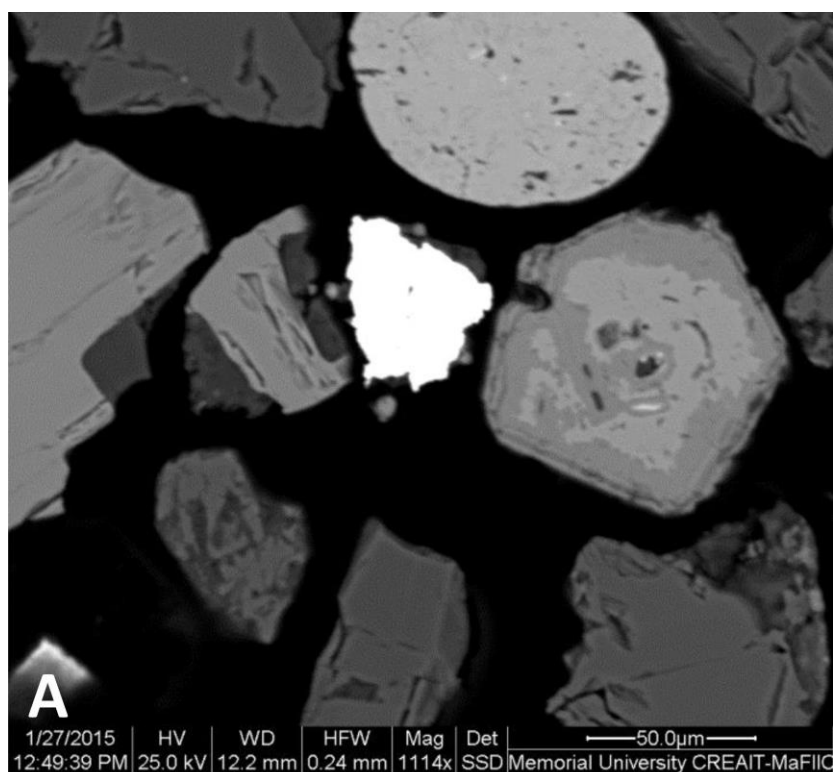
Figure 4. Mineralogy of HMCs in stream sediments, South Fiord area, Axel Heiberg Island. **A.** BSE-SEM image of cinnabar (bright) in stream sediment HMC; note scale bar in lower right. **B**. BSE-SEM image of framboidal pyrite in stream sediment HMC; note scale bar in lower right.
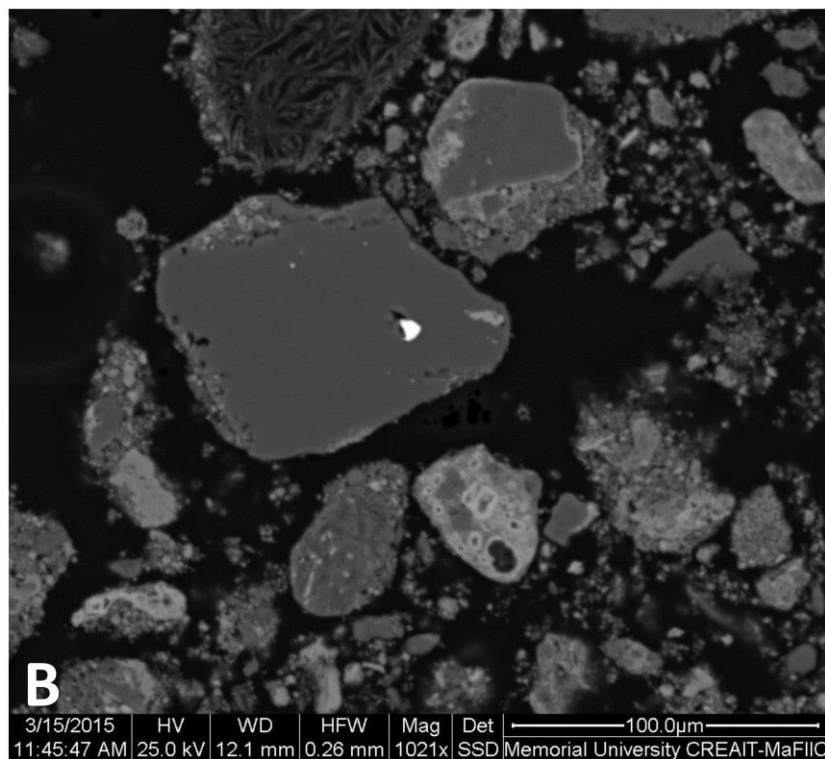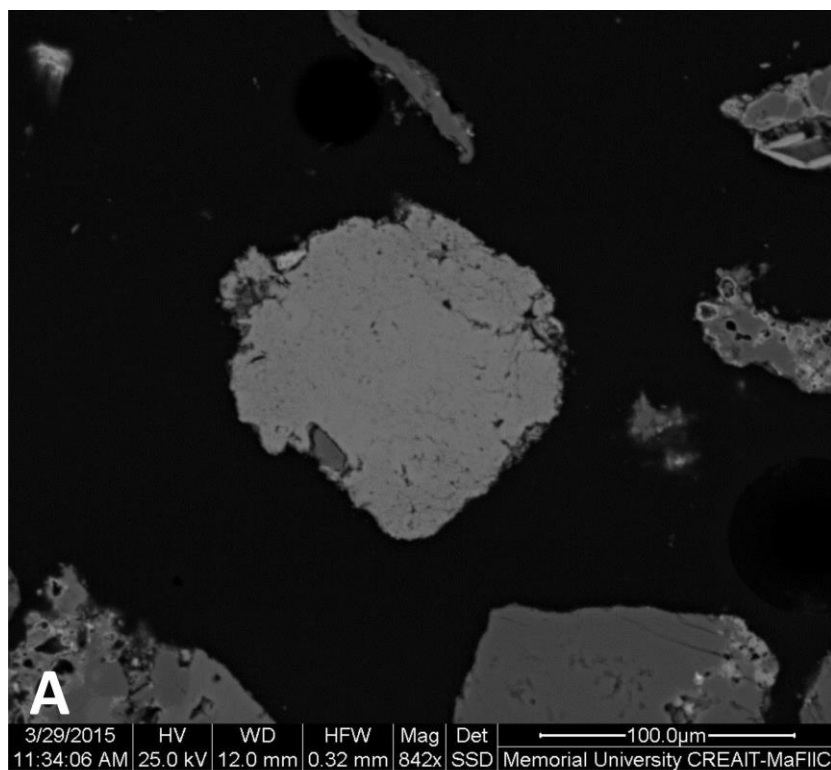
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Figure 5. Mineralogy of gossans, South Fiord area, Axel Heiberg Island. **A.** BSE-SEM image of jarosite in Dome Gossan; note scale bar in lower right. **B.** BSE-SEM image of cobaltite (bright) inclusion in quartz, Ridge Gossan; note scale bar in lower right.

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ORIGIN OF BASE METAL SHOWINGS ASSOCIATED WITH EVAPORITE DIAPIRS AND HALIP INTRUSIVE ROCKS

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Introduction

The High Arctic Large Igneous Province (HALIP) exposed on Axel Heiberg Island consists of sills, dykes and flood basalts emplaced in the thickest Mesozoic succession of the Sverdrup Basin. Sills and dykes locally intrude some of the evaporite structures found on the island. The common occurrence of metal-rich breccias, gossanous soils and alteration zones suggest that hot fluids may have concentrated base metals where igneous rocks and evaporites from a mélange. Recent studies indicate that sulphide-rich chimneys and alteration zones occur within and/or at the periphery of evaporite diapirs [1-4].

Gossans are widespread in the Strand Fiord-Expedition Fiord area, in western Axel Heiberg Island, where salt diapirs and canopies modify the regional stratigraphy (Figure 1). In this region, a 60 km wide structural area is interpreted to detach on a shallow, partly exposed canopy of coalesced evaporite sheets [5]. Metalliferous, pipe-like structures are prominently exposed at the periphery of some of the still-rising, "active" diapirs in this region. There is also evidence of past hydrothermal activity along the margins of some "dormant" evaporite diapirs [5]. In this report, we describe base metal showings in four areas (Figure 2) and discuss some aspects of their metallogenesis.

Base Metal Showings

North Agate Fiord Diapir

In this area (Area 1, Figure 2), basaltic rocks and sandstones in the Isachsen Formation and Strand Fiord Formation form a mélange with anhydrite. Alteration zones at the periphery of the North Agate Diapir contain pyritiferous structures which typically measure 2 to 5 meters in cross-section. The structures consist of a central sulphide-rich breccia surrounded by wide bands of whitish-yellow to ochre alteration. Some mineralized zones (predominantly altered basalt) contain up to 25% chalcopyrite by volume [1].

South East Fiord Diapir

Field work at this locality (Area 2, Figure 2) resulted in a unique mineralogical and geochemical database pertaining to gossans and stream sediments. Heavy mineral separates collected during the stream surveys yielded remarkably high concentrations of chalcopyrite [6]. Remnant cone-shaped breccia deposits and the associated gossans sampled along the walls of South East Fiord Diapir, for example, are similar to the pipe-likes structures found in Area 1 [3].

Junction Diapir

At Junction Diapir (Area 3, Figure 2), carbonate breccias and blocks of basaltic rock occurring in a 'chaotic zone' at the tail of the evaporite dome contain mineralized alteration zones [1]. Thin sections of altered, porphyritic, and amygdaloidal basaltic flows sampled show relict textures and 5-10 % pyrite occurring in concentrated zones.

Between Lake

A massive sulphide showing was discovered at this locality in 2008 (Area 4, Figure 2) [7]. The outcrop consists of buff to grey dioritic host rocks exposed over an area of ~ 5 m by 20 m. The igneous host is in contact with a heterogenous deposit consisting of highly altered breccia, gabbro scree and gossanous soil. Our preliminary analysis of the massive sulphide indicates that it is dominated by pyrite and pyrrhotite [8].

Salt Tectonics

The bedrock geology of the Strand Fiord-Expedition Fiord region is dominated by the presence of Triassic through Lower Cretaceous mudrocks and coarse clastic rocks intruded by volcanic and intrusive rocks, and overlain by

Late Cretaceous through Eocene sediments (Figure 3). Regional anticlines, which formed during the Paleogene Eurekan Orogeny, trend roughly north on a regular ~20 km wavelength and probably detach on the autochthonous Carboniferous Otto Fiord Formation evaporites [9]. These evaporites comprise halite overlain by thick anhydrite containing thin limestone beds. Unlike the rest of the island, a 60 km wide area, known as the wall-and-basin (WAB) region, has bimodal fold trends and irregular (<10 km) fold wavelengths. Here, crooked, narrow walls of superficially gypsified anhydrite crop out in tight anticline cores, which are separated by wider synclinal mini-basins. The WAB region is interpreted to detach on a shallow, partly exposed canopy of coalesced allochthonous evaporite sheets (Figure 4) [5] [9]. This inference is based on four lines of evidence: (1) a halving of fold wavelength relative to folds outside the WAB region, (2) the exposure of anomalously young strata of Paleogene and Late Cretaceous age, (3) the occurrence of clustered equant mini-basins having similarities to those in the northern Gulf of Mexico, and (4) a strikingly uniform level of piercement pointing to a stratiform allochthonous source layer [5]. A canopy would require an evaporite depocentre, which may have ponded in a sinistral pull-apart basin of Carboniferous age. The strata record a salt-tectonic history spanning the Late Triassic (Norian) epoch to the Paleogene period. Stratigraphic thinning against diapirs and angular unconformities up to 90 degrees indicate mild regional shortening in which diapiric roof strata were bulged up and flanking strata steepened. This bulging culminated during Hauterivian times, when diapiric evaporites broke out and coalesced at the surface to form a canopy. Importantly, burial of the canopy yielded *second-generation diapirs*, which rose between mini-basins subsiding into the canopy (Figure 4). A consistent high emplacement level indicates that all exposed diapirs inside the WAB region rose from the canopy. In contrast, diapirs along the WAB margins were sourced in autochthonous salt as *first-generation diapirs*.

Metallogenesis

Allochtonous evaporite beds and diapirs can focus metalliferous basinal fluids and lead to sulphide mineralization. In the case of volcanic basins, the heat to drive the circulation of hypersaline brines could be supplied by hot basaltic magma erupted as lava flows at volcanic centres or intruded in the sedimentary succession as sills and dykes. A model for salt-allochton controlled base-metal (sedex) accumulation [e.g. 10] could explain the spatial distribution of base metal showings along the margins of the wall-and-basin region. Figure 5 shows, in a conceptual manner, how basinal fluids could become enriched in this type of structural setting, leading to local concentrations of base metals at the periphery of evaporite domes. Work in progress to test this model involves detailed mapping of the White Glacier Basin area to clarify (1) the location and surficial extent of gossans exposed along the margins of Thompson Glacier [11]; and (2) their potential association with faults at the periphery of mapped evaporite structures [5] [8] [9].

Conclusions

The occurrence of base metal showings that appear to be spatially distributed along the limit of the wall-and-basin (WAB) region in the Strand Fiord-Expedition Fiord area suggests that this structural boundary represents a key feature in the search for mineral deposits. The evidence for second-generation diapirs in the WAB region (Figure 4) implies that both regional (deep) and local (shallow) faults could have focused Cu-rich fluids and formed deposits along the margins of the salt canopy. Future work will focus on the White Glacier Basin area, Expedition Fiord, to resolve the origin of significant mineralization associated with a dioritic host at Between Lake.

Acknowledgements

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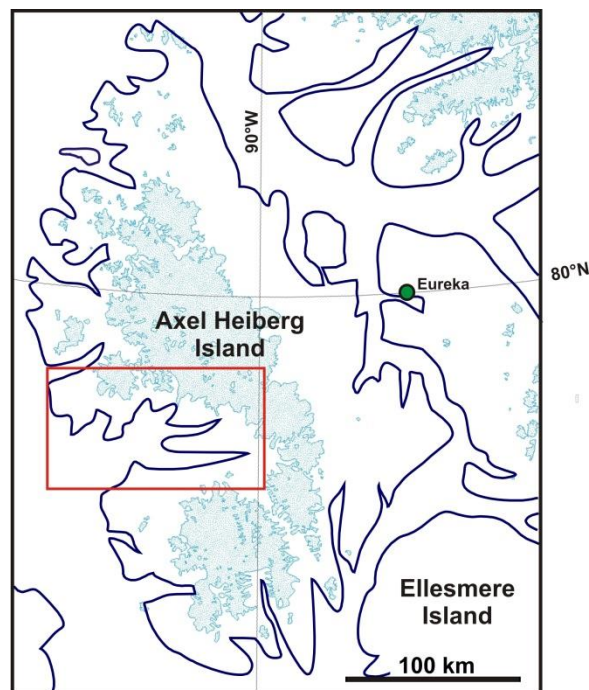
Figure 1. Location of the Strand Fiord-Expedition Fiord area (red box) on Axel Heiberg Island, Nunavut.
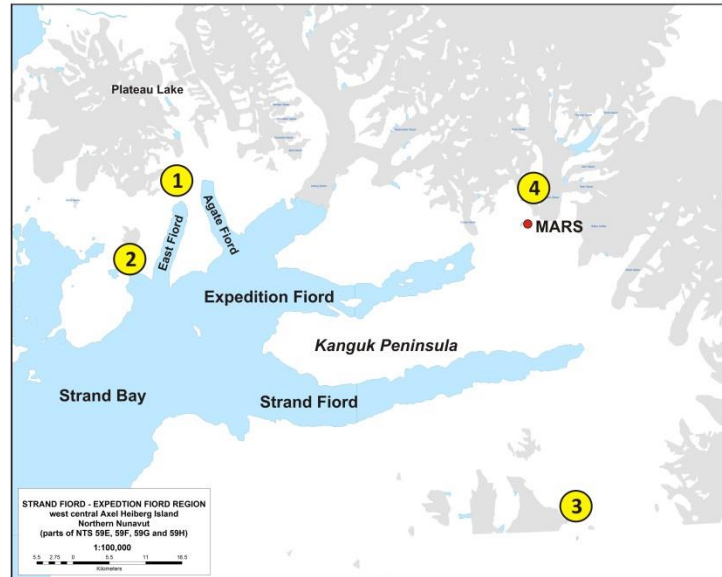
Figure 2. Location of base metal showings in the Strand Fiord-Expedition Fiord area. See text for explanation. **MARS**: McGill Arctic Research Station located in the White Glacier Basin area, head of Expedition Fiord.
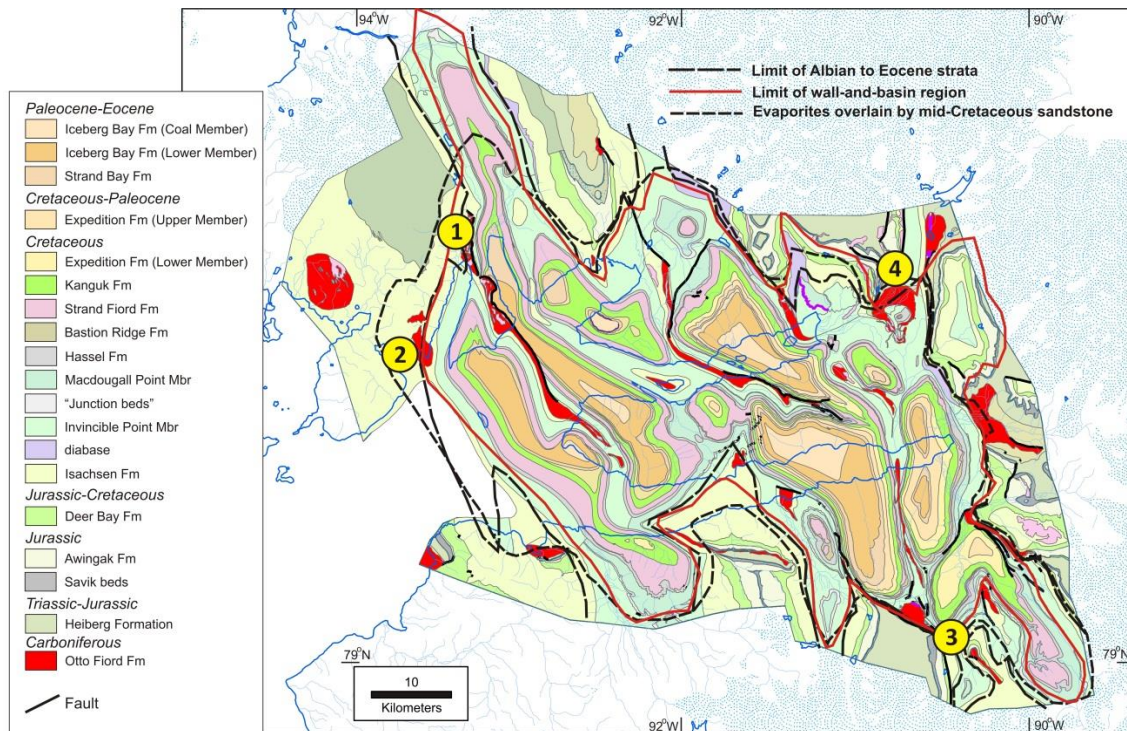

Figure 3. Bedrock geology of the Strand Fiord-Expedition Fiord area showing three proxies to delineate the limits of a salt canopy in this region. The limit of the wall-and-basin region is shown by a red line. Location of base metal showings as in **Figure 2**. Modified from [5].
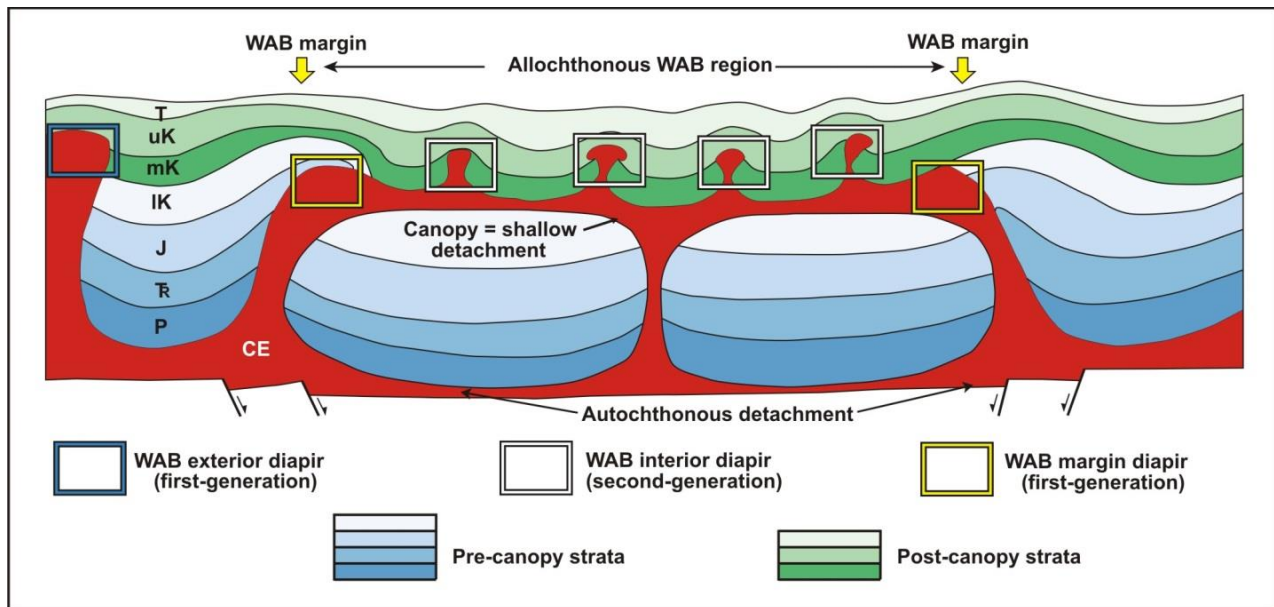
Figure 4. Conceptual sketch of the wall-and-basin (WAB) region in the Strand Fiord-Expedition Fiord area. In this interpretation, a distinction is made between diapirs that are sourced within the autochtonous layer at the margins of the canopy (first-generation) and diapirs that are sourced from a shallow allochtonous salt canopy (second-generation). Labels: **CE**, Carboniferous evaporites; **P**, Permian; **TR**, Triassic; **J**, Jurassic; **lK**, Lower Cretaceous; **mK**, mid-Cretaceous (Albian); **uK**, Upper Cretaceous; **T**, Tertiary (Paleocene, Eocene). Modified from [5].
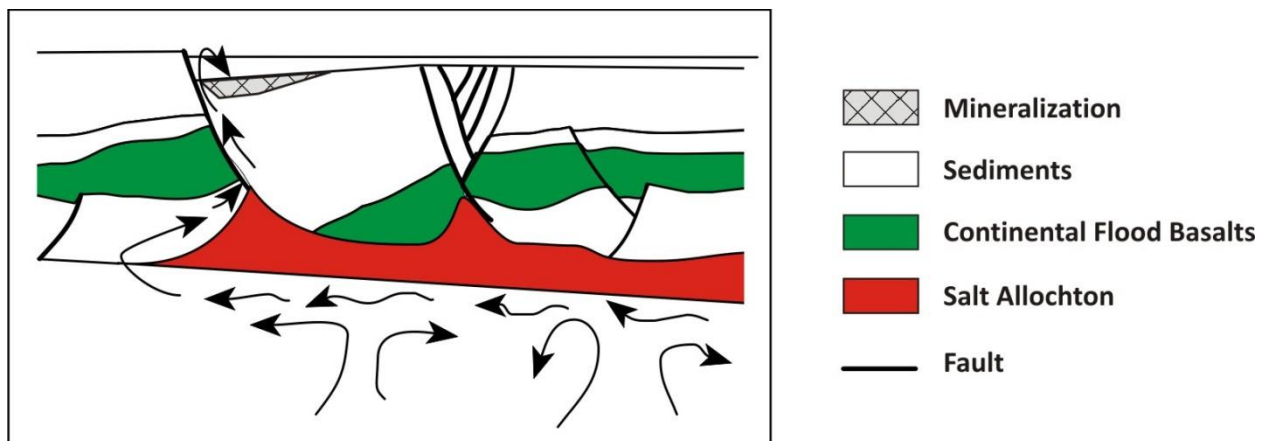

Figure 5. Schematic cross section of a faulted volcanic-sedimentary succession in an extensional setting characterized by (1) a basalt salt allochton and (2) a flood basalt sequence. The **arrows** show a hypothetical path for mineralized fluids to circulate along the detachement surface at the base of the salt allochton and along faults cross-cutting the stratigraphy. Basaltic rocks and/or shales could provide a source of base metals. Modified from [10].